

UNIVERSIDAD POLITÉCNICA DE MADRID
Escuela Técnica Superior de Ingenieros de Telecomunicación



Light Manipulation with Reconfigurable Phase-Only Devices

DOCTORAL THESIS

Submitted for the degree of Doctor by:

Javier Pereiro García

Máster Universitario en Ingeniería de Telecomunicación

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**Doctoral Degree in Communications Technologies and
Systems**

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Abstract

In the past five decades, light-based technologies based have caused increasing interest due to their applications in various sectors such as medicine, optical communications, and microfabrication. Optical systems are becoming increasingly complex, needing tunable parts.

One of the most used materials for creating these devices are liquid crystals due to their electro-optical properties: they are birefringent and can be reconfigured under an external electric field, making them optimal candidates for reconfigurable phase devices without moving parts.

This thesis encompasses the design, manufacturing, and characterization of three different kinds of reconfigurable optical devices. All the processes have been carried out at the Centro de Materiales y Dispositivos Avanzados para las TICs (CEMDATIC) research center of the Universidad Politécnica de Madrid. Additionally, the employed driving electronics have also been developed and characterized.

The first device is a tunable optical vortex beam generator, known as a spiral phase plate. Optical vortex beams are light beams with a helical wavefront, defined by a parameter called topological charge (l). These beams are characterized by having a phase singularity and their ability to transfer orbital angular momentum. Because of these two features, vortex beams have generated significant interest in sectors such as optical manipulation and communications. The developed device consists of 72 independently addressable pie-slice shaped pixels, enabling the generation of optical vortices with 72 different topological charges, 36 positives and 36 negatives. Furthermore, its ability to generate optical vortices with arbitrary fractional charges has been demonstrated. Lastly, these devices have been used to generate perfect vortex beams, vortex beams whose radial power distribution is independent of their topological charge.

The second device presented is a reconfigurable spiral axicon. Traditionally, axicons are glass or polymer cones that focus light along a line rather than a point, making them particularly useful in laser fabrication and metrology. The designed flat device includes 24 spiral-shaped electrodes, capable of emulating 12 positive and 12 negative different focus depths with a single device. Moreover, it has been shown that this axicon can generate perfect vortex beams when used in combination with a conventional converging lens.

The third device is a tunable spiral lens. These lenses are composed of 72 electrodes allowing the focal length to be electronically adjusted, offering 36 convergent and 36 divergent configurations. Different types of lenses with diameters ranging from 0.5" to 1" and various base focal lengths have been developed. Additionally, a strategy to minimize chromatic aberration through dynamic tuning is proposed. The influence of these lenses inherent optical vortices has been characterized, and techniques to correct their topological charge have been demonstrated. Finally, the use of these lenses in a zoom system has been presented, demonstrating its ability to reduce and magnify objects.

Resumen

En las últimas cinco décadas, las tecnologías basadas en la utilización de la luz han captado un interés creciente debido a sus aplicaciones en diversos sectores como la medicina, las comunicaciones y la microfabricación. Los sistemas ópticos contemporáneos son cada vez más complejos, poniendo de relieve la necesidad de desarrollar dispositivos ópticos sintonizables sin partes móviles.

Una de las familias de materiales más utilizada para la realización de estos dispositivos son los cristales líquidos debido a sus propiedades electroópticas: son birrefringentes y pueden ser reconfigurados mediante la aplicación de un campo eléctrico externo, lo que los convierte en candidatos óptimos para desarrollar dispositivos de fase reconfigurables sin partes móviles.

Esta tesis abarca tanto el diseño, como la fabricación y caracterización de tres dispositivos ópticos reconfigurables. Todos los procesos han sido llevados a cabo en las instalaciones del centro de investigación Centro de materiales y dispositivos avanzados para las TICs (CEMDATIC), perteneciente a la Universidad Politécnica de Madrid. Además, la electrónica de control utilizada ha sido desarrollada y caracterizada en este mismo centro.

El primero de los dispositivos fabricados es un generador de vórtices ópticos sintonizables, conocido en inglés como spiral phase plate. Los vórtices ópticos son un tipo de haces de luz que están caracterizados por poseer un frente de onda helicoidal, definidos por un parámetro llamado carga topológica. Estos haces de luz poseen una singularidad de fase y pueden transmitir momento angular orbital. Debido a estas características han suscitado gran interés en sectores como la manipulación y las comunicaciones ópticas. El dispositivo desarrollado está compuesto por 72 píxeles triangulares que pueden ser direccionados de forma independientemente. Se ha logrado generar vórtices ópticos con 72 cargas topológicas enteras diferentes, 36 positivas y 36 negativas. A su vez, se ha demostrado como este dispositivo permite la generación de vórtices ópticos con cargas fraccionales arbitrarias. Por último, se ha corroborado la capacidad de este dispositivo la generación de vórtices perfectos, vórtices ópticos con una distribución de potencia radial independiente de la carga topológica.

El segundo dispositivo presentado es un axicon espiral reconfigurable. Los axicones son conos hechos de cristal o polímero que, en vez de enfocar la luz en un punto, lo hacen a lo largo de un volumen. Esta característica los hace particularmente interesantes en sectores como la fabricación por láser y la metrología. En este trabajo se presenta un dispositivo plano compuesto por 24 electrodos con forma espiral capaz de generar 12 profundidades de enfoque positivas y 12 negativas. Se ha demostrado además como este dispositivo puede usarse para generar vórtices ópticos perfectos cuando se utiliza en combinación con una lente convergente convencional.

El último dispositivo presentado son las lentes espirales sintonizables. Estas lentes formadas por 72 electrodos permiten cambiar su distancia focal mediante las señales eléctricas aplicadas dando lugar a 36 configuraciones convergente y 36 divergentes. Se han desarrollado diferentes tipos de lentes con diámetros de entre 0.5" y 1" y diversas distancias focales base. Además, en esta tesis se propone una estrategia para minimizar la aberración cromática mediante la sintonización dinámica de las lentes. Se ha caracterizado a su vez la influencia de los vórtices ópticos inherentes a este tipo de lentes y se han demostrado técnicas para compensar la carga topológica de las mismas. Finalmente, se ha propuesto el uso de estas lentes en un sistema de zoom, demostrando su capacidad para reducir y magnificar objetos.

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Abbreviations and Acronyms

AR	Augmented Reality
B2B	Back-To-Back
BS	Beam Steerer
CEMDATIC	Centro de materiales y dispositivos avanzados para las TICs
DSA	Diffraction Spiral Axicon
DAC	Digital-to-Analog Converter
DMD	Digital Micromirror Device
DLW	Direct Laser Writing
D	Duty Cycle
GRIN	Gradient-index
GUI	Graphical User Interface
IC	Integrated Circuit
ITO	Indium Tin Oxide
LiDAR	Light detection and ranging
LC	Liquid Crystal
MEMS	Microelectromechanical system
OAM	Orbital Angular Momentum
OPL	Optical Path Length
OV	Optical Vortex
SDL	Spiral Diffraction Lens
SLM	Spatial Light Modulator
SPP	Spiral Phase Plate

PWM	Pulse-Width Modulation
ROI	Region Of Interest
SPI	Serial Peripheral Interface
UPM	Universidad Politécnica de Madrid
PB	Pancharatnam-Berry
PVB	Perfect Vortex Beam
V_{RMS}	Root-Mean-Square Voltage
VR	Virtual Reality
VB	Vortex Beam

1. Introduction

Light studies and light-based technologies have been subject of great interest for thousands of years. A few historic highlights to mention could be the earliest inquiries about the nature of light in ancient Greece (3rd-5th century B.C.), the study of refraction by Ibn Al-Haytham (10th-11th century A.C.), the discussions about light nature addressing the schism of Newton's particle theory vs. Huygens' wave theory (17th-18th century), the unification of electromagnetic theory by Maxwell (19th century), and Einstein's proposition of photoelectric theory (20th century A.C.) [1].

Knowledge advancements about light gave rise to the emergence of well-known light-based instruments such as the microscope (Hans and Zacharias Janssen 16th century), the telescope (Hans Lippershey 17th century), or the light bulb (19th century). For many years, light-based technologies were restricted to the use of lenses and static optical elements that were manually actuated. In the 20th century, photonics became a new scientific area by its own, whose paramount realization was the laser. At the same time, the rise of electronics led to a technological revolution, resulting in the creation of myriads of new electro-optical devices, including new photodetectors and light sources such as LEDs and laser diodes. Modern laser diodes offer a wide spectral range and are gradually substituting a number of solid-state and gas lasers. All these findings paved the way to the implementation of light-based technologies in new sectors such as medical diagnose and therapy [2], surgery [3], machining [4], or displays [5].

New applications require ever more complex systems for the control and manipulation of light. From sets of lenses, there was an evolution to more advanced systems that modified the amplitude, polarization, frequency or phase of light. Liquid crystals (LC) emerged as one of the most widely used technologies to enable the reconfigurability of light-based devices, especially in the display industry. At present, the use of these materials encompasses an ample span of sectors such as microwave communications [6], pathogen detection [7], [8], micro-robotics [9], [10], or the emerging field of programmable photonic circuits [11], [12], [13]. This thesis is centered on tunable LC devices, used in the manipulation of the phase of a passing light wave.

In the subsequent sections of this introductory chapter, the most relevant non-display LC applications and their alternative technologies are reviewed. The following devices are discussed:

- Beam steerers
- Tunable cartesian oval lenses
- Tunable axicon lenses
- Orbital Angular Momentum (OAM) devices

1.1. Reconfigurable Beam Steerers

An optical beam steerer (BS) is a device capable of redirecting an input light beam to a desired output direction. Beam steering devices can be classified in two families, depending whether they rely on mechanical or non-mechanical control. Furthermore, steering systems may work either in transmission or reflection. The optimal technology depends on the specific application, thereby a brief summary is included below.

1.1.1. Mechanical steering systems

Mechanical steering systems usually rely on the utilization of moving parts to deflect an incoming beam through electronic control [14]. These devices commonly have advantages such as insensitivity to polarization and wavelength, as well as rapid response times.

The most widely used technology for light steering is the galvanometer scanners, also known as galvos. These systems deflect an incoming laser beam by rotating a motorized mirror (Figure 1.1). A 2D steering system can be easily implemented by combining two galvanometers [15]. These systems are commercially distributed by a wide number of companies (*e.g.*, Hamamatsu, Edmund Optics, and, Thorlabs). Microelectromechanical system (MEMS) galvanometers have also been presented and are commercially available [16].

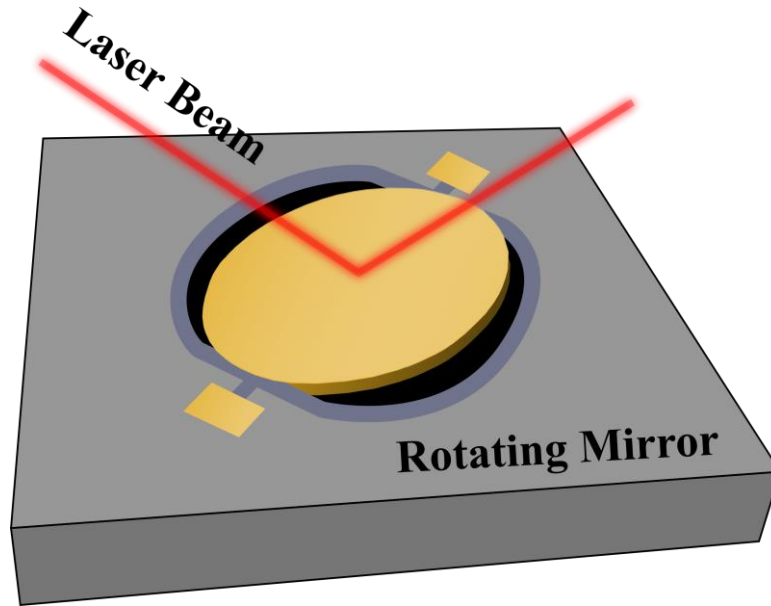


Figure 1.1: Sketch of a MEMS beam steerer where the light deviation is controlled by the angle of rotation of a mirror.

A more complex steering technology are the optical-phased arrays, a solution to enable 2D light steering by controlling electronically the position of multiple mirrors. The main challenge of this technology is achieving a fine mirror positioning that produces the required 2π phase shift. Large area ($\sim 3\text{mm}^2$) steering system with microsecond response times composed of multiple reflective gratings have been reported [17], where the steering angle is tuned by controlling the position of the individual grating pixels. Furthermore, the employment of these reflective systems has been demonstrated suitable for working in a broadband wavelength range including ultraviolet [18], albeit unlike the single mirror galvo only for one wavelength at a the same time. One of the main drawbacks of this technology is that it requires a rather complex manufacturing process and driving [19].

1.1.2. Liquid crystal beam steerers

Liquid crystals electro optical characteristics makes them suitable for non-mechanical beam steering. Non-mechanical devices are particularly interesting for systems where the absence of moving parts leads an extended operating life span, and where low voltage, power consumption, weight and footprint is of relevance. Conversely, the majority of LC BSs are sensitive to polarization and are not suitable for high-power applications.

Analog beam steering can be generated by continuous refractive index gradients, or thickness gradients like those of conventional glass prisms. Dynamically controlling the refractive index gradients, the device becomes tunable, i.e., light can be steered to diverse output angles. Such structures can be implemented using conventional LC cells where the reorientation of the molecules, and therefore the refractive index gradient, can be electronically tuned. Analog and transmissive BSs have been demonstrated using this approach; however, the continuous analog deviation of an incoming beam comes at the expense of reduced steering angles [20], [21].

The deviation angle can be increased employing diffraction gratings (Figure 1.2) where the incident beam is diffracted into beams with a main lobe determined by the geometry of the grating, refractive index and light wavelength [22]. The highest first order diffraction efficiency, is achieved using the saw-tooth blazed phase grating, with the discrete phase difference between periods is a multiple of 2π [21]. Light steering can be achieved by modifying the grating period. LC blazed tunable beam steering systems have been achieved following different approaches such as compound blazed gratings [23], patterned high-resistivity electrodes [24], or, independent electrode addressing [22].

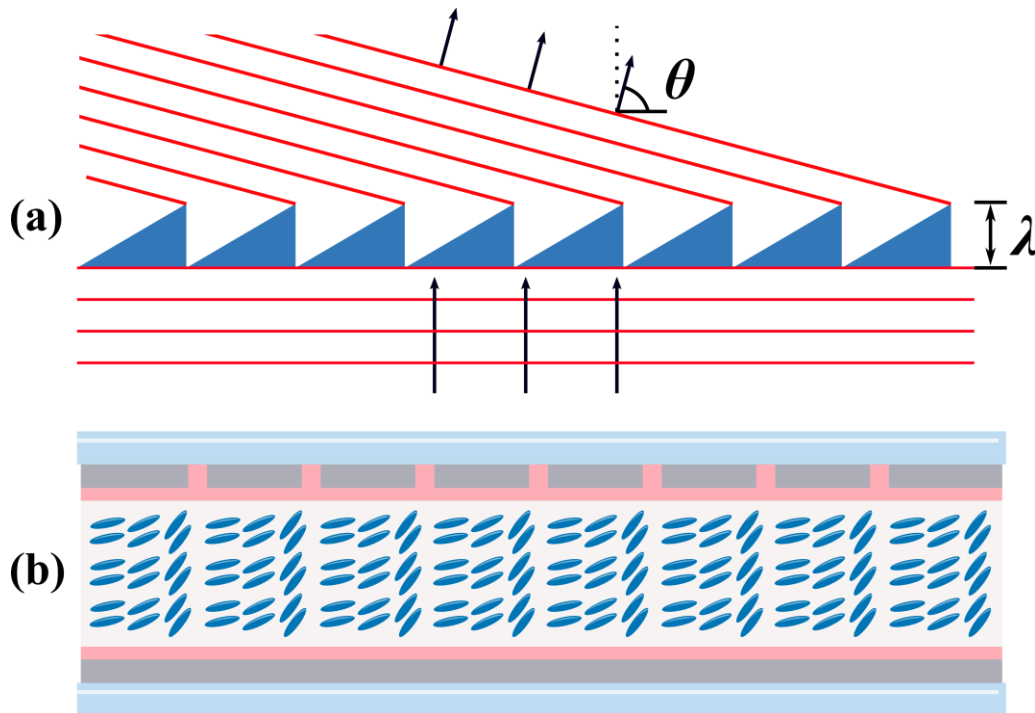


Figure 1.2: Transmissive blazed grating beam steering sketch. a) The incoming wavefront is deviated an angle (θ) to the first diffractive order. b) The blazed phase profile can be achieved by periodical reorientation of LC molecules.

An alternative approach to achieve high-efficient beam steering are the Pancharatnam-Berry (PB) deflectors. In contrast with previous LC devices where the introduced phase difference is achieved by out-of-plane realignment of the LC molecules, in PB elements the phase shift is generated by inducing a LC director in plane orientation pattern (Figure 1.3). These devices work for circularly polarized light, deflecting left and right circular polarization to opposite steering angles. Different PB-based beam steering approaches have been developed [25], [26], [27], however most of them are switchable rather than tunable devices. The simplest approach that has been developed to obtain PB devices with different steering angles consists of cascading multiple ON-OFF switchable devices [28].

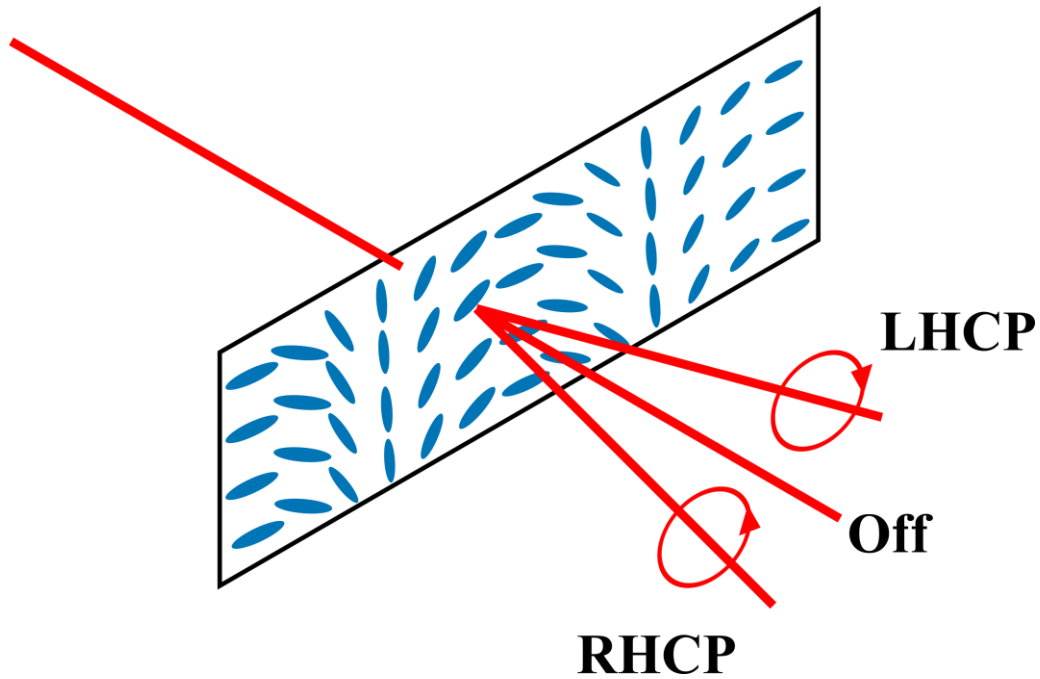


Figure 1.3: LC PB polarization grating working principle, where left-handed and right-handed circular polarizations are deviated to opposite angles. The blue ellipses represent the LC director orientation varying pattern.

1.1.3. Applications

Beams steering systems are crucial for free space optical communications to maintain a continuous link between transmitter and receiver. Liquid crystal 2D beam steering have been employed to develop free space optical communication links [29]. The implementation of optical links between satellites and ground stations have being accomplished, where satellite drift compensation has been demonstrated [30]. Next generation of satellite networks will implement of pointing and tracking systems between satellites [31], which may be LC based.

Autonomous vehicles have recently increased the interest in Light detection and ranging (LiDAR) systems. In this application, beam steering is essential to enable 3D mapping of the moving vehicle surroundings [21], [32]. Likewise, LiDAR technologies have also been employed for remote sensing, including topographic, vegetation measurements or atmospheric measurements [33].

Precisely positioning a laser beam of light is also essential for laser micro-machining [34]. Furthermore, 3D printing manufacturing techniques (*i.e.*, two-photon polymerization) include beam steering to perform the resist polymerization over the working area [35], [36]. Usually, commercially available systems (*e.g.*, Nanoscribe and Heidelberg Instruments) rely on galvanometer BS due to their higher scanning speed.

Lastly, it is necessary to underline the importance of steering systems in the display and projector sector. Common commercially available projectors are based on steering digital micromirror device [37]. Virtual reality (VR) and augmented reality (AR) displays using PB gratings have been manufactured [26]. Recently, steering systems have also been developed to enable glasses-free 3D visualization systems such as light field displays. A time multiplexed multi-view 3D displays has been developed, where color projections with up to 36 different points of view have been achieved using a pico projector array and a steering system [38].

1.2. Tunable Lenses

Lenses are optical elements that focus a passing collimated beam of light to a single focal point (Figure 1.4). In conventional lenses, the focal length is given by the shape and refractive index of the lens. Traditionally, lenses have been manufactured by grinding a slab or by using molds. However, there are many situations that require the use of adaptive lenses, lenses that can reconfigure their focal length.

Tunable lenses can be obtained following different approaches. The most widely used technologies are briefly discussed below as well as the potential applications of these devices.

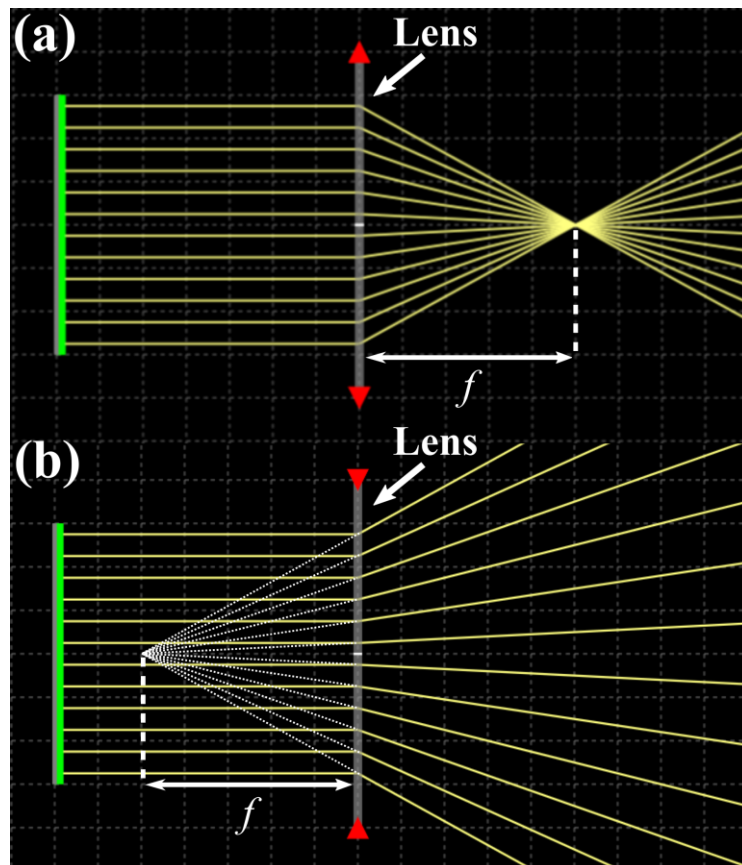


Figure 1.4 Ray optics simulations for different type of lenses: a) Convergent. b) Divergent [35].

1.2.1. Fluid-based lenses

Light focusing tuning can be achieved by controlling the curvature of a meniscus between two immiscible liquids [36]. The most studied technology within this area is based on the electrowetting effect. These lenses consist of a conductive liquid droplet that is in contact with an insulating-coated electrode and an insulating liquid (Figure 1.5). Applying a voltage between the conductive liquid droplet and the insulated electrode the curvature of the droplet is modified, varying the focal length [37], [38].

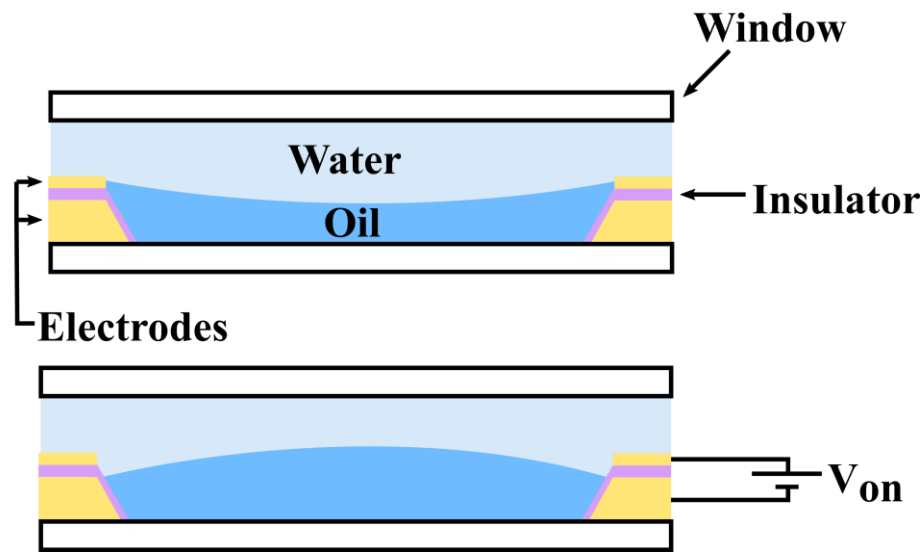


Figure 1.5 Fluidic lenses focal length tuning sketch based on the electrowetting effect.

Other fluidic lenses are based on mechanically changing the shape of the liquid cavity, thus changing the lens focal length. Lenses including piezoelectric actuators have been presented, where the fluidic cavity was directly modified by changing the piezoelectric curvature following an external electric field [39], [40] (Figure 1.6). Moreover, lenses structure relying on magnetic actuation have been implemented as well [41], where the cavity shape was determined by the position of a metal ring between the coils.

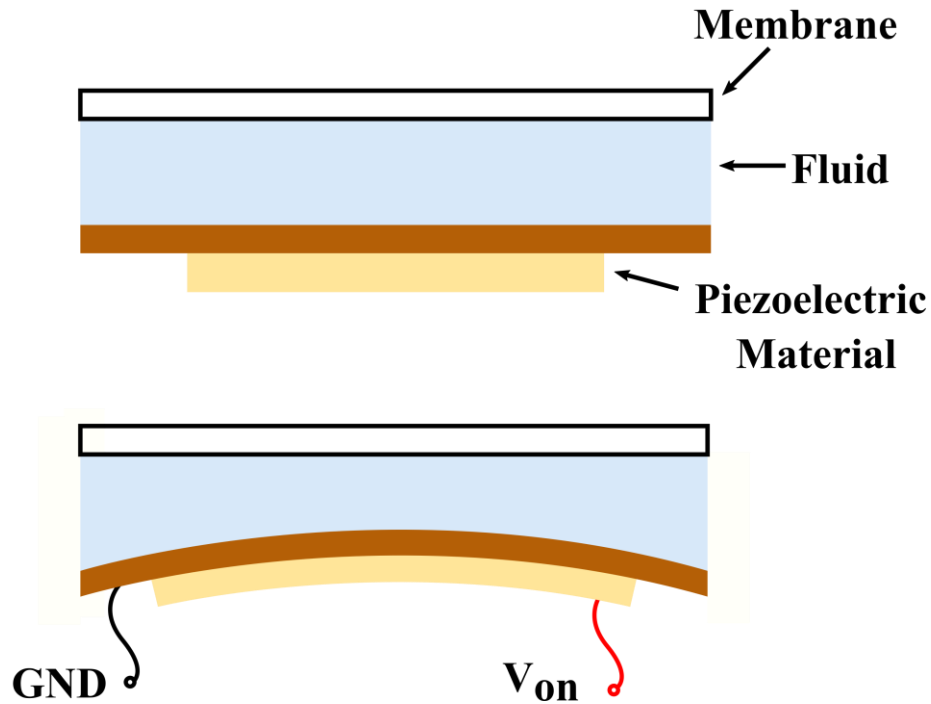


Figure 1.6 Mechanically shaped lenses based on a piezoelectric actuator.

Comparing these two technologies, it appears that lenses based on mechanical actuation could potentially achieve faster speeds than electrowetting [36]. However, the latter technology offers longer expected lifetime (it does not rely in moving parts) and allows operation with lower voltages [37]. Both technologies present cumbersome manufacturing procedure. Furthermore, like every other type of gradient-index (GRIN) lenses, the maximum optical power is limited by the device thickness.

1.2.2. Liquid crystal modal lenses

In LC modal lenses, the lens phase profile is achieved by generating a continuous gradient of LC molecules reorientation. Usually, these lenses are manufactured as a conventional LC cell sandwich-like structure with high resistance indium tin oxide (ITO) electrodes [42]. The LC reorientation gradient is generated by applying a voltage gradient pattern. To modulate the focal length of the lens, the voltage or frequency applied to the control electrode is varied [43].

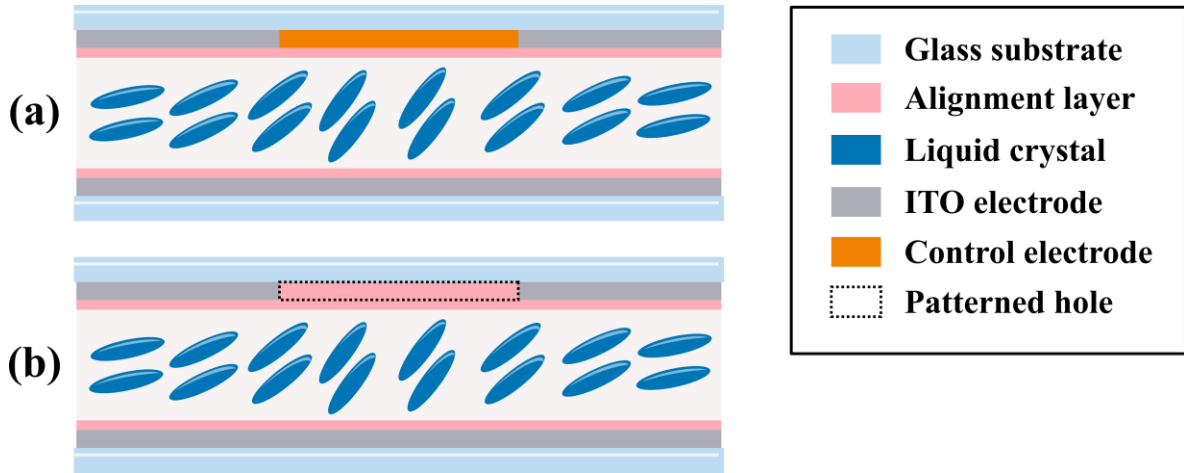


Figure 1.7 Modal lenses structure examples: *a) Control-electrode based. b) Hole LC lens.*

Different solutions have been presented in the literature, such as multielectrode scheme [42], lenses with a hole-patterned electrode [44], or modal lenses including floating electrodes to get a better phase profile approximation [45] (Figure 1.7).

Modal LC lenses work only for the polarization parallel to the LC switching plane without affecting the other polarization. Additionally, like the previous GRIN lenses, the optical power is limited by the device thickness. However, in contrast with the previously mentioned fluidic lenses, the focal length electrical tuning does not involve moving parts. Thereby, these lenses have a potential longer life span.

1.2.3. Liquid crystal Fresnel lenses

Liquid crystal lenses can also be generated by distributing the applied electric field in different areas of the LC cell by means of patterned electrodes (*e.g.* Figure 1.8). The desired phase profiles are approximated by a succession of motifs determined by the electrode geometry. Typically these lenses are designed as LC Fresnel lenses with an extended tuning range[46].

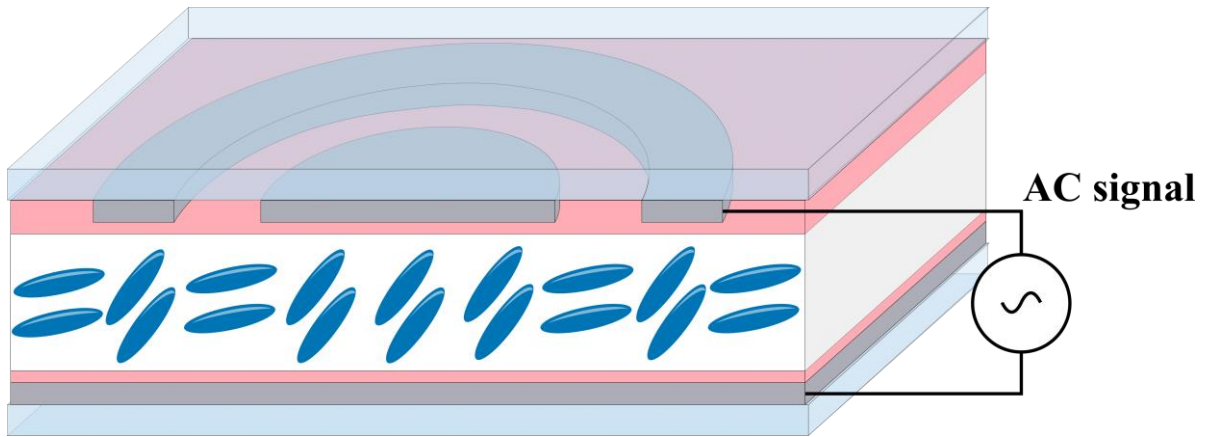


Figure 1.8 Example of a LC Fresnel zone plate based on a concentric ring structure.

Static [47] and reconfigurable [48], [49] Fresnel-type lenses based on concentric ring electrodes have been presented. More complex serpentine electrode designs have also been developed [50]. Furthermore, approaches to achieve polarization-independent performance have been published, either by multiple device cascading [51] or spatial LC alignment control [52].

These lenses patterned electrode design implies a more complex manufacturing process. Moreover, the electrode geometry may lead to different aberrations and image quality defects. However, compared with previously presented lenses, the blazed profile enables the generation of significantly higher optical power lenses for any given thickness and diameter.

1.2.4. Applications

Traditionally, adjustable optical systems have been achieved by means of glass lenses that were moved manually or using electrical motors. The utilization of tunable lenses simplify the optical systems while reducing size, weight and power consumption [36].

One application for tunable lenses have been machine vision systems. Particularly, drone industry has been investing in miniaturization and weight reduction to increase autonomy. Therefore, electrically tunable lenses could be a suitable solution [36]. Additionally, LC lenses have also been employed in autofocus systems in devices like mobile phone cameras [53].

Recently, adaptive lenses have also been demanded for head mounted displays. Tunable optical zoom systems for AR have been demonstrated by Yi-Hsin et al. [54]. The developed system consisted of a set of liquid crystals modal lenses mixed with polymeric layers. Adaptive lenses have also been implemented for AR and VR displays allowing devices to adapt to the visual capabilities of users and reducing accommodation problems [55]. Additionally, the use of tunable lenses has also been proposed to reduce user fatigue by minimizing AR registration problem (*i.e.*, the projected virtual image is not coincident with the real physical object due to the optical system fixed properties) [56].

Wavefront distortions caused by spatial inhomogeneities in optical systems or in the atmosphere is a crucial problem in optical science (*i.e.*, astronomical imaging). Liquid crystal modal lenses have been used to develop wavefront correctors [57]. The manufactured device consists of an hexagonal structure of modal LC lenses and may be employed to replace conventional deformable mirrors and thus avoid the need of moving parts [58].

Vision correction and eyewear sector can also benefit from the adaptability of tunable lenses. Companies such Pixieray and 32°N have presented prototypes of LC glasses with dynamic focus control [59], [60]. Furthermore, LC lenses have also been shown as a compact solution to develop vision correction contact lenses [61], [62], [63].

The applications of this type of devices extend to many more sectors such as: laser micro-machining [64], photovoltaic light concentrators [65], DVDs pickups [66], or optical fiber coupling [67].

1.3. Reconfigurable Axicons

Axicons are a particular case of lenses with conical shape (Figure 1.9). Conic lenses deviate all the incoming collimated light rays with the same output angle. Axicons were first presented by McLeod in 1954, as an element capable of imaging a point source into a continuum of points forming a focal line along the optical axis [68]. The length of this segment is known as depth of focus (DOF) [69], and contrasts with the single focal point of conventional lenses.

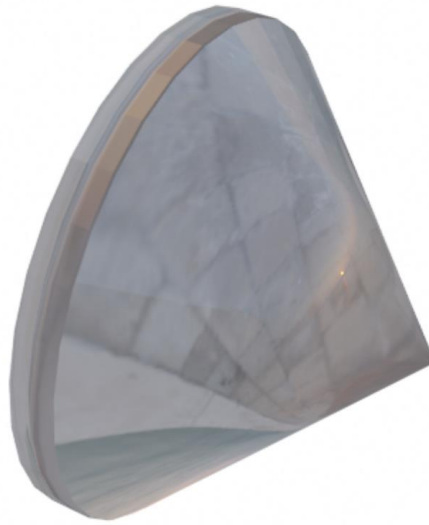


Figure 1.9 Usually, conventional axicons are manufactured as glass or polymer cones.

Traditionally, axicons are manufactured in polymer or glass (Figure 1.9). There are multiples companies that offer this type of lens in their product catalog (*e.g.* Thorlabs or Edmund Optics) [70], [71]. In these devices the DOF is determined by the refractive index (n), the entering beam radius (r_{beam}), and the axicon apex angle (α). The lack of reconfigurability of these devices has given rise to major research efforts to obtain a tunable DOF.

1.3.1. Mechanically actuated optical systems.

The most straightforward method to obtain a tunable DOF is modifying the incoming beam radius by means of a diaphragm or beam expander [72]. Alternatively, the DOF can be modified by manually modifying the distance between a convex lens and an axicon. This distance change introduces an modification on the axicon input light diameter, leading to a variation in the DOF [73] (Figure 1.10). The underlying principle of this approach is simple, but it increases the optical setup complexity and alignment efforts.

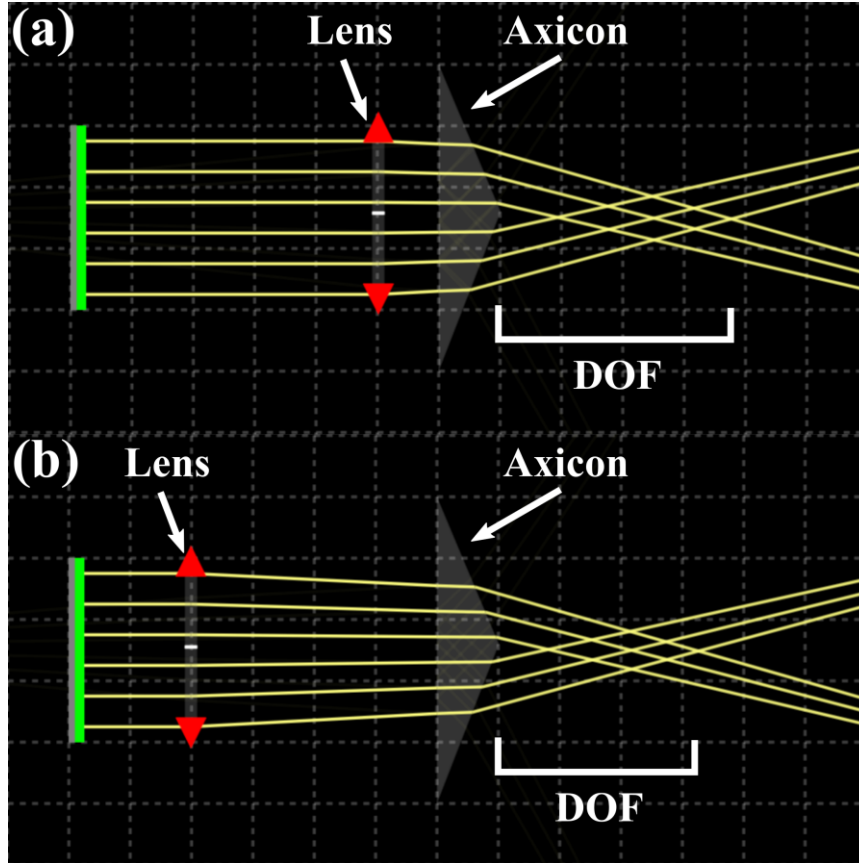


Figure 1.10 Ray optics simulations illustrating how the depth of focus (DOF) of an axicon may be tuned (a, b) by modifying the distance between axicon and lens [35].

Other systems such as fluidic axicons have been manufactured [74]. In this work a conical cavity was filled with different liquids, the DOF being tuned by the refractive index of the filling material. The manufacturing of this type of devices is extremely simple, and, in contrast with liquid crystal axicons, it is suitable for use with high-power lasers. However, having to refill the device each time the devices have to be reconfigured imposes a time restriction.

Additionally, tunable axicons based on piezoelectric materials have been developed [75]. This approach is also suitable for high-power and high-speed applications.

1.3.2. Liquid crystal axicons

Axicons based on liquid crystals have been reported, where the axicon performance is reconfigured in response to an external electric field. Most of the implemented approaches have been based on spatial light modulators (SLMs) [76], [77]. The utilization of SLMs entails a convenient way of generating dynamic devices at the expense of a relatively high cost, bulkiness and undesired diffraction effects arising from the pixels finite size.

Tunable axicons based on microstructured “modal” transmission lines have been designed as well [78], [79]. This proposal involves a simple manufacturing and driving process to develop purpose-build tunable axicons. However, the power is limited by the LC cell thickness. Furthermore, the phase profile approximation to an ideal axicon is compromised by the limited control of the LC switching profile along the transmission line.

1.3.3. Applications

The axicon ability to generate ring patterns can be used to optically trap particles [80], [81]. Using reconfigurable axicons, the particle trapping area can be dynamically changed.

The ability to define a linear power distribution along the optical axis can be used in applications such micro-machining [82]. Axicons have been integrated in optical systems to drill cylindrical or ring-like holes in stainless steel. Axicon generated Bessel beams have also been shown to be an efficient way to generate sharper sub-micron sized structures in tungsten [83].

Axicons have been used to improve imaging techniques in biomedical applications. Axicon assisted irideocorneal gonioscopy presents better spatial resolution compared to currently available tools [84], thus enhancing the eye internal structures mapping. Moreover, axicons have also been employed to improve the axial and lateral resolution of coherence tomography [85].

1.4. Optical vortex beams generation

Optical vortices (OV) were first discovered in 1989 by Coulet et al. [86]. Later, in 1992, Allen et al. demonstrated that in vortex beams (VB), light possesses a helical wavefront, and could transfer orbital angular momentum (OAM) [87]. Thus, using a laser, the authors experimentally demonstrated that VBs could transmit a mechanical torque to particles.

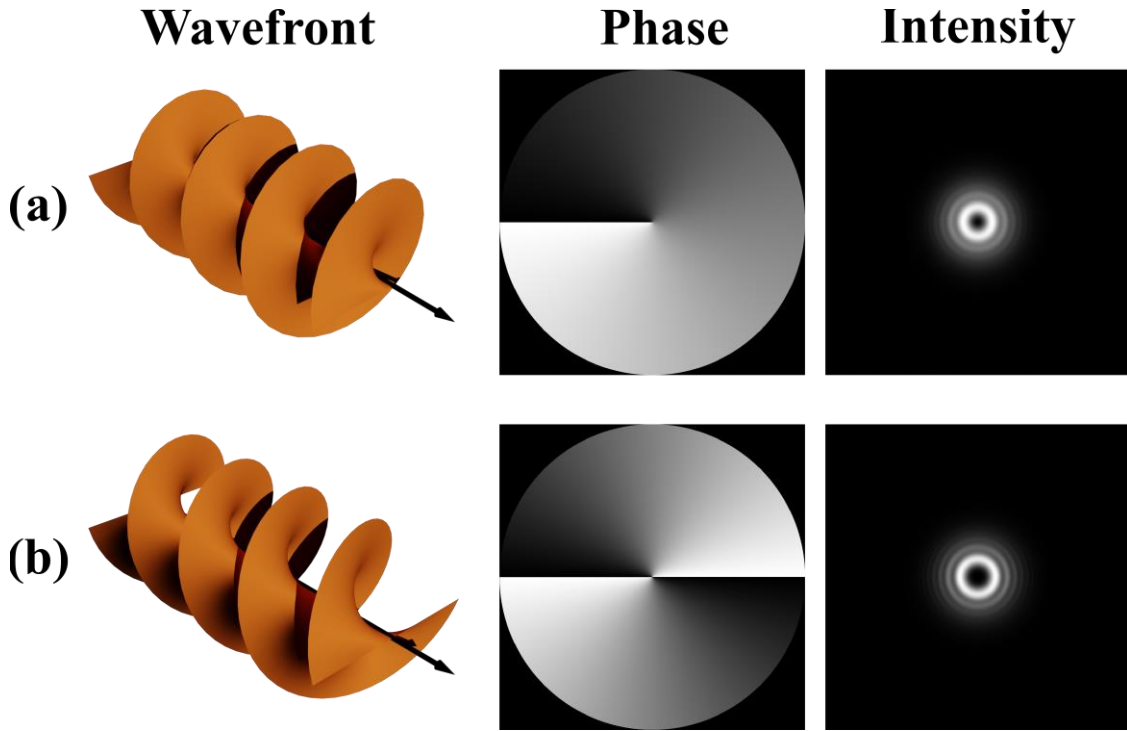


Figure 1.11 Vortex beams sketch depicting wavefront, phase and intensity for different topological charges (l): a) $l = -1$. b) $l = -2$.

VBs are characterized by carrying an OV possessing a phase singularity along the optical axis, resulting in an intensity ring pattern. This phenomenon arises from the coexistence of all phases on the optical axis, creating destructive interference.

VBs have a characteristic parameter called topological charge (l) determined by the number of intertwined helices describes the wavefront. When observing the phase profile of a cross section of the wavefront, VBs exhibit azimuthal phase variation. The absolute value of the topological charge is equivalent to the number of 2π jumps present about a complete turn (Figure 1.11). Additionally, the sign of the topological charge indicates the handedness of the wavefront spirals. It is standard to assign positive topological charges to left-handed handed spirals.

The following sections summarize the most used VBs passive generation mechanisms, followed by a brief description of potential applications.

1.4.1. Q-Plates

Q-Plates were invented in 2006 by Marucci et al [88], [89]. The underlying physics principle is the Pancharatnam-Berry (PB) geometrical phases (Figure 1.12). Usually, these devices are essentially LC cells with a specific azimuthal in-plane molecular director (n) pattern and a constant $\lambda/2$ retardation [90], that leads to an inversion of hand of an incident circularly polarized light beam. The in-plane angle (α) determines the introduced phase delay (δ) to the circularly polarized passing light beam:

$$\delta = \pm 2 \cdot \alpha \quad (1.1)$$

The sign of the induced phase delay depends on the handedness of the incident circular polarized light. Therefore, the same device produces opposite behavior for different handedness (e.g., left and right circular polarization give rise to beams carrying opposite topological charges).

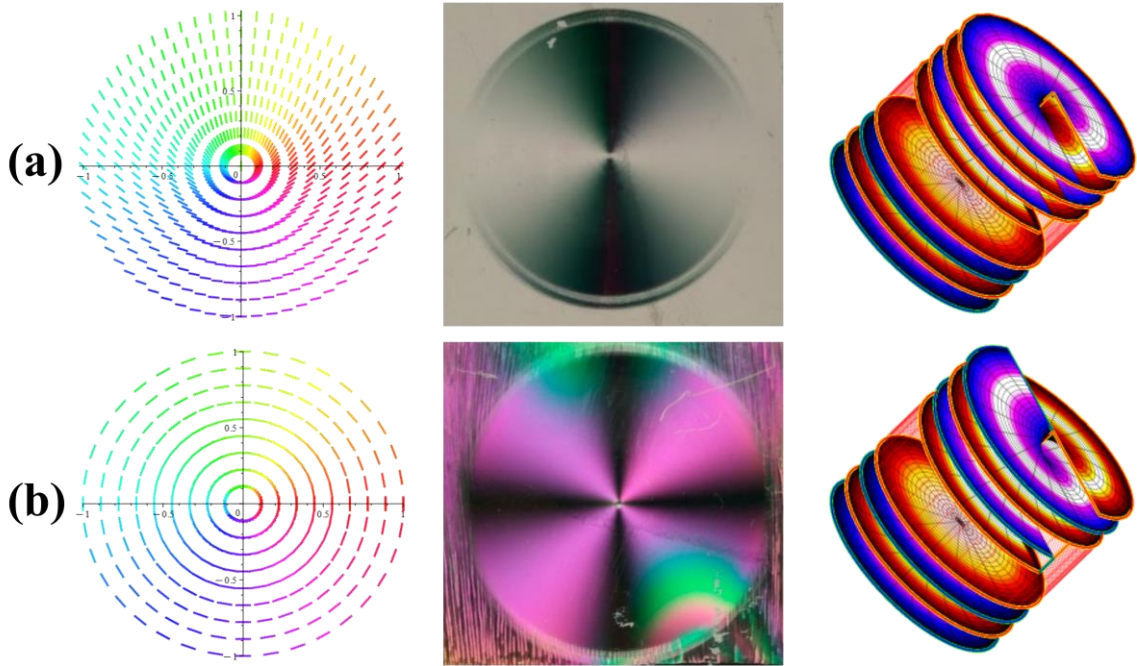


Figure 1.12 Q-Plates examples introducing different topological charges (l): a) $l = \pm 1$. b) $l = \pm 2$. The left column shows the alignment patterns, the central column shows micrographs of the configurations between crossed polarizers, and the right column depicts the generated wavefronts with incident RCP light [91].

Several techniques have been proposed to manufacture LC q-plates of different topological charges, with patterned photo-alignment being the most used [92], [93], [94].

Alternatively, patterned alignment has also been achieved using self-assembly techniques in droplets or more conventionally by alignment layer rubbing [95], [96].

Q-plates main drawback is their limited tunability. However, some approaches have shown switchable topological charges [32] in response to an external electric field. There has also been a lot of research related to the use of q-plates to generate vector vortex beams, light beams possessing both OAM and inhomogeneous polarization state [90], [97], [98], [99]. The increased interest in these products has resulted in commercially available products on the market (e.g., BEAM Co. and Thorlabs)[100], [101].

1.4.2. Fork gratings

Fork gratings are devices that convert an incoming Gaussian beam into a series of VBs with various l [102]. Their phase profile result from the combination of a linear grating with a spiral phase plate (SPP) (Figure 1.13) [103].

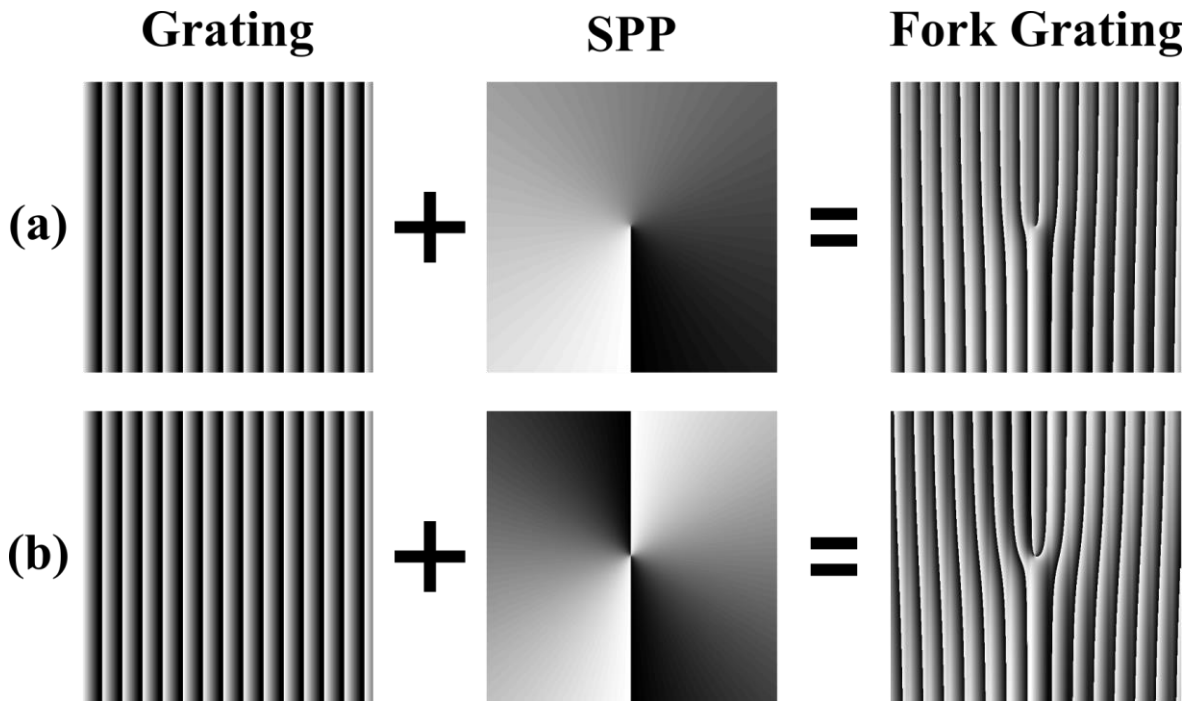


Figure 1.13 The combination of a linear grating and different spiral phase plate leads to fork gratings with different topological charges (l): a) $l = 1$. b) $l = 2$. In the figure all the phases have been wrapped between 0 and 2π .

These devices have been manufactured in many different ways including using polymer dispersed or blue phase LCs [104], [105]. To obtain reconfigurable forked gratings, SLM-based approaches have been developed [106], [107]. Gratings based on spatially varying LC directors with optical reconfigurability have been demonstrated as well [102]. However, these devices share a common drawback, it is not possible to obtain a control of the topological charge independent of other parameters of the light passing through them (e.g., beams are diffracted at different exit angles carrying different topological charge and circular polarization handedness).

1.4.3. Spiral Phase Plates

Spiral phase plates are devices that create VBs by introducing a azimuthal varying retardation to a passing light beam only [108]. In this way, the incoming beam wavefront gets twisted without affecting to its divergence.

