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Achromatic Doublet on Glass Fresnel
lenses for Concentrator Photovoltaic
Systems

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Resumen

En los últimos años, el aumento constante de la demanda energética, junto con un incremento en la preocupación por el cuidado del medio ambiente, han resultado en grandes avances en el campo de las energías renovables. Entre ellas, la energía fotovoltaica (PV del inglés photovoltaic) se ha expandido rápidamente por todo el mundo, consiguiendo un coste de la electricidad (LCOE del inglés levelized cost of electricity) comparable y en muchos casos inferior al de otras tecnologías convencionales basadas en combustibles fósiles. Dentro del campo de la energía solar cabe destacar el papel de la energía solar fotovoltaica de concentración (CPV del inglés concentrator photovoltaic), cuya eficiencia es la más alta de entre todas las tecnologías PV existentes, con un módulo récord del 43 % en el año 2016. En este contexto, esta tesis está basada en el desarrollo, fabricación y caracterización de una nueva óptica para aplicaciones CPV, capaz de incrementar la máxima concentración alcanzable, además de aumentar la tolerancia a los posibles errores de ensamblaje, seguimiento, temperatura y variación del espectro solar, manteniendo al mismo tiempo costes competitivos.

Actualmente, la mayoría de módulos CPV en el mercado, están basados en lentes de Fresnel híbridas de silicona sobre vidrio (SoG del inglés silicone on glass). Esta tecnología debe su éxito principalmente a su excelente estabilidad en el exterior, así como a la sencillez de su proceso de fabricación. Sin embargo, tiene una limitación muy importante: la aberración cromática. Este fenómeno hace que la luz de diferentes longitudes de onda se enfoque a distintas distancias de la lente, limitando la concentración máxima alcanzable a un factor de poco más de 200 soles, sin pérdida significativa de luz. Para atenuar este efecto, los módulos CPV pueden incluir un elemento óptico secundario (SOE del inglés secondary optical element) acoplado a la célula fotovoltaica, que consigue aumentar la concentración y, al mismo tiempo, contribuir a una mayor uniformidad de la luz sobre la célula. Sin embargo, la implementación del SOE en el módulo CPV tiene ciertas desventajas inherentes, como la introducción de una nueva fuente de pérdidas o costes adicionales de fabricación y ensamblaje del propio SOE. En el trabajo llevado a cabo en esta tesis, el objetivo principal es el desarrollo de un nuevo concepto de lente de Fresnel acromática de bajo coste para aplicaciones fotovoltaicas de alta concentración, llamada doblete acromático sobre vidrio (ADG del inglés achromatic doublet on glass). La tecnología de lentes propuesta, gracias al diseño acromático, consigue una atenuación del fenómeno de la aberración cromática, permitiendo aumentar la máxima concentración alcanzable, sin la necesidad de implementar la óptica secundaria, lo que conlleva una serie de beneficios desde el punto de vista económico y de fiabilidad. El diseño de la lentes consiste en un sustrato rígido de vidrio y en una lente de plástico con dientes de Fresnel en ambas caras pegados entre sí mediante un material elastomérico. Eligiendo un par de materiales con propiedades ópticas adecuadas, el concepto de doblete acromático delgado se ha podido poner en práctica, manteniendo además costes bajos gracias a la sencillez del proceso de fabricación. De hecho, la fabricación de la pieza de plástico es realizable por procesos ya desarrollados en la industria como: inyección de plástico, inyección a compresión, o estampado en caliente. Por último, el proceso de fabricación acaba con la realización de la lente ADG por laminación, un proceso con características muy similares al comúnmente usado para laminar los módulos fotovoltaicos planos.

En la primera parte de la tesis, se presenta la investigación llevada a cabo sobre los posibles materiales utilizables en el proceso de fabricación de lentes ADG, y la explicación sobre los

principales motivos que han conducido al desarrollo del diseño actual de lente propuesta. El estudio de optimización del par de materiales que producirían una mayor reducción del fenómeno de aberración cromática se ha desarrollado mediante simulaciones de trazado de rayos basadas en métodos de Montecarlo. De todos los materiales disponibles, finalmente se han seleccionado un elástomero termoplástico (TPE) y el policarbonato (PC) con alta transmisión en la región ultravioleta (UV) del espectro solar. Con esta configuración, las simulaciones de trazado de rayos predicen una eficiencia óptica relativa (es decir, una eficiencia óptica de ADG normalizada con la eficiencia óptica de una lente SoG usada como referencia) del 92.6 %, además, las simulaciones predicen también una concentración máxima alcanzable con las lentes ADG del doble que para las SoG. Además, se ha hecho uso asimismo de las simulaciones para entender la tolerancia a los posibles errores de fabricación en la estructura de la lente, con objeto de definir los requisitos de calidad necesarios para conseguir una alta eficiencia en términos ópticos.

Una vez definidos estos estándares, se estableció el método de fabricación de lentes ADG y se llevó a cabo la fabricación de una laminadora necesaria para laminar las lentes en el Instituto de Energía Solar, en la Universidad Politécnica de Madrid (IES-UPM). Se realizaron un gran número de prototipos que fueron caracterizados en el laboratorio del IES-UPM, demostrando experimentalmente desde el comienzo el comportamiento acromático de los prototipos, y consecuentemente, la viabilidad del concepto.

Más tarde, el trabajo se centró en la optimización de los prototipos de ADG, realizándose tres generaciones distintas. En la primera generación, la eficiencia óptica relativa conseguida fue del 85.5 %. Desde entonces, se han optimizado aspectos tales como el diseño y el procedimiento de fabricación para conseguir llegar, en la tercera generación, a una eficiencia relativa del 89.4 %, muy cercana al valor límite teórico predicho por trazado de rayos. Si comparamos la tercera generación con la primera, la tercera tiene un diseño mejorado, nuevos materiales con una mayor transmisión, un tratamiento de la superficie cuyo objetivo es mejorar la adhesión de los materiales, y un equipo de fabricación completamente automático.

Por otra parte, también ha sido objeto de esta tesis el estudio de los mayores retos derivados de la fabricación de arrays compuestos de lentes ADG. El principal obstáculo, ha sido la ausencia de un molde capaz de inyectar el parqué de lentes de plástico de una sola vez. No obstante, se han llevado a cabo satisfactoriamente la laminación y caracterización de numerosos parqué, compuestos de numerosas lentes pegadas manualmente de forma individual, obteniendo eficiencias tan solo un 1 – 2 % menores que las conseguidas durante la realización de unidades elementales compuestas de una sola lente. El principal motivo de esta reducción de eficiencia, es la alta dispersión de valores de eficiencia medidos, que es causado por las limitaciones intrínsecas del pegado manual de las lentes que componen el array, y por posibles efectos de borde durante el proceso de laminación. Sin embargo, estas limitaciones podrían evitarse fácilmente en una línea de producción a gran escala.

Finalmente, se ha llevado a cabo el ensamblaje y la caracterización en el exterior de módulos fotovoltaicos completos con células de triple unión (3J) de alta eficiencia durante un periodo de tiempo de más de cuatro meses. Los módulos ensamblados fueron dos. El primero de ellos, un mono-módulo, es un sistema compuesto de una lente de Fresnel ADG con una célula solar 3J, mientras el segundo es un módulo de grande superficie compuesto por 10x5 lentes con las correspondientes células 3J. Por un lado, el mono-módulo se usó para destacar el potencial de la tecnología ADG y obtener los mejores resultados posibles alcanzables con esta tecnología al nivel de desarrollo actual. Por otro lado, el objetivo del montaje del módulo completo fue la demostración de la viabilidad de la tecnología ADG que, en tan solo tres años y medio, ha conseguido ser desarrollada experimentalmente y satisfactoriamente caracterizada. La caracterización del módulo demostró, no solo que el diseño acromático es capaz de alcanzar mayores niveles de concentración, sino también que contribuye a la reducción de su sensibilidad a las condiciones ambientales tales como la temperatura o el espectro solar.

En los últimos meses, se ha llevado a cabo también un análisis de costes de la tecnología desarrollada para probar si la tecnología ADG, además de las ventajas tecnológicas ya demostradas,

es capaz de resultar en un ahorro económico significativo. En este caso, teniendo en cuenta la reducción en coste por los materiales usados, cuyo precio es menor que el de la silicona óptica usada comúnmente en las lentes de Fresnel convencionales, y el mayor rendimiento energético anual derivado de la mayor estabilidad térmica y espectral, ha sido demostrado asimismo que la contribución del coste de las lentes al LCOE es significativamente menor en el caso de las lentes ADG en comparación con las lentes SoG. Esta diferencia podría llegar a resultar incluso mayor, si un escenario de alta concentración fuera considerado.

Abstract

In the last years, the constantly growing energy demand of the population on earth, together with the increasingly topical environmental ethics, resulted in relevant advances in the field of the renewable energy sources. Among them, photovoltaic (PV) energy is one of the most widespread around the world and has often achieved a levelized cost of electricity (LCOE) comparable with conventional fossil fuels. Within this field, a special interest is dedicated to the concentrator photovoltaic (CPV) technology, whose measured efficiencies are the highest among all the existing PV technologies, achieving the record efficiency of 43 % in 2016. This thesis is dedicated to the development, manufacturing, and characterization of a novel optics for CPV applications capable of either increase the maximum attainable concentration or to widen the tolerance to assembly errors, tracking, temperature, and spectral variation, while simultaneously maintaining competitive costs.

Nowadays, most of the CPV modules in the market are based on hybrid silicone on glass (SoG) Fresnel lenses. Such technology, whose success has been ensured by its excellent stability under outdoor exposition and by the easiness of the processing required for the manufacturing, has an important limitation: the chromatic aberration. Such phenomenon causes light with different wavelength to focus at different distances from the lens, limiting the maximum attainable concentration to a factor of slightly more than 200 *suns*, if no light spillage is assumed. In modern CPV module, a secondary optical element (SOE) is commonly coupled with the solar cell in order to increase the concentration and, at the same time, smooth the spectral distribution of the light over the cell. The implementation of SOE in a CPV module, apart from introducing a new source of losses or fails, results in additional costs due to manufacturing, assembly, etc. of the SOE itself. The work carried out in this thesis aims to the development of an novel cost-effective achromatic lens for CPV applications, named achromatic doublet on glass (ADG) Fresnel lens. The proposed lens technology, thanks to the achromatic design resulting in a reduced chromatic aberration, allows to increase the maximum attainable concentration and to smooth the spectral distribution of the light, without the implementation of a SOE, with obvious benefits from the financial and the reliability points of view. The lens design consists in a rigid glass substrate on which a plastic piece featuring Fresnel grooves on both its sides is glued using an elastomeric materials. As a consequence, by choosing the pair of materials with the adequate optical properties, the well-known concept of a thin achromatic doublet can be applied, while maintaining low costs thanks to the simple manufacturing process. In fact, the plastic piece is manufactured using high reliable industrial processes such as injection molding, compression molding, or hot embossing. Finally, the ADG sandwich is obtained by lamination, which is envisaged to be similar to the method commonly used to laminate conventional flat PV modules.

In the first part of the thesis, a comprehensive investigation over the materials that may be potentially used to manufacture ADG lenses is presented, together with the reasons which led to the current ADG design. Ray-tracing simulations based on Montecarlo method have been used as a tool to assess which pair of materials provided the strongest reduction of the chromatic aberration. Among all the materials available, a thermoplastic elastomer (TPE) and the polycarbonate (PC) with high transmission in the ultraviolet (UV) region have been selected. With this configuration, ray-tracing simulations predicted a relative optical efficiency (*i.e.* the ADG optical efficiency normalized with the optical efficiency of a reference SoG lens used as benchmark) of 92.6 % and, in

addition, the maximum attainable concentration of the simulated ADG lens is the double than the concentration simulated for the SoG lens. Furthermore, the simulations results have been used to understand the tolerance of the lens structure to manufacturing errors with the purpose of understanding what is the quality required in order to achieve a high performance optics.

Afterwards, the method for manufacturing ADG lenses was defined and the required equipment (a laminator machine) was manufactured ad-hoc at the laboratory of the Solar Energy Institute, Technical University of Madrid (IES-UPM). A huge number of prototypes were manufactured and characterized at the IES-UPM laboratory, experimentally demonstrating from the beginning the achromatic behavior of the prototypes and, consequently, the feasibility of the concept.

Later, the work focused on the optimization of the ADG prototypes. Three ADG generations have been developed. From the first generation, whose measured relative optical efficiency is equal to 85.5 %, many things have been optimized in order to achieve, for the third generation, the relative efficiency value of 89.4 %, which is close to the theoretical limit value predicted by ray-tracing. The third generation with respect to the first includes an improved design, new materials with enhanced transmission, a surface treatment aimed to enhance the adhesion between the materials of the sandwich, and a completely automated machinery used in the manufacturing process.

Also, the challenges deriving from the manufacturing of arrays composed of many ADG lenses have been studied in the thesis. The main obstacle was the absence of a mold designed to inject the parquet of plastic all in once. Nonetheless, manually gluing the individual lenses, several parquets composed of many lenses have been successfully laminated and characterized resulting an overall efficiency only 1 – 2 % lower than the elementary units composed of one individual lens. The main reason of the efficiency reduction is the high dispersion of the measured efficiency values, which in turn is caused by the handmade procedure employed to glue together all the lenses composing the array and by a possible border effect during the lamination. However, both these limitations would be easily avoided in a utility-scale production line.

Finally, complete CPV modules including modern high-efficiency triple-junction (3J) solar cell have been assembled and measured outdoor over a time lapse of more than four months. Two modules were assembled. The first is a mono-module, *i.e.* a system composed of one ADG Fresnel lens and one 3J solar cell, while the second is a full area module composed of 10x5 lenses and as many 3J solar cells. The mono-module was used in order to highlight the potential of the ADG technology and to obtain the best possible results attainable with the current development level. Conversely, the full module was needed to show that the ADG technology is actually possible and that, in only three years and a half of development, was already conceptually demonstrated and experimentally tested in relevant industrial environment. The characterization of the module demonstrated that the achromatic design, apart from providing a higher concentration, contributes to reduce the sensitivity of the module to ambient conditions such as temperature and spectrum.

In the last months, a cost analysis of the developed technology is carried out in order to prove that the ADG technology, apart from the technological advantages already remarked, provides also a significant economic saving. The pair of materials selected are cheaper than the silicone used for conventional Fresnel lenses. This, together with the enhanced annual energy yield provided by the improved thermal and spectral stability, demonstrated that the contribution of the lens cost to the LCOE is significantly lower for the ADG lens than for the SoG lens. Such difference results to be even higher if a high concentration scenario is considered.

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$B_{d,m}(h)$	hourly measured direct normal irradiation normalized with CSOC conditions.
C	light optical path.
$C_T(h)$	temperature coefficient of a lens.
D	lens diameter.
$E(\lambda)$	light spectrum.
F	object focus.
F'	image focus.
$F_{others}(y)$	annual coefficient for general losses.
$F_{soiling}(y)$	annual coefficient for soiling losses.
$F_{spec}(m)$	monthly coefficient for spectral losses.
$F_{tracking}(y)$	annual coefficient for tracking losses.
G_{in}	irradiance at the lens aperture.
G_{out}	irradiance at the receiver area.
H	principal object point.
H'	principal image point.
I	electric current.
I_n	electric current normalized by the DNI .
$N_{sunny-days}(m)$	monthly number of sunny days.
P_{CSOC}	DC power at CSOC conditions.
P_{in}	power at lens aperture.
P_{out}	power at the receiver area.
R_d	annual degradation rate.
S_i	<i>electrical response</i> , spectral response of the i subcell multiplied by the solar spectrum.
T_a	half of the amplitude of daily temperature variation.
T_m	average daily temperature.
V_d	Abbe number.
V_{solar}	solar Abbe number.
W_p	watt peak power.
Y	energy yield of a plant in year one.
η_{CSOC}	module efficiency at CSOC.
η_λ	spectral optical efficiency for the wavelength λ .
$\eta_{op,rel}$	relative optical efficiency.
$\eta_{op,rel}^i$	relative spectral optical efficiency of the i subcell.
η_{op}	optical efficiency.
η_{op}^i	spectral optical efficiency of the i subcell.

λ	wavelength.
ρ	lens curvature.
NO_x	nitrogen oxides.
SO_x	sulfur oxides.
θ	acceptance angle.
θ_i	angle between the incident ray and the surface normal.
θ_r	angle between the reflected ray and the surface normal.
θ_t	angle between the refracted ray and the surface normal.
ϑ	acceptance angle.
c	speed of light in the vacuum of space.
c_{capital}	initial capital cost of a plant.
c_n	plant cost in year n .
d	annual discount rate.
e_n	energy produced in year n .
f	object focal distance.
f'	image focal distance.
n	refractive index.
t	time.
t_{down}	sunrise time.
t_{peak}	time of the day corresponding with the peak temperature.
f-number	lens f-number (f/D).
I_{SC}	short-circuit current.
J_{SC}	short-circuit current density.
T	temperature.
V_{OC}	Open circuit voltage.
X	concentration ratio.

List of Acronyms

3J	triple-junction.
ADG	achromatic doublet on glass.
AM	air mass.
AM0	reference extraterrestrial spectral distribution (air mass 0).
AM1.5D	reference spectral distribution (air mass 1.5 direct).
ARC	antireflective coating.
ASTM	American Society for Testing and Materials.
BPF	band-pass filter.
CAP	concentration acceptance angle product.
CCD	charge-coupled device.
CM	current-matching ratio.
COC	cyclic olefin copolymer.
CPV	concentrator photovoltaic.
CSOC	concentrator standard operation condition.
CSTC	concentrator standard test condition.
CTE	coefficient of thermal expansion.
DC	direct current.
DNI	direct normal irradiance.
DUT	device under test.
ESRA	European Solar Radiation Atlas.
EU	European Union.
EVA	ethylene-vinyl acetate.
FF	fill factor.
GNI	global Normal irradiance.
HCPV	high concentrator photovoltaic.
HDT	heat deflection temperature.
IES	Instituto de Energía Solar.
IES-UPM	Instituto de Energía Solar - Universidad Politécnica de Madrid.

ISI	Instruments and System Integration.
JRC	Joint Research Center.
LCE	liquid crystal elastomer.
LCOE	levelized cost of electricity.
LED	light emitting diode.
LR	learning rate.
MJ	multi-junction.
PC	polycarbonate.
PDMS	poly-dimethylsiloxane.
PE	polyester.
PID	proportional-integral-derivative.
PMMA	polymethyl methacrylate.
POE	primary optical element.
PS	polystyren.
PSPI	polystyrene-block-polyisoprene-block-polystyrene.
PV	photovoltaic.
PVB	polyvinyl butyral.
PVGIS	Photovoltaic Geographical Information System.
QE	quantum efficiency.
SCA	solar cell assembly.
SMR	spectral matching ratio.
SOE	secondary optical element.
SoG	silicone on glass.
SR	spectral response.
TIR	total internal reflection.
TMY	typical meteorological year.
TPE	thermoplastic elastomer.
TRL	technology readiness level.
UPM	Universidad Politécnica de Madrid.
UV	ultraviolet.
WMO	World Meteorological Organization.

Chapter 1

INTRODUCTION

Nowadays, the necessity for green solutions to provide electricity is becoming increasingly topical. Conventional fossil fuels, such as coal or natural gas, constitute a not negligible source of pollution, be it for the carbon dioxide, the main responsible for the greenhouse effect, or for the other generic pollutants (*i.e.* NO_x, SO_x, particulate matter, etc.) which represent a serious hazard for the human beings. Thanks to the green policies put in place in the European Union (EU), several measures have been taken in order to reduce the emissions of conventional power plants and, as a consequence, to reduce their contribution to the public health risk and to the greenhouse effect. Despite such provisions, conventional fossil fuels still consist in one of the main causes of earth contamination. Because of these reasons, together with the constantly growing energy consumption of the population on earth, a lot of companies and research centers all over the world invested resources and time to investigate renewable energy sources, which provide a clean and unlimited reservoir of energy.

Renewable energy sources are very promising for the future despite their limitations, which are mainly related to their diffuse and intermittent nature. On one side, energy sources such as solar radiation or wind are essentially boundless, providing a not-exhaustible amount of energy. On the other side, because the energy source is so diffuse, vast areas need to be covered in order to harvest this diffuse energy, with obvious economical and social consequences. In addition, the energy output of such sources is continuously fluctuating over time, arising the need of a large amount of additional infrastructures in order to regularize the output to satisfy the energy demand. For these reasons, satisfying the whole energy consumption exclusively using renewable energies could result in an unaffordable cost of electricity.

Nevertheless, solar photovoltaics (PV) energy is one of the most widespread and investigated renewable technology all around the world and, in the last years, achieved a competitive cost, even if compared with conventional energy sources.

The figures of merit commonly used to analyze the costs of an energy generating technology are the cost per watt peak power W_p , which depends exclusively on materials, processing, and infrastructure costs, and the *levelized cost of electricity* (LCOE), which takes into account additional factors such as the discount rate, the lifespan of the power plant, and the real annual energy production. When speaking about costs and prices many variables can be considered and, depending on the assumptions made, different costs can be assessed for the same technology. The LCOE is expressed in cost per kWh , and it is defined as the net present value of the unit-cost of electricity over the lifetime of a generating asset. It is a first-order economic assessment of the cost competitiveness of an electricity-generating system that incorporates all costs over its lifetime: initial investment, operations and maintenance, cost of fuel, cost of capital.

The large cumulated installed capacity of flat plate PV (402 GW at the end of 2017 [1]) has

made it progress quickly through the learning curve and has already brought module prices to $0.57 \$/W_p$ and an LCOE of $3 - 6 \text{ c\$/kWh}$ for flat plate PV [1, 2]. In addition, it is worth to remark that, among the wide variety of renewable energy sources, solar is prominent because of its scalability. There is no significant efficiency loss when switching from plants providing a few watts of power to bigger gigawatt systems. Furthermore, the "fuel" (sunlight) is abundant, free and present worldwide thus making solar energy one of the most promising resources for the green future of the planet.

Currently, most of the commercial PV systems widespread in the market are based on flat plate PV modules including silicon crystalline solar cells. Such systems have been proven to be reliable, easily integrated on both utility-scale and small scale, and, in the last years, cost competitive with conventional fossil fuels.

Despite the fast progress of the learning curve, the conversion efficiencies (ratio between the solar irradiance and the electric power generated by the PV device) commonly measured for silicon crystalline solar cells is slightly over 20 %, with the maximum recorded value of 25 % in 2017 [3]. Since in the last ten years no significant improvement have been reported (in the year 2000 the record efficiency of these kinds of solar cells was already close to 25 % [3]), no further significant advance is expected without radically changing cells' architecture.

Apart from silicon crystalline devices, there are several other types of solar cells, some of them already commercialized (*i.e.* thin films or multi-junction (MJ) solar cells) and others still at development level (*i.e.* perovskite or quantum dots solar cells). Among them, the MJ technology is one of high interest in the PV field because of the outstanding measured efficiencies, which are much higher than any other kind of solar cells technology.

Such devices are solar cells with multiple p-n junctions made of different semiconductor materials. Each material's p-n junction is designed and optimized to convert into electricity a different range of the solar spectrum. Conventional silicon solar cells electricity conversion is limited by the silicon's spectral response (SR), which is defined as the ratio between the current generated by the solar cell to the power incident on the solar cell for a certain wavelength λ :

$$SR(\lambda) = \frac{I(\lambda) [A/nm]}{P_{in}(\lambda) [W/nm]} \quad (1.1)$$

where $I(\lambda)$ is the current generated by the solar cell and $P_{in}(\lambda)$ the incident power. Silicon's SR is limited to the wavelength range of $350 - 1100 \text{ nm}$ [4, 5], while the useful light of the solar spectrum is distributed over a much wider range ($200 - 2500 \text{ nm}$). Therefore, it is clear how silicon solar cells are not capable of fully exploiting the potential of the solar radiation. Conversely, MJ solar cells overcome this limitation by series connecting several single-junction cells (from now on called *subcells*) in such a way that each one of them is able to convert a specific region of the spectrum. The possibility of converting a wider region of the spectrum, together with the optimization of the SR of each subcell in the spectral region of interest, resulted in the world record efficiency of 46 % [3], value which is almost the double than the one measured for conventional silicon solar cells.

Despite the fact that MJ solar cell's efficiency is much higher than silicon solar cells, the excessive cost of semiconductor materials used for their manufacturing, and the complex processing techniques used for their fabrication limited their expansion in the market to solar cells for space application. However, these cells could become cost-effective if, for the same power delivered, the solar cells area is reduced. In this context, concentrator photovoltaic (CPV) technology has appeared as a promising solution, aiming to substitute expensive solar cells area with cheap optics used to concentrate the light onto the photovoltaic device. Such systems possess the highest efficiency of all existing PV technologies and, even if their cost per W_p is still higher than conventional silicon PV systems [2], they have the potential to become competitive in the near future .

1.1 Concentrator photovoltaic technology

CPV technology uses optical systems to concentrate the light onto high-efficiency MJ solar cells achieving on the cell surface an irradiance value hundreds of times higher than without optics.

The current generated by a solar cell is directly proportional to the irradiance level impinging on it [6]. Consequently, a small solar cell under an optical system able to multiply by X the irradiance onto the cell surface would deliver X times the electric current than without any optical concentrating system. The MJ high-efficiency solar cells used in CPV systems require to work under concentrated light mainly for two reasons: in the first place, is demonstrated that their efficiency increases under higher irradiance [7] and, in the second place, the high cost of the materials used for their growth make necessary to reduce as much as possible the ratio between the total solar cell surface and the power delivered by the system. The optical systems commonly used in CPV plants to concentrate light and, as a consequence, to reduce the solar cell area for the same system power, are manufactured using cost-effective materials that might potentially reduce the overall system cost, which becomes competitive with flat PV technology and also with conventional power plants based on fossil fuels.

However, concentrating systems designed to operate at high concentration ($> 300 \text{ suns}$) imply some issues that need to be considered. First, they only work with direct irradiance, losing all the contribution of the diffuse light scattered in the atmosphere. Furthermore, they only work under collimated light, requiring the use of tracking infrastructure whose purpose is to ensure that the CPV modules are always perpendicular to the light beam proceeding from the sun. A second problem is the high power flux on the solar cell surface under concentrated irradiance, which could result in a high cell temperature. Since solar cell's performance decreases as the temperature increases [8] a heatsink is often required in order to limit the maximum cell's operating temperature and to avoid unbearable efficiency losses. Finally, MJ solar cells performance is strongly influenced by the spectral distribution of the incident light [9], which in turn can be changed by the optics, especially in refractive concentrating systems.

A CPV module is an assembly composed of a primary optical element (POE), capable of concentrating the light that reaches its aperture area onto a solar cell, the solar cell itself, the housing used to fix the cell-optics distance and to protect the internal part of the module from weathering, and the electrical interconnection required to connect it to the grid. As mentioned above, CPV modules must aim toward the sun and accurately follow it during the day. The accuracy required in order to avoid unbearable efficiency losses depends on the geometrical concentration of the system, which is defined as the ratio between the optical aperture of the POE and the solar cell's area. The *étendue conservation principle* [10] states that, in an optical system, the product of the square of the acceptance angle sine and the concentration (CAP) is conserved. As a consequence, the higher is the concentration the lower is the acceptance angle. The CAP of a perfectly ideal system is equal to the square of the refractive index of the medium in which the receiver is immersed n^2 . Obviously, in real systems the actual CAP value is lower and follows the expression $\text{CAP} = C \cdot \sin^2 \vartheta \leq n^2$, where ϑ is the acceptance angle. Then, the higher is the CAP, the closer is the system to the ideal. Therefore, especially for the so-called high concentrator photovoltaic systems (HCPV), which work with concentration factors higher than 300 suns , a secondary optical element (SOE) is usually coupled with the solar cell in order to increase the system CAP and, consequently, to increase either the angular tolerance or the maximum attainable concentration [11]. Apart from the higher angular tolerance, another benefit provided by the SOE is the homogenization of the spectrum over the cell surface, which reduces the losses due to spectral mismatch [9, 12].

In the last decades, many different CPV configurations have been developed and tested using both refractive [13–16] and reflective [17, 18] optical elements. In general, even though similar efficiency values have been recorded for CPV module with very different configurations (reflective or refractive, number of optical stages, low, high or medium concentration factor, type of solar cell),

proving that there is not an absolute "best configuration", most of the commercial CPV systems developed nowadays are refractive systems based on Fresnel lenses because of their simplicity and higher manufacturing tolerances [6, 18].

Up to now, the highest measured efficiency for a PV system has been recorded in a CPV lens-based (refractive) system that achieved an efficiency value higher than 43 % [19].

1.2 Refractive optical systems and Fresnel lenses

A refractive system is an optical system designed to redirect the light passing through it following the refraction law, which derives from the Fermat principle [20–23]. Such systems are commonly used in the field of imaging optics to manufacture devices such as cameras, beamers, telescopes, and most of the equipment commonly used in the photographic industry. In these cases, the aim of the optics is to accurately reproduce images on the camera sensor. Therefore, in order to guarantee the high resolution of the photographs taken, high quality compound optical systems are usually employed. When using refractive components to concentrate the light over a small surface, which is the case of the CPV refractive system, the important factors are the amount of power transmitted by the optics, the size of the light spot cast by the optics, which determines the attainable concentration of the system, and, finally, the cost of material and processes used.

Therefore, when designing an optical system for CPV applications, it is important to define the concepts of *optical efficiency* and *maximum attainable concentration*. The first is defined as the fraction of radiant power at its input aperture P_{in} which reaches a designated receiver area P_{out} [24, 25]

$$\eta_{op} = \frac{P_{out}}{P_{in}} \quad (1.2)$$

while the second is defined as the ratio between the optical aperture of the optics and the area of the light spot cast by the optics in its focus.

CPV modules, due to the high cost of the MJ solar cells, generally needs to have an efficiency much higher than conventional flat PV modules in order to be cost competitive. As a consequence, the optical efficiency of the optical elements must be high enough.

Conversely, the maximum attainable concentration is one of the factors determining the size of the solar cells implemented in a module, unless the high concentration provided by the optics is used in order to improve the angular tolerance of the system instead than reducing the solar cell area. Generally, when a CPV system is designed to operate at high concentration, the solar cell size must be as small as possible, but large enough to capture all the light transmitted by the optics, *i.e.* the higher is the attainable concentration, the lower is the solar cell area, which is one of the largest contribution to the module price.

Most of the refractive systems used in CPV are composed of converging lenses featuring a special structure called Fresnel structure. A circular Fresnel lens is defined as a succession of concentric rings, called *grooves*, each consisting of an element of a simple lens, assembled in a proper relationship on a flat surface to provide a short focal length. These contours act as individual refracting surfaces, bending parallel light rays to a common focal length. As a result, a Fresnel lens, while physically narrow in profile, is capable of focusing light similarly to a conventional optical lens but has several advantages over its thicker counterpart. The most significant benefits of using Fresnel lenses instead of classic aspheric lenses is that, thanks to the Fresnel structure, it is possible to obtain thin lenses with short focal length, reducing at the same time absorption losses, module thickness (distance between the lenses and the solar cells), and the amount of material used for the lens manufacturing.

Fresnel lenses for CPV applications can be manufactured in different materials, usually plastic such as poly(methyl methacrylate) (PMMA) or polydimethylsiloxane (PDMS) laminated on glass

[26]. The latter, despite the more expensive raw material, is the most commonly used because of the reliability provided by the glass together with its outstanding optical behavior and the ease of the manufacturing process.

The performance of all refractive optical systems is limited by phenomena widely known in the optics field and named *aberrations*. In optics, an aberration is a property of optical systems such as lenses that causes light to be spread out over some region of space rather than focused to a point [27]. Aberrations widen the light spot formed by a lens limiting the maximum attainable concentration. There are mainly two kinds of aberrations: *monochromatic aberrations* and *chromatic aberration*. The firsts are those independent from the wavelength of the incident light while the second is caused by the variation of the material refractive index as a function of the incident light wavelength. In all the optical refractive systems the chromatic aberration, the sun angular aperture, and, if the facets have been designed to be flat, their width are the main factors limiting the maximum concentration.

1.2.1 Chromatic aberration

Chromatic aberration, also called chromatic distortion and spherochromatism, is a failure of a lens to focus all wavelengths to the same point [28]. This is caused by the refractive index variation of the material composing a lens as a function of the wavelength of the incident light. The refractive index of most transparent materials decreases with increasing wavelength [29]. Since the focal length of a lens depends on the refractive index, it is obvious how light rays with different wavelengths focus at different distances on the optical axis, widening the light spot cast by the lens. Figure 1.1a shows a graphic representation of the chromatic aberration phenomenon.

Figure 1.1: (a) Schematic representation of the chromatic aberration phenomenon. Light rays with short wavelength (blue lines) focus closer to the lens than rays with high wavelength (red lines). (b) Schematic representation of an achromatic doublet use to partially compensate the chromatic aberration phenomenon. Rays with short and long wavelength focus to the same point.

The chromatic aberration, together with the sun angular aperture, is the main factor limiting the maximum attainable concentration in a CPV refractive module. In addition, such dependency with incident light wavelength modifies the spectral distribution of the light over the solar cell surface. As mentioned in the previous section, MJ solar cells' performance is strongly spectrum dependent. Consequently its alteration caused by chromatic aberration could generate local current limitation [9, 12] reducing the overall performance of the solar cell.

To summarize, chromatic aberration phenomenon has a strong detrimental effect on the performance of CPV refractive modules. First, it widens the light spot resulting in the need of using larger (more expensive) MJ solar cells and, second, alters the spectral distribution over the cell surface directly affecting the solar cell efficiency.

In most of the commercial refractive CPV systems, SOEs are included in the optical path of the light with the purpose of, among other things, partially compensate the described behavior. There are essentially two kinds of SOEs currently available in the market: reflective SOEs, which use reflection on their walls to deviate the light proceeding from the POE onto the solar cell, and refractive SOEs, made of dielectric materials and which use refraction together with the total internal reflection (TIR) principle to redirect the light onto the receiver. In general, the use of SOE provides three advantages:

1. it significantly increases the geometrical concentration (*i.e.* the ratio between POE aperture area and solar cell surface);
2. it improves the angular tolerance of the module. Thanks to the SOE also light impinging the POE with a certain angle would reach the solar cell allowing higher tolerance to conditions different from ideality (perfectly aligned system, no tracking error, etc.);
3. it may be designed in such a way that it is capable to smooth the irradiance distribution and to reduce the losses caused by the spectral mismatch over the solar cell.

On one side, the use of SOEs allows compensating most of the negative effects caused by the chromatic aberration. On the other side, they also have drawbacks: in the first place, the SOE and the optical glue used to attach it to the cell are mounted exactly where the concentration is the highest, resulting in high flux power which could compromise the bonding or the optical properties of the SOE, consequently reducing the reliability of the system. In the second place, the SOE is an additional element implemented, as such it implies more expenses for material, processing, assembling, and maintenance. Finally, the presence of another optical stage after the POE results in additional losses due to absorption and/or Fresnel reflection.

Another path to avoid the problems derived from the chromatic aberration is widely known in literature: the so-called *achromatic doublet* [30]. The achromatic doublet is a compound lens composed of two simple lenses made of materials having different dispersion. From the theory is known that coupling a diverging lens with a converging lens, one with high dispersion, and the other with low dispersion, it is possible to design a lens capable of focusing light with short wavelength (blue light) and light with long wavelength (red light) to a single focal point (see figure 1.1b).

Despite achromatic doublets are known since the 18th century they are not used in the PV industry because of their price. In fact, they are commonly manufactured in glasses whose processing costs are not compatible with the PV requirements.

1.3 Framework of this research

In this context, the development of the achromatic doublet on glass (ADG) Fresnel lens has been carried out in the Instituto de Energía Solar (IES) of the Universidad Politécnica de Madrid (UPM), in particular within the Instruments and System Integration (ISI) group. The ISI group, apart from the development and testing of several novel CPV systems, deals also with design, modeling,

and manufacturing of instrumentation and tools appropriate to be used in test and characterization of CPV devices (modules and components).

One of the main ideology of the ISI group has always been the closeness with the reality. In most of the project managed and developed within the group, apart from the theoretical dissertation of new promising concepts, their applicability in the real world from either practical (manufacturing issues and limitations), and economical (price of materials and processes involved) point of view has always been considered as important as the scientific idea itself.

The ADG Fresnel lens developed in this thesis is a clear example of the ISI group philosophy. In fact, as mentioned earlier in this chapter, achromatic lenses are known since a long time as well as all the advantages they could provide if included in a CPV systems [31–33]. Languy and co-workers already presented the idea of an achromatic doublet featuring a Fresnel structure made out of PMMA (low dispersion material) and polycarbonate (PC) (high dispersion material). In their work, they were able to experimentally demonstrate that the concentration factor of the doublet is almost three times higher than the one achieved with a singlet (2400 *suns* and 950 *suns* respectively for the doublet and the singlet. Concentrations calculated for the 90 % of the encircled energy). However, in Languy’s work there is no mention neither to a feasible manufacturing process aimed to actually make cost-competitive prototypes nor to any strategy to incorporate the proposed technology in the market. In fact, Languy’s design requires to glue together the two individual Fresnel lenses. Such process could introduce significant misalignment error between the two lenses and, in addition, the thin layer of glue would introduce additional Fresnel losses. Also, the necessity of injecting separately two lenses with a Fresnel profile would probably result in high processing costs. Moreover, in their publications no absolute optical efficiency values are disclosed, limiting the completeness of the results.

The ADG Fresnel lens proposed and developed in this thesis aims to go one step further, merging the concepts of the achromatic doublet and of the silicone on glass (SoG) Fresnel lens in order

Figure 1.2: Schematic representation of the ADG Fresnel lens design. The theoretical concept of the achromatic doublet and the concept of the SoG Fresnel lens are merged together to create the ADG Fresnel lens, which is an achromatic doublet laminated on glass.

to obtain a cost-effective achromatic lens for PV applications (see figure 1.2). From the first, the design concept of a conventional achromatic doublet is taken, whereas from the second is taken the idea of including a rigid glass substrate on which the doublet is laminated. The presence of the glass substrate provides many advantages in comparison with the design proposed by Languy. First, it provides protection against weathering and, being the glass highly resistant to scratches, improves the reliability of the module and eases the cleaning process. Second, its durability when exposed to outdoor conditions is widely proved. Therefore, the ADG sandwich is going to be composed of three elements:

1. a rigid solar-grade glass substrate needed as structural support and to guarantee the flatness of the laminated lens;
2. a rigid plastic piece having Fresnel structure on both sides. This part serves at the same time as the high dispersion converging lens and, during the lamination phase, acts as a mold to shape the elastomer in the low dispersion diverging lens;
3. a thin layer of elastomeric material which is molded into the low dispersion diverging lens during the lamination and, at the same time, acts as a glue to keep together the glass substrate and the plastic.