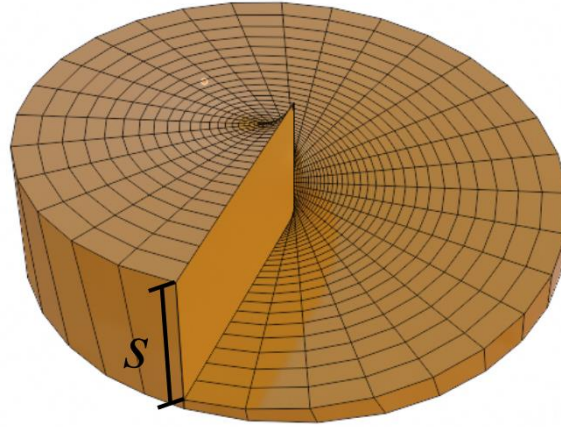


Figure 1.14 Conventional solid SPP sketch where the azimuthal phase variation is achieved by modulating the device thickness (S).

Conventional solid SPPs are manufactured with an azimuthally increasing thickness [109] (Figure 1.14). Historically these devices have been produced by performing machining or using molds [109], [110], however more advanced photolithographic techniques based on electron beam [111], [112], direct laser written gray masks [113], or, two-photon polymerization, have been also been employed [114]. Various approaches to generate an azimuthally varying phase profile based on metasurfaces or geometric phase plates have also been published [115], [116], [117]. SPPs are also commercially available in glass or polymer versions [118], [119].

As in the previous devices, to obtain reconfigurable performance, the use of SLMs has been employed [120], [121] as have reconfigurable LC SPP based on multilevel phase profiles [122], [123], [124].

1.4.4. Applications

One of the applications that has generated significant interest is the use of vortex beams in optical communications [125]. The utilization of such beams in this sector is motivated by the orthogonality of beams with different topological charges. Consequently, information can be multiplexed using beams with different l over the same channel and subsequently recovered without data loss. This multiplexing technique introduces a new degree of freedom since it is compatible with existing multiplexing methods (*e.g.*, polarization, time, wavelength) [126]. Therefore, the adoption of this technology has the potential to drastically increase the bandwidth of optical communications. Examples of transmission have been demonstrated by multiplexing channels with topological charges in free space [127], [128], [129]. The transmission capacity has been increased up to the Petabit range using spatial multiplexing of vortex beams [130]. A specific case of non-guided communication is the utilization of this technology in submarine links, as implemented by Ren et al. [126]. Additionally, the possibility of implementing this multiplexing technique over conventional fiber has been demonstrated [131], [132], at a limited distance. Finally, the possibility to transmit the beams using special fibers with ring-shaped cores has been studied. However, the latter presents a limitation for integration into deployed communication systems [133], [134], [135], [136].

Another application where significant research efforts have been made is the manipulation of particles by light [137], or the tools designed for so-called optical tweezers, a discovery awarded the Nobel Prize in Physics to Arthur Askin in 2018. The ability to transfer OAM from VBs can be used to induce controlled rotation of particles [138], [139]. The use of these beams has been instrumental in demonstrating more complex manipulations such as particle filtering or alignment [140], [141].

Other notable areas within the vast range of applications include imaging and microscopy. The most notable example is the use of VBs in stimulated emission depletion microscopy, a discovery honored with the Nobel Prize in Chemistry in 2014. This technology is based on exciting fluorophores in a sample over a certain area at a specific wavelength, followed by stimulated depletion by illuminating at another wavelength with a beam having a toroidal intensity pattern generated by a VB, thus achieving submicrometer resolutions [142], [143], [144]. Additionally, the chirality of these beams can interact with the intrinsic chirality of organic molecules, thus making them extensively used in biomedicine and chemistry [145], [146].

Vortices have also been applied to astronomy. It has been showed that certain astronomical phenomena give rise to VBs, as in the case of rotating black holes, which could facilitate detection [147]. On the other hand, a tool used in this sector is the vortex coronagraph [148], [149]. These instruments utilize the optical singularity of vortex beams to mask light from very intense sources and thus enable the resolution of other astronomical objects.

In the realm of quantum physics, the use of VBs for creating twisted photons, photons with entangled OAM, has been discussed [150]. The potential of such photons to be employed in communication systems and quantum encryption, such as high-dimensional quantum key distribution has been demonstrated [151]. Beyond communication, OAM-based quantum storage systems or quantum teleportation have been proven as well [152], [153].

1.5. Outlook of the presented work

This thesis is focused on the design, manufacturing, and characterization of reconfigurable liquid crystal optical devices. The scope of this work comprises both the theoretical study of the behavior of these devices as well as the experimental assessment of their performance.

This manuscript is dividing into the following chapters, describing the work realized during this thesis:

- **Chapter 1. Introduction:** In this initial chapter the main concepts and state of the art related to this thesis are presented.
- **Chapter 2. Theoretical Background:** Theoretical concepts common to all the following chapters are described here. This section starts by providing an initial description of liquid crystal materials properties for then explaining the specific theory of devices based on these materials. Lastly, the underlying theory behind the operating principle of the devices presented in this thesis is presented as well as the employed modeling tools.
- **Chapter 3. Experimental:** This chapter provides an overview of the employed experimental setups. Additionally, the quality control and calibration protocols are described in this section.
- **Chapter 4. Spiral Phase Plates:** The design, characterization, and obtained experimental results related to these VBs generating devices are presented in this chapter. Furthermore, two ongoing research lines that have arose after developing these devices are also reported.

- **Chapter 5. Diffractive Spiral Axicons:** A mathematical description and the reasoning behind the spiral geometry of the developed devices are discussed in this chapter. Moreover, the design and experimental results obtained with this specific device are also presented.
- **Chapter 6. Spiral Diffractive Lenses:** Different strategies to compensate the intrinsic OAM of the developed devices are discussed and demonstrated in this chapter. Moreover, reconfigurable lenses that can be electronically switched between convergent and divergent configurations are presented. Lastly, these lenses imaging aberrations (and strategies to overcome them) as well as their integration in a zoom system are reported.
- **Chapter 7. Perfect Vortex Beams Generation:** The concept of perfect vortex beams (PVBs) is discussed in this chapter. Furthermore, two different optical setups to generate these beams are experimentally demonstrated.
- **Chapter 8. Conclusions and Future Research Lines:** The achieved milestones and proposed future research lines are summarized in this chapter. Additionally, all the published results are gathered.

2. Theoretical Background

Light monochromatic plane wave electric field complex amplitude can be described by:

$$E(A, \phi) = A \cdot e^{j\phi} \quad (2.1)$$

where A represents the amplitude and ϕ is the phase. All the devices presented in this thesis are based on the same underlying principle: light phase manipulation. Specifically, the phase delay experienced by light wavefronts is spatially controlled in order to achieve different functions such as focusing, defocusing, beam steering, or introducing an orbital angular momentum (OAM).

Spatial light modulation is achieved by varying the optical path length (OPL): $\Gamma = L \cdot n$, where L is the light path length and n is the light propagating material refractive index [157]. Traditionally, OPL variation has been achieved by manufacturing optical devices with variable thickness (L) while maintaining a constant refractive index (n). This is the technology usually employed by conventional prisms or lenses (Figure 2.1a). In contrast, the devices presented in this work are based on spatial modifications of the device refractive index (n) while keeping a constant thickness (Figure 2.1b).

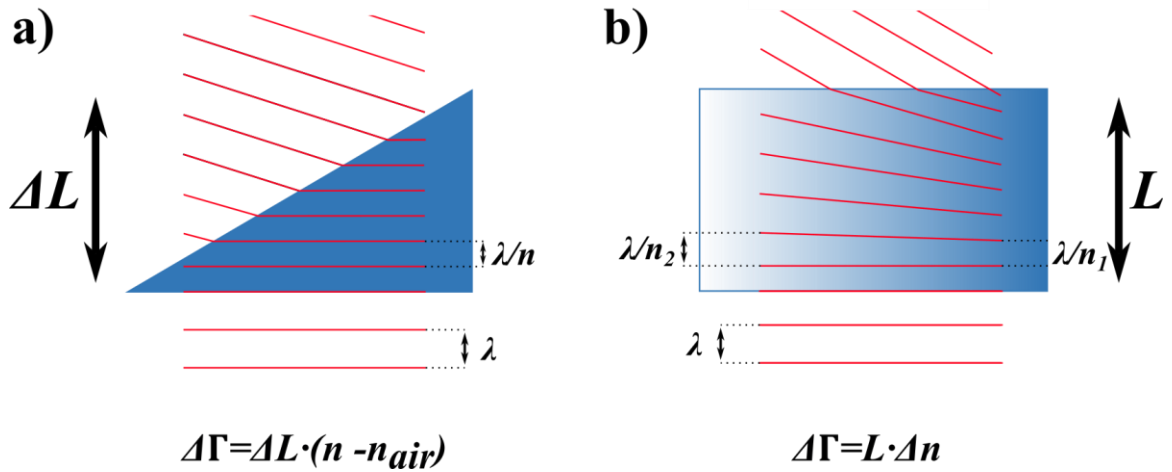


Figure 2.1: Spatial light modulation is achieved by modifying the OPL: a) Thickness (L) variation, b) Refractive index (n) modulation.

This spatial refractive index modulation is achieved by using liquid crystals (LC). These materials possess both electrical and optical anisotropy thus making them responsive to an externally applied electrical field.

This chapter will provide a brief introduction to the liquid crystal materials and their birefringence. Later, the limitations of liquid crystal optical devices and some approaches to overcome these challenges are discussed. Lastly, the tools to model the behavior of these devices are introduced.

2.1. Liquid Crystals

Liquid crystals are a state of matter with properties intermediate between solids and liquids: they show a certain molecular order like solids, but they are fluid like liquids. There are two big LC families: lyotropics and thermotropics, being the latter more relevant for technical applications. Depending on their molecular shape, thermotropic LCs may be classified in discotic (disc-shaped) or calamitic (rod-shaped), the calamitic LCs being the most widely used [158].

Thermotropic LCs feature several phases (so called mesophases), characterized by the orientational and positional order of their molecules with respect to each other. As described by their name, thermotropic LCs exist in a within a certain range of temperature, below which the material is solid, and above which the material is liquid (so called isotropic). In the intermediate range, a number of mesophases may show up at different temperature intervals (Figure 2.2).

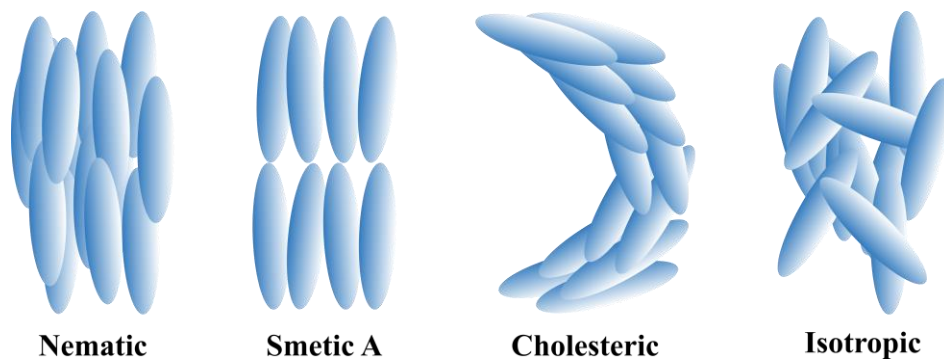


Figure 2.2: Sketch depicting some liquid crystal phases composed by calamitic molecules.

In the lower temperature intervals, closer to solid state, one or several smectic phases may appear. About 10 smectic mesophases are known, but only one or two, if any, are shown by a given material. Smectic mesophases possess positional and orientational order, hence being highly ordered, they tend to align in layers or planes where motion is restricted.

In the higher temperature interval, a different type of phase, called nematic, may appear. This mesophase lacks positional order (i.e., the centers of mass of the molecules are independent to each other). However, the molecules are approximately pointing towards the same direction (called director), thus possessing orientational order. This nearly parallel structure confers the anisotropic properties to the bulk LC material.

Chiral molecules, i.e., molecules with optical activity, can generate liquid crystals as well. Chiral nematics, or cholesterics, are a particular case in which the molecules spontaneously produce helical configurations perpendicular to the molecular axes. This selectively reflects circularly polarized light [159].

Cholesteric LCs sometimes show a small range called blue phases (BPI, BP II, BP III), which occur between the helical and isotropic phase of highly chiral LC [160]. These phases are composed of double twisted cylinders and their use has been traditionally limited by their narrow temperature range ($\sim 2^\circ\text{C}$) [161]. However, recent advances have shown the existence of polymer stabilized blue phases increasing this range over 70°C [162].

Nematic LCs are the most commonly used LCs both in research and commercial applications due to their lower rotational viscosity, and consequently their superior dynamic response. All the devices developed in this thesis employ calamitic nematic LCs.

2.1.1. Nematic LCs

In the nematic phase, the LC molecules are oriented with their long axes approximately parallel to the molecule director, denoted with a unit vector $\hat{n}$. A scalar order parameter (S), the second order Legendre polynomial [163], is used to quantify the molecules order:

$$S = \frac{3\langle(\hat{n} \cdot \hat{p})^2\rangle - 1}{2} = \frac{3\langle\cos^2(\theta)\rangle - 1}{2} \quad (2.2)$$

Where $\hat{n}$ is the molecules average direction or director and $\hat{p}$ is the direction of a particular mesogens molecule. As they are both unit vectors, the dot product can be simplified and replaced with the cosine of the angle between these two vectors (θ). This order parameter will be one ($S=1$) for a perfectly ordered material (i.e., a crystalline solid) and zero ($S=0$) for a perfectly disordered one (i.e., an isotropic liquid). In a nematic LC, S typically ranges between 0.3 and 0.9 being highly dependent on temperature [164].

Described by a single unique director make these materials symmetrically uniaxial. As uniaxial materials they possess electric and optical anisotropy, having different properties (i.e. dielectric permittivity and refractive index) between the unique (extraordinary) and degenerate (ordinary) axes of the molecules:

$$\Delta x = x_e - x_o \quad (2.3)$$

Where x represents any of the previously mentioned properties.

2.1.2. Electrical anisotropy and birefringence

Optical anisotropy, also known as birefringence, is given by the difference between the extraordinary and ordinary and refractive indices (n_e and n_o) (Figure 2.3a).

$$\Delta n = n_e - n_o \quad (2.4)$$

The birefringence is specific to each material and varies with the light wavelength and temperature [165].

LC molecules are electrically anisotropic meaning that their orientation can be controlled by an externally applied electric field (Figure 2.3b). The uniform "relaxed" alignment of the molecules in the absence of external fields is usually assured by providing an alignment layer [166]. An external electric field above a certain threshold can modify the relaxed orientation, effectively rotating the molecules so that their higher anisotropic axis (either ordinary or extraordinary) lies parallel to the field direction. The plane defined by the excited and the relaxed directors is known as the *switching plane*. Alternatively, LCs may also be manipulated by magnetic or optical fields, but that is not relevant to this thesis.

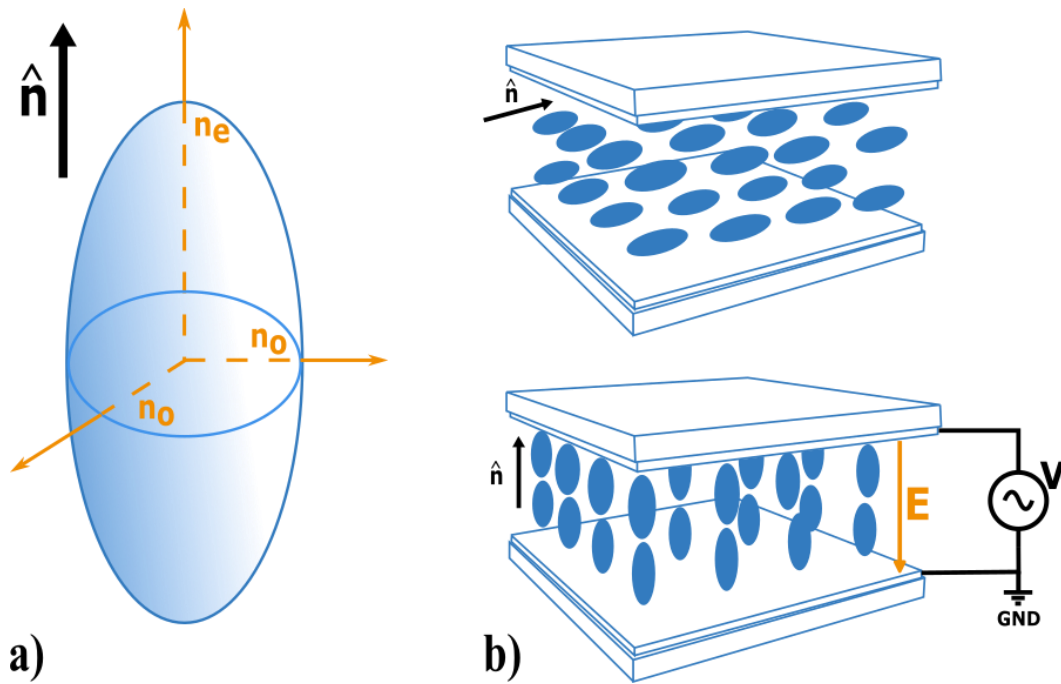


Figure 2.3: LC uniaxial molecule positive anisotropy sketches: a) Optical anisotropy given by the ordinary and extraordinary refractive indices (n_o and n_e). b) Molecules reorientation under an applied external electric field.

The significance of these properties is evident when these materials are utilized in conjunction with polarized light. When a light beam, linearly polarized in the switching plane, passes through a nematic LC cell, light will experience an effective refractive index (n_{eff}) ranging between n_e and n_o depending on the LC molecules orientation (Figure 2.4):

$$n_{eff} = \frac{n_e \cdot n_o}{\sqrt{n_o^2 \cdot \sin^2 \theta + n_e^2 \cdot \cos^2 \theta}} \quad (2.5)$$

Where θ is the angle between the LC optic axis and the direction of light propagation.

Materials possessing positive or negative electrical anisotropy are available, where the LC molecules tend to reorient with the optical director parallel or perpendicular to the applied electric field respectively. For a positive LC, the alignment conditions of the cell will typically be designed so that, if no voltage is applied, light will experience n_e whereas if the molecules are completely reoriented lying parallel to the incident light and applied electrical field, n_o will be experienced. Therefore, by controlling the applied electric field, the molecules orientation can be driven leading to the tunability of the effective refractive index (n_{eff}).

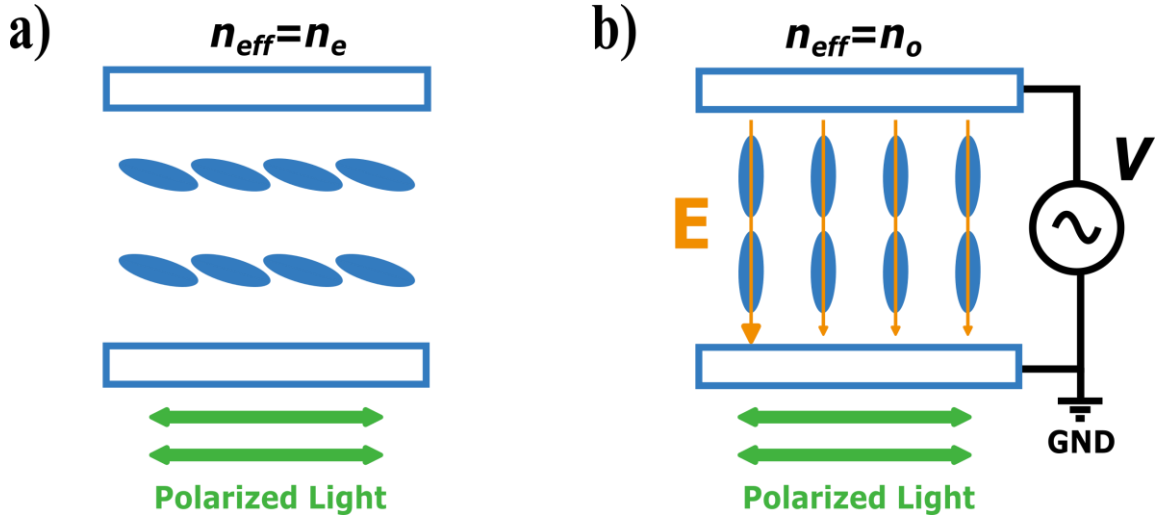


Figure 2.4: Polarized light experienced n_{eff} depending on the applied voltage for a positive LC: a) $n_{eff} \approx n_e$, b) $n_{eff} \approx n_o$.

Consequently, this mechanism allows the electrical tuning of the OPL or the induced phase delay (δ) for a polarized light beam:

$$\delta(V) = \frac{2\pi}{\lambda} \cdot [n_{eff}(V) - n_o] \cdot L \quad (2.6)$$

Where V denotes the applied voltage, λ the wavelength and L the LC thickness. The n_e and n_o dependence with λ has been removed to simplify the equation.

Note that in the following chapters we may use indistinctly phase delay (δ) and OPL difference ($\Delta\Gamma$), but they are expressed in different units, radians or nanometers respectively:

$$\delta(V) = \frac{2\pi}{\lambda} \cdot \Delta\Gamma \quad (2.7)$$

2.2. Phase-Only lenses

The optical path length in ideal lenses (if positive) focus an incident planar wave to a single point at the lens focal length (F) (Figure 2.5). The OPL must decrease quadratically with distance to the lens center to obtain such a perfect lens, being obtained by varying either the thickness (L) or the refractive index (n).

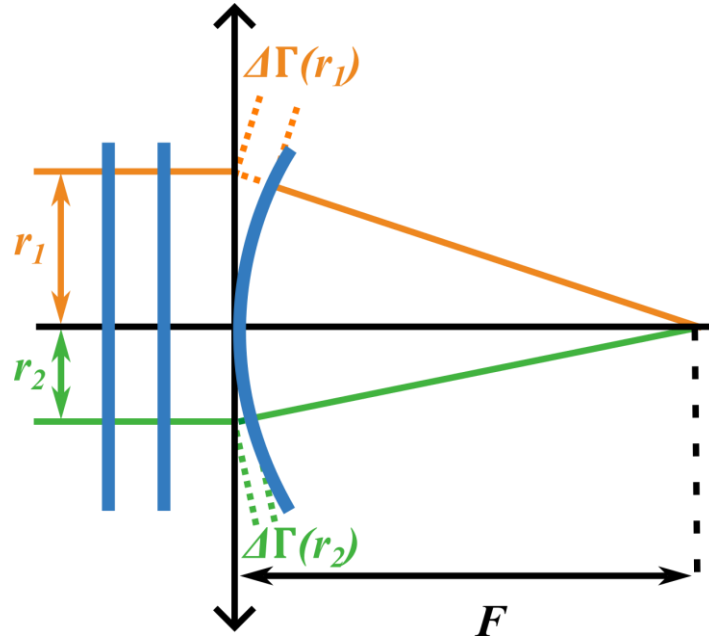


Figure 2.5: A perfect convergent lens deforms the incident planar wavefront focusing it to a single point at its focal length (F). The depicted relative optical path ($\Delta\Gamma$) is negative, it has to be shorter in the periphery than in the center of a positive convergent lens.

There are LC lenses that are based on inhomogeneous cell gap, achieving the focusing by thickness variation [167]. However, all the devices presented in this thesis have a constant cell gap, relying only in the refractive index spatial modulation [82]. Therefore, the following discussion is restricted to this kind of lenses. The theory presented below can be applied to any lens made from a birefringent material; however, it has been illustrated using liquid crystal, as this is the type of material utilized in this work.

2.2.1. Graded index lenses

A conventional glass lens is optically equivalent to a flat LC graded index (GRIN) lens where the molecules orientation mimic the glass OPL profile [95]. Moreover, the LC lens would be tunable, however there are some practical limitations related to the lens geometry and power.

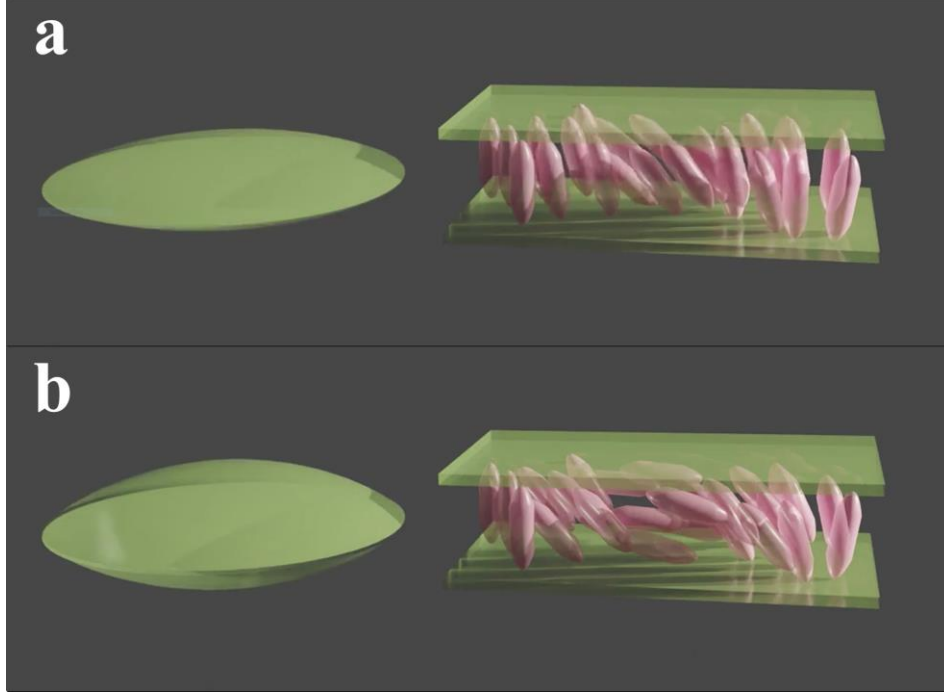


Figure 2.6: Increasing power glass lenses could be emulated by a switchable LC lens [95].

In a traditional glass lens the optical power (P_G) can be derived with the thin-lens approximation using the lens maker formula [168]:

$$P_{Glass} = \frac{n_{glass} - n_{air}}{n_{air}} \left(\frac{1}{R_1} - \frac{1}{R_2} \right) \quad (2.8)$$

Being n_{glass} and n_{air} the glass and air refractive indices, and R_1 and R_2 the two lens surfaces curvature radius.

However, the power of a GRIN LC lens (P_{GRIN}) can be derived from [50]:

$$P_{GRIN} = \frac{2 \cdot \Delta n_{LC} \cdot L}{r_{LC}^2} \quad (2.9)$$

Where L and r_{LC} are the thickness and radius of the LC cell and Δn_{LC} is the refractive index difference between the center and the edge of the lens (assuming normal incidence).

By assuming $\Delta n_{LC} \approx 0.22$ (similar to the E7 LC @ $\lambda=589\text{nm}$ [169], [170]), $L = 7\ \mu\text{m}$, and a radius of 12.5 mm, the approximated power of the lens will be $P_{GRIN} \approx 0.02\ D$. Clearly, there is a trade of between GRIN lenses dimensions and its power. However, there are some strategies to overcome this challenge.

- The most obvious solution is to decrease the cell radius; making microlenses will enhance the lens power [171]. This approach is suitable for some applications like microlenses arrays for displays but definitively not for other uses where large apertures are required (i.e. wearables, telescopes...).
- An alternative solution may be increasing the cell thickness; however this approach will degrade the device response time and material orientation [172].
- A high birefringence LC can be employed to increase the lens power but it is not a drastic improvement (i.e. $\Delta n_{LC} = 0.4 - 0.5$) [173].
- Lastly, building Fresnel structures can be a potential solution to obtain thin, fast, large-aperture, high-power lenses [174].

2.2.2. Fresnel Lenses

Fresnel devices are made up of series of repeated features rather than being a solid piece of material like the previously presented lenses. By removing the excess of material of a conventional lens, a Fresnel lens made by a set of concentric annular sections with similar optical properties can be created (Figure 2.7). Thereby, achieving thinner and lighter lenses or increasing the optical power compared to conventional lenses. These Fresnel sawtooth structures are usually divided on two types: Those with a constant pitch and a different amplitude, or the ones with variable pitch and constant amplitude [95]. The latter model is the most used and the approach that is employed in the devices that are presented in the following chapters.

In Fresnel lenses light manipulation is governed both by refraction and diffraction. As the feature sizes get closer to the wavelength of light, the diffractive effects are more significant. In this case, the light focusing arises from the superposition of light diffracted from different zones, leading to a far field constructive interference at the lens focal length. Fresnel structures with features sizes closer to the wavelength can be explained by the concept of phase wrapping (Figure 2.7). If we consider a light plane as a wave composed by a train of wavefronts, introducing a phase delay of $2\pi \cdot k$ (being k an integer number), is equivalent to provoking no delay. Hence, the lens wavefront transformation remains unaltered. However, there are some undesired effects that arise from the dominance of the diffraction such as the inversion of chromatic aberration or the generation of multiple orders of diffraction leading to a loss of power in the main lobe.

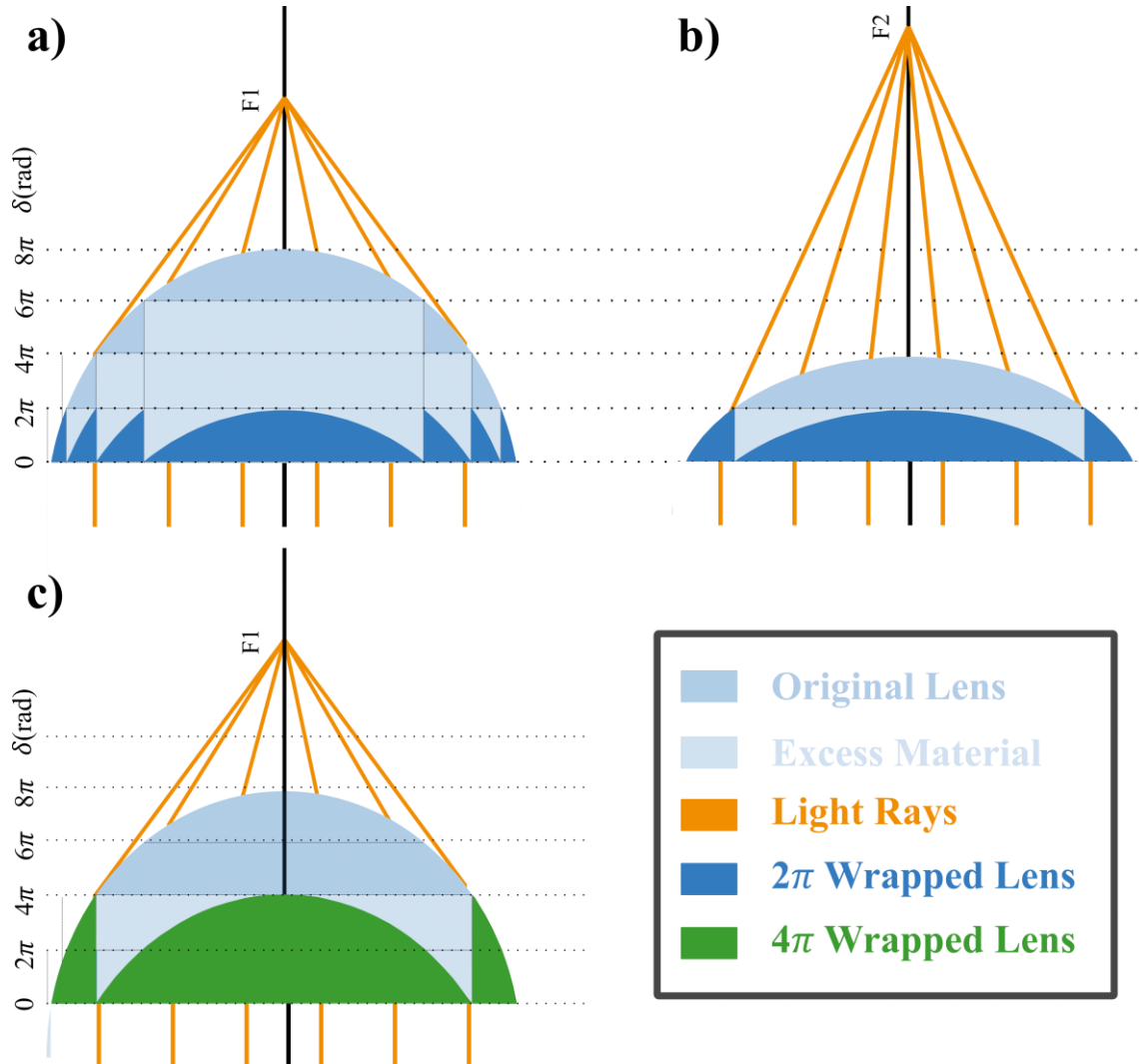


Figure 2.7: Sketch representing phase wrapping for two arbitrary shaped lenses. a, b) Lenses with different focal length can be recreated by employing different features while maintaining a constant 2π phase wrapping. a, c) The same lens is emulated by performing 2π and 4π phase wrapping respectively.

In Fresnel LC lenses based on phase wrapping, the lens power ($P_{Fresnel}$) is given by:

$$P_{Fresnel} = \frac{2 \cdot (\Delta n_{LC} \cdot L + N \cdot \lambda \cdot m)}{r_{LC}^2} \quad (2.10)$$

Where N is the number of Fresnel rings and m is the number of 2π delayed by each ring. By comparing this relation with equation (2.9), it is clear that the power of the lens can be incremented using these sawtooth structures. Using the above-mentioned parameters and making a lens divided in $N = 150$ sections the lens power is increased from $P_{GRIN} \approx 0.02 D$ to $P_{Fresnel} \approx 1.15 D$. Hence, this type of devices overcome the low-power limitation of thin lenses, but at the expense of increasing the complexity of the electrode design and driving. Both drawbacks and their potential solutions are discussed in Chapter 5: Diffractive Spiral Axicons.

2.3. Discretized Phase Devices

Any continuous function can be subjected to a discretization process. This means dividing its original form into levels of finite features. However, this process will give rise to a discretization error, the difference between the original function and the recreated one (Figure 2.8).

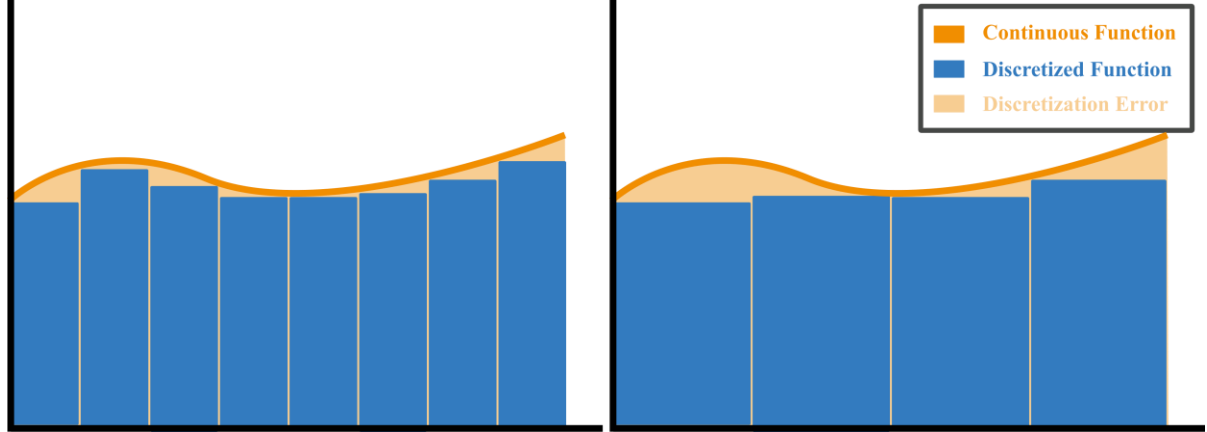


Figure 2.8: Sketch representing function discretization where a larger discretization step leads to a greater discretization error.

The phase profiles mentioned above cannot be ideally recreated because of limited spatial control of the phase, due to practical manufacturing constraints. Therefore, a discretization process may be carried out. In this way, optical devices composed of discrete phase levels can be generated to perform light manipulation. All the devices presented in this thesis are based on phase control with discrete levels wrapped over 2π (Figure 2.9). Hence, reconfigurable Fresnel-based devices where the phase profiles have both a spatial and phase limited resolution are presented in the following chapters. However, it must be noted that these devices discretization error will lead to a loss of diffraction efficiency and other undesired effects [175].

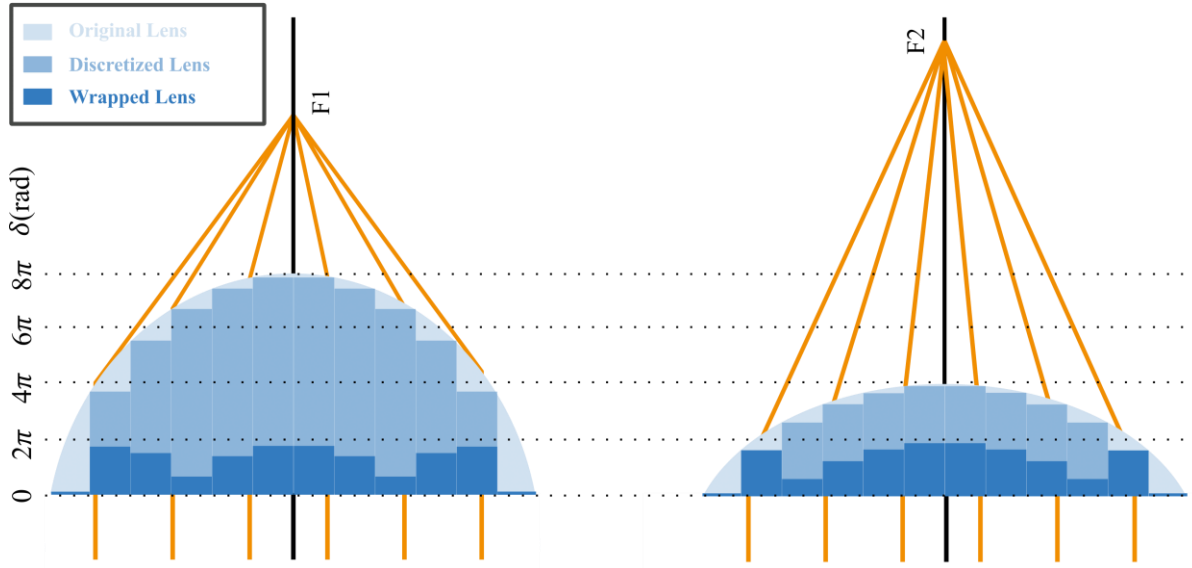


Figure 2.9: Sketch representing that two lenses phase profiles after being discretized and wrapped about 2π .

2.4. Modeling tools

In this thesis, free space light propagation modeling tools based on scalar diffraction theory are employed. These tools facilitate a comprehensive analysis of the evolution of both amplitude and phase of the electric field after being manipulated by the devices.

2.4.1. Scalar Diffraction Theory and Angular Spectrum

Light is an electromagnetic wave possessing coupled magnetic and electric fields traveling through space. Considering a homogeneous medium (*i.e.* free space) and disregarding polarization, the electric and magnetic fields can be described by scalar functions $U(x, y, z)$. For a detailed treatment of the scalar diffraction theory, see the work of Joseph W. Goodman [176].

A particular formulation of this scalar diffraction theory is the angular spectrum. This derivation is based on the fact that a monochromatic complex field distribution falling upon a transverse plane can be decomposed in plane waves travelling in different directions away from that plane. In this way, the field amplitude at any other point can be computed as the contribution of all these plane waves considering the phase shifts that they have suffered during the propagation [176].

Therefore, supposing a monochromatic light source impinging a known aperture, the initial complex field distribution $E(x, y, 0)$ (Source Plane) is known, being then possible to calculate the resulting complex field $E(x, y, z)$ at a distance z (Observation plane) (Figure 2.10):

$$E(x, y, z) = \frac{1}{4\pi^2} \iint \mathcal{F}\{E(x, y, 0)\} \left(\frac{k_x}{2\pi}, \frac{k_y}{2\pi} \right) \cdot \exp \left(i(k_x x + k_y y + k_z z) \right) \cdot dk_x dk_y \quad (2.11)$$

Where:

$$k_z = \sqrt{\left(\frac{2\pi}{\lambda} \right)^2 - k_x^2 - k_y^2} \quad (2.12)$$

Being (k_x, k_y) the spatial frequencies, λ the wavelength in the material and $\mathcal{F}\{E(x, y, 0)\}$ the Fourier transform of the source electric field complex distribution evaluated at the spatial frequencies.

2.4.2. Software Implementation

The previous propagation model has been implemented in Matlab; thus, the source and observation planes are discretized, being represented by a matrix containing the electric field complex distribution values (Figure 2.10). This propagation method is implemented using the following functions provided by Jason D. Schmidt [177]:

$$E(x_{obs}, y_{obs}, z) = \exp \left(\frac{ik(m-1)(x_{obs}^2 + y_{obs}^2)}{2mz} \right) \quad (2.13)$$

$$\cdot Ftt2^{-1} \left\{ \exp \left(\frac{-i\pi^2 2z \left(\left(x_s \frac{x_s}{N\Delta_s} N \right)^2 + \left(y_s \frac{y_s}{N\Delta_s} N \right)^2 \right)^2}{mk} \right) \right. \\ \left. \cdot Ftt2 \left\{ \exp \left(\frac{ik(1-m)(x_s^2 + y_s^2)}{2mz} \right) \cdot E(x_s, y_s, 0) \right\} \right\}$$

Where Ftt2 denotes the 2D fast Fourier transform, the subindices *obs* and *s* refer to the observation and source planes respectively, Δ represent the pixel size (or sampling), N the total number of pixels, z is the propagation distance, and $m = \Delta_{obs}/\Delta_s$ is the scaling parameter between the two planes.

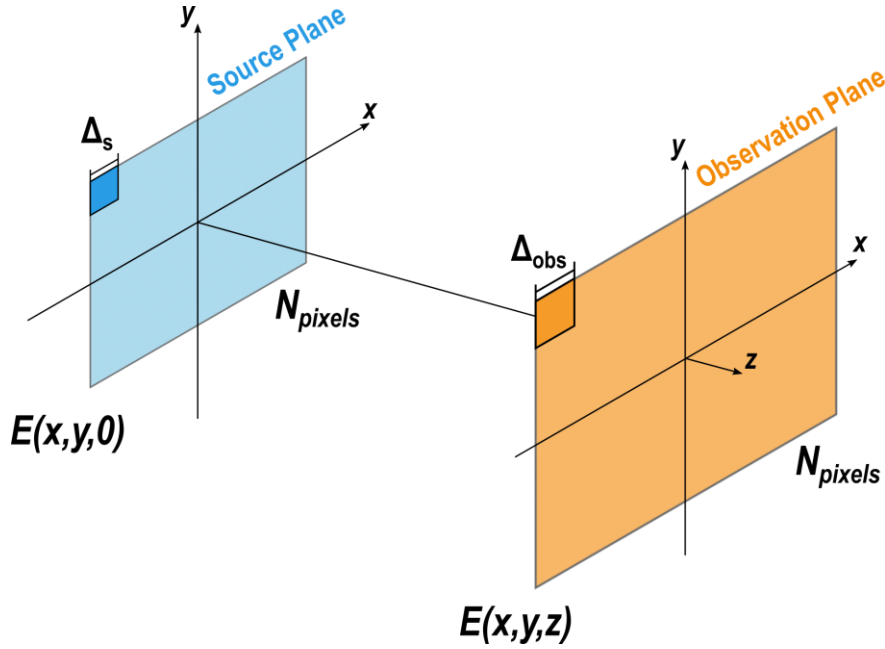


Figure 2.10: Angular spectrum space sketch [178].

The observation plane pixel size Δ_{obs} is linked to the source plane pixel size (Δ_s) by the following relation:

$$\Delta_{obs} = \frac{\lambda * z}{N * \Delta_s} \quad (2.14)$$

Knowing these relationships, it is possible to define an arbitrary aperture and calculate the intensity and phase distribution at a given distance (Figure 2.11). This source can be replaced with the phase distribution of the desired LC device (i.e. Lens, Axicon, SPP) to compute the light intensity and phase at a given distance after being impinged by a light beam.

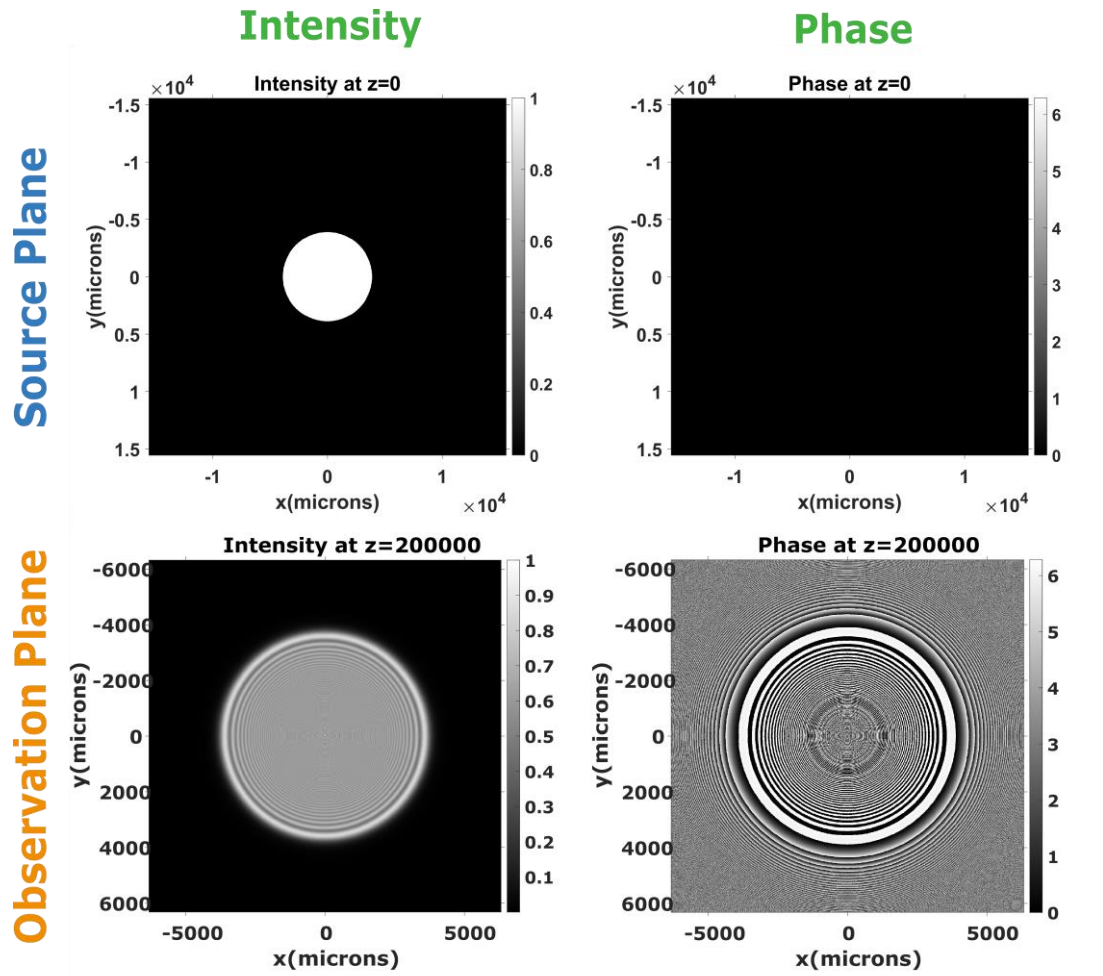


Figure 2.11: Angular spectrum simulation for a circular aperture illuminated by a plane wave.

3. Experimental

This section provides a brief introduction to the devices structure, control, quality verification and calibration procedures and setups. All the devices presented in this thesis have been manufactured in the CEMDATIC clean room facilities, following the protocol described in “Appendix I: Manufacturing Protocol”.

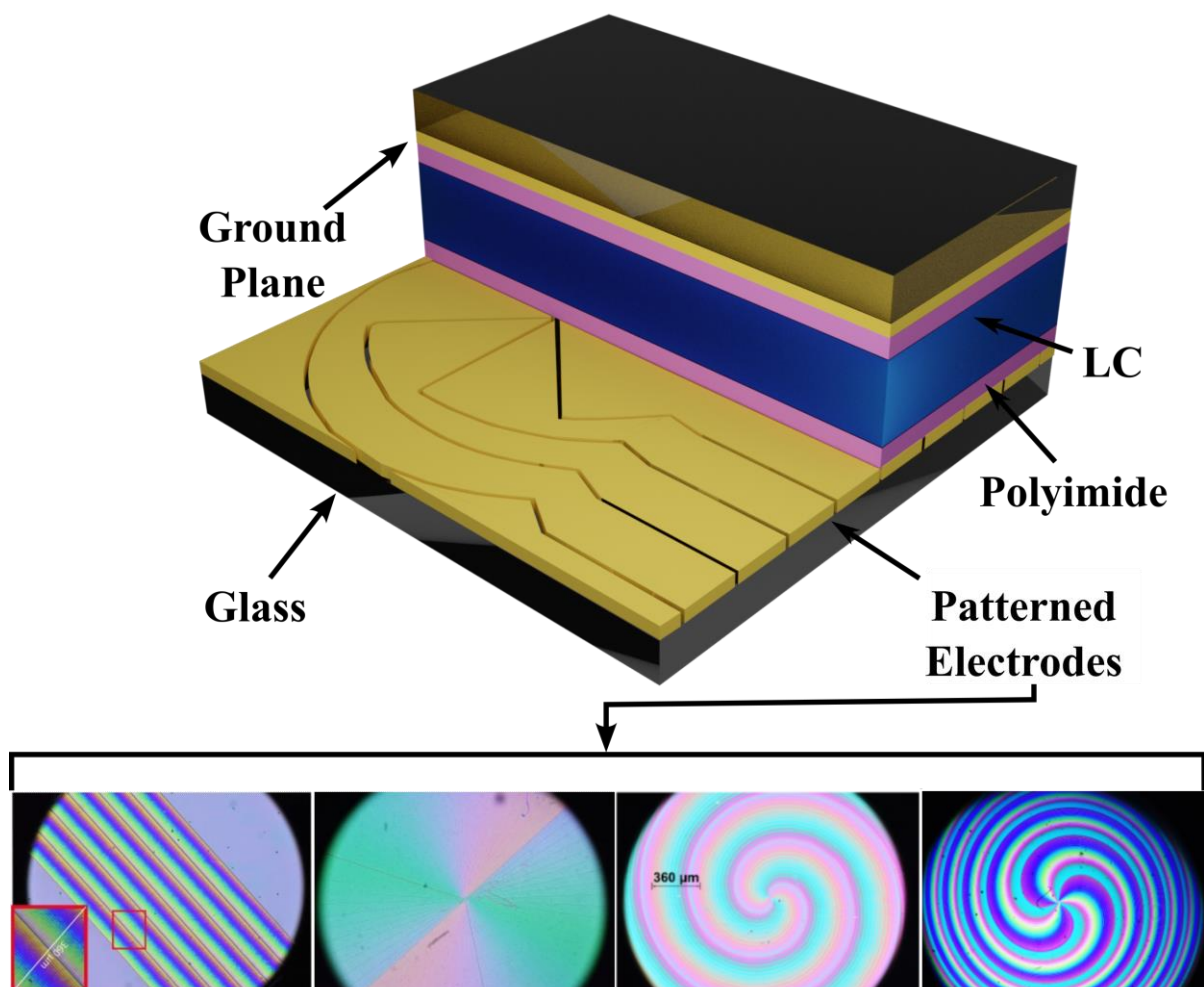


Figure 3.1: Liquid crystal cell structure sketch. Different electrode patterning gives rise to multiple devices.

The liquid crystal cells are made up of two indium tin oxide (ITO) coated glasses, in a sandwich-like configuration whose inner layer is a nematic LC. The thickness of the LC layers, a few μm , is made constant by depositing calibrated silica spacers in the gap between the glasses. One of the ITO planes is used as a counter electrode while the other is pixelated by ITO ablation using a direct laser writing (DLW). A UV laser combined with a computer numerical control (CNC) controlled XYZ-stage (Lasing SA) system is used to carry out the ITO ablation [179]. This electrode patterning is the key process that defines how the light is going to be spatially manipulated. Different electrode geometries give rise to different devices (*i.e.* axicons, lenses, beam steerers, spiral phase plates (SPP)) (Figure 3.1). All the different electrodes (or pixels) are directly and independently addressed by inhouse-tailored electronics.

3.1. LC device drivers

All the electronic drivers described below follow the same simplified control scheme showed in Figure 3.2. A graphical user interface (GUI) in a computer enables the user to set the desired device configuration. The commands are sent to a microcontroller that acts as an interface between the computer and the electronic driver. These instructions are responsible for generating the electronic signals that are generated/conditioned by the driver integrated circuits (ICs). Finally, the signals reach the LC cell electrodes inducing the desired phase delay profile.

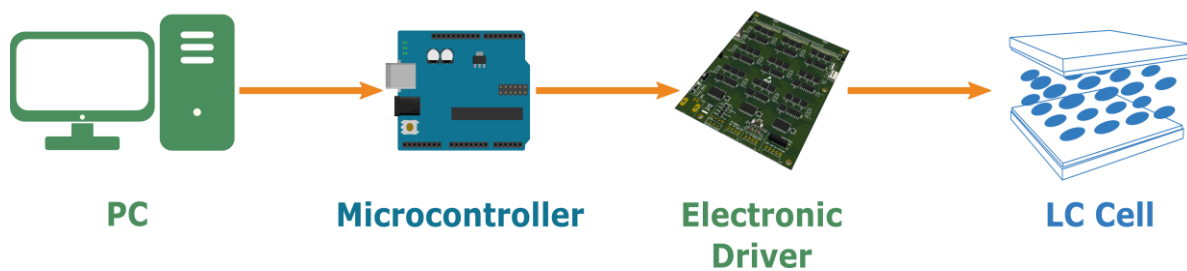


Figure 3.2: LC devices simplified control scheme.

3.1.1. CEMDATIC Driver

The electronics are based on two integrated circuits: TLC5947 (Texas Instruments) and ADG5413 (Analog Devices). The first is a 24 channel constant-current sink LED driver [180], while the second is an analog switch [181]. The LED driver generates for each channel a 12-bit (@1KHz) pulse-width modulated signal (PWM), a square digital signal with constant amplitude but tunable duty cycle. This signal drives the ADG5413 switches, connecting the LC electrode to ground or to an AC signal of the desired frequency and amplitude (Figure 3.3). The AC signal must be externally provided by a function generator.

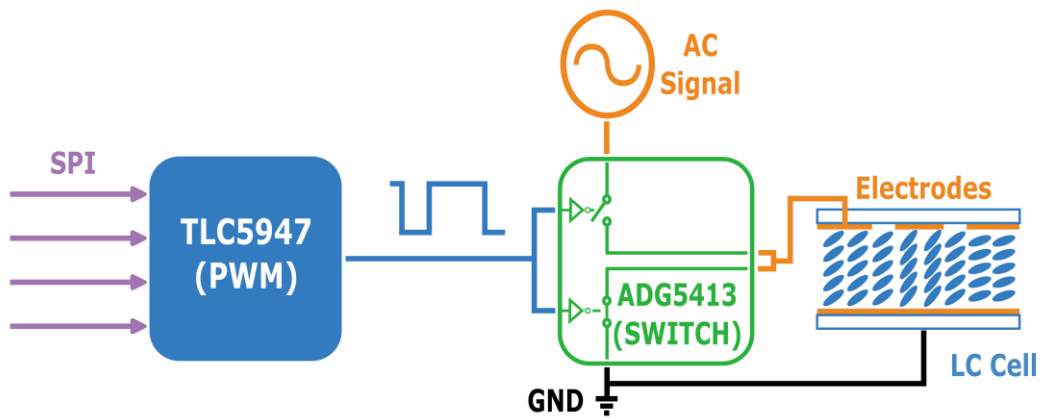


Figure 3.3: CEMDATIC driver electrode control schematic.

A GUI developed in LabVIEW, allows the user to control the electronic driver selecting the desired RMS voltages that are independently applied to the electrodes. The interfacing between the computer and the electronics is done by an Arduino UNO, converting the serial port commands into serial peripheral interface (SPI) instructions. Each driver board can handle a maximum of 72 simultaneous signals. However, the design is modular, so that an arbitrary number of 72 electrode modules can be cascaded. In this work, a maximum of 288 simultaneous electrodes (4 modules) has been satisfactorily tested.

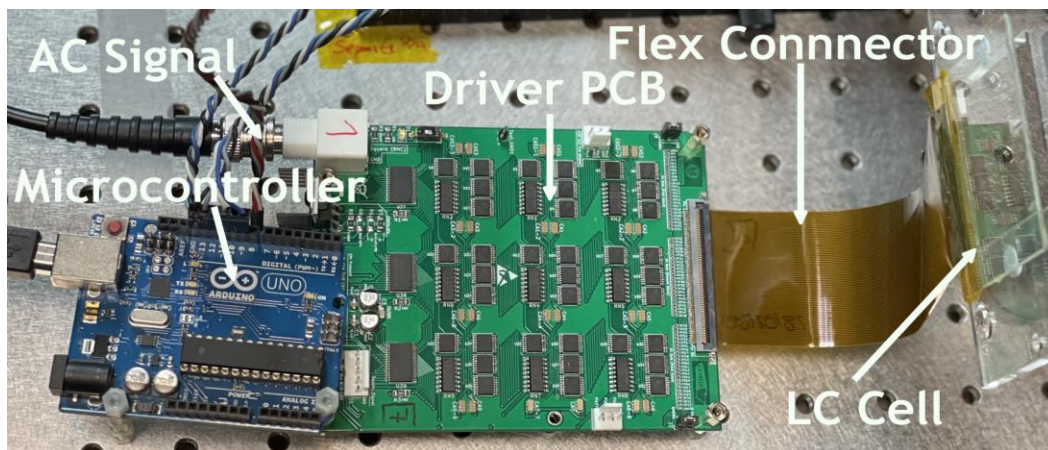


Figure 3.4: LC cell control using CEMDATIC driving system.

All the results shown in this thesis were obtained employing this electronic driver. However, the design showed some drawbacks:

- Need of external AC signals
- External power sources
- Lack of synchronization between the TLC5947

These pitfalls stimulated the design and development of newer alternative electronics.

3.1.2. CEMDATIC-ADTelecom Driver

A new electronic driver has been developed in the context of an ATTRACT Phase 2 European project in collaboration with ADTelecom [182], [183].

In contrast with the previous developed drivers, these electronics are based on three 96-channel integrated digital-to-analog converters (DACs) and a STM32 Arm microcontroller [184], [185]. The DACs remove the need of an external AC function generator and allow the synchronization of the different outputs. The microcontroller is now integrated in the PCB along with the power supply, thus resulting in a more compact design. This microcontroller enables communication with the PC through an embedded USB to UART converter.

Each driver can control up to 288 independent electrodes, using a differential driving method. In contrast with the driver previously developed in the CEMDATIC, where one of the ITO planes is always grounded, this one developed in collaboration with ADTelecom applies a square signal of negative amplitude to the backplane. This backplane signal is adjusted depending on the maximum V_{RMS} that is applied to the electrodes. In this way, the DACs resolution is maximized.

The GUI and control have been designed using Python, and the performance of the driver has been evaluated. Anyhow, further improvements are scheduled in the short term.



Figure 3.5: ADTelecom electronic driver.

3.2. LC cell quality control

After manufacturing the devices in the clean room, their performance needs to be assessed. The quality control is divided in two steps: thickness homogeneity evaluation and electrode integrity assessment.

The LC cell thickness homogeneity is extremely important within the active area, the device region where the light manipulation occurs. This evaluation is done by placing the manufactured LC cell between a polarized backlight and a linear polarizer. The device is oriented with the LC indicatrix oriented at $\pm 45^\circ$ respect to the polarized light. Due to the LC birefringence, there is a phase difference between the light components travelling aligned with the fast and slow axes that varies with thickness. Thus, for a given wavelength, the final polarization state will depend on this thickness. The second polarizer partially transmits or absorbs the passing light depending on the state of polarization. Since each wavelength will undergo slightly different SOP changes, they will be transmitted slightly differently. Therefore, a perfectly homogeneous material shows a single color between crossed polarizers while non-homogeneities are displayed as a variation of colors (Figure 3.6). Knowing the birefringence of the material, the sample thickness can be estimated by using the Michel-Levy charts [186].

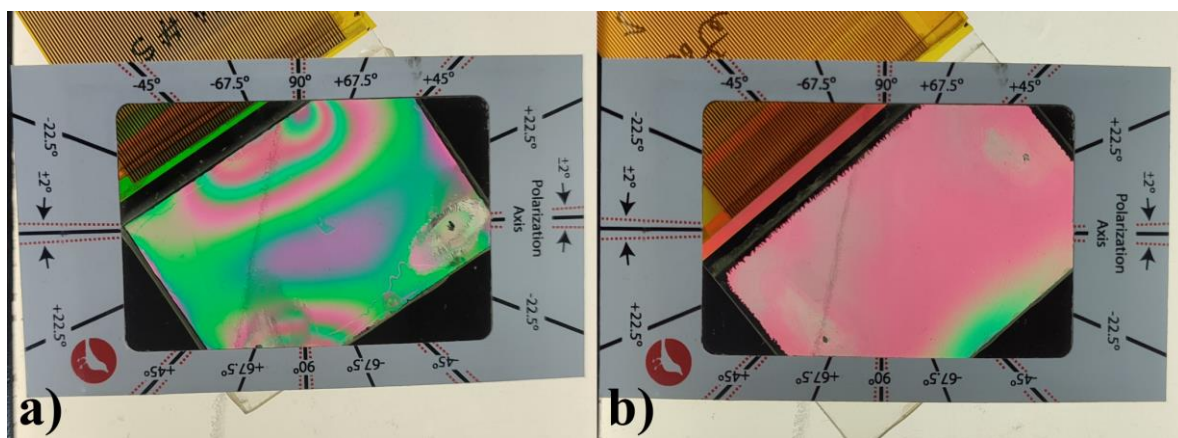


Figure 3.6: LC cell thickness assessment: a) Poor thickness quality. b) Acceptable thickness homogeneity.

After this visual inspection, LC cells with unacceptable thickness homogeneity are discarded. The samples that pass this evaluation are considered for electrode integrity analysis. It is crucial to verify that no short-circuits between adjacent electrodes exist since this could damage the electronic drivers. A low resistance between electrodes with different configured voltage levels may cause current and subsequent damage of the ICs output pins. This undesired phenomenon usually comes from a poor ITO ablation during the electrode patterning. Furthermore, the voltage drop across adjacent electrodes prevents the generation of the desired phase profile. This manufacturing mistake can be appreciated in Figure 3.7a, where only one electrode is active, but the electrode signal leak is manifested as the neighbor pixel is also partially activated.

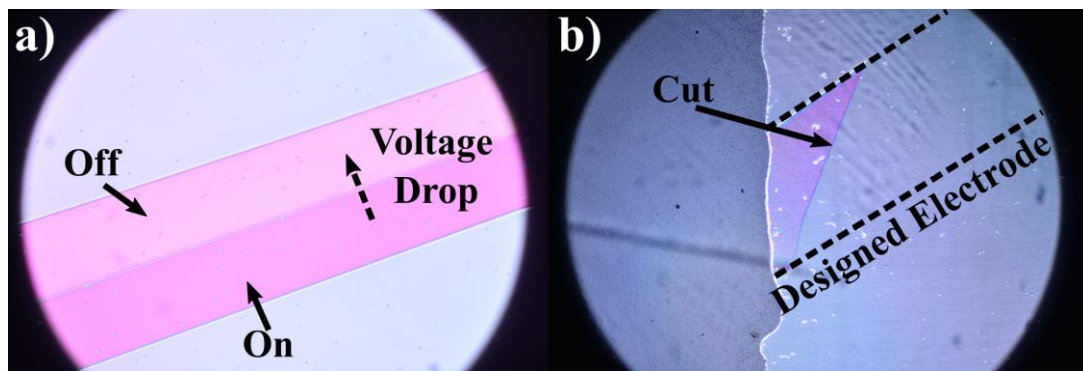


Figure 3.7: LC cell electrodes assessment: a) Low-resistance between adjacent electrodes, is manifested as a voltage drop activating both pixels. b) Broken electrode, original designed pixel (dashed lines) is not properly manufactured due to a scratch in the ITO layer.

Another manufacturing problem are the broken electrodes, electrodes that do not have the proper shape because the ITO layer is damaged (Figure 3.7b). To prevent this problem, all the glass substrates are optically inspected doing a manual scan over the whole surface. However, a small scratch (micrometer scale) may go unnoticed. The main sources for these broken electrodes are scratches during glass cutting where glass shards can damage the ITO layer, or commercial substrates with imperfect ITO deposition.

LC cell electrode integrity is crucial, a single mistake in a cell (i.e. one of 72 electrodes) renders it unusable. The electrode integrity assessment protocol is manually carried out with a multimeter testing the electrodes one by one (Figure 3.8). This manual verification is performed once cell manufacturing has been completed, leading to a significative waste of time and money. Therefore, these drawbacks have led to the development of an automated electrode verification system that is not ready to be implemented yet.

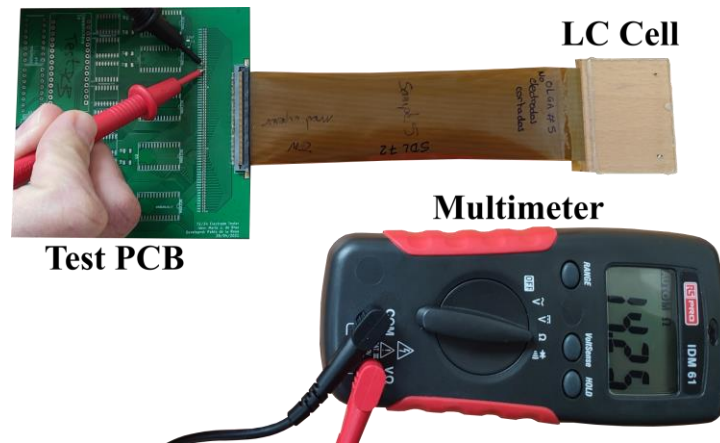


Figure 3.8: LC cell electrodes manual assessment protocol.

3.3. LC Cell Calibration

It is crucial to establish the correlation between the LC induced phase delay and the applied electronic signals. This calibration process is carried out in a 25°C temperature controlled dark room, placing the LC cell between crossed polarizers at $\pm 45^\circ$ with respect to the LC cell rubbing direction. A calibration optical setup is sketched in Figure 3.9a. For single wavelength calibration, a He-Ne laser emitting at 632.8 nm has been used. A spatial filter and beam expander are attached to the laser, increasing the spot size to calibrate the entire active area of the device. For devices that operate within the full visible light range (i.e. imaging lenses), a white light source followed by a color filter wheel are used. If required, an adjustable diaphragm is used to adapt the spot size to small-aperture devices. The transmitted intensity is recorded using a digital camera equipped with an objective focused at the LC cell surface [187].

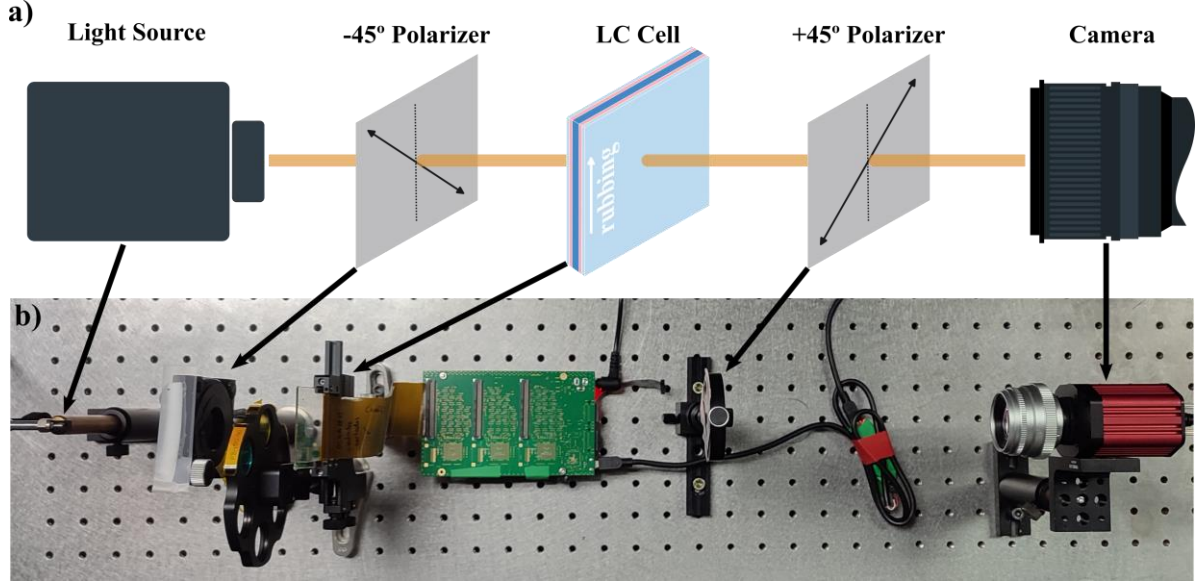


Figure 3.9: Calibration optical setup: a) Simplified setup scheme. b) Experimental optical setup using a white light source with a color filter wheel.

The transmission of the birefringent LC element depends on the induced phase difference (δ), between the ordinary light beam (polarized perpendicularly to the switching plane) and the extraordinary light beam (polarized parallel to the switching plane):

$$I \propto \sin^2 \left(\frac{\delta}{2} \right) \quad (3.1)$$

where δ directly correlates to the induced phase retardation of the extraordinary light beam relative to the invariant retardation of the ordinary light beam, and thus the variation of phase retardation of the device itself.

A calibration curve is obtained by sweeping the driver signal V_{RMS} while measuring the transmitted intensity. With the CEMDATIC driver the 12-bit (4096 values) driver PWM signal driver signal duty cycle (D) is swept. When using the ADTelecom driver, the V_{RMS} is directly modified instead of the PWM duty cycle. The signal sweep is automatized, with the same V_{RMS} level is sent to all the device electrodes and the transmitted intensity is recorded. Intensity readings of various regions of interest (ROIs) -defined by the user- is stored [112]. Each one of these ROIs provides a set of 4-pixels data with an RGGB configuration, performing a spatial averaging over the selected area for each pixel.

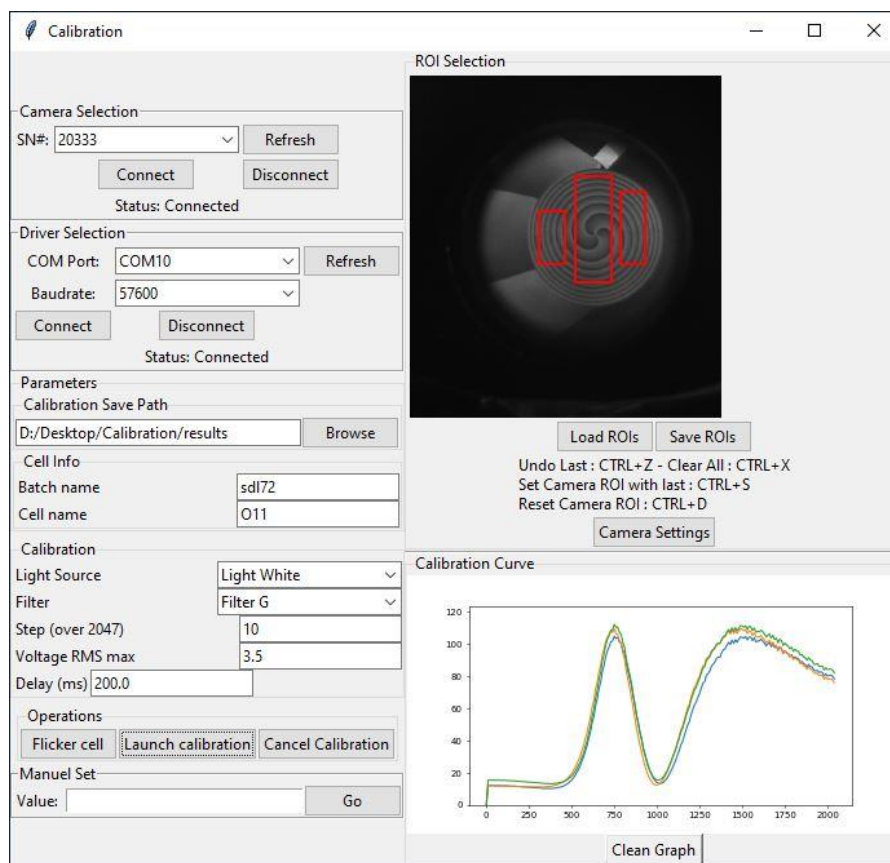


Figure 3.10: ROIs definition using ADTelecom driver on the LC cell active area.

The devices presented in this thesis employ 2π phase wrapping; therefore, gathering the relation between electrical signals and phase delay over a single wavelength is just required (Figure 3.11). It is advisable to adjust the external driving V_{RMS} to extend this 2π region over the 4096 values PWM range. By minimizing the external AC voltage, the 2π fitting region is expanded, increasing the resolution. Hence, phase errors are minimized. This effect can be appreciated in Figure 3.11, where a 2π phase variation is highlighted in blue. The higher the driving voltage, the more compressed is the 2π phase variation calibration curve.

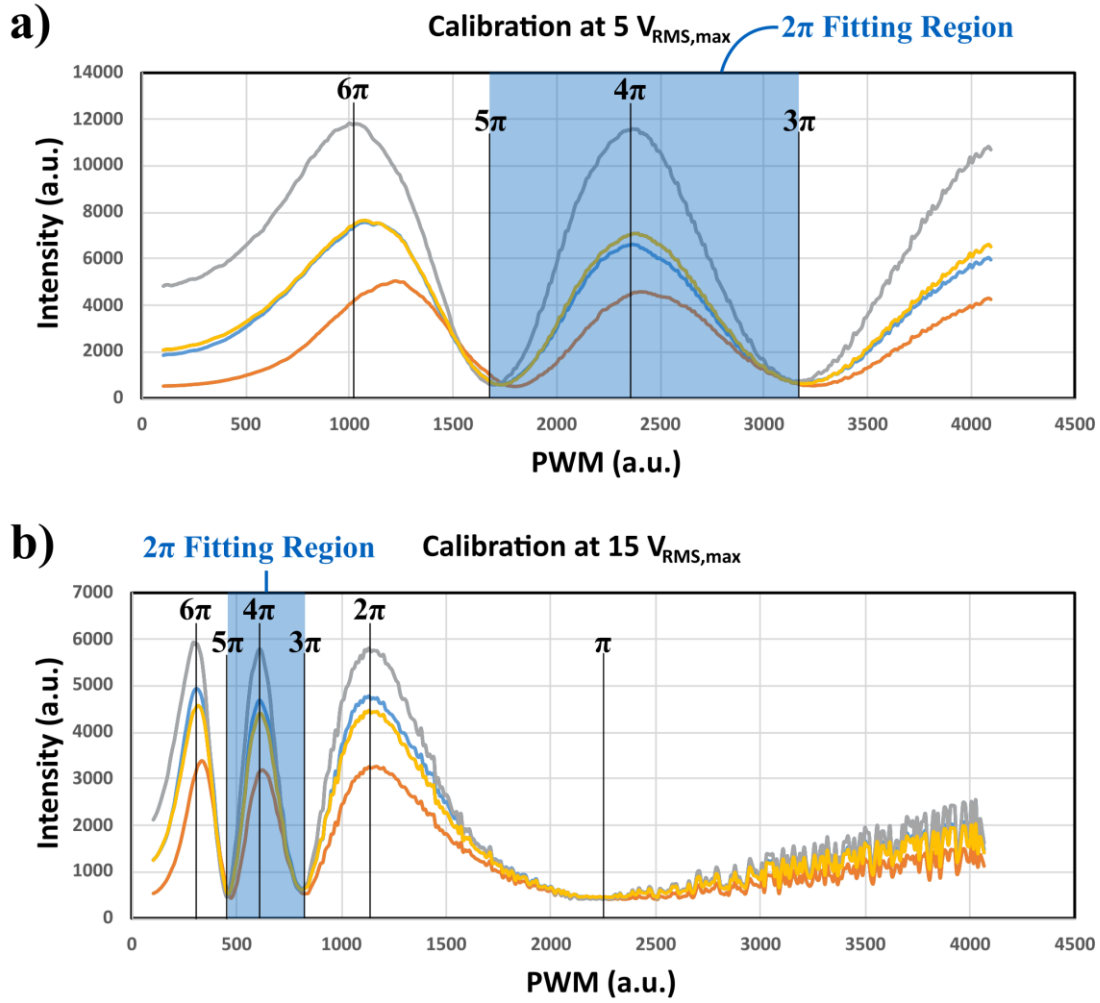


Figure 3.11: LC cell calibration for different external V_{RMS} voltages: a) $V_{RMS,max} = 5$ V. b) $V_{RMS,max} = 15$ V. Each line represents a different ROI red pixel set of data.

The relationship between induced phase delay and the applied duty cycle may be approximated by [112]:

$$\delta = A \cdot e^{-B \cdot V_{RMS}} + C \quad (3.2)$$

After adjusting the external $V_{RMS,max}$, one set of data is selected to perform the fitting following equation (3.3) using GRG Nonlinear Microsoft Excel Solver. Saturated ROIs should be avoided to correctly perform this fitting. It should be noted that, for a given cell, different calibration peaks positions across various ROIs, manifest order parameter or thickness fluctuations. This phenomenon can be appreciated in Figure 3.11a, where the different maxima and minima of the different ROIs are not present at the exact same PWM value.

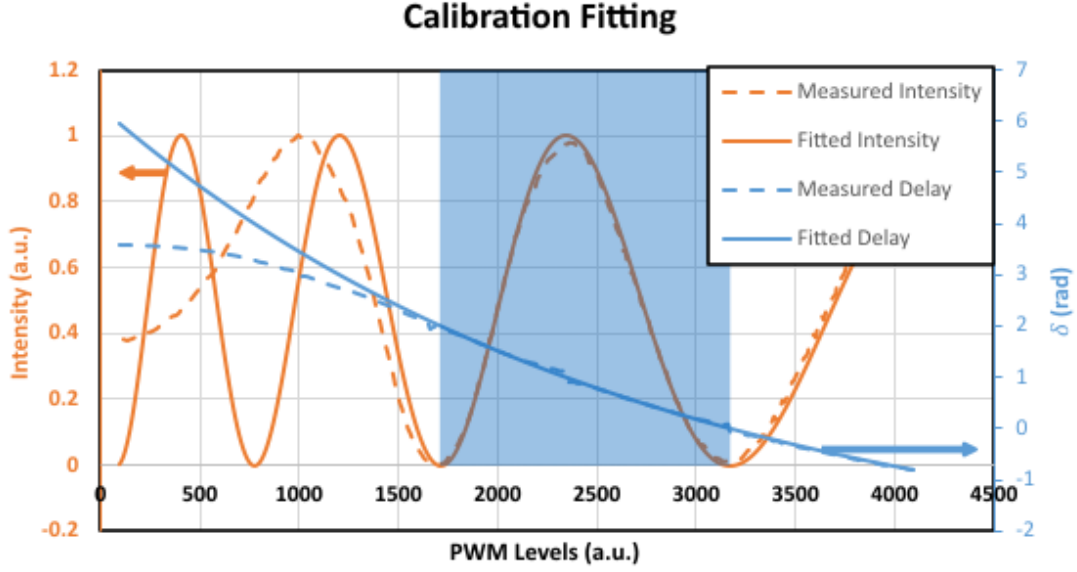


Figure 3.12: Calibration over 2π region. The graphs depict the measured intensity and phase delay (dashed lines) as well as the fitted (solid line).

A correctly fitted calibration is shown in Figure 3.12. The relation between the measured intensity (orange) and phase delay (blue) is plotted respect to the applied electronic signal PWM. The fitted curves using the previously presented pseudo exponential approximation are overlapped (dashed lines), showing the agreement between the measurements and the fitted curve.

Inverting the calibration fit, makes it possible to determine the voltage to employ for any given desired relative phase delay between 0 and 2π for each pixel.

$$V_{RMS}(\delta) = V_{RMS,max} \cdot D(\delta) = \frac{1}{B} \cdot \ln\left(\frac{A}{\delta - C}\right) \quad (3.3)$$

The same procedure can be performed for the ADTelecom driver where instead having a varying PWM duty cycle, the V_{RMS} is directly controlled by modulating the DAC output amplitude.

4. Spiral Phase Plates

Optical vortex beams (VBs) have lately become a target of extensive research mostly due to the peculiar properties and varied applications. These span many fields, including particle trapping [188], microscopy [146], and free space communications [132], [189], [190, p.]. This escalating interest underscores the imperative of developing optical devices capable of generating VBs.

Spiral phase plates (SPPs) are devices characterized by a continuously varying azimuthal phase delay [114]. Therefore, SPPs can induce the characteristic helical wavefront of VBs [90] from an incoming planar wavefront. At a given distance of propagation, the phase wavefront of a VB can be described by:

$$\phi(\theta) = e^{jl\theta} \quad (4.1)$$

where l is the topological charge and θ is the azimuthal angle about the optical axis. Thus, this phase profile is just an azimuthal phase variation within the active area of the SPP. This topological charge can be described as the number of entwined helices describing the wavefront, or the multiples of 2π phase delays in any transversal section of the VB. The phase profile may be generated by a conventional planar wave passing through an SPP (Figure 4.1) [112]. l is directly linked to the orbital angular momentum (OAM) [91] carried by the VB. This OAM is $l\hbar$ per photon travelling in the beam.

Positive and negative values of the l are determined by the handedness of the azimuthal phase delay. In this work positive TC values are assigned to the generation of left-handed helical wavefronts, which corresponds to a positive OAM.

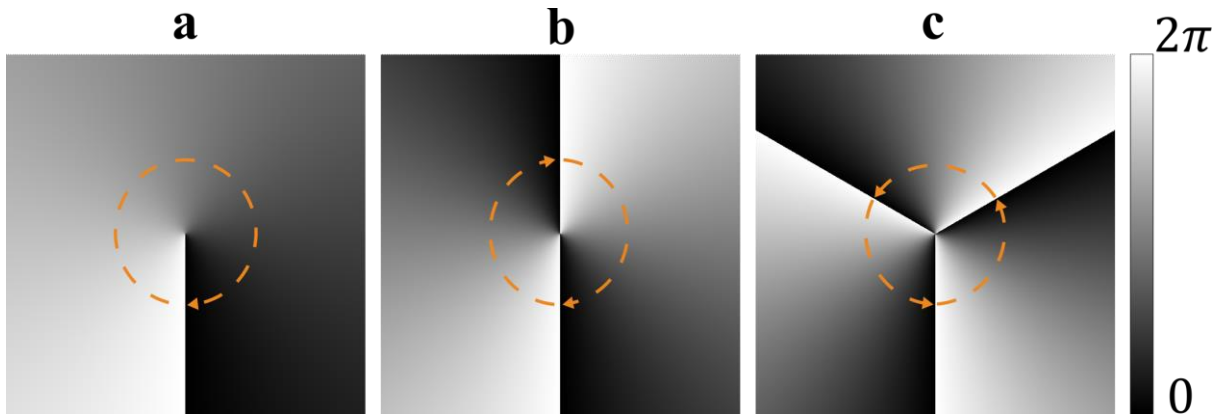


Figure 4.1: Phase profile of a continuous SPP that induces topological charges (l) in a light beam propagating out of the paper: a) $l = 1$. b) $l = 2$. c) $l = -3$. Note that the l sign is determined by the azimuthal delay handedness.

4.1. Design

In this work, tunable discrete SPPs are used. This kind of devices creates a phase profile divided into discrete steps, approximating a continuous phase delay (Figure 4.2) [191], [192].

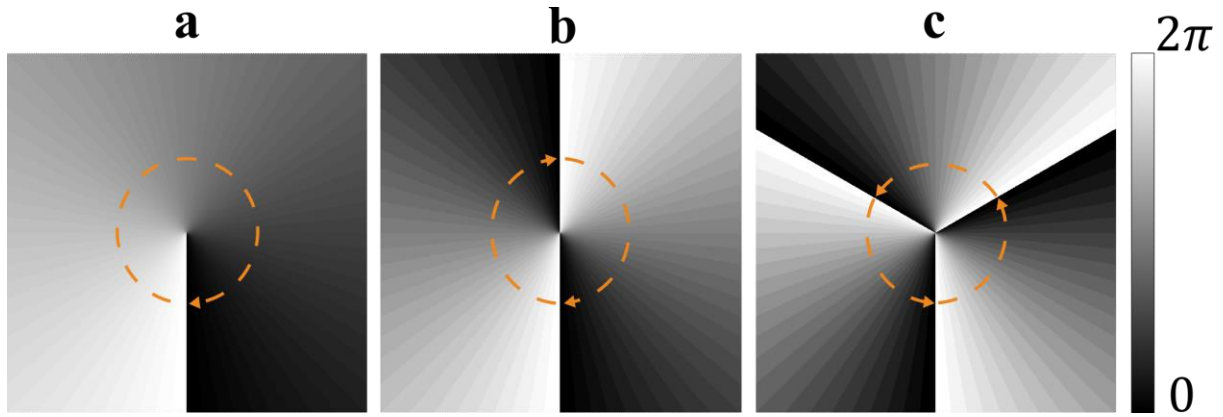


Figure 4.2: Phase profile of a discretized SPP with different topological charges (l): a) $l = 1$. b) $l = 2$. c) $l = -3$.

The developed SPP has been manufactured following the same LC structure and protocols described in the previous section (Chapter 3. Experimental). The patterned electrode design consists of 5 different regions (Figure 4.3):

- **Contact area** (yellow) consisting of 72 $250\mu\text{m}$ -width pads having a $500\mu\text{m}$ pitch. This is the area where an 80-conductors flex connector is attached using anisotropic conductive adhesive. High density ablation is performed between pads to avoid conduction between the contact area pads. The driving SPP electronic voltages are generated by the previously described drivers.
- **Counter Electrode contact** (green): Counter electrode voltage is the one transferred to the backplane. To provide this voltage to the LC cell, the outer 8 conductors of the flex connectors are used. The contra electrode voltage is connected to the opposing substrate using a silver-based conductor paste. The contra electrode is common ground when using the CEMDATIC driver or a negative amplitude square signal for the ADTelecom electronics.
- **Fan Out** (red): The signals must be transmitted from the contact area to the active area, for this purpose these curved electrodes are used.
- **Active Area** (purple): The 25.4 mm diameter active area is divided into 72 independent “pie slices”. This area induces the desired phase delay profile to generate optical vortices from an incoming light beam.

- **Design Contour** (blue): Ablation area limit that defines the minimum size of the the ITO covered glass substrate. Usually, glass substrates of 45×50 mm are used. It is important to ensure the proper ablation of the contour to avoid conduction between the contact area pads.

Each line in the design represents an area where the indium-tin oxide (ITO) is ablated using direct laser writing (DLW) technique (Figure 4.3). The DLW engraves 2 μm cuts that isolate one electrode from the adjacent ones [193]. The patterned design has also alignment marks to ease the backplane assembly. There are additional ablation hatched areas to ensure proper isolation between the different electrodes. These details have been omitted in the figure to ease the device design visualization.

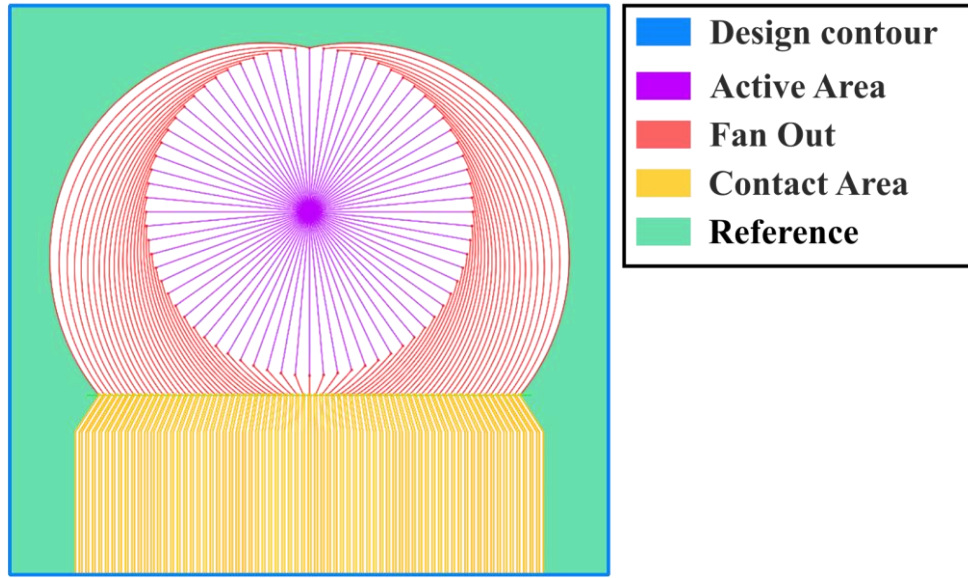


Figure 4.3: Patterned SPP electrode design sketch.

The independent control of these 72 pie-slice shaped pixels within the active area enables the approximation to any desired phase profile. Therefore, by modifying the pattern of the applied voltages, different OAM may be transferred to a passing beam.

SPPs were manufactured following the proposed design. The devices were filled with a nematic LC (MDA 98-1602, Merck GmbH).

4.2. Phase Profile Assessment

To achieve a wide range of topological charges in a thin device (*i.e.* $7\ \mu\text{m}$), 2π phase wrapping is employed. An SPP that introduces two phase-discontinuities of 2π in one revolution will produce an equivalent effect to an SPP that introduces a single phase-discontinuity of 4π (Figure 4.4a,b) [112]. However, the manufactured SPPs topological charge range is limited by its finite number of discrete electrodes (72), where the maximum l is obtained for a binary phase profile consisting of electrodes with an alternating phase delay of 0 and π . Therefore, achievable l ranges from $l = -36$ to $l = 36$ (Figure 4.4c), with the caveat that the two binary patterns are identical with a very small diffractive efficiency [179].

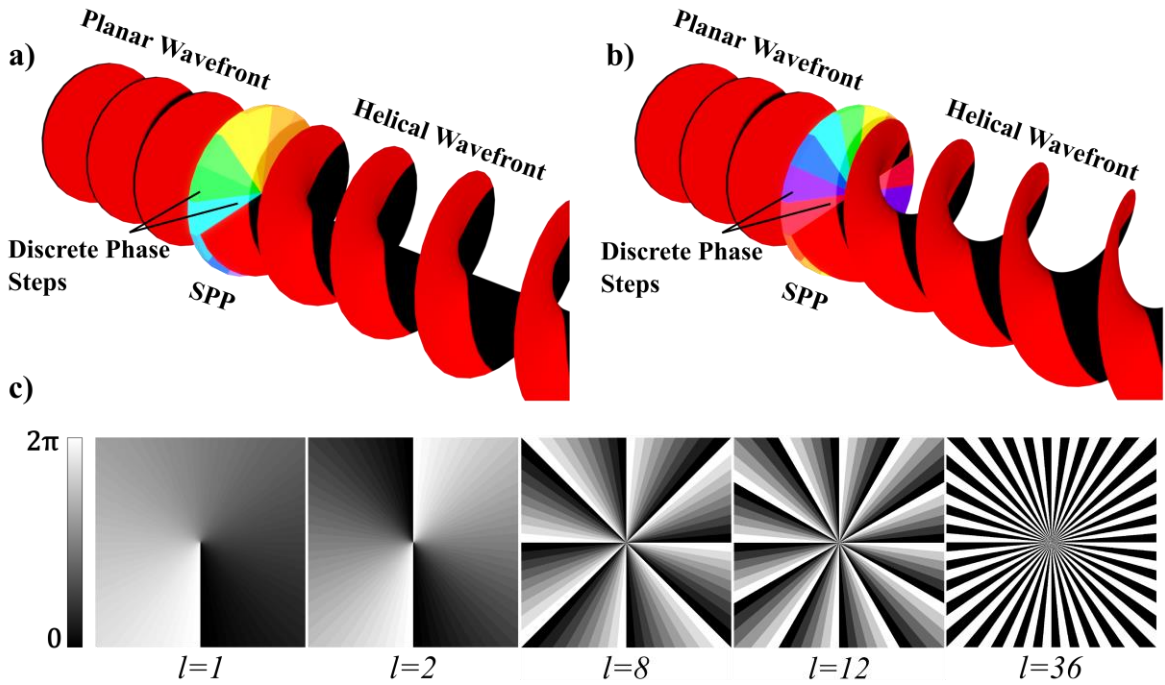


Figure 4.4: Optical vortex wavefront scheme, generated by a reconfigurable SPP with different topological charges [179]. a) $l = -1$. b) $l = -2$. c) Required discrete 72-electrodes SPP phase profiles to generate vortex beams carrying different topological charges. Note that the maximum achievable topological charges are the identical $l = \pm 36$.

The electrodes discretization evidence another limitation of the developed device, the phase profile approximation degradation with increasing l absolute value. The higher the topological charge is, the fewer available electrodes per 2π period (Figure 4.5). Additionally, the diffraction efficiency is jeopardized [194].

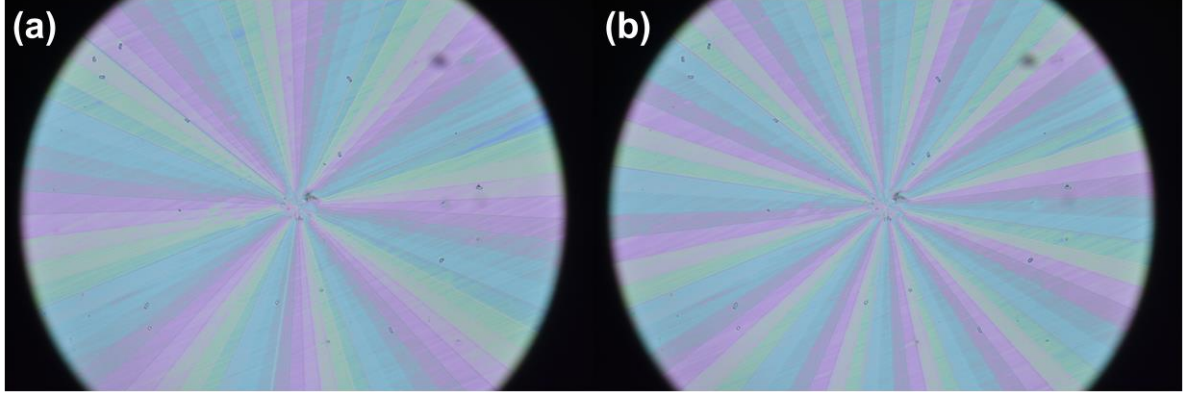


Figure 4.5: Manufactured SPP micrographs showing two different configurations under white illumination between crossed polarizers. (l): a) $l = 8$. b) $l = 12$. The higher l , the smaller number of electrodes per period.

Different approaches may approximate phase profile closer to the ideal for a given device:

- **Work with lower l absolute values.** This is the more straightforward solution. However, the performance of some applications requires high transferred OAMs, and thus high l absolute values.
- **Increase the number of electrodes.** The optimal number of electrodes will depend on the specific application. A large number of electrodes may compromise the fill factor, while a small number may result in unacceptable high diffraction losses. Additionally, increasing the pixel number requires a more complex driving. Lastly, this approach increases the possibility of manufacturing errors derived from the enlarged ablation area.
- **Implementation of a floating electrode layer.** Including an additional layer of a conductive material can help to smooth the phase profile at the expense of complicating the manufacturing process [195].

These limitations can be applied to all the devices presented in this thesis, as they arise from their discretized-pixel nature. On the contrary, these design approach enables the development of easily addressable thin devices with a high tunability.

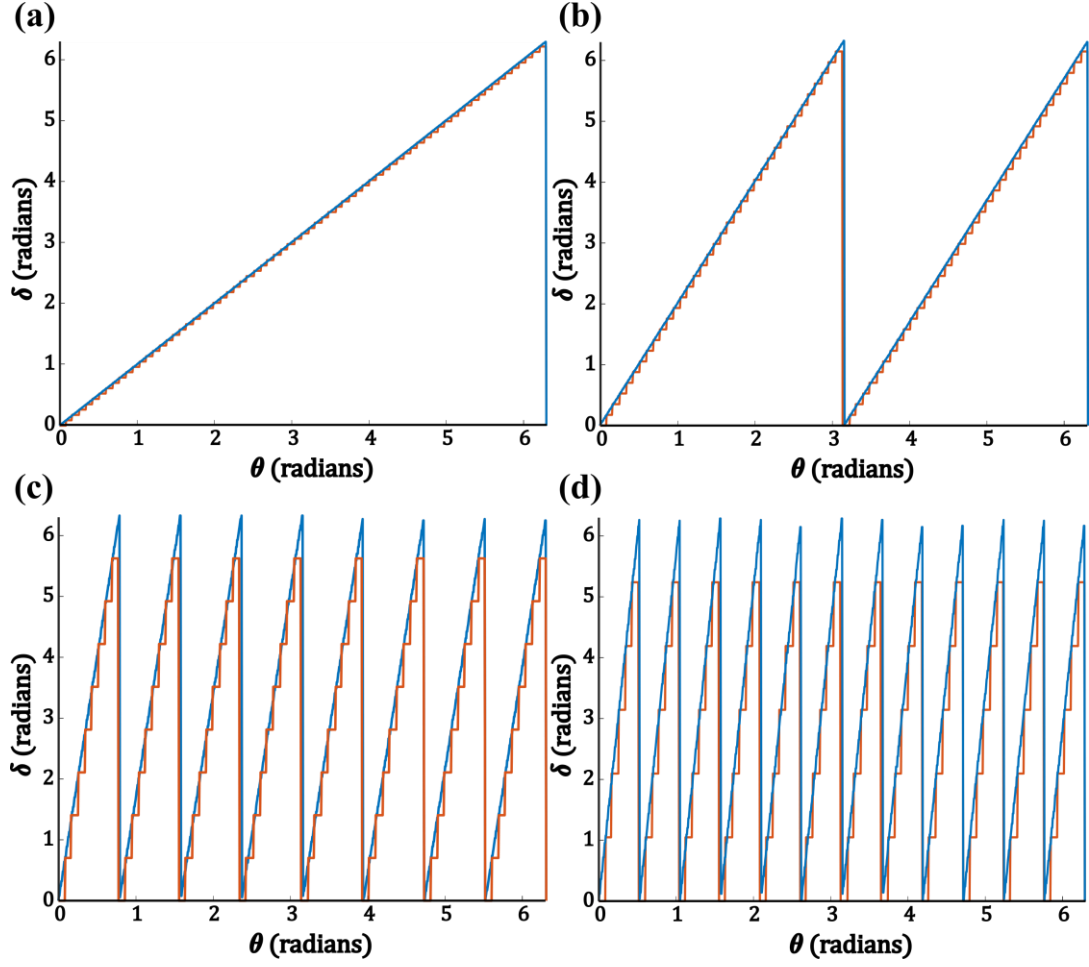


Figure 4.6: Comparison of the phase profiles for both discrete (orange) and continuous (blue) SPPs for different topological charges: a) $l = 1$. b) $l = 2$. c) $l = 8$. d) $l = 12$. The increasing the absolute value of l , the worse the approximation of the ideal phase profile.

The phase profile degradation relationship with the device topological charge can be better compared by unfolding the phase profile. To do so, the phase profiles for both a discrete SPP (shown in orange) and a continuous one (in blue) are simulated (Figure 4.6). Then, the values over one turn ($\theta = 0$ to $\theta = 2\pi$) are extracted and overlapped. The discrepancy between these two phase profiles becomes more evident as the topological charge is increased.

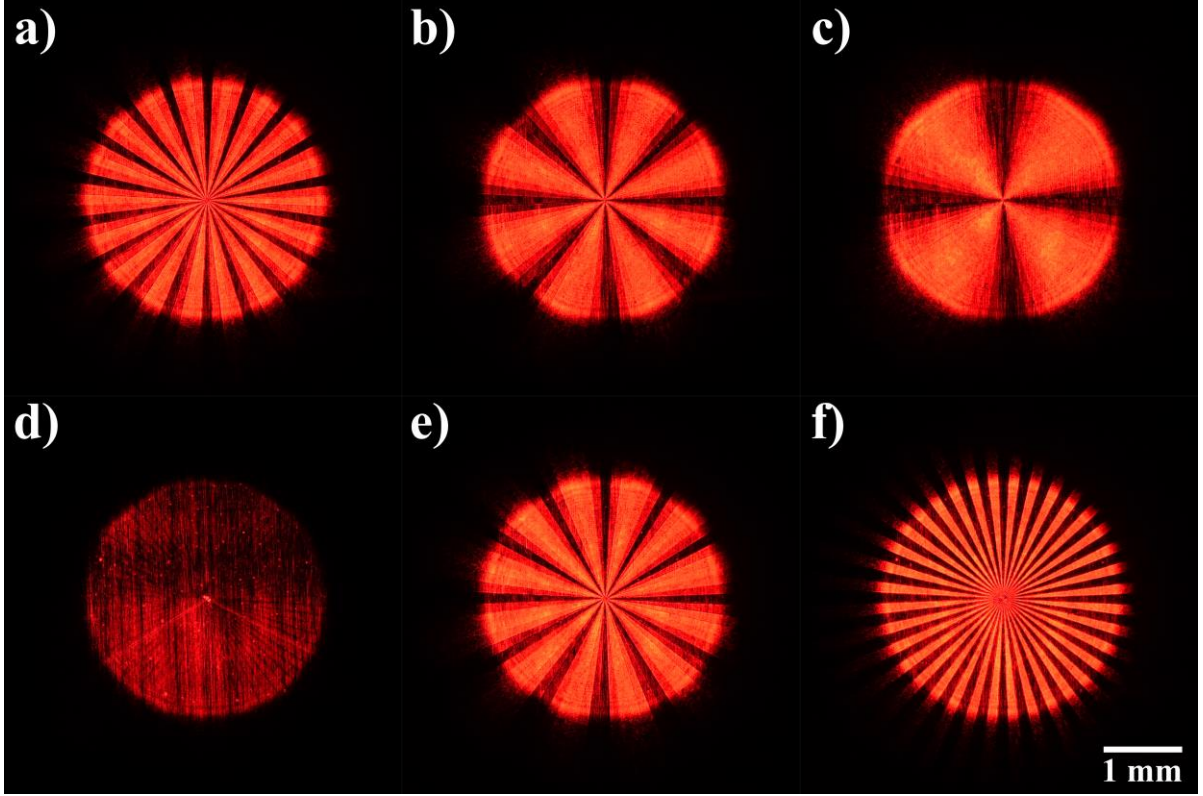


Figure 4.7: Manufactured SPP recorded phase profiles between crossed polarizers for different topological charges. (*l*): a) $l = -18$. b) $l = -8$. c) $l = -4$. d) $l = 0$. e) $l = 12$. f) $l = 36$.

One of the advantages of using this technology is that all the devices work in transmission mode. Therefore, the phase profile of the manufactured SPPs can be easily evaluated, simply interfering the two light paths using a conventional crossed polarizers setup; no complex interferometric optical setups are required. The different phase profiles are experimentally assessed by placing the device between crossed polarizers (Figure 4.7). An expanded He-Ne laser beam (632.8 nm) is used as a light source to illuminate the device active area. A camera objective is employed to image the active area of the SPP.

The obtained results confirm the tunability of the developed device. Integer topological charges ranging from -36 to 36 have been obtained. A manufacturing imperfection has been detected when observing the results: minor vertical lines in the phase profiles can be attributed to imperfect LC alignment. This alignment issue has been originated from an inappropriate polyimide rubbing during the LC cell manufacturing. The velvet roll height has not been properly adjusted, scratching the polyimide layer provoking these grooves. This alignment issue is also visible when illuminating the sample in the microscope between crossed polarizers Figure 4.5.

4.3. Vortex Ring Size

Optical vortices are characterized by having a phase singularity giving rise to an annular intensity pattern. This singularity originates from the coexistence of all phases ranging from 0 to $2\pi \cdot l$ at the optical axis [196]. The circular intensity pattern diameter depends on the absolute value of l [197].

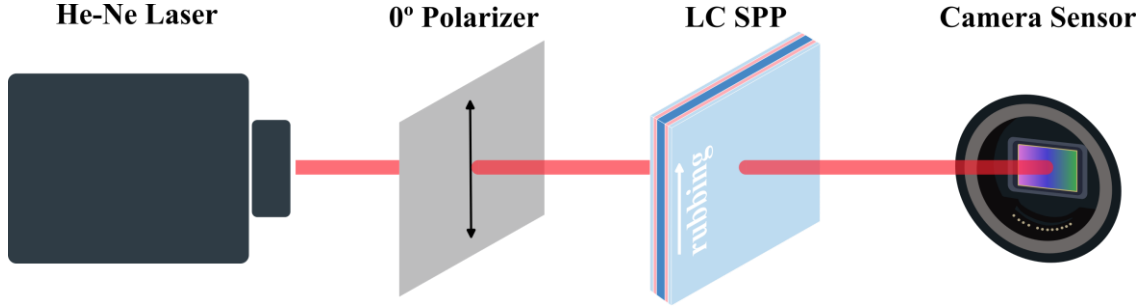


Figure 4.8: Singularity measurement setup. The SPP is illuminated by a laser source followed by a polarizer aligned with the SPP LC switching plane. The far field intensity is directly projected onto the camera CMOS sensor.

Creating OV's carrying different OAMs is useful in previously mentioned applications such as optical trapping or optical communications. To illustrate the developed device capacity of generating structured OV light beams, the device far field intensity generated patterns have been captured. The same setup of the previous section is used but employing just one polarizer aligned with the device LC switching plane (Figure 4.8). The light beam is projected directly onto the camera CMOS sensor.

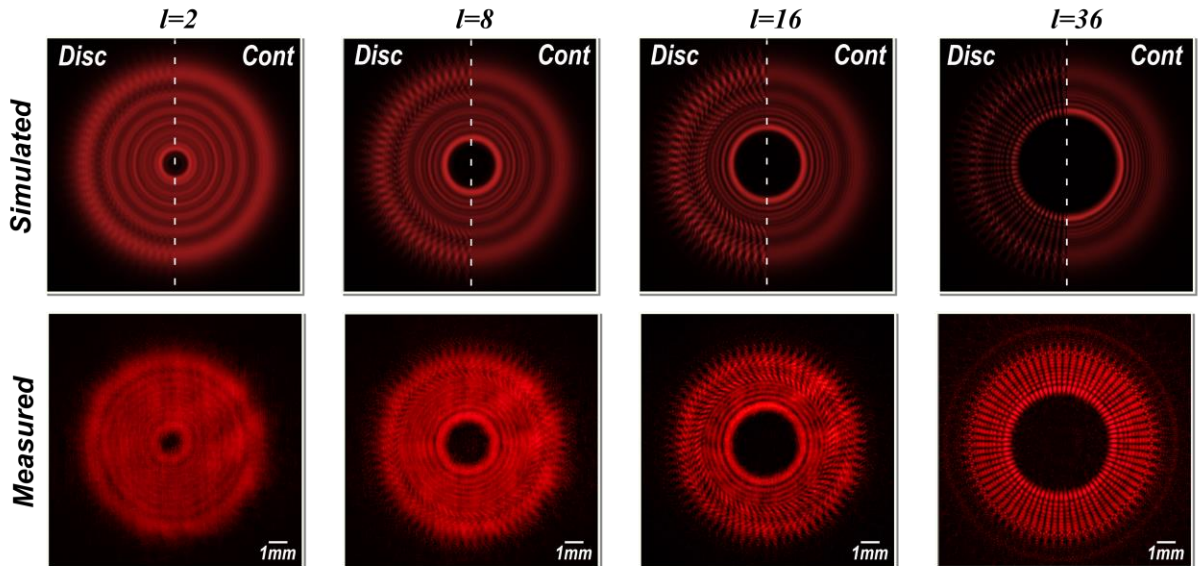


Figure 4.9: SPP intensity for different topological charges (l). Upper row contains simulations of a continuous ideal SPP as well as of a discrete one. Bottom row shows the measurements obtained from the LC SPP. The effect of the 10 mm diameter diaphragm giving rise to the Airy pattern has been included in the simulations [179].

Intensity pattern measurements were recorded for topological charges ranging from -36 to 36 . The measurements show a clear dark disk with a diameter that increases with the topological charge absolute value (Figure 4.9, bottom row). This phenomenon along with the recorded phase profiles demonstrates that the SPP is indeed capable of generating OV's with different l . The absence of light at the centre singularity validates the calibration process.