The manufacturing of the ADG lens is divided into two steps: first, the plastic piece is obtained using well-known processes such as injection molding, compression molding or hot embossing. Second, the ADG sandwich composed of the rigid glass substrate, the elastomer, and the plastic are bonded together by a lamination process similar to the one used to laminate conventional flat PV panels. The proposed method relies upon cost competitive processes widely covered in the mass production industry. For this reason, the manufacturing costs are predicted to be in the same order of magnitude than the conventional SoG lenses. Furthermore, since silicone rubbers are usually expensive materials, substituting it with a cheap plastic and a cheap elastomer could provide a significant economic benefit that, if added to the reduction of the solar cell area obtained thanks to the enhanced concentration, and to the removal of the SOE and its costs, have the potential to bring the LCOE of CPV at a very competitive level.

The development of the ADG technology was carried out in the framework of the Spanish project Acromalens (ENE2013-45299-P), which is funded by the Spanish government. The aim of the project is the development of a novel cost-effective achromatic lens for HCPV applications capable of attaining a concentration factor between 600 *suns* and 800 *suns* with a single optical stage.

Since the ISI group maintains close relations with different European industrial partners, some of them have been involved in the project from the very beginning, with the goal of moving as fast as possible towards the introduction of this lens technology into commercial CPV modules. In particular, the ADG technology have been included in the development of a complete high-efficiency CPV module within the framework of the European project CPVMatch, which is funded by the (EU). The overall aim of the project is to bring practical performance of HCPV modules closer to theoretical limits, and it should be achieved through the investigation of novel multijunction (MJ) solar cell architectures using advanced materials and processes for better spectral matching and, in parallel, the development of innovative HCPV module concepts with improved optical and interconnection design. The main objective is to realize a complete CPV module with a concentration ratio higher than 800 *suns*, an efficiency of 40 %, and a low environmental impact. The ADG technology developed at the IES-UPM has been used as POE in the prototype module assembled and characterized along the CPVMatch project.

Several European universities, research centers, and companies contributed to achieve the goal of the project: AIXTRON (Germany), ASSE (Italy), AzurSpace (Germany), CEA (France), CyCleco (France), Fraunhofer-ISE (Germany), IES-UPM (Spain), RSE (Italy), and Tecnalia (Spain).

The development of a cost-effective Fresnel lens capable of attaining a concentration of 800 *suns* with a single optical stage (no SOE) was the task designated for the IES-UPM, and it consists in

the research work described in this thesis.

1.4 Objectives of the thesis

The purpose of the work carried out in this thesis is the design, modeling, manufacturing, optimization, and characterization of a novel cost-effective achromatic Fresnel lens for HCPV applications, called achromatic doublet on glass (ADG) Fresnel lens. The ADG technology aims to reduce the LCOE cost in comparison with similar existing technologies and, at the same time, to maintain or even improve the overall system performances.

In order to demonstrate the feasibility of the general objective proposed, *i.e.*, the development of an achromatic Fresnel lens doublet for HCPV applications, the following goals must be achieved:

1. developing the optical design of the achromatic Fresnel structure and verifying its achromaticity by means of ray-tracing tools. Optimization of the developed design;
2. investigating in deep the materials available in the market and studying their compatibility with the new proposed Fresnel structure from optical, mechanical, and thermal point of view. Manufacturing and characterization of small sample with the aim of identify the challenges that the selected materials might introduce in the manufacturing process;
3. designing, fabrication, and optimization of the necessary equipment that will be used to manufacture the ADG Fresnel lens prototypes;
4. designing and fabrication of the necessary equipment that will be used to experimentally analyze the chromatic aberration of a lens, and the potential attenuation provided by the ADG achromatic design. Adaptation of existing methods to the specific case of study. Analysis of the experimental error;
5. manufacturing and characterization of the first ADG prototypes with the optical design developed in 1, and the equipment and methods defined in 3 and 4;
6. testing the influence on the lens performance of the manufacturing parameters and optimization of the latter. Applying the necessary modification to the design, the materials, and the manufacturing process in order to fulfill the potential of the technology;
7. analyzing the resistance of the prototypes to a prolonged outdoor exposition by means of both accelerated aging tests and real outdoor exposition. Including in the manufacturing process the necessary provisions to achieve the required level of reliability;
8. manufacturing and exhaustive characterization of the optimized prototypes. The optical efficiency and the maximum attainable concentration will be investigated, together with the thermal sensitivity and reliability of the lenses;
9. adaptation of the developed manufacturing process for the fabrication of a parquet composed of many lenses;
10. assembly and outdoor characterization of complete CPV modules including 3J high-efficiency solar cells. Testing the overall performance of both a mono-module (one lens and one cell) and a full area module composed of many lenses and cells.

1.5 Outline of the thesis structure

After this chapter, that included a general description of the context in which the work has been carried out, the thesis is divided into four more technical chapters plus one for conclusions.

- Chapter 2 begins with a short summary of the basic principles of geometric optics which will be used to carry out the lens design. Moreover, the second part includes a comprehensive investigation carried out at the beginning of the thesis in order to identify the best pair of materials to be used in the ADG Fresnel lens lamination, together with the description of the design method. Finally, the last part shows the results obtained from the ray-tracing simulations carried out in order to confirm the suitability of the materials and the design proposed.
- Chapter 3 describes in details all the methods and equipments implemented and used to experimentally characterize ADG Fresnel lens prototypes. This chapter includes, for every method described, challenges and limitations encountered, and the solutions adopted to overcome such issues.
- In chapter 4 the manufacturing method and its evolution are exhaustively described. Throughout this thesis the manufacturing process, as well as the equipments developed at the IES to carry it out, have constantly evolved aiming to continuously improve lens prototypes. In parallel, all the results obtained by the indoor characterization of ADG Fresnel lens prototypes are exposed. The characterized samples include from the very first laminated ADG lenses whose characterization provided the proof-of-concept, to the last batch of lenses distinguished for their higher efficiency and proven reliability. The final part of this chapter shows the results obtained by the outdoor characterization carried out over two complete CPV modules including ADG Fresnel lenses as POE.
- Chapter 5, describes a preliminary cost analysis of the ADG technology. First, the cost per W_p is estimated considering materials and processing costs. Second, an energy prediction model particularly suited to be used in the prediction of the energy harvested in a CPV plant is described and implemented in order to estimate the annual energy production. The cost per W_p , together with the estimated annual energy yield, give the contribution to the LCOE, which is found to be beneficial in comparison with the conventional SoG technology.
- Finally, chapter 6 summarizes the main contributions of this work and outlines the work that could be done in the future to further improve this new promising technology. Also, a list of author's publications, both in conference proceedings or peer-review scientific journals, is mentioned in this chapter.

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Chapter 2

DESIGN AND RAY-TRACING

2.1 Introduction - geometrical optics

Optics is the branch of physics whose content comprises light generation, propagation, and detection. Depending on the phenomena or process taken into consideration, on the required precision, and the size of the obstacles the light is going to encounter, different approaches could be used. The most general is the *classic optics*, is derived from the electromagnetic theory of radiation and considers light as an *electromagnetic wave*.

When structures with which the light interacts are of macroscopic size (*i.e.* much bigger than light wavelength) the undulatory behavior cannot be discerned. In these cases, light can be described by mean of a set of curvilinear trajectories (rays) that follow certain geometrical laws. This type of study is called *ray optics* or *geometrical optics*.

Geometrical optics has been found to be very useful in the fields of imaging optics and in the calculation of the energy transmitted by an optical system throughout an aperture (*photometry* and *radiometry*).

The *ray* in geometric optics is an abstraction useful for approximating the paths along which light propagates under certain circumstances.

The simplifying assumptions of geometrical optics include that light rays:

- propagate in straight-line paths as they travel in a homogeneous medium;
- bend, and in particular circumstances may split in two, at the interface between two dissimilar media;
- follow curved paths in a medium in which the refractive index changes;
- may be absorbed or reflected.

Geometrical optics is often simplified by making the *paraxial approximation*, or *small angle approximation*, in which it is considered that all the rays form a small angle with the optical axis. Such approximation is valid for angles below $\sim 15^\circ$ with a relative error of less than 1 %. The mathematical behavior then becomes linear, allowing optical components and systems to be described by simple matrices. This leads to the techniques of Gaussian optics and paraxial ray tracing, which are used to find basic properties of optical systems, such as approximate image and object positions and magnifications (more details in section 2.1.4).

2.1.1 Refractive index

Macroscopic interaction of light with material media may be characterized by a velocity ratio named *refractive index* commonly represented with n . If c is the speed of light in the vacuum of space, considered as a reference medium, and v the speed of light in a certain medium for a certain wavelength λ , then

$$n = \frac{c}{v} \quad \text{being} \quad v < c. \quad (2.1)$$

In vacuum $v = c$, therefore $n = 1$; in whatever different medium, $n > 1$. It is worth to notice that equation (2.1) is valid only if the considered medium is homogeneous and isotropic; in materials which do not comply with these conditions the refractive index depends on other variables such as position in space (x, y, z) , time t or temperature T in such a way that the dependency may be represented by means of a multivariable function:

$$n = n(x, y, z, t, T). \quad (2.2)$$

2.1.2 Optical path

Being C a generic curve in a medium whose refractive index is equal to n , the *optical path* between two points A and B of said curve is defined as the integral

$$[AB]_c = \int_A^B n ds \quad (2.3)$$

where s is the length of the arch along C . If the medium is homogeneous then

$$[AB]_c = n \int_A^B ds \quad (2.4)$$

that is, the optical path between two points is given by the product of the refractive index of the medium and the length of the portion of the curve comprised between the two points.

Fermat's principle

Equation (2.4) may be used to express the Fermat principle, which describes light rays propagation, and represents a starting point from which it is possible to deduce the geometrical optics theory. Fermat principle can be formulated as follows: *a light ray in going from point P_1 to point P_2 must traverse an optical path length that is stationary with respect to variations of that path*. In term of mathematics it becomes

$$\delta C = \delta \int_{P_1}^{P_2} n ds = 0 \quad (2.5)$$

where δ means variation and s is again the length of the arch along C . Therefore, the optical path along a ray can be a maximum, a minimum or maintain constant with respect to close paths.

Another commonly accepted formulation for the same Fermat's principle states that *the optical path of all the rays belonging to the same wavefront is constant*. The two formulations are interchangeable, but the second is the one that will be used in the next sections to describe the lens design method.

Laws of reflection and refraction

Using Fermat's principle it is possible to describe how light behaves when reflects or refracts on surfaces respectively reflective or refractive. A detailed disclosure of such derivation can be found in literature [1–4].

In figures 2.1a and 2.1b respectively the *law of reflection* and the *law of refraction (Snell's law)* are schematically represented. $f(x, y, z) = 0$ represents a generic surface.

Figure 2.1: In both (a) and (b) θ_i is the angle between the incident ray and the surface normal, n_1 and n_2 are the refractive indexes of the media separated by the surface $f(x, y, z) = 0$. (a) Scheme representing reflection law. θ_r represents the angle between the reflected ray and the surface normal. (b) Scheme representing refraction law (Snell's law). θ_t represents the angle between the refracted ray and the surface normal.

It is possible to demonstrate that the following relations are valid:

$$\theta_i = \theta_r \quad \text{and} \quad n_1 \sin \theta_i = n_2 \sin \theta_t \quad (2.6)$$

respectively for reflection and refraction.

2.1.3 Optical systems: conventions and nomenclature

An *optical system* is defined as a set of surfaces which separate homogeneous media with different refractive indexes. If all the surfaces composing the system are refractive the system is called *dioptric*, if all the surfaces are reflective the system is called *catoptric*, if there are both reflective and refractive surfaces the system is called *catadioptric*.

Commonly all the surfaces composing an optical system have revolution symmetry. When all the curvature centers of the surfaces are aligned the system is called *centered* and its axis is called *optical axis* or *system axis*.

Being Σ_e and Σ_s the first and the last surfaces of a certain optical system, on the assumption that light propagates from left to right, the area before Σ_e is called *real object space*, that is the space where real light source might be (see figure 2.2a).

Let call F a light source placed in the real object space, if all the rays coming out from the source, after crossing the optical system, converge in a point F' , the last is called the *image* of the point *object* F . The image is *real* if it is on the right side of the surface Σ_s (see figure 2.2a). If the light beam diverges but the backward prolongations of the rays converge in a point on the left of the surface Σ_s , the image is said to be *virtual* (see figure 2.2b). The area on the right of the surface Σ_s is then called *real image space* and the area on the left of the surface Σ_s *virtual image space*.

Figure 2.2: Graphic representation of the main concepts of a centered optical system.

Similarly, When on the surface Σ_e impinges a light beam whose forward prolongation converges in a point F located on the right of the surface Σ_e , F is then called *virtual object* and the area on the right of the surface *virtual object space* (see figure 2.2c).

Finally, taken two points O and O' , if all rays emerging (really or virtually) from O , pass (really or virtually) through O' we can say that O' is the image of O throughout the optical system. Points O and O' are called *conjugated points*.

2.1.4 Paraxial approximation

To provide context for the next sections it is useful to introduce the concept of *paraxial approximation*. If we take into consideration only rays that, passing through a centered optical system, form small angles with the optical axis, it is possible to consider that

$$\sin \theta \sim \theta \quad \text{and} \quad \cos \theta \sim 1 \quad (2.7)$$

where θ , in every point, is the angle between the ray and the optical axis.

A comprehensive dissertation on all the advantages and the validity conditions of the paraxial approximation is presented elsewhere [2–4].

For the purpose of this thesis it is enough to know that all the equations and formulae presented from now on are in the framework of *paraxial geometrical optics*.

In particular, considering a refractive spherical surface separating two homogeneous media, with refractive indexes n_0 and n_1 , being R the radius of the sphere, and P_0 and P_1 two conjugated points in the optical axis (see figure 2.3) it is possible to demonstrate that the following condition is valid:

$$n_1\left(\frac{1}{R} - \frac{1}{z_1}\right) = n_0\left(\frac{1}{R} - \frac{1}{z_0}\right) \quad (2.8)$$

and it is called *Abbe's invariant for a spherical diopter*.

Figure 2.3: Graphical representation of a ray refracting through a spherical diopter.

Using equation (2.8) is possible to determine the position z_1 of the image P_1 of a punctual axial object P_0 knowing its position z_0 .

It is worth to notice that z_0 and z_1 may be positive or negative depending on the position of the points P_0 and P_1 with respect of the origin O . Similarly the curvature radius R is positive if the diopter is convex with respect to the incident beam and negative if otherwise.

2.1.5 Sign convention

Let consider a spheric surface whose center lies in the point C of the optical axis, and that separates two media with refractive index n and n' , let suppose that, in the framework of the paraxial approximation, the segment $A'B'$ is the image of the segment AB (see figure 2.4).

The following sign convention must be respected:

1. incident light flow from left to right;
2. distances perpendicular to the optical system are positive upward and negative downward;
3. distances from O to a point in the axis (s and s' in figure 2.4) are positive if said point is located on the right of O and negative otherwise;
4. the curvature radius R of the diopter is positive if the center of the sphere (C) is on the right of O , negative otherwise.

Figure 2.4: Representation of the sign convention adopted.

2.1.6 Basic elements and relations in paraxial geometrical optics

In this section centered optical systems composed of several spherical surfaces that separate homogeneous media will be considered. Axis z will always be the revolution symmetry axis.

Foci, focal planes, and focal distances

It is called *object focus*, F , the point in the z -axis such as every ray passing from it emerges from the optical system parallel to said axis. It is called *image focus*, F' , the point in the z where all the rays impinging the system parallel to said axis converge. *Object focal plane* and *image focal plane* are defined as the planes perpendicular to the optical axis and passing respectively through F and F' .

Let consider an optical system with known foci, and an incident ray parallel to z -axis passing through the image focus F' after traversing the optical system. Let call A_i the intersection between the incident ray and the refracted ray (or of their prolongations). Repeating this process for every incident ray parallel to the z axes a set of points A_i is identified and corresponds to a revolution plane named *principal image plane*. Its intersection with z -axis, H' , is known as *principal image point* (see figure 2.5a).

Considering now a ray passing through F , it would emerge from the optical system parallel to the optical axis. Let call B_i the intersection point between the incident ray and the refracted ray (or of their prolongations). Repeating this process for every incident ray passing through F it is possible to identify another revolution plane named *principal object plane*. Its intersection with z -axis, H , is known as *principal object point* (see figure 2.5b).

It is called *object focal distance* and is noted as f , the distance between the principal object point H and the object focus F . Similarly, the distance between the principal image point H' and the image focus F' is called *image focal distance*. The quantities $\varphi = 1/f$ and $\varphi' = 1/f'$ are called respectively *object power* and *image power* and are expressed in diopters.

It is worth to notice that, considering a pair of generic conjugated points P_0 and P_1 located on the optical axis at distances z_0 and z_1 from the principal image plane. If $z_0 \rightarrow -\infty$ then $z_1 = f'$ and, similarly, if $z_1 \rightarrow +\infty$ then $z_0 = f$.

Figure 2.5: Schematic representation of the graphical method used to define (a) the *principal image plane* with the associated *principal image point* H' and (b) the *principal object plane* with the associated *principal object point* H .

Basic relations between object and image

Consider a linear object AB , perpendicular to the optical axis. Its image $A'B'$ will be determined graphically by tracing from the point B rays 1 and 2, the first parallel to the axis, and the second passing through the object focus F (see figure 2.6).

Let be the planes defined by B_1C and B'_1C' respectively the principal object plane and the principal image plane, the object focal distance f and the image focal distance f' respectively the distances FH and $H'F'$, z and z' the distances FA and $F'A'$. Following the sign convention $z, f < 0$ and $z', f' > 0$. Therefore the following relations are valid:

$$\begin{aligned} z &= s - f \\ z' &= s' - f' \end{aligned} \quad (2.9)$$

where s and s' are respectively the distance between the linear object and the principal object plane (AH), and the distance between the image of the object and the principal image plane ($H'A'$). Also, the two triangles AFB and HFC are similar, therefore

$$\frac{y'}{y} = -\frac{f}{z} \quad (2.10)$$

where y and y' are the ordinates of the point B and B' of the object AB and its image $A'B'$.

Analogously triangles $F'H'B'$ and $F'A'B'$ are similar, therefore

$$\frac{y'}{y} = -\frac{z'}{f'}. \quad (2.11)$$

Equations (2.10) and (2.11) together give

$$zz' = ff' \quad (2.12)$$

and, if $f = -f'$, lead to

$$zz' = -f^2. \quad (2.13)$$

Therefore, using equations (2.12) and (2.9) leads to

$$\frac{f}{s - f} = \frac{s' - f'}{f'} \quad (2.14)$$

Figure 2.6: Schematic representation used to deduce some basic geometric relations.

that is

$$\frac{f}{s} + \frac{f'}{s'} = 1 \quad (2.15)$$

and, if $f = -f'$

$$\frac{1}{s'} - \frac{1}{s} = \frac{1}{f'}. \quad (2.16)$$

Compound optical systems

A compound optical system is defined as a system composed of a succession of independent simpler optical systems. It is theoretically possible to deduce several useful relations between the cardinal elements (*i.e.* focal distances, principal planes, etc.) of the compound system and the cardinal elements of every individual system composing it. In this section, such relations will be briefly introduced.

It is possible to demonstrate that [2–4]

$$\frac{1}{f'} = \frac{1}{f'_2} - \frac{1}{f'_1} \frac{f_2}{f'_2} - \frac{d}{f'_1 f'_2} \quad (2.17)$$

where subscripts 1 and 2 refer respectively to the optical system 1 and the optical system 2.

2.1.7 Lenses

It is called *lens* a transparent portion of material limited by two surfaces. Therefore a lens could be considered an compound optical system composed of two refractive surfaces containing a medium with refractive index n .

Usually, the medium surrounding the lens is air (that is $n_{air} = 1$).

Figure 2.7: Schematic representation of a compound optical system used to deduce some basic relations between individual systems and the compounded. H_1 and H'_1 are the object and image principal planes of the optical system 1, H_2 and H'_2 are the object and image principal planes of the optical system 2. F'_1 is the image focal distance of the optical system 1. F_2 and F'_2 are object and image focal distances of the optical system 2. d is the distance between the image principal plane of system 1 H'_1 and the object principal plane of the system 2 H_2 . F' is the image focal distance of the compounded system.

It is possible, in the framework of the paraxial approximation, to obtain a simple equation for the image focal distances of the two diopters. Using equation (2.8) the image focal distance f' of a spheric diopter can be calculated considering that if $z_0 = +\infty$, then $z_1 = f'$. Therefore, in the case of a lens, the following equations are valid:

$$\frac{1}{f'_1} = \frac{n-1}{nR_1} \quad (2.18)$$

for the first diopter and

$$\frac{1}{f'_2} = \frac{1-n}{R_2} \quad (2.19)$$

for the second diopter. R_1 and R_2 are respectively the curvature radius of the first and the second diopter.

It is demonstrated that, for a spherical diopter, the principal object plane and the principal image plane coincide with the plane tangent to the diopter, as a consequence, the distance between the principal points H'_1 and H_2 is the thickness of the lens [2–4].

Therefore, using equation (2.18), (2.19) and (2.17) leads to

$$\begin{aligned} \frac{1}{f'} &= \frac{1-n}{R_2} + \left(\frac{n-1}{nR_1} \right) n - \frac{d(n-1)(1-n)}{nR_1R_2} = \\ &= (n-1) \left(\frac{1}{R_1} - \frac{1}{R_2} \right) + \frac{d(n-1)^2}{nR_1R_2} \end{aligned} \quad (2.20)$$

where f' is the image focal distance of the optical system composed of the two diopters, *i.e.*, the lens.

A special case of interest regards *thin lenses*. A lens is considered thin when its thickness is small compared to the curvature radius of the composing dioptrs. In this case equation (2.20) becomes

$$\frac{1}{f'} = (n - 1) \left(\frac{1}{R_1} - \frac{1}{R_2} \right) \quad (2.21)$$

which is known as *Lensmaker's equation*.

Conversely, due to the negligible thickness, the separation between the principal planes can be considered null, therefore $H_1 = H'_1 \simeq H_2 = H'_2$. That is why a thin lens is usually graphically represented with a segment perpendicular to the optical axis, limited by arrowheads pointing outwards in the case of a converging lens and inward in the case of a diverging lens.

When there are two thin lenses with a common optical axis, from equation (2.17) the following equation is deduced

$$\frac{1}{f'} = \frac{1}{f'_1} + \frac{1}{f'_2} - \frac{d}{f'_1 f'_2} \quad (2.22)$$

where d is the distance between the two lenses. When $d = 0$ it is called *cemented doublet* and equation (2.22) reduces to

$$\frac{1}{f'} = \frac{1}{f'_1} + \frac{1}{f'_2}. \quad (2.23)$$

2.2 Chromatic Aberration

In chapter 1 the phenomenon of chromatic aberration was already introduced. Such aberration is caused by the refractive index variation as a function of the incident light wavelength. In fact, the Lensmaker's equation (2.21) is a function of the refractive index n , which in turn is a function of the wavelength λ . Therefore, since the refractive index n decreases as the light wavelength λ increases, rays with longer wavelength (red light) focus further to the lens with respect to rays with shorter wavelength (blue light, see figure 2.8).

Figure 2.8: Schematic representation of chromatic aberration.

It is possible to partially compensate the chromatic aberration by coupling two lenses, one negative and one positive, manufactured with materials having different dispersion.

2.2.1 Thin Achromatic Doublet

The design of achromatic lenses using two materials with distinct dispersion is well-known since the 18th century. The classic achromatic doublet is composed of a crown glass whose dispersion is low and a flint glass with high dispersion.

The key concept when designing an achromatic doublet is the *achromaticity condition*, which consists in the equivalence of the focal distances corresponding to two different wavelengths of interest, one short λ_{blue} , and the other one longer λ_{red} .

From section 2.1.7, it is possible to use equation (2.23) to express the focal distance of a system composed of two cemented lenses and, using the Lensmaker's equation (2.21), it is possible to write the focal distances of each individual lens as follows:

$$\frac{1}{f_i} = (n_i - 1)\rho_i, \quad i = 1, 2 \quad (2.24)$$

where the subscript $i = 1, 2$ refers to the two lenses composing the doublet and $\rho_i = (\frac{1}{R_{a,i}} + \frac{1}{R_{b,i}})$ is the curvature of the lens (subscript a and b refer the two diopeters limiting each lens i).

Substituting equation (2.24) in equation (2.23) leads to:

$$\frac{1}{f} = (n_1 - 1)\rho_1 + (n_2 - 1)\rho_2 \quad (2.25)$$

where f is the focal distance of the cemented doublet and subscripts 1 and 2 refer to the two individual lenses composing the system.

Equation (2.25) is wavelength dependent through $n_1(\lambda)$ and $n_2(\lambda)$. Using wavelength specific values $n_i(\lambda_{blue})$ and $n_i(\lambda_{red})$ in the equation it is possible to obtain the focal distance of the doublet corresponding to those specific wavelength values. The achromaticity condition previously introduced imposes the equivalence of the focal distances for blue and red light:

$$\frac{1}{f_{blue}} = \frac{1}{f_{red}} \quad (2.26)$$

and, using equation (2.25),

$$(n_{1,blue} - 1)\rho_1 + (n_{2,blue} - 1)\rho_2 = (n_{1,red} - 1)\rho_1 + (n_{2,red} - 1)\rho_2 \quad (2.27)$$

which can be expressed as follows:

$$\frac{\rho_1}{\rho_2} = -\frac{(n_{2,blue} - n_{2,red})}{(n_{1,blue} - n_{1,red})}. \quad (2.28)$$

Let define the *yellow wavelength* λ_{yellow} as a wavelength value between λ_{blue} and λ_{red} . For each component lens, equation (2.24) can be used to express the focal distance for yellow light:

$$\frac{1}{f_{1,yellow}} = (n_{1,yellow} - 1)\rho_1 \quad \text{and} \quad \frac{1}{f_{2,yellow}} = (n_{2,yellow} - 1)\rho_2 \quad (2.29)$$

hence

$$\frac{\rho_1}{\rho_2} = \frac{(n_{2,yellow} - 1) f_{2,yellow}}{(n_{1,yellow} - 1) f_{1,yellow}}. \quad (2.30)$$

Equating equations (2.28) and (2.30) leads to

$$\frac{f_{2,yellow}}{f_{1,yellow}} = -\frac{\frac{(n_{2,blue} - n_{2,red})}{(n_{2,yellow} - 1)}}{\frac{(n_{1,blue} - n_{1,red})}{(n_{1,yellow} - 1)}}. \quad (2.31)$$

The quantities

$$\frac{1}{V_2} = \frac{n_{2,blue} - n_{2,red}}{n_{2,yellow} - 1} \quad \text{and} \quad \frac{1}{V_1} = \frac{n_{1,blue} - n_{1,red}}{n_{1,yellow} - 1} \quad (2.32)$$

are called *dispersive powers* of the materials of the two lenses composing the doublet. Their reciprocal V_2 and V_1 are commonly called *Abbe numbers*. The lower the Abbe number, the greater the dispersive power. Thus

$$\frac{f_{2,yellow}}{f_{1,yellow}} = -\frac{V_1}{V_2}$$

$$f_{1,yellow}V_1 + f_{2,yellow}V_2 = 0. \quad (2.33)$$

Since the refractive index decreases as the wavelength increases $n_i(\lambda_{blue}) > n_i(\lambda_{yellow}) > n_i(\lambda_{red})$, therefore Abbe numbers are always positives. As a consequence, in order to satisfy equation (2.33), one of the two lenses must be negative.

When designing achromatic doublets for imaging optics, the wavelength range of interest is the visible spectrum of light. In this case, *blue*, *yellow*, and *red* wavelengths are commonly defined as the wavelengths associated to specific spectral lines whose refractive indexes are known with high precision: the *Fraunhofer lines* *F* (486.13 nm), *C* (656.28 nm), and *d* (587.56 nm) for blue, red and yellow.

The Abbe number equation becomes

$$V_d = \frac{n_d - 1}{n_F - n_C}. \quad (2.34)$$

In the case of an achromatic lens to be used as primary optics in an HCPV system the concept of *blue* and *red* light have to be extended the spectral range converted in electricity by a multi-junction (MJ) solar cell (350 – 1800 nm). Therefore, in order to have a figure of merit measuring the dispersion in such spectral range the *Solar Abbe number* is introduced. In this case blue, red, and yellow light correspond to wavelength values equal to 400 nm, 1000 nm, and 700 nm leading to

$$V_{solar} = \frac{n_{700} - 1}{n_{400} - n_{1000}} \quad (2.35)$$

As red light 1000 nm has been used instead of 1800 nm because, for most of the materials of interest in CPV applications, the refractive index after 1000 nm is practically constant. Therefore the spectral range in which is important to obtain achromaticity is between 350 nm and 1000 nm. Furthermore, in the triple-junction (3J) solar cells commonly used in modern CPV system, the bottom subcell, which convert in electricity light whose wavelength is longer than 1000 nm, is never the limiting one. Consequently, a reduced performance in this wavelength range is negligible.

2.3 Lens design

In this section, the techniques used to design concentrating lenses for CPV applications will be described. Several design methods will be analyzed:

- design of a simple aspheric concentrating lens with known focal distance using Fermat principle;
- design of a conventional Fresnel lens using Fermat principle;
- design of an aspheric achromatic doublet using iterative method;
- design of a Fresnel lens achromatic doublet.

2.3.1 Simple plano-convex concentrating lens using Fermat principle

As already mentioned in section 2.1.2 the Fermat's principle states that the optical path along a ray can be a maximum or a minimum.

In figure 2.9 a scheme representing the path of a ray coming from the infinity, refracting at the lens surface and focusing at the focal distance F is shown.

Figure 2.9: Ray-tracing scheme.

The angle α is the slope of the lens profile in the coordinate (x_i, y_i) , θ is the angle between the refracted ray and the optical axis, n_1 is the refractive index of the material composing the lens and $n_2 = 1$ is the refractive index of air.

The optical path C of a generic ray coming from infinity and exiting the lens in the generic point with coordinates (x, y) , in the specific case of a plano-convex converging lens, can be written as

$$C = n_1 y + n_2 \sqrt{(F - y)^2 + x^2}. \quad (2.36)$$

Fermat principle states that the optical path must be the shortest, which corresponds to the minimum of equation (2.36), therefore

$$dC = \frac{\partial C}{\partial x} dx + \frac{\partial C}{\partial y} dy = 0 \quad (2.37)$$

being

$$\frac{\partial C}{\partial x} = \frac{x}{\sqrt{(F - y)^2 + x^2}} \quad \text{and} \quad (2.38)$$

$$\frac{\partial C}{\partial x} = \frac{n_1 \sqrt{(F-y)^2 + x^2} - (F-y)}{\sqrt{(F-y)^2 + x^2}}.$$

Therefore, equation (2.37) becomes

$$dC = \frac{x}{\sqrt{(F-y)^2 + x^2}} dx + \frac{n_1 \sqrt{(F-y)^2 + x^2} - (F-y)}{\sqrt{(F-y)^2 + x^2}} dy = 0. \quad (2.39)$$

Using equation (2.39) it is possible to calculate the profile of a generic lens with a focal distance equal to F . To do so a discretization is required; applying equation (2.39) to k pairs of (x, y) points the profile of the lens is obtained. For the same lens diameter the more pairs of point are used the more the lens profile will be similar to the continuous profile, up to the limit where $k \rightarrow +\infty$.

So, to begin the process design the value of the diameter D , the focal distance F , and the x step dx are decided. Considering that $dx = x_i - x_{i-1}$ and $dy = y_i - y_{i-1}$ it is possible to calculate the (x, y) coordinates of the lens profile starting from $x_1 = D/2$ and $y_1 = 0$ and calculating x_i as $x_i = x_{i-1} - dx$ and y_i as

$$y_i = \frac{x_i}{n_1 \sqrt{(F-y_{i-1})^2 + x_i^2} - (F-y_{i-1})} (x_i - x_{i-1}) + y_{i-1}. \quad (2.40)$$

Using equation (2.40) it is possible to write the following table

Table 2.1: Table used to compute the coordinates (x, y) of the aspheric lens profile.

	x	y
1	$x_1 = D/2$	0
2	$x_2 = x_1 - dx$	$y_2 = \frac{x_2(x_2 - x_1)}{n_1 \sqrt{(F-y_1)^2 + x_2^2} - (F-y_1)} + y_1$
...	...	...
k	$x_k = x_{k-1} - dx = 0$	$y_k = \frac{x_k(x_k - x_{k-1})}{n_1 \sqrt{(F-y_{k-1})^2 + x_k^2} - (F-y_{k-1})} + y_{k-1}$

Once 2.1 is completed the lens is obtained by revolution around the z -axis.

Design of a conventional Fresnel lens using Fermat principle

A Fresnel lens is defined as a succession of concentric rings, called *grooves*, each consisting of an element of a simple lens, assembled in a proper relationship on a flat surface to provide a short focal length (see figure 2.10). These contours act as individual refracting surfaces, bending parallel light rays to a common focal length. As a result, a Fresnel lens, while physically narrow in profile, is capable of focusing light similar to a conventional optical lens but has several advantages over its thicker counterpart. In fact, the strongly reduced thickness of the lens reduces significantly the absorption losses, the material consumption, and the weight of the lens.

When designing a Fresnel lens the first step is to establish lens parameters. Apart from diameter D and focal distance F , that are the same than for the plano-convex lens, other Fresnel-related parameters have to be fixed before to begin the design. Such parameters are maximum pitch and maximum height of each groove (see figure 2.10), the draft angle value, and if design curved or flat facets.

Figure 2.10: Schematic representation of a Fresnel lens.

The last is very important when designing a Fresnel lens. Both choices have advantages and disadvantages. For example, in the case of flat facets the manufacturing process is simpler and, being the geometry less complex, the ray-tracing simulations faster. However, all the light ray entering a certain groove refract parallel and result in a less efficient light concentration (see figure 2.11).

Figure 2.11: Schematic representation of the limited concentration capability of a Fresnel lens designed with flat facets.

In order to limit the problem a large number of small grooves is required but, in this case, the lens would suffer higher losses for tips rounding. Conversely, lenses with curved facets permit a concentrating power equal to a traditional aspheric lens. In this case, the drawbacks are the more complex manufacturing process and slower and heavier simulations. The main obstacle in the manufacturing of a Fresnel lens featuring curved facets is the radius of the tips rounding of the lens

peaks (mold valleys). The curved profile makes difficult to efficiently carry out the diamond turning of the mold insert, resulting in larger tips rounding if compared with the flat profile (see section 4.2.1 for a detailed description of the manufacturing process and for an experimental comparison of flat and curved prototypes).

Once decided all the geometrical data is it possible to begin the design using the same equations introduced for the aspheric lens design (see table 2.1). In this case, when the groove reach one limit condition (*i.e.* maximum height or maximum pitch) the n^{th} groove finishes and the $(n + 1)^{\text{th}}$ groove begins.

2.3.2 Design of the aspheric achromatic doublet

The design of the aspheric achromatic doublet follows the same principles of the simple aspheric lens design. The difference is that, in the case of a simple aspheric lens, during the design phase, the refractive index associated to the design wavelength was used to carry out all calculations. In the case of the achromatic doublet, as explained in section 2.2.1, there is not a design wavelength but only a design focal distance, *i.e.* the distance at which rays with two different wavelengths must focus. To achieve such condition an iterative method is required.

There are several different configurations that is possible to use in order to obtain an achromatic doublet. For the aim of the project the achromatic lens is composed of a low-index diverging lens followed by a high-index converging lens (the reason of such choice is discussed in section 2.4). The doublet, for manufacturing reasons, is going to be cemented, and the first optical surface is going to be flat in order to permit the lamination on a flat glass substrate (for more detail about lens structure refer to 4.2).

Therefore, the light comes from the left and enters the lens through the first flat surface, then diverges in the first interface (low index - high index material) and finally converges in the second interface (high index material - air) and focuses in the optical axis at a focal distance F .

Figure 2.12 shows a scheme of the configuration chosen for the aspheric achromatic doublet together with the paths of blue and red light. Since in most of the transparent materials the refractive index is higher for shorter wavelengths [5], the blue light diverges more in the first interface and converges more in the second if compared with red light. This is how the achromatic effect is achieved.

From the mathematical point of view, the equations used to design the doublet are more complex than in the case of a simple lens. In this dissertation, Snell's law has been used.

Figure 2.13 shows a scheme with all the angles involved in the procedure of using the Snell's law in the two refractive interfaces of the achromatic lens.

From now on, the high dispersion converging lens is called *external lens* and the low dispersion diverging lens *internal lens*.

Looking at the converging lens-air interface, angle θ is the angle between the traced ray and the optical axis and is a function of the point of the external lens where the ray is being traced. Angle α_2 is the slope of the external lens in the considered point. Angle β_2 is the angle between the refracted ray and the normal to the lens profile. Then the relation $\beta_2 = \alpha_2 + \theta$ is valid (see figure 2.13). Angle γ is the angle between the incident ray before the refraction and the normal to the lens profile. Angle φ is the angle between the refracted ray before refraction and a line parallel to the optical axis. The relation $\gamma = \alpha_2 - \varphi$ is valid (see figure 2.13).

Snell's law at the interface between the converging lens (external) and air is the following

$$n_2 \sin \gamma = n_3 \sin \beta_2 \quad n_2 \sin(\alpha_2 + \theta) = n_3 \sin(\alpha_2 - \varphi). \quad (2.41)$$

Figure 2.12: Scheme of the achromatic doublet configuration. Paths of blue and red rays are also represented. The achromaticity condition imposes that blue and red light focus at the same focal distance F

Conversely, looking at the diverging lens - converging lens interface, angle β_1 is the angle between the refracted ray and the plane normal to the internal lens profile. Angle α_1 is the slope of the profile of the internal lens and, being the ray before the refraction parallel to the optical axis, also the angle between the incident ray and the plane normal to the internal lens profile.

Snell's law at the interface between the diverging lens and the converging lens is the following

$$n_1 \sin \alpha_1 = n_2 \sin \beta_1 \quad n_1 \sin \alpha_1 = n_2 \sin(\alpha_1 - \varphi). \quad (2.42)$$

The iterative method employed in order to design the achromatic lens consists in recursively design lens profiles in such a way that, on each iteration, the convergence of either blue light or red light to the focus F is ensured. After a certain number of iterations, the profiles required to make blue and red light converge to the focus stop changing, meaning that light with both wavelengths of interest focus at the same point F of the optical axis. In each iterations, the profile (internal or external) defined in the previous iteration is used as a starting point to define the new profile (external or internal).

When the external profile is used as starting point to define the internal profile, *reverse ray-tracing* is used. Reverse ray-tracing refers to a ray-tracing where the focus of the lens is used as the origin of the ray that afterwards goes back up to the actual light source. Conversely, when the internal profile is used as starting point to define the external profile, *direct ray-tracing* (from the source to the focus) is used.