These measurements show clearly azimuthal and radial diffraction patterns. The azimuthal patterns are a consequence of the discretized phase profile, while the radial diffraction is the consequence of a finite beam diameter.

Angular spectrum intensity simulations for both an ideal continuous SPP and a discrete SPP. The results of these simulations are overlaid on the upper row of Figure 4.9. The simulation results confirm that the diffraction patterns only arise for the discretized devices. Furthermore, as the topological charge is increased, less pixels are used to recreate the ideal phase profile aggravating this effect.

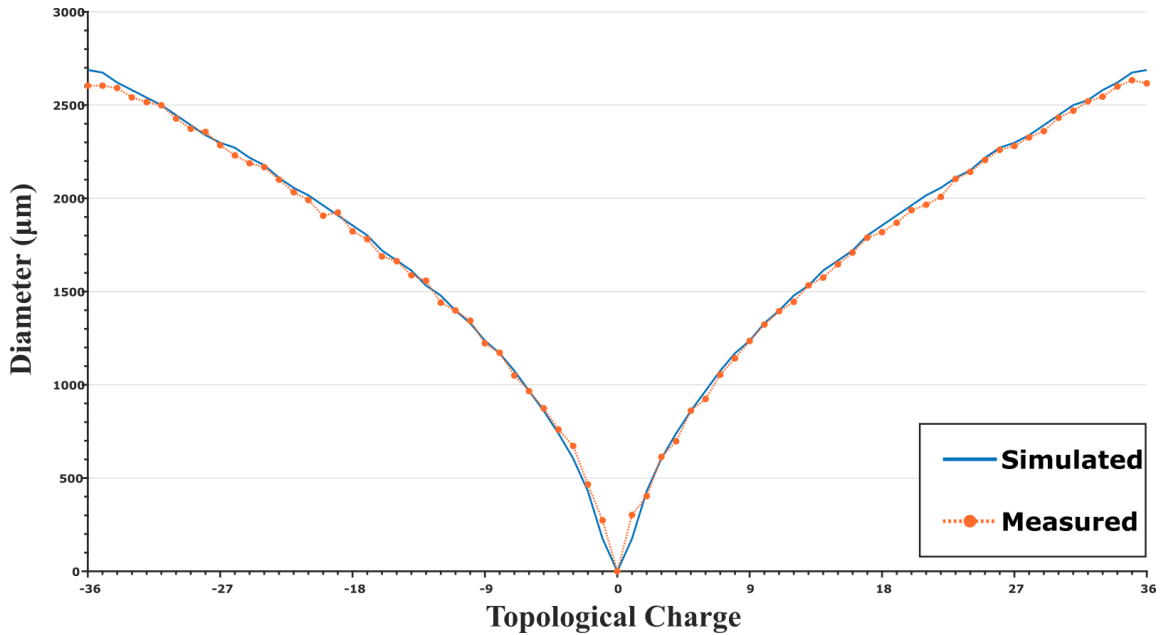


Figure 4.10: Evolution of dark disc radius respect to topological charge (l).

The diameter evolution was measured using a Matlab program to detect the edges of the dark disc intensity measurements and simulations. The intensities were stored as matrices and normalized individually. Subsequently, the matrices were sliced, to obtain the dark disc center row containing the profile of the intensity pattern. The position where the intensity reached 10% of the maximum one was established as the edge. Lastly the distance between the edges was computed. The disk diameter dependence on topological charge is plotted in Figure 4.10, showing a good agreement between simulated and measured data.

It is important to highlight that the radius dependence limitation is intrinsic to the generation of regular OVs. This phenomenon does not arise from the specific design of the device presented here. Different approaches have been considered to unlink l and intensity distribution. Particularly, in this thesis an optical setup to generate perfect vortex beams (PVBs) is proposed in section Chapter 7:

Perfect Vortex Beam Generation.

4.4. Fractional Topological Charge

The Spiral Phase Plates presented in this thesis represent various improvements compared to the previously presented LC SPP [112]. On one hand, the number of electrodes has been triplicated. Thereby, both increasing by three times the topological charge range and improving the phase profile approximation for any given topological charge number. On the other hand, the software and driving has been updated. The previous presented results have shown the generation of integer topological charges being integer fraction of the total number of electrodes in the device. However, this updated version can produce optical vortices with arbitrary topological charge (within the range from $l = -36$ to $l = 36$) [198].

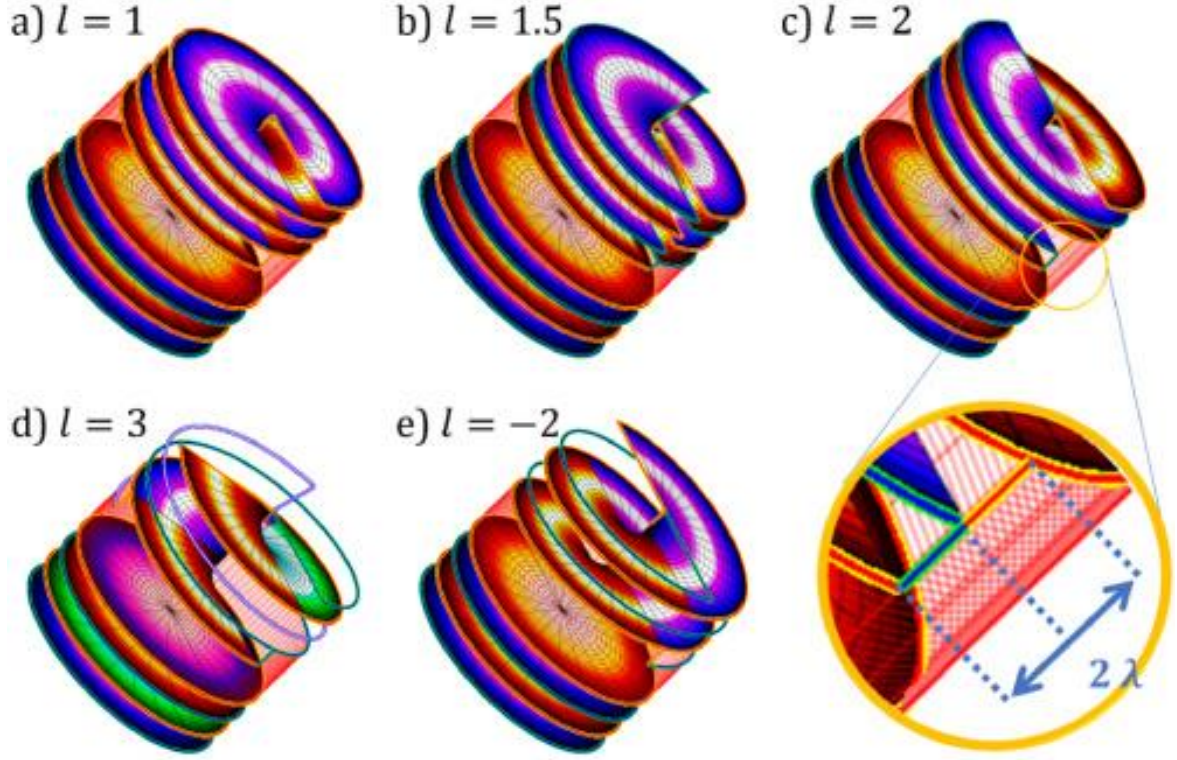


Figure 4.11: Propagating wavefronts scheme for five arbitrary topological charges ($l = 1, 1.5, 2, 3, -2$) [198]. In a, c, d and e, continuous helical intertwined wavefronts are occurring because of integer l . However, in b, a fractional topological charge ($l = 1.5$) produces a π phase discontinuity.

OVs having an integer topological charge are characterized by having a continuous phase evolution between successive wavefronts (Figure 4.11a, c, d, e). However, when l is a fractional value phase continuity is no longer occurring. A phase discontinuity now arises between neighboring sections of a propagation light beam (Figure 4.11b) [198], [199]. This phenomenon gives rise to radial destructive interferences.

The performance of a new LC SPP was assessed. The design of the device as well as the employed LC remained the same, but the thickness has been reduced to 4 μm . Additionally, LC alignment problem due to improper polyimide rubbing has been solved, as no defects are shown in the top row of Figure 4.12.

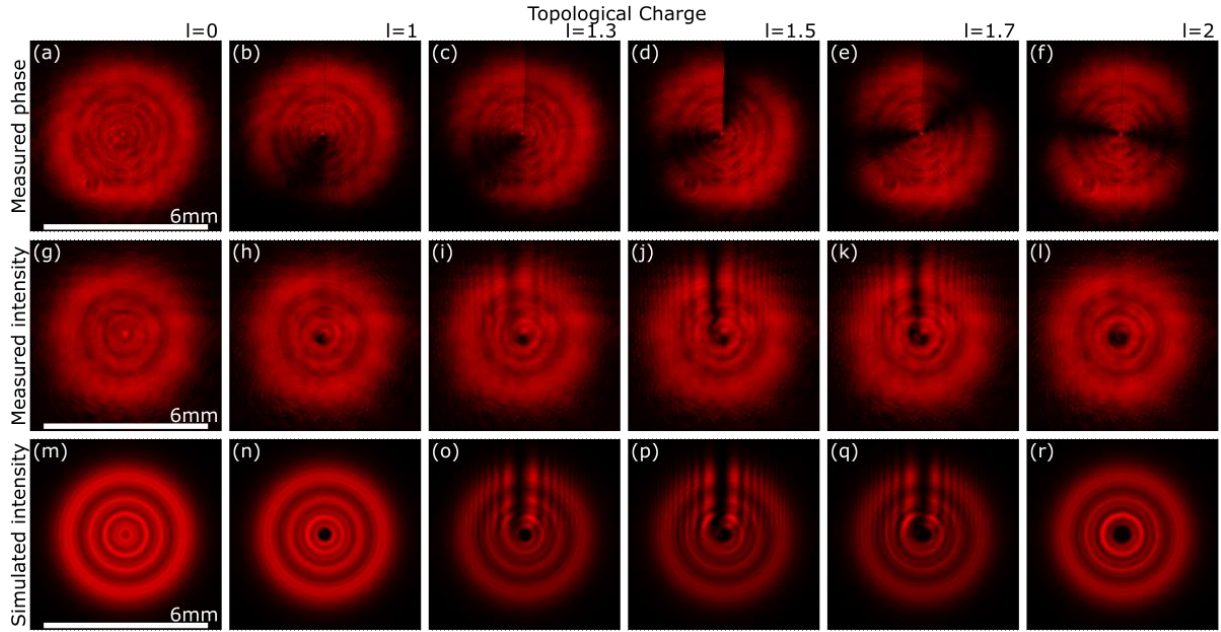


Figure 4.12: Generation of OV with fractional l where the radial interference appearance and elimination can be observed [198]. (a)-(f) Phase profile recording placing the device between crossed polarizers. (g)-(l) Measured intensity distributions. (m)-(r) Simulated intensity distributions including the optical setup pinhole ($\sim 3\text{mm}$ radius).

The correct functioning of the device with integer topological charges was confirmed. Subsequently the device was electronically addressed to study the evolution of fractional l .

The phase profile evolution depending on the l fractionality was assessed imaging the sample between crossed polars, as above, shown in the top row of Figure 4.12. The phase discontinuity can be appreciated at the 12 o'clock, corresponding to the transition between the pixel 1 and 72 of the SPP, with a maximum contrast for a half integer topological charge (*i.e.* $l=1.5$).

The phase distributions can directly be linked to the far field intensity distributions shown in the middle row of Figure 4.12. The radial destructive interference related to the phase discontinuity is clearly visible at the same position. The radial opening becomes more pronounced as the discontinuity is increased. Additionally, angular spectrum simulations were carried out being in good agreement with the obtained results (Figure 4.12, bottom row).

This kind of structured light beams have recently attracted an increasing attention in fields like particle sorting, optical encoding, or optical imaging. Most of the solutions proposed to generate these fractional OVs are based on SLMs [200], [201].

4.5. OAM Multiplexing in optical communications

One of the OV applications attracting more interest is related to the OAM data multiplexing. This technique relies on the orthogonality of OVs carrying different topological charge. Orthogonality allows the transmission of multiple (theoretically, infinite) simultaneous independent channel, largely increasing the transmission channel capacity [128, p.], [197], [202].

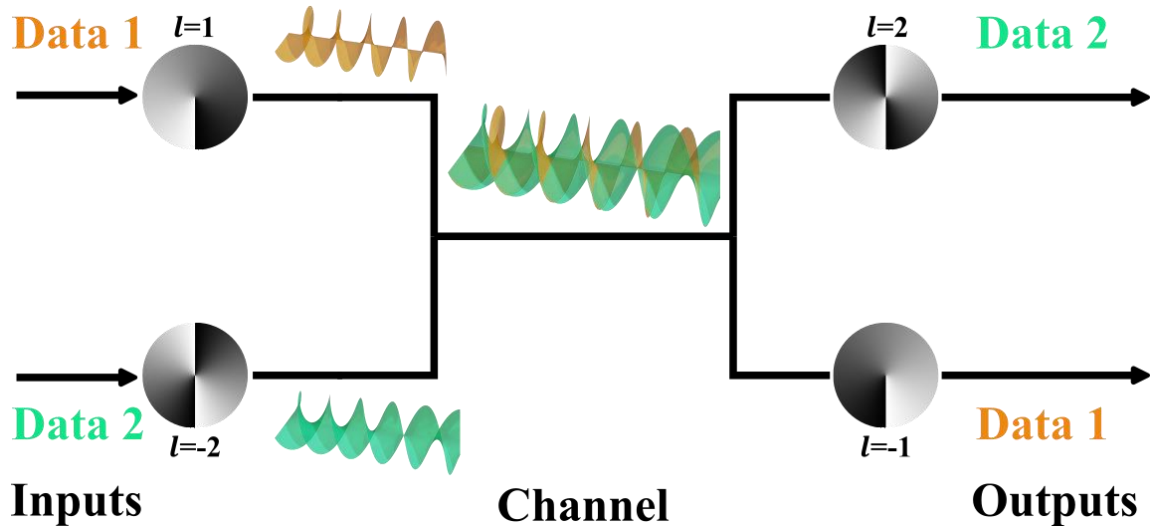


Figure 4.13: OAM Multiplexing sketch.

To achieve OAM multiplexing, different azimuthal phase variations are introduced onto planar light beams, producing a set of OVs with different l 's. All the OVs are transmitted through the same channel and demultiplexed by the receiver (Figure 4.13).

There are four key points in this technology:

- **Orthogonality of the different channels:** VBs possessing different l do not interfere between each other. Therefore, it is possible to transmit and recover them.
- **Decoding:** A specific VB can only be fully recovered (or untwined) by using an azimuthal phase variation with the opposite l of the original beam.
- **Complementary to existing modulations:** This technique is orthogonal to existing techniques like time or frequency multiplexing.

- **Theoretical infinite number channels:** As l can be any integer number, any arbitrary number of channels can be theoretically multiplexed over the same channel.

Therefore, OAM multiplexing is a new degree of freedom that has the potential to dramatically increase the transmission capacity. Nevertheless, there is a strict limitation when using this technique, namely preservation of the azimuthal phase variation. This is the reason why most of the studies or implementations of this technique have been carried out in free space optics. When using an anisotropic medium, like an optical fiber, the orthogonality between different OAMs significantly decreases. Some approaches have been proposed to solve this limitation, like vortex fibers, successfully accomplishing data transmission [136], [203]. Even so, this challenge jeopardizes the implementations of multiplexing in the deployed fiber optics communication systems.

This technology is still promising for free space optical communications, specifically through scattering-free mediums like satellite communications. Hence, a system to implement this OAM-based technology using two SPPs is proposed in this work. The SPPs ability to generate and decode VBs carrying arbitrary l make them suitable for being both modulator and demodulator.

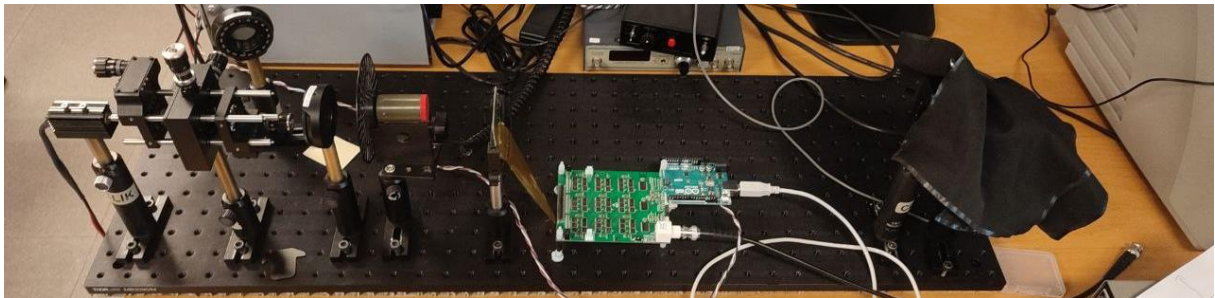


Figure 4.14: Proposed SPP OAM multiplexing setup. a) Simplified setup scheme. b) Experimental setup.

As a proof of concept, an optical setup has been built consisting of:

- Laser source
- Linear polarizer
- Mechanical chopper
- Two SPPs
- 4 μm -diameter pinhole
- Photodetector

The laser beam is carefully aligned with the center of the SPPs and the pinhole. The laser beam is being chopped to ease the detection of the signal by the photodetector. Having the SPPs being turned off, the photodetector will detect the chopped laser light as a square signal being discriminated from the noise. Once the first SPP is turned on, polarized light will be transformed into an OV of a given l , producing a singularity. When properly aligned, the dark disc of the singularity will be manifested as a decrease in the received photodetector signal. However, if the second SPP is activated to induce the opposite l , the VB will be untwined resulting in a beam with $l = 0$. The recovered beam will not possess a phase singularity, thus being detected as a high amplitude signal by the photodetector. This experiment can be seen as OAM coding/decoding setup translated to an ON/OFF amplitude modulation. Preliminary experiments have been carried out with satisfactory results, but the system needs to be re-assembled and evaluated again for a more detailed analysis.

4.6. Optical manipulation

A collaboration with researchers from the Department of Física de Materiales of the Universidad Autónoma de Madrid (UAM) has been initiated during this thesis. The goal of this collaboration is exploring the applicability of the developed LC SPP to optical trapping.

Optical trapping refers to the capture of particles by a strongly focused light beam [204]. Optical trapping makes possible to develop light-based non-contact tools to isolate, sort or filter different particles or cells [205], [206], [207]. VBs can transfer different OAM to the particles, by using different l [208]. Most of the reported experiments are achieved using SLM-based optical setups [144], [209]. A transmissive device like the developed SPP can be a purpose-built solution to simplify optical trapping setups.

The UAM developed optical trapping setup relies on a 980 nm laser (Lumics) with a power of 500 mW. The use of this laser entails two main challenges:

- **Working wavelength:** The maximum induced phase delay is inversely proportional to the light wavelength (Chapter 2: Electrical anisotropy and birefringence LC Cell Calibration) assuming a constant birefringence (Δn). Thus, to achieve 2π phase delay, the LC cell thickness needs to be increased. By increasing this cell thickness, the cell response is becoming slower, and the LC ordering in the cell is reduced.

- **High power:** The employed high-power laser could lead to two considerations. First, light-induced LC reorientation could be produced, leading to undesired lensing effects [210]. Secondly, if the LC cell temperature gets too high, a phase transition to isotropic phase may occur rendering the device unusable [211].

A 72-electrodes SPP has been successfully manufactured using MDA 98-1602 nematic LC with a $14\ \mu\text{m}$ thickness. It has been calibrated, showing that it possesses the required 2π phase range for the laser working wavelength (Figure 4.15). The thickness homogeneity has been assessed and considered acceptable. The LC response time has been evaluated being around 1 s.

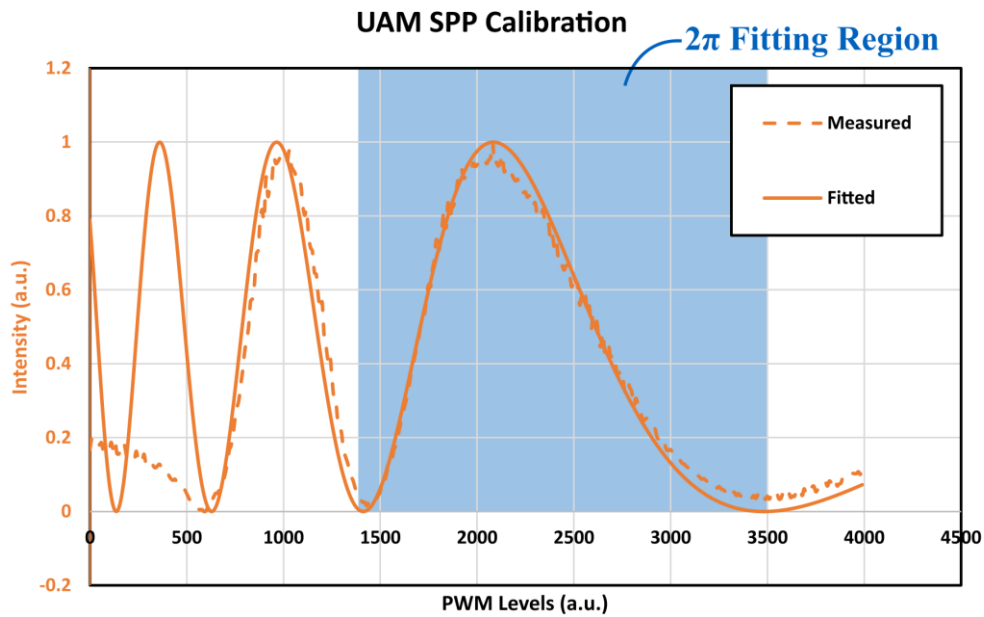


Figure 4.15: Optical trapping SPP calibration obtained using 980 nm laser

To ensure that the obtained calibration worked properly, the intensity pattern generated by the SPP has to be measured. The cells were shone with laser beam coupled to a linear polarizer aligned with the LC cell rubbing direction. The laser beam was directly projected onto the CMOS camera sensor; it must be stressed that the sensitivity of the sensor at $\lambda = 980\ \text{nm}$ was quite low. The shutter speed and ISO of the camera had to be modified to increase the gain and obtain images of the generated patterns. Optical singularities were measured for topological charge ranging from $l = -36$ to $l = 36$. Some of these measurements are shown in Figure 4.16. Additionally, no thermal or

reorientation degradation was observed. These measurements validate the proper performance of the device, being ready to be integrated in the optical trapping setup.

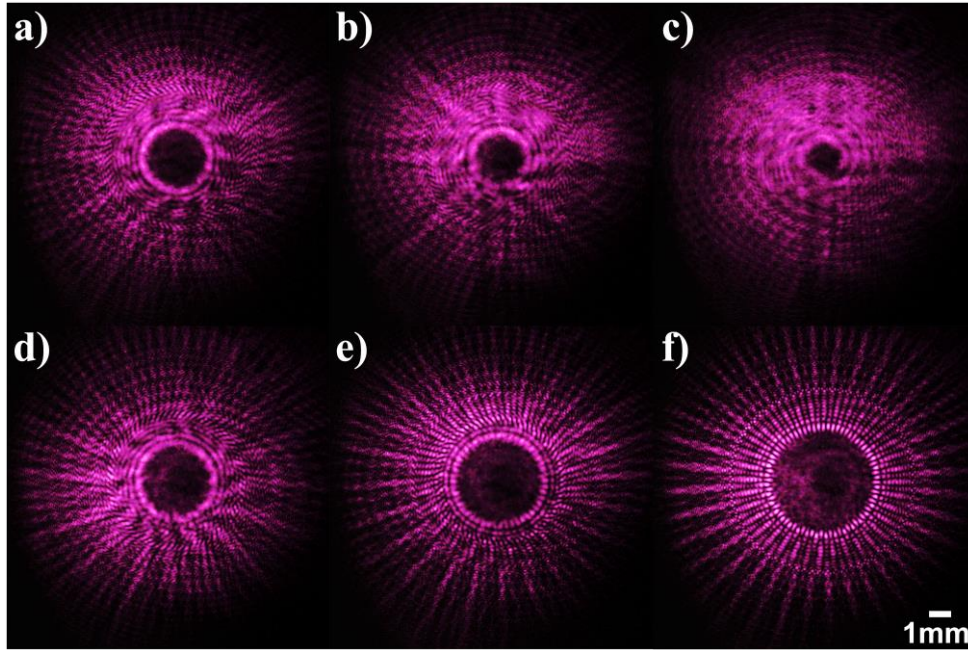


Figure 4.16: SPP recorded intensity patterns for different topological charges at $\lambda = 980$ nm. (l): a) $l = -16$. b) $l = -8$. c) $l = -4$. d) $l = 12$. e) $l = 24$. f) $l = 36$.

The integration in the optical setup has been challenging; several modifications had to be carried out. At present, only preliminary studies have been carried out. The electronic drivers and the LC cell along with the control software have been integrated in the setup (Figure 4.17). Laser power tests as well as different types of particles are being evaluated. Further experiments need to be performed to assess the potential of the developed SPP in optical trapping applications.

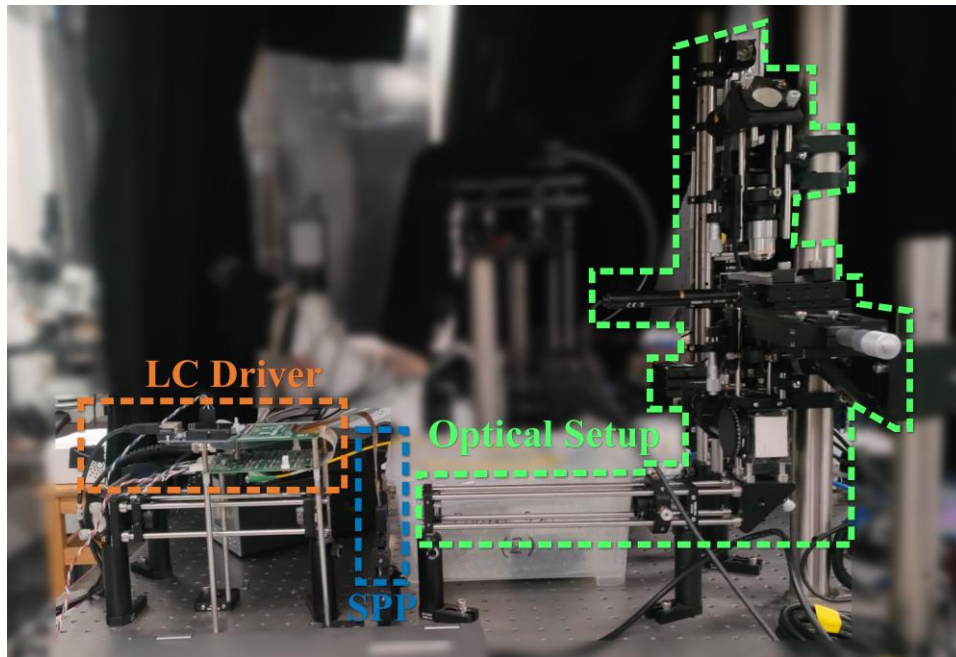


Figure 4.17: Optical trapping setup current state.

5. Diffractive Spiral Axicons

A conventional refractive axicon has a conical structure, but as all the devices presented in this thesis, a phase-wrapping over 2π has been performed resulting in a blazed axicon [212]. By dividing the cone into periodic conical sections and applying a phase wrapping of 2π , a radial blazed phase profile is obtained [86], [178] (Figure 5.1).

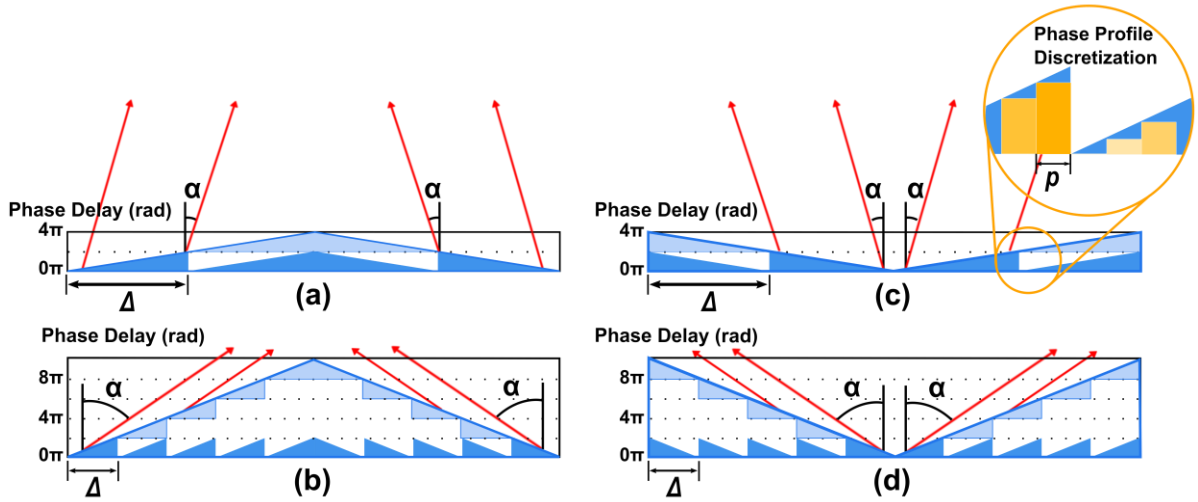


Figure 5.1: Illustration of convergent (a, b) and divergent (c, d) blazed axicons wrapping over a 2π range. The two different rows show two different grating pitches (Δ) leading to different output angles (α). The insert shows the discrete pixel distribution and pixel pitch (p).

For a given wavelength (λ), the output angle of the axicon (α) can be obtained as a function of the blazed grating pitch (Δ), similar to the case of a linear diffractive blaze grating [22]:

$$\alpha = \tan^{-1}\left(\frac{\lambda}{\Delta}\right) \approx \sin^{-1}\left(\frac{\lambda}{\Delta}\right) \approx \frac{\lambda}{\Delta} \quad (5.1)$$

Therefore, by controlling the blazed profile it is possible to create axicons with different outputs angles. However, in contrast with the previously presented Spiral Phase Plate, addressing Fresnel devices composed of concentric sections is a challenge.

Electrical connections need a continuity from the periphery of the device to the different sections that need to be addressed. This limitation is illustrated in Figure 5.2 [95]. In this figure, colors are used to depict different phase delays. When addressing a concentric device, like the Fresnel lens represented in the bottom left a multilayer scheme could be employed [174]. This figure illustrates the manufacturing complexity for a small number of sectors, an actual device may possess larger number of zones.

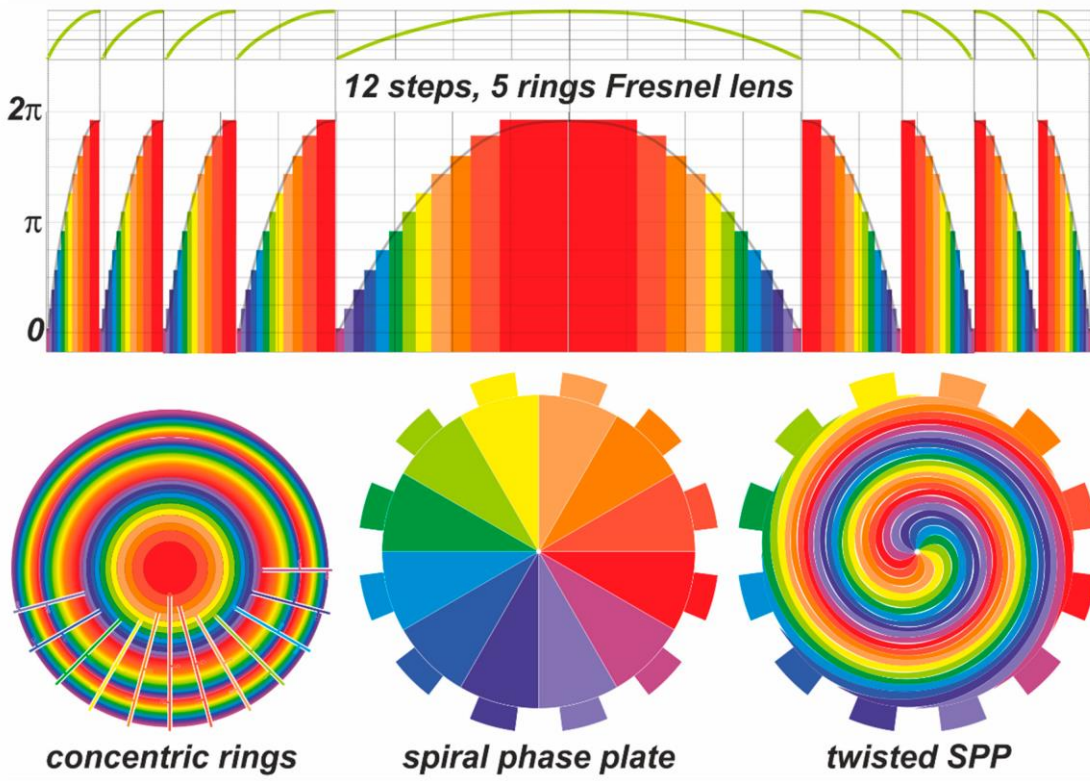


Figure 5.2: Simplified illustration of concentric Fresnel devices addressing challenge [95].

Some authors have proposed complex electrode designs such as microstructured transmission lines [82], [213], serpentine electrodes [214], [215], or interdigitated comb electrodes [216]. In this work, a solution to the interconnection challenge using devices consisting of spiral electrodes is proposed.

5.1. Design

The electrical connections can be simplified by using spiral-shaped pixels rather than concentric sections as each electrode reaches the periphery of the cell. This has been employed for creating both, axicons and lenses (Chapter 6:

Spiral Diffractive Lenses), each one with a different spiral geometry (Figure 5.3).

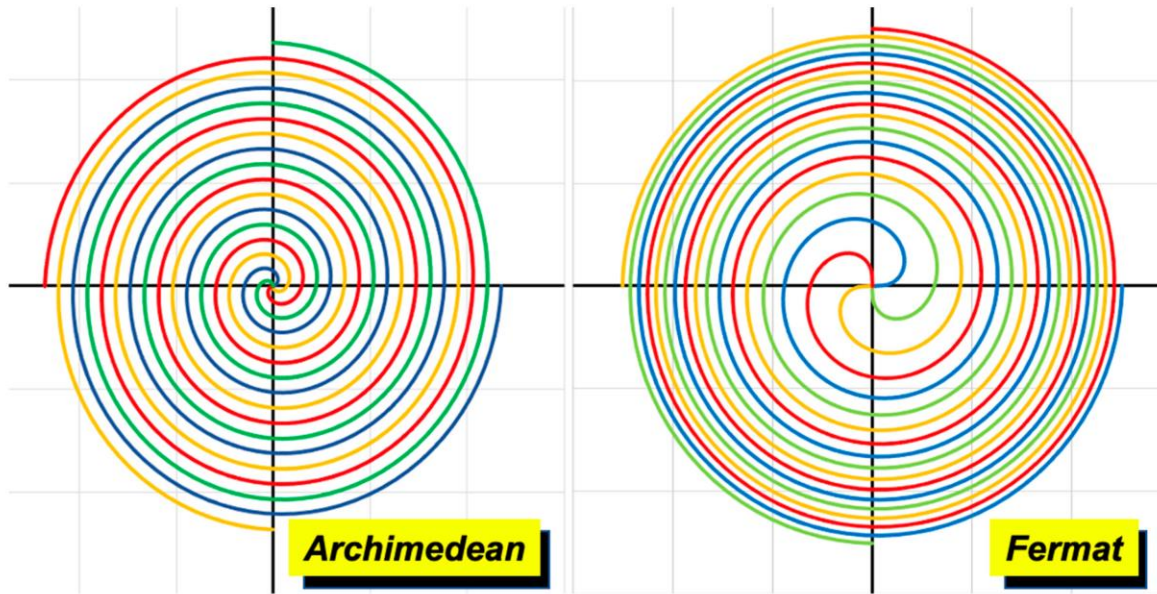


Figure 5.3: Sketch showing two types of spirals used. On the left, four interleaved Archimedean spirals. On the right, four Fermat spirals are drawn [95].

The manufactured LC Diffractive Spiral Axicon (DSA) consists of Archimedean spiral-shaped pixels [217]:

$$r(\theta) = a \cdot \theta \quad (5.2)$$

where r is the radial distance, θ is the polar angle and a is an arbitrary coefficient. This kind of spiral have a constant separation between turns independently of the radial distance.

The spiral phase profile of the diffractive spiral axicon results from the addition of one of an SPP with the one of a Fresnel Axicon, wrapped about 2π (Figure 5.4).

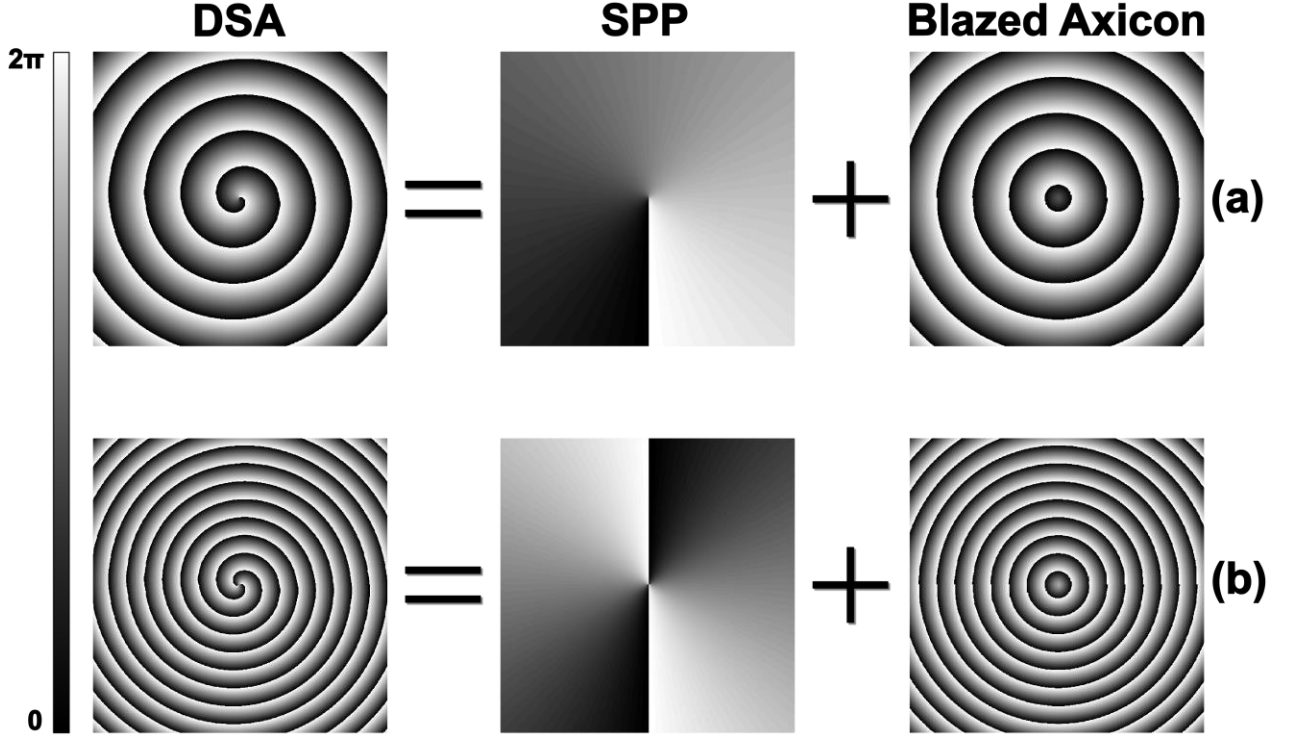


Figure 5.4: DSA phase profile simulation [178]. It is obtained as the addition of a SPP and a blazed axicon for different topological charges. (a) $l = 1$. (b) $l = 2$.

From the figure it is noticeable that the phase profile possesses a constant separation, or blaze pitch (Δ), between different turns, being equivalent to an Archimedean spiral. The phase transmission function can be described as [178], [217]:

$$t(r, \theta) = \exp [(iar + il\theta)] \quad (5.3)$$

where a is the axicon parameter. This parameter is related to the output angle (α) and is dependent on the blaze pitch (Δ):

$$a = \frac{2\pi}{\lambda} \alpha = \frac{2\pi}{\lambda} \sin^{-1} \left(\frac{\frac{2\pi}{\Delta}}{\frac{2\pi}{\lambda}} \right) = \frac{2\pi}{\lambda} \sin^{-1} \left(\frac{\lambda}{\Delta} \right) = k \sin^{-1} \left(\frac{k_r}{k} \right) \quad (5.4)$$

where k is the light wave number and k_r is known as the radial wave number:

$$k_r = \frac{2\pi}{\Delta} \quad (5.5)$$

The spiral pitch of the axicon and the blaze pitch are equivalent. In our implementation the spiral pitch is obtained by multiplying the number of spiral shaped pixels per period times the pixel pitch (p). In contrast with previously presented axicons where the spiral pitch is constant, hence having a constant axicon parameter, the present device has a tunable pitch (Δ_l):

$$\Delta_l = p \cdot \frac{N}{l} \quad (5.6)$$

The spiral pitch of the DSA is dependent on the total number of pixels (N) and the selected topological charge (l). The pixel pitch (p) and N are design parameters, while l can be electronically tuned. The spiral pitch tunability can be appreciated in Figure 5.5, where a change in the topological charge leads to spirals with a different pitch. Thus, leading to a tunable axicon parameter (a_l) and output angle (α_l):

$$a_l = \frac{2\pi}{\lambda} \sin^{-1} \left(\frac{\lambda \cdot l}{p \cdot N} \right) \Leftrightarrow \alpha_l = \sin^{-1} \left(\frac{\lambda \cdot l}{p \cdot N} \right) \quad (5.7)$$

The DSA spiral phase profile concertedly modifies the topological charge of a passing light beam while changing the output angle.

A number of DSAs have been manufactured with an active area formed by $N = 24$ spiral shaped pixels. The pixel pitch (p) has been designed to be $30 \mu\text{m}$, resulting in a device with a maximum spiral pitch of $\Delta_l = 720 \mu\text{m}$ ($@ l = \pm 1$). The LC cell thickness was set to $7.2 \mu\text{m}$ by employing silica spacers and filled with MDA-98-1602 nematic LC.

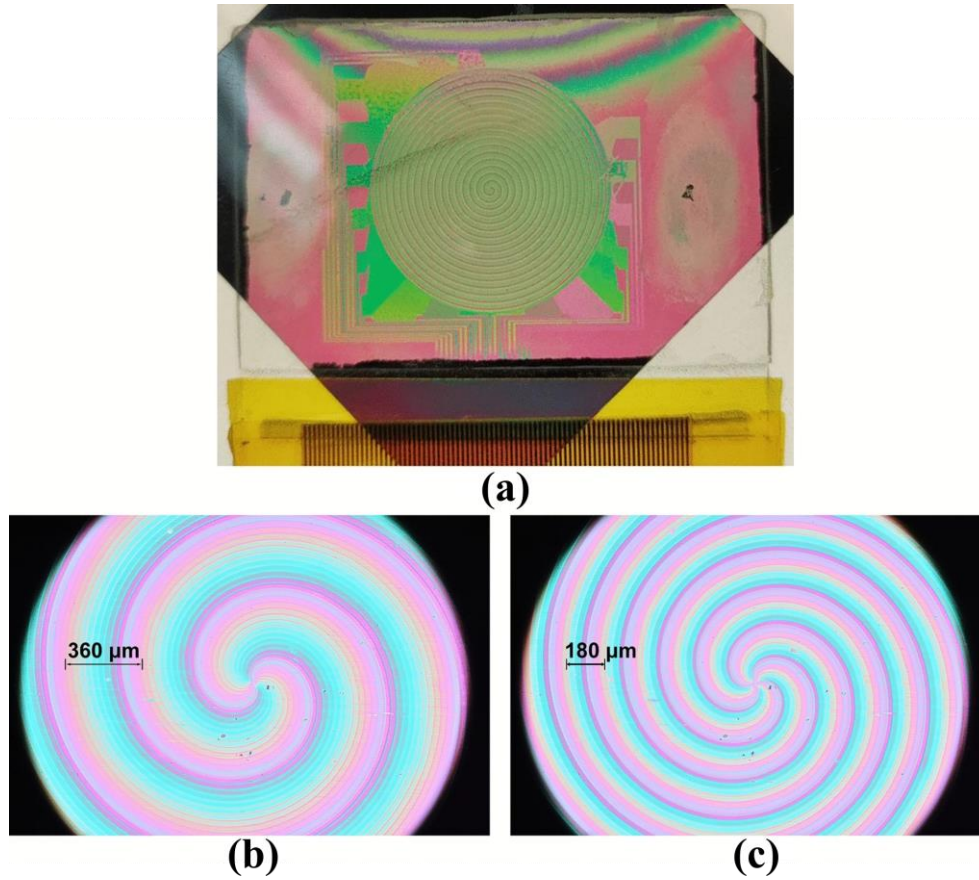


Figure 5.5: Manufactured DSA between crossed polarizers under white illumination. On top (a), general view of the LC cell. On the bottom, micrographs showing different topological charges and spiral pitches: (b) $l = 2$ ($\Delta_l = 360 \mu\text{m}$). (c) $l = 4$ ($\Delta_l = 180 \mu\text{m}$).

5.2. Depth of focus and ring diameter

All light rays from a planar incident beam are bent the same output angle (α) by an axicon, creating a conical wave. If working with a convergent configuration, the DSA creates a n th-order Bessel beam defined by [218], [219]:

$$E(r, z, l, \theta) = J_l(k_r r) \cdot \exp(j(k_z z + l\theta)) \cdot \exp\left(-\frac{r^2}{\omega_g^2}\right) \quad (5.8)$$

where J_l is the l th-order Bessel function, ω_g is the original gaussian beam radius and z represents the longitudinal component. Bessel beams are characterized by having a transverse profile where the beam center amplitude is not modified and is surrounded by concentric rings of lower intensity. Because of this reason, they are known as “non-diffractive” beams. Concentric phase profiles of conventional axicons may only generate 0th-order Bessel beams. However, the presented DSA is able to generate high-order Bessel beams characterized by possessing a phase singularity in the central lobe.

For a convergent configuration, we may define the depth of focus (DOF) that can be calculated as:

$$DOF = \frac{r_{beam}}{\tan(\alpha)} \quad (5.9)$$

where r_{beam} is the beam radius. In the developed DSA, the DOF can be tuned by modifying the output angle (α).

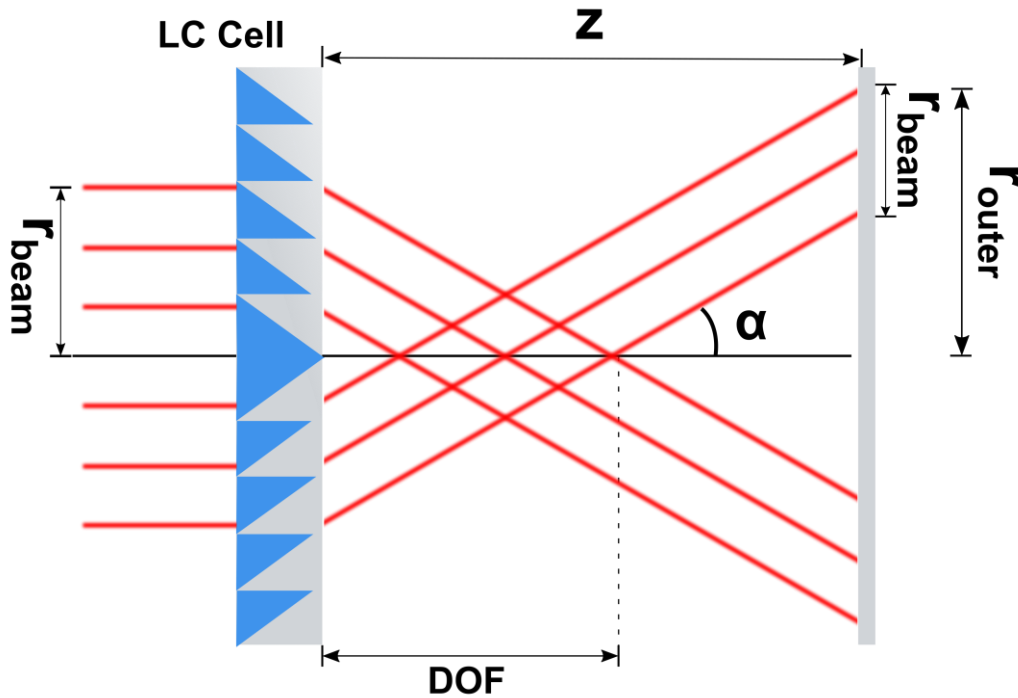


Figure 5.6: Blazed axicon ray diagram showing relevant parameters [178].

The DOF gives the length of the volume where the light is focused. From Figure 5.6, it is clear that after the end of this segment, crossing light rays give rise to a ring pattern. The outer radius of the resulting annular pattern (r_{outer}) is given by:

$$r_{outer}(z) = \begin{cases} r_{beam} - z \cdot \tan(\alpha), & z < DOF \\ z \cdot \tan(\alpha), & z > DOF \end{cases} \quad (5.10)$$

In contrast, for a divergent configuration, light is deviated away from the optical axis leading to a ring pattern through all the propagating distance. Hence, the outer ring radius is now:

$$r_{outer}(z) = r_{beam} + z \cdot \tan(\alpha) \quad (5.11)$$

To understand the light propagation, simulations of the designed device have been carried out. A convergent DSA with a topological charge $l = 6$ and a spiral pitch of $\Delta_l = 120 \mu\text{m}$ was defined. Then, an incident Gaussian beam with a radius $r = 4.2 \text{ mm}$ was used as light source. The angular spectrum simulations enable the computation at a single distance. Therefore, to obtain the beam propagation evolution, multiple simulations had to be carried out. However, as the output pixel size is dependent on the distance (Chapter 2: Theoretical Background) the input aperture plane had to be rescaled to maintain a constant output pixel size.

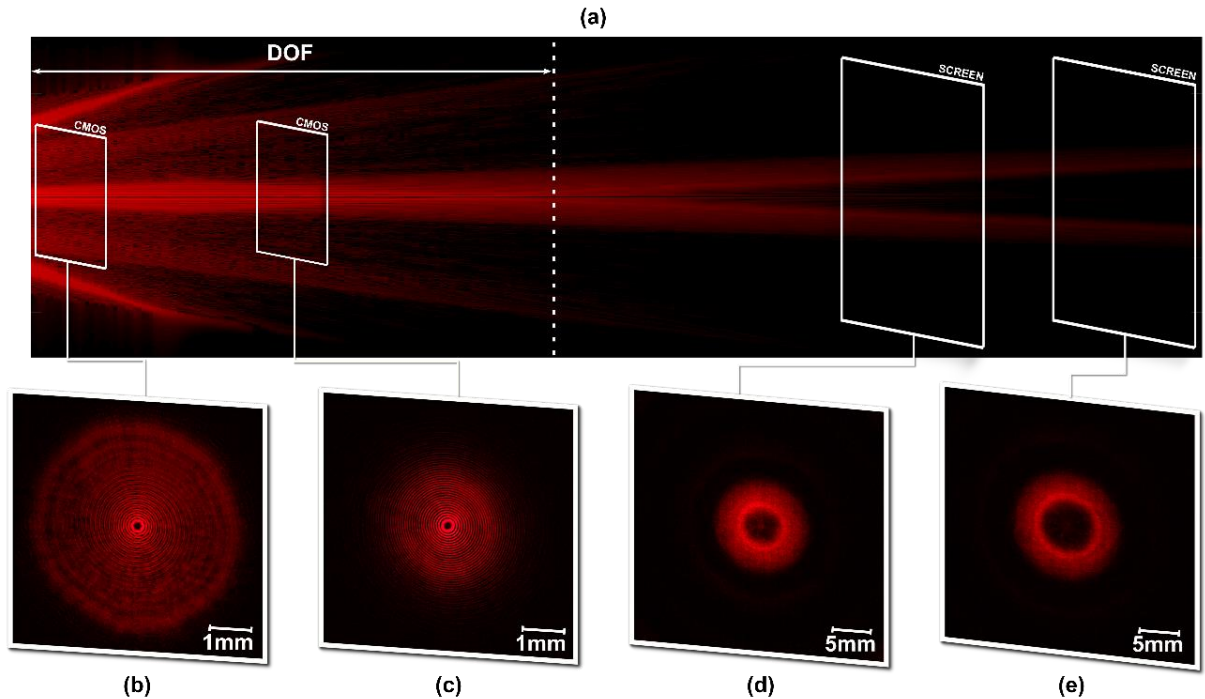


Figure 5.7: Beam evolution for a convergent DSA with $l = 6$. (a) Simulated cross-section along 150 cm. (b-e) Measured intensity patterns at $z = 25 \text{ cm}$, 50 cm , 125 cm and 150 cm , respectively. (b-c). The resultant pattern has been projected directly onto the camera CMOS sensor. (d-e). The resultant pattern has been projected onto an opaque millimeter screen. The intensity has been individually normalized in each measurement image [178].

The simulation results are shown in Figure 5.7a, depicting the diffracted beam propagation profile. The characteristic phase singularity from high-order Bessel beams can be appreciated at the beam optical axis within the DOF. To analyze the validity of these simulated results, an experimental setup is built to characterize the DSA (Figure 5.8). The optical singularity generation is confirmed by experimental results projecting the beam directly onto the camera sensor shown in Figure 5.7b, c. Within the DOF, the measurements depict a diffraction pattern composed by positive and negative concentric interferences. Additionally, the incoming beam is being focused (the disc radius decreases with distance) while maintaining a constant power distribution around the main lobe.

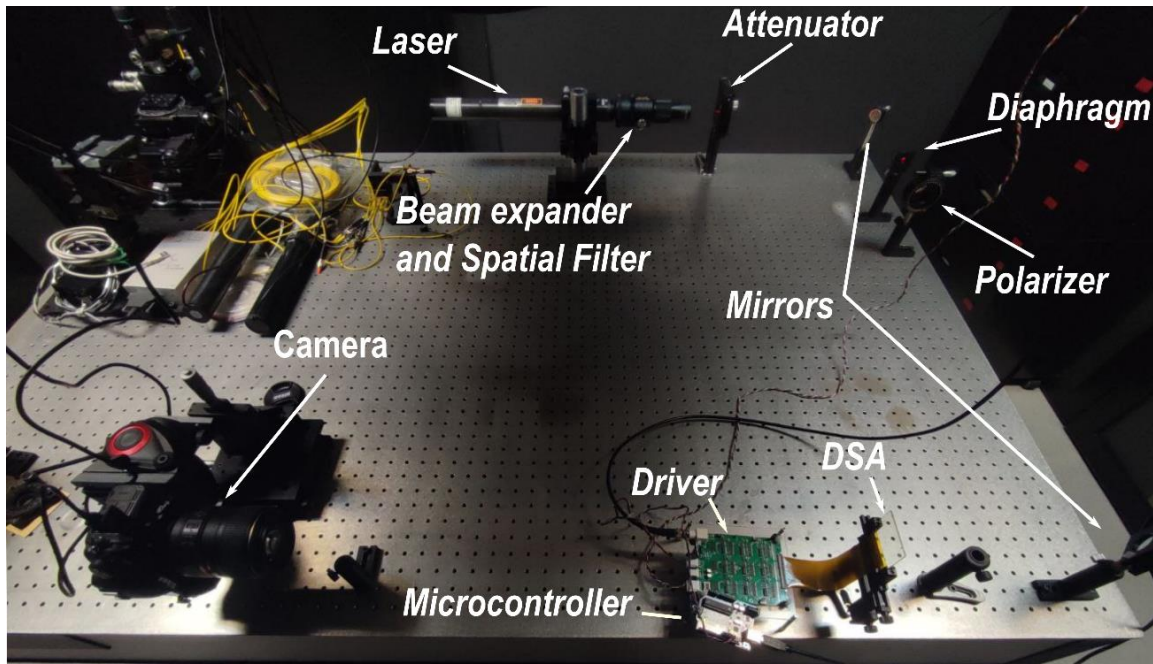


Figure 5.8: *Experimental setup to characterize the DSA in the CEMDATIC dark room facilities.*

In contrast, beyond the DOF region, the diffracted beam leads to an annular ring-shaped pattern (Figure 5.7d, e). Both simulations and results show that the ring diameter increase with the propagation distance as expected.

The presented simulations and results serve to understand the light propagation evolution after impinging a DSA with a constant topological charge. Nevertheless, one of the main strengths of the developed device is its tunability. Being formed by 24 electrodes, the presented devices can be switched between 24 –12 convergent and 12 divergent-different configurations. Therefore, this reconfigurability leads to multiple configurations where the output angle is varied as a function of the configured topological charge. To study this reconfigurability, intensity measurements were recorded at a fixed distance, for different topological charges.

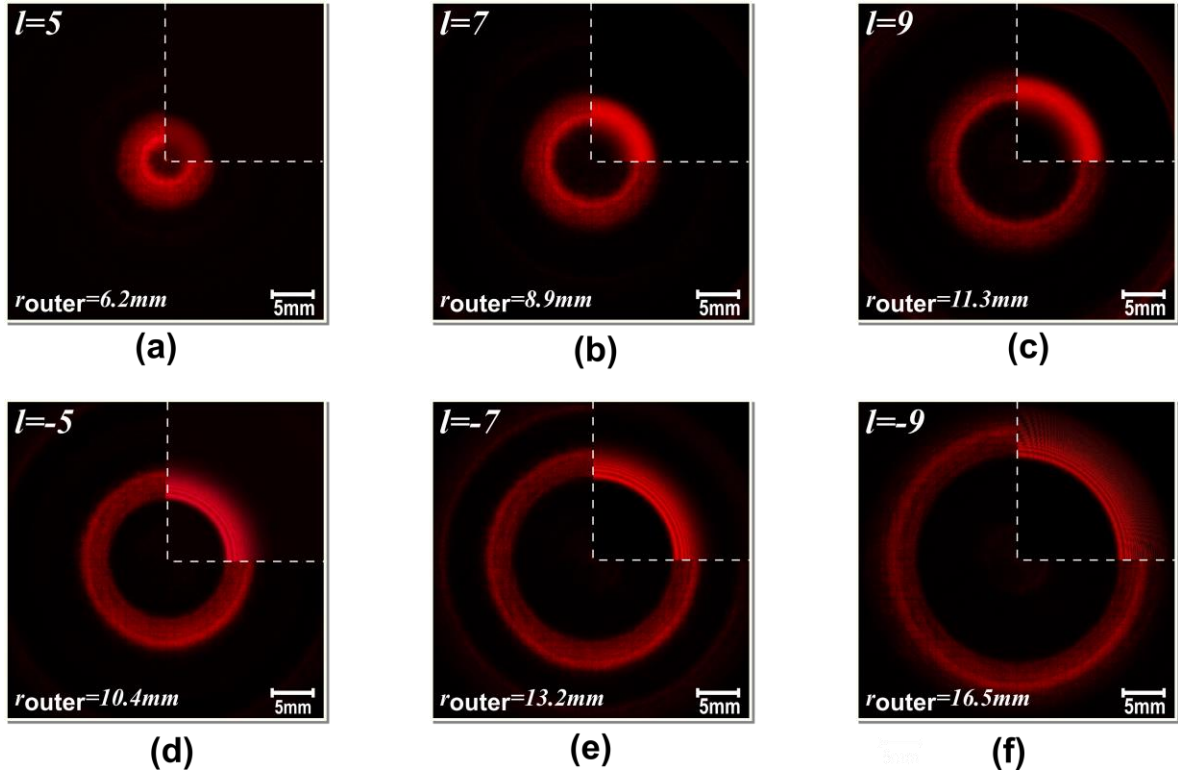


Figure 5.9: Experimental results of the developed DSA with corresponding simulations being overlaid (top-right corner in the dashed lines). On top row, convergent simulations with different topological charges: (a) $l = 5$. (b) $l = 7$. (c) $l = 9$. On bottom row, divergent configurations are displayed: (d) $l = -5$. (e) $l = -7$. (f) $l = -9$. The employed topological charge and the resulting outer ring radius are indicated in each image. [178].

The diffracted patterns are projected onto a calibrated graph paper at 150 cm from the DSA while the acquisition camera is focused onto the screen. These experimental measurements are displayed in Figure 5.9 with overlaid simulations; good agreement is found between experimental and simulated results. Top row of this figure shows different convergent configurations. As predicted (eq 5.12), the ring diameter grows with increasing output angle (or topological charge). The same conclusion can be drawn from the bottom row, where negative topological charges are displayed. These measurements illustrate the reconfigurability of the device and the good concordance between measurements and simulations.

5.3. Phase Singularity

Tuning the topological charge of the DSA modifies not only the output angle but the phase singularity radius as well. The generated Bessel-Gauss beam within the DOF volume and its dependence with the topological charge has been studied.

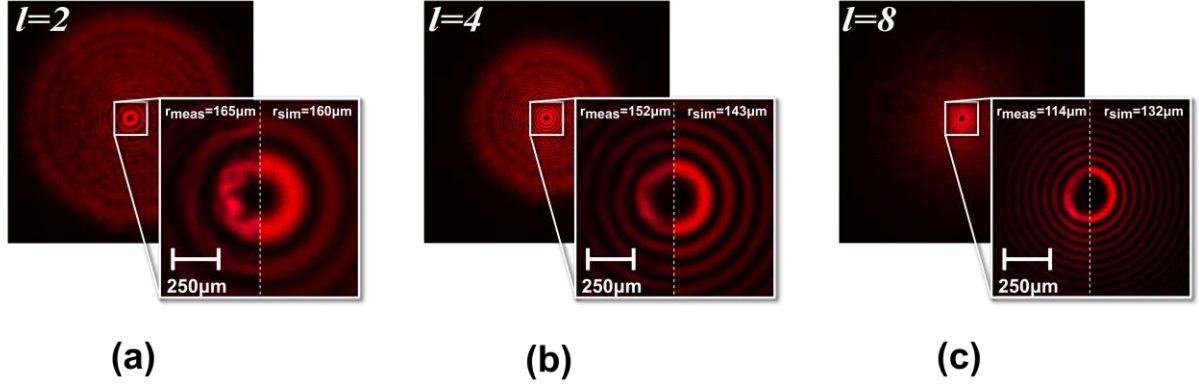


Figure 5.10: Bessel Gauss beam intensity patterns generated by the DSA compared with the corresponding simulated results for different topological charges. (a) $l = 2$. (b) $l = 4$. (c) $l = 8$. The obtained radius for both simulations and experimental measurements are overlaid [178].

To be able to measure the phase singularity for different distance, the generated patterns were projected onto the CMOS camera sensor at a distance of $z = 50 \text{ cm}$. The experimental results are plotted in Figure 5.10. Simulations were also carried out and superposed in the right part of the zoomed sections. It is noticeable that all the results show a clear phase singularity at the main lobe. The diameter of this dark singularity has been measured and compared to the simulation.

Besides changing the phase singularity, the change in topological charge also implies a variation of the output angle. Hence, resulting in Bessel-Gauss patterns characterized by having concentric patterns with different width and separation. The higher the topological charge, the smaller the periodicity of the interference fringes.

Both these results and those generated by the spiral phase plates, show an increment of the singularity radius with the absolute value of the topological charge. However, the evolution of the singularity is completely different. The vortex beams generated by the SPP continuously diverge with the propagating distance, decreasing the power distribution of ring surrounding the singularity. In contrast, the DSA generated vortex beams present a tightly focused optical singularity within the DOF, with a sharp power decay after it. Hence, this device enables the generation of an optical singularity over a desired volume.

6. Spiral Diffractive Lenses

Tunable lenses refer to all lenses possessing tunable focal length. These optical elements have attracted a great deal of interest due to their potential application in a broad range of sectors such as tunable eyewear [44], microscopy [220], smartphone cameras [221], astronomy [222], or augmented reality (AR) [58].

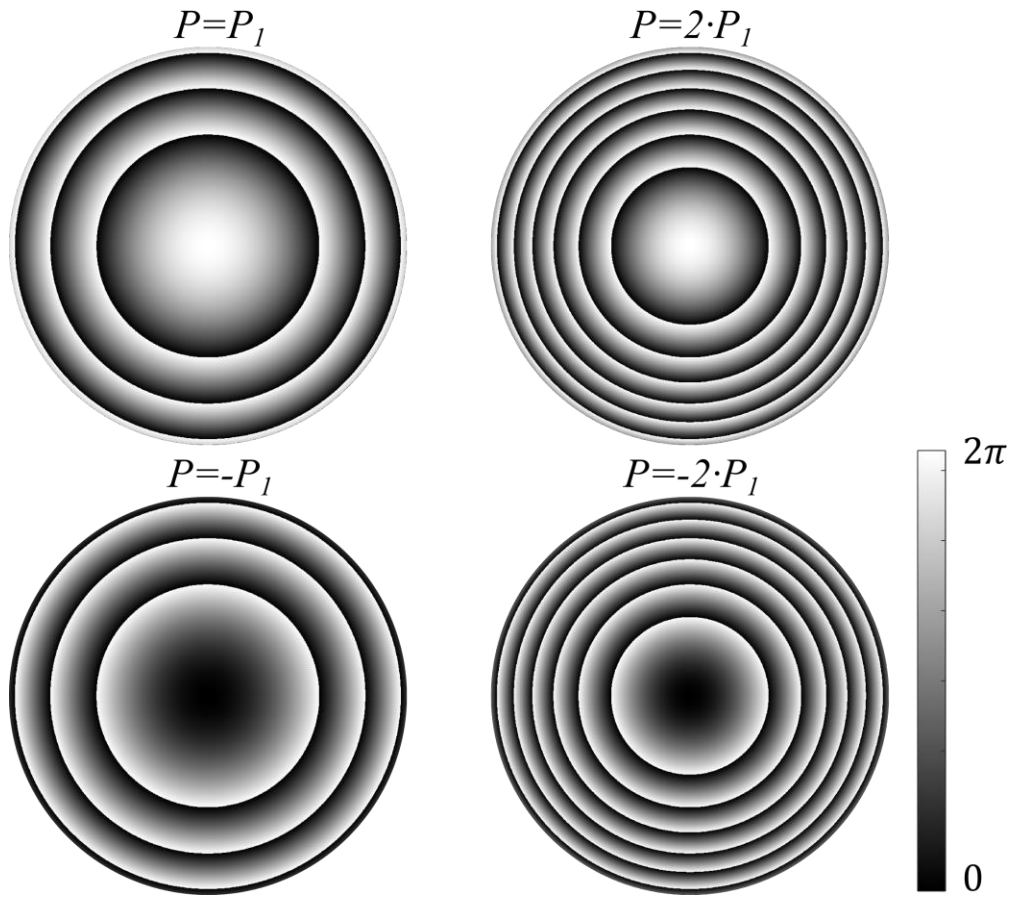


Figure 6.1: Examples of four different diffractive Fresnel lens phase profiles. Gray levels represent phase delay (δ). The periodicity of the phase profile is related to the lens optical power. Arbitrary numbers have been used for determining optical powers.

As previously discussed, the addressing of concentric rings in devices is a challenge that can be overcome by using spiral shaped electrodes. The reconfigurable lenses developed in this thesis are spiral diffractive lenses (SDL) characterized by having a spiral phase wrapped profile over 2π .

An intrinsic characteristic of these spiral shaped lenses is the OAM transfer to the passing light beam, leading to the generation of a phase singularity at the optical axis. In this chapter, several strategies are proposed to obtain lenses with phase profiles free of azimuthal phase variation. Besides, the impact of the topological charge compensation on imaging performance is assessed.

The last part of this chapter is focused on more complex optical systems where multiple devices are integrated, such as zoom systems or back-to-back lenses (B2B). Lastly, some approaches to improve the image quality like chromatic aberration issues or hazing minimization are explored.

6.1. Design

The developed SDLs are designed with pixel separations in shapes resembling a Fermat spiral:

$$r(\theta) = a\sqrt{\theta} \quad (6.1)$$

In contrast to the previous presented spiral axicon design, the separation between different turns decreases with the radial distance to the spiral center.

The Fermat spiral used to recreate the Fresnel lens phase profile has been discussed in detail in [223]. Contours of constant phase delay in lens may be represented by the spiral symmetry given by:

$$r^2 = \left(2f + l \cdot \lambda \cdot \frac{\theta}{2\pi}\right) \cdot l \cdot \lambda \cdot \frac{\theta}{2\pi} \quad (6.2)$$

where f is the lens focal distance, λ is the wavelength of light and l is the lens topological charge. Employing phase wrapping and assuming that $2f \gg l \cdot \lambda \cdot \frac{\theta}{2\pi}$ equation (6.2) becomes:

$$r^2 = a^2 \cdot \theta = 2f \cdot l \cdot \lambda \cdot \frac{\theta}{2\pi} \quad (6.3)$$

Since the wavelength is usually in the order of hundreds of nanometers, while the focal length is at least 5 orders of magnitudes larger it is a valid assumption for most applications.

The spiral geometry design determines the base focal length (or optical power), *i.e.*, the focal length with topological charge one [6.3]. However, these devices are electronically reconfigurable and the optical power has a linear dependence with the applied topological charge (Figure 6.2):

$$f(l) = \frac{f_b}{l} \Leftrightarrow P(l) = l \cdot P_b \quad (6.4)$$

where f_b and P_b are respectively the base focal length and optical power.

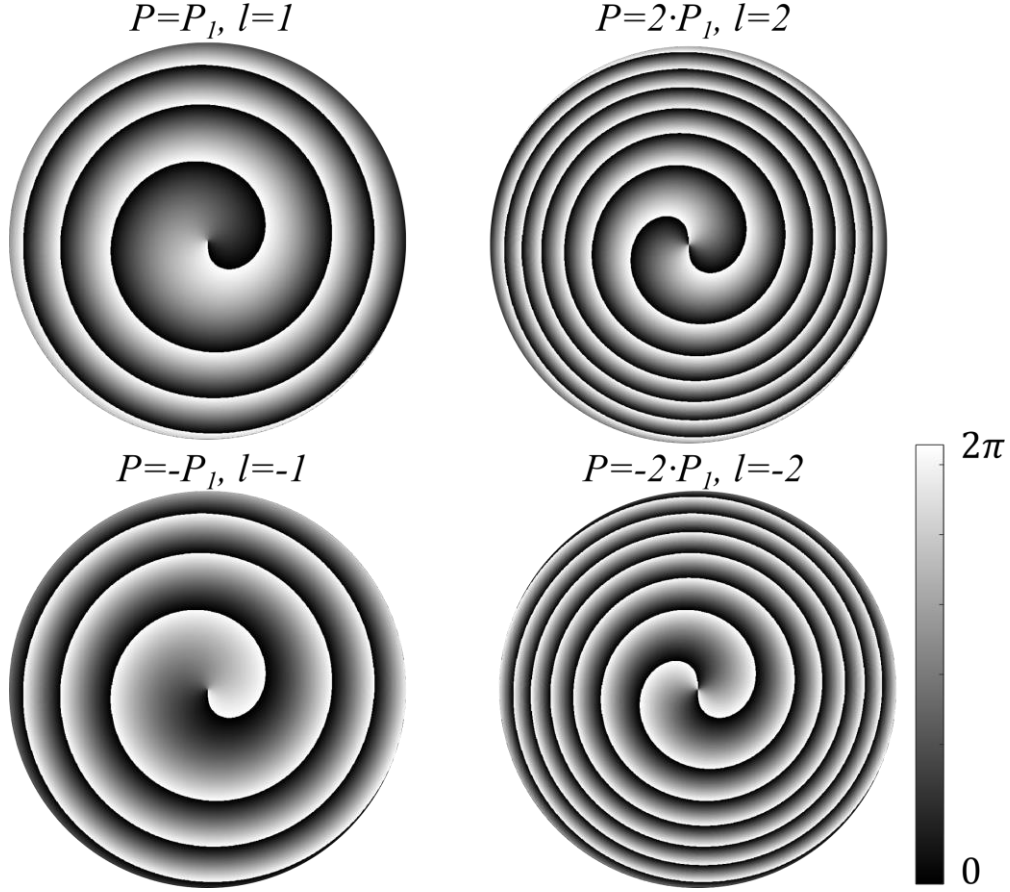


Figure 6.2: *SDL phase profile for different topological charges. By changing the topological charge of a given device both convergent and divergent lenses with different optical powers can be generated.*

The available number of configurations depends on the number of pixels. Convergent and divergent configurations (Figure 6.2) can be generated, just by changing the topological charge governed by the pattern of applied voltages. The focal distance of the lens is determined by the radial variation of the configured phase profile. However, the handedness, i.e., the sign of the induced l , depends on the orientation of the device with respect to the incident light. Therefore, for a given configuration, the topological charge sign can be modified by flipping over the device, without affecting the optical power (Figure 6.3).

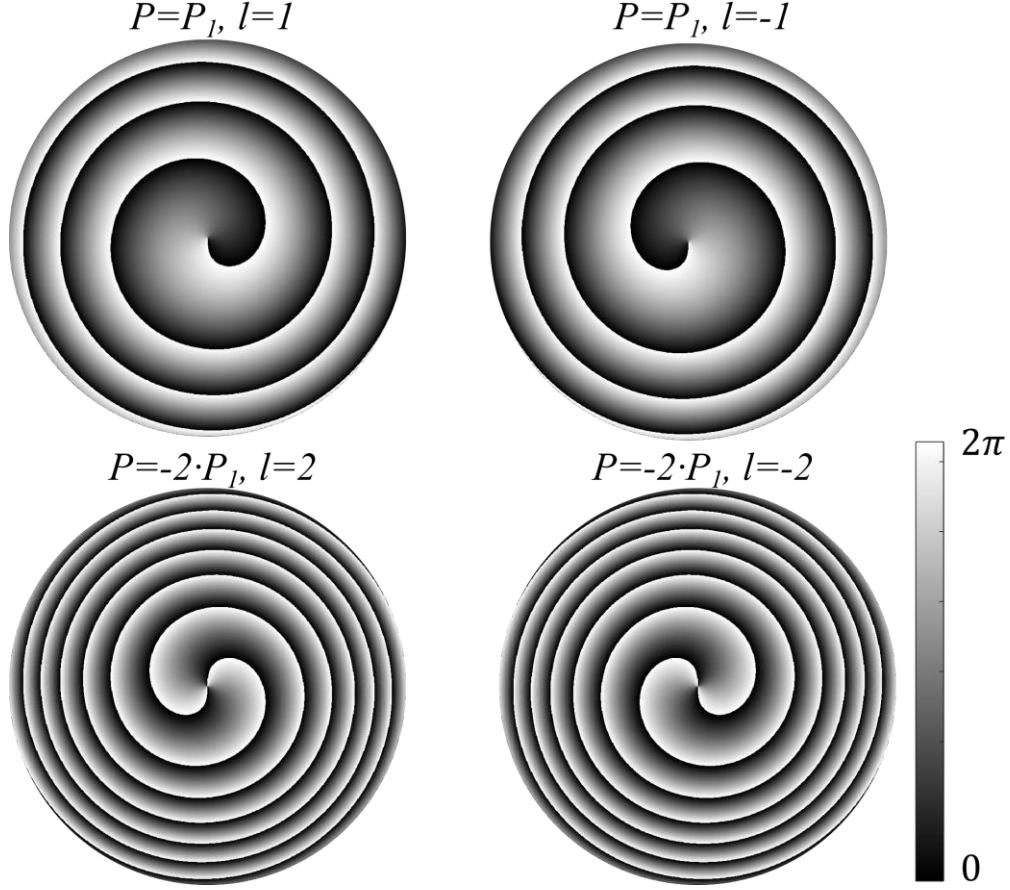


Figure 6.3: *SDL phase profiles illustrating topological charge inversion caused by flipping over the device respect to the incident light. In each row, two mirror images of the same device are shown, changing the handedness without affecting the optical power.*

In the spiral design process, there is a manufacturing limit that impairs the generation of arbitrary SDL. This limitation is related to the ITO ablation of the patterned electrodes. The spiral pitch decreases with the distance from the center (Figure 6.4). In turn, the laser ablation system is limited to a $\sim 2 \mu\text{m}$ resolution, and the quality of the substrate is finite, which means that imperfections of the ITO layer does occur. These imperfections may be a consequence of imperfect ITO deposition, or later scratching of the surface. A separation of $\sim 12 \mu\text{m}$ between ablated spirals leads to an acceptable yield in the lens manufacturing. This constrain restricts the following design parameters: number of electrodes, base focal distance, and active area diameter.

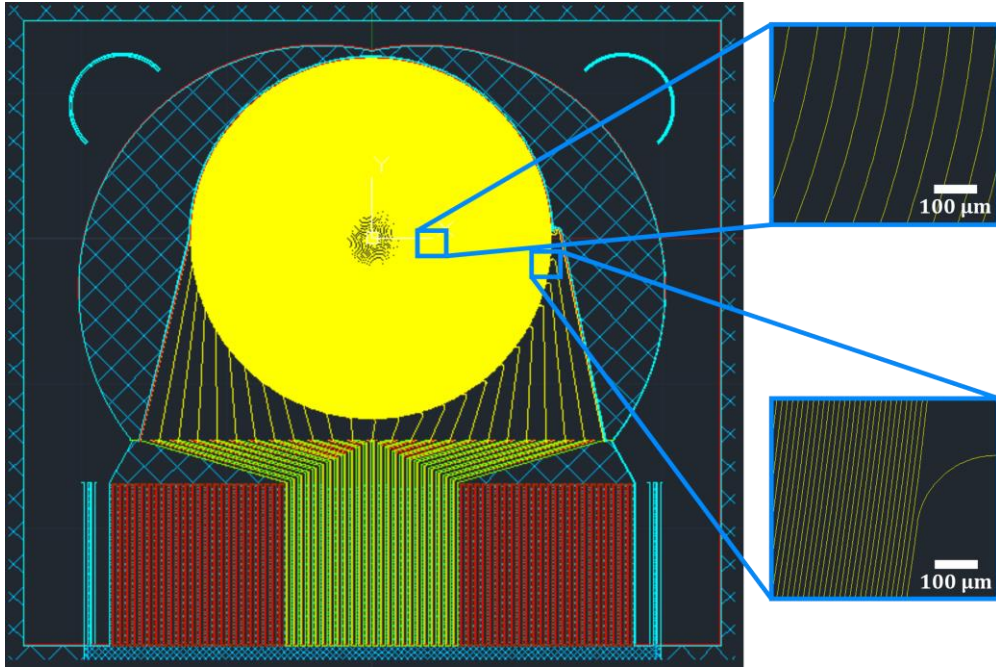


Figure 6.4: 24-Electrode SDL ablation design with active area diameter of 0.5". The insets show the spacing near the center of the lens and in the periphery, illustrating the pitch decrease.

Bearing in mind this manufacturing limitation, a number of different SDLs having different parameters have been developed (Figure 6.5). Lenses with active areas of 0.5" and 1" in diameter, featuring varying numbers of electrodes and types of liquid crystals, have been manufactured.

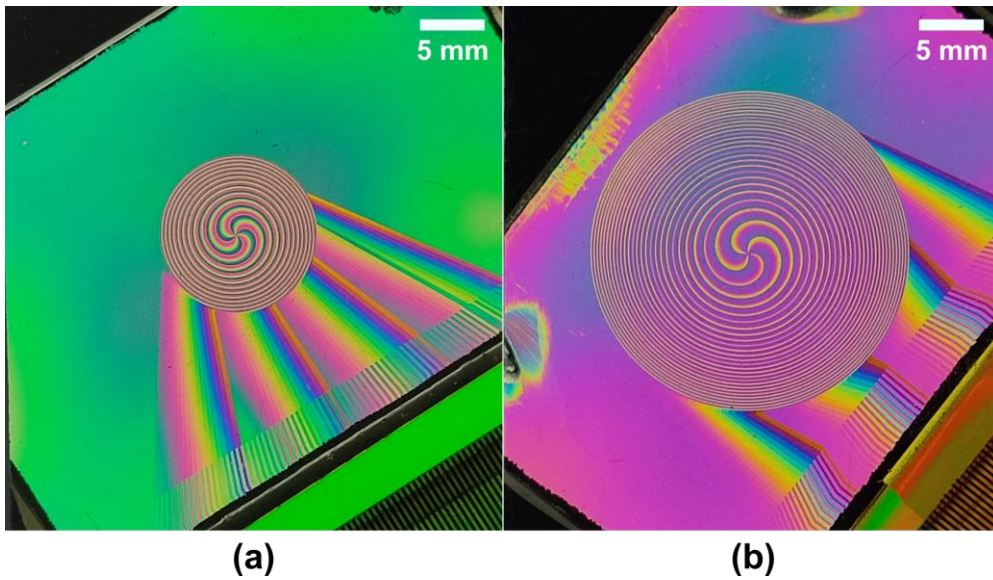


Figure 6.5: Example of manufactured 72-Pixels SDLs configured at $l = 4$ with different active area diameters: a) $d = 0.5''$; b) $d = 1''$.

6.2. Topological Charge Compensation

A single SDL with its intrinsic azimuthal phase variation gives rise to various aberrations. Firstly, the discrete phase approximation to the ideal analogue phase Fresnel lens profile, leads to diffractive aberration. Secondly, the generated vortex beams give rise to an image distortion on the optical axis whose size depends on the applied topological charge. These two phenomena will degrade the image quality. Two strategies are proposed to compensate the topological charge by assembling multiple devices, one of which also improves the approximation to the analogue phase lens profile.

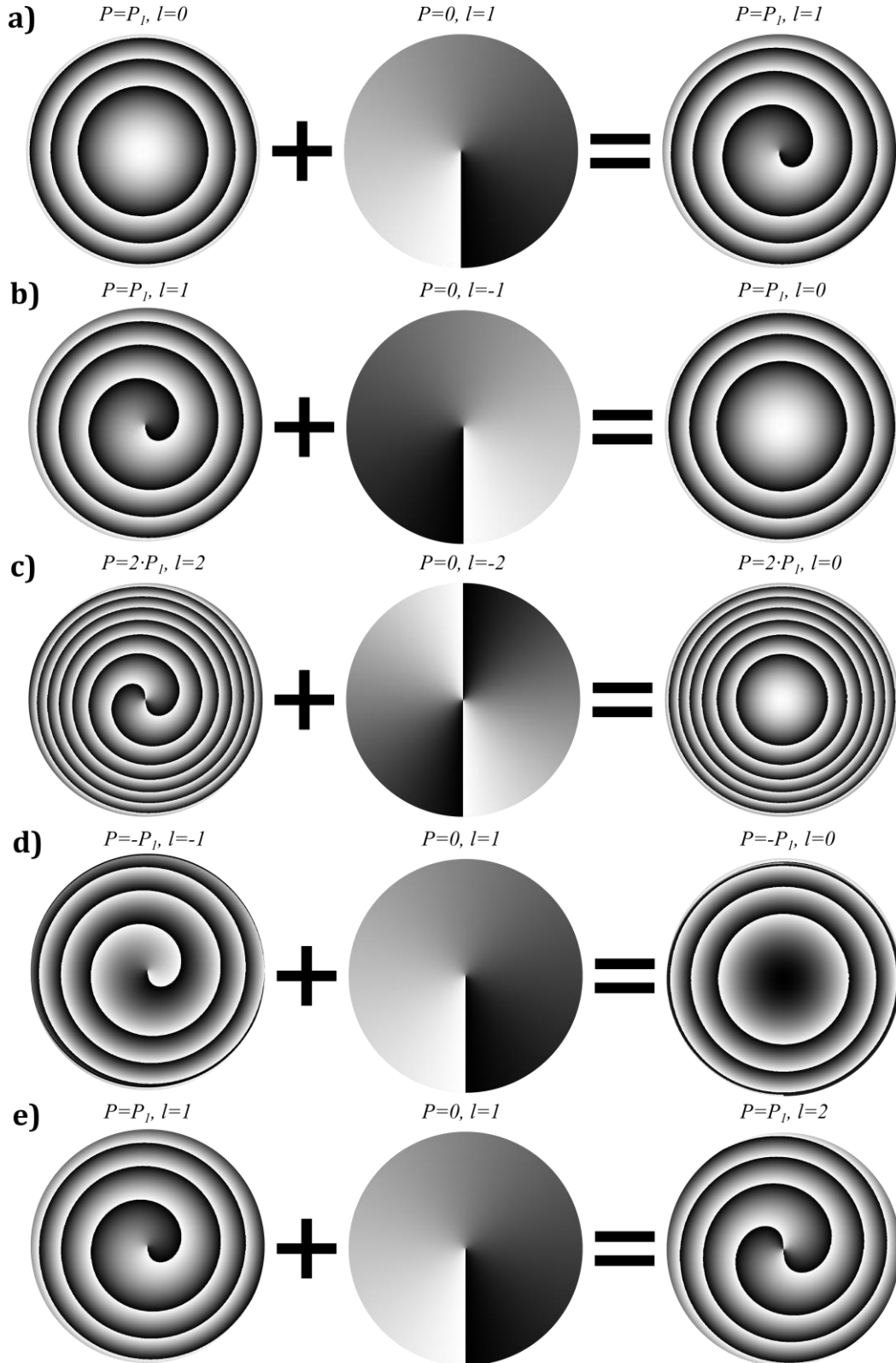


Figure 6.6: Compensating topological charge by stacking a spiral diffractive lens and a spiral phase plate with opposite handedness: a, b) The SDL phase profile is a reversible combination of a Fresnel lens and a SPP. b, c, d) Using a SDL and a SPP with opposite l give rise to different Fresnel lenses while maintaining the optical power. e) Adding a SPP to a SDL leads to an SDL with increased l .

The simplest approach to making a lens with net zero topological charge is assembling a SDL with a SPP together. The SDL phase profile is obtained by applying an azimuthal variation (*i.e.* SPP) to the phase profile of an ideal Fresnel lens. This is a reversible process. Therefore, the SDL azimuthal phase variation can be compensated by inserting a SPP with the opposite topological charge. This process is illustrated in Figure 6.6. The combination of these two devices gives rise to a Fresnel lens with the same optical power as the SDL and $l = 0$. This strategy is valid for both positive and negative lenses. This strategy allows the fabrication of tunable lenses with concentric Fresnel profiles while maintaining the electrode addressing from the periphery on each single component.

Another strategy leading to the same goal is to assemble two identical SDL back-to-back (B2B) (Figure 6.7). As mentioned above, the device topological charge can be inverted mirroring the LC cell, without affecting the optical power of the lens. In this way, two SDL assembled with the same orientation lead to a lens with double power and double topological charge. Assembling them B2B, on the contrary, the topological charges are cancelled out, and the resulting lens has double power with zero topological charge. [224].

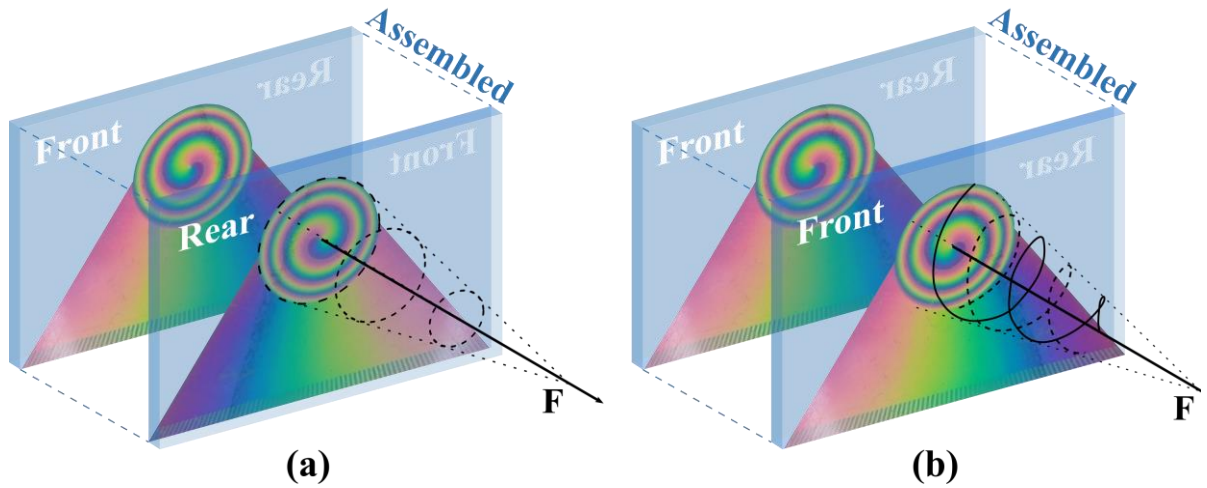


Figure 6.7: Illustration of how the resulting topological charge depends on the orientation of the assembled devices: a) B2B configuration results in $l = 0$. b) SDLs with the same orientation results in $l = 2$ [224].

This double lens strategy can be implemented for both convergent and divergent lenses. The combination of different phase profiles and the resulting lens can be observed in Figure 6.8.

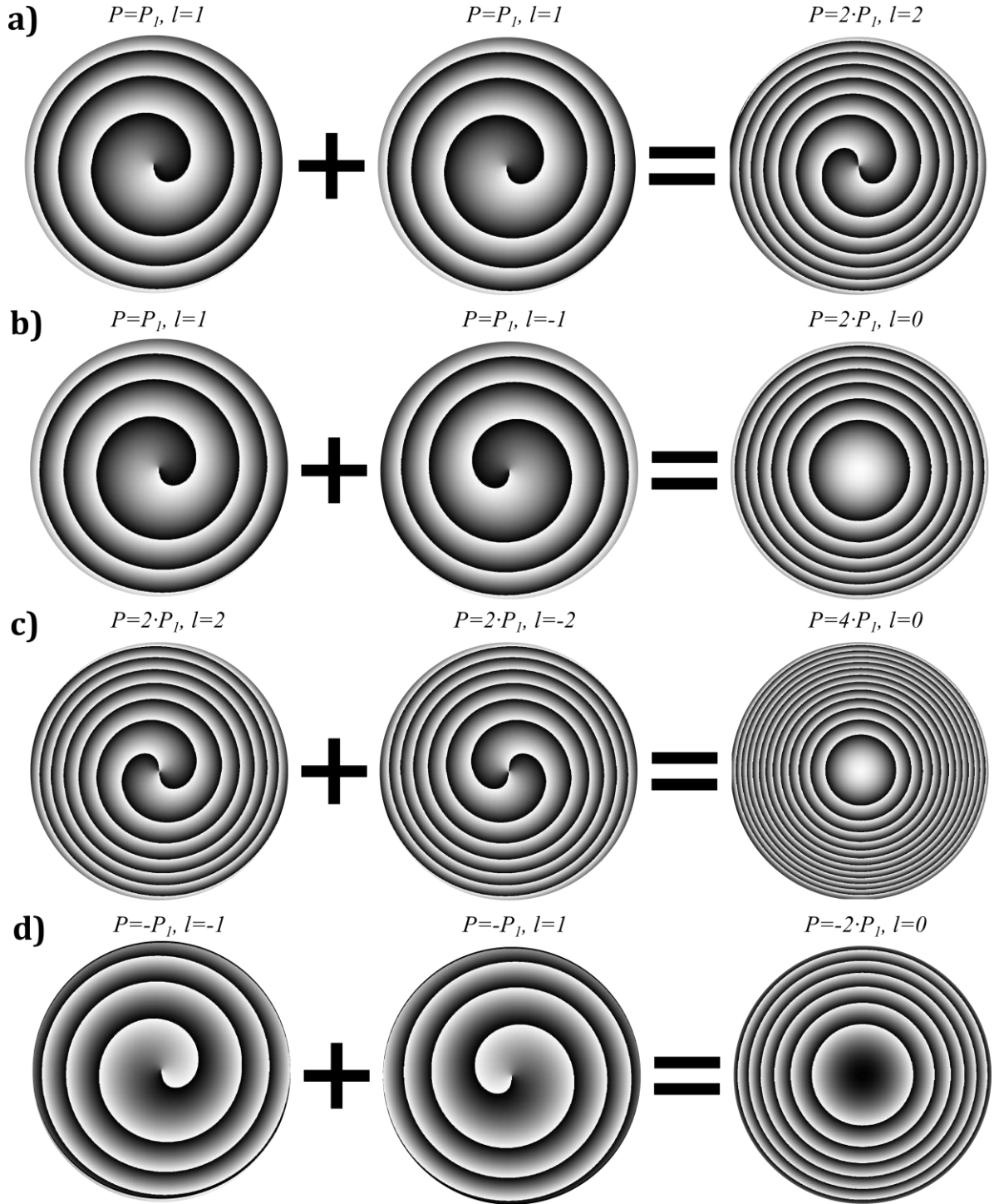


Figure 6.8: Phase profile combinations of a double SDL assembly. a) Two SDL with the same topological charge leads to a lens with twice optical power and l . b, c, d) B2B assembly give rise to lenses with net zero l and doubled optical power.

In the following sections these two techniques are experimentally evaluated as well as the imaging performance impact of the topological charge compensation.

6.3. Large Area Spiral Diffractive Lens Characterization

In this section multiple experimental setups are described using 25.4 mm diameter lenses. These two SDL have 24 pixels and a base focal length $f_b = 6\text{ m}$ ($@\lambda = 632\text{ nm}$). After successful verification of the electrode integrity and thickness homogeneity, these lenses were calibrated using a He-Ne green laser ($\lambda = 550\text{ nm}$).

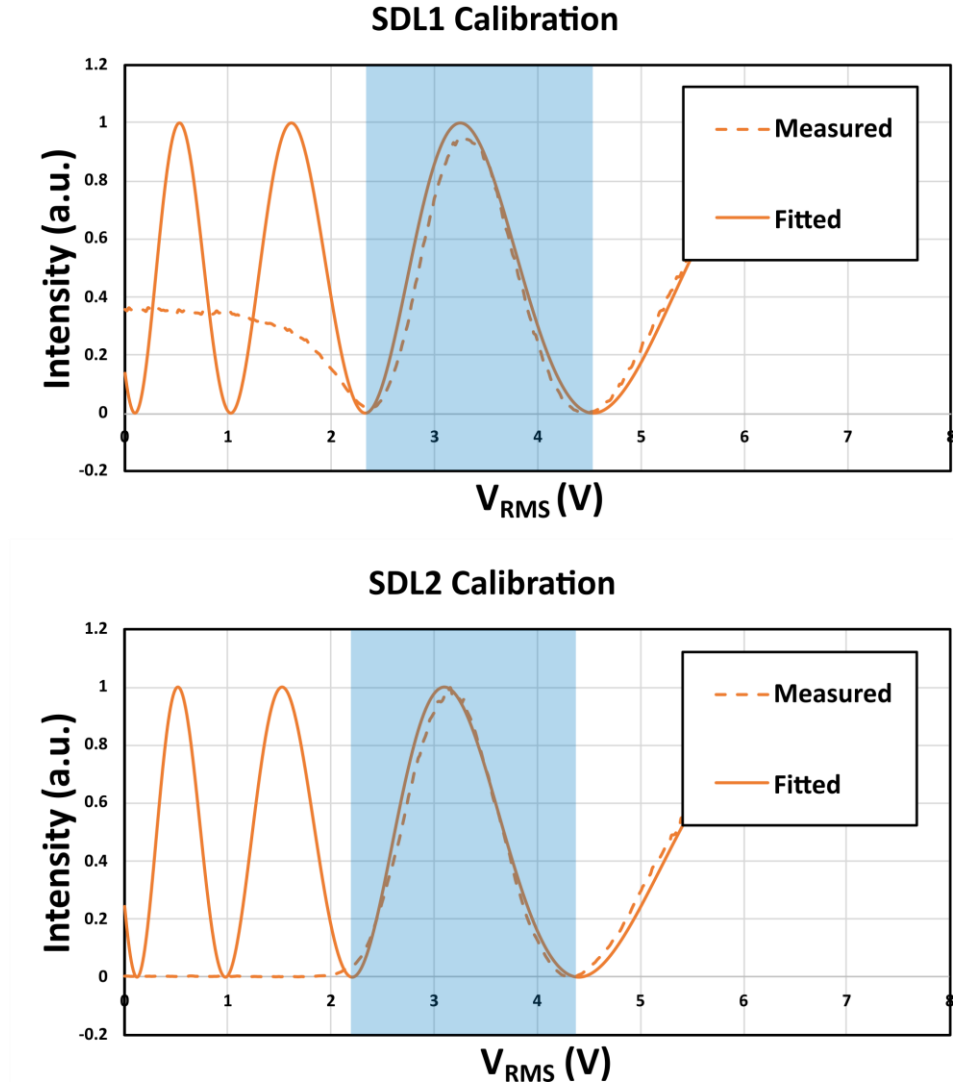


Figure 6.9: Big diameter SDL calibrations. Both intensity calibrations are obtained using an external AC signal with $V_{RMS,max} = 7.5\text{ V}$. Shaded blue area indicates the 2π fitted region.

The two SDL calibrations showed a sufficient 2π phase range and fitting curves were obtained (Figure 6.9). SDL phase profiles were recorded placing the devices between crossed polarizers, showing the expected variation of bright and dark electrodes (Figure 6.10).

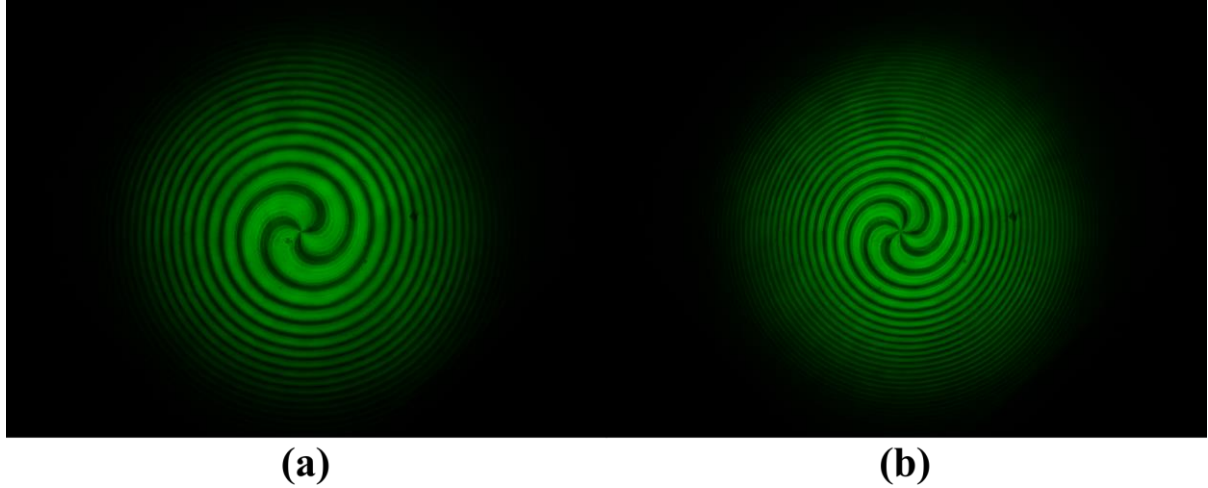


Figure 6.10: SDL recorded phase profile placing the LC cell between crossed polarizers under green illumination. a) $l_{SDL1} = 3$. b) $l_{SDL1} = 5$.

The measurements showed the characteristic helical phase profile, with a number of helices dependent on the configured topological charge.

A preliminary assessment of the focusing ability of the lenses was carried out. A target is placed at different distances being kept on focus by changing the SDL topological charge. After this initial evaluation the two SDLs were mounted B2B using a 3D printed holder and aligned manually in an optical microscope (Figure 6.11). In this image the proper alignment of both lenses can be appreciated. Additionally, it can be verified that both spirals have the same phase profile, but the different spiral orientation respect to the incident light leads to an opposite sign l .

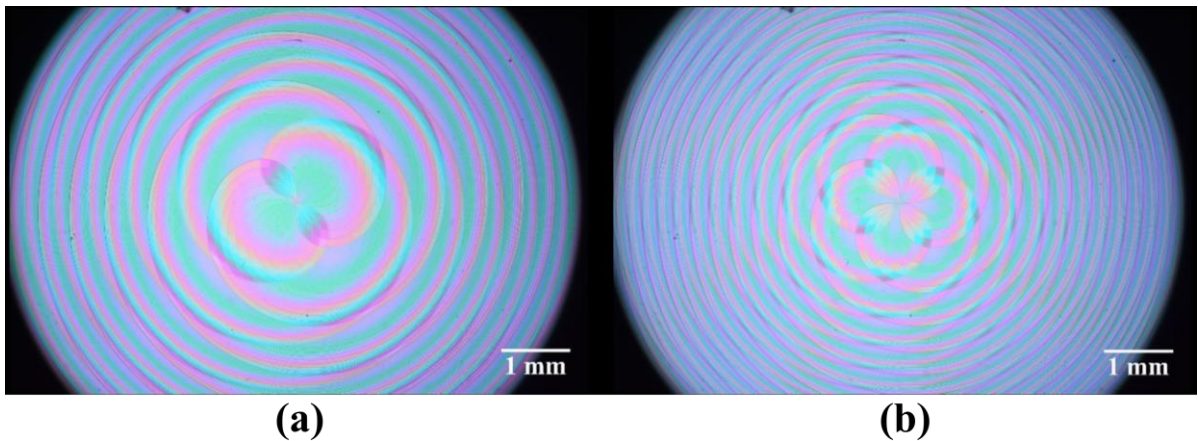


Figure 6.11: Micrographs showing B2B SDLs between crossed polarizers under white light illumination for different configurations. A) $l_{SDL1} = 2$, $l_{SDL2} = -2$. B) $l_{SDL1} = 4$, $l_{SDL2} = -4$. The two and fourfold symmetry visible in the micrographs confirms the correct alignment. The lack of circular symmetry reflects that a high visual contrast, rather than calibrated, electrical addressing is employed.

Once both lenses are aligned, the previous optical setup is used to record their phase profiles. In Figure 6.12, different combinations of phase profiles are obtained. The first two columns depict different active topological charges for l_{SDL1} while l_{SDL2} remains turned off and vice versa. The third column shows the combination of the previous phase profiles when both lenses are active. The insets in the upper left corner of every picture are simulated transmission of the phase profiles. A good agreement is found between experimental and simulated results. These measurements prove that stacking two elements can be used to generate devices with zero net topological charge.

The lens generated using B2B doubles the power of the SDL+SPP combination for any given topology. Thus the discrete approximation for any focal strength is done using twice the number of electrodes, and thus the diffractive efficiency is improved.

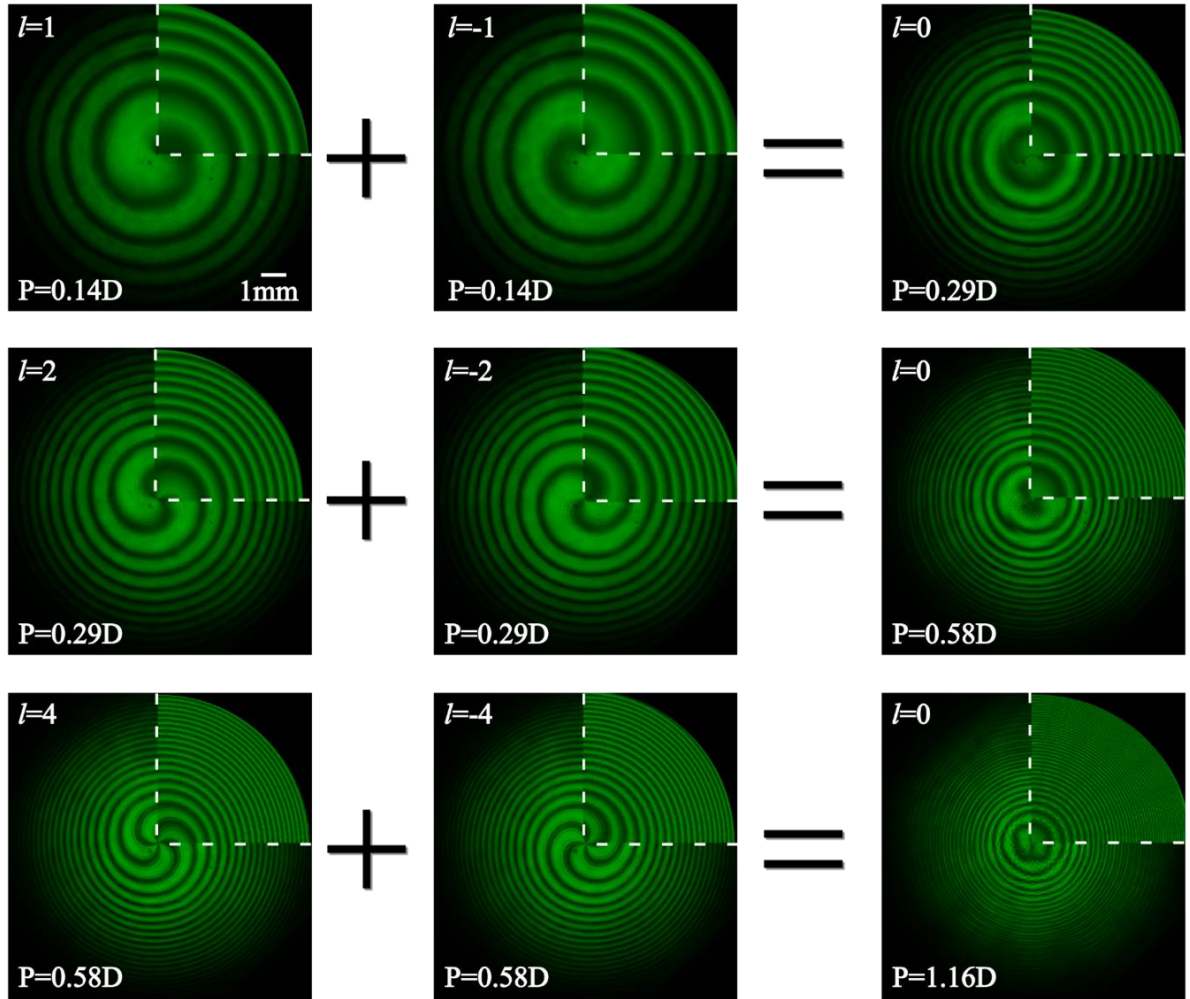


Figure 6.12: B2B SDLs recorded phase profiles for different topological charge (l) configurations with the corresponding simulations (top-right corners). Theoretical optical powers are included for each configuration.

Subsequently, an optical setup to measure the focal length of the assembly was built (Figure 6.13). For this purpose, a camera with a fixed focusing distance $f_{cam} = 50 \text{ cm}$, followed by the B2B lens (at a distance $d_{Lens} = 20 \text{ cm}$). The two single LC SDLs were aligned using a PLA 3D printed cage mounted on a 2-axis micro positioner and a linear polarizer was aligned with the LC switching plane. To minimize the camera depth of field, and thus highlighting when the image is focused, the camera aperture was maximized. An image target was placed after the lens and its position (d_{Target}) was varied until the visually best-defined pattern was found. This distance was recorded as the system focal distance. The printed target was fixed on aluminum rails to manually change its position. Lastly, the electronic driver was connected to a function generator, a DC power supply, and a computer. The latter elements were removed from the picture to make the setup clearer. The different parameters of this setup linked to the calculation of the B2B lens assembly focal length (f_{Lens}) are illustrated in Figure 6.14.

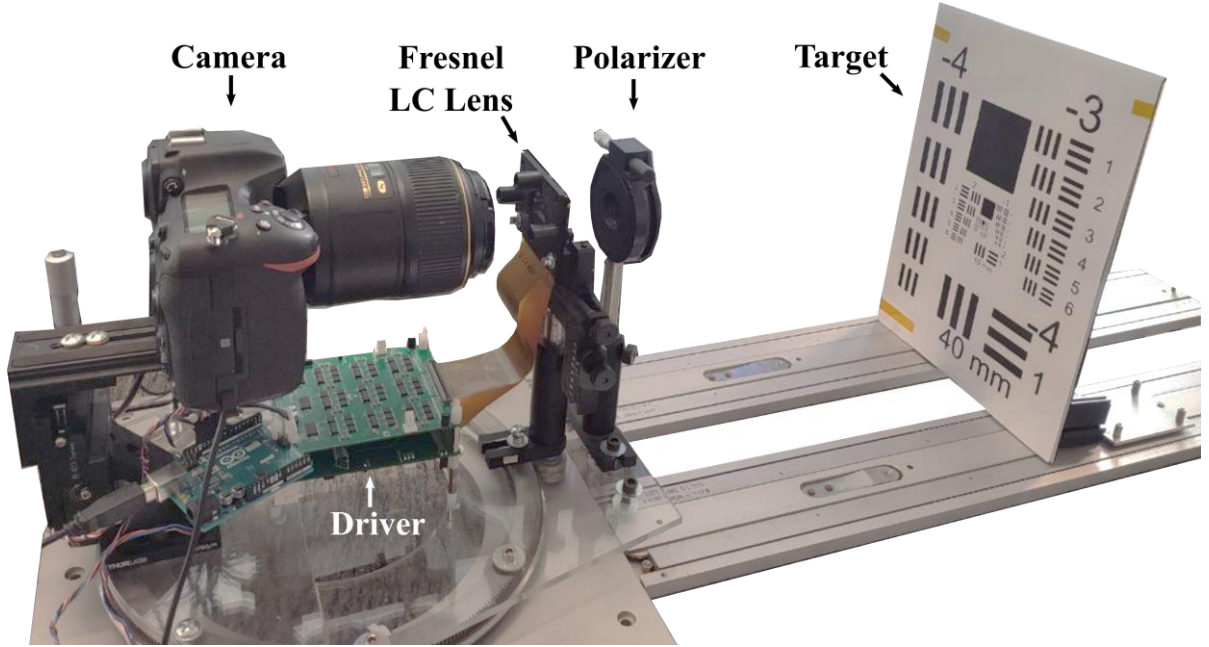


Figure 6.13: Experimental setup to measure B2B SDL focal length.