After this introduction on the lens geometry and basic ray-tracing equations the actual design method will be described. Let call the two wavelengths of interest λ_b (short wavelength, blue light) and λ_r (long wavelength, red light). With a simple lens light with wavelength λ_b focuses closer to the lens than light with wavelength λ_r . The approach developed and used along this work to design an achromatic doublet is the following:

Figure 2.13: Ray-tracing scheme for the achromatic doublet design

1. design a simple aspheric lens (external profile) capable to concentrate light with wavelength λ_r exactly at the design focal distance F (figure 2.14a). Since the profile designed during the first step is the external, the refractive index used is $n_2(\lambda_r)$, where subscript 2 refers to the material used for the external lens;
2. using the lens profile defined in 1, design a second lens (internal profile) before the previous such that all the light with wavelength λ_b , after traversing both lenses, focuses at the design focal distance F (figure 2.14b). In this case the refractive indexes used are $n_1(\lambda_b)$ for the internal lens and $n_2(\lambda_b)$ for the external lens. Again, subscripts 1 and 2 refer to the materials used respectively for the internal and the external lenses;
3. redesign the first external lens such that, again, all the light with wavelength λ_r , after traversing both lenses, focuses at the design focal distance F (figure 2.14c);
4. redesign the first internal lens such that, again, all the light with wavelength λ_b , after traversing both lenses, focuses at the design focal distance F (figure 2.14d);
5. repeat steps 3 and 4 until the lenses geometry of two different iterations coincide. At this point light with both wavelength λ_r and wavelength λ_b focus at the design focal distance F (figure 2.12).

To carry out step 1 the method exposed in section 2.3.1 is used while, for steps from 2 to 4, equations and geometrical relations disclosed in this section are used.

Design of the achromatic doublet Fresnel lens

The procedure to design an achromatic doublet Fresnel lens is quite similar to the one described in section 2.3.1 for a conventional Fresnel lens. The only difference is that every Fresnel ring is going to be double, the first ring is the Fresnel equivalent of the internal lens and the second ring the Fresnel equivalent of the external lens.

Figure 2.14: Representation of the first four steps of the design method employed to design an aspheric cemented achromatic doublet.

Also in this case, apart from diameter D and focal distance F , maximum pitch and height, draft angle value and if design curved or flat facets have to be decided prior to the design.

Once decided all the geometrical parameters the design method is the same than for a conventional Fresnel lens. The process begins using the same equations introduced in section 2.3.2 for the aspheric achromatic doublet. Afterward, once that one of the two lenses (internal, diverging, and external, converging) reaches one limit condition (*i.e.* maximum height or maximum pitch) the n^{th} groove finishes and the $(n + 1)^{\text{th}}$ groove begins.

2.4 Achromatic Doublet on Glass (ADG) Fresnel lens

In chapter 1 a short introduction on the ADG Fresnel lens configuration was already presented. The lens is composed of a rigid glass substrate, an elastomeric material, and a plastic bi-Fresnel lens having the Fresnel structure on both its sides (see figure 1.2 in chapter 1). A detailed description of the manufacturing process is disclosed in chapter 4. For this context is enough to remember that, after manufacturing the plastic piece by plastic injection, the ADG sandwich composed of glass-elastomer-plastic is obtained by lamination.

The rigid glass substrate is a key element in the proposed design. More than twenty years of field experience with conventional silicone on glass (SoG) demonstrated the high reliability and durability of such technology. In fact, the low-iron solar glass ensures the flatness of the silicone lens cast on it, limits the thermal expansion of the silicone thanks to a low CTE, provides protection against weather conditions, it is chemically resistant and easily cleanable, and, at the same time,

have an outstanding transmission over all the wavelength of interests for CPV applications. All these advantages apply also for the case of the ADG technology, where the only difference is the lamination of a doublet composed of two materials instead of a conventional lens made of silicone.

As a consequence, in order to allow the lamination over a flat rigid substrate, the first surface (the one facing the sun) of the doublet must be flat. In addition, from section 2.2.1 it is known how an achromatic doublet must include a converging lens and a diverging lens. Thus, excluding from the beginning any configuration featuring the first surface concave or convex, there are mainly four possible structures that are theoretically equivalent:

1. low-refractive-index diverging lens (convex) facing the sun and high-refractive-index converging lens (convex) toward the receiver;
2. high-refractive-index diverging lens (concave) facing the sun and low-refractive-index converging lens (convex) toward the receiver;
3. low-refractive-index converging lens (concave) facing the sun and high-refractive-index diverging lens (concave) toward the receiver;
4. high-refractive-index converging lens (convex) facing the sun and low-refractive-index diverging lens (concave) toward the receiver.

Languy and co-workers already presented a performance comparison of four kinds of achromatic Fresnel doublets made of polycarbonate (PC) and polymethyl methacrylate (PMMA) featuring four different structures [6]. Two of them have not the first flat surface, therefore they are not taken into consideration, whereas the other two are of the type 1 and 2. The difference between them is the materials order: the first have the PMMA lens (low dispersion and low refractive index) on the top of PC lens (high dispersion and high refractive index). The lens *on the top* is always the one facing directly the sun. This configuration shows a lot of *dead zones* caused by the rays that, after diverging at the first PMMA-PC interface, hit either the vertical side (draft facets) of the previous groove or the border of the lens (see figure 2.15a). Conversely, in the case where the PC lens is on top, since its refractive index is higher than PMMA's, in order to have the first lens converging it is necessary to change its curvature from convex to concave (see figure 2.15b). Therefore, since the curvature of the first lens is negative, with this configuration the doublet do not have the aforementioned dead zones, apart from the rays lost in the perimeter of the lens (see figure 2.15b). The points 3 and 4 were not contemplated in Languy's work, and consist in the configurations where the lens of the top is the converging one. In option 3, since the lens on the top is made of a material with low refractive index, both lenses must be concave. Therefore, as it is schematically represented in figure 2.15c, there are not rays lost in the perimeter but the dead zones caused by the draft facets appear again. Finally, in configuration 4, where the material order is the opposite than in case 3, the lens on the top is convex and the other is concave. Thanks to this last configuration, the losses caused by both the perimeter and the draft factes are avoided, achieving a condition in which coupling two lenses in a doublet do not suppose additional geometrical losses than manufacturing a conventional simple lens. It is worth to remark that, in configurations 3 and 4 the required curvature of the diverging lens is minimal, thus the number of Fresnel grooves of such lens could be inferior than the number of grooves of the converging one.

From the optical point of view, the configurations 4 (figure 2.15d) is the one resulting in the lowest light loss. Nevertheless, the manufacturing process envisaged for the ADG Fresnel lens, in order to allow the lamination on the glass substrate, requires that the lens on the top (the one facing the sun) is made of an elastomeric material. As it will be described later in section 2.5, at the beginning of the thesis it was complicated to find in the market cost-effective and easily processable elastomers with high dispersion and high refractive index. Therefore, despite the higher losses due to the dead zones caused by the draft facets and the perimeter of the lens, the only feasible configurations were 1 and 3 (figures 2.15a and 2.15c). Even if the second does not have dead zones caused by the perimeter of the lens, the first was chosen. The reason of this choice is the high curvature required by the converging lens in configuration 3, which results in a higher

Figure 2.15: Schematic representation of four possible configurations of an achromatic Fresnel doublet. (a) Case with the low dispersion/low index material on top of the high dispersion/high index material and with the diverging lens facing the sun. (b) Case with the high dispersion/high index material on top of the low dispersion/low index material and with the diverging lens facing the sun. (c) Case with the low dispersion/low index material on top of the high dispersion/high index material and with the converging lens facing the sun. (d) Case with the high dispersion/high index material on top of the low dispersion/low index material and the converging lens facing the sun.

number of grooves and in a higher number of rays lost in the draft facets.

2.5 Materials

The choice of the pair of materials to be used in the ADG manufacturing process is a decisive step in the lens development.

As described in chapter 1, the ADG lens is composed of a rigid plastic and an elastomeric material, which is molded in one of the two individual lenses of the doublet during the lamination step. Nowadays, the PV market offers a wide range of well-known materials whose properties have been deeply investigated [7–12]. For the context of this thesis, it is useful to separate the materials between plastics and elastomers, which in turn can be divided in thermoplastic (*i.e.* that become pliable or moldable above a specific temperature and solidifies upon cooling [13]) and thermoset (*i.e.* that is irreversibly hardened by curing from a soft solid or viscous liquid prepolymer or resin [14]). An elastomer is generally defined as a polymer with high viscoelasticity (*i.e.*, both viscosity and

elasticity) and very weak intermolecular forces, and generally low Young's modulus and high failure strain compared with other materials [15]. Conversely, a plastic is a material consisting of any of a wide range of synthetic or semi-synthetic organic compounds that are malleable and so can be molded into solid objects.

In the last decade, many companies and research centers dedicated time and resources in the investigation of materials suitable to be used in the PV field. Very interesting and useful informations derived from their studies. However, it should be mentioned that, depending on the specific formulation of a certain material, very different properties (either optical, mechanical, or thermal) can be obtained. As an example, every material including any number of polymers containing alternate silicon and oxygen atoms is defined as *silicone*. The properties of a specific kind of silicone are determined by the organic groups attached to the silicon atoms. Therefore, it is clear how, depending on the application, different material formulations should be synthesized to successfully meet the specific process requirements.

As a consequence, throughout the years, new materials, and/or new formulations of existing materials, constantly enter and leave the market. This real-time continuous changing in the marketplace represents an important limitation to the development of new technologies, where prototypes are manufactured at laboratory scale, and the small material quantities required do not justify for big companies the investment of time and money needed to develop tailored compositions aiming to the performance optimization of the investigated application. For that reason, ADG technology was developed based on off-the-shelf materials, which have been carefully selected among the wide range of possibilities, but still are far away from the optima.

Figure 2.16: Dispersion graph representing the refractive index and the solar Abbe number for all the plastics and the elastomers investigated.

Figure 2.16 shows the refractive index vs. the solar Abbe number for the plastics and the elastomers taken into consideration when selecting the best pair. Unfortunately, not all the materials (or specific formulations) represented in the dispersion graph were available at the beginning of the thesis. For example, the only high-dispersion elastomers available in the market were too expensive to be used in this application. This fact led to the choice of the current ADG lens configuration (low dispersion diverging lens facing the sun, and high dispersion converging lens facing the receiver). Recently, several new high dispersion elastomers are being developed and investigated. Some examples of these materials are the high dispersion cross-linking silicone (LS-3354), polystyrene-block-polyisoprene-block-polystyrene (PSPI) and liquid crystal elastomers (LCE). Also, thermoplastic thiourethane (SK series from Mitsui Chemicals) despite they are defined as plastics, since they are cross-linking materials with low polymerization temperature, could act as elastomers for the purpose of ADG lens manufacturing.

Another limitation encountered at the beginning of the thesis was the lack in the market of elastomers with high transmission in the UV region. It is known how, many plastics and encapsulants get yellow after an extended exposure to UV radiation [16–19]. For this reason, additives are usually added to the chemical formulations in order to block such harmful radiation, and to improve the durability of the material under real operating conditions. As it will be shown in section 2.6, the high material absorption in the UV region is one of the larger contributions to the low maximum attainable efficiency of ADG lenses. Recently, thermoplastic elastomers (TPE) with high transmission in the UV region have been commercialized and, despite the need to carry out degradation tests in order to ensure that UV radiation does not cause yellowing, they could significantly improve lens performances.

Table 2.2 gathers a list of several plastics and elastomers that have been investigated during the thesis. Some of them were known from the beginning, while others have been discovered only in the last months of the ADG development.

2.5.1 Candidate materials

The selected pair of materials must satisfy several requirements, from the optical properties needed to obtain an achromatic lens, to their compatibility from mechanical, thermal, and financial points of view. The lamination step of the ADG Fresnel lens manufacturing process (a detailed description of such procedure is reported in chapter 4) is very similar to the process used to encapsulate conventional flat PV modules. Consequently, candidates materials have been selected among the wide range of possibilities offered by flat PV market. Obviously, the requirements are slightly different when, instead of encapsulating an array of silicon solar cells, the purpose is to use the encapsulant (*i.e.* the elastomer) to glue together the rigid glass substrate and the plastic piece, while simultaneously molding the Fresnel structure of the elastomer.

The pair of materials to be used in the manufacturing of the ADG Fresnel lenses must meet certain requirements listed below:

1. as mentioned in section 2.2.1, in order to get the achromatic behavior one materials must have high dispersion (low solar Abbe number) and the other low dispersion (high solar Abbe number);
2. the light transmission over the wavelength of interest of the MJ solar cells ($350 - 1800 \text{ nm}$) must be as high as possible in order to limit absorption losses;
3. the coefficients of thermal expansion (CTE) of the two materials should be as similar as possible in order to avoid detrimental thermal-generated stresses when the operating temperature changes;
4. the adhesion between the materials, either in the glass-elastomer interface and in the elastomer-plastic interface, must be strong enough to avoid delamination in operation.
5. the materials (especially the plastic) must be easily processable even in the case where a high optical quality is required;
6. both raw materials and their processing must be as cheap as possible.

Among all the materials available at the beginning of the thesis two elastomers and two plastics have been identified as possible candidates. Polycarbonate and PMMA have been selected as possible plastics exactly because they are cheap and easily processable. The state-of-the-art technology ensure that both plastics can be processed (also when the application requires a complex geometry such as a Fresnel structure) using common techniques such as injection molding, compression molding, or hot embossing. Furthermore, especially with PMMA, there is a lot of field experience in manufacturing reliable and efficient Fresnel lenses for CPV.

Plastics							
Name	Refractive index	Conventional Abbe number	Solar Abbe number	CTE	dn/dT	HDT (1.8 MPa) ¹	Ref.
				$10^{-6}/K$	$10^{-5}/K$	$^{\circ}C$	
Polycarbonate (PC)	1.585	29	10	70	−12	123	[20, 21]
Polymethyl methacrylate (PMMA)	1.485	57	23	60	−10	101	[20, 22]
Cyclic olefin copolymer (COC)	1.530	52	19	60	−11	122	[20, 23]
Polystyren (PS)	1.590	29	10	73	−16	85	[23, 24]
Polyester (OKP4)	1.607	27	—	72	−13	106	[21]
Polyester (OKP4H)	1.632	23	—	69	−11	123	[21]
Polyester (OKP-1)	1.642	22	—	71	−12	115	[21]
Polyester (generic)	1.607	26	9	—	—	—	Provider datasheet
Lux opticlear (3D printing)	1.529	42	15	—	—	—	Provider datasheet
Thiouretane-based plastic (SK-400)	1.600	41	15	—	—	118	Provider datasheet
Thiouretane-based plastic (SK-500)	1.670	31	11	—	—	85	Provider datasheet
Thiouretane-based plastic (SK-600)	1.670	31	12	—	—	100	Provider datasheet
Thiouretane-based plastic (SK-700)	1.740	32	12	—	—	78	Provider datasheet
Elastomers							
Name	Refractive index	Conventional Abbe number	Solar Abbe number	CTE	dn/dT	Softening temperature (for thermoplastic only)	Ref.
				$10^{-6}/K$	$10^{-5}/K$	$^{\circ}C$	
Ethylen-vinyl acetate (EVA)	1.484	62	21	180	−31	<i>Thermoset</i>	[25, 26]
Polydimethylsiloxane (PDMS)	1.412	51	18	340	−48	<i>Thermoset</i>	[25] and provider datasheet
Polyvinyl butyral (PVB)	1.481	54	19	400	−69	150	[25, 27] and provider datasheet
Thermoplastic elastomer (TPE)	1.484	76	26	170	−28	87	[7] and provider datasheet
Optically clear soft silicone gel LS2-3354 (NuSil)	1.541	34	11	—	—	<i>Thermoset</i>	Provider datasheet
Polystyrene-block-Polyisoprene-block-Polystyrene (PSPI)	1.528	50	18	—	—	—	[28]
Liquid crystal elastomer (LCE)	1.573	10	4	—	—	—	[28]
Thermoplastic polyurethane (TPU)	1.568	34	—	—	—	—	[29]
Thermoplastic polyolefin (TPO)	1.485	180	65	—	—	—	[25]

Table 2.2: List of investigated plastics and their properties.

¹The heat deflection temperature or heat distortion temperature (HDT) is the temperature at which a polymer or plastic sample deforms under a specified load. In this case 1.8MPa.

Conversely, polydimethylsiloxane (PDMS), commonly called silicone, and a thermoplastic elastomer (TPE) whose optical properties are quite similar to the well-known ethylene-vinyl acetate (EVA) have been selected as possible elastomers. On one side, the silicone is the most spread material used to manufacture Fresnel lenses for CPV, therefore its weaknesses and strong points are well-known to the scientific community, as well as the method and reliability of its processing. On the other side, raw silicone is quite expensive and, being a thermoset, needs a long time to completely cure and to achieve its polymerized form. Since the processing time is one of the factors directly affecting the production costs of a technology, it is advisable to reduce such time as much as possible. The silicone curing time is a function of temperature, therefore it is possible to reduce it significantly by rising up the process temperature.

An in-deep investigation on the physical properties of these four materials is presented in the following.

2.5.2 Optical properties

First and most important property in order to assess if a material is suitable to be used in ADG manufacturing process is the refractive index.

Figure 2.17: Refractive index of the possible materials previously selected. Thermoplastic elastomer and silicone data have been provided by suppliers while PC and PMMA data come from [30].

Figure 2.17 shows the refractive index of the candidate materials. From the figure is clear how PC and PMMA have a higher dispersion if compared with silicone and the elastomer, which confirm the lower Abbe numbers.

In order to evaluate which pair of materials is the best choice aiming to an attenuated chromatic aberration, it is convenient to represent the focal distance variation as a function of the incident light wavelength.

Let begin with the case of a conventional converging lens manufactured with silicone. First step is to define the design refractive index, n_d which is the refractive index value used to design the lens. Light with wavelength equal to λ_d (with $n(\lambda_d) = n_d$) converges exactly at the design focal distance F_d .

To find the right n_d let consider red and blue light as the light associated to $\lambda_{red} = 1000 \text{ nm}$ and $\lambda_{blue} = 400 \text{ nm}$ (see section 2.2.1). Being $n_{red} = n(\lambda_{red})$ and $n_{blue} = n(\lambda_{blue})$, the n_d is the mean value between n_{red} and n_{blue} .

From the lensmaker equation (2.21) the focal distance corresponding to the design wavelength λ_d can be written as

$$\frac{1}{f_d} = (n_d - 1)\rho \quad (2.43)$$

where $n_d = n(\lambda_d)$ and ρ is the lens curvature ($1/R$).

Conversely, for a generic wavelength λ

$$\frac{1}{f} = (n - 1)\rho \quad (2.44)$$

where $n = n(\lambda)$ and ρ is the lens curvature.

Making the ratio between equation (2.43) and (2.44) leads to

$$\frac{f}{f_d} = \frac{\rho(n_d - 1)}{\rho(n - 1)} = \frac{(n_d - 1)}{(n - 1)} \quad (2.45)$$

which only depends on n_d , that is a constant value calculated a priori, and on wavelength λ through $n(\lambda)$.

A similar development can be done for the case of a generic cemented achromatic doublet composed of two materials. The focal distance of a cemented doublet can be written using equation (2.23)

$$\frac{1}{f} = \frac{1}{f_1} + \frac{1}{f_2} \quad (2.46)$$

where subscripts 1 and 2 refer to the two lenses composing the doublet. Therefore, using again the Lensmaker equation, the previous equation becomes

$$\frac{1}{f} = \rho_1(n_1 - 1) + \rho_2(n_2 - 1). \quad (2.47)$$

For the design focal distances n_{1d} and n_{2d}

$$\frac{1}{f_d} = \rho_1(n_{1d} - 1) + \rho_2(n_{2d} - 1). \quad (2.48)$$

Making the ratio between equation (2.47) and (2.48) brings to

$$\frac{f}{f_d} = \frac{\rho_1(n_{1d} - 1) + \rho_2(n_{2d} - 1)}{\rho_1(n_1 - 1) + \rho_2(n_2 - 1)} = \frac{\frac{\rho_1}{\rho_2}(n_{1d} - 1) + (n_{2d} - 1)}{\frac{\rho_1}{\rho_2}(n_1 - 1) + (n_2 - 1)} \quad (2.49)$$

which depends on λ through $n(\lambda)$ and on the dimensional parameter ρ_1/ρ_2 . In order to exclude the dimensional dependency let consider the achromaticity condition defined with equation (2.28) and reported here again for the sake of clarity

$$\frac{\rho_1}{\rho_2} = \frac{n_{2,blue} - n_{2,red}}{n_{1,red} - n_{1,blue}}.$$

Consequently, equation (2.28) depends on λ_{red} and λ_{blue} , which are parameters chosen before the lens design. Therefore, using equation (2.28) in equation (2.49), the last becomes only dependent on λ_d , which is calculated from λ_{red} and λ_{blue} , and from the incident light wavelength λ .

A graphical representation of equation (2.49) for several pairs of materials compared with a graphical representation of equation (2.45) for single converging lens manufactured in silicone is very useful to understand the potential attenuation of chromatic aberration.

Figure 2.18: Graphic representation of the change in the relative focal distance for the four possible doublets obtained combining the candidate elastomers and plastics. In each graph, the blue curve represents the relative focal distance variation for a generic converging lens made of silicone while the red curve represents the variation for a cemented achromatic doublet composed of the pair of material of the title

From figure 2.18a and 2.18b it can be seen how both doublets made out of PMMA do not provide a significant reduction of the chromatic aberration and therefore they have been excluded. Conversely, both doublets made out of PC show a strong reduction of the chromatic aberration.

Second important optical property is the transmittance over the wavelength range converted in electricity by MJ solar cells (*i.e.* 350 – 1800 nm).

In figure 2.19 the transmittance of candidates materials is represented. It is obvious that, from the transmission point of view, the best material is silicone. In fact, all the others filter UV light and part of the infrared spectrum, with the exception of the PC without any UV filter, which has a good transmission also in the UV region. On one side, the UV through PC would allow a higher radiant power transmission which translates in a higher efficiency. On the other side, it is known that PC under prolonged UV exposition becomes yellow. However, since in operation the PC is protected by the TPE, which filters the most harmful UV radiation, it has not been excluded as a candidate material. As a matter of fact, experimental outdoor degradation demonstrated the reliability of the PC when protected by the TPE (a description of such test is exposed in chapter 4).

2.5.3 Thermal properties

The two most important properties from the thermal point of view are the melting point (or curing temperature for a thermoset elastomer) and the coefficient of thermal expansion (CTE). The first is a key element in the manufacturing process while the second plays an important role in the reliability of the lenses under realistic operating conditions. Another important factor is the refractive index variation as a function of the temperature (dn/dT).

Figure 2.19: Transmittance of the candidate materials. Data found in literature [7, 25].

Numerical values of the melting point, the CTE, and the dn/dT for the four candidate materials are reported in table 2.2. Again the TPE seems to be the best choice since both the CTE and the dn/dT are lower than PDMS. Furthermore, the melting point of TPE is lower than the melting point of PC, confirming their compatibility from the manufacturing point of view.

2.5.4 Selected best pair of materials

After the described investigation over all the materials suitable to be used for the ADG lens manufacturing, the PC with high transmission in the UV region was selected as high dispersion plastic, whereas the TPE was selected as the low dispersion elastomers. Among the candidate materials PC was selected over PMMA because, coupled with anyone of the candidate elastomers, provides a stronger attenuation of the chromatic aberration (see figure 2.18). Conversely, the TPE was selected over silicone despite the high transmission and proven stability of the latter. The main reasons for this choice are the ease of the TPE processing compared to silicone, the closeness of the refractive index values of PC and TPE, which results in reduced losses for Fresnel reflection, and the significantly lower prices of the raw material. Moreover, the higher absorption of the TPE in the UV region, allows the use of the UV through formulation of the PC, allowing a partial recovery of the UV absorption losses.

From now on, every mention to the "ADG Fresnel lens" refers to the specific selected configuration, which consists in a low dispersion/low index diverging lens made of TPE and a high dispersion/high index converging lens made of PC with high transmission in the UV region.

2.6 Ray-Tracing

A comprehensive set of ray-tracing simulations was performed in order to predict and analyze the performance of the ADG Fresnel lens previously described. The simulated ADG configuration comprises the flat rigid glass substrate, the diverging lens of thermoplastic elastomer (TPE), and the converging lens of PC. The subsections hereafter reproduce the main results including optical efficiency, profile of the irradiance spot, acceptance angle, and photocurrent distribution on every subcell within the MJ solar cell. The results are presented for the flat facets design. In the last subsection, the main differences and improvements provided by the curved facets design are introduced. The following assumptions are made in every simulation:

- the real sun angular size ($\pm 0.27^\circ$) and the reference spectrum AM1.5D for Direct Normal Irradiance (DNI) are assumed [31];
- the receiver at the focal plane is considered to be ideal, *i.e.*, it absorbs every ray impinging its surface;
- for every material involved (glass, silicone, PC, and TPE), spectrally-resolved values for transmittance and refractive index are used. Data has been provided by the manufacturer or found in the literature [11, 30, 32];
- Ideal surfaces with no losses due to surface roughness (scattering), waviness, or shape errors are assumed.

2.6.1 Model description

The 3D model used to carry out ray-tracing simulations is composed of the light source, the lens to be simulated and the receiver (solar cell). In order to compute the lens' efficiency, a surface receiver is added on the lens aperture plane. The power in watts measured by such receiver is considered to be the input while the power measured by the solar cell receiver the output, which consists in the power that has not been absorbed, reflected, deviated by the lens and can be used to generate electricity using a photovoltaic device.

Figure 2.20: Screenshot of the model used to carry out ray-tracing simulations. All elements composing the model are included together with the ray paths drawn by the software

Figure 2.20 shows a screenshot of the model used to carry out ray-tracing simulations. Light source, simulated lens and solar cell receiver are represented. Embedded in the rear surface of the lens there is also the aforementioned lens receiver that is not visible in figure 2.20.

The simulations are carried out tracing a minimum of one million rays up to a maximum of four millions, depending on the complexity of the model and the number of active receivers. The number of rays is chosen in order to ensure that the estimated error at peak is always lower than 5 %.

2.6.2 Optimal focal distance

The decision of lens' focal distance is a key factor in lens design, especially in lenses with Fresnel profile. More precisely, the important parameter is the *f-number*, which is defined as the ratio between the lens' focal distance F and the lens' diameter D . The f-number is a direct measure of the power of a concentrating lens.

On one side, a small f-number results in a more compact module with clear advantages from the point of view of transportation, integration, etc. On the other side, the faster is the lens, the more Fresnel grooves it needs (for the same thickness), resulting in more losses due to tips rounding. Furthermore, the grooves slope of a faster lens is higher, and consequently the reflection losses also increase, up to the limit of the total internal reflection (TIR), where the rays are completely reflected instead of refracted.

Also, the maximum attainable concentration is affected by the f-number. Lenses with low f-number are usually more sensible to optical aberrations.

Figure 2.21: Optical efficiency and spot diameter as a function of lens' f-number. (a) SoG Fresnel lens. (b) ADG Fresnel lens

Figure 2.21 shows both efficiency and spot diameter as a function of the f-number. The efficiency strongly decreases for very low f-number as well as the spot diameter increase. For both lenses, a higher f-number corresponds to a higher simulated efficiency, which increases up to a limit value. The slope of the SoG efficiency curve is higher, meaning that it achieves the maximum value for a lower f-number if compared with an ADG lens.

Conversely, the spot diameter in both cases strongly decreases for small f-numbers up to a minimum, then slowly increases again. The minimum corresponds to an f-number equal to 1.2 for the SoG and 0.8 for the ADG. The optimum f-number, from the spot diameter point of view, is at smaller f-number for the ADG because the chromatic aberration attenuation is stronger for lenses with a higher power.

For design, simulations, and manufacturing of ADG Fresnel lenses, the chosen f-number is 1.5. Considering a lens aperture of $40 \times 40 \text{ mm}^2$ the corresponding focal distance is 85 mm^2 . In order to make a fair comparison, the same f-number has been used to simulate the SoG Fresnel lens used as benchmark.

²The real optimal focal distance resulting from a specific lens design could be slightly different to the one previously chosen.

Table 2.3: Optical efficiency predicted by ray-tracing for the ADG Fresnel and the equivalent SoG Fresnel lens used as benchmark

<i>Simulations</i>	<i>Optical efficiency</i>		<i>Relative optical efficiency</i>
	SoG	ADG	
<i>Ideal materials (only draft angles and round tips ($3\mu\text{m}$ for SoG, $5\mu\text{m}$ for ADG))</i>	97.6 %	93.0 %	95.1 %
<i>Realistic simulation (materials absorption, Fresnel reflection added)</i>	88.5 %	82.0 %	92.6 %
<i>Realistic simulation (ADG potential improvement)</i>	88.5 %	84.2 %	95.1 %

2.6.3 Lens optical efficiency

The optical efficiency is defined as the fraction of radiant power at its input aperture P_{in} which reaches a designated receiver area P_{out} [33, 34]

$$\eta_{op} = \frac{P_{out}}{P_{in}}. \quad (2.50)$$

For the results included in this subsection the size of the receiver is large enough to capture every ray refracted by the useful region of the facets. In this way, the computed efficiency takes into account only those phenomena which lower the throughput of radiant power through the lens: absorption in the materials, reflections at any of the lens faces, geometrical losses caused by draft angles and tips rounding, etc.

Table 2.3 summarizes the results for the SoG Fresnel lens and the ADG Fresnel lens. The last column shows *relative efficiency* values. The relative efficiency $\eta_{op,rel}$ is defined as

$$\eta_{op,rel} = \frac{\eta_{op,ADG}}{\eta_{op,SoG}} \quad (2.51)$$

and is the figure of merit used along all the thesis to evaluate the performance of the proposed ADG Fresnel lens.

For every lens, the first line shows the efficiency when only geometrical losses related to draft angles and tips rounding are considered, that is, materials are assumed to be ideal and neither absorption nor Fresnel reflection in any surface are taken into account. Since the ADG includes two Fresnel surfaces with larger tip rounding, the geometrical losses associated with rounding at valleys and corners cause a lower optical efficiency. It should be remarked here that the value assumed for tips rounding was that estimated by the manufacturer but, if sharper tips were obtained in the fabrication, the optical efficiency values predicted for both lenses would be closer. For every lens, the second line in table 2.3 reproduces the optical efficiency estimated for a more realistic situation, that is, including not only geometrical losses but also materials absorption and losses due to Fresnel reflection.

Finally, the third line in table 2.3 reproduces the optical efficiency estimated for a realistic situation, but taking into account reduced tip rounding values ($3\mu\text{m}$) and an improved material transmission in UV region, which are two parameters that could be easily improved considering an industrial manufacturing process and tailored up material compositions.

Subcell optical efficiency. In order to better characterize the spectral behavior of the simulated lenses, it is convenient to define the concepts of *top optical efficiency* η_{op}^{top} and *middle optical*

efficiency η_{op}^{mid} . Such efficiencies are conceptually equivalent to the optical efficiency defined in equation (2.50), but they take into consideration only the radiant power comprised between 350 nm and 660 nm for the top efficiency, and between 660 nm and 900 nm for the middle. Such spectral ranges correspond to the limits of the spectral response of the top subcell and the middle subcell, respectively. In order to calculate such values, *wavelength filters* can be added to the simulation model, allowing to precisely select the wavelength range of interest before every simulation.

Table 2.4: Table reporting the spectral efficiencies obtained from the ray-tracing simulations of the reference SoG Fresnel lens and the ADG Fresnel lens under study.

	SoG	ADG
<i>Global efficiency</i>	88.5 %	82.0 %
<i>Top efficiency</i>	88.7 %	80.3 %
<i>Middle efficiency</i>	88.2 %	84.3 %

Table 2.4 summarizes the simulated subcell efficiencies together with the global efficiency reported again for comparison. It immediately stands out that, for the reference SoG Fresnel lens, the three efficiency values are almost identical. Conversely, for the ADG Fresnel lens, the middle efficiency is 4 % higher than the top efficiency. The lower top efficiency is caused by the material absorption in the UV region of the spectrum. As it will be shown in section 2.6.9 and in chapter 4, the high absorption in the UV region is one of the most significant source of losses for the ADG technology.

2.6.4 Attainable concentration

Figure 2.22: Encircled energy as a function of the receiver radius (concentration). The two dashed lines represent the maximum attainable concentration of both lenses, the SoG and the ADG.

In order to make a fair comparison regarding the concentration attainable by both lenses, it is convenient to plot the encircled energy of the lens as a function of the size of the receiver considered, in other words, as a function of the geometric concentration at which the lens will be operated (figure 2.22).

Encircled energy is defined as the percentage of the total energy transmitted by a lens, which is captured by a receiver of a certain radius, *i.e.*, with the lens working at a certain concentration.

In figure 2.22 the encircled energy is represented. The maximum attainable concentration for a certain relative transmission is equal to 332 *suns* for a conventional SoG Fresnel lens and 716 *suns* for the ADG Fresnel lens. Therefore, thanks to the achromatic design, using an ADG lens instead of a conventional SoG lens it is possible to double the maximum attainable concentration.

Unfortunately, the graph in figure 2.22, since it does not represent absolute efficiency values, could be misleading. In fact, as exposed in section 2.6.3, absolute optical efficiency is higher for a conventional SoG Fresnel lens with respect to the ADG Fresnel lens. As a consequence, despite the improved concentration capability of the ADG, only at higher concentration factors the absolute efficiency is actually higher.

Figure 2.23: Absolute optical efficiency as a function of the receiver radius (concentration). The four black dashed lines represent the maximum attainable concentration of both lenses, the SoG and the ADG, and the intersection point of the two curves. Also the case, considering an improved ADG lens (see section 2.6.3) is represented with the orange dashed line.

Figure 2.23 shows the absolute optical efficiency as a function of the receiver radius (concentration). It is clear how, up to the intersection point of the two curves, that is for a concentration factor of 623 *suns*, despite the reduced spot size of the ADG lens, a conventional SoG lens still works better. Conversely, for concentration factors higher than 623 *suns*, the ADG lens has a higher efficiency.

It is worth to notice that, considering the potential industrial scale-up introduced in section 2.6.3, the position of the ADG curve rises and the intersection point move to lower concentration.

The yellow dashed line in figure 2.23 shows the potential improvement of the ADG lens.

Considering a slightly higher optical efficiency the intersection point switches from 623 *suns* to 524 *suns*.

As it will be described in the next sections, the attainable concentration is only one of the advantages provided by the achromatic design of the lens.

2.6.5 Concentration - acceptance angle product

The most adequate figure of merit for CPV is the concentration-acceptance angle (CAP) product. The CAP indicates the similarity of a certain concentrating optics to an ideal system that conserves light étendue [35]. CAP is calculated according to equation (2.52):

$$CAP = \sqrt{X_g \cdot \sin \vartheta} \quad (2.52)$$

where X_g is the geometric concentration and θ is the acceptance angle. The geometric concentration X_g is defined as the ratio of the input area A_{in} to the output area, that is, the receiver area, A_{out} :

$$X_g = \frac{A_{in}}{A_{out}}. \quad (2.53)$$

The acceptance angle θ for a certain geometrical concentration is defined as the deviation angle such that the optical efficiency is 90 % of its maximum. Put it simply, the higher the CAP the better the optic performance.

Figure 2.24: Misalignment angle θ resulting in the 90% of the maximum optical efficiency as a function of the geometrical concentration X_g predicted by ray-tracing simulation for the ADG Fresnel lens and the equivalent classic SoG Fresnel lens. The misalignment angle is defined as the deviation angle such that the optical efficiency is 90% of the maximum.

Nevertheless, at high geometrical concentration, the definition of acceptance angle could be misleading. At high concentration the maximum efficiency is already low with a perfectly aligned system, therefore, it makes no sense to consider acceptable a misalignment leading to 90 % of a low number. That is why, in order to evaluate the performance of the ADG lens, and to compare it with a conventional SoG lens, the reference value of the optical efficiency considered is the maximum

efficiency at low concentration. In this way at high concentrations, for instance when the efficiency of the aligned system is 90 % of the efficiency at low concentration, the allowed misalignment is equal to zero, because also the smallest angle would bring the lens efficiency below 90 %.

Figure 2.24 depicts the different combinations of X_g and θ achievable by the ADG Fresnel lens and the SoG Fresnel lens. Since the ADG tolerance is higher, one can choose either to increase the concentration maintaining the same tolerance to misalignment or to keep the same concentration and use the ADG to widen the tolerance to misalignment, thus increasing the tolerance to assembly positioning, tracking errors, and lens temperature variations.

2.6.6 Photocurrent distribution produced by the ADG Fresnel lens and the equivalent SoG Fresnel lens

In this subsection, the distribution of photogenerated current for the different subcells and the impact of lens temperature on them is analyzed. To estimate photocurrent instead of light power, the emitting source of the ray-tracing simulations is modified. Instead of using the reference spectrum for the emitting source, it is multiplied by the MJ solar cells spectral response $SR_{i-subcell}(\lambda)$ to obtain a wavelength-dependent electrical response $S_{i-subcell}(\lambda)$.

$S(\lambda)$ weights every wavelength by its capacity to generate an electron-hole pair in the solar cell, avoiding the usual overestimation of 'blue' light which, due to the shorter wavelengths, has lower conversion efficiency. Therefore, instead of predicting irradiance distribution over the cell, the simulation output represents the photogenerated-current distribution for every subcell, making it possible to determine which subcell produces the least current at any part of the cell. The sensitivity to lens temperature has been investigated by taking into account the dependence of refractive index on temperature for the different materials involved. Simulations were run at 25 °C, 40 °C, and 55 °C lens temperatures, representative of cold, warm and hot environmental conditions.

Non-uniformities, where the spectral content of the flux varies across the cell, are inherent to refractive CPV systems because of the optical transfer function and chromatic aberration in the optics. When the photogenerated current distribution are such that there are different regions over the cell either limited by the top or the middle subcell, the limiting subcell will be determined by the resistance of the layers connecting the subcells [36,37]. As it can be observed in figure 2.25, the ADG Fresnel lens does not only cast a smaller irradiance spot but it provides two significant benefits compared to a classic SoG Fresnel lens. On the first place, the photogenerated current distribution for top and middle subcells are much more similar reducing the losses associated with lateral current flows. On the second place, the irradiance distribution is less sensitive to the temperature of the primary lens. This thermal sensitivity is one of the main drawbacks of SoG Fresnel lens [38–40] and reducing its impact on the irradiance distribution over the cell is expected to increase the energy harvested throughout the year [41]. The refractive index variation with temperature for the involved materials can be found in references [42, 43]. The significant deformations experienced by the SoG lens [38–40] have not been taken into account, though, which might further worsen its temperature sensitivity.

It should be remarked here that, for the sake of clarity, the irradiance distribution over the bottom subcell was obviated in the previous discussion. Two facts justify this decision. Firstly, for the majority of optical materials, the dispersion is far more significant at shorter wavelengths than at longer ones (see figure 2.17 for the refractive index as a function of wavelength of the materials used in the ADG lenses), hence the bottom subcell irradiance profile is expected to be very similar to that of the middle subcell. Secondly, in classic Germanium-based 3J solar cells the bottom subcell generates an excess of current and consequently the current flowing throughout the device is limited by any of the other subcells.