The LC lens assembly (B2B SDLs) optical power ($P_{Lens} = \frac{1}{f_{Lens}}$) can be derived from:

$$P_{Lens} = \frac{1}{f_{Lens}} = \frac{1}{d_{Target}} + \frac{1}{(d_{Lens} - f_{Cam})} \quad (6.5)$$

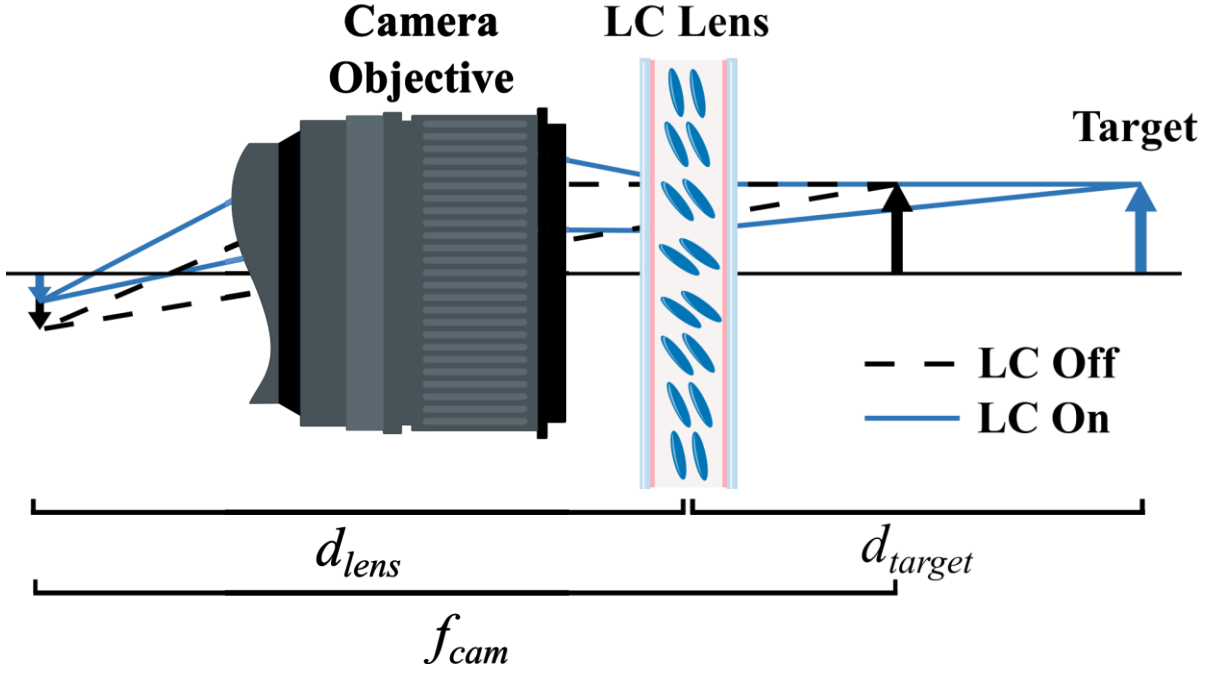


Figure 6.14: Focal length measurement setup sketch. The dark dashed line represents f_{cam} , the camera focal distance when the LC lens is turned off. The solid blue line sketches the system focal length variation when the LC lens is on.

The expected correlation between designed lens and measured focal distances was confirmed for topological charges between $l = -16$ ($l_{SDL1} = -8$, $l_{SDL2} = -8$) to 22 ($l_{SDL1} = +11$, $l_{SDL2} = +11$) (Figure 6.15). For more extreme configurations of the lenses the image becomes too blurred to accurately measure the optimal d_{Target} . The measured distances agreed with the expected values for combination two SDLs, each with a basic focal power of 0.15 D (@ $l = 1$) or a maximum system optical power of ± 3.5 D for an individual topological charge of $l_{SDL1} = l_{SDL2} = 12$.

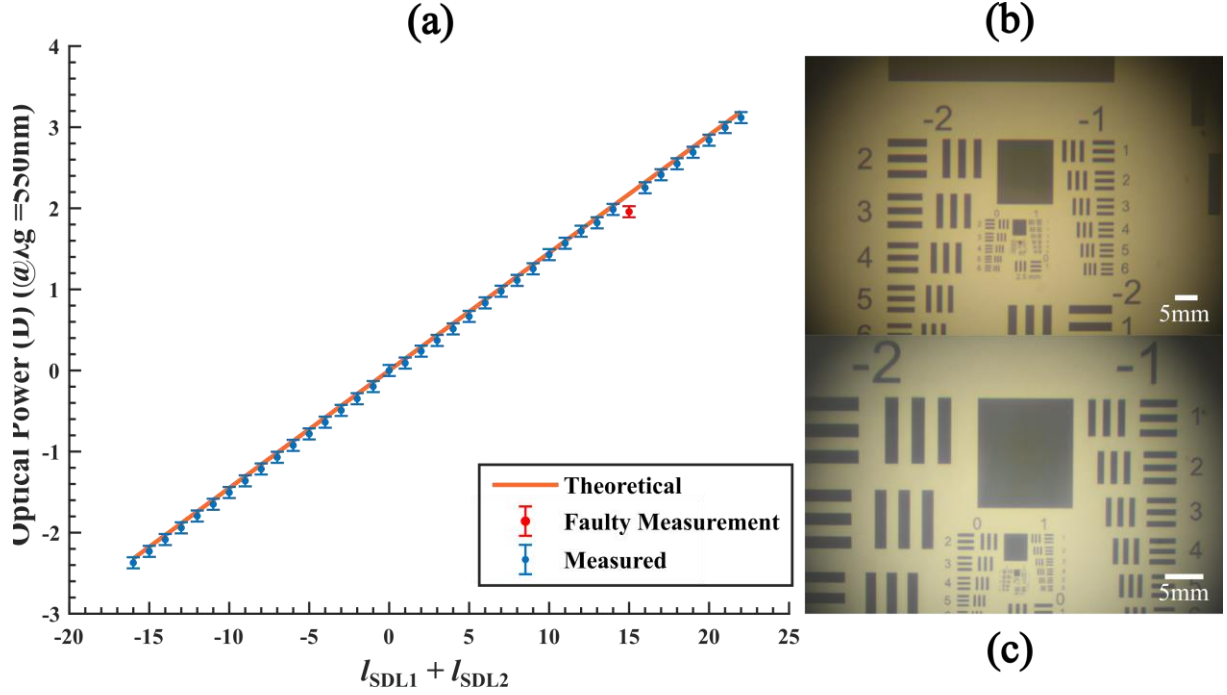


Figure 6.15: B2B SDLs assembly optical power measurements. a) Theoretical and calculated optical power plot. b) Image acquired with $P_{\text{Lens}} = -0.87\text{ D}$ ($l_{\text{SDL1}} = -3$, $l_{\text{SDL2}} = -3$). c) Image acquired with $P_{\text{Lens}} = +0.87\text{ D}$ ($l_{\text{SDL1}} = +3$, $l_{\text{SDL2}} = +3$).

6.4. Small area Spiral diffractive lens characterization

After characterizing SDLs with 1-inch active area diameter, lenses with a higher number of electrodes have been manufactured (from 24 to 72 electrodes) (Figure 6.16). In turn, the active area has been decreased (0.5-inch diameter), and the base focal distance has been designed to be $f_b = 11.5\text{ m}$ ($@\lambda = 550\text{ nm}$).



Figure 6.16: Manufactured SDL with half inch active area diameter configured with different topological charges: a) $l = 1$. b) $l = 2$.

The same calibration procedure as with the previous characterized lenses was carried out. In this occasion, a spiral phase plate was calibrated to explore its use to remove the lens topological charge (Figure 6.17).

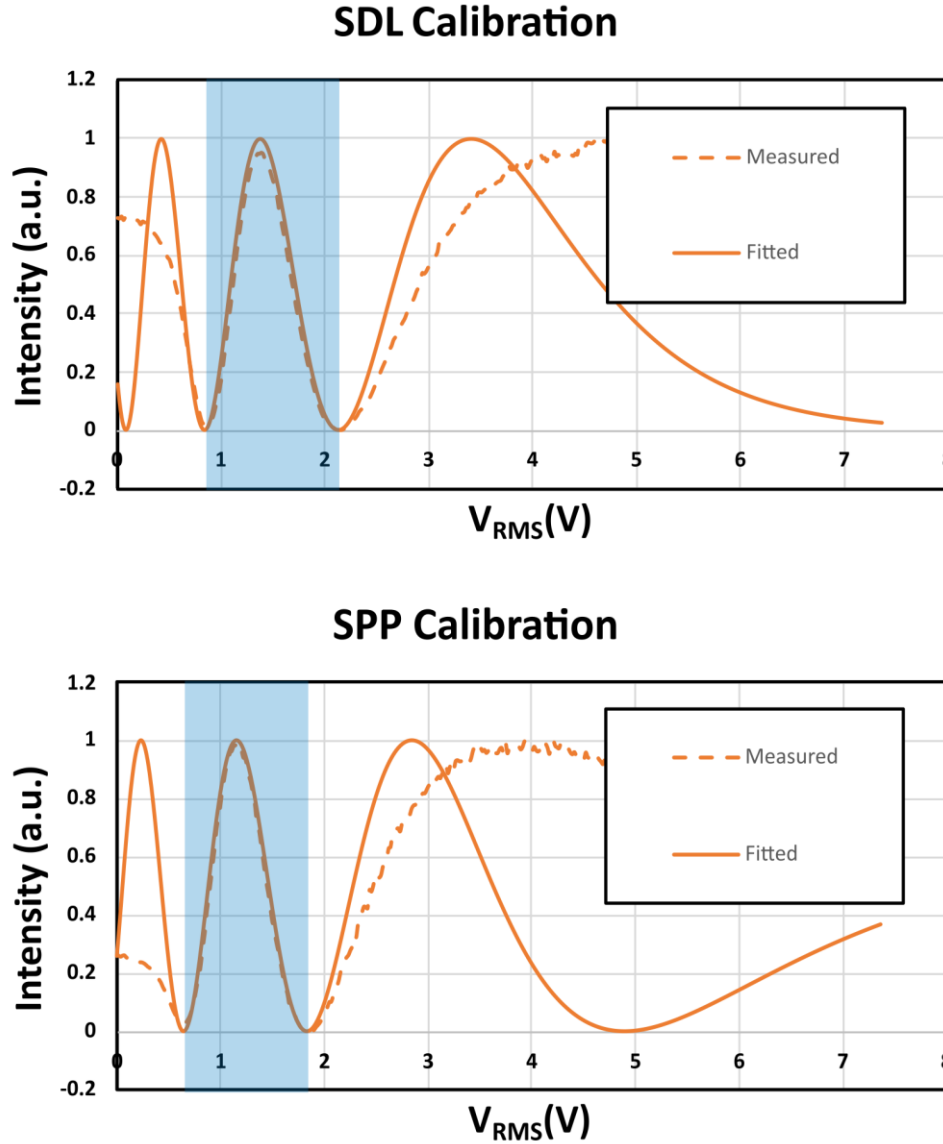


Figure 6.17: Calibrations obtained for the employed SDL and SPP. Both intensity calibrations are obtained using an external AC signal with $V_{RMS\ Max} = 7.5\ V$. Shaded blue area indicates the 2π fitted region.

Once the calibrations were fitted, both devices were manually aligned in the optical microscope using a 3D printed holder. In Figure 6.18, the proper alignment and the effect of the topological charge compensation can be observed.



Figure 6.18: Micrographs under white illuminations showing under crossed polarizers the SPP and SDL assembly for different configurations. a) $l_{SDL} = 8$, $l_{SPP} = -8$. b) $l_{SDL} = 10$, $l_{SPP} = -10$.

Then, a setup to characterize far field phase profile was assembled. The setup is very similar as the setup of the previous section; the assembly was placed between crossed polarizers. However, in this case, the green laser light was directly projected onto the CMOS camera sensor (Figure 6.19). These measurements confirm that the topological charge can be compensated with a SPP, leading to a phase profile free of phase singularities or azimuthal phase variation. In contrast with the measurements obtained with B2B lenses, the SPP activation does not change the optical power of the assembly.

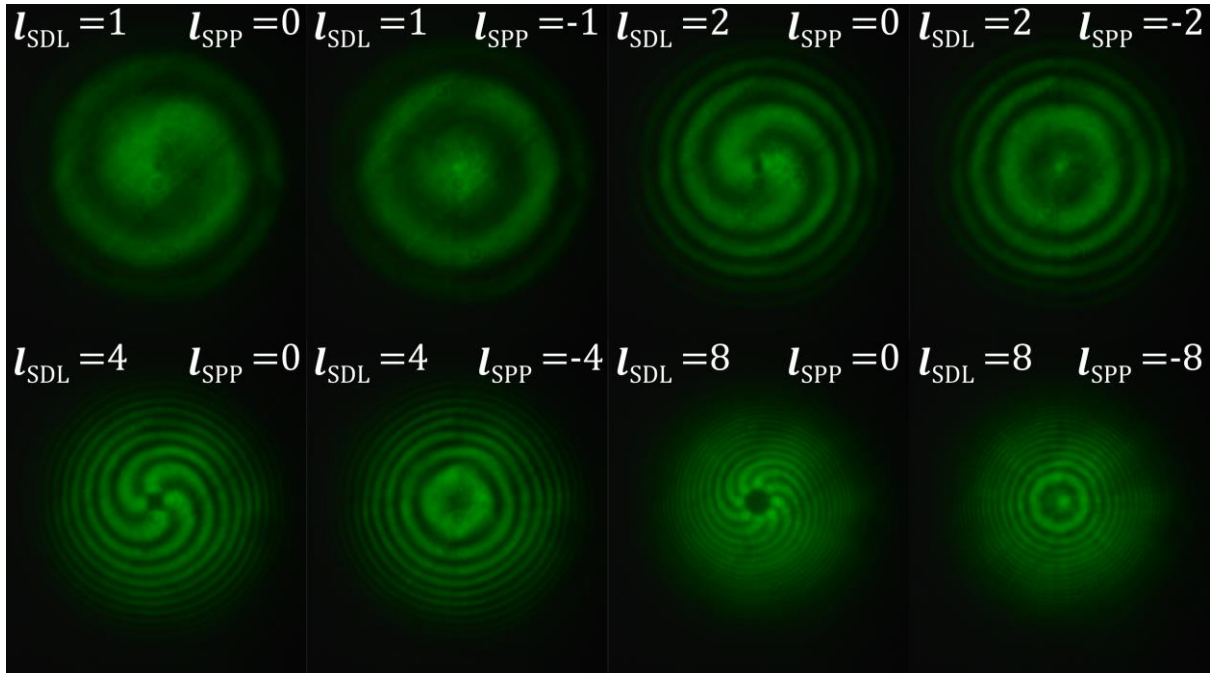


Figure 6.19: SDL and SPP assembly measured phase profiles for different configurations. Setting the SPP with an opposite l to the SDL results in a compensated phase profile without azimuthal phase variation.

Lastly, an experiment to characterize the focal length tunability was carried out. Like in the previous case, a paper target was manually placed at different distances to resolve the lens focal length (Figure 6.20). The developed lenses exhibited an optical power range spanning from -3.13 to 3.13 dioptres ($@\lambda = 550 \text{ nm}$), having 36 positive and 36 negative different configurations. The minimum focal length step was 9 mm, corresponding to the transition between $l_{SDL} = \pm 35$ and $l_{SDL} = \pm 36$. These measurements confirm the manufactured SDL lens reconfigurability as well as the diffraction efficiency decrease and image quality deterioration with increasing topological charge, the latter being mainly attributed to the inherent discretization of the devices.

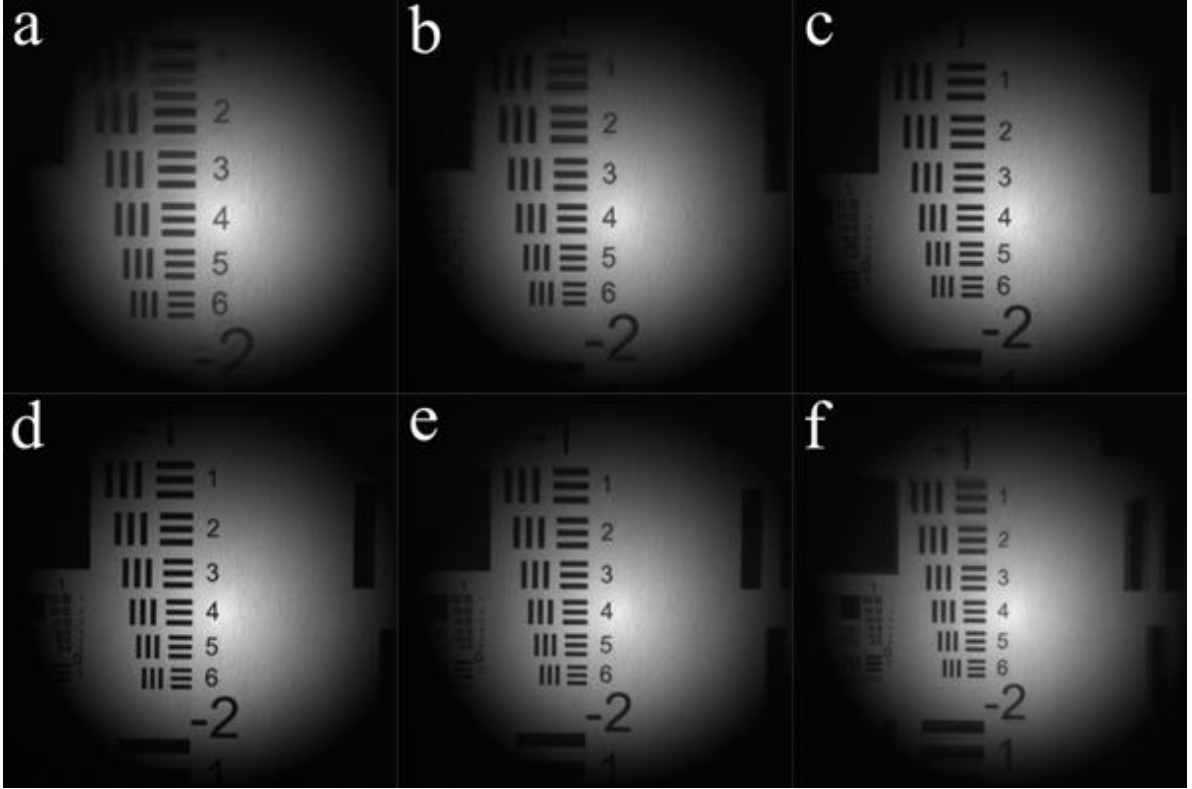


Figure 6.20: SDL focal length experimental measurements. a) $f_{SDL} = 0.958 \text{ m}$ ($l_{SDL} = 12$). b) $f_{SDL} = 1.95 \text{ m}$ ($l_{SDL} = 6$). c) $f_{SDL} = 5.745 \text{ m}$ ($l_{SDL} = 2$). d) $f_{SDL} = \infty$ ($l_{SDL} = 0$). e) $f_{SDL} = -5.745 \text{ m}$ ($l_{SDL} = -2$). f) $f_{SDL} = -1.915 \text{ m}$ ($l_{SDL} = -6$).

6.5. Imaging

A preliminary imaging assessment was carried out. Firstly, the impact of topological charge in image acquisition degradation was studied. Furthermore, two strategies to improve image quality in relation to chromatic aberration and hazing are proposed. Lastly, a reconfigurable zoom system is proposed where three LC devices were employed.

6.5.1. Vortex Aberrations

In previous sections, lenses with topological compensation have been experimentally demonstrated. A reconfigurable lens with zero net topological charge can be generated by stacking multiple devices with opposite topological charges. However, it must be verified whether this compensation has a non-negligible impact on the quality of the acquired images. Otherwise, single SDLs could be employed, reducing the complexity of the optical system and the electronic addressing.

Using the previously mentioned setup to measure the focal distance, different images were acquired utilizing an SPP/SDL assembly. In this way, images with and without SPP activation to compensate the SDL topological charge were obtained.

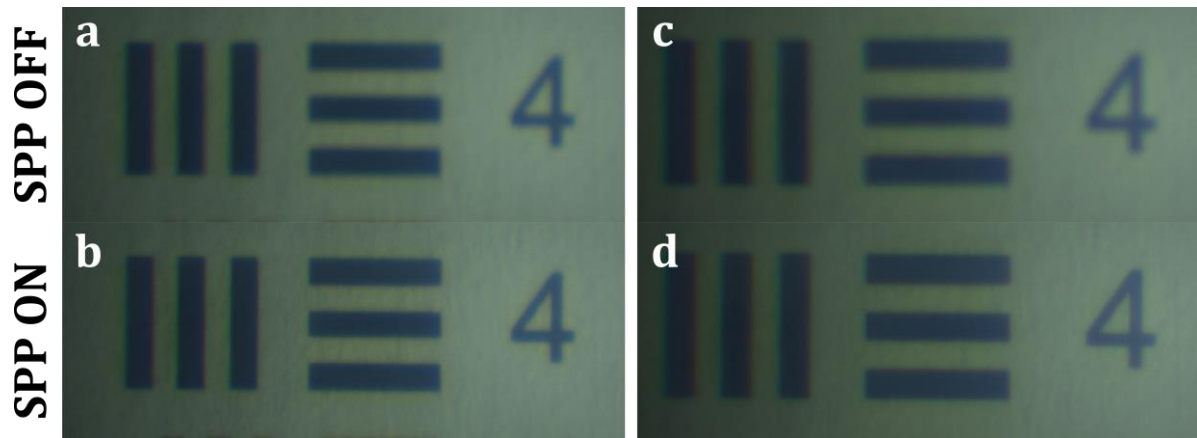


Figure 6.21: Impact of topological charge compensation on image sharpness. Insets of recorded images are shown for different configurations. a) $l_{SDL} = 12$, $l_{SPP} = 0$. b) $l_{SDL} = 12$, $l_{SPP} = -12$. c) $l_{SDL} = 18$, $l_{SPP} = 0$. d) $l_{SDL} = 18$, $l_{SPP} = -18$.

Figure 6.21 shows representative samples of the captured data; a central part of the images is blown up to better appreciate the improvement in sharpness of the acquired images. This experiment shows a clear improvement when the SPP is activated. Hence, the topological charge compensation improves the quality of the image. Additionally, there is a slight rotation pattern effect that disappears when the SPP is activated.

Apparently, there is no appreciable degradation due to the appearance of the phase singularity destructive interference about the optical axis even for higher topological charges, where it should be more pronounced. This phenomenon may not be appreciated because the size of the singularity is very small compared to the size of the target motifs. Instead, the topology effect was studied using a laser light aligned with the optical axis of the previous assembly and directly projected onto the CMOS camera sensor.

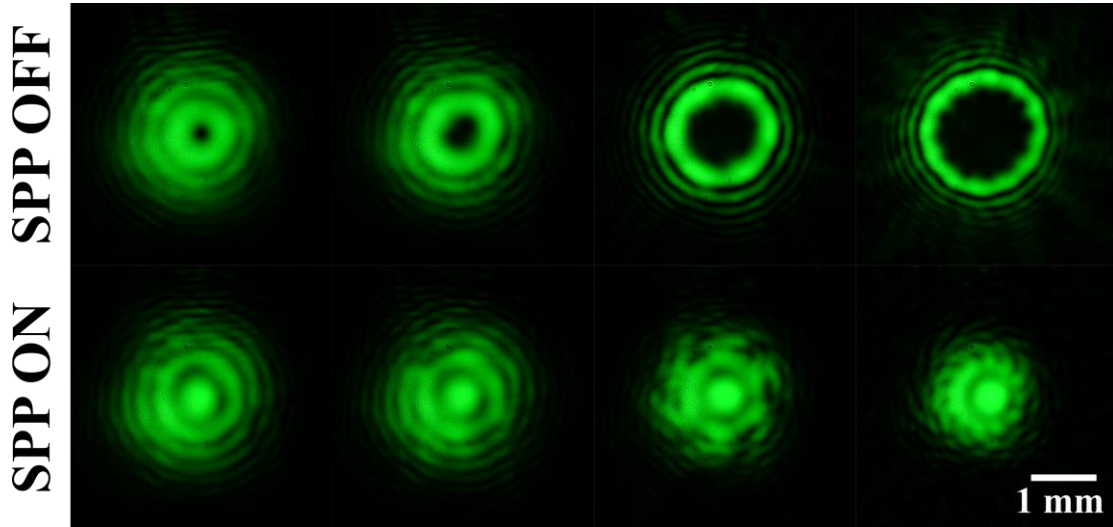


Figure 6.22: Singularity removal by counterbalancing SDL topological charge with a SPP. Top row shows the intensity when the SPP is deactivated, while bottom row depicts images with the l compensation. From left to right the topological charge is increased $l = 1, 2, 6, 12$.

The results of this experiment are shown in Figure 6.22. On the top row, the destructive interference can be observed about the optical axis as a dark disc that increases its size when the topological charge is increased. In the bottom row, the SPP is activated with an l opposite to the SDL topological charge, cancelling out the phase singularity. Clearly, the topological charge may be eliminated in systems where the intensity and phase around the optical axis are relevant.

Vortex aberrations in B2B SDLs were studied as well. In this occasion, two lenses were aligned under the microscope and assembled using a photocurable adhesive (Norland optical adhesive). This assembly method was chosen to ease the integration of the lenses into a number of demonstrator setups. The setup also included a USB camera, and ADTelecom electronic driver. The camera was configured with the largest possible depth of focus, so that the acquired images would be focused independently on the focal length of the LC lenses. It is possible to appreciate how the target patterns rotate around the vortex singularity when only one SDL is activated (Figure 6.23). This phenomenon almost completely disappears when both B2B lenses are addressed.

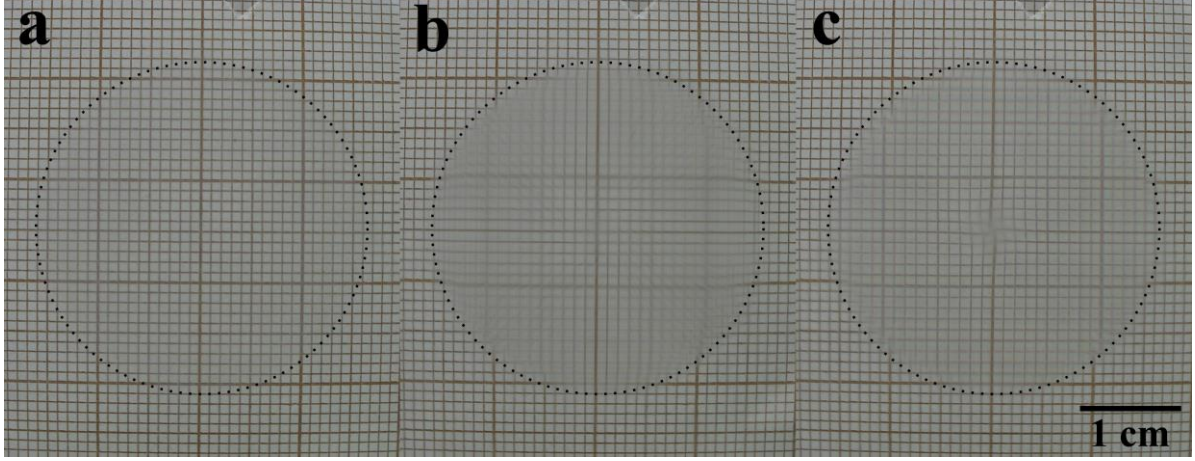


Figure 6.23: Vortex aberration removal by using B2B lenses. *a)* Both lenses are turned off. *b)* B2B lenses with $l_{SDL1} = 12$ and $l_{SDL2} = -12$. *c)* A single lens is configured with the same optical power as the previous configuration ($l_{SDL1} = 24$, $l_{SDL2} = 0$) giving rise to a vortex aberration around the optical axis. The contour of the lenses is highlighted with a black dot line.

Removing the topological charge improves the image quality. This improvement is related to sharpness increase and quality of the image around the optical axis. However, using single SDLs could be an attractive option for those applications which strives for simple setups and could tolerate these aberrations.

6.5.2. Chromatic Aberration Correction

One significant drawback of Fresnel lens imaging systems, such as the proposed ones, is the chromatic aberration. The chromatic dispersion in the SDL follows the one of conventional diffractive lenses [225]. Chromatic aberration arises from the wavelength dependence of the lens focal length. For one specific spiral design and topological charge, the focal length variation with respect to the wavelength can be approximated to the dispersion of a zone plate as [226]:

$$f_{\lambda_x} = f_{\lambda_0} \cdot \frac{\lambda_0}{\lambda_x} \quad (6.6)$$

where f_{λ_0} is the reference focal length for the design specific wavelength λ_0 , and f_{λ_x} is the focal distance for any for an arbitrary wavelength λ_x . In equation (6.6) the diffraction efficiency caused by the material refractive index dispersion is not taken into account, as this will affect the efficiency of the lens rather than the focal length dispersion.

Conventionally, the most widely used approach to reduce chromatic aberration is the achromatic doublet [227], a pair of elements with different dispersion coefficients and focal lengths. Alternatively novel approaches such as hybrid metalenses [228], multi-level microstructures [229], refractive and diffractive elements hybridization [230] or lens multiplexing [231] have been also suggested. These aberration minimization techniques usually involve complex manufactured lenses and are not generally suitable for varifocal lenses. In this thesis, we intend to develop a simple technique for chromatic aberration minimization targeting machine vision or camera applications. This approach relies on the dynamic analog tuneability of the developed LC lenses, allowing for a sequential capture of images optimized for every camera color filter wavelength separately. The optimized images are subsequently recombined in the postprocessing of the image data resulting in an image free of chromatic aberrations.

To carry out this strategy, the first step is to obtain the lenses calibration for three different wavelengths ($\lambda_b = 450\text{ nm}$, $\lambda_g = 550\text{ nm}$, $\lambda_r = 650\text{ nm}$). The green calibration was measured while the LC response for the other wavelengths was extrapolated by making a third-degree polynomial fitting of the LC MDA-98-1602 birefringence dispersion based on experimental measurements [232]. These extrapolated calibrations were initially assessed by performing additional calibrations using red and blue illumination and comparing the calculated extrapolated and measured transmission and derived phase delay data (Figure 6.24).

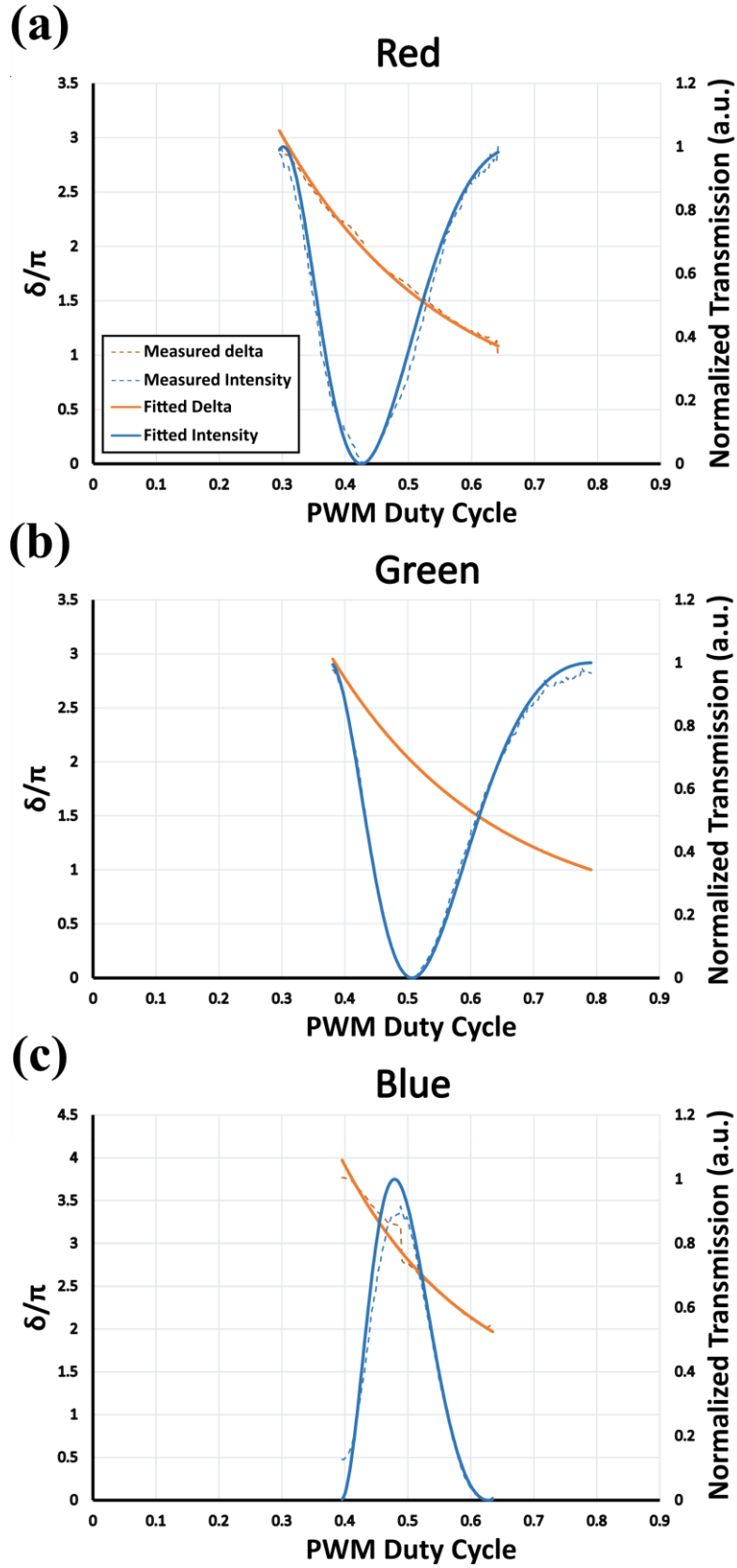


Figure 6.24: LC cell calibration graphs for different wavelengths [224]. The graphs depict the measured intensity and phase delay (dashed lines) as well as the fitted (solid lines) extrapolated from λ_g calibration. a) $\lambda_r = 650\text{nm}$. b) $\lambda_g = 550\text{nm}$. c) $\lambda_b = 450\text{nm}$.

Subsequently, the extrapolated calibrations were employed in the lenses, confirming the validity of the approach. The focal distances for the different wavelengths and topological charges were calculated; having these values the different target distances (d_{target}) were computed.

l	$f_{\text{fens}}(\lambda_b) [m]$	$f_{\text{fens}}(\lambda_g) [m]$	$f_{\text{fens}}(\lambda_r) [m]$	l	$d_{\text{Target}}(\lambda_b) [m]$	$d_{\text{Target}}(\lambda_g) [m]$	$d_{\text{Target}}(\lambda_r) [m]$
-24	-0.351	-0.287	-0.243	-24	2.061		
-23	-0.366	-0.300	-0.254	-23	1.656		
-22	-0.383	-0.313	-0.265	-22	1.384	7.022	
-21	-0.401	-0.328	-0.278	-21	1.189	3.479	
-20	-0.421	-0.345	-0.292	-20	1.042	2.312	
-19	-0.444	-0.363	-0.307	-19	0.927	1.732	13.076
-18	-0.468	-0.383	-0.324	-18	0.835	1.384	4.034
-17	-0.496	-0.406	-0.343	-17	0.760	1.153	2.385
-16	-0.527	-0.431	-0.365	-16	0.697	0.988	1.693
-15	-0.562	-0.460	-0.389	-15	0.644	0.864	1.312
-14	-0.602	-0.492	-0.417	-14	0.598	0.768	1.071
-13	-0.648	-0.530	-0.449	-13	0.558	0.691	0.905
-12	-0.702	-0.575	-0.486	-12	0.524	0.628	0.783
-11	-0.766	-0.627	-0.530	-11	0.493	0.575	0.691
-10	-0.843	-0.689	-0.583	-10	0.466	0.531	0.618
-9	-0.936	-0.766	-0.648	-9	0.441	0.493	0.558
-8	-1.053	-0.862	-0.729	-8	0.419	0.460	0.510
-7	-1.204	-0.985	-0.833	-7	0.400	0.431	0.469
-6	-1.404	-1.149	-0.972	-6	0.381	0.406	0.434
-5	-1.685	-1.379	-1.167	-5	0.365	0.383	0.404
-4	-2.107	-1.724	-1.458	-4	0.350	0.363	0.378
-3	-2.809	-2.298	-1.945	-3	0.336	0.345	0.355
-2	-4.213	-3.447	-2.917	-2	0.323	0.329	0.334
-1	-8.427	-6.895	-5.834	-1	0.311	0.314	0.316
0	--	--	--	0	0.300	0.300	0.300
1	8.427	6.895	5.834	1	0.290	0.287	0.285
2	4.213	3.447	2.917	2	0.280	0.276	0.272
3	2.809	2.298	1.945	3	0.271	0.265	0.260
4	2.107	1.724	1.458	4	0.263	0.256	0.249
5	1.685	1.379	1.167	5	0.255	0.246	0.239
6	1.404	1.149	0.972	6	0.247	0.238	0.229
7	1.204	0.985	0.833	7	0.240	0.230	0.221
8	1.053	0.862	0.729	8	0.233	0.223	0.213
9	0.936	0.766	0.648	9	0.227	0.216	0.205
10	0.843	0.689	0.583	10	0.221	0.209	0.198
11	0.766	0.627	0.530	11	0.216	0.203	0.192
12	0.702	0.575	0.486	12	0.210	0.197	0.186
13	0.648	0.530	0.449	13	0.205	0.192	0.180
14	0.602	0.492	0.417	14	0.200	0.186	0.174
15	0.562	0.460	0.389	15	0.196	0.182	0.169
16	0.527	0.431	0.365	16	0.191	0.177	0.165
17	0.496	0.406	0.343	17	0.187	0.172	0.160
18	0.468	0.383	0.324	18	0.183	0.168	0.156
19	0.444	0.363	0.307	19	0.179	0.164	0.152
20	0.421	0.345	0.292	20	0.175	0.160	0.148
21	0.401	0.328	0.278	21	0.172	0.157	0.144
22	0.383	0.313	0.265	22	0.168	0.153	0.141
23	0.366	0.300	0.254	23	0.165	0.150	0.137
24	0.351	0.287	0.243	24	0.162	0.147	0.134

Figure 6.25: Summary of focal distances and their corresponding target distances for the different wavelengths and topological charges [224].

The focal distances were measured using the extrapolated calibrations knowing that the camera CMOS sensor uses a Bayer RGGG pixel color configuration. When decomposing the image into three different color channels the chromatic aberration is easily appreciated, as only one color is focused. In Figure 6.26, the different channels (RGB) and the combined color image are shown using the B2B SDLs configurations calibrated for the three different wavelengths. The chromatic aberration can be seen as the non-targeted channels are defocused (Calibrated channel is highlighted with a colored square). The chromatic focus dispersion leads to a blurred combined color image. This is especially true for the colors spectrally farthest apart, *i.e.* red and blue. However, it is also clear that simply by changing the electronic addressing of the LC lens, images optimized for each of the colors may be acquired separately. Furthermore, this experiment validates the calibrations extrapolations.

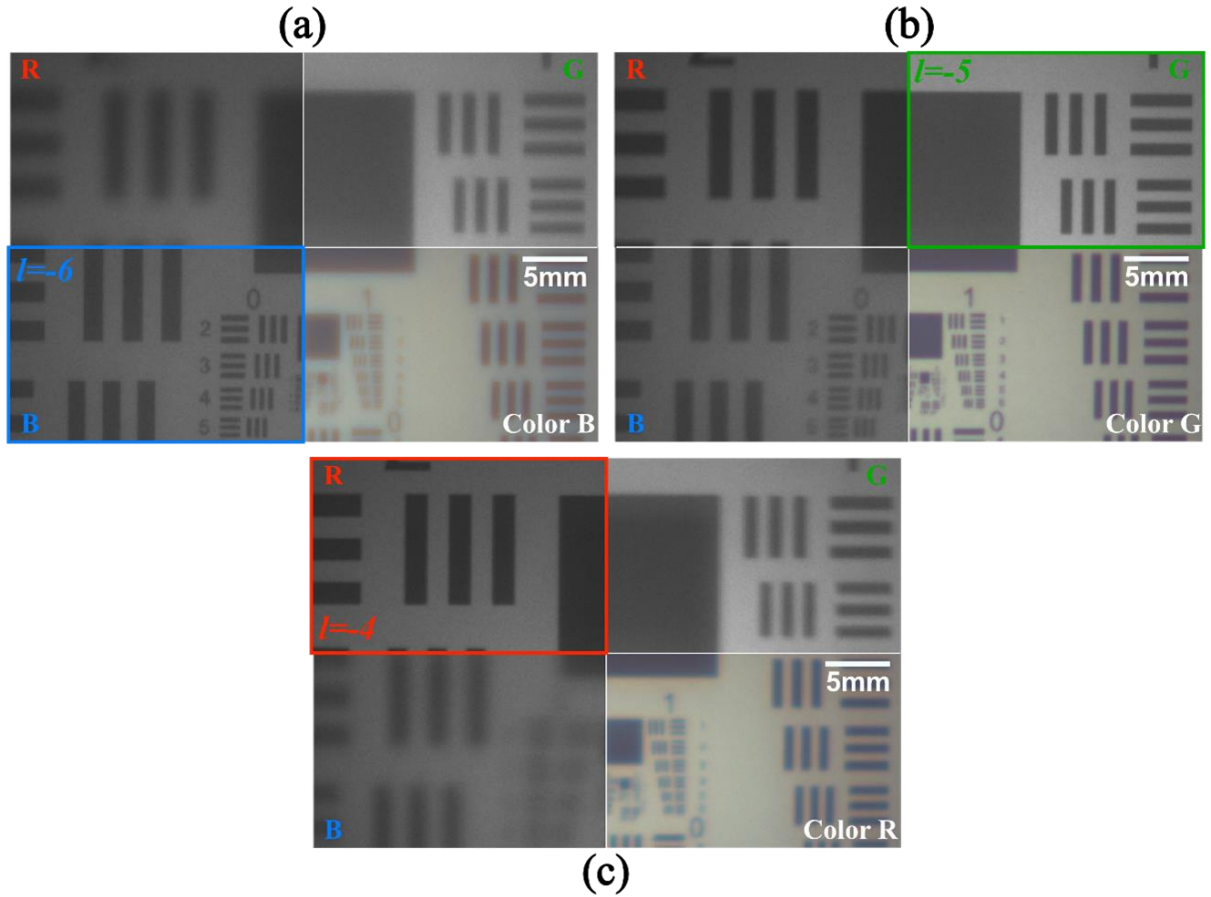


Figure 6.26: Captured images using B2B SDLs optimized for different wavelengths [224]: a) $\lambda_b = 450 \text{ nm}$ ($@l = -6$). b) $\lambda_g = 550 \text{ nm}$ ($@l = -5$). c) $\lambda_r = 650 \text{ nm}$ ($@l = -4$). Each picture depicts three sectors corresponding to each channel luminance (RGB) in grey scale, and the last one is the combined color image.

The lenses focal length can be optimized for any desired visible wavelength. This allows a strategy to dynamically compensate chromatic aberration. The previous experiment showed that it is possible to capture three different images for a given position, each image being optimized for a different camera filter wavelength. Therefore, the color channel can be extracted from each picture and eventually recombined, obtaining a processed image with minimized chromatic aberration (Figure 6.27). The complete set of lens focal distances (f_{Lens}) for the different wavelengths ($\lambda_b, \lambda_g, \lambda_r$) with their corresponding target distances are shown in Figure 6.25.

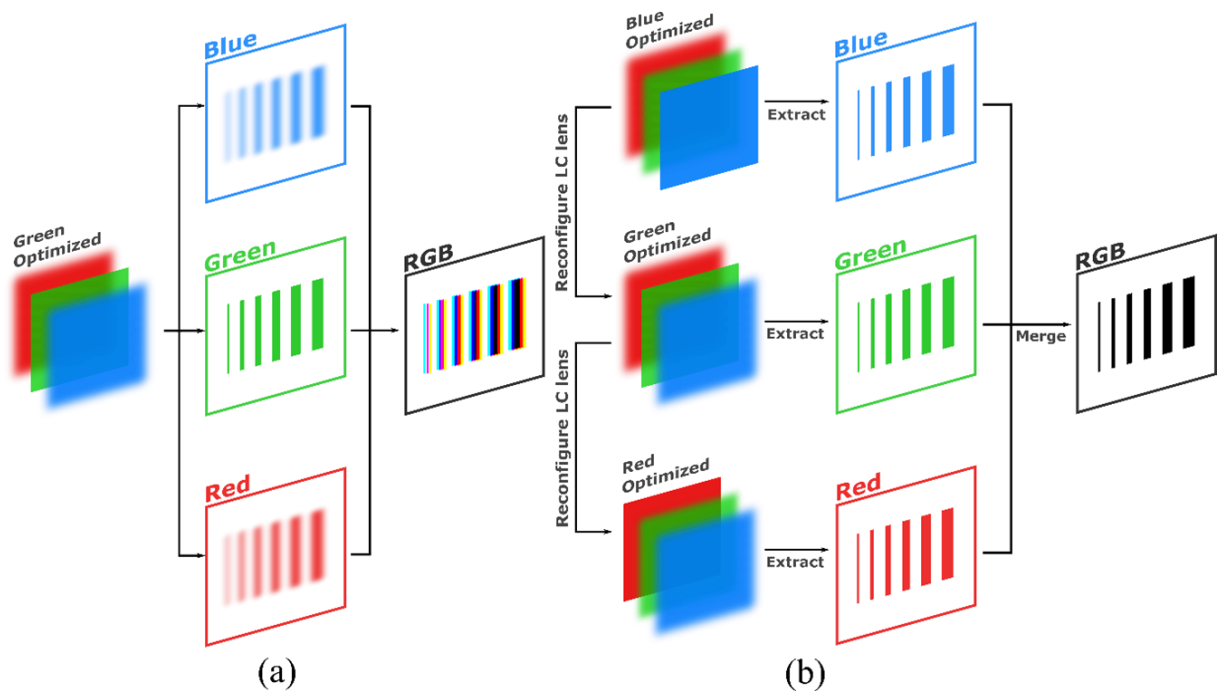


Figure 6.27: Sketch illustrating the chromatic aberration compensation process [224]. a) Single picture acquisition where the non-optimized (blue and red) channels blur leads to chromatic aberration. b) The LC lenses can be reconfigured to obtain three different images, where the optimized channel wavelength is extracted and then merged to minimize chromatic aberration

The experiment was carried out for different target distances (highlighted in white in Figure 6.25). The results are shown in Figure 6.28 [224]. Top row shows the intensity readouts in the independent RRGB color pixels for captured images with the lens optimized for each wavelength separately. The bottom row shows the comparison between the color images captured with the different lens settings (optimized for the different wavelengths) and the combined wavelength-optimized image. These results show a sharpness increase and haze reduction.

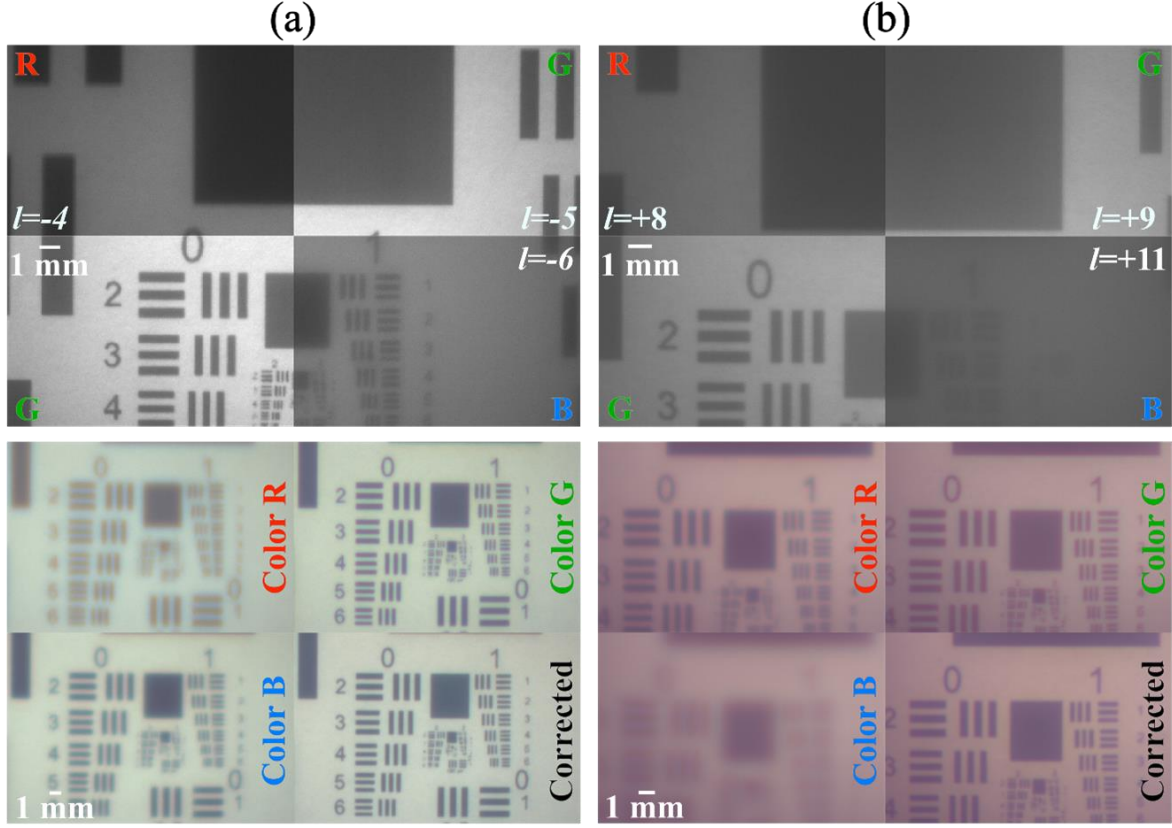


Figure 6.28: Chromatic correction strategy obtained results [224]. a) $d_{\text{target}} = 38.1 \text{ cm}$ ($P_{\text{Lens}} = -0.71 (\pm 0.02) \text{ D}$). b) $d_{\text{target}} = 21.4 \text{ cm}$ ($P_{\text{Lens}} = +1.33 (\pm 0.04) \text{ D}$). The upper row images are subdivided in four sectors corresponding to three different images optimized for each wavelength. In the bottom row the comparison between the combined colors acquired images against the processed chromatic compensated one.

To have a quantitative measurement of the observed relative sharpness improvement, the Tenenbaum gradient [233] was used for quantification. This algorithm evaluates the whole image based on the convolution of the original image with the Sober operators [233], [234]. The higher the positive values represent a greater sharpness enhancement, while negative values are associated to image degradation. Table 6.1 shows the relative change in Tenenbaum gradient between original color images and the chromatic corrected color image for five different optical power configurations. The trend of enhanced sharpness across various configurations may be appreciated. It must be noted that two data points appear to exhibit a minor image quality degradation, which is attributed to target positioning errors ($\pm 1 \text{ mm}$).

Table 6.1: Tenenbaum gradient relative sharpness improvement (%) in chromatic corrected images compared to simple color images.

	Relative Sharpness Improvement (%)				
	$-0.85 D$	$-0.71 D$	$+0.85 D$	$+1.33 D$	$+1.89 D$
	$l_r=-5, l_g=-6, l_b=-7$	$l_r=-4, l_g=-5, l_b=-6$	$l_r=5, l_g=6, l_b=7$	$l_r=8, l_g=9, l_b=11$	$l_r=11, l_g=13, l_b=16$
Red (λ_r)	44.9	51.9	-13.7	22.4	10.6
Green (λ_g)	-18	31.5	30.7	10.4	10.3
Blue (λ_b)	37.8	78.8	89.7	57.9	31.8

The obtained results confirm that the proposed technique enables chromatic aberration correction for several distances. To increase the number of coincident distances for three different wavelengths the spirals design must be modified (i.e. changing base focal length or number of electrodes). Considering that the switching speed of the lenses are in the order of ms, this strategy could be potentially implemented at video frame rates.

6.5.3. Zoom system

One of the possible applications of the varifocal lenses shown above is a reconfigurable zoom system. The simplest zoom system is a two-lens system formed by an objective lens and an image lens. If the distance from the target to the objective lens is very big compared to the lens separation (L) and lens focal length (f_i), this system can be approximated to a telescopic configuration [235]. To modify the diameter of an input collimated beam without altering the system focal length the following condition must be fulfilled:

$$L = f_i + f_o \quad (6.7)$$

where L is the distance between lenses, f_i is the lens focal length, and f_o is the objective lens focal length.

The magnifying power (MP) of the telescope system is determined by the relation between the focal length of the lenses:

$$MP = -\frac{f_o}{f_i} \quad (6.8)$$

where magnifying power smaller than one implies image reduction and greater than one are related to magnifications [236].

The proposed zoom system follows a Galilean telescope to create a more compact system. The setup is formed by a convergent and a divergent lens. The developed LC lenses can behave as both divergent or convergent lenses, thus by electronically reconfiguring them, both magnification and reduction can be achieved (Figure 6.29). Therefore, the focal length tuning of our SDLs will lead to both positive and negative zoom systems with magnifying powers given by eq. (6.8).

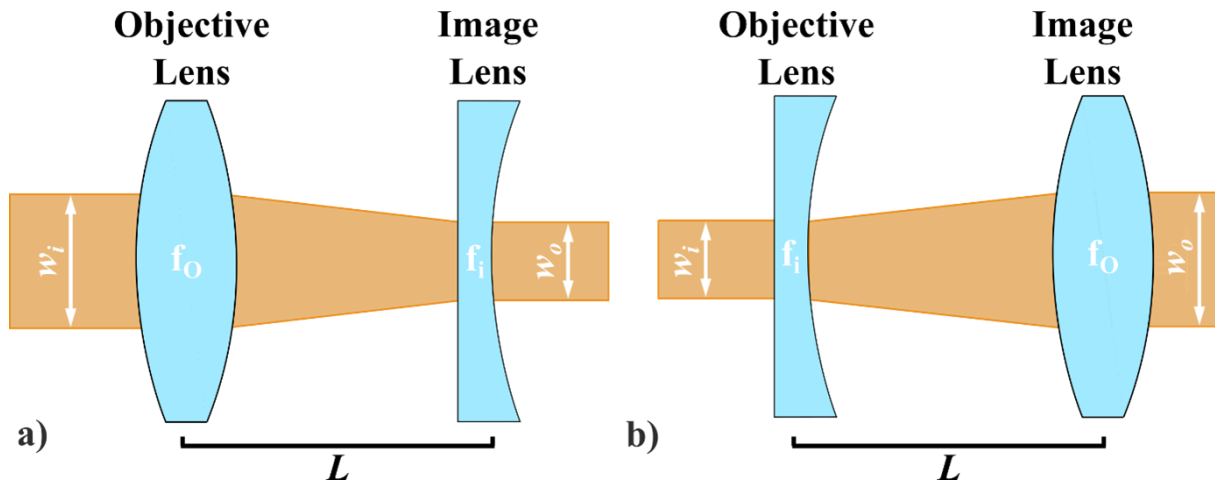


Figure 6.29: Beam diameter modification based on different Galilean telescope configurations [237]: a) Reduction. b) Magnification.

The zoom system integrates three LC devices: two SDLs with individual focal length reconfigurability and a SPP to compensate any residual topological charge [237]. As previously used, a 3d printed holder is employed to align the SPP and SDL. This assembly along with the other lens are mounted on XY linear micro-positioning stages to ease the alignment. A Nikon camera D500 followed by a linear polarizer are employed to record the images. The setup is completed with the electronic drivers along the power supply and function generator to enable the LC devices reconfiguration (Figure 6.30).

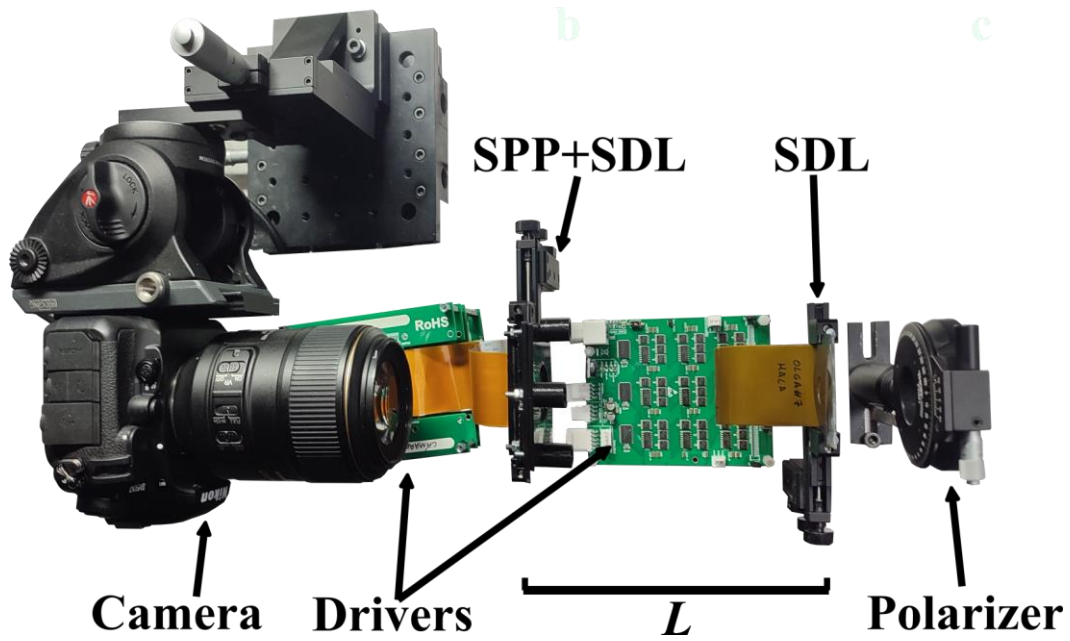


Figure 6.30: Top-View of the zoom system experimental setup depicting the camera, LC devices, distance between lenses, electronic drivers, and polarizer.

The whole set of 72 different SDL focal lengths have been calculated. It has been verified way that the condition of equation (6.7) is fulfilled within a 2 mm error. A separation between lenses $L = 16$ cm to test the system under actual working conditions. A total of seven different configurations (with different magnifying powers) can be obtained, three configurations that produce a positive zoom, three with negative zoom, and the off state with zero magnification. These configurations are summarized in the following table:

Table 6.2 Zoom system configuration for different magnifications and reductions.

Theoretical Magnifying Power	f_{SDL1} (m)	f_{SDL2} (m)	l_{SPP}	l_{SDL1}	l_{SDL2}
1.181	1.044	-0.884	2	11	-13
1.125	1.436	-1.277	1	8	-9
--	∞	∞	0	0	0
0.889	-1.277	1.436	1	-9	8
0.847	-0.884	1.044	2	-13	11
0.75	-0.4788	0.638	6	-24	18

The acquired images are shown in Figure 6.31. For the selected configurations, the proposed system shows a zoom range of $\sim 1.57:1$. This zoom ratio has been obtained as the difference in size between the maximum reduction (Figure 6.31f) and magnification (Figure 6.31a). The experiment supports that it is possible to create a fast reconfigurable zoom system employing the lenses developed above. However, as with previous cases, the image degrades as the topological charge is increased. One specific source of degradation in this system is that both lenses have the same diameter. Consequently, a significant part of light in magnification configurations will fall outside of the image lens, thus increasing the image haze.

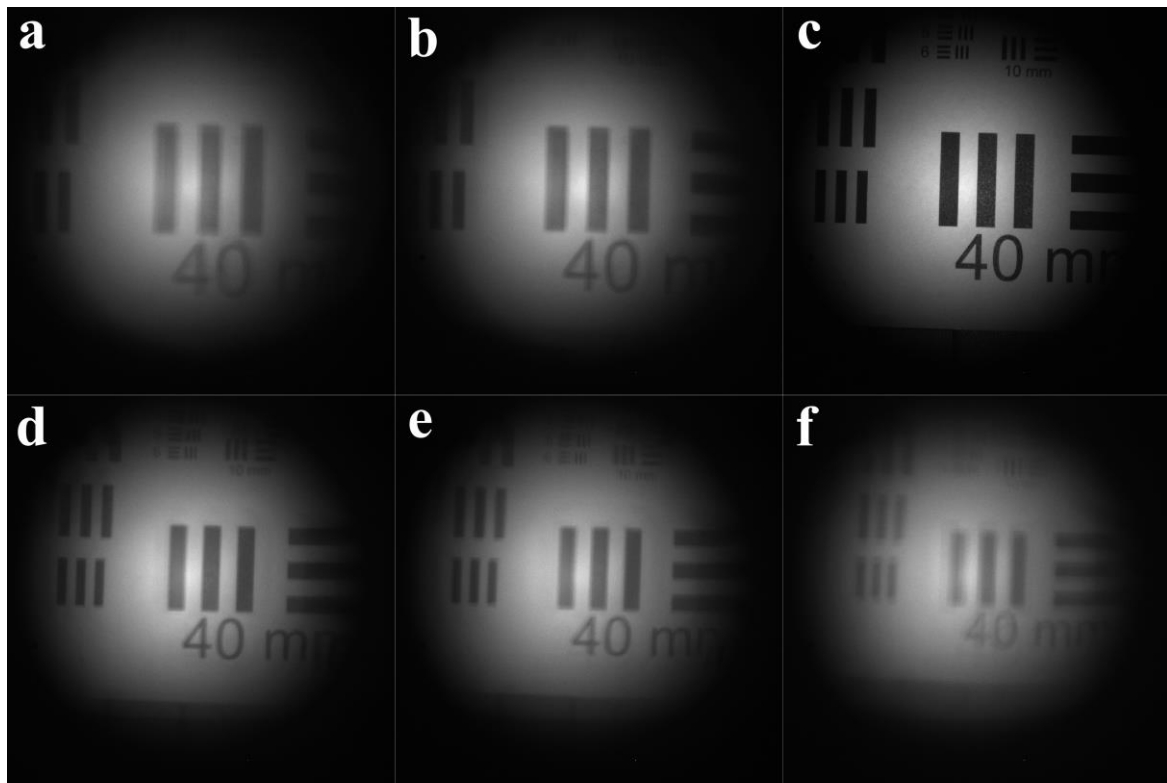


Figure 6.31: Measured magnifying power for different configurations. *a) $MP = 1.15$. b) $MP = 1.08$. c) Off state. d) $MP = 0.89$. e) $MP = 0.85$. f) $MP = 0.75$.*

7. Perfect Vortex Beam Generation

The power distribution about the singular point in a simple optical vortex beam depends on the topological charge (l) of the beam. This may compromise applications such as optical manipulation. Indeed, in some cases, the exerted rotational force should preferably be independent of the power distribution. Clearly, any application where beams with different l have to be focused into an optical fiber (*i.e.* guided optical communications) are also jeopardized [238].

To overcome this challenge, Ostrovksy et al. proposed in 2013 the perfect vortex beam (PVB) concept [239]. In these beams, the radius of the intensity ring created by the vortex does not depend on the carried topological charge.

Several ways of generating PVBs have been proposed, including spatial light modulators (SLMs) [239], [240], [241], [242], digital micromirror devices (DMDs) [243], [244], metasurfaces [245], polymer-based plates [217] or Pancharatnam-Berry (PB) elements [246]. For devices based on polymer plates, PB elements or metasurfaces, there is a limitation on the tunability of the generated beam l . SLM-based systems, on the other hand, have three major drawbacks: a relatively high cost, limitations arising from the SLMs finite pixel size [238], [247], and more complex electronic driving requirements. Additionally, most of the previously reported configurations based on SLMs, metasurfaces, and DMDs are reflective devices, which conditions their implementation.

In this chapter, two different reconfigurable PVB systems are presented. The first is based on the employment of a diffractive spiral axicon (DSA) and different glass lenses. The second use a spiral phase plate (SPP) as core element. Both approaches are electronically reconfigurable and transmissive, thus suitable for applications where compactness is a critical factor. The details, limits, and strengths of the two different systems are discussed below.

7.1. PVB generation based on DSA

In 2015, Vaity and Rusch demonstrated that PVBs could be generated using the Fourier transform property of a Bessel Beam [241]. Therefore, this phenomenon could be replicated by inserting a converging lens after a DSA (in a convergent configuration) within the DOF. In their work, they used an SLM followed by a lens. Here we propose an optical setup composed of a liquid crystal DSA and a refractive lens to generate PVBs [178] (Figure 7.1).

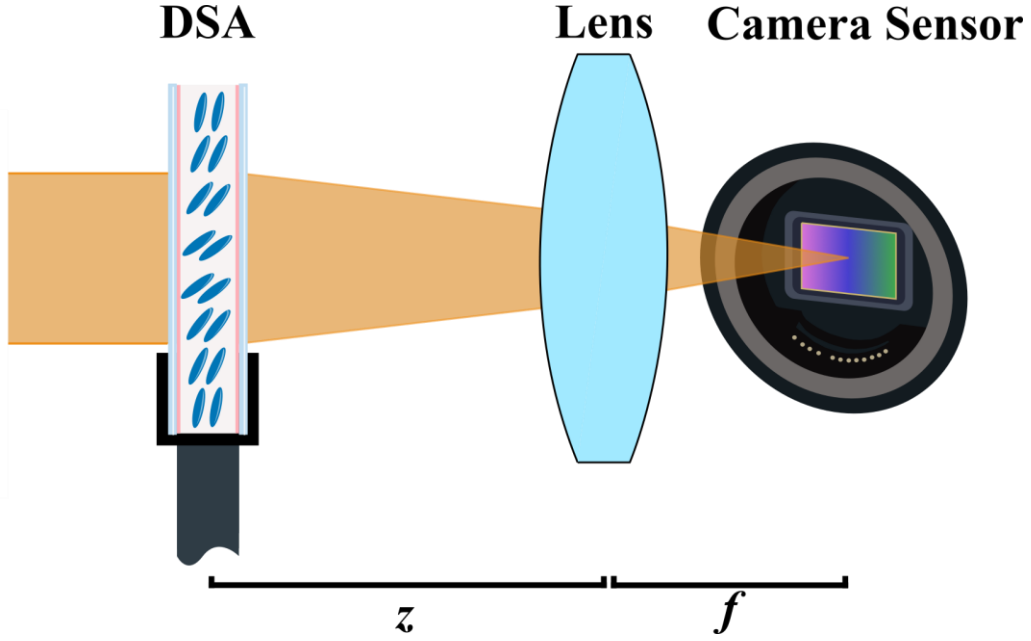


Figure 7.1: PVB generation based on a DSA proposed optical setup sketch.

It is important to highlight that the focal distance of the converging lens must be modified for different PVBs since the developed DSA simultaneously changes the output angle and topological charge. This can be done either by replacing the lens or by using a reconfigurable varifocal lens [223]. For the sake of simplicity, a set of two glass lenses were used to verify the proposed design.

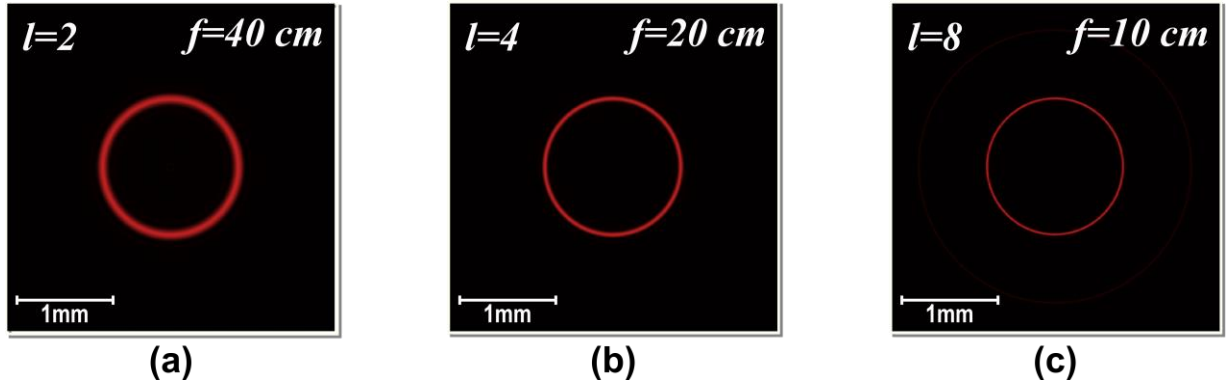


Figure 7.2: PVB simulations by adding convergent lenses after the DSA at a distance 15 cm. The lens focal length (f) depends on the DSA topological charge (l): a) $l = 2, f = 40$ cm. b) $l = 4, f = 20$ cm. c) $l = 8, f = 10$ cm.

Light propagation simulations are conducted prior to mounting the proposed setup generating vortex beams with constant diameter (Figure 7.2). A multi-step simulation was performed, including all the optical elements and the distances separating them. The simulation steps are sketched in Figure 7.3. Simulations predicted, as expected, that the output annular pattern at the lens focal length has a constant diameter.

The optical setup consisting of red laser, DSA, glass lens, and camera was assembled. A glass lens of focal length $f = 20$ cm was used for the DSA with $l = 4$, and another with $f = 10$ cm for $l = 8$. Both lenses were placed at a distance $z = 5$ cm (within the DOF). It is important to note again that the lens focal length must compensate the DSA output angle variation to maintain the PVB diameter. In other words, the product $l \cdot f$ must remain constant. Experimental results employing the described setup are shown in Figure 7.4. Both configurations showed a dark hollow with a bright constant radius. Therefore, using the DSA as a tunable topological charge system and modifying the extra lens, a perfect vortex beam can be generated [178]. The results show good agreement with the overlaid simulations.

The dependence of the DSA output angle with the topological charge in the setup is a major limitation. Indeed, the lens needs to be replaced for every configured topological charge. Furthermore, the constant radius ring appears at the focal length of the lens, meaning that the target or the acquiring sensor must be displaced as well. Therefore, a different optical setup based on SPPs has been designed to overcome these limitations.

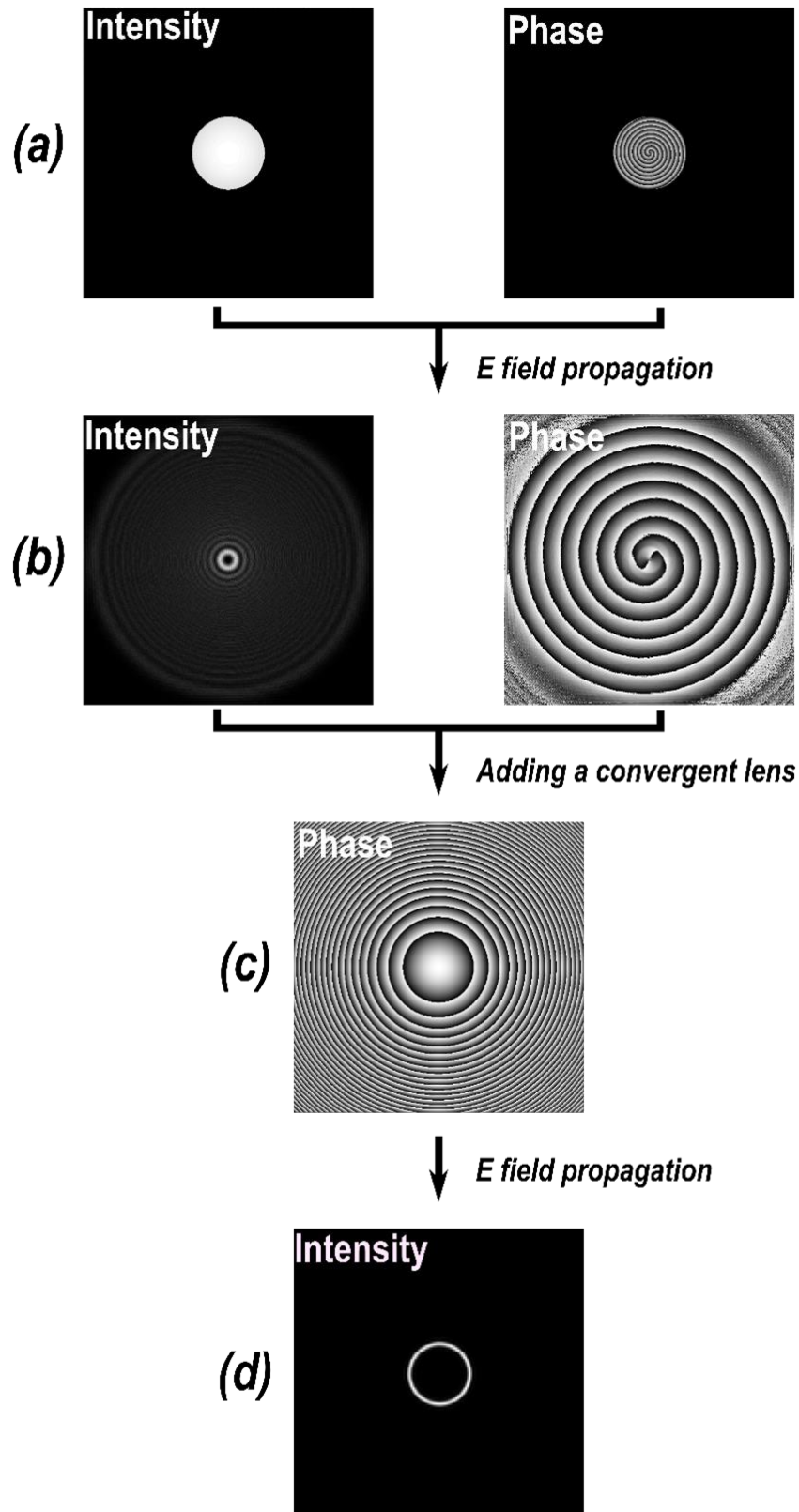


Figure 7.3: PVB Simulation process scheme [178]: a) Generate the DSA and the Gaussian Beam. b) Calculate the electric field at $z=15\text{cm}$. c) Lens phase matrix added to the calculated electric field. d) PVB intensity pattern calculated at the focal point of the lens.

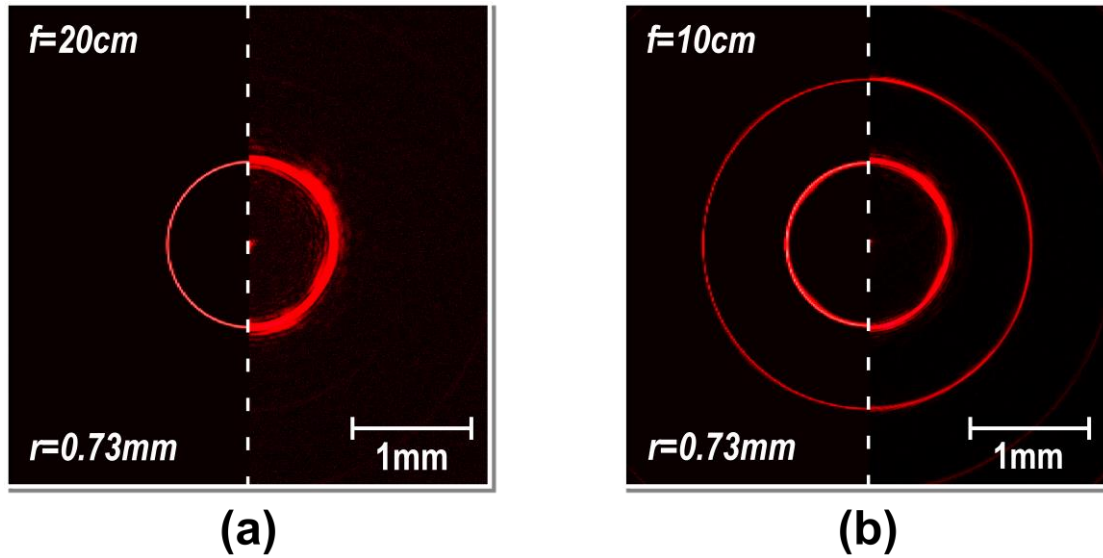


Figure 7.4: PVBs projected onto the camera sensor compared with the corresponding simulated results (overlaid in the left part) [178]. The measurements show different lens and DSA configurations: a) $l = 4, f = 20 \text{ cm}$. b) $l = 8, f = 10 \text{ cm}$.

7.2. PVB generation based on SPP

The proposed system can be made amazingly simple, employing just three elements, SPP, conventional fixed axicon and lens [179]. The setup is based on the SPP ability of generating different l without affecting other parameters such as the output angle. The light transformed by the SPP falls upon the 2° angle axicon (Thorlabs [74]) forming a Bessel-Gauss beam, having a l determined by the SPP configuration only (Figure 7.5). Lastly, a convergent lens ($f = 20 \text{ cm}$) focuses the light onto a CMOS sensor. Light propagation through the different elements of this setup is simulated (without considering the effect of the diaphragm). Simulations illustrate the transformations carried out by each element; these results are shown in the insets of Figure 7.5.

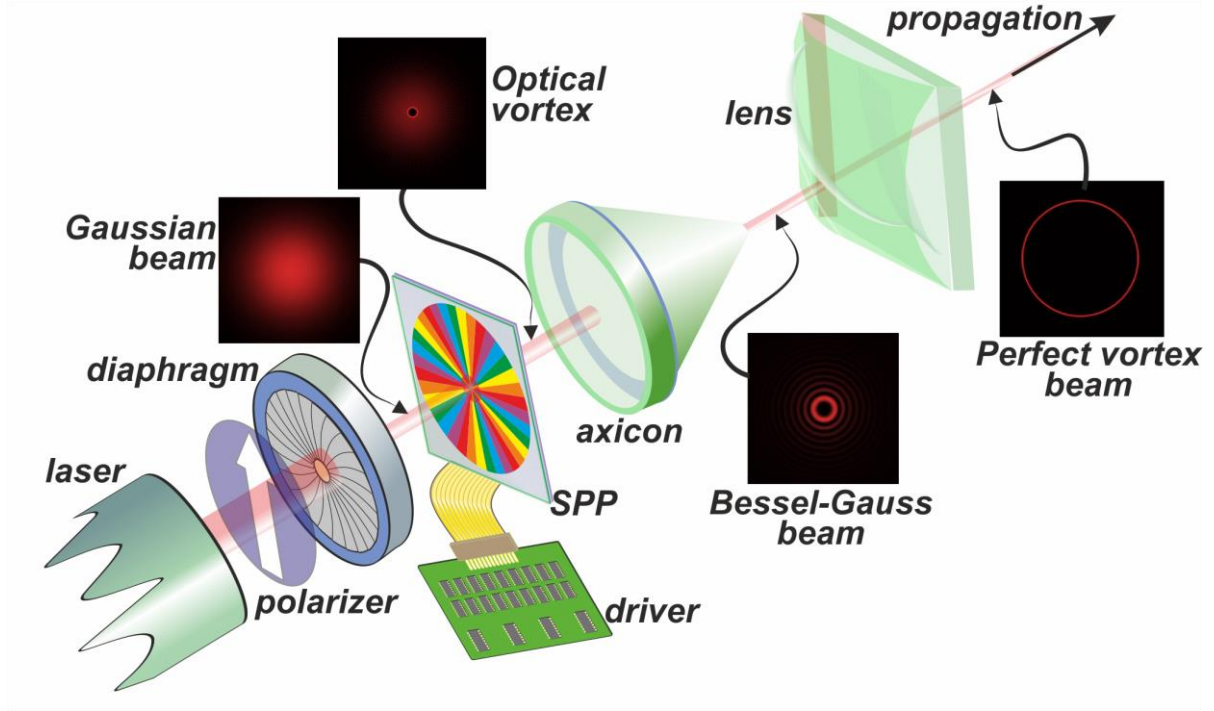


Figure 7.5: Proposed PVB generation optical setup based on a LC SPP. The insets show beam propagation simulations, not taking the effect of the diaphragm into consideration [179].

After aligning all the optical devices, intensity measurements were performed at the output of each main element to evaluate the similarity with the simulations. The characteristic singularity radius dependence with topological charge is observed at the SPP output. The higher order diffraction arising from the SPP discretization (Chapter 4: Spiral Phase Plates) could also be observed as l is increased. Measurements for the 73 different configurations are shown in Figure 7.6.

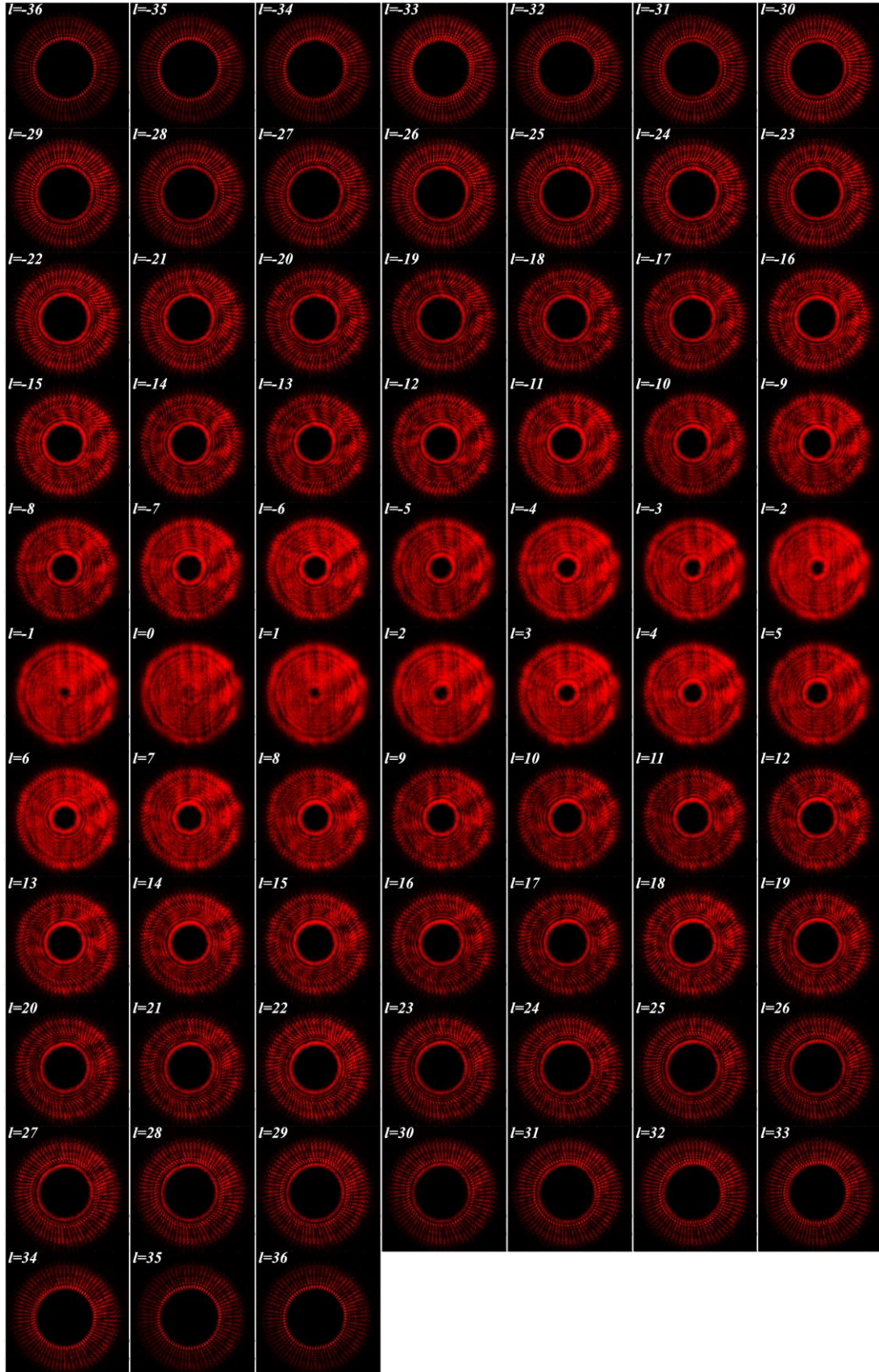


Figure 7.6: Measured intensity the SPP output for different topological charges (l) [179].

After passing through the SPP, the light is transformed by the axicon located at 8 cm. Representative axicon output measurements (at 14 cm) are displayed on Figure 7.7. The high-order Bessel-Gauss beams composed of concentric rings are observed within the axicon DOF. As expected, there is a dependence on the size of the main dark disc with the topological charge. Additionally, it is clear that using negative or positive topological charges does not influence the output angle, as the interference pattern is not modified. The obtained patterns are not perfectly symmetric, this asymmetry is attributed to an inhomogeneous laser distribution and to minor alignment errors.

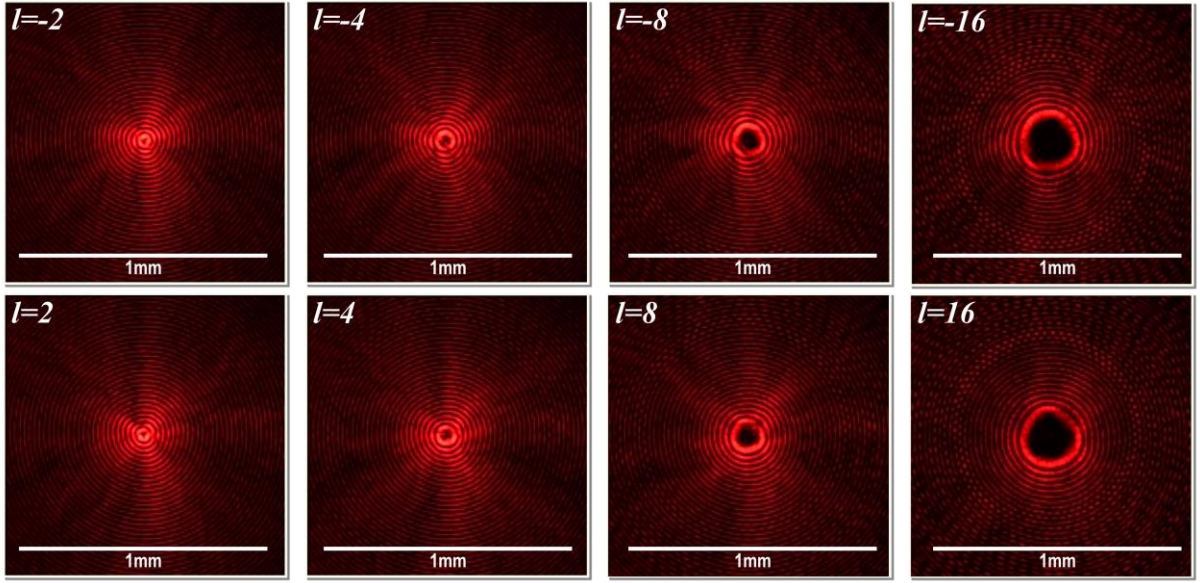


Figure 7.7: Measured intensity patterns at the axicon output (including SPP) for different topological charges (l) [179].

Lastly, the Bessel-Gauss beams are focused by the convergent refractive lens placed within the axicon DOF onto the camera sensor. The intensity patterns generated by the combination of the tunable SPP, the axicon and the lens are measured at the lens focal point ($f = 20$ cm). The measurements show a bright ring with a diameter independent of l . Using this setup a set of PVB with l ranging from $l = -36$ to $l = 36$ were generated (Figure 7.8) [179].

The inhomogeneity intensity distribution previously appreciated is still present. Additionally, the finite number of SPP electrodes results into diffraction which in turn leads to periodic oscillation of the light intensity in the PVBs. This intensity oscillation is inherent to the developed discrete SPP. This undesired effect may be reduced by employing the previous suggested techniques such working with lower topological charges or increasing the number of pixels (Chapter 4: Spiral Phase Plates).

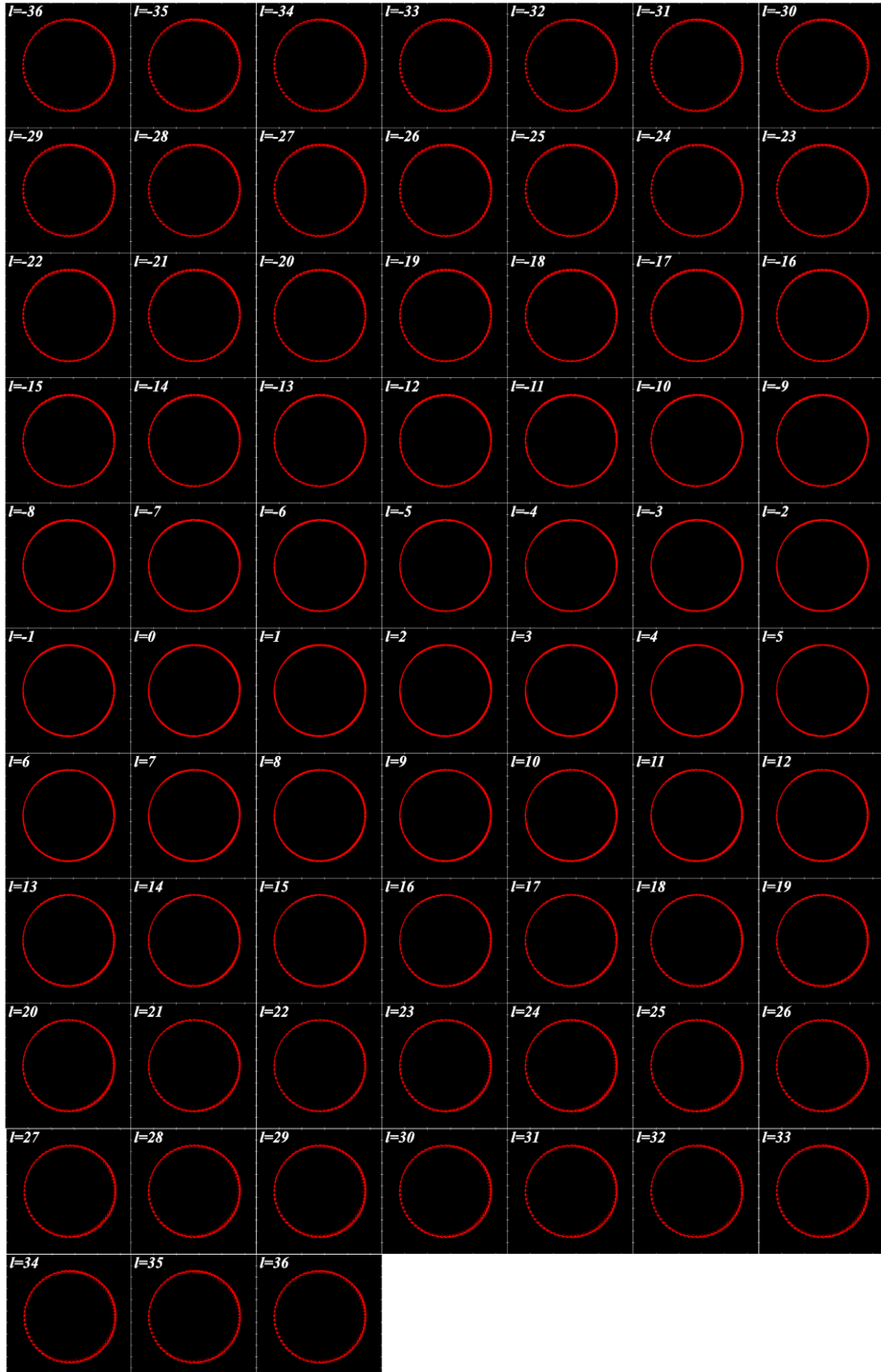


Figure 7.8: Recorded PVBs for different l , measured at the lens focal point using the camera sensor [179].

The proposed setup based on a SPP has proven to be a versatile system with less implementation limitations than the one based on a DSA. In this design, the PVBs are generated at the lens focal point regardless of the imprinted topological charge. Additionally, there is no need to replace the employed lens, thereby all PVB are generated without needing mechanical parts. Furthermore, the proposed system possesses an unparalleled simplicity compared to literature reported SLM-based approaches.

8. Conclusions and Future Research Lines

8.1. General Conclusions

This PhD work has been focused on the development of liquid crystal phase devices. Numerous different devices have been developed and their integration as optical systems has been carried out.

1. A light propagation simulator based on angular spectrum theory has been developed. The simulations compare well with experimental results.
2. 72-electrodes reconfigurable spiral phase plates (SPPs) have been manufactured. The vortex beams generated by these devices have been characterized. Additionally, a driving technique to generate arbitrary topological charges (l) has been demonstrated.
3. Diffractive spiral axicons (DSAs) consisting of 24 directly addressed Archimedean spiral-shaped electrodes have been manufactured. The depth of focus (DOF) of these devices can be changed electronically, changing simultaneously the output angle and the carried topological charge.
4. Numerous spiral diffractive lenses (SDLs) have been developed during this thesis. The focal length of these lenses is tuned in response to the pattern of the applied electronic signals. A novel technique to dynamically minimize chromatic aberration based on the tunability of these LC lens has been presented. Furthermore, imaging aberrations arising from the induced vortex beams have been assessed.
5. The tunable lenses along with SPP have been integrated in a reconfigurable zoom system. The proposed setup enables both image enlargement and reduction.
6. Two different strategies to generate perfect vortex beams (PVBs) –light beams whose power distribution about the phase singularity radius is independent from the applied l – have been developed.
7. Two different electronic drivers for LC devices have been characterized. The drivers enabled the control of the different optical elements. Their pros and cons have been discussed.

8.2. Future Lines

The present work gives room to several future improvements or unresolved questions:

1. A graphical user interface (GUI) must be designed to ease the implementation and use of the developed simulation tools.
2. The newer electronic driver (ADTelecom) must be thoroughly characterized and a GUI enabling the control of multiple parameters needs to be developed. A total rewriting of the driver firmware must be considered.
3. Combining DSA with an SPP to create linear axicons, or to generate PVB with independent control of the radius and topological charge, would be an interesting topic to pursue.
4. The presented zoom system should be rebuilt with specifically designed SDLs to enhance its tunability and image quality. An optimization of the lens diameters to a given detector would be optimal.
5. A study into adding additional layers of isolating and conducting layers onto the device electrodes have in similar lenses reduced the hazing. A similar approach should be tested.
6. Optical trapping systems based on the SPP need to be tested with different particle sizes and densities.
7. The duplex communication orbital angular momentum (OAM) system based on discrete SPP must be assembled and assessed.

8.3. Publications and awards related to this thesis

8.3.1. Awards

1. Best Research Work Presented as Poster. SINFOTON2-CM: Feria de Invierno 2022, February 2022, Getafe, Spain.
2. SPIE - Best Student Paper Prize. XIII Reunion Optoelectrónica (OPTOEL2023), June 2023, Seville, Spain.

8.3.2. International Journal Papers

1. J. Pereiro-García, B. Gaznahapa, O. Blanco-Fernández, M. Caño-García, X. Quintana, M. A. Geday, "Tunable magnification and minification zoom system based on liquid crystal spiral lenses", [In Preparation].
2. J. Pereiro-García, M. Caño-García, O. Blanco-Fernández, R. Ramos-Uña X. Quintana, M. A. Geday, "Chromatic aberration compensation using thin, transparent, large aperture, wide focal range, adaptive liquid crystal lens". [In Production].
3. J. M. Otón, J. Pereiro-García, X. Quintana, M. Caño-García, E. Otón, Geday, M. A. Geday, "Optimizing Tunable LC Devices with Twisted Light", Crystals (2023), 14, 16. <https://doi.org/10.3390/cryst14010016>
4. J. Pereiro-García, M. García-De-Blas, P. De La Rosa, M. A. Geday, X. Quintana, and M. Caño-García, "Reconfigurable perfect vortex beam generator based on a liquid crystal spiral phase plate", Opt. Express 31, 37653-37662 (2023). <https://doi.org/10.1364/OE.501796>
5. J. Pereiro-García, M. García-De-Blas, M. A. Geday, X. Quintana, and M. Caño-García, "Flat variable liquid crystal diffractive spiral axicon enabling perfect vortex beams generation", Sci. Rep. 13, 2385 (2023). <https://doi.org/10.1038/s41598-023-29164-0>
6. P. de la Rosa, J. Pereiro-García, M. Caño-García, J. M. Otón, X. Quintana, and M. A. Geday, "Generation of integer and fractional vortex beams based on liquid crystal electronically reconfigurable spiral phase plates", Opt. Express 31, 31212-31220 (2023). <https://doi.org/10.1364/OE.494676>
7. M. García-De-Blas, J. Pereiro-García, S. Vera, X. Quintana, M. Caño-García, and M. A. Geday, "High resolution 2D beam steerer made from cascaded 1D liquid crystal phase gratings", Sci. Rep. 12, 5145 (2022). <https://doi.org/10.1038/s41598-022-09201-0>

8.3.3. Conference Papers

1. J. Pereiro-García, P. de la Rosa, J.M. Otón, X. Quintana, M. A. Geday, M. Caño-García, "Tunable orbital angular momentum vortex beam generation based on liquid crystal devices," Proc. SPIE 13016, Liquid Crystals Optics and Photonic Devices, 130160L (18 June 2024); <https://doi.org/10.1117/12.3021869>
2. J. Pereiro-García, M. Caño-García, X. Quintana, J.M. Otón, M. A. Geday, "Easy manufacture large aperture wide range variafocal liquid crystal diffractive lens", Proc. SPIE 12907, Emerging Liquid Crystal Technologies XIX, 1290706 (13 March 2024); <https://doi.org/10.1117/12.3012669>
3. Jiayi Liu, Lukas Van Iseghem, J. Pereiro-García, Wim Bogaerts, Jeroen Beeckman. "Finite Element Modelling of Liquid Crystal Orientation and Its Applications in a Tunable Bimodal Periodic Waveguide". (27th IEEE Photonics Benelux Symposium 2023).
4. J. Pereiro-García, O. Blanco-Fernández, Rafael Ramos, M. A. Geday, X. Quintana, M. Caño-García, "Reconfigurable liquid crystal devices for light handling", Proc. OPTOEL2023, 13^a Reunión Española de Optoelectrónica; <https://dx.doi.org/10.12795/9788447225507>
5. J. Pereiro-García, M. Caño-García, X. Quintana, J.M. Otón, Carlos Carrasco Vela, P. de la Rosa, M. A. Geday, "Widely tunable large area thin liquid crystals lens", Proc. SPIE 12217, Current Developments in Lens Design and Optical Engineering XXIII, 1221709 (3 October 2022); <https://doi.org/10.1117/12.2631487>

8.3.4. Congress Contributions

1. J. Pereiro-García, P. de la Rosa, J.M. Otón, X. Quintana, M. A. Geday, M. Caño-García, "Tunable orbital angular momentum vortex beam generation based on liquid crystal devices," SPIE Photonics Europe 2024, April 2024, Strasbourg, France.
2. X. Quintana, J. Pereiro-García, O. Blanco-Fernández, B. Ganazhapa, M. A. Geday, J.M. Otón, M. Caño-García, "Recent progress in variafocal liquid crystal diffractive lens," SPIE Photonics Europe 2024, April 2024, Strasbourg, France.
3. J. Pereiro-García, M. Caño-García, X. Quintana, J.M. Otón, M.A. Geday. "Easy manufacture large aperture wide range variafocal liquid crystal diffractive lens". SPIE Photonics West 2024, January 2024, San Francisco, USA.

4. J. Liu, L. Van Iseghem, J. Pereiro-García, W. Bogaerts, J. Beeckman. "Finite Element Modelling of Liquid Crystal Orientation and Its Applications in a Tunable Bimodal Periodic Waveguide". 27th IEEE Photonics Benelux Symposium 2023, November 2023, Ghent, Belgium.
5. P. de la Rosa, J. Pereiro-García, X. Quintana, M.A. Geday, J.M. Otón, M. Caño-García. "Liquid crystal spiral phase plates for generation of fractional vortex beams with arbitrary topological charge". 20th Optics of Liquid Crystals Conference (OLC 2023), September 2023, Szczecin, Poland.
6. J. Pereiro-García; P. de la Rosa, B. Gaznahapa, O. Blanco-Fernández, M.A. Geday, M. Caño-García. "Adaptive spiral liquid crystal lenses chromatic aberration correction". 20th Optics of Liquid Crystals Conference (OLC 2023), September 2023, Szczecin, Poland.
7. B. Ganazhapa, J. Pereiro-García, X. Quintana, M.A. Geday, J.M. Otón, M. Caño-García. "A double UV laser system for nanostructural LC alignment". 20th Optics of Liquid Crystals Conference (OLC 2023), September 2023, Szczecin, Poland.
8. X. Quintana, I. Hernández, M.A. Geday, P. de la Rosa, J. Pereiro-García, M. Caño-García. "Electrical drivers design for liquid crystal phase devices". 16th edition of the European Conference of Liquid Crystals (ECLC2023), July 2023, Rende, Italy.
9. M. A. Geday, X. Quintana, J. Pereiro-García, P. de la Rosa, J.M. Otón, M. Caño-García. "Light with a twist". 16th edition of the European Conference of Liquid Crystals (ECLC2023), July 2023, Rende, Italy.
10. J. Pereiro-García, B. Gaznahapa, P. De La Rosa, M.A. Geday, M. Caño-García. "Reconfigurable Liquid Crystal Beam Expander". 16th edition of the European Conference of Liquid Crystals (ECLC2023), July 2023, Rende, Italy.
11. J. Pereiro-García, O. Blanco-Fernández, R. Ramos, M.A. Geday, X. Quintana, M. Caño-García. "Reconfigurable liquid crystal devices for light handling". XIII Reunion Optoelectrónica (OPTOEL2023), June 2023, Seville, Spain.
12. J. Barbero, J. Pereiro-García. "Smart Heaters". European Space Thermal Engineering Workshop (ESTEW 2022), October 2022, Noordwijk, Netherlands.
13. J. Pereiro-García, M. García-De-Blas, P. de la Rosa, X. Quintana, M. Caño-García, M.A. Geday. "Perfect Vortex Beam generation based on liquid crystal Spiral Phase Plate". 28th International Liquid Crystal Conference (ILCC2022), July 2022, Lisbon, Portugal.
14. M. García-De-Blas, J. Pereiro-García, X. Quintana, M. Caño-García, M.A. Geday. "Tunable liquid crystal phase-only devices for non-mechanical applications". 28th International Liquid Crystal Conference (ILCC2022), July 2022, Lisbon, Portugal.

15. L.F. Paz, M. García-De-Blas, J. Pereiro-García, M. Caño-García, X. Quintana, J.M. Otón. "Simple fluorescent light coupling to organic ridge waveguide employed on optical sensor". SINFOTON2-CM: Feria de Invierno 2022, February 2022, Getafe, Spain.
16. M. García-De-Blas, J. Pereiro-García, L.F. Paz, P. de la Rosa, M. Caño-García, M.A. Geday. "Two dimensional beam steering based on a high resolution liquid crystal diffractive grating". SINFOTON2-CM: Feria de Invierno 2022, February 2022, Getafe, Spain.
17. P. de la Rosa, M. García-De-Blas, J. Pereiro-García, L.F. Paz, J.M. Otón, X. Quintana. "Design and development of electronic drivers based on microprocessors for LC addressing". SINFOTON2-CM: Feria de Invierno 2022, February 2022, Getafe, Spain.
18. J. Pereiro-García, M. García-De-Blas, L.F. Paz, P. de la Rosa, M.A. Geday, M. Caño-García. "Tunable Spiral Diffractive Axicon (SDA) based on Liquid Crystal Phase configurations". SINFOTON2-CM: Feria de Invierno 2022, February 2022, Getafe, Spain.
19. M. Caño-García, F. J. Gordo, M. García-De-Blas, L.F. Paz, J. Pereiro-García, J.M. Otón, M.A. Geday, X. Quintana. "Microfabrication of tunable LC optical components". XXIII Conference on Liquid Crystals Chemistry, Physics and Applications (CLC2021), October 2021, Karpacz, Poland.
20. M. García-De-Blas, L.F. Paz, J. Pereiro-García, M. Caño-García, X. Quintana, J.M. Otón, M.A. Geday. "2D beam steering based on liquid crystals phase gratings". XXIII Conference on Liquid Crystals Chemistry, Physics and Applications (CLC2021), October 2021, Karpacz, Poland.
21. J. Pereiro-García, M. García-De-Blas, M. Caño-García, X. Quintana, J.M. Otón, M.A. Geday. "Tunable axicons based on spiral LC configurations". XXIII Conference on Liquid Crystals Chemistry, Physics and Applications (CLC2021), October 2021, Karpacz, Poland.

9. References

- [1] M. S. Zubairy, 'A Very Brief History of Light', in *Optics in Our Time*, M. D. Al-Amri, M. El-Gomati, and M. S. Zubairy, Eds., Cham: Springer International Publishing, 2016, pp. 3–24. doi: 10.1007/978-3-319-31903-2_1.
- [2] M. A. Fujino *et al.*, 'Electronic endoscopy in perspective', *J Gastroenterol*, vol. 29 Suppl 7, pp. 85–90, Jul. 1994.
- [3] I. G. Pallikaris, M. E. Papatzanaki, D. S. Siganos, and M. K. Tsilimbaris, 'A corneal flap technique for laser in situ keratomileusis. Human studies', *Arch Ophthalmol*, vol. 109, no. 12, pp. 1699–1702, Dec. 1991, doi: 10.1001/archophth.1991.01080120083031.
- [4] D. Petring, 'Laser Applications in European Automotive Manufacturing: Historical Review and Recent Trends', *Journal of the Japan Welding Society*, vol. 73, pp. 539–546, Dec. 2004, doi: 10.2207/qjwjs1943.73.539.
- [5] H.-W. Chen, J.-H. Lee, B.-Y. Lin, S. Chen, and S.-T. Wu, 'Liquid crystal display and organic light-emitting diode display: present status and future perspectives', *Light Sci Appl*, vol. 7, no. 3, pp. 17168–17168, Mar. 2018, doi: 10.1038/lssa.2017.168.
- [6] 'Crystals | Free Full-Text | Microwave Liquid Crystal Technology'. Accessed: Apr. 13, 2024. [Online]. Available: <https://www.mdpi.com/2073-4352/8/9/355>
- [7] M. Khan, A. R. Khan, J.-H. Shin, and S.-Y. Park, 'A liquid-crystal-based DNA biosensor for pathogen detection', *Sci Rep*, vol. 6, no. 1, p. 22676, Mar. 2016, doi: 10.1038/srep22676.
- [8] 'Rapid detection of pathogens using lyotropic liquid crystals'. Accessed: Apr. 13, 2024. [Online]. Available: <https://opg.optica.org/oe/fulltext.cfm?uri=oe-27-7-10098&id=407704>
- [9] T. Yao *et al.*, 'Nematic Colloidal Micro-Robots as Physically Intelligent Systems', *Advanced Functional Materials*, vol. 32, no. 44, p. 2205546, 2022, doi: 10.1002/adfm.202205546.
- [10] G. Vitale *et al.*, 'Photoresponsive Polymer-Based Biomimetic Contractile Units as Building Block for Artificial Muscles', *Macromolecular Materials and Engineering*, vol. 307, no. 9, p. 2200187, 2022, doi: 10.1002/mame.202200187.
- [11] W. Bogaerts *et al.*, 'Programmable photonic circuits', *Nature*, vol. 586, no. 7828, Art. no. 7828, Oct. 2020, doi: 10.1038/s41586-020-2764-0.
- [12] L. Torrijos-Morán, D. Pérez-Galacho, and D. Pérez-López, 'Silicon Programmable Photonic Circuits Based on Periodic Bimodal Waveguides', *Laser & Photonics Reviews*, vol. n/a, no. n/a, Art. no. n/a, Oct. 2023, doi: 10.1002/lpor.202300505.
- [13] J. Liu, L. Van Iseghem, J. Pereiro-García, W. Bogaerts, and J. Beeckman, 'Finite Element Modelling of Liquid Crystal Orientation and Its Applications in a Tunable Bimodal Periodic Waveguide', *Proceedings 27th IEEE Photonics Benelux Symposium 2023*.
- [14] C. Knoernschild, C. Kim, F. P. Lu, and J. Kim, 'Multiplexed broadband beam steering system utilizing high speed MEMS mirrors', *Opt. Express, OE*, vol. 17, no. 9, pp. 7233–7244, Apr. 2009, doi: 10.1364/OE.17.007233.