Figure 2.25: Spatial distribution of the photogenerated current for the top J_{sc}^{top} (upper half graphs) and middle J_{sc}^{mid} (lower half) subcells at different temperatures predicted by ray-tracing simulations. Contour graphs (third line) show the ratio between top and middle photocurrents $J_{sc}^{top}/J_{sc}^{mid}$. Blue areas represent cell regions where there is an excess of top photogenerated current (middle limited) while red areas represent an excess of middle photogenerated current (top limited). Regions where both subcell photocurrents are matched are shown in white. Gray areas represent regions where both photocurrent values are below 0.1 % of the maximum, that is, dark areas.

2.6.7 Thermal sensitivity

As described in section 2.6.6, ADG lens, apart from the higher attainable concentration, also shows a reduced temperature dependency. The reasons are the achromatic behaviour together with materials whose properties change less as a consequence of temperature variation. Since conventional SoG performance is strongly influenced by temperature [38–40], it is interesting to investigate how such dependency is reduced using an ADG Fresnel lens.

To do so, ray-tracing simulations over the temperature range from 10 °C to 50 °C have been carried out. However, it is worth to mention that only the refractive index dependence with temperature was accounted, whereas the deformation of the grooves caused by thermal dilatation is not considered. The last it is known to be very significant in the performance of conventional SoG Fresnel lenses [38, 42], even more than the refractive index. Conversely, for the ADG lenses, whose materials have a CTE lower than silicone, this effect is not expected to be that important; thus, the simulations reproduce a scenario that is more advantageous for the SoG than for the ADG. Two different scenarios have been simulated: the first with a geometrical concentration equal to 385 *suns*, and the second with a geometrical concentration of 800 *suns*.

Figure 2.26: Optical efficiency of the SoG reference lens and ADG lens at 385 *suns* and 800 *suns* as a function of lens temperature predicted by ray-tracing simulations. The effect of the deformation of the grooves caused by the thermal dilatation of materials is not included.

Figure 2.26 shows the results predicted by ray-tracing simulations. In both simulated scenarios ADG performance is much more stable than conventional SoG performance. For the low concentration scenario, despite the reduced temperature sensitivity a conventional SoG lens is still able to work at higher efficiencies. This is due to the lower efficiency of the ADG lens caused by technical limitations described in section 2.6.3. Conversely, with a geometrical concentration of 800 *suns*, since the SoG efficiency strongly decreases as a consequence of light spillage, ADG lens efficiency is higher in the whole temperature range.

2.6.8 Geometrical and manufacturing tolerances

Ray-tracing simulations result very useful to analyze the influence that manufacturing errors may have on the system performance. Figure 2.27a depicts the impact of draft angle and tip rounding on the optical efficiency of the ADG Fresnel lens. For every dot in the plot, the ADG with the corresponding geometrical parameters was generated and a simulation was conducted. Based on the previous experience of the plastic injector, the most probable values for average draft angle and tip rounding are 3.5° and $5\mu\text{m}$ respectively (indicated in figure 2.27a with a black circle). The first result that can be observed is that, since the ADG includes two Fresnel surfaces, if wider draft angles were necessary the losses caused by optically inactive surfaces will decrease the optical efficiency to unbearable values. The second result is related to tip rounding at valleys and corners. Currently, a conservative value ($5\mu\text{m}$ tip) has been assumed for this figure. The sharpness of injected PC is expected to be worse than that attained by silicone in SoG Fresnel lenses ($3\mu\text{m}$ tip). Nevertheless, according to figure 2.27a, if the optimization of the injection process allows a better tip rounding value than initially expected an increase in the optical efficiency of 1 – 2 % may be obtained.

Figure 2.27: (a) Optical efficiency of the ADG Fresnel lens as a function of the average draft angle and tip rounding values. Simulations include neither materials' absorption nor Fresnel reflection losses. An average draft angle is used since the draft angle varies along the lens profile in order to ease the manufacturing of the plastic injected piece. The black circle marks the simulation assuming the most probable geometry according to the manufacturer.

Consequently, those values are included in the simulation in table 2.3. Simulation include neither materials absorption nor Fresnel losses reflection. (b) Normalized efficiency vs. manufacturing error affecting concentricity of the two Fresnel faces of the plastic piece when the ADG is used at different concentration ratios. The efficiency values have been normalized using the value attained when perfect concentricity is assumed.

Concentricity of the two optical inserts including the Fresnel pattern (both sides of the plastic piece) has been identified as one of the most critical requirement to ensure the correct performance of the lens. Figure 2.27b shows the efficiency drop as a consequence of errors in concentricity when the ADG Fresnel lens is operated at different concentration ratios. For higher concentration values ($> 700 \text{ suns}$) concentricity tolerance should be below $100 \mu\text{m}$ to avoid a significant efficiency reduction.

Conversely, tolerance in the total thickness of the plastic piece (from peaks on the first surface to valleys on the second) does not seem to be that critical. Ray-tracing simulations predict that the optical efficiency value is kept constant for variations of $\pm 250 \mu\text{m}$ around the nominal value of 2 mm .

2.6.9 Losses of the final ADG design

In this section, all the efficiency losses of the final ADG Fresnel lens design are quantified. This is going to be useful in order to understand the reason of the limited maximum efficiency value as well as to determine where and how the ADG lens might be improved.

Losses taken into account are the following:

- switch from aspheric to fresnelized profile;
- draft angle losses;
- tips rounding losses;
- reflection losses;
- absorption losses.

Figure 2.28: Sankey diagram showing all the losses that contribute to bring down the efficiency from 100 % (ideal aspheric lens with no absorption nor reflection) to 82 % (real simulated lens with Fresnel structure, draft angles and tips rounding, and materials absorption and reflection).

Figure 2.28 reveals a Sankey diagram showing the contribution of each entry of the aforementioned list. As already mentioned in section 2.6.3, with an improved manufacturing process and a tailored up materials composition it would be possible to reduce tip roundings and absorption losses. Apart from these two factors, it is worth to notice that only switching from the aspheric profile to the Fresnel profile a 3 % of efficiency is already gone, even considering ideal geometry without neither draft angles nor tip roundings. With the actual lens configuration it is impossible to avoid this 3 % of losses.

2.6.10 Flat facets vs. curved facets design

In this section, a comparison between the flat facets design and the curved facets design is presented. The main advantage provided by the curved facets design is an enhanced concentration,

achieved because of the reason explained in section 2.3.1.

Figure 2.29: Encircled energy as a function of the receiver radius (concentration). The dashed red line represents the ADG Fresnel lens featuring flat facets while the continuous red line represents the ADG Fresnel lens featuring curved facets. The two black dashed lines represent the maximum attainable concentration of the two lens designs.

Figure 2.29 shows the encircled energy as a function of the receiver radius (*i.e.* the geometrical concentration) for the two ADG designs: with flat facets (dashed line) and with curved facets (continuous line). It is easy to see how, switching to the curved facets design, it is possible to increase the concentration from 716 *suns* to 1401 *suns*. It is worth to remark that, as mentioned in the beginning of this section, the ray-tracing simulation does not take into account losses due to surface roughness (scattering), waviness, or shape errors, which are factors that directly contribute to widen the spot cast by a lens. Therefore, the concentration values predicted are overestimated and, in real operating conditions, the light spot is larger. Nevertheless, since the concentration increase is significant, the curved facets design is definitely worthy even if, as reported in section 2.3.1, it implies a more complicated manufacturing process.

The optical efficiency is not affected by the groove shape. Looking at the Sankey diagram showed in figure 2.28, none of the sources of loss is design related, meaning that a variation of the predicted efficiency was not expected.

2.7 Conclusions

Several conclusions can be deduced from this chapter. First, in order to design an achromatic doublet for CPV applications, it is possible to adapt the same design principles commonly used in imaging optics, but extended to the spectral range of interest of MJ solar cells currently used in most of CPV systems. Therefore, as well as the conventional doublets, the achromatic lens for CPV must include a positive lens and a negative lens. Moreover, when the doublet is Fresnelized, not all the possible configurations are equally efficient. In fact, based on basic ray-tracing considerations, the most performing design would consist in a doublet in which the lens facing the sun is a converging lens made of high-dispersion and high refractive index material, and the other lens is a diverging lens of a low-dispersion and low refractive index material. Unfortunately, such configuration was not

possible because of the lack in the market of materials whose properties were compatible with the lens design. Therefore, for practical reason, the opposite configuration was chosen: the achromatic doublet on glass (ADG) Fresnel lens consists in a diverging lens facing the sun and made of a material with low dispersion and low refractive index, and of a converging lens made of a material with high dispersion and high refractive index.

In this regard, several materials were deeply investigated along this thesis as possible candidates to be used in the ADG manufacturing. Thanks to such investigation, an in-deep knowledge of the materials suitable to be used in the CPV field have been acquired. The pair of materials chosen for the ADG technology was the best trade-off between obtaining a high optical performance while keeping in mind the compatibility with the manufacturing process. This material pair consists in a thermoplastic elastomer (TPE) used as the low-dispersion diverging lens, and the polycarbonate (PC) for the high-dispersion converging lens. In addition, it is worth to remark that, if all the materials currently available in the market had been accessible at the beginning of the thesis, an even better design could have been developed. Nevertheless, despite the limitation imposed by the materials, outstanding performances have been predicted by ray-tracing simulations.

The optical efficiency of the ADG lens was studied and compared with the optical efficiency of a conventional SoG lens whose properties (aperture, f-number, etc.) were the same than the ADG lens under study. The results showed that the highest efficiency predicted for the optimized ADG lens is 4 % lower than for the SoG lens. This is due to several reasons: firstly, the ADG lens configuration chosen, which consists in the diverging lens facing the sun and the converging lens toward the receiver, results in a lot of dead zones caused by the draft facets and the perimeter of the lens. Secondly, due to the fact that only materials with a limited transmission in the UV region were available at the beginning of the thesis, very high absorption losses in the top region of the spectrum (350 – 660 nm) are predicted.

Despite these limitations, that could be overcome by using different materials and an improved manufacturing process, several advantages have been identified. First, the light spot size predicted by ray-tracing simulation is smaller for the investigated ADG lens than for the reference SoG lens. Second, the maximum concentration is equal to 716 *suns* for the ADG lens and 332 *suns* for the reference SoG. Nevertheless, because of the lower optical efficiency of the ADG lens, its absolute efficiency value is going to be higher only for a concentration factor higher than 524 *suns*.

Another outstanding result is the strongly reduced temperature sensitivity found for the ADG lens. Ray-tracing simulations showed that the irradiance distribution over the receiver (*i.e.* a solar cell) is much more uniform for the ADG lens than for the SoG lens. Simulations have been carried out in the temperature range between 25 °C and 55 °C, which are reasonable outdoor operating conditions, and at each simulated temperature, the ADG lens irradiance distribution outperforms SoG lens exhibiting a nearly uniform irradiance spot distribution. Conversely, the SoG lens, as soon as the temperature differs from the manufacturing temperature, starts casting an irradiance profile on the receiver where some zones have an excess of red light (top limited), and other zones an excess of blue light (middle limited). This kind of non-uniformity in operation, directly translates into an efficiency reduction of the solar cell caused by local current mismatch. In addition, the optical efficiency has been also analyzed as a function of temperature and, even in this case, the ADG performance is much more stable. Two scenarios were simulated, the first with a concentration of 385 *suns* and the second with a concentration of 800 *suns*. For the first, despite the lower temperature dependence of the ADG, SoG efficiency is higher along most of the simulations because of the higher initial efficiency. Conversely, for the high concentration scenario, the efficiency of the ADG is higher and more stable at the same time along all the temperature range. Nevertheless, it is worth to notice that in these simulations the effect of the grooves deformation caused by the thermal expansion was not accounted for. Because of the lower CTE of the materials composing the ADG lens, this effect is expected to be more detrimental for the SoG lens than for the ADG, meaning that including the deformation in the simulations would worsen more the performance of the SoG lens than of the ADG.

Finally, the sources of losses of the ADG lens have been investigated in order to understand their causes and to find where there is room for improvement.

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Chapter 3

CHARACTERIZATION TECHNIQUES

3.1 Introduction

This chapter is entirely dedicated to the description of all the characterization methods used to assess the performance of the proposed achromatic doublet on glass (ADG) Fresnel lens technology.

Sections 3.2 and 3.3 exhaustively describe the methods used to measure both the lens optical efficiency and the diameter of the light spot cast by the lens. Together with the description of the equipment and methods, also an analysis of their repeatability and their reliability is presented. Moreover, section 3.4 describes the necessary adaptations implemented in order to measure big arrays composed of many lenses, and section 3.5 describes the thermal chamber used to evaluate the performance of the ADG lenses at different temperatures. All these measurements were carried out using two different solar simulators implemented at the Solar Energy Institute - Technical University of Madrid (IES-UPM). The first is called HELIOS 3030 and it is used in order to characterize the solar cells that will be used as light sensor in the optical efficiency measurements. Conversely, the second solar simulator, bigger in size than the former, is equipped with a large parabolic mirror used to collimate the light onto the optics to be measured, be it a lens, a mirror, or a complete concentrator photovoltaic (CPV) module. This simulator, called HELIOS 3198, is used to measure both the optical efficiency and the diameter of the irradiance spot cast by the optics. In the first case, a solar cell previously characterized with the HELIOS 3030 is used as a sensor in order to assess the transmission efficiency of the lens. Conversely, in the second case, the concentrated spot is focused on a Lambertian diffuser. Then, a charged-coupled device (CCD) camera is used to take the photograph of the light spot. Appendix A contains a general description of the two solar simulators previously introduced, whereas appendix B describes how to use the aforementioned solar simulators to measure multijunction (MJ) solar cell.

Finally, the last chapter briefly describes the outdoor characterization method used to measure the complete CPV modules assembled and measured in the last stage of this thesis.

3.2 Optical efficiency measurement

Figure 3.1 shows a scheme of the laboratory set-up for the method proposed to estimate the optical efficiency value. The HELIOS 3198 solar simulator described in appendix A is employed to illuminate the entrance aperture of the primary optics with collimated light whose spectral distribution is similar to AM1.5D. An integrating sphere is used to attain an angular collimation

Figure 3.1: Scheme of the set-up used to carry out experimental testing.

of $\pm 0.27^\circ$. The radiant power at the entrance of the optics and at the focal plane is measured from the short-circuit current of a solar cell previously measured using the solar simulator HELIOS 3030 described in appendix A. Either a silicon or a MJ solar cell can be used. For the latter, the subcell limitation diagrams can be used to determine the optical efficiency corresponding to the wavelength range converted into electricity by the top and middle subcells (see appendix B). The subcell limitation diagram represents the evolution of the ratio of the short-circuit currents of the MJ solar cell to the isotype cell (*i.e.* a single-junction cell with the same spectral response (SR) of one of the subcell within a MJ solar cell) vs. the variation of the spectral distribution through the flash decay. Such diagram allows the determination of the short-circuit current of every subcell within the MJ solar cell.

The solar cell used as light collector is mounted in an automated three-axes moving platform through which it is possible to center the cell with respect to the optics and to vary the distance between the primary optics and the solar cell to find the optimal focus. In addition, the lens can be placed inside a regulated enclosure to perform the measurement at different temperatures.

The concerns that should be considered to reduce experimental errors include: the size of the solar cell must be large enough to ensure that all the light transmitted by the optics is collected by it; the cell's response should be linear for the concentrated irradiance cast by the lens; and errors due to non-uniformity effects, front-grid shading, and distinct angular distribution over the cell must be avoided. The uniformity across the area illuminated by the CPV solar simulator probably introduces additional and significant uncertainty. To reduce the uncertainty a single lens of similar size and material must be kept as a reference and remeasured prior to every measurement session. In this case, a silicone on glass (SoG) Fresnel lens provided by Fraunhofer-ISE is used as a reference. Such lens has the same optical aperture than the ADG Fresnel lens prototypes ($40 \times 40 \text{ mm}^2$).

The optical efficiency η_{op} of a lens, already introduced in section 2.6.3, is defined as the fraction of radiant power at its input aperture P_{in} which reaches its output P_{out} [1, 2] (see equation (3.1)). Both P_{in} and P_{out} can be expressed as a function of the average irradiance at the lens aperture G_{in} and at the measurement plane G_{out} multiplied by the aperture area A_{optics} and receiver area A_{cell} ,

respectively. The measurement of G_{in} and G_{out} is strongly dependent on the irradiance sensor used to measure it, as well as on the angular distribution and the spectral features of the light impinging the entrance. In order to limit the dependence of the measured efficiency on external factors, a MJ solar cell is used as irradiance sensor. In this case both G_{in} and G_{out} can be estimated by measuring the photocurrent of a pair of identical solar cells illuminated by the light at the lens entrance and at its focus [2]:

$$\eta_{op} = \frac{P_{out}}{P_{in}} = \frac{G_{cell} \cdot A_{cell}}{G_{optics} \cdot A_{optics}} = \frac{I_{sc,out}/I_{sc,out}(1)}{I_{sc,in}/I_{sc,in}(1) \cdot X_{geo}} \quad (3.1)$$

where G_{cell} and G_{optics} are the average irradiances at the focus plane and at the lens aperture, $I_{sc,out}$ and $I_{sc,in}$ are the photocurrents generated by the solar cells located at the focus plane and at the lens entrance plane, and $I_{sc,out}(1)$ and $I_{sc,in}(1)$ are the calibrated values of the photocurrents of the two solar cells under reference spectrum¹. X_{geo} is the geometrical concentration and it is calculated as the ratio between the aperture of the optics A_{optics} and the solar cell area A_{cell} .

Moreover, if in equation (3.1) the specific subcell short-circuit current is used instead of the global, the efficiency calculated is related to the spectral band of interest of the subcell took into account, *i.e.* 350 – 660 nm for η_{op}^{top} and 660 – 900 nm for η_{opt}^{mid} .

The main limitation of this method is its dependency on the solar cell performance and on the reliability of its preliminary calibration. Therefore, different measurements carried out using different solar cells as light sensors, or under different conditions, are not always comparable. To overcome this limitation, instead of the optical efficiency value, the reported figure of merit is the *relative efficiency* already defined in section 2.6.3, and calculated as follows:

$$\eta_{op,rel} = \frac{\eta_{op}}{\eta_{op}^{ref}}$$

where η_{op}^{ref} is the optical efficiency of an optics used as reference and measured again before any experimental testing. In this way, it is always possible to compare results obtained from different tests and with different and/or not well-calibrated light sensors. In practice, substituting equation (3.1) in equation (2.51), and assuming that the same light sensor is used, the relative optical efficiency reduces to the ratio of the short-circuit current measured using the optics to be tested as concentrator, and the short-circuit current measured using the reference optics as concentrator, corrected by the ratio of their respective apertures:

$$\eta_{op,rel} = \frac{\eta_{op}}{\eta_{op}^{ref}} = \frac{I_{sc,out}/I_{sc,out}(1)}{I_{sc,in}/I_{sc,in}(1) \cdot X_{geo}} \cdot \frac{I_{sc,in}^{ref}/I_{sc,in}^{ref}(1) \cdot X_{geo}^{ref}}{I_{sc,out}^{ref}/I_{sc,out}^{ref}(1)} = \frac{I_{sc,out}}{I_{sc,in}} \cdot \frac{I_{sc,in}^{ref}}{I_{sc,out}^{ref}} \cdot \frac{X_{geo}^{ref}}{X_{geo}} \quad (3.2)$$

where superscript *ref* refers to the measurement carried out using the reference optics as concentrator. Finally, if the reference optics has the same aperture area than the optics to be measured and is mounted in the same position of the solar simulator, $X_{geo} = X_{geo}^{ref}$ and $I_{sc,in} \approx I_{sc,in}^{ref}$, therefore equation (3.2) reduces to

$$\eta_{op,rel} = \frac{\eta_{op}}{\eta_{op}^{ref}} = \frac{I_{sc,out}}{I_{sc,out}^{ref}}. \quad (3.3)$$

The use of the relative efficiency contributes to increase the repeatability of the measurement, especially when the time passed between two measurements is enough to results in different test conditions. For instance, even if the set-up is prepared to control the optics temperature, it cannot control the solar cell temperature, resulting in a possible alteration of the measured efficiency depending on the external weather. As an example, figure 3.2a shows the absolute optical efficiency of a random ADG sample, measured five times in a period of two years. The standard deviation is equal to 3.6 % for the top subcell and 5.3 % for the middle subcell. Conversely, figure 3.2b shows the relative efficiency recorded the same measurement days for the same ADG sample. In this case the standard deviation is equal to 0.8 % for the top subcell and 1.1 % for the middle subcell.

¹1000 W/m² and reference spectrum AM1.5D

Figure 3.2: (a) Bar chart representing the absolute efficiency value measured for a random ADG sample in five different days. (b) Bar chart representing the relative efficiency value measured for a random ADG sample in five different days. In both cases, the average value and the standard deviation are reported.

Observing the absolute efficiency measurement carried out in March 2018, it is clear how the short-circuit current is higher than the other days. Such difference is not visible in the relative efficiency graph because, whatever conditions affected the measurement, it influenced both the ADG sample and the SoG lens used as reference.

3.2.1 Spectrally resolved optical efficiency

The set-up used to measure the optical efficiency can be modified in order to assess the *spectrally-resolved* optical efficiency, *i.e.* the transmission efficiency of the optics evaluated at certain specific wavelengths.

Figure 3.3: Scheme of the measuring set-up for the spectrally-resolved optical efficiency measurement. A band-pass filter (BPF_i) centered at wavelength λ_i is placed in front of both, the MJ solar cell illuminated by the CPV optics and the set of three component cells that compose the spectroheliometer and whose function is to measure the irradiance at the entrance of the optics. In addition, bias light is produced by the same source of light when adding the adequate filter (e.g., in this case the BPF_i is assumed to be within the top subcell spectral range, hence a cold mirror is used to bias the middle and bottom subcells). Figure taken from [3].

The spectrally-resolved optical efficiency has many applications: first, the knowledge of the spectrum dependent efficiency is an useful information when optimizing a CPV system, especially in balancing the photocurrent generated by the different subcells composing a MJ solar cell. Second, it may be used to include the influence of the optics in energy prediction models commonly used to forecast the annual energy harvesting of a system. Most of the commonly used models do not take into consideration the influence of the optics [4–6], despite it might be remarkable. Lastly, the time evolution of the spectral transmittance of a certain optics can help to detect a possible degradation and determine its cause.

The experimental set-up used to evaluate the spectral efficiency is the same described in the previous section with a few additional implementations. First, two identical narrow band-pass filters BPF_i centered at wavelength λ_i are placed in front of the solar cell and the three-tube containing the isotype cells. As a consequence, only a small portion of the total irradiance emitted during the flash decay reaches the solar cell and, moreover, such "active" light is going to be transformed in electricity only by the subcell whose SR includes the wavelength λ_i . In such condition, only one subcell is generating current but, being the subcells within a MJ solar cell series connected, the MJ device generates a quasi-zero current. In order to solve this problem, the same flash light source is used to saturate the two subcells that are not generating current, in such a way that the current generated by the MJ solar cell corresponds to the current generated by the subcell of interest, which only receive light with wavelength λ_i .

From a practical point of view, the solar cell used as receiver is placed close to the light source and an optical path allowing the light emitted from the light source to directly hit the cell is created. Such light is filtered using either a high-pass or a low-pass filter, depending on which ones of the subcells need to be saturated. In figure 3.3 the scheme of the described set-up is shown.

Hence, the spectral optical efficiency η_λ at each spectral band λ_i is defined as follows:

$$\eta_\lambda(\lambda_i) = \frac{I_{sc}^{\lambda_i} / I_{sc}(1)}{X_{geo} \cdot I_{sc}^{ref, \lambda_i} / I_{sc}^{ref}(1)} \quad (3.4)$$

where $I_{sc}^{\lambda_i}$ is the short circuit current of the solar cell used as receiver when illuminated through the BPF_i , $I_{sc}(1)$ is the photocurrent under reference conditions, I_{sc}^{ref} refers to the same quantities but for the reference cell (the corresponding isotype cell in the three-tube) and X_{geo} is the geometrical concentration ratio.

Figure 3.4: Spectrally-resolved optical efficiency of the Achromatic Doublet on Glass (ADG) Fresnel lens. The reference spectrum AM1.5D is shown in gray. Figure taken from [3].

Figure 3.4 shows the spectrally-resolved efficiency measured for a ADG Fresnel lens prototype.

As expected, the efficiency measured using band-pass filters with low λ_i are quite low because of the low transmission in the UV region, whereas they stabilize for higher wavelengths.

3.3 Irradiance spot measurement

The set-up is the same as shown in figure 3.1. In this case, the solar cell is replaced by the set composed of the CCD camera and the bandpass filters whose cut-off wavelength is equal to approximately 700 nm. There are two possible methods to measure the size of the irradiance spot. The first consists in focusing the light spot directly onto the CCD camera sensor used to take the photographs, whereas the second consists in focusing the CCD camera coupled with an objective on a plane where a Lambertian diffuser is placed. Then, the light spot cast by the lens is focused onto the diffuser. On one side, the first method avoids both the uncertainty due to the quality and the uniformity of the diffuser and the need of moving simultaneously the camera and the diffuser in order to maintain the first correctly focused on the last. On the other side, when the light spot is focused directly on the CCD sensor, the light intensity must be carefully controlled in order to have a good signal-to-noise ratio, and, at the same time, to reduce the sensitivity of the measurement to external light sources which could compromise the reliability of the results. The method using the Lambertian diffuser has been identified as the more repetitive and reliable, as it will be described later in section 3.3.1.

The previously mentioned bandpass filters are required in order to investigate the spectral behavior of the lens. The SR of the CCD camera together with bandpass filters, either a cold mirror, which blocks light with wavelengths under 700 nm, or a hot mirror, which blocks light with wavelengths above 700 nm, has a similar shape respectively to the SR of top and middle subcells (see figure 3.5a). Once the set-up is prepared, a flash is triggered and a photograph of the light spot is taken setting an exposure time much higher than the flash duration. Afterwards, the image is processed for the determination of the centroid of the focused spot. Using the centroid as the origin, the encircled energy graph can be calculated and the intercept radius assessed (figure 3.6). The previous steps are repeated as the primary to diffuser separation distance is varied, to find the optimal position, *i.e.* the position where the intercept radius is minimized. The temperature of the lens can be modified to study the thermal sensitivity of the optics.

The image processing has been carefully performed: saturated pixels were avoided by reducing the irradiance level (adding neutral density filters) and background noise was subtracted from the photographed image to obtain a proper encircled energy graph.

3.3.1 Comparison of the irradiance spot measurement methods

The first method consists in focusing the light spot directly onto the CCD sensor avoiding the use of the diffuser. In this case, since no objective is used, the sensor is receiving a huge amount of light from both the lens to be measured and the surrounding environment. Therefore, in order to not saturate the sensor and, at the same time, to have a good signal-to-noise ratio, it is necessary to place neutral filters between the lens and the camera. Conversely, the second method consists in focusing the light spot onto a Lambertian diffuser. Then, the CCD camera coupled with an objective is used to take a photograph of the light spot projected onto the diffuser. In this case, the challenges are the quality of the diffuser and the preparation of a set-up capable of moving it integrally with the CCD camera, in order to always take photograph focused on the receiver plane. For the second method, the diffuser has been prepared depositing a thin layer of magnesium oxide over a 200 μm cover glass [7].

In order to understand what method is the one providing the higher reliability, the same lenses have been measured using both strategies and the results have been compared. In addition, a comparison of the two CCD camera available at the IES-UPM is also presented.

Figure 3.5: (a) Spectral response of the CCD camera silicon sensor filtered by a cold mirror or a heat glass (empty dots) to simulate the SR of the middle and top subcells of a 3J solar cell (solid dots). This figure has been modified from [2]. (b) Photograph of the structure implemented in order to have the Lambertian diffuser integral with the CCD camera. In the photograph, instead of the diffuser there is a graph paper used to focus the camera and calculate the pixel to millimeters relation.

Figure 3.6: (a) Efficiency as a function of the spot radius. The intercept radius $r_{\text{intercept}}$, is defined as the radius of a circular area that results in a previously determined percentage of the radiant flux incident on the entire target area. The target area, in this case, the diffuser, must be larger than twice the intercept radius. (b) Schematic of a focused spot at the target area where $r_{\text{intercept}}$ and $2r_{\text{intercept}}$ are indicated. This figure has been modified from [2].

In particular, four measurements have been carried out:

1. using a Kodak camera (sensor KAI-16000) and the spot size cast directly on the CCD sensor;
2. using a Kodak camera (sensor KAI-16000) with an objective used to take a photograph of the Lambertian diffuser where the spot is cast;
3. using a QImaging RETIGA EXi camera (sensor Sony ICX285) and the spot size cast directly on the CCD sensor;
4. using a QImaging RETIGA EXi camera (sensor Sony ICX285) with an objective used to take a photograph of the Lambertian diffuser where the spot is cast.

From figure 3.7 a first comparison of the results obtained with every possible combination of methods and cameras is shown. Several conclusions can be taken from this first measurement. Firstly, it can be observed that, regardless which camera is used, the optimal focal distance results 3 – 4 mm longer for the measurements in which the light spot is focused directly on the camera sensor. Such difference is caused by the presence of the filters placed between the lens and the

Figure 3.7: Graphs showing the light spot diameter as a function of the distance between the lens and the measuring plane where the photograph is taken. The spot diameter is defined as the circumference diameter containing the 95 % of transmitted light. a) Kodak camera without diffuser. b) Kodak camera with diffuser. c) QImaging camera without diffuser. d) QImaging camera with diffuser. Results obtained with the SoG reference lens.

camera sensor. In figure 3.8 such effect is schematically represented: the filters act as a refractive surface. Since both their surfaces are plane, the rays are displaced further from the lens but their orientation does not change. The relevance of this effect depends on the ratio between the filters thickness and the lens focal distance. It is worth to notice that such limitation of the direct measurement (without diffuser) can be avoided by placing the filters before the lens in such a way that they do not interfere with the light transmitted by the optics. However, this solution is not easily implementable. In fact, when no objective is coupled with the CCD sensor, without filtering the light directly at its entrance the background noise, *i.e.* light proceeding from light sources different than the lens, would be higher than the signal compromising completely the reliability of the results. Therefore, the set composed of the camera and the lens to be measured should be perfectly isolated from the external environment in order to completely block external light sources. Such set-up is not easy to implement and would require a different (or highly adaptable) structure for every specific lens to be measured. In addition, the filters should be larger than the lens aperture and, depending on the lens size, they are not easy to find in the market.

Conversely, when the measurement is carried out using the Lambertian diffuser, the use of neutral filters is not required, and, however, the filters would be placed between the objective of the camera and the diffuser, not interfering with the light trajectory. Secondly, the diameters measured with the Kodak camera are in both cases slightly higher than the diameters measured with the QImaging. Despite the difference is only in the order of a tenth of a millimeter, this means that the specifications of the camera used to perform the measurement affects the results. Thirdly, regardless the camera used, the spot size measured using the diffuser results to be slightly smaller than the one measured with the spot focused directly on the sensor. This is due to the scattering taking place when the light crosses the filters which, apart from moving the optimum focal point, widen the light spot (see figure 3.8). Finally, it is possible to notice how the measurements carried out

Figure 3.8: Scheme showing the effect of the filters on the optimal focal distance when the measurement is carried out focusing the light spot directly on the CCD sensor.

with the diffuser clearly show the effect of the chromatic aberration of the SoG lens, represented by the displacement of the minimum points of the red and blue curves, which correspond to the points where the spot diameter is minimized. Conversely, for the measurements carried out with the spot directly focused on the CCD camera, the SoG lens looks almost perfectly achromatic. This is caused by the effect of the filters previously described. In fact, when measuring with neutral and spectral filters together, not always the same number of filters are used in order to achieve a good signal-to-noise ratio. As a consequence, different measurements carried out using a different number of filters result in an altered focal distance. How much altered with respect to the reality depends on the number of filters used and on their thickness. Therefore it is obvious that, in order to achieve repetitive and comparable measurements, the total filters thickness (*i.e.* the sum of the thickness of every single filter) must be always the same. This conditions is difficult to achieve while maintaining the good signal-to-noise ratio through every measurement.

From the above, it is obvious that the measurements realized using the Lambertian diffuser are more accurate than focusing directly on the sensor. However, the reliability of this method is strongly dependent on the quality of the diffuser that, in order to do not alter the results, must be infinitely thin. For the measurements carried out throughout this thesis, the diffuser has been prepared evaporating a thin layer of magnesium oxide over a cover glass with a thickness of $200\mu\text{m}$. The challenge here is to obtain a uniform magnesium oxide layer. However, the diffuser prepared at the IES-UPM laboratory resulted to be thin and uniform enough to give reliable measurements.

Figure 3.9: Graphs showing the light spot diameter as a function of the distance between the lens and the diffuser where the light spot is projected. The photographs are taken using the Kodak CCD camera. The spot diameter is defined as the circumference diameter containing the 95 % of transmitted light. a) Results obtained with the SoG reference lens. b) Results obtained for an ADG prototype. In both cases the colored circles identified with the letters A, B, C, D, E, and F are the specific points whose light profiles and encircled energies are shown in figure 3.10.

Conversely, the black circles highlight the points whose processed photographs are shown in figure 3.11.

Figure 3.10: (a) and (c) represent the illumination profiles as a function of the receiver radius for the reference SoG lens and the ADG lens, respectively. (b) and (d) represent the encircled energy of the reference SoG lens and the ADG lens, respectively. The points studied for the SoG correspond to the positions A, B, and C highlighted with colored circles in figure 3.9a, whereas the points studied for the ADG correspond to the positions D, E, and F highlighted with colored circles in figure 3.9b.

Furthermore, the measured light spot size depends on two factors which must be decided arbitrarily prior to the measurement: which camera to use and which percentage of energy defines the spot size. It is difficult to declare which one is the "right" method, the most important thing in order to achieve reliable and comparable measurements is to always define the light spot, and always compare exclusively measurements carried out with the same CCD camera.

Once selected the best method and device, in order to better understand the measurements and how to interpret the results, let observe in more details two sample measurements carried out using the Kodak camera and the Lambertian diffuser.

Figure 3.9 shows the irradiance spot measurement for the SoG Fresnel lens used as reference and for one prototype of ADG Fresnel lens. In this figure, the x-axis shows the relative focal distance variation, where the zero corresponds to the optimal position identified only observing the spot with naked eye. By way of example, let observe the red curves corresponding to the middle subcell for both the SoG and the ADG lenses. Every point of the curves in figure 3.9 derives from the computer processing of a photograph taken at the lens-diffuser relative distance corresponding to the x-axis. As explained earlier in this section, first the encircled energy is calculated starting from the illumination profile of the photograph, then, the radius of the spot corresponding to a certain percentage of energy is assessed. Throughout this section the spot is defined as the circle containing the 95 % of the light. In figure 3.10 the light profiles and the encircled energies corresponding to the points highlighted with the colored circles in figure 3.9 are shown. It can be noticed that, for the case of the SoG lens, the depicted profiles are perfectly consistent with the position of the minimum. In fact, in figure 3.10a, the green continuous curve that corresponds to the optimal position (point

A) has the highest peak and the highest slope. In addition, in figure 3.10b, the green curve is the one reaching faster the 95 % of the energy. Conversely, for the case of the ADG lens, such consistency is not that evident. In fact, observing the points D, E, and F highlighted with colored circles in figure 3.9b, it seems obvious that the points D and E have a similar diameter while the diameter corresponding to the point F is higher. Then, observing the profiles in figure 3.10c and the encircled energies in figure 3.10d, the former results is not clearly visible. Observing the green continuous curve corresponding to the optimal point (point E), as expected, in the profile graph has the highest peak and in the encircled energy graph the highest slope. In contrast, observing the pink curve corresponding to the point F, which in figure 3.9b is the point with the largest spot diameter, in the profile graph as well as in the encircled energy graph the curves look similar to the optimal (point E): the profile peak and the slope of the encircled energy curve almost coincide. Furthermore, the point D, whose spot diameter is almost the same than the optimal, in the profile graph looks clearly less focused and, in the first part of the encircled energy graph, it is the curve with the smallest slope. Finally, observing the encircled energies in figure 3.10d, the curves corresponding to the points D and F intersect at a radius value of 0.6 mm , meaning that the light profiles have not the classic Gaussian shape.

Figure 3.11: Processed photographs of the light spot cast by an ADG lens in two different positions. (a) lens position 3 mm closer to the diffuser than the optimal. (b) lens position 3 mm further to the diffuser than the optimal. The photographs correspond to the two points highlighted with black circles in figure 3.9b.

Despite this effect should be further investigated in order to achieve a complete understanding, some hypotheses can be raised. Observing figure 3.11, which represents the processed photographs taken for the positions corresponding to 3 mm further or closer to the lens with respect to the optimal point (black circles in figure 3.9b), it is clear how there is not symmetry, and that distancing the lens from the optimum has not the same effect on the shape of the light spot than moving it closer. This is an expected effect caused by the achromatic design, which causes the rays with different wavelength to be mixed. Nevertheless, figure 3.11b, which shows the photograph taken with the lens placed 3 mm further from its optimal position, clearly shows a high-concentrated central spot surrounded by a cross-shaped halo. Conversely, when the lens is 3 mm closer than the optimal position (figure 3.11a), the spot looks like a diffuse square with no concentration peaks. Only observing the processed figures with naked eye, one would say that the best position between the two corresponds to the position 3 mm further from the lens, whereas the processing calculated a reduced radius for the first (2.30 mm against 3.31 mm). As already mentioned, when preparing the set-up the optimal lens-diffuser distance (point zero in the graphs shown in figures 3.7 and 3.9) is selected only by observing with naked eye the light spot. Then, the computer processing takes care of identify the real minimum, which should be close to the center position visually selected. The visual method results very efficient for the SoG lens, where the minimum of the not filtered spot size (black curve in figure 3.9a) corresponds exactly with the zero selected by eyes. Conversely, for the ADG lens the minimum results to be 1.5 mm closer to the lens than the optimal position visually identified. This behavior is a consequence of the cross-shaped halo shown in figure 3.11b. In fact,

figure 3.12 shows a photograph of the light spot cast on the diffuser when the lens is at its optimal position identified by observing the spot with naked eye. It is evident that in such position, the cross-shaped halo is visible, resulting in a larger light spot. Therefore, the optimal position obtained by means of the image processing does not correspond with the position identified by naked eye. Moving the lens closer to the diffuser results in an enlargement of the focused central peak, and in the shrinking of the cross-shaped halo. Consequently, the computer processing recognizes the smallest spot diameter when the lens is in the position such as the central focused spot is still concentrated but, at the same time, is large enough to include most of the cross-shaped halo. Since such effect is not caused by the measurement method, the calculated light spot diameter is reliable as well as it is the optimal focal distance. However, it is important to identify the source of the cross-shaped halo, since it does not proceed from the lens design itself, and worsens significantly the ADG lens performances.

Figure 3.12: Photograph of the light spot cast by the ADG lens onto the Lambertian diffuser. The lens is placed in the optimal position identified by observing the spot with naked eyes. Such distance is different than the one obtained after the computer processing of the photograph. The cross-shaped halo is clearly visible.

This behavior is caused by the corner of the lenses. In fact it is known that, also with conventional SoG lenses, because of manufacturing issues due to the square shape, the corners of the lens, where the Fresnel rings are not complete, work less efficiently than the center. In order to confirm such hypothesis some ADG lens prototypes have been cut in a circular shape and, as expected, the cross-shape halo disappeared. Then, on one side, the source of the error has been successfully identified but, on the other side, what is worsening the functioning of the corners of the lens is not completely clear. One possible explanation is that the profiles of the grooves on the corners are not perfectly coincident with the lens design, resulting a focal distance different than the center of the lens.

To conclude, once fixed the percentage of energy which define the light spot, the use of a CCD camera coupled with an extremely thin Lambertian diffuser provides reliable irradiance spot measurements which can be used to assess the diameter of the light spot and the optimal focal distance. All the measurement results presented in chapter 4 have been carried out using the Kodak camera and a Lambertian diffuser made out of a cover glass $200\ \mu m$ thick. The kodak camera have been chosen over the QImaging because the higher pixel deep (16383 against 4095) provides higher resolution.

Figure 3.13: Bar chart representing the light spot diameter of the reference SoG Fresnel lens measured in five different days. Blue and red bars represent results obtained filtering the light using a hot mirror and a cold mirror, respectively. Grey bars represent global results obtained without any spectral filter.

3.3.2 Measurement error

In this case, the repeatability of the measurement is lower than in the case of the optical efficiency. As a matter of fact, spot size measurements are much more sensible to external conditions such as temperature, external light (which varies along the day), and the alignment of the diffuser with the lens and of the whole system with the collimated beam. By way of example, figure 3.13 shows the spot size of the reference SoG lens measured in five different days. Both spectral measurements (using high-pass and low-pass filters) and global measurements are shown and, in all cases, the error is on the scale of 10 %.

Since the uncertainty of the measurements carried out in different days is so high, in order to be able to reliably contrast the results it is advisable to perform all the measurement to be compared on the same day or, if not possible, leaving a time lapse between measurements as short as possible.

3.4 Measurement of arrays composed of many lenses

In order to measure both the optical efficiency and the irradiance spot of an array composed of many lenses the previously described set-up needs to be adapted allowing to move the solar cell used as light sensor, or the CCD camera in the case of the irradiance spot measurement, in front of every lens composing the array. To do so, a computer-controlled three-axes moving platform is used (see figure 3.14).

In this way, the optical efficiency (or the spot size diameter) of every lens composing the array can be determined without moving the parquet. In the first step, the solar cell (or CCD camera) is placed in front of the first lens of the array. Then, the flash light is triggered and the photocurrent produced by the solar cell is measured (or the photograph of the light spot is taken). As a next step, using the moving platform the cell (or CCD camera) is placed in front of the second lens and the procedure is repeated until all the lenses have been measured.

The main limitation of this method is caused by the manufacturing error of the parquet of lenses. The automated moving platform is programmed to automatically move the cell or the CCD camera in front of the next lens to be measured, assuming that the distance between the foci is the

Figure 3.14: Photograph of the moving platform used to place the solar cell used as light sensor in front of every lens of the array (also visible in the photograph). The set-up used to measure the spot size diameter is the same substituting the solar cell with the CCD camera.

nominal (40 mm as the lens edge). Nevertheless, due to the manual laboratory method employed to glue together the lenses composing the parquet (for detail on the array manufacturing process refer to chapter 4), the distance between the foci of two adjacent lenses is different than the nominal. Therefore, prior to any measurement, it is convenient to identify the real position of the spot of every lens, in order to ensure that, every time that the sensor is moved in front of a lens, it is centered in the real lens focus.

3.4.1 Position of the lenses foci

There are mainly four factors that may introduce differences on the real foci position:

1. the real dimensions of the bi-Fresnel sublens manufactured by plastic injection could be different from its nominal values;
2. the process to align the sublenses described in section 4.2.2 may introduce some errors. This, together with the presence of a thin layer of glue between the lenses, makes that the lenses are slightly separated between them increasing the real distance between their foci;
3. the glued array of bi-Fresnel sublenses and the rectangular glass on which it is laminated may not be perfectly aligned resulting in a rotation of the first with respect to the second;
4. the structure holding the parquet during measurements may not be perfectly aligned with the axis of the computer-controlled moving structure.

Note that the rotations described in points 3 and 4, depending on the direction, could also compensate each other. Consequently, the real positions of the spots deduced by processing photographs taken with the CCD camera will not be coincident with the theoretical locations. In order to analyze the accuracy attained in the position of the lenses for the parquet prototypes, it is mandatory to process the data so that the aforementioned effects are taken into consideration. To that purpose, the approach consists in calculating the values of the following parameters that minimize the mean squared error between the real and the calculated foci positions:

1. the pitch between two foci along the x axis (Δx);
2. the pitch between two foci along the y axis (Δy);
3. the angle of rotation (ϑ).

Figure 3.15: (a) Schematic representation of the lenses within the array with lens numbers and reference x and y axes. (b) Mean squared error between the real and calculated foci position as a function of the different values assumed for every parameter: pitch along the x and y axes (respectively Δx and Δy) and angle of rotation (ϑ).

Figure 3.15a shows the position of the coordinate axis with respect to the lens parquet while figure 3.15b shows the mean squared errors for different values of Δx , Δy , and ϑ for one parquet of 10x5 lenses.

Applying the set of optimized parameters (the ones resulting in a minimum squared mean error) it is possible to calculate the displacement in millimeters corresponding to every lens composing the array.

Figure 3.16 represents the displacement of the foci of every lens once the previously calculated corrections have been applied. Considering a solar cell whose diameter is 3 mm the error is unaffordable. Nevertheless, as mentioned in section 4.2.2, if the subarray of plastic lenses was obtained by one single injection or hot-embossing, the positioning error is expected to decrease significantly.

3.5 Temperature measurement

Generally, the temperature of the room with the solar simulator HELIOS 3198 is maintained between 20 °C and 25 °C and the real temperature of the optics to be measured is monitored by means of thermocouples. Nevertheless, when the influence of temperature on the optics performance is evaluated, a more flexible control is required. Furthermore, when the method described in section 3.2 is used to assess the thermal sensitivity of an optics, it is important to take into account the dependency of the SR of a MJ solar cell with the temperature. For instance, if the temperature of the whole simulator is raised up to a certain value, the efficiency measured corresponds to the condition in which both the lens and the light sensor are at a higher temperature. In this way it is impossible to separate the influence of the temperature on the optics and on the solar cell.

In order to precisely control the temperature of the optics measured, maintaining the solar cell at ambient temperature throughout all the measurements, a thermal chamber was implemented

Figure 3.16: Displacement of the measured focus of every lens with respect to the corrected theoretical position. Red line on the top represents the radius of a solar cell of 3 mm of diameter (reasonable choice in a module using ADG lenses as primary optics).

at the IES-UPM. The equipment consists in an thermally insulated space with two Peltier cells which are able to either warm up or cool down the system. A thermocouple connected to a temperature controller is placed inside the chamber to measure the air temperature, while other two thermocouples are directly connected to the devices under test in order to monitor the precise lens temperature at the time of the measurement. The walls of the regulated enclosure are transparent in order to be able to place the light sensor, be it the solar cell or the CCD camera, outside of the chamber. Figure 3.17a shows the scheme of the measurements set-up, which is the same showed in figure 3.1 with the addition of the thermally regulated enclosure around the lens to be measured. More details about the components and the operation of the implemented thermal chamber can be found in [8].

Figure 3.17b shows a photograph of the previously described thermal chamber. In this figure several ADG prototypes are visible inside the temperature controlled enclosure. Once the desired temperature is achieved, the same three-axes moving platform described in section 3.4 is used to move the solar cell (or the CCD camera) in front of every lens to be measured. Then, both optical efficiency and irradiance spot measurement can be executed using the same methods described in sections 3.2 and 3.3.

3.6 Outdoor characterization

In this section all the outdoor characterization methods employed to measure either ADG Fresnel lenses or complete CPV modules are described. There are mainly two outdoor characterization techniques: first, the optimum cell-lens distance of single components is investigated using elementary units (single lens prototypes) and a MJ solar cell. To identify the optimal cell-lens distance the electrical performance and the electrical characteristics are measured varying the lens position with respect to the cell. Second, complete photovoltaic modules are installed onto a solar tracker and measured for an extended time lapse. In both cases, the ambient conditions are recorded at the

Figure 3.17: (a) Scheme of the solar simulator HELIOS 3198 with the implemented thermal chamber represented with a red rectangle. (b) Photograph of the thermal chamber implemented at the IES-UPM used to carry out temperature measurements.

test tracker in order to ensure that different results are not caused by their variation.

In order to investigate the optimum cell-lens distance, the lens to be measured is mounted in a moving structure installed in a solar tracker through which is possible to vary the distance between the lens and the cell. At each position, the electrical characteristic (IV curve) is measured and the optimal position, corresponding to the highest photocurrent generation, is determined.

For what concern complete CPV modules characterization, the modules under test are installed in a solar tracker and manually aligned. Afterward, one measurement is recorded every few minutes. Each measurement includes the electrical characteristic (IV curve), from which it is possible to extract most of the useful data such as photocurrent I_{SC} , open circuit voltage V_{OC} , fill factor FF , and module efficiency η_{module} . Apart from electrical data, at each measurement ambient and tracking conditions are monitored. Among them the most important are ambient temperature T_{amb} , spectral matching ratios (SMR_{middle}^{top} , SMR_{bottom}^{top} , and SMR_{bottom}^{middle}), global normal irradiance GNI, direct normal irradiance DNI, tracking misalignment, DNI deviation, solar azimuth, and solar elevation. The software used to manage outdoor measurement applies preliminary filtering before to output the results. Such filtering aims to exclude all the measurements including physically impossible values, such as negative current values or alike. Outdoor measurements are usually stopped during winter period because of poor measurement conditions (short length of the day, weather mainly cloudy, etc.).

3.7 Conclusions

To summarize, several characterization methods have been introduced and described highlighting for each one of them the strong points and their limitations. Firstly, the method employed to measure the optical efficiency of an optics is described. Such procedure was already used in previous work [1, 2]. Nevertheless, the introduction of the figure of merit of the *relative efficiency* provided two advantages: the measurement results do not depend on the characteristics of the solar cell used as light sensor, and, additionally, the measurement error drastically reduces, even when the measurements are realized under different conditions. Of course, the reference optics used as benchmark must be the same and its optical quality must be preserved in order to do not confuse an increase of the relative efficiency measured with a degradation of the reference.

Secondly, the method used to measure the diameter of the irradiance spot transmitted by the

lens is described. As well as for the optical efficiency, this method was used in previous work [2]. During the thesis, the assessment of the light spot diameter was a crucial step in order to understand the ADG lens performance and its limitations. Therefore, a comprehensive characterization of several possible set-ups and methods has been carried out with the purpose of identifying the most reliable. Whatever method is used, irradiance spot measurement resulted to be more sensible and less repetitive than optical efficiency measurement. Nevertheless, after comparing the experimental results obtained using the different described methods, it can be assessed that, using the CCD camera coupled with an objective to take a photograph of a Lambertian diffuser where the concentrated light spot is focused on, gives consistent and repetitive results. However, despite the optimized procedure, the uncertainty of the measurements is still on the order of 10 %, meaning that is advisable to always compare measurements performed within a short period of time, in order to limit as much as possible the variations of the external conditions.

Thirdly, the two methods previously introduced have been adapted to measure an array composed of many lenses by means of a three-axes automated moving platform, which permits to move either the solar cell or the CCD camera used as receiver in front of every lens composing the array. Thanks to this method, the efficiency and the diameter of the irradiance spot can be measured for every lens of the parquet with the same precision as for the elementary units. This is achieved thanks to the use of the same receiver to measure all the lenses of the array. Furthermore, once optimized the parameters Δx , Δy , and ϑ used to ensure that the cell or the camera are always centered in the concentrated spot, the procedure can be automatized.

Afterwards, a short description of the thermal chamber used to evaluate ADG lenses performance at different temperatures is presented together with the measurement method. Such chamber resulted very useful in order to assess the thermal sensibility of the ADG technology. In fact, its implementation within the solar simulator HELIOS 3198 permitted to precisely control the lens temperature while simultaneously maintaining the receiver at room temperature. In this way, the effect of the temperature on the optics can be investigated excluding any influence of the solar cell temperature on the results.

Finally, a short description of the method used to fully characterize outdoor the complete CPV modules assembled at the end of the thesis is also presented.

Appendices

Appendix A

Solar simulators

The American Society for Testing and Materials (ASTM) standard states that: *a solar simulator (also artificial sun) is a device that provides illumination approximating natural sunlight. The purpose of the solar simulator is to provide a controllable indoor test facility under laboratory conditions, used for the testing of solar cells, sun screen, plastics, and other materials and devices [9], and that: a solar simulator usually consists of three major components [9]:*

1. *light source(s) and associated power supply;*
2. *any optics and filters required to modify the output beam to meet the classification requirements.*

Thus, when implementing a solar simulator, selecting the adequate light source that approximates the solar spectrum to simulate, be it air mass zero (AM0) for space applications or AM1.5 for terrestrial, is crucial for the reliability of the measurements. Furthermore, the possibility of manipulating the beam using an optical system such that the spectrum and spatial uniformity of irradiance can be optimized for the required application is also important.

Both solar simulators implemented at the solar energy institute include xenon arc lamps. Such kind of lamps provides an output that fairly approximates the AM1.5 spectrum, despite shows large infra-red spikes which must be attenuated to achieve a closer spectral match [10, 11].

Figure A.1: Emission spectrum of a xenon lamp [12] compared with the solar spectrum AM1.5D. The intensity of the lamp emission is unitless because it depends on the lamp power and can be controlled.

Figure A.2: Photograph of the solar simulator used to characterize solar cells under concentrated irradiance. On the top of the figure, it is possible to observe the lamp whose position determines the concentration level. On the bottom, the measuring plane is shown. On the left of the photograph, it is possible to appreciate the electronic equipment (power supply and DAQ) and the computer used to control the devices.

Figure A.1 shows a comparison of the xenon lamp and real sun spectra. The lamp's spectrum, a part for the aforementioned infrared spikes, qualitatively matches well with the solar spectrum.

A.1 Solar simulator HELIOS 3030

The solar simulator HELIOS 3030 is the equipment used to carry out the preliminary solar cell characterization. It is composed by a xenon flash lamp directly pointed toward the measuring plane where are placed both the device under test (DUT) and the isotype component cells used to monitor the spectrum during the measurement. The isotype component cells are single-junction solar cells whose spectral response (SR) coincides with one of the subcell of a MJ solar cell (a detailed description on their use to monitor the spectrum during the flash decay is presented in appendix B). A computer is connected to the data acquisition board (DAQ) which directly measures current and voltage. The xenon lamp is connected to a flash controller through which is possible to trigger the flash either manually or using the self-developed computer software (figure A.2 shows a photograph of the described solar simulator). The height of the flash lamp is adjustable and permits to control the spectrum and the concentration: the further the lamp is from the measuring plane, the lower the concentration achieved. The spectral distribution depends on the position of the lamp and on the flash intensity. It is possible to add the necessary filters to adjust the spectral distribution.

Once the flash is triggered, the light intensity throughout the flash decay has an initial peak and then starts to decrease (figure A.3). The light spectral distribution is also modified throughout the flash pulse (see appendix B). To perform an accurate measurement, the current generated by the cell has to be measured at an irradiance level where both isotypes, corresponding to the top and middle subcells, indicate exactly the same irradiance level corresponding to effective AM1.5D spectrum (see appendix B and [13]). This confirms that the cell is measured under the target concentration level and spectrum. The fact that the irradiance level indicated by the bottom subcell is not coincident can be neglected. This is because commercial Ge-based MJ solar cells are never

Figure A.3: Time evolution of the measured magnitudes throughout the flash decay. On the graph, it has been marked the instant when the isotype cells, corresponding to the top and middle subcells, measure the same irradiance level. Following the black dashed line which starts from the intersection of the curves corresponding to top and middle subcells, it is possible to identify the DUT current value (black circle) as the current measured in the precise moment in which top and middle reference subcells see the same irradiance level.

current limited by this subcell [14]. Figure A.3 depicts a graphical explanation of this procedure.

The HELIOS 3030 is suitable to measure the photocurrent generated by a solar cell and also the electrical characteristic (current-voltage (IV) curve). To do so, an electric source is used to bias the DUT. All the bias points are defined in a text file prior to the measurement, then the software automatically reads the points and for each one of them polarizes the cell, triggers the flash, and measures the current generated by the solar cell.

Measuring a certain solar cell at different concentrations (*i.e.*, different lamp heights) demonstrates the linearity between the current generated and the concentration level. Therefore, when using the solar simulator HELIOS 3198 described in section A.2, the calibrated cell can be used as a light sensor to determine the irradiance at the lens focal plane.

A.2 Solar simulator HELIOS 3198

The solar simulator HELIOS 3198 is the equipment used to carry out measurements of the primary optics. As well as for the HELIOS 3030 described in section A.1, the light source is a xenon arc lamp. Since the purpose of this simulator is to measure optics, or complete CPV systems including optics, it is mandatory to achieve a collimated light beam. Such condition is achieved thanks to a large area parabolic mirror where the light proceeding from the lamp reflects and collimates (see figure 3.1). Also in this case isotype component cells are used to monitor the spectrum during the flash decay. The same method as described in section A.1 is used to monitor irradiance and spectral condition during measurement. The only difference is that, since when optics is included in the measurement only collimated light is converted in electricity, the isotypes are mounted inside a *collimating three-tube* (see figure 3.1 and A.4) in order to filter all the light proceeding from external sources (*e.g.*, normal daylight or artificial illumination of the simulator room).

Figure A.4 shows a photograph of the solar simulator HELIOS 3198 together with most of its components and a prototype ADG Fresnel lens to be measured.

Figure A.4: Photograph of the experimental setup and its components (light source with integrating sphere, lens sample, CCD camera, and solar cells used as light sensors). The parabolic mirror and the filters are not visible in this photograph.

For more details about the design and the working principles of the solar simulator HELIOS 3198, refer to [15].

Appendix B

Solar simulator to measure multi-junction (MJ) solar cells

A detailed description on how to use a solar simulator to measure MJ solar cells is presented in [13]. The basic principles of such method are reported here again for the sake of clarity. In most of the commercial concentrated photovoltaic (CPV) systems MJ solar cells are used. Such solar cell technology achieved the highest electrical efficiency measured up to date [16–19]. Since an MJ solar cell consists of a series connection of several subcells, its current is limited by the least generating subcell. Each subcell is able to convert in electricity a different spectral band of the light, therefore their spectral responses (SR) are adjusted to generate the same current under the reference spectrum (AM1.5D for terrestrial applications [20]). Any change in the spectrum breaks such equilibrium: the subcells start generating different currents and, being series connected, the current generated by the MJ solar cell is the same than the lowest generating subcell. Such current limitation introduces efficiency and energy losses [21]. Therefore, when measuring MJ solar cell based systems, since any variation of the spectrum could cause efficiency losses, one of the most important issues is its monitoring and control. The control of the spectral condition in a solar simulator is achieved by means of reference component cells (top, middle, and bottom for a conventional germanium based triple-junction (3J) solar cell), also known as *isotypes*, which were calibrated under reference spectrum. Such isotype cells are single-junction cell designed to present the same SR as one of the subcells in the whole MJ solar cell. Thus, their short-circuit current is proportional to the light within the spectral region in which the corresponding subcell has electrical sensitivity [13]. In order to calculate the current generated by the i^{th} subcell under the spectrum $E(\lambda)$, an integration weighted by the SR of the interested subcell is required (equation (B.1)):

$$I_{SC,i\text{-component}} = A \int SR_i(\lambda) E(\lambda) d\lambda \quad (\text{B.1})$$

where A stands for the active area of the cell.

If the short-circuit current under the reference spectrum (*i.e.*, calibrated I_{SC}^*) is known, the cell can be used as a sensor to measure the irradiance at the corresponding spectral band [13].

$$DNI_{i\text{-component}} = \frac{I_{SC,i\text{-component}}}{I_{SC,i\text{-component}}^* (1000 \frac{\text{W}}{\text{m}^2}, \text{AM1.5D}, 25^\circ\text{C})} [\text{suns}]. \quad (\text{B.2})$$

In equation (B.2), $DNI_{i\text{-component}}$ represents the irradiance that effectively generates current at the i -component cell. Since in conventional CPV systems only direct beam radiation is converted in electricity, the acronym for direct normal irradiance has been used. For simplicity, it is given

in *suns*, where one *sun* corresponds to a light intensity of 1000 W/m^2 with a relative spectral irradiance distribution of AM1.5D.

Using equation (B.2) for n different isotype cells, it is possible to obtain an n -dimensional vector that describes the spectrum in all the spectral bands of interest. In a conventional 3J solar cell, if $DNI_{top} = DNI_{middle} = DNI_{bottom}$, means that the spectrum is equivalent to the reference spectrum [13]. Likewise, in order to assess the similarity between a simulator spectrum and the reference spectrum in two different spectral bands, *i.e.* top and middle, the balance between DNI_{top} and DNI_{middle} is used. In order to study the spectrum generated by a solar simulator is useful to introduce the concept of spectral matching ratio (SMR), which is defined for any pair of subcells as the ratio between the effective irradiances corresponding to the subcells of interest. Therefore, considering 3J solar cells, the similarity between an arbitrary spectrum and AM1.5D is studied using two SMRs, top over middle and middle over bottom [13].

$$SMR_{middle}^{top}(E(\lambda)) = \frac{DNI_{top}}{DNI_{middle}}. \quad (\text{B.3})$$

In customary 3J solar cells, the bottom subcell always has an excess of current under realistic outdoor spectral conditions [14], therefore under any spectral condition the current is limited by either top or middle subcell. That is the reason why, when considering state-of-art technology of CPV systems based on 3J cells, the similarity of the spectrum with the reference AM1.5D can be assessed comparing effective irradiances in the top and the middle subcell.

Throughout the experimental part of this thesis, $SMR_{middle}^{top} = 1$ indicates an effective AM1.5D spectrum. An SMR value smaller than 1 indicates a red-rich spectrum, whereas SMR values larger than 1 indicate blue-rich spectra.

When an MJ solar cell is measured, if it is limited by one of its subcells, any change in the irradiance produces similar variations of the photocurrent generation in both the measured solar cell and the isotypes cell corresponding to the limiting subcell. If apart from the irradiance, the spectral conditions vary too, the current of the other isotype cell varies with a different trend, allowing to identify in any condition the limiting subcell. Measuring simultaneously the current generated by the MJ solar cell to be measured and the $DNI_{i-component}$ of every isotype it is possible to know which subcell is limiting at any time of the flash decay. The spectrum of the light varies throughout the flash pulse (see earlier) reproducing a wide range of SMR values. For every spectral condition simulated (every SMR) across the flash pulse it is possible to calculate the photocurrent normalized by the $DNI_{i-component}$ of each component cell as follows:

$$I_{N,i-component} = \frac{I_{SC,MJ}}{DNI_{i-component}}. \quad (\text{B.4})$$

where $I_{N,i-component}$ indicates the MJ cell current normalized to the DNI corresponding to the spectral band of interest (*i.e.* top or middle). If one of the subcells is limiting the current for all the different spectra simulated during the flash decay, $I_{N,i-component}$ will be constant throughout all the measurement. However, if the spectral ranges reproduced by the flash pulse are such that the limitation condition shifts from one subcell to the next, $I_{N,i-component}$ will be constant for only that portion of the spectral range where the corresponding subcell is limiting.

In order to illustrate this dependence, these ratios are plotted as a function of the SMRs simulated during the flash decay. If there is an SMR range in which one of the normalized currents remains constant, then the corresponding subcell is limiting the MJ cell current. Figure B.1 shows a qualitative example of a subcell limitation diagram for a conventional 3J solar cell.

In figure B.1, the MJ solar cell current has been normalized with the effective DNI measured by the top and middle isotype cells to obtain $I_{N,top}$ and $I_{N,middle}$, respectively.

In the spectral zone A, the MJ current normalized to the top DNI remains constant (the MJ cell is said to follow the top-component cell). In this zone $I_{SC,MJ} = I_{SC,top}$. Therefore the photocurrent

Figure B.1: Sample subcell-limitation graph for the top and middle subcells of a customary 3J cell.

actually generated by the measured MJ solar cell in every moment of the flash pulse included in zone *A* can be calculated as follow:

$$I_{SC,MJ} = DNI_{top} \cdot I_{N,top}. \quad (B.5)$$

Analogously, in zone *B*, the MJ current normalized to the middle DNI remains constant (the MJ cell is said to follow the middle-component cell). In this zone $I_{SC,MJ} = I_{SC,middle}$. Therefore the photocurrent actually generated by the measured MJ solar cell in every moment of the flash pulse included in zone *B* can be calculated as follow:

$$I_{SC,MJ} = DNI_{middle} \cdot I_{N,middle}. \quad (B.6)$$

Therefore, if it is assumed that there are no local current limitations, the overall MJ cell short-circuit current can be calculated as the minimum of the subcell currents as follows:

$$Ideal\ I_{SC,MJ} = \min \left\{ DNI_{top} \cdot I_{N,top}, DNI_{middle} \cdot I_{N,middle} \right\} \quad (B.7)$$

For more details about the described method refer to [13].

Appendix C

Spectrometer

Figure C.1: Photograph of the setup used to carry out transmittance measurements.

The spectrometer used to perform transmittance measurements is composed of the following components:

- light source composed of two different bulbs, the first is a deuterium lamp able to cover wavelength up to approximately 1000 nm , while the second is a tungsten halogen lamp able to emit light in the infra-red zone (up to 1800 nm);
- optical fiber used to transmit the light emitted by the source from the lamp to the spectrometer passing through the sample to be measured;
- homemade metal structure used to hold the sample in its position during measurement;
- real spectrometer which analyzes the transmitted spectrum;
- personal computer with the spectrometer software used to set-up all the configuration prior to measurement and to process and export measurement results.

Figure C.1 shows the system and all its components. Before going forward with the description of the measurement it is worth to remark a few precautions that is better to take in order to achieve reasonably reliable measurements. First, the optical fibers used to transmit the light from the source to the spectrometer need to transmit light in the whole wavelength range of interest for an MJ solar cell, *i.e.* from 350 nm to 1800 nm . Furthermore, since optical fibers are very sensitive to

their physical position, it is convenient that they are not bent and, once the measurement started, do not change their position. Second, the emission spectrum of both bulbs included in the light source should be in a steady state in order to avoid changes in the spectrum between two subsequent measurements. To do so, a time lapse of about 20 minutes should be waited between switching on the source and the beginning of the experiment. Third, a reference sample should be always measured as a first test in order to ensure the equivalence of measurement conditions. Finally, since Fresnel reflection strongly depends on the incident light angle, it is very important to ensure perfect orthogonality between the light beam and the sample to be measured.

C.1 Transmittance measurement

The transparency of the plastic materials used to manufacture ADG Fresnel lenses is one of the most important parameters to take into account when selecting suitable plastics. Therefore is mandatory to have a reliable procedure to evaluate such material property. In the following the method employed to analyze and interpret the results is described.

C.2 Measurement method

Once the set-up is prepared, the measurement method is divided in four steps:

1. measure the reference spectrum, *i.e.* the spectrum emitted by the light source without any sample in the holding structure;
2. measure the dark spectrum, *i.e.* the spectrum measured with the light source's shutter closed. This spectrum corresponds to the *noise* proceeding from external light sources such as daylight and artificial illumination in the room;
3. set-up all the measurement parameters such as the number of scans to average the final result, the number of points for the moving average, and the integration time;
4. place the sample in the holding structure and proceed with the real measurement.

When the real measurement is carried out the spectrometer software automatically performs the following actions:

- measures the spectrum actually transmitted by the sample under test;
- subtracts to such spectrum the dark spectrum previously saved (point 2 of the previous list);
- compares the measured spectrum with the reference spectrum previously saved (point 1 of the previous list) obtaining for each wavelength the attenuation produced by the sample absorption.

Once obtained the transmittance curve as a function of the light wavelength, some observations need to be done. First, often is quite complicated to get a sample perfectly flat, with a good surface finishing, and with a uniform thickness. This is particularly true in the case of the elastomers, which are usually provided in resin or opaque sheet forms and need lamination in order to attain the final transparency. To achieve such conditions the elastomeric samples can be encapsulated between two thin cover glasses which provide flatness and good surface finishing. Nevertheless, when the sample is encapsulated, the transmission curve provided by the spectrometer includes absorption and reflection of the cover glasses, which should be subtracted in retrospect in order to know the actual transmittance of the sample under test. Therefore, on one side, encapsulating the sample between two glasses helps from the sample quality point of view but add the uncertainty of the required post-processing. On the other side, a bad surface finishing together with some curvature caused by poor mechanical properties can significantly affect the results. Conversely,

Figure C.2: Graphs showing an example of the transmittance measurement carried out at the Solar Energy Institute compared with data found in literature.

when measuring conventional plastics, such as polycarbonate (PC) or polymethyl methacrylate (PMMA), measurements usually are more precise and reliable since the original samples already are flat, well polished, and uniform.

Despite such limitations make complicated to obtain a reliable transmittance value, useful information can still be deducted from the measurement results. Some of the most important parameters when evaluating plastic transmittance are the cut-off wavelength (*i.e.* wavelength starting from which the material transmits light), and the position of the absorption peaks commonly present in most of the commercial plastics. Both this data can be easily found using the described equipment and method and can be used to assess if a certain material satisfies the basic requirements to be a candidate in the ADG Fresnel lens manufacturing process. For what concern absolute values, values found in literature have been used, relying upon the fact that they have been carried out using a more accurate method than the one used at the solar energy institute.

Figure C.2 shows the transmittance measurement of a PMMA and a PC samples compared with data found in literature. There is a good match between experimental and literature data. In particular, the cut-off wavelength is exactly the same and the absolute values coincide well enough.

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Chapter 4

MANUFACTURING AND CHARACTERIZATION RESULTS

4.1 Introduction

In the first part of this chapter, the process employed to manufacture ADG Fresnel lenses is exhaustively described, for both elementary units (composed of one single Fresnel lens) and for parquets composed of many lenses. ADG manufacturing process includes two steps: first, a plastic bi-Fresnel lens (a thin lens with Fresnel grooves on both surfaces) is manufactured using standard injection molding, compression molding or hot embossing, all inexpensive and reliable processes commonly used in high volume industry. Then, a lamination process is used to join the bi-Fresnel lens to the rigid glass substrate, with the elastomeric material serving as an adhesive while simultaneously being formed into the low dispersion lens of the doublet. The lamination step is similar to that used in the manufacturing of flat-plate silicon solar panels. Since both mentioned processes (plastic injection or hot embossing, and lamination) are inexpensive and highly reliable the final overall manufacturing cost of ADG Fresnel lenses is expected to be similar to the fabrication cost of classic SoG Fresnel lenses.

The manufacturing process, as well as the equipment developed for this purpose, have been continuously evolving along the thesis. This chapter begins with the description of the first lamination machine, and successively describes all the improvements and optimizations applied to achieve the current state of the process, which is highly reliable and almost completely automated.

Later, the second part of this chapter focuses on the performance of the ADG Fresnel lens prototypes. From the beginning of the investigation to the end of the thesis, three different ADG Fresnel lens generations have been developed and tested, both indoors and outdoors. In table 4.2 a summary of the efficiency measured for each generation is reported, together with their most important characteristics. In addition, the type and size of the solar cells used in the measurements is also disclosed. In this second part of the chapter, the outdoor degradation test carried out in order to assess the materials resistance to ultraviolet (UV) radiation is described. An explanation for the differences observed in the efficiencies values measured indoors and outdoors, together with a short description of the outdoors measurements, are included in section 4.4.1.

In the last part of the chapter, results of a comprehensive outdoor characterization of complete CPV modules are shown. As the last step of the project, a mono-module (system composed of one lens and one solar cell) and a full area module composed of 10x5 lenses have been assembled

and installed in a solar tracker at the Fraunhofer ISE facility (Freiburg, Germany) where they have been measured for more than four months. Results definitely demonstrate that, despite the limitation encountered, the ADG technology could provide remarkable benefits with respect to the state-of-the-art of the technology for CPV primary refractive optics.

4.2 Manufacturing process

As mentioned in the introduction, the manufacturing process proposed in this work is essentially divided into two steps: the plastic injection of the bi-Fresnel lens and the lamination of this plastic part to a glass substrate with an optical encapsulant. For the production of the plastic pieces, injection molding has been selected over compression molding and hot embossing because of its reliability, simplicity, and limited cost.

4.2.1 Injection molding

The profile of the plastic bi-Fresnel lens was designed using the method described in section 2.3 and taking into account manufacturing constraints suggested by the company. Injection molding procedure has some limitations that could not be overcome and directly affect the optical efficiency of the manufactured lenses. First, in order to easily release the mold, the vertical walls of each groove cannot be perfectly vertical. Second, tips and valleys of the grooves will always have a certain radius, corresponding to the radius of the diamond tip used to turn the mold. These two limitations are called respectively *draft angles* and *tips rounding* and contribute to reduce the maximum attainable optical efficiency (see section 2.6.8).

Figure 4.1: Drawing showing the concept of both draft angle and tips rounding. (a) Ideal case. (b) Real case. Figure not in scale.

Figure 4.1 shows a schematic representation of a single groove of a Fresnel lens profile, figure 4.1a the ideal case, where the vertical wall makes an angle of 90° with the horizontal, and tips and valleys are perfectly sharp. Conversely, figure 4.1b shows the real case, with a draft angle equal to γ and rounded tip and valley with a radius equal to R .

The minimum values for both tips rounding and draft angles depend on both the molded material and the process used to manufacture the piece. The state-of-the-art of the injection molded technology allows a minimum tip rounding value of $3 \mu\text{m}$ for silicone and of $5 \mu\text{m}$ for polycarbonate (PC). Conversely, regarding the draft angle, for both silicone and PC, the average value estimated by the company is 3.5° . The terms "average value" refers to the fact that the mold release of the outer part of the lens is more challenging, requiring a larger draft angle to further ease the release step.

<i>Measurement date</i>	2016/08	2016/08	2017/05	2017/05	2018/06	2018/06
<i>Cell type</i>	3J Ge based (GaInP/ GaInAs/Ge)	3J Ge based (GaInP/ GaInAs/Ge)	3J Ge based (GaInP/ GaInAs/Ge)	4J Ge based (AlGaInP/ GaAs/GaInAs/Ge) [1]	3J Ge based (GaInP/ GaInAs/Ge)	3J Ge based (GaInP/ GaInAs/Ge)
<i>Cell diameter [mm]</i>	2.3	3.0	3.0	3.0	1.6	2.3
<i>Geometrical concentration</i>	385X	226X	226X	226X	796X	385X
<i>SoG Fresnel lens</i>	40x40 mm f-number 1.5		40x40 mm ² f-number 1.5		40x40 mm ² f-number 1.5	
<i>ADG Fresnel lens</i>	Gen1 40x40 mm ² f-number 1.5 glass-TPE-PC(UVcut) Flat facets Old mold No adhesion enhancement		Gen2 40x40 mm ² f-number 1.5 glass-TPE-PC(UVthrough) Curved facets Old mold Adhesion enhancement not optimized		Gen3 40x40 mm ² f-number 1.5 glass-TPE-PC(UVthrough) Curved facets New mold Adhesion enhancement optimized	
<i>Relative optical efficiency outdoor</i>	72.9 %	75.7 %	82.8 %	82.7 %	82.9 %	90.8 %
<i>Relative optical efficiency indoor (1 cm² cell target)</i>	85.5 %		87.3 %		89.4 %	

Table 4.2: Summary table with the efficiency values measured both indoors and outdoors. The characteristics of each ADG lens generation are reported, as well as the aperture and f-number of the SoG Fresnel lens used as benchmark. In bold, the differences between one generation and the previous are highlighted. Type and size of the solar cells used for the measurement are reported.

Characterization of injected pieces

Several characterization techniques were applied to analyze the injected pieces. In the first place, the outer dimensions of the samples and the center position were measured for the injected samples. For the flat-facets lens, the only remarkable difference was found in the thickness (measured to be $200\text{ }\mu\text{m}$ larger than expected). The rest of the dimensions were within the expected tolerance. For the curved-facets lens, the external dimensions, as well as the center position, for every measured sample were within the expected tolerance.

Figure 4.2: Photograph of the silicone replica of a flat-facets bi-Fresnel lens taken using an optical microscope. Outer lens contour along the lens diagonal. The grey area shows the silicone replicate.

In the second place, the injected pieces were replicated in silicone. The replicas can be easily cross-cut and examined in the microscope (see figure 4.2). As it can be seen in figure 4.3, where the draft angles were measured using a magnified pictures of a silicone replica, the draft angles experimentally determined were coincident with that of the design for both lenses (flat- and curved-facets designs). The draft angle is equal to 2° for grooves within the circle inscribed in the square and, from that point, they increase up to 5° for outermost grooves.

Finally, the tips rounding at the peaks and valleys were measured on the silicone replicas. For the flat-facets design, the attained tips rounding at the peaks and valleys were similar to that initially estimated, that is, rounding whose radius is below $5\text{ }\mu\text{m}$. However, for the curved-facets design, larger tips rounding were measured (see figure 4.4). According to the manufacturer, this is caused by the high tilt of the tool required during precision diamond turning.

Figure 4.4 shows a comparison of four photographs taken using an optical microscope. The two of the first line represents an ADG lens with flat facets while the two on the second line an ADG lens with curved facets. Since the optical inspection of injected pieces was performed by the company in two different times the scale is different in each photograph. Nevertheless, regardless of the magnification, it is possible to measure the tips rounding with good accuracy. From the figure is clear how the tips rounding corresponding to curved facets design are larger than for the flat facets.

4.2.2 Lamination

The lamination of the sandwich composed of the rigid glass substrate, the elastomeric low dispersion lens, and the plastic high dispersion lens is carried out in a lamination machine designed and manufactured ad-hoc for this goal. Two different laminators have been designed and assembled at the Solar Energy Institute, Technical University of Madrid (IES-UPM). The first prototype laminator was built to manufacture ADG elementary units and its functioning was manually controlled by an operator, whereas the second one is bigger in size in order to permit the lamination of larger arrays and has been completely automated.

Laminator 1.0

The first lamination system is composed of (see figure 4.5a):

1. vacuum chamber;
2. temperature controller;
3. vacuum pump;

Figure 4.3: Photograph of a silicone replicate of the ADG lens profile taken using a 50X optical microscope and used to measure the draft angle values. The replica is of a flat-facets prototype. Similar results are obtained for curved-facets prototypes.

4. laminator.

In figure 4.5b a functional scheme of the laminator and of every component composing the whole lamination system is shown.

The components are described below.

Vacuum chamber. The vacuum chamber is made of glass and is connected with the vacuum pump by means of the black tube exiting from the cover (see figure 4.5a). A metallic valve on the cover is used to break the vacuum while another valve on the tube, not visible in the picture, is used to isolate the chamber from the pump. Chamber's volume is approximately 17 liters.

Temperature controller. The temperature controller is directly connected with the electrical resistance located inside the body of the laminator whose purpose is to warm up the laminator during operation. To control the temperature a thermocouple, which is in direct contact with the internal part of the laminator, is connected to the controller. If necessary, it is possible to apply different control loop mechanisms such as a proportional-integral-derivative (PID) controller.

Vacuum pump. The vacuum pump, used to make vacuum in the vacuum chamber and/or in the laminator, is an oil pump purchased from Pfeiffer, precisely model DUO 20 capable to reach a vacuum of $4 \cdot 10^{-3} \text{ Pa}$ with a maximum pumping speed of about $20 \text{ m}^3/\text{h}$. The upper part with the red top is an oil filter used to recirculate vapors generated during the process. The suction duct has a T junction with two valves through which it is possible to connect the pump to the vacuum chamber and/or to the laminator.

Laminator. The laminator can be seen on the top right corner of figure 4.5a. The two holes in the cover are used to make vacuum in the upper side of the laminator while the two holes on the right edge of the body of the laminator are used to make vacuum in the lower side. White semi-transparent tubes, exiting from the front side, are connected to a closed circuit in which a refrigerant circulates. Such a circuit is the cooling system used to cool down the temperature quickly after laminations, which are usually carried out at high temperatures. In order to be able to make vacuum on both sides independently, a thin silicone sheet is used (about 4 mm thickness). In this way, when the pump sucks out air from both sides, the whole laminator chamber is vacuum-sealed. Meanwhile, sucking out air only from the lower part would cause the thin silicone layer to be pressed against the body of the laminator generating the lamination force. The intensity of the

Figure 4.4: Enlargement of the photographs taken with the optical microscope of silicone replicate of PC bi-Fresnel lenses. The first line shows two grooves of a replicate of a lens with flat facets. Conversely, the second line shows the same two grooves of a replicate of a lens featuring curved facets. Photographs have not the same magnification.

lamination force can be obtained by calculating the difference between ambient pressure and the minimum pressure achievable with the vacuum pump (about $4 \cdot 10^{-3} Pa$).

Finally, it is worth to notice that, in order to avoid the silicone layer to tap the suction holes, a metallic mesh (not shown in the figure) is put between the silicone film and the laminator base.

The laminator machine 1.0 described in this section has been used to successfully laminate ADG Fresnel lens prototypes for more than one year and a half. After this period of time, the need of a new equipment with improved properties arose.

The main reason was that the machine began to fail: in the first place, the continuous temperature cycles from room temperature to 120 °C damaged the welding between upper and lower parts of the laminator, causing leakage of the refrigerant from the circuit. In the second place, the continuous thermal dilatation due to the high process temperature bended the working plane. As a consequence, the glasses used as rigid substrate often crack during the lamination step.

Figure 4.6 schematically shows how the crack of the glass substrate happens. When the lamination step begins, a pressure of $\sim 1 atm$ is applied on the glass, therefore, if the working plane is not perfectly plane, the flexure stress cracks the substrate.

Lamination process

The ADG Fresnel lens lamination process is divided into four steps:

1. **preliminary heating** up to 120 °C;
2. **degasification** inside the laminator chamber for 60 minutes;
3. **lamination** inside the laminator chamber for 10 minutes;

(a)

(b)

Figure 4.5: (a) Picture of the first prototype laminator built at the IES-UPM and used to laminate the first ADG Fresnel lens prototypes. (b) Functional scheme of the laminator system built at the IES-UPM.

Figure 4.6: Functional scheme representing the stress suffered by the glass as a consequence of the bended laminator plane.

4. cooling down to 30 °C.

The temperature value of 120 °C, as well as the degasification and lamination times have been selected after the optimization of the lamination parameters described in section 4.2.2

The preliminary heating is required in order to bring the system up to a temperature at which the thermoplastic elastomer (TPE) is partially melted and, at the same time, the plastic part is still solid and conserves its mechanical properties. The second step is necessary in order to avoid air bubbles inside the elastomer. Air bubbles, even micro-bubbles not visible with naked eye, interfere with the optical path of the light by absorbing or scattering the rays, consequently reducing the optical efficiency of the lens. The lamination is clearly the most important step, since is when the sandwich takes its form. In this phase, the components are pressed against one another. A longer time it is not required since the process conditions are already reached in the previous steps. Finally, in order to avoid delamination, the whole system needs to be cooled while maintaining the lamination pressure. Cooling down to 70 – 80 °C is enough, a lower temperature has been chosen in order to limit the risk of burning for the operator.

Figure 4.7 shows a photograph of the first ADG Fresnel lens prototype. No defect can be appreciated with naked eye.

Characterization of the laminator

Before proceeding with the lamination of the first samples, a characterization has been carried out. The most critical point is temperature control. In fact, during the lamination process, the

Figure 4.7: Photograph of the first laminated ADG Fresnel lens prototype.

elastomer must be above its processing temperature, *i.e.* temperature at which its viscosity is low enough to be easily molded, while, at the same time, the plastic must be below its security temperature, *i.e.* temperature at which it starts to lose its mechanical properties. The minimum processing temperature of the TPE is equal to 87 °C. For the plastic, as security temperature the heat deflection temperature (HDT) has been used. The HDT is defined as the temperature at which a polymer or plastic sample deforms under a specified load. For the PC, the HDT temperature under a load of 1.8 MPa is equal to 123 °C. Therefore, the temperature of the laminated sample should always stay in the range between ~ 95 °C and ~ 115 °C, in order to have some tolerance with respect to the limit values. As a consequence, knowing if there is a difference between the temperature measured by the thermocouple and the actual temperature of the sample being laminated is crucial.

To understand the dynamic evolution of the sample temperature during the lamination process three thermocouples have been used. The first thermocouple was placed inside the laminator chamber under the sample using a thin hole crossing the entire machine. The second one was placed on one side of the laminator body. The last one was directly attached to the rigid glass substrate of the sample¹.

In figure 4.8 the temperatures measured by the three thermocouples are represented as a function of time. Obviously, the sample temperature is slightly lower than the one measured in the center of the laminator, which is the control temperature. Therefore, it is convenient to set-up the temperature controller with a set point a bit higher than the desired, in order to take into account the thermal resistance between the actual thermocouple position and the laminator plane where the samples are placed.

Optimization of the laminator process

The quality of the laminated lenses depends on many parameters, most important of which are:

- lamination time;
- degasification time;
- temperature.

In order to obtain lenses having good optical properties an optimization of those parameters has been carried out.

¹The cable of the thermocouple passing through the laminator seal has probably slightly compromised the vacuum. Since the aim of the characterization was not the manufacturing of a "good" lens prototype, the compromised vacuum does not affect the laminator characterization.

Figure 4.8: Graph representing temperature evolution as a function of time during the lamination process.

Lamination time Lamination time is the less critical of the three listed above. Observing figure 4.8, the sample temperature drops down of about 15 °C immediately after the beginning of the lamination step; it takes approximately four minutes to reach again the process temperature. The temperature drops is caused by the sudden contact of the silicone sheet pressed against the sample as a consequence of the vacuum. Such sheet, since it was not in direct contact with the hot laminator working plane, is still cold when the lamination begins. The lamination time must be longer than this lapse of time in order to avoid the hardening of the elastomer that could result in bad adhesion or air trapped inside the elastomer. After some tries, ten minutes has been identified as the best choice being longer than four minutes but still a relatively short time.

Temperature and degasification time Optimization of temperature and degasification time have been carried out at the same time, that is why they are presented in the same section. Temperature is the most critical factor because of the reasons previously mentioned, *i.e.*, the delicate balance between the fusion points of the materials composing the lens. In order to properly degasify the elastomer prior to lamination, its viscosity has to be as low as possible and, as a consequence, the temperature as high as possible. In contrast, the temperature has to be lower than the HDT of the plastic to avoid deformation caused by the lamination force. To identify the optimum value many lenses have been laminated, and their efficiency and the size of the cast light spot have been measured.

A detailed description of the characterization methods used to quantify the efficiency and size of the irradiance spot can be found in chapter 3. In figure 4.9a, the average efficiency of the samples used for the purpose of the process optimization, which have been laminated at different temperatures, is shown.

On one side, from figure 4.9a, is evident how the relative efficiency has a maximum value in 120 °C, meaning that, increasing further the temperature, results in a plastic deformation while decreasing it results in bad degasification. This is the expected behavior considering that the HDT of the PC is equal to 123 °C (see table 2.2) and the melting point of the TPE is 87 °C. On the other

Figure 4.9: (a) Averaged relative efficiency variation as a function of the lamination temperature. (b) Spot size diameter variation as a function of the lamination temperature.

side, from figure 4.9b is easy to see the spot diameter magnification corresponding to a lamination temperature above 130 °C.

To summarize: from the efficiency point of view temperature values giving the highest efficiencies are 110 °C, 120 °C, and 130 °C. Since from the spot size point of view, 130 °C results in a significantly larger light spot, in further tests the temperature has been maintained between 110 °C and 120 °C.

That is why the next set of experimental testing has been carried out laminating several samples at those temperature values and varying the degasification time.

Efficiency results from this second set of experimental tests are shown in figure 4.10. From this figure it is possible to notice that the efficiency of the samples laminated varying the manufacturing parameters does not change significantly. However, the samples laminated at 120 °C have an efficiency slightly higher than samples laminated at 110 °C and, furthermore, samples that have undergone 60 minutes of degasification, show a slight efficiency improvement with respect to samples laminated at the same temperature but degasified only during 20 minutes.

That is the reason why, with respect to the current pair of material used to fabricate ADG

Figure 4.10: Relative efficiency variation as a function of the lamination temperature and the degasification time. Each series is the average of three prototypes laminated in the same conditions.

Fresnel lenses, optimal identified operating conditions are a lamination temperature equal to 120 °C and a degasification time equal to 60 minutes.

Laminator 2.0

After almost two years it has been necessary to implement a new more efficient laminator because of the reasons previously exposed in this section. In addition, the working plane of the laminator 1.0 was not large enough to laminate arrays composed of 10x5 lenses (400x200 mm^2), that is the size decided for the full area CPV module aim of the thesis.

The design of the laminator 2.0 includes a working plane of 570x270 mm^2 , a set of electro-valves used to ease the control over both air and refrigerant circuits, a sealed entrance for two thermocouples used to directly monitor the sample temperature, and a flow-meter capable of precisely control the refrigerant flow in the cooling phase (cooling down the system too quickly could beak the sample as a consequence of thermal shock). Furthermore, the welding between upper side and lower side of the laminator has been substituted with thermal silicone. The use of an elastomeric sealant instead of welding provides one benefit: the elastomeric behavior compensate the different thermal expansion of the two sides of the laminator, avoiding the bending of the working plane and improving durability and reliability of the system.

Figure 4.11: (a) Photograph of the new lamination system. The new components absent in the former system are highlighted in yellow. (b) Photograph of the laminator together with the implemented automated controller.

Figure 4.11a shows a photograph of the new implemented lamination system with all its components. Components highlighted in yellow are the ones not implemented in the first laminator.

Later, an automated controller have been added to the system [2]. Components such as the electro-valves switches, the temperature controller, and the electro-valves source have been included inside the new controller making the system more compact and efficient.

Figure 4.11b shows on the left the automated controller. Such controller permits to set up a priori all the lamination parameters such as operating temperature, degasification, and lamination time. Then, the intervention of a human operator is needed only to place the sample in the laminator and to start the process. Apart from a more compact system, digitally controlling the lamination process improved the repeatability of the process, reducing the influence of human mistakes on the performance of laminated prototypes.

Lamination of arrays composed of many lenses

In order to manufacture arrays composed of many lenses, it is necessary to take into consideration some factors that were not that important when only elementary units were laminated. First, the uniformity of the lamination pressure over the parquet aperture becomes an issue. In the case of elementary units, the small aperture area of a single lens was enough to ensure the required level of uniformity. This is not true when laminating arrays, in fact there is a dissimilarity of the lamination pressure concentrated on the borders (*border effect*). A first attempt to solve this issue was the introduction of an anti-adherent frame around the lenses to be laminated. Based on the experimental results disclosed in section 4.3.1, the border effect has been limited but not completely avoided. Second, the mold manufactured was designed to inject only single lenses. Therefore, in order to prevent the sublenses from moving during the lamination process, they are glued together using a heat-resistant adhesive for plastic. This handmade procedure introduces errors, such as alignment errors among the lenses composing the array and possible leakage of the glue inside the grooves of the plastic pieces. It is worth to remark that this kind of manufacturing errors would be easily avoided in an industrial process for mass production, where high throughput process such as hot embossing, compression molding or injection molding of the entire sublens parquet would be used. Figure 4.12 shows a photograph of the first laminated array composed of 10x5 ADG Fresnel lenses.

Figure 4.12: Photograph of the first laminated ADG Fresnel lens array.

4.3 Indoor experimental results

Along the thesis, three different ADG Fresnel lens generations have been developed, and several elementary units, as well as arrays composed of many lenses, have been manufactured and characterized for every lens generation. This section focuses on the results obtained and what has been learned after the characterization of each generation. Also, every action adopted to improve lens performance, or to solve problems encountered, will be adequately explained and motivated. To conclude, the last section describes the results obtained from the outdoor degradation test carried out in order to guarantee the suitability of certain materials in the ADG technology.

In order to fully characterize ADG Fresnel lens prototypes, the methods described in chapter

3 have been used. First, a large area solar cell is used indoors to estimate the lens efficiency (that is, the percentage of the light transmitted by the lens). Secondly, the irradiance spot is photographed using a charge-coupled device (CCD) camera and adequate filters to measure the size of the spot. Therefore, for each lens generation, the figures of merit used to evaluate lens performance are the optical efficiency and the attainable concentration. For what concern the efficiency, the *relative optical efficiency* is used instead of the absolute optical efficiency. As exposed in section 3.2, the relative optical efficiency is defined as the ratio between the absolute optical efficiency of a conventional SoG Fresnel lens and the absolute optical efficiency of the ADG Fresnel lens prototypes (see equation (2.51)). This choice derives from the need to exclude any influence of the light sensor (*i.e.*, the large area solar cell) on the measurement results. The SoG Fresnel lens used as benchmark has been manufactured by Fraunhofer-ISE, has the same aperture area of the manufactured ADG lenses ($40 \times 40 \text{ mm}^2$ and a focal distance equal to about 80 mm).

4.3.1 First ADG Fresnel lens generation

The first ADG Fresnel lens generation have been used to optimize the lamination parameters (see section 4.2.2), and to gather information necessary to get a first understanding over all the advantages and drawbacks of this new technology. The materials are a TPE with low dispersion, PC with high dispersion that blocks UV radiation, and low iron glass for the rigid glass substrate. Materials properties are described in section 2.5. Moreover, the optical design features flat-facets. All the ADG lenses of first generation have been laminated using the first lamination system implemented.

Elementary units

A relative optical efficiency equal to 85.5 % have been measured for the first ADG generation. It is worth to remark that ray-tracing simulation predicted a maximum theoretical value equal to 92 % with current choice of materials. For what concern the spot size measurements, the smallest diameter comprising the 98 % of transmitted energy is 2.9 mm , which correspond to a concentration of 242 *suns*, much lower than the expected based on ray-tracing (716 *suns*, see section 2.6). Conversely, the spot-size diameter measured for the SoG Fresnel lens used as benchmark is equal to 2.3 mm , which correspond to a concentration of 385 *suns*, and it is much closer to the predicted value (405 *suns*).

Several reasons could be taken as causes for this difference, among them a profile slightly different to the designed one, and a high surface roughness. The first is related to the plastic injection molding process. Such process is carried out at high temperature since the plastic needs to be in liquid state to enter the mold. As a consequence, in the cooling process, the profile slightly changes because of thermal dilatation. Conversely, the second is probably due to the mold release phase, which could impact the optical finishing of the surface increasing roughness and waviness. High roughness and/or waviness contribute to the surface scattering, which is a phenomenon widely known and that contributes to widen the diameter of the spot size cast by the lens. Unfortunately, since both causes come from the injection molding process, which is carried out by an external company, they are quite difficult to investigate and just hypotheses have been proposed. Another possibility is that the lamination force distorts the PC profile during the lamination.

Despite the lower achieved concentration, the spot size measurements have been used to experimentally prove the achromatic behavior of the ADG Fresnel lenses.

Figure 4.13 shows the spot size diameter as a function of the lens-concentrated spot distance for both a conventional SoG Fresnel lens and the ADG Fresnel lens. Band-pass filters with a cut-off wavelength of 700 nm have been used to evaluate the spectral behavior of the lenses. On one side, for the SoG lens, the minimum points of the two curves are displaced between each other, and this is a direct consequence of the chromatic aberration, which makes the blue light focusing closer

Figure 4.13: Measured spot diameter as a function of the receiver displacement from the optimal focal distance (minimum spot). Spot diameter is defined as that including 98 % of the energy. Red lines represent spot diameters for longer wavelengths (those typically converted by middle subcell in MJ solar cells, *i.e.*: 650 – 900 nm) and blue lines represent spot diameters for shorter wavelengths (those typically converted by top subcell, *i.e.*: 350 – 650 nm).

to the lens than the red light. On the other side, for the ADG lens, the minimum points of the two curves coincide, meaning that the optimal focal distance is the same for blue and red light, experimentally confirming the achromatic behavior of the lens.

Arrays composed of 10x5 lenses

Using ADG lenses of the first generation, arrays composed of 10x5 lenses have been successfully laminated. In order to assess both the optical efficiency and the light spot diameter of every lens composing the array, the solar simulator HELIOS 3198 and the methods described in section 3.4 were used.

Optical efficiency. Figure 4.14a shows the distribution of the relative efficiency values for every lens within the array.

The average value of the relative efficiency for all the lenses within the first array is 84.7 %. According to previous measurement, the average efficiency for the unitary lenses is equal to 85.5 %. Looking at the histogram in figure 4.14a it is possible to observe that there is a significant variability on the relative efficiency values of the different lenses across the parquet. The standard deviation is equal to 2 % while the maximum measured relative efficiency value is 88.1 %. This value is higher than the maximum value measured for unitary lenses (86.3 %).

When the optical efficiency of every lens is plotted as a function of the position of the lens (see figure 4.14b), it can be observed that higher efficiencies are achieved for lenses located in the center of the array. This is due to the *border effect*, which is common in this kind of application. In fact, while in the center of the array the surface is large enough to ensure the uniformity of the pressure applied during the lamination phase, this is not the case for the border. Since the force applied to the lenses in the border is not uniform, such lenses could be not perfectly horizontal causing a deformation of the light spot cast. The border effect justifies the higher efficiencies measured for the lenses in the center, but it does not explain why some of such lenses has higher efficiency than the elementary units. It is not clear what causes the described efficiency increase.

When evaluating the efficiency values of this prototype array composed of many lenses, it is important to remark that it is the first manufactured prototype and there is still a significant room for improvement. Even so, most of the lenses achieved the same efficiency value measured for unitary lenses and only those lenses located at the border suffered an efficiency loss of approximately 4 – 5 %.

Figure 4.14: (a) Histogram representing the efficiency distribution of the lenses composing the first laminated ADG Fresnel lens array. (b) Color graphs representing the relative optical efficiency of the lenses across the parquet. Every square represents one lens whose identification number is indicated through a white number. Rows and columns numbers refers to the actual rows and columns of the arrays. As indicated by the color bar on the right, dark red colors represents the highest efficiency values while dark blue colors the lowest. Lenses with higher efficiency are predominately located in the center of the array.

Spot size diameter. Figure 4.15a shows the distribution of spot size diameter values for every lens within the array.

The average value of the light spot diameter for all the lenses within the measured array is 3.2 mm . According to previous measurement, the average light spot diameter measured for the unitary lenses is equal to 2.9 mm . Looking at the histograms in figure 4.15a it is possible to observe that, as well as in the case of the efficiency, there is a significant variability on the light spot diameter values of the different lenses across the parquet. The standard deviation is equal to 3.1% . The minimum measured light spot size value is 3.0 mm .

When the light spot diameter of every lens is plotted as a function of the position of the lens (see figure 4.15b), it does not look like there is any correlation between lens position and measured spot diameter.

Figure 4.16a shows a processed photograph of the light spot cast by the lens number 33 in the middle of the array while figure 4.16b shows the same for the lens number 46 in the corner. It is obvious how lenses in the corner cast a spot with a non-circular shape. The distortion of the light spot is due to the border effect already mentioned in section 4.3.1.

4.3.2 Second ADG Fresnel lens generation

After the first ADG generation, a significant amount of work has been carried out in order to improve lenses performance from both efficiency and spot size diameter points of view. In the first place, the PC used to manufacture plastic bi-Fresnel lenses has been substituted with a PC UV through, *i.e.*, a PC able to transmit light in the UV region of the spectrum. This choice has been taken as a consequence of the outdoor degradation test described in section 4.3.5. Despite it is widely known that PC UV through under UV radiation becomes yellow, outdoor degradations proved that the TPE used to manufacture ADG lenses is enough to protect the plastic from harmful solar

Figure 4.15: Histograms representing the spot-size diameter distribution of the lenses composing the first laminated ADG Fresnel lens array. b) Color graphs representing the spot-size diameter of the lenses across the parquet. Every square represents one lens whose identification number is indicated through a white number. Rows and columns numbers refers to the actual rows and columns of the arrays. As indicated by the color bar on the right, dark red colors represents the smaller measured spot diameter values while dark blue colors the largest.

radiation. In the second place, a new optical design including curved facets have been developed. Curved facets, especially in the central region of the lens, significantly enhance the concentration capability of the lens.

With the second ADG generation, only elementary units have been manufactured. This choice derives from the fact that, from the manufacturing point of view, using first or second generation to laminate arrays composed of many lenses is irrelevant. In fact, the challenges faced when laminating a big array are related neither to the optical design nor to the material used. Therefore, since the only differences between first and second ADG generation are the introduction of the curved facets in the design, and the use of the PC UV through, when laminating an array the same obstacles encountered for the first generation are expected, and it is irrelevant which lens generation it is used to investigate and understand them. Consequently, the second batch of lenses has been used to carry out the optimization of the new laminator described in section 4.2.2 and to deeply investigate the thermal behavior of ADG lenses, without further study the array manufacturing process.

Elementary units

A relative optical efficiency equal to 87.3 % has been measured for the second ADG generation, meaning that, changing the PC with the UV through formulation allowed an efficiency increase of 1.8 %. In order to ensure the UV stability of the second ADG generation, several flat laminated samples composed of glass-TPE-PC-TPE-glass have been mounted on a solar tracked where they stayed during more than one year. After this time of outdoor exposition, no transmission lost was measured, confirming the suitability of the PC UV through as possible material for the manufacturing of ADG lenses (see section 4.3.5 for the detailed results of outdoor degradation). For what concern the spot size measurements, the smallest diameter comprising the 98 % of transmitted energy is 2.5 mm, which correspond to a concentration of 326 suns, corresponding to almost 35 % more if compared with the first ADG generation. Despite the improvement provided

Figure 4.16: Processed photographs of the spot size cast by the lenses composing the array. (a) Lens number 33 in the middle of the array. (b) Lens number 46 on the corner of the array.

by the curved facets design, the measured light spot diameter is still larger than expected. Since the mold technology is the same as well as the material (what changes is the chemical formulation) the problems exposed which cause the enlarged light spot for the first ADG generation remains unsolved.

Thermal sensitivity

In order to analyze the thermal sensitivity of ADG prototypes a thermal chamber has been assembled at the IES-DEF (see chapter 3 and [3]). The equipment consists of a thermally insulated space with two Peltier cells which are able to either warm up or cool down the system. A thermocouple connected to a temperature controller is placed inside the chamber to measure the air temperature, while other two thermocouples are directly connected to the devices under test in order to monitor the precise lens temperature at the time of the measurement.

As already mentioned in section 2.6.7, conventional SoG lenses are highly temperature dependent because of both, thermal dilatation of materials, and refractive index variation as a function of temperature. As a consequence, when the lens temperature is lower or higher than the manufacturing temperature the focus will move respectively closer or further from the lens [4–6]. This results in an enlargement of the light spot on the receiving plane. However, there are two characteristics that can improve the thermal sensitivity of the ADG Fresnel lens. First, the refractive index of the materials used to manufacture ADG Fresnel lenses is less sensitive to temperature than the silicone (see table 2.2). Second, the grooves deformation caused by the thermal expansion of materials is less significant for the ADG than for the SoG Fresnel lenses.

The experimental procedure that has been used is fully described in chapter 3.

The temperature variation ranges from 10 °C to 50 °C with a step of 10 °C. Since the interior of a CPV module, when operating outdoors, is approximately 15 – 25 °C warmer than the surrounding environment, the temperature range is a reasonable assumption in order to analyze the system performance for temperature variation between winter and summer.

The graphs on figure 4.17 represent the relative spot diameter evolution as a function of the lens temperature. The relative spot diameter is defined as the spot diameter measured at each temperature divided by the value corresponding to the optimal temperature. The graph on figure 4.17a shows the results obtained blocking the red light with a hot mirror, that is the spot corresponding to light useful for the top subcell. The graph on figure 4.17b represents results obtained blocking blue light using a cold mirror, that is, the spot corresponding to light useful for the middle subcell. Observing both graphs it is clear how the light spot enlargement resulting from a lens temperature variation is significantly smaller for the ADG Fresnel lens than for the SoG

Figure 4.17: Relative spot size as a function of the lens temperature. (a) Results for the top subcell (measurement carried out using a dichroic hot mirror filter). (b) Results for the middle subcell (measurement carried out using a dichroic cold mirror filter). The relative spot size is obtained by dividing the spot size by the minimum value measured for each lens.

Fresnel lens.

This behavior was predicted by ray-tracing simulations (see section 2.6.7) and it is mainly due to two different reasons. First, the refractive index dependence with the temperature of both materials composing the ADG lens is lower than the dependence of the silicone used to laminate the investigated SoG lens (see section 2.5 for thermal properties of materials). Second, the lower difference in the coefficient of thermal expansion (CTE) of the materials composing the ADG sandwich (plastic-elastomer) when compared to those comprising the SoG (silicone-glass) results in a reduced facets deformation and, as a consequence, a smaller spot enlargement. This two effects are plausible explanations that justify why, for the same temperature variation, the ray trajectory changes less for the ADG prototype than for the SoG lens.

Figure 4.18: Schematic representation of the light spot enlargement resulting from a temperature variation with respect to the manufacturing condition. On the top of the figure a SoG Fresnel lens is represented while on the bottom an ADG Fresnel lens is shown.

Figure 4.18 schematically represents the effect of temperature variation on the projected light

spot for both, a SoG and an ADG Fresnel lens. Cyan and orange lines represent ray trajectory when the lenses are at a temperature respectively lower and higher than the optimal temperature. Therefore, the performance of a real system in which SoG lenses are substituted by ADG lenses would be much more stable throughout the year because of this reduced temperature dependence. The power provided by the system in winter and summer would be similar.

The set of measurements carried out to experimentally prove the reduced temperature dependency of ADG Fresnel lenses had also an undesired effect: the lenses moved out from the thermal chamber showed delamination. Therefore, on one side, from the optical point of view, ADG lens showed encouraging performance. On the other side, from mechanical point of view, they were not able to stand the stresses generated by thermal dilatation. The delamination is probably caused by the difference in the CTE of the materials.

Thermal cycling and adhesion enhancement

The delamination mentioned in the previous section takes place in the TPE-PC interface. In comparison to the PC, the elastomer has a higher CTE (see section 2.5). As a consequence, when temperature rises, the elastomer push out the plastic causing delamination (see figure 4.19a). In order to study and understand the problem, samples of ADG lenses have been thermally cycled in a thermal chamber. The temperature has been varied from -5°C to 65°C for 120 cycles (see figure 4.19b).

Figure 4.19: (a) Scheme representing the force that the TPE applies on the PC as a consequence of different coefficients of thermal expansion between the two materials. (b) Graph representing the temperature evolution during the thermal cycling through which ADG lenses have gone through.

In order to avoid the delamination, it is necessary to enhance the adhesion between elastomer and plastic up to the point that stresses generated by thermal dilatation are lower than the strength of the adhesion.

Several strategies commonly used to increase the strength of the bond between two materials are well documented in literature [7], but their benefit is not clear when used in optical systems, as the involved surfaces need to maintain a high optical quality. After a comprehensive investigation over these methods and their compatibility with the materials composing the ADG lens, two kinds of surface treatments (*i.e.*, corona treatment and vacuum plasma treatment), the application of an adhesion promoter in the elastomer-plastic interface, and the application of a tie layer have been tried [8].

The relative optical efficiency of all laminated ADG lenses has been measured before and after the thermal cycling allowing to assess both the efficiency of the method and its compatibility with optical applications. Results are represented in figure 4.20. Based on these results, the strategy which resulted in the best adhesion enhancement while non-altering the optical surface is the

Figure 4.20: Graph showing the efficiency the ADG prototypes before and after the thermal cycling. Three lens samples have been treated with every treatment. Shown efficiency values are the average of the three. The adhesion promoter showed the best result although a significant dispersion is measured. This is probably caused by the low repetitivity of the initial deposition process for the adhesion promoter.

application of an adhesion promoter, and so this option was selected. However, first samples displayed a high dispersion among the prototypes laminated using the adhesion promoter in the efficiency values measured before and after the thermal cycle (see error bars in figure 4.20). Such dispersion is due to inadequate control of the amount and uniformity of the deposited layer of adhesion promoter. In fact, the manufacturers recommendation says the adhesion promoter should be poured onto a soft lint-free cloth to be used to wipe the bonding area to guarantee the deposition of a very thin layer capable of improving the adhesion and, at the same time, not reducing the transmittance of the surface. However, in this case, with a plastic piece having Fresnel grooves, this method is inapplicable because it would be impossible to reach grooves valleys with a cloth. In order to obtain a similar thin layer an automated system including a spray valve has been implemented (see figure 4.21a).

The spray valve has the following adjustable parameters:

- dispensing time, which can control overall amount of material deposited;
- atomizing pressure, which can control the size of the particles in the spray;
- valve opening, which can control the amount of dispensed product over time;
- valve-lens distance, which can control the area of the surface on which material is deposited and uniformity.

ADG samples with several possible combinations of listed parameters have been laminated and thermally cycled and their efficiency has been measured before and after the cycle. Results are represented in figure 4.21b. From the bar graph it is clear how, regardless the combination of parameters used to deposit the adhesion promoter, the adhesion enhancement results quite

(a)

(b)

Figure 4.21: (a) Photograph of the automated dispensing system used to deposit the adhesion promoter on ADG lenses with a detail showing a first plane of the spray valve. (b) Graph showing the efficiency loss of the ADG prototypes as a consequence of the thermal cycling. Three lenses have been treated with every combination of the parameters. Each bar represent an average value. Normal bars represent samples treated with a low atomizing pressure while dashed bars samples treated with high atomizing pressure. Results suggest that in order to optimize the adhesion without compromising the optical efficiency the deposited layer should be as thin as possible.

effective. None of the cycled lenses shows efficiency loss after the thermal cycling. Nevertheless, the sample on which a high quantity of primer have been deposited at low pressure shows a decreased efficiency prior to the thermal test. This happens because the adhesion promoter is not completely transparent, therefore, a too high quantity deposited provides enhanced adhesion but, at the same time, absorbs light limiting the maximum efficiency. Hence, in order to guarantee the required adhesion strength without compromising the optical transmission, the amount of adhesion promoter deposited should be as low as possible and the deposited layer as uniform as possible. This condition is achieved by placing the sample far from the valve (obtaining a uniform spray coating) and with a short dispensing time (low quantity).

4.3.3 Third ADG Fresnel lens generation

The third ADG Fresnel lens generation has two main differences with respect to the previous. First, the adhesion enhancement provided by the application of the liquid adhesion promoter in the plastic-elastomer interface is included in the manufacturing process. Thanks to the treatment, ADG Fresnel lens reliability significantly improved: lens prototypes were able to stand both accelerated aging test and real long-term outdoor exposition (see section 4.4) without any sign of degradation. Second, a new mold for the plastic injection of PC bi-Fresnel lenses have been manufactured. As mentioned in section 4.2.1, tip rounding values measured were higher than expected, especially in the samples featuring curved facets. The new mold technology based on nickel stampers provides much higher precision allowing the final injected pieces to satisfy best geometrical requirements.

A third change has been introduced with the third lens generation: over the glasses used to laminate some of the ADG lenses an anti-reflective (AR) coating have been deposited. This feature is treated separately from the rest of the improvements of the ADG technology for two reasons. First, the optical efficiency gain provided by the AR coating, since regards the glass substrate that is not included in the lens design, it would be the same for every lens generation. Second, the SoG Fresnel lens used as benchmark along all the thesis does not include AR coating, making unfair the comparison between the two.

New mold

The first injected bi-Fresnel lens prototypes, due to the complex geometry of the "fresnelized" faces, had tip rounding values higher than expected, especially in the lens peaks (mold valleys). Nominal value is equal to $5\ \mu m$ but the first visual inspections measured values up to $15\ \mu m$. According to the manufacturer, this is caused by the required high tilt angle of the tool during precision diamond turning. The new mold is based on nickel stampers and is able to meet higher requirements. With the tip rounding value moving closer to the expected of $5\ \mu m$, an increase of the prototypes optical efficiency is predicted. Tips rounding of bi-Fresnel lenses molded with both the old and the new mold have been measured on silicone replicates using an optical microscope (see figure 4.22).

As it is possible to see in figure 4.22, the average tips rounding value of the latest injection is significantly smaller than the previous. Nevertheless, some of them are still higher than the expected $5\ \mu m$. Thanks to the improved geometry the measured relative optical efficiency increased from 87.3 % to 89.4 %. Conversely, since the optical design is the same as it is in the second ADG generation, no improvement in the light spot diameter is expected.

Anti-reflecting coating

The development and optimization of the AR coating used to manufacture ADG lenses have been carried out by the research center Tecnalia, located in Bilbao, Spain, in the framework of the CPVMatch project. In this section, only a short summary of the most remarkable results and the properties of the selected AR coating will be exposed.

After a preliminary investigation over several combinations of materials and processes three different types of AR coatings have been identified as possible candidates:

- AR coating consisting in a single, porous monolayer (PH5);
- AR coating consisting in a double layer, a dense layer plus a porous layer (DPH5);
- AR consisting in a double layer, a dense layer plus a porous layer, and with a easy-to-clean treatment carried out at the end of the deposition process (D5F240).

	GROOVE 1 (CURVED SLOPE)	GROOVE 15 (CURVED SLOPE)
OLD MOLD
	10.5 μm	14.99 μm
NEW MOLD
	3.0 μm	6.7 μm

Figure 4.22: Enlargement of the photographs taken with the optical microscope of silicone replicate of PC bi-Fresnel lenses. First line shows two grooves of a replicate of a lens injected with the old mold. Conversely, second line shows the same two grooves of a replicate of a lens injected with the new mold.

The investigated AR coatings have been deposited using sol-gel method [9,10]. Several low iron glasses of the same size of the ones used to laminate ADG elementary units have been used for the deposition. Since the beneficial effect of the AR coating is the same regardless the lens generation, prototypes of second ADG generation have been used for AR coatings characterization. With each type of coating listed, three ADG lenses have been laminated and characterized. Results have been compared with ADG lenses laminated on uncoated low iron glasses.

Figure 4.23 shows results obtained from the lenses characterization. Shown values are relative efficiency values, *i.e.*, normalized with the efficiency of a conventional SoG Fresnel lens. It can be observed that, to a different extent, all the three types of coating provided an increase in the transmitted light and, as a consequence, in the optical efficiency measured. The improvement, in the case of the double layer coating with easy-to-clean process, is almost negligible. This is probably caused by the easy-to-clean process, which, despite being useful to ease the cleaning process of the modules, results in an unacceptable performance decrease. Both the other two coatings, porous layer and double layer (porous more dense), show efficiency improvement. The double layer is slightly better providing an efficiency increase of 2.3 % in the top range against the 1.38 % provided by the monolayer. It is worth to remark that the double layer deposition process includes a step more, increasing the overall cost of a system. After the described characterization, the AR coating technology chosen to be used in the prototypes laminated in order to manufacture complete CPV modules is the DPH5 (dense plus porous layers).

After this first characterization, researcher from Tecnalia tried to adapt the deposition process for glasses with bigger size, with the purpose of manufacturing a full area module composed of 10x5 lenses (400x200 mm^2). Unfortunately, the deposition procedure, that was highly efficient and reliable for small size glasses (maximum 12x12 mm^2), failed with larger substrate. The reason of the failure was the high temperature involved in the process, which resulted in the bending of the glasses. Hence, the deposition process for big size glasses still needs improvements.

Figure 4.23: Bar chart representing the relative efficiency measured for the ADG Fresnel lenses which include AR coatings. Each group represents the average efficiency of the three lenses laminated and measured with a certain type of AR coating. First group refers to the lenses laminated over uncoated glasses used as reference. Blue bars represent the efficiency of the top subcell (350 – 660 nm), while red bars represent efficiency of the middle subcell (660 – 900 nm).

Elementary units

A relative optical efficiency equal to 89.4 % has been measured for the third ADG generation (without AR coating), meaning that, the new mold technology described in this section provided an efficiency increase of 2.1 %. It is worth to remark that, as exposed in section 2.6, the maximum theoretical value predicted by ray-tracing simulation is 92.6 %. Achieving the measured 89.4 % is a very positive results and means that, with the current lens design and the current choice of materials, the ADG technology developed is very close to its maximum potential.

For what concern the spot size measurements, the smallest diameter comprising the 98 % of transmitted energy is 2.5 mm, which correspond to a concentration of 326 suns, and is unvaried with respect to the second generation. Since the lens optical design did not change, and no actions have been taken to improve surface finishing, an improvement in the maximum attainable concentration was not expected.

Arrays composed of 10x5 lenses

In order to measure optical efficiency and spot size diameter of the lenses composing the array, the same method employed to measure the arrays composed of lenses of first ADG generation has been used.

Optical efficiency. Figure 4.24a shows the distribution of the relative efficiency values for every lens within the array. Only results of the best laminated array are shown since all the others are similar.

The average value of the relative efficiency for all the lenses within the characterized array is 87.7 %. According to previous measurement, the average efficiency measured for the unitary lenses is equal to 89.4 %. It is worth to point out that loosing less than 2 % of efficiency switching from elementary units to full area array is a very positive results. To laminate the third generation arrays,

Figure 4.24: (a) Histogram representing the efficiency distribution of the lenses composing the array laminated using third generation ADG Fresnel lens. (b) Color graph representing the relative optical efficiency of the lenses across the parquet. Every square represents one lens whose identification number is indicated through a white number. Rows and columns numbers refers to the actual rows and columns of the arrays. As indicated by the color bar on the right, dark red colors represents the highest efficiency values while dark blue colors the lowest.

a plastic frame have been used in order to avoid the border effect seen during the characterization of the arrays made with lenses of third ADG generation. Such frame is manufactured in teflon, a widely known non-stick plastic material, in order to be able to easily remove it once the lamination process ended. Despite the implementation of the frame in the manufacturing process it is possible to observe that there is still a significant variability on the relative efficiency values of the different lenses across the parquet. The standard deviation is equal to 2 %, that is very similar to the value calculated for the first generation. The maximum measured relative efficiency value is 92.0 %, which is higher than the maximum value measured for unitary lenses (90.3 %).

When the optical efficiency of every lens is plotted as a function of the position of the lens (see figure 4.24b), it can be observed that, on the contrary that in the case of the array composed of lenses of the first ADG generation, the position of the lens do not seem to be related with its efficiency value. Nevertheless, there is still a high dispersion of measured efficiency value, which can be explained with both the border effect (limited, but not completely avoided, by the anti-adherent frame) and the handmade manufacturing process. As explained in section 4.2.2, every plastic bi-Fresnel lens of the parquets is glued manually to the other. During this process some glue leaked out and filled the grooves, limiting the real lens aperture and, as a consequence, the lens optical efficiency.

Spot size diameter. Figure 4.25a shows the distribution of spot size diameter values for every lens within the array.

The average value of the light spot diameter for all the lenses within the measured array is 2.7 mm. According to previous measurement, the average light spot diameter measured for the unitary lenses is equal to 2.5 mm. Looking at the histograms in figure 4.25a it is possible to observe that, as well as in the case of the efficiency, there is a significant variability on the light spot diameter values of the different lenses across the parquet. The standard deviation is equal to 7.4 % while the minimum measured light spot size value is 2.3 mm. Such results fit with the spot size

Figure 4.25: (a) Histograms representing the spot-size diameter distribution of the lenses composing an array laminated using lenses of the third ADG Fresnel lens generation. (b) Color graphs representing the spot-size diameter of the lenses across the parquet. Every square represents one lens whose identification number is indicated through a white number. Rows and columns numbers refers to the actual rows and columns of the arrays. As indicated by the color bar on the right, dark red colors represents the smaller measured spot diameter values while dark blue colors the largest.

diameter measured for ADG third generation elementary units. As well as for the first generation, the average light spot diameter of the lenses within the array is slightly higher, but is lower than the average value measured for the first ADG generation thanks to the curved facets design.

When the light spot diameter of every lens is plotted as a function of the position of the lens (see figure 4.25b), the dispersion is even higher than for the first ADG generation. Many reasons could cause the observed dispersion. Among them, the handmade manufacturing process and the border effect are the most probable. However, with the current state of the manufacturing process, the extent of the dispersion seems to be random, *i.e.* the higher dispersion measured for the array composed of third generation ADG lenses does not have any correlation with the specification of the lenses.

4.3.4 Summary of characterization results

In this section, all the results obtained from the experimental characterization of both elementary ADG units, and arrays composed of many lenses will be summarized. Table 4.3 shows the efficiency and the spot size diameter measured for each lens generation. First line represents elementary units while second line arrays composed of 10x5 lenses.

Results summarized in table 4.3 are positive and bode well for future development. In the first place, the efficiency of elementary units increased up to 89.4 %, which is very close to the theoretical limit equal to 92 %. This suggests that, without a radical change in the lens configuration (*e.g.* different material or different design concept), the ADG prototypes, in only three years and a half, fulfilled almost entirely their potential. Furthermore, the array composed of 10x5 lenses achieved

Table 4.3: Summary of the results obtained by the experimental characterization.

	First generation		Second generation		Third generation	
	<i>Relative efficiency</i>	<i>Spot size diameter</i>	<i>Relative efficiency</i>	<i>Spot size diameter</i>	<i>Relative efficiency</i>	<i>Spot size diameter</i>
	%	mm	%	mm	%	mm
Elementary unit	85.5 %	2.90	87.3 %	2.5	89.4 %	2.5
Array 10x5 lenses	84.7 % $\pm$ 1.8 %	3.2 $\pm$ 3.1 %	—	—	87.7 % $\pm$ 2 %	2.7 $\pm$ 7.4 %

an average efficiency value of 87.7 %, which is less than 2 % lower than the one measured for elementary units. Considering the additional challenges arose with the larger size, and the handmade manufacturing process, the measured efficiency is a very promising outcome. Nevertheless, some points need to be clarified: some lenses of the measured parquets have an efficiency valued higher than the highest efficiency measured for elementary units. This means that either there is some problem inherent with the characterization method used to measure array's efficiency or, for some reason, there are individual lenses within the array that are *better laminated* and achieve higher efficiency. In both cases, further investigation is required to come up with a conclusion. In the second place, the spot size diameter measured for ADG prototypes, despite the improvements attained from first to third generation, is still larger than expected. The reasons causing the wider light spot are not completely clear, however, the most probable hypothesis is that the cause is the optical defects resulting from plastic injection process and/or possible profile deformation resulting from the lamination process. Also in this case, further investigation is needed to fully clarify the reasons of the low concentration.

In the short-term several actions could be taken in order to further improve ADG technology. First, TPE with high transmission in the UV region could be used. Despite this provision requires further investigation over lens reliability, could limit losses due to high absorption. Second, as mentioned in chapter 2, the lens design could be inverted, resulting in an achromatic doublet where the first lens is the converging one and the second the diverging one. As explained in section 2.6.9 the inverted design significantly reduce draft angles and perimetral losses.

4.3.5 Outdoor degradation

It is well known that many plastic materials suffer yellowing degradation under UV radiation [11–14]. That is the main reason because additives are commonly added to plastic chemical formulations with the aim of blocking UV radiation and avoid the yellowing. It is important to understand and avoid this phenomenon before the choice of the material. In fact, on one side, a high transmission in the UV region results in more energy transmitted and higher optical efficiency. On the other side, a lens for CPV stays all its life outdoor, if after a few months it becomes yellow because of the sun exposition, it is not suitable for PV application.

In order to understand this degradation phenomenon and to ensure that chosen materials keep their transmission properties after a long-term UV exposition, an outdoor degradation test has been carried out. Several flat samples with a different combination of materials have been laminated and installed in a solar tracker where they stayed for more than two years.

Figure 4.26 shows the frame used to hold the flat samples to be degraded. The transmittance of all the samples has been measured before starting the test (July 2015), after one year of outdoor exposition (July 2016), and after two years of outdoor exposition (October 2017). Figure 4.27

Figure 4.26: Photograph of the samples installed on the solar tracker for the long-term degradation test.

shows the results for the candidate materials. Silicone is not considered because there is enough field experience and it is already known that it is not affected by degradation due to UV radiation.

First thing to remark is that, as already mentioned in appendix C, the uncertainty of the measurement is high because of its sensitivity to factor like the quality of the sample to be measured and its orientation. However, the transmittance decrease observed for both the PC samples is definitely higher than the measurement error, meaning that this plastic, even when its formulation includes additives for the UV protection, degrades quickly under solar radiation. Conversely, both the TPE and the PMMA show no reduction in their transmission within the experimental error. Finally, the *cutting wavelength*, which is the wavelength starting from which a material starts to transmit light, is accurately identified using this measurement method.

As mentioned earlier in this section, despite it becomes yellow under UV radiation, starting from the second ADG generation the PC UV through is used. This choice derives from the fact that, in the ADG design, the PC is protected by the TPE. Therefore, the most harmful region of the UV radiation is filtered by the elastomer before reaching the plastic. In order to prove that the elastomer protection is enough to avoid the yellowing of the PC, flat samples composed of glass-TPE-PC-TPE-glass have been laminated and installed on the holding structure in November 2017 where they stayed until August 2018.

Figure 4.28 shows the transmittance measurements carried out before and after the outdoor exposition for two of the tested samples. In both cases, no degradation was observed, confirming that the PC with high transmittance in the UV region, if protected by the TPE, is suitable to be used in the ADG technology.

4.4 Module assembly and outdoor characterization

Various modules with the developed ADG lenses and reference modules with the SoG technology were successfully manufactured. First, only elementary units were characterized outdoors using the same type of MJ solar cell used later in the complete modules assembly. Then, mono-modules composed of one cell and one lens were produced and measured outdoors over a longer period. Finally, full area modules with aperture equal to 800 cm^2 were developed. Always both, modules

Figure 4.27: Graph representing the transmittance measurements before the degradation test (blue curves), after one year of outdoor exposition (red curves), and after two years of outdoor exposition (yellow curves). (a) TPE. (b) PC. (c) PC with high transmission in the UV region. (d) PMMA.

Figure 4.28: Graph representing the transmittance measurements before the degradation test (blue curves) and after nine months of outdoor exposition (red curves). a) and b) are two flat sample. No degradation detected.

with ADG lenses and SoG² lenses, were assembled. Different generations of ADG lenses were investigated. Results obtained from outdoor measurements at different cell-lens distances, and with different cell sizes, confirm the results obtained from the indoor characterization exposed in section 4.3.

4.4.1 Cell-lens units: comparison of different geometrical concentration ratios

In the first stage, pairs of cells and lenses were investigated to determine the optimum cell-lens distance. In this way, the same solar cell can be measured with different lenses excluding the influence of solar cell performance on the assessment of the lens quality. During the project, several measurements have been carried out at the test tracker at the Fraunhofer-ISE in Freiburg, Germany.

The z-scan device is mounted on the outdoor test tracker (figure 4.29a) where the distance between cell and lens can be varied and the IV-curve measured. The set-up is completely automated and permits a high precision control of the displacement of the lens along the optical axis. In this way the optimum cell-lens distance at the prevailing conditions can be determined (figure 4.29b).

Figure 4.29: (a) z-scan device used to adjust the cell-lens distance. (b) Efficiency versus module height for the different lenses (SoG Fresnel lens and ADG Fresnel lens) using a 3J solar cell with a diameter equal to 2.3 mm.

Three generations of ADG lenses were measured with different solar cell sizes and always comparing to a measurement with the same SoG Fresnel lens from Fraunhofer ISE. For analyzing the electrical characteristics an exemplary result is shown in figure 4.30 and figure 4.29b. The diameter of the designated cell diameter was 2.3 mm leading to a concentration of 385x. The 3J solar cells are mounted with electrical interconnection. For the measurements, the same solar cell was used for both lens types. The measurements were carried out on a clear day (20/06/2018) within one hour to minimize differences in spectral conditions. In figure 4.30a, it can be clearly seen that the fill factor (FF) is not as sensitive to module height for the ADG lens as for the SoG Fresnel lens. Two reasons could explain such behavior: first, the reduced chromatic aberration in the ADG lens provides a more uniform spectral distribution in the focal spot and, second, the higher materials absorption in the UV region causes the MJ solar cell to be almost always top-limited, with obvious benefits for the FF stability. Moreover, the constant FF also leads to a wider plateau of the electrical efficiency for different module heights (figure 4.30b). As the optimum module height changes for different spectral conditions and different ambient temperatures, this is an advantage for the energy production over the year. Still, the peak efficiency is lower for the ADG lens compared

²The full area SoG module's aperture is equal to 832 cm². Single lenses aperture is 40x40 mm²

to the SoG lens. However, this is expected as the current is lower due to higher light absorption in the materials selected for the ADG optics.

Figure 4.30: (a) Fill factor and (b) normalized short circuit current density versus module height when measured in 06/2018.

To investigate the lens performance at different geometrical concentration levels, the lenses were measured also using a solar cell with a diameter of 1.6 mm resulting in a geometrical concentration of 796 suns. The behavior for (FF) and efficiency is the same as for the larger cell area. It is interesting to compare the generated current for the different cell areas. This can be seen in figure 4.30b where the measured current density (J_{SC}) normalized to the irradiation intensity (DNI) and lens aperture for different module heights and geometrical concentration ratios is shown. It can be seen that, even at a very high concentration, of 796X, the losses of current due to light spillage is low (6.1 % for the SoG lens and 14.3 % for the ADG lens). The losses are lower for the SoG lens compared to the ADG lens. This is due to a wider focal spot cast by ADG lenses (see section 4.3). However, as for the efficiency described above, the plateau at the peak of the curve of the ADG lens is broader leading to a lower sensitivity for varying the module height.

In table 4.2 the relative optical efficiencies of different generations of the ADG lenses are summarized. Different solar cell structures were measured. The cells have different areas leading to different geometrical concentrations.

In the course of the thesis, a big development progress can be seen, starting with a relative efficiency of 72.9 % in 2016 and improving to 90.8 % in 2018 (both measurements with a 3J solar cell and the same concentration level). From table 4.2 immediately stands out the difference between outdoor and indoor measurements, especially for the first and second generation. Such discrepancy is caused by two factors. For the case of the first lens generation, outdoor measurements were carried out using solar cells with a diameter equal to 2.3 mm and 3 mm. For the second, since the cell size is larger than the measured spot diameter (2.9 mm), there should not be any difference in using a 3 mm solar cell or a 10 mm solar cell, which is the cell size used for indoor measurements. Therefore, since the lens measured was manufactured before the optimization of the lamination process, intrinsic defects of the lens probably resulted in the low efficiency value. For the first, apart from the above, cell size is larger than the spot diameter, resulting light spillage that further reduces the measured efficiency. Conversely, for the case of the second ADG lens generation, the ADG prototypes measured outdoor include a layer of adhesion promoter that was not deposited using the automated spray-valve described in section 4.3.2. Then, the efficiency difference between outdoor and indoor measurements is caused by the not optimized adhesion promoter deposition, which results in the desired adhesion enhancement but is detrimental from the point of view of light transmission (see section 4.3.2). Finally, the measurements match very well for the third ADG generation.

4.4.2 Mono-modules

In the second stage, mono-modules with single lenses and one solar cell were assembled. For the mono-modules, solar cells and bypass diodes are mounted to the metal heat distributor and electrically interconnected. This device is referred to as solar cell assembly (SCA). The SCA(s) are mounted to a rear glass plate. They are positioned to match the location of the focal spot given by the lens array. Mono-modules with one cell-lens pair were built in the thesis. All lenses have an aperture of $40 \times 40 \text{ mm}^2$. Finally, the modules are en-housed with a frame and equipped with a junction box to be able to measure them outdoors for long periods. All measurement data was filtered for $DNI > 700 \text{ W/m}^2$, DNI deviation during measurements less than $\pm 1 \%$, ratio $DNI/GNI > 0.7$, $I_{SC} > 0$, $V_{OC} > 0$, $V_{MPP} > 0$, $FF > 0$, efficiency $\eta > 0$, ratio I_{MPP}/I_{SC} always between 0 and 1, ratio V_{MPP}/V_{OC} always comprised between 0 and 1 and solar elevation $> 25^\circ$.

Mono-modules with Gen2 ADG lenses

The first mono-modules were built in 2017 using ADG lenses of Gen2 and SoG lenses for benchmark. Different solar cell sizes (diameter of 2.3 mm and 3 mm) were used. These first modules were measured outdoors since the end of June 2017.

Figure 4.31: (a) Picture of four mono-modules, two with ADG and two with SoG lenses. The modules have been measured at Fraunhofer ISE for more than one year since June 2017. (b) Relative module efficiency (ADG efficiency divided by SoG efficiency) for a module with solar cell diameter 3 mm is shown in the graph. The measurement gap between November and March is due to the winter break. Still, the modules were kept installed outdoors. Over the measurement period, the efficiency slightly decreases for the ADG lens module. The lens is of second generation and the manufacturing process was improved afterward (see table 4.2).

Figure 4.31 shows the relative efficiency measured over the whole measurement period for the modules including solar cell of 3 mm of diameter. Results for the mono-modules including solar cell of 2.3 mm of diameter are not shown because they are qualitatively similar and the measurement period is shorter (measurements stopped in the beginning of June 2018).

A decreasing tendency can be easily identified starting for the beginning of the outdoor exposition. The ADG lenses used to assemble such modules include the adhesion enhancement treatment (see section 4.3.2), nevertheless, the automated spray-valve was not implemented and the procedure to deposit the primer was not optimized, resulting in prototypes not fully reliable over long-term periods. That is the reason why the explanation for such efficiency decrease seemed to be delamination of primary optics.

In July 2018, in order to ensure that the relative efficiency decrease was caused by ADG lens delamination, the two modules including 2.3 mm solar cell were disassembled and both ADG

Table 4.4: Optical efficiency of the ADG lens used to assemble one of the two mono-modules which have been characterized outdoor during more than one year. The first column represents the relative optical efficiency measured indoor while the second column the relative efficiency of the whole module. The decrease of the global relative efficiency reflects the optical efficiency loss caused by lens degradation due to outdoor exposition.

	Before module assembly	After one year outdoor	
	η [%]	η [%]	$\Delta\eta$ [%]
Relative lens optical efficiency [%]	86.7	77.8	-8.9
Relative global module efficiency [%]	~ 83	~ 73	~ -10

lens and the solar cells were measured indoors. Comparing the one sun (AM1.5d, $1000W/m^2$) measurements to initial measurements (before outdoor exposure) did not reveal a decrease in short circuit current, meaning that a degradation of the solar cell performance can be excluded.

Conversely, comparing the optical efficiency measurement carried out before and after the year of outdoor exposition, the relative efficiency loss measured indoor is consistent with the overall efficiency decrease observed in the outdoor measurement (see table 4.4).

Table 4.4 shows the indoor optical efficiency measurement before and after the outdoor exposition compared with the relative efficiency decrease measured over the whole measurement period. The optical efficiency loss is almost equal to the global efficiency reduction, confirming that the slope seen in figure 4.31 was caused by ADG lens delamination.

Mono-modules with Gen3 ADG lenses

Two additional mono-modules have been assembled and characterized outdoor at the Fraunhofer-ISE facility. One of them includes an ADG Fresnel lens of Gen3 while the other is assembled using a conventional SoG Fresnel lens which is used as benchmark. Both modules have an aperture area of $40 \times 40 \text{ mm}^2$ and a 3J solar cell with a diameter of 2.3 mm , which corresponds to a concentration of 385X.

The measurement period spans from the beginning of June 2018 to the beginning of October 2018. The first remarkable result is the efficiency over the full measurement period. Looking at the graphs in figure 4.32, we see immediately that the average efficiency of the SoG reference module is slightly higher than the efficiency of the ADG module, respectively 30.1 % and 28.4 % in average. Nevertheless, values measured for the ADG lens show lower dispersion, meaning that the overall performance of the module is more stable.

The efficiency fluctuation recorded for the SoG module is mainly caused by the temperature and spectrum-dependent behavior of the SoG Fresnel lens. Such dependency is caused by different focusing of short and long wavelengths as temperature changes (see sections 2.6.7 and 4.3.2). As explained in section 2.6.7 and experimentally confirmed in section 4.3.2, the achromatic design of ADG Fresnel lens strongly reduces such dependencies, in part because the spectral distribution over the solar cell surface is much more uniform thanks to the achromatic design, and in part because the materials used to manufacture the ADG lens have a lower CTE than silicone.

Figure 4.33 shows the FF as a function of ambient temperature. The ADG module FF is at the same time higher and more stable, explaining the more constant efficiency shown in figure 4.32. Comparing the FF measurements to the measurement of the cell-lens distance in figure 4.30, the lower FF of SoG could be caused also by a non-optimum module height for the ambient temperature range during the measurement period. In addition, because of the TPE absorption in the UV region

Figure 4.32: Graphs showing the mono-module efficiency during the whole measurement period. a) Data of the SoG reference mono-module. b) Data of ADG mono-module.

Figure 4.33: Graphs representing the FF as a function of the ambient temperature. (a) Data of the SoG reference mono-module. (b) Data of ADG mono-module.

(see section 2.5 for material characterization), the ADG module most of the time is limited by the top subcell in the 3J solar cell. This might also contribute to the higher and more stable FF.

Figure 4.34 shows the relative efficiency (ADG efficiency divided by SoG efficiency) over the measurement period. There is an initial decreasing slope which corresponds to the initial increasing slope detected in the SoG module efficiency shown in figure 4.32 (and thus not to a delamination of the ADG lens). Afterward, the relative efficiency stabilizes to a value of approximately 93 %. This is remarkably higher compared to the 90.8 % of relative optical efficiency exposed in table 4.2. Such difference is partially due to the AR coating, which has been deposited only on the glass used for the ADG lens lamination, and partially to the more stable FF, which partially compensate the lower ADG optical efficiency.

To summarize, the overall results obtained from outdoor characterization are very positive. First, the average efficiencies of the two modules are similar, while the dispersion is much higher for the SoG based mono-module. This is a direct consequence of the slightly higher and much more stable FF, which reduces the variation in the module performance caused by temperature variation. Second, the higher FF contributes to bring the ADG efficiency closer to the SoG module. The average relative efficiency over the whole measurement period is 94.5 %. Finally, after almost five months of outdoor exposure, the ADG mono-module did not show any sign of degradation, leading to encouraging expectations for the future.

4.4.3 Full area modules

Apart from the four mono-modules, whose characterization has been described earlier in this section, two full area modules have been successfully assembled and characterized at Fraunhofer ISE. Also in this case, one of them includes ADG Fresnel lenses while the other is assembled using conventional SoG Fresnel lenses and the latter is used again as benchmark. The ADG module is composed of 10x5 lenses (Gen3) for an aperture area of 800 cm^2 , while the SoG reference module is composed of 13x4 lenses resulting in an aperture area of 832 cm^2 . All individual lenses have an

Figure 4.34: Graph showing the module relative efficiency over the whole measurement period. Relative efficiency is defined as the ratio between the ADG based module efficiency and the SoG based module efficiency.

aperture of $40 \times 40 \text{ mm}^2$. Both modules include 3J solar cells with a diameter of 2.3 mm , which leads to a concentration of 385 suns . The lower concentration factor was chosen as the current density was lower for the ADG lens because of light spillage of this prototype lenses (figure 4.29b). Pictures of the modules are shown in figure 4.35.

Figure 4.35: Module with 50 ADG lenses of third lens generation (top). Reference FLATCON module with 52 lenses (bottom). The aperture of each lens is 16 cm^2 in both modules. The module areas are 800 cm^2 for ADG and 832 cm^2 for the SoG module.

The measurement period spans from the end of June 2018 to the end of September 2018. Figure 4.36 shows the module efficiency over the whole measurement period for both modules. On one side, the full reference SoG module maintains its average efficiency value of 30.8% expected from the mono module performance shown above. On the other side, the average efficiency of the ADG module drops by almost 5% from 28.4% for the mono-module to 23.6% for the full module. Moreover, also the dispersion of measured values is much higher for the large area ADG module compared to the results on mono-module level.

This means that the overall performance of the full area ADG module is lower than for the mono-module. It is likely that the reason is that the optical efficiencies of the lenses composing the array are non-uniform (see section 4.3.3). This results in lower average FF compared to the ADG mono-module.

In order to improve the performance of a full module, it is essential to improve the lens parquet manufacturing process. In fact, the industrial process envisaged to obtain the parquet of ADG Fresnel lenses includes a preliminary step in which the parquet of bi-Fresnel plastic sublenses is manufactured by a high throughput process such as hot embossing, compression molding or injection molding of the entire sublenses parquet. As mentioned in section 4.2.2, at this moment, the individual sublenses obtained by plastic injection are manually glued together to produce an array of plastic bi-Fresnel sublenses. This handmade procedure introduces errors, such as alignment errors among the lenses composing the array and possible leakage of the glue inside the grooves of the plastic pieces. This kind of manufacturing errors would be easily avoided in an industrial process for mass production.

Figure 4.36: Graphs showing the large area module efficiencies during the whole measurement period. (a) Data of the SoG reference module. (b) Data of ADG module.

4.5 Conclusions

Firstly, the process employed to manufacture ADG Fresnel lenses has remarkably evolved throughout the ADG development. On one side, a lot of useful information about the injection molding process have been learned. Such process is cost-effective and widely known in the plastic industry, nevertheless, when used to inject the PC bi-Fresnel pieces it faces some limitations, *i.e.*, it is very complicated to achieve tips rounding values below $5\ \mu m$, even if nickel stampers are used as in the new mold. In addition, the light spot wider than expected could be justified with a poor surface finishing of the PC. Nevertheless, further investigation is needed to confirm such hypothesis. Therefore, plastic injection is suitable to be used to fabricate the plastic piece, but for the future different processes such as hot embossing will be tested in order to understand if better geometrical and optical requirements could be met. On the other side, the lamination phase, key step in the ADG manufacturing process, was entirely developed at the IES-UPM, from the design and fabrication of the laminator machine, up to the optimization of its processing parameters and, finally, the automation of the process. At the end of the thesis, the operator intervention is needed exclusively to place the sample inside the machine, then the automaton carry out all the other steps. In this way the process became repetitive and highly reliable and was used to successfully laminate both elementary units and arrays composed of many lenses.

Secondly, the comprehensive indoor characterization of all the laminated ADG prototypes gave outstanding results. First, the indoor measurements of the first ADG generation allowed to experimentally demonstrate the achromatic behavior of the ADG lenses, proving from the beginning the feasibility of the technology. Then, generation by generation, the ADG lens prototypes continuously improved from both the performance and reliability points of view. The relative optical efficiency measurement increased from 85.5 % for the first ADG generation to the 89.4 % for the third ADG generation. Ray-tracing simulations, for the current choice of process and materials, predicted a maximum relative efficiency value of 92 %, meaning that the ADG technology achieved 97 % of its potential. In addition, promising results were also obtained measuring parquet composed of many lenses, whose global relative efficiency is equal to 84.7 % for the first generation and 87.7 %

for the third. It is worth to remark that, even if the average efficiency of the lenses composing the array is less than 2 % lower if compared with elementary units, the standard deviation of such measurement is in the order of 2 %, resulting in current limitation issues when the solar cells of a CPV module are series connected. The high dispersion is a random side effect probably caused by the handmade method used to glue together the plastic pieces prior to the lamination and by the border effect during the lamination. Further investigation is required to solve this issue, however, it is reasonable to think that such limitation could be easily solved with a mass production industrial process.

Conversely, irradiance spot measurement revealed additional issues. Despite from the first generation to the second and third the light spot diameter measured decreased from 2.9 mm (242 suns) to 2.5 mm (326 suns), it is still much larger than the value predicted by ray-tracing simulations, that is equal to 1.7 mm (716 suns) for the flat facets design (first generation) and to 1.2 mm (1401 suns) for the curved facets design (second and third generation). Obviously, since ray-tracing simulations consider ideal surfaces with no scattering, waviness, and roughness, the experimental value is expected to be lower than the theoretical. Nevertheless, the difference between ray-tracing and measured spot diameter is much higher for the ADG lens than for the SoG lens used as benchmark, where, for the curved facets design the measured light spot diameter is equal to 2.3 mm (385 suns), while the predicted by ray-tracing is 2.2 mm (405 suns). This means that, the casting of the silicone on the glass substrate permits to meet a much better optical quality if compared with the manufacturing process used to inject the PC and successively laminate the ADG sandwich. To conclude, further investigation is required to fully understand what widens the light spot cast by the ADG lens, because the current state of the technology is far from its theoretical potential.

At the same time, the reliability of the ADG lens prototypes was investigated. The intrinsic design of the ADG lenses, being composed of two materials, implies thermal stresses caused by the different CTE of the elastomer and the plastic. Such stresses, together with the poor adhesion between the PC and the TPE, resulted in the delamination of the ADG prototypes after a few soft thermal cycles. The problem was successfully solved by the implementation of an automated spray valve, through which it is possible to accurately deposit a thin layer of a liquid adhesion promoter, whose function is to enforce the binding between elastomer and plastic and avoid the delamination. Several prototypes submitted to such treatment have been capable to stand a thermal cycling of almost 120 cycles (temperature varied between -5°C and 65°C) showing no delamination and, moreover, the mono-modules assembled in the end of the thesis, after six months of outdoor exposition does not show any kind of degradation, confirming the efficacy of the adhesion enhancement method.

Apart from the characterization of ADG prototypes, also the plastics and the elastomers suitable to be used in the ADG manufacturing process have been investigated. Most of their properties, either optical, mechanical, or thermal, have been taken from literature and are disclosed in chapter 2. Here, reliability has been tested. In particular, before selecting the best pair of materials, it was important to ensure their stability under UV radiation. Outdoor degradation test demonstrated the UV stability of the TPE selected, while the PC, especially the UV through formulation, showed a not negligible transmission losses. Nevertheless, since in the ADG sandwich the PC is protected by the TPE, which filters the most harmful UV radiation, transmission measurement demonstrated that the two materials coupled together do not yellow and can be used to manufacture ADG lenses.

Finally, in the last months of the thesis, complete CPV modules have been assembled and characterized outdoor at the Fraunhofer ISE facilities. Also here, the results are very promising. At mono-module level the ADG-based module efficiency is close to the SoG-based module efficiency, 30.1 % and 28.4 %, respectively. In addition, the ADG-based module resulted to be less sensible to ambient conditions such as temperature and spectrum, providing a more constant energy output throughout the year. This is the result of the achromatic behavior of the ADG lenses, which provides a more uniform light distribution over the solar cell surface in comparison with the conventional SoG technology.

Apart from the mono-module, also a full area ADG-based module was assembled and tested. As expected, the performance of the full module are lower than the mono-module. While the SoG full module has approximately the same efficiency of the mono-module, equal to 30.8 %, the ADG-based full module efficiency is equal to 23.6 %, almost 5 % less than the ADG-based mono-module. The reduced performance are caused by the high dispersion of the optical efficiency of the lenses within the array, which contributes to a lower and less stable FF. Despite the limitation imposed by the handmade manufacturing process of the ADG lens parquet, observing the evolution of the FF as a function of the ambient temperature, there is no a clear correlation between the temperature and the FF, which is evident for the case of the SoG-based module. This fact suggests that, the worse performance of the full module is caused by manufacturing issues that can be easily solved in a mass production process where the entire parquet of lenses is manufactured all in once.

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Chapter 5

COST ANALYSIS OF AN ADG FRESNEL LENS ARRAY

5.1 Introduction

The main objective of this chapter is to present a complete cost analysis of the achromatic doublet on glass (ADG) Fresnel lens developed within this thesis. To that end, section 5.2 includes the estimation of costs associated with the materials and processes involved in the manufacturing of the ADG Fresnel lens. Section 5.3 describes the methodology applied to estimate the energy produced by a CPV module comprising the ADG Fresnel lens. Finally, section 5.4 includes the economic evaluation of the ADG Fresnel lens. Similarly to what has been done in the other chapters of this thesis, in order to evaluate the competitiveness of the ADG Fresnel lens, its cost is compared to that of a conventional silicone on glass (SoG) Fresnel lens. Hence, SoG is used through this text as a benchmark to evaluate ADG Fresnel lens.

5.2 Material and manufacturing process costs

As described in chapter 2, the ADG Fresnel lens is composed of a glass substrate, a thin layer of an elastomeric material and a polycarbonate (PC) piece having Fresnel grooves on both sides. The manufacturing process is divided in two steps: first, the PC piece is manufactured by plastic injection and, second, the sandwich comprising the three materials is obtained by lamination. Within the thesis, modules comprising 10x5 Fresnel lenses have been assembled. For the sake of simplicity, for the cost estimation an elementary unit comprising one ADG Fresnel lens and one multi-junction (MJ) solar cell is used. The general hypotheses including lens optical aperture, efficiency, and reference irradiance are summarized in table 5.1. The ADG lens has an aperture area of 40x40 mm². To estimate the cost of the ADG Fresnel lens two main contributions are considered: material costs and processing costs.

Table 5.2 gathers all the costs associated with materials. For the ADG Fresnel lens, the PC thickness is approximately 1.8 mm and the elastomer thickness is equal to 0.5 mm. Based on the density and per-weight cost of those materials [1], a cost contribution of 0.014 €/W_p and 0.005 €/W_p is estimated for PC and elastomer respectively. The cost of solar-grade glass substrate, which is estimated to be 0.014 €/W_p (for the ADG-based module) according to the price for square meter reported in [2], is also included. Moreover, table 5.2 also includes the cost of optical silicone. This material is not necessary to manufacture ADG Fresnel lens but its cost is included for a later cost comparison with the SoG Fresnel lens. The cost of silicone is estimated by subtracting the cost

Table 5.1: General hypotheses assumed for the ADG Fresnel lens cost estimation.

Reference elementary unit	Reference elementary unit	
	SoG-based	ADG-based
<i>Module efficiency</i> [%]	38.3	36.1
<i>Lens area</i> [cm^2]	16	16
<i>Irradiance</i> [W/m^2]	1000	1000
<i>Elementary unit peak power</i> [W_p]	0.61	0.53

of solar-grade glass ($0.013 \text{ €/}W_p$, for the SoG-based module) of the total material costs of SoG Fresnel lenses ($0.071 \text{ €/}W_p$) reported in [3].

Table 5.2: Hypotheses regarding materials costs.

Material	Ref.	
<i>Solar-grade glass (flat PV panels)</i> [€/m^2]	5.1	[2]
<i>Solar-grade glass (SoG-based module)</i> [$\text{€/}W_p$]	0.013	
<i>Solar-grade glass (ADG-based module)</i> [$\text{€/}W_p$]	0.014	
<i>Elastomer</i> [€/kg]	4.3	[1]
<i>Elastomer</i> [$\text{€/}W_p$]	0.005	
<i>PC</i> [€/kg]	2.15	[1]
<i>PC</i> [$\text{€/}W_p$]	0.013	
<i>Optical silicone</i> [$\text{€/}W_p$]	0.057	[2, 3]

Table 5.3 summarizes the costs associated with materials processing. First, the costs associated with the injection of PC to manufacture the piece whose both faces have a Fresnel structure was estimated. Up to now, only an injection mold for a single lens was designed and bought. Consequently, the cost associated with the manufacturing of the injection mold has been assumed to be 25 % lower to account for the cost reduction due to mass production.

Similarly, for the lamination process where the glass, the TPE, and PC composing the ADG Fresnel lens are glued together, only data from laboratory experience are available. Both laminators used to produce the first ADG Fresnel lens prototypes, whether they are elementary units or parquets, were designed and manufactured at the laboratories of the Solar Energy Institute - Technical University of Madrid (IES-UPM) (see chapter 4). Hence, it is difficult to estimate the industrial costs associated with this process. Nevertheless, the ADG lamination is similar to the process used to laminate conventional flat PV modules, which is known to have a marginal influence over the global module costs. Therefore, since a reliable number for the cost of this process was not available at the time of the analysis, a worst case scenario was assumed. The ADG lens lamination costs have been estimated to be similar to the costs associated to the casting of silicone over glass, even though the latter are definitely higher. The cost of the silicone casting, used to estimate the processing costs of both the SoG and the ADG Fresnel lenses, is taken from the bottom-up analysis presented in [3].

Table 5.3: Hypotheses regarding plastic injection cost estimation.

Injection mold	
<i>Injection mold, including optical inserts [€]</i>	5,800
<i>Number of injection</i>	500,000
Injection process	
<i>Injection machine cost [€/year]</i>	20,000
<i>Production [m²/year]</i>	16,000
<i>Operator cost [€/year]</i>	12,500
<i>Rigid lens thickness [cm]</i>	0.18
<i>PC density [gr/cm³]</i>	1.2
<i>Material losses (in injection process)</i>	10 %
<i>Material weight per lens [gr]</i>	3.8
<i>Injection process - TOTAL [€/W_p]</i>	0.050
Lamination	
<i>Lamination process [€/W_p]</i>	0.041

5.3 Energy prediction model

In this section, the annual energy yield of a CPV system including a parquet of ADG Fresnel lenses is estimated. The prediction is performed by using a simplified energy model, described below, which is particularly suited for CPV energy modeling. Also the annual energy yield of a module including SoG Fresnel lenses is estimated in order to allow the calculation of the potential economic benefit.

5.3.1 General model description

The model comprises two main steps. The objective of the first step is to determine the power of the CPV system or plant under analysis at reference conditions (CSOC: *concentrator standard operating conditions* defined in [4]), *i.e.*, the power rating of the single system or a whole plant. In our case, an elementary unit prototype (mono-module) is used to estimate the annual energy yield. Two mono-modules (one comprising an ADG Fresnel lens and one including a SoG Fresnel lens) have been continuously measured outdoors during four months (from June to October 2018) together with operating conditions (temperature, irradiance, spectral distribution of the direct normal irradiance (DNI), etc., see section 4.4.2). The measured data is filtered for measuring conditions similar to CSOC.

In the second step, the aim is to determine the influence of operating conditions, such as DNI and its spectral distribution, ambient temperature or wind, on the power delivered by the system. This leads to a model suitable to predict the peak power of the module as a function of the operating conditions, and consequently to predict the generated energy when power is integrated over time.

Finally, the energy harvested throughout the year is estimated using equation (5.1).

$$\begin{aligned}
 & \text{Annual energy generation} \\
 &= \left[\sum_{m=1}^{12} \left[\sum_{h=1}^{24} B_{d,m}(h) \cdot C_T(h) \cdot P_{CSOC} \cdot 1h \right] \cdot N_{sunny-days}(m) \right. \\
 & \quad \left. \cdot F_{spec}(m) \right] \cdot F_{tracking}(y) \cdot F_{soiling}(y) \cdot F_{others}(y)
 \end{aligned} \tag{5.1}$$

where:

- a. $B_{d,m}(h)$ is the hourly measured direct normal irradiation divided by the direct normal irradiation at CSOC conditions, *i.e.* 900 Wh/m^2 . $B_{d,m}(h)$ can be modeled starting from monthly DNI data available in databases such as the *Photovoltaic Geographical Information System* (PVGIS) from the Europe *Joint Research Center* (JRC);
- b. $C_T(h)$ is a coefficient taking into account the dependence of the module efficiency with the module temperature, which in turn depends on the ambient temperature. $C_T(h)$ can be extracted, for both modules ADG-based and SoG-based, from the outdoor measurements;
- c. P_{CSOC} is the system power in CSOC conditions, expressed in W . As well as the previous coefficient, P_{CSOC} can be extracted from outdoor measurement data;
- d. $N_{sunny-days}(m)$ is the monthly average number of clear-sky days. $N_{sunny-days}(m)$ can be calculated considering the daily irradiance profile calculated assuming that all the days are clear-sky and comparing that value with the total monthly radiance provided by PVGIS database;
- e. $F_{spec}(m)$ is a coefficient considering the losses due to spectral variations of the DNI in every month;
- f. $F_{tracking}(y)$ is a factor considering the losses due to tracking error in a year;
- g. $F_{soiling}(y)$ is a factor considering the losses due to soiling every year;
- h. $F_{others}(y)$ is a factor considering the losses due to any other possible sources each year.

Parameters a and b are calculated hourly and denominated intrinsic parameters. Parameter c is constant throughout the year as it only depends on the reference conditions, while parameters from d to h are estimated on a monthly or annual basis and denominated extrinsic parameters.

5.3.2 Description of the elementary unit

The two mono-modules prototypes used in this analysis, one including an ADG Fresnel lens and one including a SoG Fresnel lens are the same mono-modules whose characterization was described in section 4.4.2. They have been installed in a solar tracker at the Fraunhofer ISE facilities and have been under continuous measurement from June to October 2018. Both mono-modules have an aperture area of $40 \times 40 \text{ mm}^2$ and include a triple-junction (3J) solar cell with a diameter of 2.3 mm , which corresponds to a concentration of 385 suns . A detailed description of the outdoor characterization results is included in section 4.4.2.

5.3.3 Determination of DC power P_{CSOC} and temperature dependency

For the energy modeling described here, the necessary data are shown in table 5.4. These include the efficiency and the power generated by every mono-module at CSOC and the coefficients describing the efficiency variation as a function of temperature.

Table 5.4: Summary of the parameters extracted from the mono-modules outdoor characterization.

		SoG reference mono-module	ADG mono-module
P_{CSOC}	W	0.43	0.41
a_T	$\%/^{\circ}C$	0.066	0.036
b_T	$\%$	28.24	27.48
η_{CSOC}	$\%$	29.6	28.2

Coefficients a_T and b_T derive from the linear fitting obtained from the measurements data representing module efficiency as a function of ambient temperature (see equation (5.2)).

$$\eta_{module} = T_{amb} \cdot a_T + b_T. \quad (5.2)$$

Figures 5.1a and 5.1b show the efficiency of the two measured mono-modules as a function of the ambient temperature. Despite the lower efficiency value showed by the ADG-based mono-module at CSOC (29.6 % for SoG-based and 28.2 % for ADG based), the ADG mono-module shows clearly two advantages. First, the slope of the linear fitting (coefficient a_T in table 5.4) is lower, meaning that the system efficiency is less temperature-dependent. Second, for a constant temperature, the dispersion of the measured efficiency value is significantly reduced. This indicates that the efficiency of the ADG-based module is less impacted by other ambient conditions.

Figures 5.1c and 5.1d show the power delivered by the mono-modules as a function of the DNI. The P_{CSOC} results slightly higher for the SoG-based mono-modules, which fits with the slightly higher module efficiency shown in figures 5.1a and 5.1b.

5.3.4 Model of the ambient temperature $T_{amb}(h)$ and temperature coefficient $C_T(h)$

When using coefficients a_T and b_T to include the temperature dependency in the energy yield estimation of a CPV system, a hourly time series of ambient temperature for the representative day of every month is required. A methodology for estimating the average profiles of daily ambient temperature based in double-cosine methods as presented in the European Solar Radiation Atlas (ESRA) [5] is considered simple and valid enough for the proposed energy model. The only necessary data are a double monthly series of average temperatures of mean daily minimum and maximum temperatures. All the necessary data can be obtained from meteorological databases such as the one provided by the World Meteorological Organization (WMO) [6]. Table 5.5 reports all the required data for Madrid, Spain, together with the sunrise and sunset times.

As reported in [5], the aforementioned model assumes that the temperature daily profile $T(t)$ can be described using three piecewise functions (equation (5.3)), dividing the day into three periods: from midnight to sunrise (t_{dawn}), from t_{dawn} to the time of peak temperature (t_{peak}), and from t_{peak} to midnight.

$$T(t) = \begin{cases} T_m - T_a \cos(\pi(t_{dawn} - t)/(24 + t_{dawn} - t_{peak})) & 0 < t \leq t_{dawn} \\ T_m + T_a \cos(\pi(t_{peak} - t)/t_{peak} - t_{dawn})) & t_{dawn} < t \leq t_{peak} \\ T_m - T_a \cos(\pi(24 + t_{dawn} - t)/(24 + t_{dawn} - t_{peak})) & t_{peak} < t \leq 24 \end{cases} \quad (5.3)$$

where T_m is the average daily temperature obtained calculating the mean between maximum and minimum temperatures reported in table 5.5, and T_a is the half of the amplitude of daily

Figure 5.1: (a) Efficiency as a function of ambient temperature for the SoG reference mono-module. (b) Efficiency as a function of ambient temperature for the ADG mono-module. In both cases, the measurements have been filtered. Only values when DNI was between 850 W/m^2 and 950 W/m^2 and the SMR_{mid}^{top} , defined in chapter 3, was between 0.95 and 1.05 are included. (c) DC Power delivered by the mono-module as a function of the DNI for the SoG-based reference mono-module. (d) DC Power delivered by the mono-module as a function of the DNI for the ADG-based mono-module. In both cases, only measurements whose temperature was comprised between 15°C and 25°C and whose SMR_{mid}^{top} was comprised between 0.95 and 1.05 are included.

temperature variation.

$$\begin{aligned} T_m &= (T_{min} + T_{max})/2 \\ T_a &= (T_{max} - T_{min})/2. \end{aligned} \quad (5.4)$$

In figure 5.2 the twelve hourly series for the representative day of every month for Madrid is shown.

Knowing the hourly ambient temperature profile $T_{amb}(h)$, and the coefficients a_T and b_T describing the temperature dependency of a certain CPV system, it is possible to use equation (5.2) to compute the efficiency as a function of time for the typical day of the month.

Finally, the coefficient $C_T(h)$ is defined as follow:

$$C_T(h) = \frac{\eta_{real}(h)}{\eta_{CSOC}} = \frac{T_{amb}(h) \cdot a_T + b_T}{\eta_{CSOC}} \quad (5.5)$$

where $\eta_{real}(h)$ is the actual CPV module efficiency at a specific time and calculated using equation (5.2), and η_{CSOC} is the efficiency at CSOC conditions extracted from outdoor measurements and reported in table 5.4.

Table 5.5: Monthly ambient temperature values for Madrid.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
<i>Mean daily minimum temp</i> [°C]	2.7	3.7	6.2	7.7	11.3	16.1	19	18.8	15.4	10.7	6.2	3.6
<i>Mean daily maximum temp</i> [°C]	9.8	12	16.3	18.2	22.2	28.2	32.1	31.3	26.4	19.4	13.5	10
<i>Sunrise</i> [hh:mm]	08:35	08:08	07:26	06:36	05:58	05:44	05:57	06:25	06:55	07:25	08:00	08:30
<i>Sunset</i> [hh:mm]	18:12	18:49	19:21	19:53	20:24	20:46	20:43	20:12	19:23	18:35	17:57	17:49

Figure 5.2: Ambient temperature hourly model for the representative day of every month.

5.3.5 Model of hourly measured direct normal irradiation $B_{d,m}(h)$ and number of sunny days $N_{sunny-days}(m)$

Modeling of solar radiation is crucial to forecast the energy produced by a solar system, including CPV plants. Radiation models need some place-representative values to generate the irradiation series, and the resolution of these values is dependent on the frequency of the desired series.

The most accurate method to predict the energy yield of a PV system is based on the use of the typical meteorological year (TMY), which is a collation of selected weather data for a specific location, listing hourly values of solar radiation and meteorological elements for a period of one year. Since the values are generated from a data bank much longer than a year in duration, their annual averages are consistent with the long-term averages for the considered location. Therefore, using TMY, it is possible to accurately model hourly energy generation of a certain power plant. The main limitation of this approach is the need of hourly data of all the other parameters involved in the model, such as ambient temperature or spectral conditions. Such approach, even if possible, is unnecessarily complicated. In fact, if the model is intended to forecast the energy production of a CPV system during an annual period, the most convenient is to use just mean monthly irradiance

values to estimate the final production [7] with errors below 3 %.

Therefore, the first step of the model development consists in the definition of the hourly irradiance value for the *typical day of the month*, that will be used to forecast the energy harvesting for every month of the year. Summing the energy production calculated individually for each month of the year gives the annual energy yield.

For what concern CPV systems, that work at medium or high level of concentration, only direct radiation should be considered. Records of DNI solar radiation are scarce all around the world (the need of a solar tracker has limited the availability and the reliability of direct irradiance data), while the global horizontal irradiation ($G_{dm}(0)$) data is widely known. Several models are known in the literature for obtaining the direct radiation ($B(0)$) from $G_{dm}(0)$ data [8–10]. From horizontal direct values ($B(0)$) the DNI (B_{dm}) can be obtained knowing the solar elevation.

Most of these methods distribute the monthly average energy along the typical day assuming that every day of the month is equal and that irradiance extends between sunrise and sunset. These approaches do not take into account that direct irradiance over a month is actually divided in clear-sky days, with a high and roughly constant DNI distribution, and cloudy days, where the direct irradiance is quasi-zero. The integration of the daily DNI distribution over a certain month must fit with the total irradiation recorded for the same month in databases such as PVGIS, therefore, if all the days of a month are considered clear-sky days, the average daily irradiance must be low enough to ensure that its integration over the month do not exceed the total measured for such month.

Figure 5.3: (a) Daily evolution of the DNI measured and modeled according to *classic models*. (b) DNI daily evolution according to the proposed trapezoidal model.

This approach results in the situation depicted in figure 5.3a, where a comparison between the measured irradiance and the irradiance estimated using classic models for a typical day of December in Madrid is shown. It is clear how the obtained distribution is far from the measured conditions. Even if the total of monthly irradiation sums the original statistical data, the model clearly can not reproduce the real profile of DNI. For CPV systems, since the efficiency and temperature of the cell depend on the irradiance, considering a constant low irradiance leads to unbearable errors. Looking at figure 5.3a it is possible to notice how the cell temperature estimated using one of the aforementioned models can be up to 24 °C below the measured value. Therefore, in order to consider realistic daily irradiance values, without overestimating the energy total of a certain month, it is convenient to introduce the concept of *sunny days* and *cloudy days* (with a DNI equal to zero).

Monthly and yearly DNI radiation data are available from several sources such as PVGIS. These sources provide radiation series of DNI and $B(0)$ for developing a model of direct irradiance valid to predict the production of CPV systems anywhere. The data available are usually the average monthly energy incident per square meter (Wh/m^2 in a month) or energy per m^2 on an average day of the month.

The followed approach consists in modeling the direct radiation profile with a trapezoidal distribution that resembles the typical clear-day profile of direct radiation (see figure 5.3b). Other more complicate models that match better the real profile are also possible, but they are not expected to improve notably the accuracy of the final forecast. The base of the trapezoid is equal to the length of the daylight in hours (from sunrise to sunset) and the top is the previous length minus the time needed by the sun to reach the sunrise and the sunset (estimated in 4 hours). The top level is constant during the day and the value is estimated to be equal to the DNI for the typical day of a given month and place reported in meteorological databases.

Obviously, a representative month is composed of sunny and cloudy days. This proportion is defined by the monthly energy expected according to the irradiation databases ($B_{dm,database}$). Therefore, in order to match the energy that is predicted each month by the model, the total cumulated energy reported in the database for a certain month must be divided by the total cumulated energy $B_{dm,model}$ predicted by the model as all the days of the month were sunny.

$$N_{sunny\ days} = \frac{B_{dm,database}^i}{B_{dm,model}^i} \quad (5.6)$$

where superscript i refers to the month of the year. In this way, the amount of cloudy days required in order to have $B_{dm,database} = B_{dm,model}$ is obtained. The number of sunny days in Madrid of each month of the year calculated using this method is reported in table 5.6.

Table 5.6: Number of sunny days in Madrid of each month of the year obtained using the trapezoid model.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
<i>Number of sunny days</i>	19	18	18	20	21	24	28	26	23	22	19	18

The described simplified model have been used by the research team at IES-UPM to model the energy yield of a CPV power plant sited in Villa de Don Fabrique, a village in Castilla de la Mancha region, in Spain at 125 km in the south of Madrid. The CPV technology is based on a two stage optical system working at 820 suns, consisting of a dome-shaped Fresnel lenses made of PMMA as primary optics, and an inverted truncated pyramid made of glass as secondary optics, which focuses light on 3J lattice matched GaInP-InGaAs-Ge solar cells.

The total energy collected from the plant is equal to 101,968 kWh and the forecast energy according to the model is 104,501 kWh. Therefore, the overestimation resulting from the model is only equal to 2.48 %, validating the described forecast method.

5.3.6 Determination of extrinsic parameters

Besides the intrinsic parameters directly related to the properties of selar cells, optical and thermal properties of the mono-module, there are other parameters, that are denominated extrinsic parameters, and which also reduce the annual energy harvested by a CPV system. The values of the extrinsic parameters are estimated on monthly or annual basis.

Spectral factor (F_{spec}). The sensitivity of the 3J solar cells to the spectral distribution of the incident irradiance is well known: the photocurrent produced by a 3J cell is reduced when the spectrum of the incident light differs from the reference spectrum [11]. Generally, the top subcell limits the current produced by the device at the beginning and at the end of the day and the middle subcell limits the current in between. However, despite this clear trend, different day lengths, the different elevation of the sun in every month (measured through the air mass parameter), and the

random presence of aerosols and precipitable water make impossible to establish hourly models for the spectral factor.

An alternative approach consists in estimating the spectral influence by using the quantum efficiencies (QE) of the subcells in a 3J cell and synthetic spectra generated with radiometric models such as SMARTS [12] fed with atmospheric parameters (aerosols and precipitable water) from sources as AERONET [13], that content annual data from more than 700 sites worldwide. This is the approach followed by the research team at the IES-UPM to determine $F_{spec}(m)$ for the energy prediction of the CPV plant at La Villa de Don Fabrique. The same values have been used here relying upon the fact that the location of the CPV plant is very close to Madrid, therefore no significant changes in the spectral conditions are expected. The values for every month are shown in table 5.7. A value $F_{spec} = 1$ corresponds to the optimum spectral condition, which coincides with the reference spectrum (AM1.5D). Any change in the spectrum results in efficiency losses and, consequently, in a lower F_{spec} .

Table 5.7: Monthly calculated spectral factor.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
F_{spec}	0.91	0.93	0.94	0.96	0.96	0.96	0.96	0.96	0.96	0.97	0.95	0.91

It is worth to notice that this kind of approach does not take into consideration the effect of the optics, which changes the light distribution over the solar cell surface. In the case of a system based on conventional SoG Fresnel lenses, even without including the optics, the estimation of F_{spec} results in realistic values. In fact, the transmission of the SoG lenses is quite similar in the top range, *i.e.*, 350 – 660 nm, and in the middle range, *i.e.*, 660 – 900 nm, meaning that the ratio between the radiant power in the top and middle ranges entering the lens aperture is similar to the ratio between the radiant power in the top and middle ranges reaching the solar cell. Conversely, the ADG lenses have a much higher absorption in the top range, which results in an unbalanced spectral transmission in the top and middle regions. Therefore, for the ADG lens, the reference spectrum (AM1.5D) is not necessarily coincident with the optimum spectrum. In addition, because of the high absorption in the UV region, ADG lenses tend to be top-limited also when the spectrum is blue-rich, with obvious advantages from the point of view of the spectral losses. To summarize, including the behavior of the ADG optics in the estimation of F_{spec} would lead to higher values than the calculated. For the energy model included in this thesis, since such calculations have not been carried out, the same values are used for both the SoG-based module and the ADG-based module, even if for the latter it results in an underestimation of the system performances.

Tracking factor ($F_{tracking}$). This parameter includes the losses due to the percentage of time that the array is not perfectly oriented towards the sun. Since information on the tracking errors throughout the year is scarce and difficult to assess because of the lack of standards [14, 15], such factor needs to be estimated based on previous field experience of the researcher at IES-UPM. Generally, the algorithms controlling modern tracking systems are able to follow the sun with a good accuracy. The tracking errors most of the times are caused by the wind speed that, when it is high enough, could bend the whole tracking structure. Furthermore, the control system is usually programmed to move the tracker in stow position when the wind speed achieves a previously set-up threshold value. Different configurations of the control system are possible, however, the most common consists in an algorithm programmed to move the tracker in stow position if the wind speed remains higher than the threshold during one fixed lapse of time, and to stay in such position until the wind speed is under the threshold for a time usually slightly longer than the previous [16].

For the energy prediction model presented in this thesis, the tracking factor previously calculated by the researchers at IES-UPM for the CPV plant of La Villa de Don Fabrique is used. This plant was already introduced in section 5.3.5 to validate the simplified model. Since La Villa de Don

Fabrique is only 125 *km* from Madrid, it seems reasonable to assume the same tracking accuracy. In this context, taking into account the described algorithm, a threshold speed of 10 *m/s* and the wind record of La Villa de Don Fabrique, the tracking factor calculated was equal to 99.6 %.

Soiling factor ($F_{soiling}$). Either thanks to the rain or by cleaning the modules, CPV system are usually kept close to their rated output value. Based on the literature [17] we have assumed a soiling factor of 0.96.

Others factor (F_{others}). An additional factor that includes all the losses such as inverter, cables, and mismatch has been considered equal to 90 %.

5.3.7 Results

Based on the described model, the estimated annual energy production predicted is equal to 884 *Wh* for the SoG-based module and 844 *Wh* for the ADG-based module. This means that, assuming the same environmental conditions and at the same concentration, the energy yield of an ADG-based system would be 5 % lower than the yield of a system based on SoG.

It is important to notice that, as already described in section 2.6.4, ray-tracing simulations showed that, substituting the conventional SoG Fresnel lens with ADG Fresnel lens it is possible to increase the concentration without additional efficiency losses. In view of the above, the estimation of the annual energy yields has been repeated for a concentration factor equal to 800 *suns*. For this concentration it is known from ray-tracing simulation that the ADG efficiency is going to be higher and this effect is included by applying a correction factor to equation (5.1).

5.3.8 High concentration scenario: 800 *suns*

The experimental results achieved in the project for the ADG lenses are limited by the manufacturing optical errors of the prototypes developed at the laboratory. In order to predict the energy yield of the ADG lens at higher concentration, data from ray-tracing simulations will be used. Figure 2.22 in section 2.6.4 (shown again here for the sake of clarity) shows the encircled energy as a function of the receiver radius for both an ADG Fresnel lens and an SoG Fresnel lens. The materials absorption and reflection losses are also taken into account in the simulations.

In this case, when the concentration is equal to 385 *suns* (measurements conditions) the ADG Fresnel lens optical efficiency is equal to its maximum (82.0 %) and the SoG Fresnel lens is equal to the 98.2 % of its maximum (88.5 %). At 800 *suns*, the optical efficiency of the ADG lens only decreases to the 98.4 % of its maximum while the SoG optical efficiency drops down to 86.9 % of its maximum. Therefore, for both lenses the efficiency reduction affects at the same time the cost per W_p (lower efficiency translates in less W_p for each module) and the annual energy yield (lower efficiency translates in lower P_{DC} and reduced energy generation). In order to apply this correction on both systems all the costs expressed in €/ W_p have been divided by 98.4 % and 86.9 % for the SoG module and the ADG module respectively. Analogously, the total energy yield expressed in *Wh/year/module* has been multiplied by 98.4 % and 86.9 % for the SoG module and the ADG module respectively. Summarizing, for the 800 *suns* scenario the estimated production costs are equal to 0.129 €/ W_p for the SoG-based module and 0.094 €/ W_p for the ADG-based, whereas the estimated energy harvesting is 768 *Wh/year/module* for the SoG-based system and 831 *Wh/year/module* for the ADG based system.

Again, in the costs estimation for the high concentration scenario, a worst-case has been considered. In fact, in the former analysis, the temperature coefficient used to calculate the annual energy yield at 800 *suns* is the same as it is at 385 *suns*. In the reality, as shown in figure 2.26, the

Figure 5.4: Encircled energy as a function of the receiver radius (concentration). The two dashed lines represent the maximum attainable concentration of both lenses, the SoG and the ADG.

ADG temperature coefficient is much more constant than the SoG. Therefore, if the temperature effect was included, the energy harvested by the SoG-based module would further decrease making even more advantageous the use of the ADG optics.

5.4 Final comparison SoG vs. ADG system

The results obtained through the analysis exposed in the previous sections are gathered to estimate the contribution of the lens costs to the *levelized cost of energy* (LCOE) as a function of the generated energy.

The LCOE is calculated using equations (5.7):

$$\text{LCOE} = \frac{\sum_{n=0}^{n_s} \frac{c_n}{(1+d)^n}}{\sum_{n=0}^{n_s} \frac{e_n}{(1+d)^n}}$$

$$c_n = \begin{cases} c_{\text{capital}} & n = 0 \\ 0 & n > 0 \end{cases} \quad (5.7)$$

$$e_n = \begin{cases} 0 & n = 0 \\ \max[Y(1 - R_d)^{(n-1)}, 0] & n > 0 \end{cases}$$

where c_n is the cost in year n , d is the discount rate, e_n is the energy produced in year n , n_s is the lifespan of the plant, c_{capital} the initial capital cost, Y is the first year energy yield and R_d is the system's annual degradation rate. Note that in the conventional LCOE calculation carried out

considering the whole system, the cost contributions when $n > 0$ is assumed to be equal to the operation and maintenance (O&M) costs. In this case, since the aim is to assess the contribution to the LCOE only of the lens excluding the influence of the rest of the system, such cost have been considered equal to zero.

Table 5.8: Summary of the cost analysis.

	SoG				ADG			
	385X		800X		385X		800X	
<i>Material cost</i> [€/W _p]	0.071		0.081		0.034		0.034	
<i>Processing cost</i> [€/W _p]	0.041		0.048		0.059		0.059	
<i>Total lens cost</i> [€/W _p]	0.112		0.129		0.092		0.094	
<i>Annual energy yield</i> [Wh/year/module]	884		768		844		831	
<i>Annual energy yield</i> [Wh/year/W _p]	1800		1800		1802		1802	
<i>Mono-module power</i> [W _p]	0.49		0.43		0.47		0.46	
<i>Lifespan of the plant</i> [years]	25		25		25		25	
<i>Degradation rate</i>	0.2 %		0.2 %		0.2 %		0.2 %	
<i>Discount rate</i>	4 %	7 %	4 %	7 %	4 %	7 %	4 %	7 %
<i>Contribution of the lens cost to the LCOE</i> [€/MWh]	4.1	5.5	4.8	6.3	3.4	4.5	3.5	4.6

Table 5.8 shows a summary of costs and predicted energy generation with both systems at the real concentration factor (385 *suns*) and at the hypothetical scenario corresponding to a concentration of 800 *suns*. To calculate the contribution of the lens cost to the LCOE a degradation rate of 0.2 % has been assumed [18] for both modules. Conversely, for the discount rate two different scenarios have been assumed: the first uses the optimistic value of 4 %, reasonable assumption for a well-established technology such as flat silicon PV. The second scenario takes into account that, being the CPV technology more recent and less developed than conventional PV, it does not get access to the same financing conditions. Therefore, for this more realistic scenario, the conservative value of 7 % has been used [18].

In every simulated scenario, thanks to the cheaper materials and to the simple and cost-effective manufacturing process, there is a significant economic saving in the ADG-based system. Considering the discount rate of 4 %, for the 385 *suns* scenario the contribution to the LCOE is 3.4 €/MWh for the ADG-based module and 4.1 €/MWh for the SoG-based module, meaning that, substituting conventional SoG Fresnel lenses with novel ADG lenses, leads to a reduction of the contribution to the electricity cost of 17 %. Furthermore, considering the 800 *suns* scenario, the benefit is even higher thanks to the enhanced concentration capability of the ADG Fresnel lenses. In this case, the cost reduction is equal to 27 %. Then, for the conservative scenario corresponding to a discount rate of 7 %, the contribution to the LCOE calculated for the 385 *suns* scenario is equal to 4.5 €/MWh and 5.5 €/MWh for the ADG lens and the SoG lens, respectively. Obviously, also in this case, the economic saving is even higher for the 800 *suns* scenario, where the contribution to the LCOE is equal to 4.6 €/MWh for the ADG lens and 6.3 €/MWh for the SoG lens. Lastly, it is worth to notice that, in all cases, the contribution is higher for the 800 *suns* scenario. This was expected because of the efficiency decrease of both lenses due to the high concentration. Nevertheless, the

costs exposed in this section only considers the contribution of the lens excluding the solar cells price from the calculation. Therefore, despite the higher contribution, in the 800 *suns* scenario the cell costs would reduce to approximately the half, resulting in a reduction of the LCOE of the whole CPV system.

Finally, the ADG technology did not achieved its maximum potential. Taking into account all the improvements to the lens performance that could be achieved with an industrial up-scale of the manufacturing process, which leads to an absolute optical efficiency of the lens 3 – 4 % higher than the real conditions, the economic benefit achieved would be approximately 2 % higher. To conclude, it is worth to point out that the application of this technology on different fields, such as micro-CPV, where a simple aspheric profile without grooves can be used, could avoid the additional geometrical losses making ADG lenses even more profitable.

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Chapter 6

CONCLUSIONS

The main objective of this thesis was the design, manufacturing, and characterization of a novel cost-effective achromatic Fresnel lens for CPV applications. In the context of this work, several conclusions have been deduced.

ADG Fresnel lens optical design

The ADG lens profile is defined by using basic principles of geometrical optics such as the Snell's law or the Fermat principle. Later, a comprehensive set of ray-tracing simulations has been carried out in order to evaluate the effectiveness of the developed design as well as its sensibility to parameters such as the f-number or the manufacturing constraints such as draft angles and tips rounding. Generally, the achromatic design resulted to be very promising, allowing a concentration factor more than two times bigger than the one simulated for a conventional silicone on glass (SoG) Fresnel lens. Unfortunately, due to the properties of the pair of material selected and to the selected configuration for the doublet (diverging lens facing the sun and converging lens toward the receiver), the efficiency transmission of the ADG lens is only the 92.6 % of the SoG efficiency (95.1 % including a slightly improved geometry and optimized materials formulations that have not been available along the thesis). Therefore, the ADG lens is actually better only starting from a concentration factor of about 623 *suns*. Despite this limitation, the achromatic behavior of the ADG lens provides other relevant advantages such as a reduced temperature dependency and an improved spectral distribution of the light over the receiver. Finally, it is worth to notice that the disclosed efficiency numbers are strictly related to the current pair of materials and to the lens structure. With alternative materials, the reverse configuration (converging lens facing the sun and diverging lens toward the receiver) would be possible and the losses due to the rays lost on the perimeter or on the draft facets (approximately 3 % of absolute efficiency) could be almost completely avoided. In addition, a different pair of materials could also reduce the absorption losses.

Two different designs have been developed: in the first, the facets of the Fresnel grooves are flat, resulting in a lower concentrating power. Conversely, in the second, the facets are curved allowing a higher concentration. The drawback of the curved facets design is the more difficult injection of the plastic parts, which resulted in higher tips rounding if compared with the flat facets. Nevertheless, it is worthy to have slightly higher geometrical losses in exchange to a significant improvement of the concentration factor (from ~ 700 *suns* to ~ 1400 *suns* from ray-tracing simulation, and from 242 *suns* to 326 *suns* from experimental results).

Material investigation

At the beginning of the thesis, the number of materials available in the market was scarce. Therefore the final choice, consisting in a thermoplastic elastomer (TPE) as a low dispersion

material, and polycarbonate (PC) as a high dispersion material, was taken based on a trade-off between the required optical properties to achieve the achromatism and the compatibility with the envisaged manufacturing process. The main limitation of the current pair of material is the high absorption of the TPE in the UV region. On one side, it protects the PC from harmful UV radiation, but, on the other side, it blocks useful light that could be converted into electricity, reducing the optical efficiency of the lens. Ray-tracing simulation predicted that, using a TPE with high transmission in the UV region, the global absorption losses would reduce from 3 % to approximately 1.5 %. Obviously, in this case, additional investigation on the reliability of the PC is required in order to avoid the yellowing caused by UV radiation. To conclude, it is worth to remark that, recently, several new materials (or new formulations of the same materials) have been developed, widening the number of possible candidates. Alternative materials could open the door to different ADG structures and alternative pairs of materials that, despite they have not been deeply studied in this work, have the potential to significantly improve the overall ADG performances.

Characterization methods and equipment

Thanks to previous work of the ISI group, the IES facilities already counted on two commercial solar simulators. One of them designed in order to characterize solar cell under concentrated light, whereas the second intended to measure optics or complete CPV modules including optics. The methods used to assess both the optical efficiency and diameter of the irradiance spot cast by a lens was already described in previous publications of the ISI group. Within this thesis, the *relative optical efficiency*, defined as the ratio between the absolute optical efficiency of the lens to be measured and the absolute optical efficiency of a reference optics, was introduced as an alternative figure of merit for the evaluation of the ADG performance. It has been proved that the relative optical efficiency reduces the measurement error and allows to reliably compare measurements carried out under very different external conditions. Furthermore, two different methods for measuring the diameter of the irradiance spot have been deeply investigated. Despite both of them are more sensitive to external conditions than the efficiency measurements, using a CCD camera coupled with an objective to take photographs of a lambertian diffuser on which the concentrated spot is focused on, has been found to be reliable within the measurement error of approximately 10 %. Two important remarks must be pointed out when measuring the size of the irradiance spot: firstly, the percentage of transmitted light which defines the spot size must be always declared together with the diameter value. Secondly, since it has been discovered that the measurement results are dependent on the specific CCD camera used, it is advisable to always compare measurement performed using the same CCD camera and the same objective.

In addition, the methods described have been adapted to individually measure every lens of a parquet composed of many lenses. This is done by means of a three-axes automated moving platform, which is used to move either the solar cell or the set composed of the CCD camera and the diffuser in front of every lens of the array one by one. Thanks to this implementation, it is possible to use the same sensor, be it the solar cell for the efficiency measurement or the diffuser for the irradiance spot measurement, to measure every lens composing the array avoiding the influence of the receiver on the results. Also, since the use of the automated moving platform makes unnecessary to move the array throughout the measurement, possible alignment errors are avoided.

Furthermore, a thermal chamber has been designed and manufactured in order to be able to precisely control the temperature of the optics during the measurement. The implemented thermally regulated space has been very useful in the evaluation of the thermal sensitivity of the ADG lenses. Thanks to the thermal chamber, it is possible to maintain the optics at a certain temperature without affecting the solar cell used as a receiver. In this way, the analysis of the thermal sensitivity of the optics can be isolated from the effects caused by the thermal sensitivity of the solar cell, which are known to be not negligible.

ADG Fresnel lens manufacturing process

The manufacturing process of the ADG Fresnel lenses consists in the prior fabrication of the plastic bi-Fresnel lens, which is done by plastic injection (even though alternative methods such as compression molding or hot embossing could be used), and its successive lamination on a glass substrate by means of an elastomeric material. During the lamination, the elastomer acts as a glue to keep together the glass and the plastic, while the last acts as a mold to shape the elastomer in one of the lenses composing the doublet. Several companies have been contacted in order to investigate the cost and the constraints of the plastic injection. The chosen company was at the same time one of the cheaper and one of the most experienced in molding optical components. Conversely, the lamination step is completely carried out at the IES-UPM laboratory, where two laminator machines have been built ad-hoc for this purpose. The laminator 1.0 was used to successfully laminate the first elementary units, and to deeply investigate the lamination process and its possible optimization by controlling its parameters such as processing temperature and time. Conversely, the laminator 2.0 is bigger in size, in order to permit the lamination of big arrays composed of many lenses, and completely automated thanks to the implementation of a self-developed automaton through which the optimized parameters can be set a priori and no human intervention is needed, beside to put the sample inside the machine. The update from the laminator 1.0 to the 2.0 provided a repetitive and highly reliable procedure similar to the one that would be used in mass production industry.

ADG Fresnel lens characterization results

Three different generations of ADG lenses have been manufactured and tested trying to continuously improve their performance. The relative optical efficiency measured grew from 85.5 % for the first generation up to 89.4 % for the third generation. Taking into account that, for the current pair of material and design, the maximum theoretical value predicted by ray-tracing is equal to 92.0%, the ADG technology is very close to its limit. From the point of view of the attainable concentration, despite from the first to the third generation the measured spot diameter reduced from 2.9 mm to 2.5 mm, is still far away from the theoretical value of 1.2 mm. This is caused by several reasons that should be further investigated in the future. To summarize, the most probable hypotheses raised are optical errors due to either the injection of the plastic pieces or to the lamination process. Such kind of errors could result in a lens profile different from the designed and/or into a poor surface finishing (high waviness and roughness) which scatters the transmitted light.

Also the characterization of the array composed of 10x5 lenses gave promising results. Despite the limitation imposed by the handmade manufacturing process, which results in a high dispersion of the efficiency and spot size measured for the lenses of the array, the relative average efficiency measured for the array composed of third generation ADG lenses is 87.7 %, while the average spot diameter 2.7 mm. This means that, laminating arrays composed of many lenses instead of an elementary unit results in a limited performance loss. There are mainly two reasons worsening the functioning of the array: first, gluing manually together the individual sublenses introduces alignment errors and possible leakage of the glue inside the Fresnel grooves. Second, the lamination force might not be uniform in the border of the array, making the external lenses to be "bad laminated". The first is easily resolvable by manufacturing a mold capable of injecting all the plastic parquet of sublenses in a single injection, removing the necessity of gluing together single lenses prior to the lamination. The second would probably be solved by using a larger laminator in order to move the border effect to non-active zones of the laminator. Nevertheless, further investigation is required.

Finally, in the last month of the thesis, two complete CPV modules have been assembled and measured outdoors at the Fraunhofer ISE facilities for more than four months. One of them is a mono-module, composed of one ADG lens of the third generation and one high-efficiency 3J solar cell with a diameter of 2.3 mm, whereas the other is a full area module composed of 10x5

lenses and as many solar cells of the same type and size than the mono-module. On one side, at mono-module level, the results are remarkable. The global module efficiency measured is almost equal to the one measured for a reference mono-module including a conventional SoG Fresnel lens. Furthermore, the reduced dependency on temperature and spectrum provided by the achromatic design has been clearly proved. Therefore, since the lower efficiency is partially compensated by the improved stability, the annual energy yield is expected to be similar. On the other side, the high dispersion measured for the lenses of the array composed of 10x5 lenses has a detrimental effect on the performance of the full area module. In this case, both efficiency and stability are much lower than for the mono-module. Nevertheless, as already mentioned, an industrial process able to inject the whole parquet with a single injection would probably significantly improve the results.

Cost analysis

The last chapter of the thesis, where the model used and the assumption taken in order to assess the costs of the ADG technology are described, the contribution of the lens cost the LCOE is calculated for both an ADG mono-module and an SoG mono-module used as a benchmark. Two different scenarios have been simulated: the first corresponds to the real module assembled and measured, whereas the second to the hypothetical high concentration scenario of 800 *suns*. In both cases, the use of the ADG lens results in a significant reduction of the LCOE contribution. In addition, for the high concentration scenario, where the optimistic data obtained from ray-tracing have been used, the financial saving is even higher.

ADG Frensel lens potential up-scale

Throughout the work of this thesis, the ADG technology has been brought from the concept to a technology readiness level (TRL) 5, which corresponds to a technology validated within a relevant industrial environment. This involved not only the identification of materials and processes, but also the development of the manufacturing equipment. Consequently, the achieved results should be scaled to the potential of the technology at an industrial level. Despite the limitations found within the project, some of the achieved results are outstanding. The achromatic behavior of the ADG lens has been clearly proved as well as its lower dependency with operating conditions, *i.e.* spectrum and temperature (see section 4.3.1), which translates into an improvement in the energy production of a CPV system. The optical efficiency of the ADG lenses reached about 96 – 97 % of their potential for the current materials and lens size, and draft angles and tips rounding in the Fresnel facets. However, there is still a significant room for improvement. It must be pointed out the high impact of the manufacturing process (shape, waviness and roughness errors) in the final optical efficiency. In addition, this also caused that the manufactured ADG lenses exhibited a lower optical efficiency at 800 *suns* (about 83 % relative to SoG), when ADG has a much superior potential.

Ray tracing simulations with the current design and manufacturing constraints predicted a relative efficiency equal to 92 %, while the current experimental value for the third ADG lens generation is 89.4 %. Hence, it seems reasonable to consider that the $\sim 1 - 2$ % losses caused by manufacturing errors could be recovered with further developments and industrial scaling-up. Furthermore, the improved manufacturing process might reduce optical errors (better surface finishing resulting in reduced surface scattering) that, in CPV optics, widens the focused light spot, limiting the maximum attainable concentration. In fact, while from the efficiency point of view the experimental results are close enough to the values predicted by ray tracing, it is far from its potential from the point of view of the maximum attainable concentration. Ray tracing predicted a minimum spot size for the curved facets design (second and third ADG generation) equal to 1.2 *mm*, while the measured value is 2.5 *mm*. Since the achromaticism of the ADG prototypes has been experimentally proved, most likely the wider light spot can be ascribed to the aforementioned optical errors. As a consequence, it is reasonable to think that an improved manufacturing process could slightly improve the lens optical efficiency and significantly reduce the light spot size, making

realistic the assumptions made in section 5.3.8 estimating the costs of the technology for the high concentration scenario.

Apart from the limitations imposed by the manufacturing process, a second limitation in the optical efficiency identified for the ADG lenses is related to a lower transmission in the UV part of the spectrum (see sections 2.5 and 2.6.4), which limits the photocurrent generated in the top subcell and consequently the optical efficiency for MJ solar cell. This limitation is caused by the materials selected: a TPE compatible with the PC. Despite this limitation is hard to overcome, the ADG lenses were developed based on off-the-shelf components. A tailored chemical composition of both materials would improve such transmission. Unfortunately, such developments were unattainable in the frame of the thesis. Ideal materials (100 % of light transmission) would allow an absolute efficiency increase of about 3 %, but the practical potential, considering only a reduced absorption in the UV region would be limited to $\sim 1.5 - 1.6$ %.

A third avoidable factor limiting the efficiency is caused by the high geometrical losses in the injected PC pieces, caused by higher tips rounding in the lens facets compared to SoG lenses ($3 \mu\text{m}$ for SoG, $5 \mu\text{m}$ for ADG), which causes an absolute efficiency loss of 2.1 %. Passing from tips rounding of $5 \mu\text{m}$ to tips rounding of $3 \mu\text{m}$ it is possible to increase the absolute efficiency by ~ 1.1 %. A detailed disclosure over the influence of manufacturing errors on ADG lens performance can be found in section 2.6.9.

Therefore, taking into account all the potential improvements described here, the absolute optical efficiency of ADG Fresnel lens could increase of ~ 3.6 % leading to the absolute value of 85.6 % (96.5 % relative).

List of Publications

G. Vallerotto, M. Victoria, S. Askins, I. Antón, and G. Sala, "Improvements in the manufacturing process of achromatic doublet on glass (ADG) Fresnel lens," in *AIP Conference Proceedings*, vol. 1812, p. 030009, Sept. 2018.

M. Victoria, C. Domínguez, N. Jost, G. Vallerotto, I. Antón, and G. Sala, "Spectrally-resolved optical efficiency using a multi-junction cell as light sensor: Application cases," *AIP Conference Proceedings*, vol. 1881, p. 030011, Sept. 2017.

G. Vallerotto, M. Victoria, S. Askins, I. Antón, and G. Sala, "Experimental characterization of achromatic doublet on glass (ADG) Fresnel lenses," *AIP Conference Proceedings*, vol. 1881, p. 030010, Sept. 2017.

G. Vallerotto, M. Victoria, S. Askins, I. Antón, G. Sala, R. Herrero, and C. Domínguez, "Indoor Experimental Assessment of the Efficiency and Irradiance Spot of the Achromatic Doublet on Glass (ADG) Fresnel Lens for Concentrating Photovoltaics," *Journal of Visualized Experiments*, Oct. 2017.

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LIST OF PUBLICATIONS