- [15] 'Sensors | Free Full-Text | Optoelectronic Angular Displacement Measurement Technology for 2-Dimensional Mirror Galvanometer'. Accessed: May 16, 2024. [Online]. Available: <https://www.mdpi.com/1424-8220/22/3/872>
- [16] E. L. Botvinick, F. Li, S. Cha, D. A. Gough, Y. Fainman, and J. H. P. M.d, 'In-vivo confocal microscopy based on the Texas Instruments digital micromirror device', in *Optical Diagnostics of Living Cells III*, SPIE, Apr. 2000, pp. 12–19. doi: 10.1117/12.384208.
- [17] Y. Wang *et al.*, '2D broadband beamsteering with large-scale MEMS optical phased array', *Optica*, *OPTICA*, vol. 6, no. 5, pp. 557–562, May 2019, doi: 10.1364/OPTICA.6.000557.
- [18] M. Hacker *et al.*, 'Micromirror SLM for femtosecond pulse shaping in the ultraviolet', *Appl Phys B*, vol. 76, no. 6, pp. 711–714, Jun. 2003, doi: 10.1007/s00340-003-1180-0.
- [19] Y. Wang, Y. Kyoungsik, and M. Wu, *MEMS Optical Phased Array for LIDAR*. 2016.
- [20] G. D. Love, J. V. Major, and A. Purvis, 'Liquid-crystal prisms for tip-tilt adaptive optics', *Opt. Lett.*, *OL*, vol. 19, no. 15, pp. 1170–1172, Aug. 1994, doi: 10.1364/OL.19.001170.
- [21] Z. He, F. Gou, R. Chen, K. Yin, T. Zhan, and S.-T. Wu, 'Liquid Crystal Beam Steering Devices: Principles, Recent Advances, and Future Developments', *Crystals*, vol. 9, no. 6, Art. no. 6, Jun. 2019, doi: 10.3390/cryst9060292.
- [22] M. G. de Blas, J. P. García, S. V. Andreu, X. Q. Arregui, M. Caño-García, and M. A. Geday, 'High resolution 2D beam steerer made from cascaded 1D liquid crystal phase gratings', *Sci Rep*, vol. 12, no. 1, Art. no. 1, Mar. 2022, doi: 10.1038/s41598-022-09201-0.
- [23] X. Shang *et al.*, 'Electrically Controllable Liquid Crystal Component for Efficient Light Steering', *IEEE Photonics Journal*, vol. 7, no. 2, pp. 1–13, Apr. 2015, doi: 10.1109/JPHOT.2015.2402592.
- [24] X. Shang, A. M. Trinidad, P. Joshi, J. De Smet, D. Cuypers, and H. De Smet, 'Tunable Optical Beam Deflection Via Liquid Crystal Gradient Refractive Index Generated By Highly Resistive Polymer Film', *IEEE Photonics Journal*, vol. 8, no. 3, pp. 1–11, Jun. 2016, doi: 10.1109/JPHOT.2016.2555585.
- [25] C. Yousefzadeh, A. V. Rynbach, and P. J. Bos, 'Design of a large aperture, tunable, Pancharatnam phase beam steering device', *Opt. Express*, *OE*, vol. 28, no. 2, pp. 991–1001, Jan. 2020, doi: 10.1364/OE.380952.
- [26] H. Chen, Y. Weng, D. Xu, N. V. Tabiryan, and S.-T. Wu, 'Beam steering for virtual/augmented reality displays with a cycloidal diffractive waveplate', *Opt. Express*, *OE*, vol. 24, no. 7, pp. 7287–7298, Apr. 2016, doi: 10.1364/OE.24.007287.
- [27] T. Zhan *et al.*, 'Pancharatnam–Berry optical elements for head-up and near-eye displays [Invited]', *J. Opt. Soc. Am. B*, *JOSAB*, vol. 36, no. 5, pp. D52–D65, May 2019, doi: 10.1364/JOSAB.36.000D52.
- [28] S. R. Nersisyan, N. V. Tabiryan, D. M. Steeves, and B. R. Kimball, 'The Promise of Diffractive Waveplates', *Optics & Photonics News*, *OPN*, vol. 21, no. 3, pp. 40–45, Mar. 2010, doi: 10.1364/OPN.21.3.000040.

-
- [29] G. Zhang *et al.*, 'Free-Space Optical Communication Link With Liquid Crystal Beam-Steering', *IEEE Photonics Technology Letters*, vol. 35, no. 22, pp. 1199–1202, Nov. 2023, doi: 10.1109/LPT.2023.3308774.
 - [30] C. Graham *et al.*, 'Steering Mirror System with Closed-Loop Feedback for Free-Space Optical Communication Terminals', *Aerospace*, vol. 11, no. 5, Art. no. 5, May 2024, doi: 10.3390/aerospace11050330.
 - [31] 'Free Space Optics for Next-Generation Satellite Networks | IEEE Journals & Magazine | IEEE Xplore'. Accessed: May 17, 2024. [Online]. Available: <https://ieeexplore.ieee.org/document/9219130>
 - [32] B. Li, Q. Lin, and M. Li, 'Frequency–angular resolving LiDAR using chip-scale acousto-optic beam steering', *Nature*, vol. 620, no. 7973, pp. 316–322, Aug. 2023, doi: 10.1038/s41586-023-06201-6.
 - [33] M. A. Lefsky, W. B. Cohen, G. G. Parker, and D. J. Harding, 'Lidar Remote Sensing for Ecosystem Studies: Lidar, an emerging remote sensing technology that directly measures the three-dimensional distribution of plant canopies, can accurately estimate vegetation structural attributes and should be of particular interest to forest, landscape, and global ecologists', *BioScience*, vol. 52, no. 1, pp. 19–30, Jan. 2002, doi: 10.1641/0006-3568(2002)052[0019:LRSFES]2.0.CO;2.
 - [34] R. R. Gattass and E. Mazur, 'Femtosecond laser micromachining in transparent materials', *Nature Photon*, vol. 2, no. 4, pp. 219–225, Apr. 2008, doi: 10.1038/nphoton.2008.47.
 - [35] H. Wei, A. K. Amrithanath, and S. Krishnaswamy, '3D Printing of Micro-Optic Spiral Phase Plates for the Generation of Optical Vortex Beams', *IEEE Photonics Technology Letters*, vol. 31, no. 8, pp. 599–602, Apr. 2019, doi: 10.1109/LPT.2019.2903151.
 - [36] B. W. Pearre, C. Michas, J.-M. Tsang, T. J. Gardner, and T. M. Otchy, 'Fast micron-scale 3D printing with a resonant-scanning two-photon microscope', *Additive Manufacturing*, vol. 30, p. 100887, Dec. 2019, doi: 10.1016/j.addma.2019.100887.
 - [37] C.-M. Chang and H.-P. D. Shieh, 'Design of illumination and projection optics for projectors with single digital micromirror devices', *Appl. Opt., AO*, vol. 39, no. 19, pp. 3202–3208, Jul. 2000, doi: 10.1364/AO.39.003202.
 - [38] X. Xia, X. Zhang, L. Zhang, P. Surman, and Y. Zheng, 'Time-multiplexed multi-view three-dimensional display with projector array and steering screen', *Opt. Express, OE*, vol. 26, no. 12, pp. 15528–15538, Jun. 2018, doi: 10.1364/OE.26.015528.
 - [39] 'Simulator - Ray Optics Simulation'. Accessed: May 08, 2024. [Online]. Available: <https://phydemo.app/ray-optics/>
 - [40] L. Chen, M. Ghilardi, J. J. C. Busfield, and F. Carpi, 'Electrically Tunable Lenses: A Review', *Front Robot AI*, vol. 8, p. 678046, Jun. 2021, doi: 10.3389/frobt.2021.678046.
 - [41] B. Berge, 'Liquid lens technology: principle of electrowetting based lenses and applications to imaging', in *18th IEEE International Conference on Micro Electro Mechanical Systems, 2005. MEMS 2005.*, Jan. 2005, pp. 227–230. doi: 10.1109/MEMSYS.2005.1453908.

- [42] X. Song, H. Zhang, D. Li, D. Jia, and T. Liu, 'Electrowetting lens with large aperture and focal length tunability', *Sci Rep*, vol. 10, no. 1, p. 16318, Oct. 2020, doi: 10.1038/s41598-020-73260-4.
- [43] F. Schneider, J. Draheim, R. Kamberger, P. Waibel, and U. Wallrabe, 'Optical characterization of adaptive fluidic silicone-membrane lenses', *Opt. Express, OE*, vol. 17, no. 14, pp. 11813–11821, Jul. 2009, doi: 10.1364/OE.17.011813.
- [44] N. Hasan, A. Banerjee, H. Kim, and C. H. Mastrangelo, 'Tunable-focus lens for adaptive eyeglasses', *Opt. Express, OE*, vol. 25, no. 2, pp. 1221–1233, Jan. 2017, doi: 10.1364/OE.25.001221.
- [45] jianqing tian, zhaozhao zhao, and L. Li, 'Adaptive liquid lens with tunable field of view', *Optics Express*, vol. 30, Oct. 2022, doi: 10.1364/OE.472756.
- [46] A. F. Naumov, G. D. Love, M. Y. Loktev, and F. L. Vladimirov, 'Control optimization of spherical modal liquid crystal lenses', *Opt. Express, OE*, vol. 4, no. 9, pp. 344–352, Apr. 1999, doi: 10.1364/OE.4.000344.
- [47] G. D. Love and A. F. Naumov, 'Modal liquid crystal lenses', *Liquid Crystals Today*, vol. 10, no. 1, pp. 1–4, Mar. 2000, doi: 10.1080/135831401750061465.
- [48] P. Hands, A. Kirby, and G. Love, 'Adaptive modally addressed liquid crystal lenses', *Proc SPIE*, vol. 5518, Oct. 2004, doi: 10.1117/12.562359.
- [49] O. Sova and T. Galstian, 'Liquid crystal lens with optimized wavefront across the entire clear aperture', *Optics Communications*, vol. 433, pp. 290–296, Feb. 2019, doi: 10.1016/j.optcom.2018.10.030.
- [50] Y.-H. Lin, Y.-J. Wang, and V. Reshetnyak, 'Liquid crystal lenses with tunable focal length', *Liquid Crystals Reviews*, vol. 5, no. 2, pp. 111–143, Jul. 2017, doi: 10.1080/21680396.2018.1440256.
- [51] X. Wang, A. K. Srivastava, V. G. Chigrinov, and H.-S. Kwok, 'P-101: Liquid Crystal Fresnel Zone Lens Based on Single-Side Patterned Photoalignment Layer', *SID Symposium Digest of Technical Papers*, vol. 45, no. 1, pp. 1367–1369, 2014, doi: 10.1002/j.2168-0159.2014.tb00360.x.
- [52] Y.-H. Fan, H. Ren, and S.-T. Wu, 'Switchable Fresnel lens using polymer-stabilized liquid crystals', *Opt. Express, OE*, vol. 11, no. 23, pp. 3080–3086, Nov. 2003, doi: 10.1364/OE.11.003080.
- [53] M. Ferstl and A.-M. Frisch, 'Static and dynamic Fresnel zone lenses for optical interconnections', *Journal of Modern Optics*, vol. 43, no. 7, pp. 1451–1462, Jul. 1996, doi: 10.1080/09500349608232817.
- [54] J. Stevens and T. Galstian, 'Electrically tunable liquid crystal lens with a serpentine electrode design', *Opt. Lett., OL*, vol. 47, no. 4, Art. no. 4, Feb. 2022, doi: 10.1364/OL.447853.
- [55] G. Williams, N. J. Powell, A. Purvis, and M. G. Clark, 'Electrically Controllable Liquid Crystal Fresnel Lens', in *Current Developments in Optical Engineering and Commercial Optics*, SPIE, Dec. 1989, pp. 352–359. doi: 10.1117/12.962998.
- [56] J. S. Patel and K. Rastani, 'Electrically controlled polarization-independent liquid-crystal Fresnel lens arrays', *Opt. Lett., OL*, vol. 16, no. 7, pp. 532–534, Apr. 1991, doi: 10.1364/OL.16.000532.

-
- [57] T. Galstian, O. Sova, K. Asatryan, V. Presniakov, A. Zohrabyan, and M. Evensen, 'Optical camera with liquid crystal autofocus lens', *Opt. Express, OE*, vol. 25, no. 24, pp. 29945–29964, Nov. 2017, doi: 10.1364/OE.25.029945.
 - [58] Y.-J. Wang and Y.-H. Lin, 'An optical system for augmented reality with electrically tunable optical zoom function and image registration exploiting liquid crystal lenses', *Opt. Express, OE*, vol. 27, no. 15, Art. no. 15, Jul. 2019, doi: 10.1364/OE.27.021163.
 - [59] R. E. Stevens, T. N. L. Jacoby, I. Ş. Aricescu, and D. P. Rhodes, 'A review of adjustable lenses for head mounted displays', in *Digital Optical Technologies 2017*, SPIE, Sep. 2017, pp. 160–178. doi: 10.1117/12.2276677.
 - [60] Y.-J. Wang, P.-J. Chen, X. Liang, and Y.-H. Lin, 'Augmented reality with image registration, vision correction and sunlight readability via liquid crystal devices', *Sci Rep*, vol. 7, no. 1, p. 433, Mar. 2017, doi: 10.1038/s41598-017-00492-2.
 - [61] S. P. Kotova *et al.*, 'Technology and electro-optical properties of modal liquid crystal wavefront correctors', *J. Opt. A: Pure Appl. Opt.*, vol. 5, no. 5, p. S231, Aug. 2003, doi: 10.1088/1464-4258/5/5/371.
 - [62] S. P. Kotova *et al.*, 'Modal liquid crystal wavefront corrector', *Opt. Express, OE*, vol. 10, no. 22, pp. 1258–1272, Nov. 2002, doi: 10.1364/OE.10.001258.
 - [63] 'LIQUID CRYSTAL LENSES', 32°Nglasses. Accessed: May 15, 2024. [Online]. Available: <https://32northglasses.com/pages/liquid-crystal>
 - [64] 'Pixieray - The Perfect Vision Company', Pixieray - The Perfect Vision Company. Accessed: May 15, 2024. [Online]. Available: <https://www.pixieray.com>
 - [65] H. E. Milton, P. B. Morgan, J. H. Clamp, and H. F. Gleeson, 'Electronic liquid crystal contact lenses for the correction of presbyopia', *Opt. Express, OE*, vol. 22, no. 7, pp. 8035–8040, Apr. 2014, doi: 10.1364/OE.22.008035.
 - [66] I. M. Syed *et al.*, 'Novel switching mode in a vertically aligned liquid crystal contact lens', *Opt. Express*, vol. 23, no. 8, p. 9911, Apr. 2015, doi: 10.1364/OE.23.009911.
 - [67] S. Kaur *et al.*, 'Graphene electrodes for adaptive liquid crystal contact lenses', *Optics Express*, vol. 24, p. 8782, Apr. 2016, doi: 10.1364/OE.24.008782.
 - [68] X. Du, S. Kang, and C. B. Arnold, 'Optimization of ultrafast axial scanning parameters for efficient pulsed laser micro-machining', *Journal of Materials Processing Technology*, vol. 288, p. 116850, Feb. 2021, doi: 10.1016/j.jmatprotec.2020.116850.
 - [69] Y.-S. Tsou, Y.-H. Lin, and A.-C. Wei, 'Concentrating Photovoltaic System Using a Liquid Crystal Lens', *IEEE Photonics Technology Letters*, vol. 24, no. 24, pp. 2239–2242, Dec. 2012, doi: 10.1109/LPT.2012.2224857.
 - [70] M. Hain, R. Gloeckner, S. Bhattacharya, D. Dias, S. Stankovic, and T. Tschudi, 'Fast switching liquid crystal lenses for a dual focus digital versatile disc pickup', *Optics Communications*, vol. 188, pp. 291–299, Feb. 2001, doi: 10.1016/S0030-4018(01)00989-0.
 - [71] Y.-H. Lin, 'An Electrically Tunable Liquid Crystal Lens for Fiber Coupling and Variable Optical Attenuation', *Journal of Electrical & Electronic Systems*, vol. 03, Jan. 2014, doi: 10.4172/2332-0796.1000124.

- [72] J. H. McLeod, 'The Axicon: A New Type of Optical Element', *J. Opt. Soc. Am., JOS A*, vol. 44, no. 8, Art. no. 8, Aug. 1954, doi: 10.1364/JOSA.44.000592.
- [73] S. N. Khonina, N. L. Kazanskiy, P. A. Khorin, and M. A. Butt, 'Modern Types of Axicons: New Functions and Applications', *Sensors*, vol. 21, no. 19, Art. no. 19, Jan. 2021, doi: 10.3390/s21196690.
- [74] 'Thorlabs - AX252 2.0°, Uncoated UVFS, Ø1'. Accessed: Mar. 25, 2024. [Online]. Available: <https://www.thorlabs.com>
- [75] 'An In-Depth Look at Axicons'. Accessed: May 07, 2024. [Online]. Available: <https://www.edmundoptics.eu/knowledge-center/application-notes/lasers/an-in-depth-look-at-axicons/>
- [76] T. Breen, N. Basque-Giroux, U. Fuchs, and I. Golub, 'Tuning the resolution and depth of field of a lens using an adjustable ring beam illumination', *Appl. Opt., AO*, vol. 59, no. 15, pp. 4744–4749, May 2020, doi: 10.1364/AO.389353.
- [77] Z. Zhai, S. Ding, Q. Lv, X. Wang, and Y. Zhong, 'Extended depth of field through an axicon', *Journal of Modern Optics*, vol. 56, no. 11, pp. 1304–1308, Jun. 2009, doi: 10.1080/09500340903082689.
- [78] G. Milne, G. D. M. Jeffries, and D. T. Chiu, 'Tunable generation of Bessel beams with a fluidic axicon', *Applied Physics Letters*, vol. 92, no. 26, p. 261101, Jun. 2008, doi: 10.1063/1.2952833.
- [79] J. Brunne, R. Grunwald, and U. Wallrabe, 'Adaptive piezoelectric axicon mirrors for high power femtosecond laser applications', in *2011 16th International Solid-State Sensors, Actuators and Microsystems Conference*, Jun. 2011, pp. 1558–1561. doi: 10.1109/TRANSDUCERS.2011.5969737.
- [80] M. M. Sánchez-López, I. Moreno, J. A. Davis, B. K. Gutierrez, and D. M. Cottrell, 'Double-ring interference of binary diffractive axicons', *OSA Continuum, OSAC*, vol. 3, no. 6, pp. 1679–1690, Jun. 2020, doi: 10.1364/OSAC.393734.
- [81] Z. Zhai, Z. Cheng, Q. Lv, and X. Wang, 'Tunable Axicons Generated by Spatial Light Modulator with High-Level Phase Computer-Generated Holograms', *Applied Sciences*, vol. 10, no. 15, Art. no. 15, Jan. 2020, doi: 10.3390/app10155127.
- [82] J. F. Algorri *et al.*, 'Positive-negative tunable liquid crystal lenses based on a microstructured transmission line', *Sci Rep*, vol. 10, no. 1, Art. no. 1, Jun. 2020, doi: 10.1038/s41598-020-67141-z.
- [83] T. Jankowski, N. Bennis, A. Spadlo, J. F. Algorri, M. del M. Sánchez-López, and I. Moreno, 'Liquid crystal anisotropic axicon for the generation of non-diffracting Bessel beams with longitudinally varying polarization', *Optics & Laser Technology*, vol. 170, p. 110255, Mar. 2024, doi: 10.1016/j.optlastec.2023.110255.
- [84] B. Shao, S. C. Esener, J. M. Nascimento, E. L. Botvinick, and M. W. Berns, 'Dynamically adjustable annular laser trapping based on axicons', *Appl. Opt., AO*, vol. 45, no. 25, pp. 6421–6428, Sep. 2006, doi: 10.1364/AO.45.006421.
- [85] W. C. Cheong *et al.*, 'Fabrication of efficient microaxicon by direct electron-beam lithography for long nondiffracting distance of Bessel beams for optical manipulation', *Applied Physics Letters*, vol. 87, no. 2, p. 024104, Jul. 2005, doi: 10.1063/1.1953876.

-
- [86] Z. Kuang, W. Perrie, S. P. Edwardson, E. Fearon, and G. Dearden, 'Ultrafast laser parallel microdrilling using multiple annular beams generated by a spatial light modulator', *Journal of Physics D: Applied Physics*, vol. 47, no. 11, Art. no. 11, Mar. 2014.
 - [87] R. Carreto, B. Lüscher, R. Holtz, and B. Resan, 'Towards Ultrafast Laser Micromachining of X-Ray Gratings and Creation of Sub-Micron Hole Patterns, Comparison of Results With Bessel and Gaussian Beams', *Front. Phys.*, vol. 10, Mar. 2022, doi: 10.3389/fphy.2022.809212.
 - [88] S. M. Perinchery *et al.*, 'High resolution iridocorneal angle imaging system by axicon lens assisted gonioscopy', *Sci Rep*, vol. 6, no. 1, Art. no. 1, Jul. 2016, doi: 10.1038/srep30844.
 - [89] Z. Ding, H. Ren, Y. Zhao, J. S. Nelson, and Z. Chen, 'High-resolution optical coherence tomography over a large depth range with an axicon lens', *Opt. Lett., OL*, vol. 27, no. 4, pp. 243–245, Feb. 2002, doi: 10.1364/OL.27.000243.
 - [90] P. Couillet, L. Gil, and F. Rocca, 'Optical vortices', *Optics Communications*, vol. 73, no. 5, Art. no. 5, Nov. 1989, doi: 10.1016/0030-4018(89)90180-6.
 - [91] L. Allen, M. W. Beijersbergen, R. J. C. Spreeuw, and J. P. Woerdman, 'Orbital angular momentum of light and the transformation of Laguerre-Gaussian laser modes', *Phys. Rev. A*, vol. 45, no. 11, Art. no. 11, Jun. 1992, doi: 10.1103/PhysRevA.45.8185.
 - [92] L. Marrucci, C. Manzo, and D. Paparo, 'Optical Spin-to-Orbital Angular Momentum Conversion in Inhomogeneous Anisotropic Media', *Phys. Rev. Lett.*, vol. 96, no. 16, p. 163905, Apr. 2006, doi: 10.1103/PhysRevLett.96.163905.
 - [93] L. Marrucci, C. Manzo, and D. Paparo, 'Pancharatnam-Berry phase optical elements for wave front shaping in the visible domain: Switchable helical mode generation', *Applied Physics Letters*, vol. 88, no. 22, p. 221102, May 2006, doi: 10.1063/1.2207993.
 - [94] A. Rubano, F. Cardano, B. Piccirillo, and L. Marrucci, 'Q-plate technology: a progress review [Invited]', *J. Opt. Soc. Am. B, JOSAB*, vol. 36, no. 5, pp. D70–D87, May 2019, doi: 10.1364/JOSAB.36.000D70.
 - [95] J. M. Otón, J. Pereiro-García, X. Quintana, M. Caño-García, E. Otón, and M. A. Geday, 'Optimizing Tunable LC Devices with Twisted Light', *Crystals*, vol. 14, no. 1, Art. no. 1, Jan. 2024, doi: 10.3390/cryst14010016.
 - [96] S. Slussarenko, A. Murauski, T. Du, V. Chigrinov, L. Marrucci, and E. Santamato, 'Tunable liquid crystal q-plates with arbitrary topological charge', *Opt. Express, OE*, vol. 19, no. 5, pp. 4085–4090, Feb. 2011, doi: 10.1364/OE.19.004085.
 - [97] S. Slussarenko, B. Piccirillo, V. Chigrinov, L. Marrucci, and E. Santamato, 'Liquid crystal spatial-mode converters for the orbital angular momentum of light', *J. Opt.*, vol. 15, no. 2, p. 025406, Jan. 2013, doi: 10.1088/2040-8978/15/2/025406.
 - [98] B. Piccirillo, V. D'Ambrosio, S. Slussarenko, L. Marrucci, and E. Santamato, 'Photon spin-to-orbital angular momentum conversion via an electrically tunable q-plate', *Applied Physics Letters*, vol. 97, no. 24, p. 241104, Dec. 2010, doi: 10.1063/1.3527083.

- [99] E. Brasselet, N. Murazawa, H. Misawa, and S. Juodkazis, 'Optical Vortices from Liquid Crystal Droplets', *Phys. Rev. Lett.*, vol. 103, no. 10, p. 103903, Sep. 2009, doi: 10.1103/PhysRevLett.103.103903.
- [100] M. Stalder and M. Schadt, 'Linearly polarized light with axial symmetry generated by liquid-crystal polarization converters', *Opt. Lett., OL*, vol. 21, no. 23, pp. 1948–1950, Dec. 1996, doi: 10.1364/OL.21.001948.
- [101] Z. Liu *et al.*, 'Generation of arbitrary vector vortex beams on hybrid-order Poincaré sphere', *Photon. Res., PRJ*, vol. 5, no. 1, pp. 15–21, Feb. 2017, doi: 10.1364/PRJ.5.000015.
- [102] L. Marrucci *et al.*, 'Spin-to-Orbital Optical Angular Momentum Conversion in Liquid Crystal "q-Plates": Classical and Quantum Applications', *Molecular Crystals and Liquid Crystals*, vol. 561, pp. 48–56, Jun. 2012, doi: 10.1080/15421406.2012.686710.
- [103] J. C. Quiceno-Moreno, D. Marco, M. del M. Sánchez-López, E. Solarte, and I. Moreno, 'Analysis of Hybrid Vector Beams Generated with a Detuned Q-Plate', *Applied Sciences*, vol. 10, no. 10, Art. no. 10, Jan. 2020, doi: 10.3390/app10103427.
- [104] 'Beamco.com: Vector Vortex Waveplates(VVW)'. Accessed: Apr. 29, 2024. [Online]. Available: <https://www.beamco.com/Vector-Vortex-Waveplates-VVW->
- [105] 'Zero-Order Vortex Half-Wave Retarders'. Accessed: Apr. 29, 2024. [Online]. Available: <https://www.thorlabs.com>
- [106] P. Chen *et al.*, 'Arbitrary and reconfigurable optical vortex generation: a high-efficiency technique using director-varying liquid crystal fork gratings', *Photon. Res., PRJ*, vol. 3, no. 4, pp. 133–139, Aug. 2015, doi: 10.1364/PRJ.3.000133.
- [107] J. Leach and M. Padgett, 'Observation of chromatic effects near a white-light vortex', *New Journal of Physics*, vol. 5, pp. 154–154, Nov. 2003, doi: 10.1088/1367-2630/5/1/154.
- [108] S.-J. Ge, W. Ji, G.-X. Cui, B.-Y. Wei, W. Hu, and Y.-Q. Lu, 'Fast switchable optical vortex generator based on blue phase liquid crystal fork grating', *Opt. Mater. Express, OME*, vol. 4, no. 12, pp. 2535–2541, Dec. 2014, doi: 10.1364/OME.4.002535.
- [109] Y. J. Liu, X. W. Sun, Q. Wang, and D. Luo, 'Electrically switchable optical vortex generated by a computer-generated hologram recorded in polymer-dispersed liquid crystals', *Opt. Express, OE*, vol. 15, no. 25, pp. 16645–16650, Dec. 2007, doi: 10.1364/OE.15.016645.
- [110] N. Matsumoto, T. Ando, T. Inoue, Y. Ohtake, N. Fukuchi, and T. Hara, 'Generation of high-quality higher-order Laguerre-Gaussian beams using liquid-crystal-on-silicon spatial light modulators', *J. Opt. Soc. Am. A, JOSAA*, vol. 25, no. 7, pp. 1642–1651, Jul. 2008, doi: 10.1364/JOSAA.25.001642.
- [111] V. Bazhenov, M. Vasnetsov, and M. Soskin, 'Laser beams with screw dislocations in their wavefronts', *JETP. Lett*, vol. 52, pp. 429–431, Jan. 1990.
- [112] M. Caño-García, X. Quintana, J. M. Otón, and M. A. Geday, 'Dynamic multilevel spiral phase plate generator', *Sci Rep*, vol. 8, no. 1, Art. no. 1, Oct. 2018, doi: 10.1038/s41598-018-34041-2.
- [113] M. W. Beijersbergen, R. P. C. Coerwinkel, M. Kristensen, and J. P. Woerdman, 'Helical-wavefront laser beams produced with a spiral phaseplate', *Optics*

- Communications*, vol. 112, no. 5, pp. 321–327, Dec. 1994, doi: 10.1016/0030-4018(94)90638-6.
- [114] S. S. R. Oemrawsingh *et al.*, ‘Production and characterization of spiral phase plates for optical wavelengths’, *Appl. Opt., AO*, vol. 43, no. 3, Art. no. 3, Jan. 2004, doi: 10.1364/AO.43.000688.
- [115] M. Massari, G. Ruffato, M. Gintoli, F. Ricci, and F. Romanato, ‘Fabrication and characterization of high-quality spiral phase plates for optical applications’, *Appl. Opt., AO*, vol. 54, no. 13, pp. 4077–4083, May 2015, doi: 10.1364/AO.54.004077.
- [116] W. C. Cheong, W. M. Lee, X.-C. Yuan, L.-S. Zhang, K. Dholakia, and H. Wang, ‘Direct electron-beam writing of continuous spiral phase plates in negative resist with high power efficiency for optical manipulation’, *Applied Physics Letters*, vol. 85, no. 23, pp. 5784–5786, Dec. 2004, doi: 10.1063/1.1830678.
- [117] J. Wang *et al.*, ‘Study of Characteristics of Vortex Beam Produced by Fabricated Spiral Phase Plates’, *IEEE Photonics Journal*, vol. 8, no. 2, pp. 1–9, Apr. 2016, doi: 10.1109/JPHOT.2016.2540362.
- [118] D. Hakobyan, H. Magallanes, G. Seniutinas, S. Juodkazis, and E. Brasselet, ‘Tailoring Orbital Angular Momentum of Light in the Visible Domain with Metallic Metasurfaces’, *Advanced Optical Materials*, vol. 4, no. 2, pp. 306–312, 2016, doi: 10.1002/adom.201500494.
- [119] R. C. Devlin *et al.*, ‘Spin-to-orbital angular momentum conversion in dielectric metasurfaces’, *Opt. Express, OE*, vol. 25, no. 1, pp. 377–393, Jan. 2017, doi: 10.1364/OE.25.000377.
- [120] X. Wang, A. A. Kuchmizhak, E. Brasselet, and S. Juodkazis, ‘Dielectric geometric phase optical elements fabricated by femtosecond direct laser writing in photoresists’, *Applied Physics Letters*, vol. 110, no. 18, p. 181101, May 2017, doi: 10.1063/1.4982602.
- [121] ‘Spiral Phase Plate Or Vortex Lenses For Sale | Vortex Photonics’. Accessed: May 06, 2024. [Online]. Available: https://vortex-photonics.de/vortex-lenses-spiral-phase-plates.html?gad_source=1&gclid=Cj0KCQjw_-GxBhC1ARIsADGgDju3OfJgCYEaZdTKELg2T1MXzMAq-ZoQWrYmqPP7Uy10a1EF2DDitkEaAhKiEALw_wcB
- [122] ‘Spiral Phase Plate (Vortex) - Holo Or - diffractive optics’. Accessed: May 06, 2024. [Online]. Available: <https://www.holoor.co.il/product/spiral-phase-plate-vortex/>
- [123] A. M. Yao and M. J. Padgett, ‘Orbital angular momentum: origins, behavior and applications’, *Adv. Opt. Photon., AOP*, vol. 3, no. 2, Art. no. 2, Jun. 2011, doi: 10.1364/AOP.3.000161.
- [124] L. Zhu and J. Wang, ‘Arbitrary manipulation of spatial amplitude and phase using phase-only spatial light modulators’, *Sci Rep*, vol. 4, no. 1, p. 7441, Dec. 2014, doi: 10.1038/srep07441.
- [125] J. Albero *et al.*, ‘Liquid Crystal Devices for the Reconfigurable Generation of Optical Vortices’, *Journal of Lightwave Technology*, vol. 30, no. 18, pp. 3055–3060, Sep. 2012, doi: 10.1109/JLT.2012.2211567.

- [126] C.-S. Guo, D.-M. Xue, Y.-J. Han, and J. Ding, 'Optimal phase steps of multi-level spiral phase plates', *Optics Communications*, vol. 268, no. 2, pp. 235–239, Dec. 2006, doi: 10.1016/j.optcom.2006.07.031.
- [127] Q. Wang, X. W. Sun, P. Shum, and X. J. Yin, 'Dynamic switching of optical vortices with dynamic gamma-correction liquid crystal spiral phase plate', *Opt. Express, OE*, vol. 13, no. 25, pp. 10285–10291, Dec. 2005, doi: 10.1364/OPEX.13.010285.
- [128] L. Gong *et al.*, 'Optical orbital-angular-momentum-multiplexed data transmission under high scattering', *Light Sci Appl*, vol. 8, no. 1, Art. no. 1, Mar. 2019, doi: 10.1038/s41377-019-0140-3.
- [129] Y. Ren *et al.*, 'Orbital Angular Momentum-based Space Division Multiplexing for High-capacity Underwater Optical Communications', *Sci Rep*, vol. 6, no. 1, p. 33306, Sep. 2016, doi: 10.1038/srep33306.
- [130] J. Wang *et al.*, 'Terabit free-space data transmission employing orbital angular momentum multiplexing', *Nature Photon*, vol. 6, no. 7, pp. 488–496, Jul. 2012, doi: 10.1038/nphoton.2012.138.
- [131] M. Singh, A. Atieh, A. Grover, and O. Barukab, 'Performance analysis of 40 Gb/s free space optics transmission based on orbital angular momentum multiplexed beams', *Alexandria Engineering Journal*, vol. 61, no. 7, pp. 5203–5212, Jul. 2022, doi: 10.1016/j.aej.2021.10.043.
- [132] J. Wang, J. Liu, S. Li, Y. Zhao, J. Du, and L. Zhu, 'Orbital angular momentum and beyond in free-space optical communications', *Nanophotonics*, vol. 11, no. 4, pp. 645–680, Jan. 2022, doi: 10.1515/nanoph-2021-0527.
- [133] T. Lei *et al.*, 'Massive individual orbital angular momentum channels for multiplexing enabled by Dammann gratings', *Light Sci Appl*, vol. 4, no. 3, pp. e257–e257, Mar. 2015, doi: 10.1038/lsa.2015.30.
- [134] J. Wang and X. Zhang, 'Orbital Angular Momentum in Fibers', *Journal of Lightwave Technology*, vol. 41, no. 7, pp. 1934–1962, Apr. 2023, doi: 10.1109/JLT.2022.3229172.
- [135] A. M. Shukla and S. Gupta, 'Joint WDM and OAM Mode Group Multiplexed Transmission Over Conventional Multimode Fiber', *IEEE Photonics Journal*, vol. 15, no. 3, pp. 1–9, Jun. 2023, doi: 10.1109/JPHOT.2023.3272737.
- [136] N. Bozinovic *et al.*, 'Terabit-scale orbital angular momentum mode division multiplexing in fibers', *Science*, vol. 340, no. 6140, Art. no. 6140, Jun. 2013, doi: 10.1126/science.1237861.
- [137] G. Wu *et al.*, 'Mode manipulation in a ring-core fiber for OAM monitoring and conversion', *Nanophotonics*, vol. 11, no. 21, pp. 4889–4898, Dec. 2022, doi: 10.1515/nanoph-2022-0493.
- [138] C. Brunet, B. Ung, L. Wang, Y. Messaddeq, S. LaRochelle, and L. A. Rusch, 'Design of a family of ring-core fibers for OAM transmission studies', *Opt. Express, OE*, vol. 23, no. 8, pp. 10553–10563, Apr. 2015, doi: 10.1364/OE.23.010553.
- [139] W. Geng, Y. Fang, C. Bao, Z. Pan, and Y. Yue, 'Emission of five OAM dispersive waves in dispersion-engineered double-ring core fiber', *Sci Rep*, vol. 14, no. 1, p. 8474, Apr. 2024, doi: 10.1038/s41598-024-57587-w.

- [140] D. G. Grier, 'A revolution in optical manipulation', *Nature*, vol. 424, no. 6950, Art. no. 6950, Aug. 2003, doi: 10.1038/nature01935.
- [141] M. Padgett and R. Bowman, 'Tweezers with a twist', *Nature Photon*, vol. 5, no. 6, pp. 343–348, Jun. 2011, doi: 10.1038/nphoton.2011.81.
- [142] M. Li, S. Yan, B. Yao, Y. Liang, and P. Zhang, 'Spinning and orbiting motion of particles in vortex beams with circular or radial polarizations', *Opt. Express, OE*, vol. 24, no. 18, pp. 20604–20612, Sep. 2016, doi: 10.1364/OE.24.020604.
- [143] S. H. Tao, X.-C. Yuan, J. Lin, X. Peng, and H. B. Niu, 'Fractional optical vortex beam induced rotation of particles', *Opt. Express, OE*, vol. 13, no. 20, pp. 7726–7731, Oct. 2005, doi: 10.1364/OPEX.13.007726.
- [144] V. Bobkova, J. Stegemann, R. Droop, E. Otte, and C. Denz, 'Optical grinder: sorting of trapped particles by orbital angular momentum', *Opt. Express, OE*, vol. 29, no. 9, pp. 12967–12975, Apr. 2021, doi: 10.1364/OE.419876.
- [145] S. W. Hell and J. Wichmann, 'Breaking the diffraction resolution limit by stimulated emission: stimulated-emission-depletion fluorescence microscopy', *Opt. Lett., OL*, vol. 19, no. 11, pp. 780–782, Jun. 1994, doi: 10.1364/OL.19.000780.
- [146] L. Yan, P. Kristensen, and S. Ramachandran, 'Vortex fibers for STED microscopy', *APL Photonics*, vol. 4, no. 2, p. 022903, Dec. 2018, doi: 10.1063/1.5045233.
- [147] K. I. Willig, S. O. Rizzoli, V. Westphal, R. Jahn, and S. W. Hell, 'STED microscopy reveals that synaptotagmin remains clustered after synaptic vesicle exocytosis', *Nature*, vol. 440, no. 7086, pp. 935–939, Apr. 2006, doi: 10.1038/nature04592.
- [148] S. B. Wang and C. T. Chan, 'Lateral optical force on chiral particles near a surface', *Nat Commun*, vol. 5, no. 1, p. 3307, Mar. 2014, doi: 10.1038/ncomms4307.
- [149] W. Brullot, M. K. Vanbel, T. Swusten, and T. Verbiest, 'Resolving enantiomers using the optical angular momentum of twisted light', *Science Advances*, vol. 2, no. 3, p. e1501349, Mar. 2016, doi: 10.1126/sciadv.1501349.
- [150] F. Tamburini, B. Thidé, G. Molina-Terriza, and G. Anzolin, 'Twisting of light around rotating black holes', *Nature Phys*, vol. 7, no. 3, pp. 195–197, Mar. 2011, doi: 10.1038/nphys1907.
- [151] A. Aleksanyan, N. Kravets, and E. Brasselet, 'Multiple-Star System Adaptive Vortex Coronagraphy Using a Liquid Crystal Light Valve', *Phys. Rev. Lett.*, vol. 118, no. 20, p. 203902, May 2017, doi: 10.1103/PhysRevLett.118.203902.
- [152] A. Aleksanyan and E. Brasselet, 'High-charge and multiple-star vortex coronagraphy from stacked vector vortex phase masks', *Opt. Lett., OL*, vol. 43, no. 3, pp. 383–386, Feb. 2018, doi: 10.1364/OL.43.000383.
- [153] G. Molina-Terriza, J. P. Torres, and L. Torner, 'Twisted photons', *Nature Phys*, vol. 3, no. 5, Art. no. 5, May 2007, doi: 10.1038/nphys607.
- [154] M. Mafu *et al.*, 'Higher-dimensional orbital-angular-momentum-based quantum key distribution with mutually unbiased bases', *Phys. Rev. A*, vol. 88, no. 3, p. 032305, Sep. 2013, doi: 10.1103/PhysRevA.88.032305.

- [155] X.-L. Wang *et al.*, ‘Quantum teleportation of multiple degrees of freedom of a single photon’, *Nature*, vol. 518, no. 7540, pp. 516–519, Feb. 2015, doi: 10.1038/nature14246.
- [156] D.-S. Ding *et al.*, ‘Quantum Storage of Orbital Angular Momentum Entanglement in an Atomic Ensemble’, *Phys. Rev. Lett.*, vol. 114, no. 5, p. 050502, Feb. 2015, doi: 10.1103/PhysRevLett.114.050502.
- [157] E. Otón Martínez, ‘Adaptive liquid-crystal phase-only passive devices’, PhD Thesis, Universidad Politécnica de Madrid, 2013. doi: 10.20868/UPM.thesis.15838.
- [158] A. Genaro and J. Francisco, ‘Adaptive micro-optical phase modulators based on liquid crystal technology’, doctoralThesis, 2015. Accessed: Jun. 23, 2023. [Online]. Available: <https://e-archivo.uc3m.es/handle/10016/21765>
- [159] M. Stebryte, I. Nys, J. Beeckman, and K. Neyts, ‘Chiral liquid crystal based holographic reflective lens for spectral detection’, *Opt. Express, OE*, vol. 30, no. 24, pp. 42829–42839, Nov. 2022, doi: 10.1364/OE.472821.
- [160] P. P. Crooker, ‘Blue Phases’, in *Chirality in Liquid Crystals*, H.-S. Kitzerow and C. Bahr, Eds., in Partially Ordered Systems. , New York, NY: Springer, 2001, pp. 186–222. doi: 10.1007/0-387-21642-1_7.
- [161] H. J. Coles and H. F. Gleeson, ‘Electric Field Induced Phase Transitions and Colour Switching in the Blue Phases of Chiral Nematic Liquid Crystals’, *Molecular Crystals and Liquid Crystals Incorporating Nonlinear Optics*, vol. 167, no. 1, pp. 213–225, Feb. 1989, doi: 10.1080/00268948908037178.
- [162] E. Otón *et al.*, ‘Orientation control of ideal blue phase photonic crystals’, *Sci Rep*, vol. 10, no. 1, Art. no. 1, Jun. 2020, doi: 10.1038/s41598-020-67083-6.
- [163] N. J. Mottram and C. J. P. Newton, ‘Introduction to Q-tensor theory’, no. arXiv:1409.3542. arXiv, Sep. 12, 2014. Accessed: Nov. 13, 2023. [Online]. Available: <http://arxiv.org/abs/1409.3542>
- [164] A. K. Singh, R. Manohar, J. P. Shukla, and A. M. Biradar, ‘Refractive Indices, Order Parameter and Optical Transmittance Studies of a Nematic Liquid Crystal Mixture’, *Acta Phys. Pol. A*, vol. 110, no. 4, pp. 485–493, Oct. 2006, doi: 10.12693/APhysPolA.110.485.
- [165] M. Franco, P. Patricio, and T. Pitarello, *Thermal tunability of photonic bandgaps in photonic crystal fibers selectively filled with nematic liquid crystal*, vol. 7839. 2010. doi: 10.1117/12.868246.
- [166] S. G. Hahm, Y.-G. Ko, Y. Rho, B. Ahn, and M. Ree, ‘Liquid crystal alignment in advanced flat-panel liquid crystal displays’, *Current Opinion in Chemical Engineering*, vol. 2, no. 1, pp. 71–78, Feb. 2013, doi: 10.1016/j.coche.2012.09.010.
- [167] S. Sato, ‘Liquid-Crystal Lens-Cells with Variable Focal Length’, *Jpn. J. Appl. Phys.*, vol. 18, no. 9, p. 1679, Sep. 1979, doi: 10.1143/JJAP.18.1679.
- [168] ‘24.3: Lenses’, Physics LibreTexts. Accessed: Jan. 05, 2024. [Online]. Available: [https://phys.libretexts.org/Bookshelves/University_Physics/Physics_\(Boundless\)/24%3A_Geometric_Optics/24.3%3A_Lenses](https://phys.libretexts.org/Bookshelves/University_Physics/Physics_(Boundless)/24%3A_Geometric_Optics/24.3%3A_Lenses)

- [169] J. Li, S.-T. Wu, S. Brugioni, R. Meucci, and S. Faetti, 'Infrared refractive indices of liquid crystals', *Journal of Applied Physics*, vol. 97, no. 7, p. 073501, Mar. 2005, doi: 10.1063/1.1877815.
- [170] 'Holographic Polymer-Dispersed Liquid Crystals: Materials, Formation, and Applications'. Accessed: Apr. 22, 2024. [Online]. Available: <https://www.hindawi.com/journals/aoe/2008/684349/>
- [171] M. Krijn, s Zwart, D. Boer, O. Willemsen, and M. Sluiter, '2-D/3-D Displays Based on Switchable Lenticulars', *Journal of The Society for Information Display - J SOC INF DISP*, vol. 16, Aug. 2008, doi: 10.1889/1.2966446.
- [172] Y.-J. Wang, H.-A. Hsieh, and Y.-H. Lin, 'Electrically tunable gradient-index lenses via nematic liquid crystals with a method of spatially extended phase distribution', *Opt. Express, OE*, vol. 27, no. 22, pp. 32398–32408, Oct. 2019, doi: 10.1364/OE.27.032398.
- [173] N. Bennis *et al.*, 'A high birefringence liquid crystal for lenses with large aperture', *Sci Rep*, vol. 12, no. 1, Art. no. 1, Aug. 2022, doi: 10.1038/s41598-022-18530-z.
- [174] A. Jamali, D. Bryant, Y. Zhang, A. Grunnet-Jepsen, A. Bhowmik, and P. J. Bos, 'Design of a large aperture tunable refractive Fresnel liquid crystal lens', *Appl. Opt., AO*, vol. 57, no. 7, Art. no. 7, Mar. 2018, doi: 10.1364/AO.57.000B10.
- [175] M. García de Blas, M. A. Geday, J. M. Otón, and X. Quintana Arregui, 'Two-Dimensional Digital Beam Steering Based on Liquid Crystal Phase Gratings', *Applied Sciences*, vol. 11, no. 8, Art. no. 8, Jan. 2021, doi: 10.3390/app11083632.
- [176] J. W. Goodman, *Introduction to Fourier optics*, vol. 1. 2005.
- [177] J. D. Schmidt, *Numerical Simulation of Optical Wave Propagation with Examples in MATLAB*. 1000 20th Street, Bellingham, WA 98227-0010 USA: SPIE, 2010. doi: 10.1117/3.866274.
- [178] J. Pereiro-García, M. García-de-Blas, M. A. Geday, X. Quintana, and M. Caño-García, 'Flat variable liquid crystal diffractive spiral axicon enabling perfect vortex beams generation', *Sci Rep*, vol. 13, no. 1, Art. no. 1, Feb. 2023, doi: 10.1038/s41598-023-29164-0.
- [179] J. Pereiro-García, M. García-De-Blas, P. D. L. Rosa, M. A. Geday, X. Quintana, and M. Caño-García, 'Reconfigurable perfect vortex beam generator based on a liquid crystal spiral phase plate', *Opt. Express, OE*, vol. 31, no. 23, pp. 37653–37662, Nov. 2023, doi: 10.1364/OE.501796.
- [180] 'TLC5947 data sheet, product information and support | TI.com'. Accessed: Jan. 12, 2024. [Online]. Available: https://www.ti.com/product/TLC5947?utm_source=google&utm_medium=cpc&utm_campaign=app-null-null-44700045336317413_prodfolderdynamic-cpc-pf-google-wwwe_int&utm_content=prodfolddynamic&ds_k=DYNAMIC+SEARCH+ADS&DCM=yes&gad_source=1&gclid=CjwKCAiA44OtBhAOEiwAj4gpOUMDDvwoXJgxUTACOOXXvhVV6ebByqSmljxSaBr-cPMki5mT-I5NNxoCHMEQAvD_BwE&gclsrc=aw.ds
- [181] 'ADG5413 Datasheet and Product Info | Analog Devices'. Accessed: Jan. 12, 2024. [Online]. Available: <https://www.analog.com/en/products/adg5413.html#product-overview>

- [182] 'IALL', ATTRACT Project phase 2. Accessed: Feb. 15, 2024. [Online]. Available: <https://phase2.attract-eu.com/projects/iall/>
- [183] 'ADTelecom'. Accessed: Feb. 15, 2024. [Online]. Available: <http://www.adtelecom.es/>
- [184] 'DAC60096 data sheet, product information and support | TI.com'. Accessed: Feb. 15, 2024. [Online]. Available: https://www.ti.com/product/DAC60096?utm_source=google&utm_medium=cpc&utm_campaign=asc-null-null-gpn_en-cpc-pf-google-ww&utm_content=dac60096&ds_k=DAC60096&dcm=yes&gad_source=1&gclid=CjwKCAiAibeuBhAAEiwAiXBoJKzS0M9W5WXm-DrjUBOd_PTOSzdT7OGXk63jGYh7V2Wye93yL_ejHhoClsAQAvD_BwE&gclsrc=aw.ds
- [185] 'STM32F4 - ARM Cortex-M4 High-Performance MCUs - STMicroelectronics'. Accessed: Feb. 15, 2024. [Online]. Available: <https://www.st.com/en/microcontrollers-microprocessors/stm32f4-series.html>
- [186] 'Michel-Levy Chart'. Accessed: Jan. 12, 2024. [Online]. Available: https://www.doitpoms.ac.uk/tlplib/liquid_crystals/michel_levy_chart.php
- [187] 'Nikon D500| DSLR de lentes intercambiables de Nikon'. Accessed: Jan. 16, 2024. [Online]. Available: <https://www.nikon.com.mx/nikon-products/product/dslr-cameras/d500.html>
- [188] J.-W. Liaw, C.-W. Chien, K.-C. Liu, Y.-C. Ku, and M.-K. Kuo, '3D Optical Vortex Trapping of Plasmonic Nanostructure', *Sci Rep*, vol. 8, no. 1, Art. no. 1, Aug. 2018, doi: 10.1038/s41598-018-30948-y.
- [189] G. Xie *et al.*, 'Performance metrics and design considerations for a free-space optical orbital-angular-momentum-multiplexed communication link', *Optica, OPTICA*, vol. 2, no. 4, pp. 357–365, Apr. 2015, doi: 10.1364/OPTICA.2.000357.
- [190] L. Zhu, M. Deng, B. Lu, X. Guo, and A. Wang, 'Turbulence-resistant high-capacity free-space optical communications using OAM mode group multiplexing', *Opt. Express, OE*, vol. 31, no. 9, pp. 14454–14463, Apr. 2023, doi: 10.1364/OE.488053.
- [191] K. Sueda, G. Miyaji, N. Miyanaga, and M. Nakatsuka, 'Laguerre-Gaussian beam generated with a multilevel spiral phase plate for high intensity laser pulses', *Opt. Express, OE*, vol. 12, no. 15, Art. no. 15, Jul. 2004, doi: 10.1364/OPEX.12.003548.
- [192] A. A. Demenev, A. V. Kovalchuk, E. A. Polushkin, and S. Yu. Shapoval, '3D Femtosecond Laser Submicron Lithography as a Way of Fabricating Spiral Phase Plates for Forming Photon Beams with Orbital Angular Momentum', *Bull. Russ. Acad. Sci. Phys.*, vol. 85, no. 2, pp. 159–164, Feb. 2021, doi: 10.3103/S1062873821020076.
- [193] M. Caño García, 'Tunable organic waveguides and microstructured devices', phd, E.T.S.I. Telecomunicación (UPM), 2018. Accessed: Feb. 26, 2024. [Online]. Available: <https://oa.upm.es/50764/>
- [194] L. Li and P. Bos, 'Detailed Modeling of the Effect of Gap Between Ring Electrodes on the MTF of Liquid Crystal Lenses and Comparison with a "Floating" Electrode Design', *Molecular Crystals and Liquid Crystals*, vol. 594, pp. 78–85, May 2014, doi: 10.1080/15421406.2014.917476.

-
- [195] L. Li, D. Bryant, T. V. Heugten, and P. J. Bos, 'Near-diffraction-limited and low-haze electro-optical tunable liquid crystal lens with floating electrodes', *Opt. Express, OE*, vol. 21, no. 7, pp. 8371–8381, Apr. 2013, doi: 10.1364/OE.21.008371.
 - [196] O. V. Angelsky, A. Ya. Bekshaev, M. V. Vasnetsov, C. Yu. Zenkova, P. P. Maksimyak, and J. Zheng, 'Optical phase singularities: Physical nature, manifestations and applications', *Frontiers in Physics*, vol. 10, 2022, Accessed: Feb. 26, 2024. [Online]. Available: <https://www.frontiersin.org/articles/10.3389/fphy.2022.1060787>
 - [197] J. E. Curtis and D. G. Grier, 'Structure of Optical Vortices', *Phys. Rev. Lett.*, vol. 90, no. 13, p. 133901, Apr. 2003, doi: 10.1103/PhysRevLett.90.133901.
 - [198] P. de la Rosa, J. Pereiro-García, M. Caño-García, J. M. Otón, X. Quintana, and M. A. Geday, 'Generation of integer and fractional vortex beams based on liquid crystal electronically reconfigurable spiral phase plates', *Opt. Express, OE*, vol. 31, no. 19, Art. no. 19, Sep. 2023, doi: 10.1364/OE.494676.
 - [199] H. Zhang, J. Zeng, X. Lu, Z. Wang, C. Zhao, and Y. Cai, 'Review on fractional vortex beam', *Nanophotonics*, vol. 11, no. 2, pp. 241–273, Jan. 2022, doi: 10.1515/nanoph-2021-0616.
 - [200] J. Leach, M. R. Dennis, J. Courtial, and M. J. Padgett, 'Vortex knots in light', *New J. Phys.*, vol. 7, no. 1, p. 55, Feb. 2005, doi: 10.1088/1367-2630/7/1/055.
 - [201] J. Leach, E. Yao, and M. J. Padgett, 'Observation of the vortex structure of a non-integer vortex beam', *New J. Phys.*, vol. 6, no. 1, p. 71, Jul. 2004, doi: 10.1088/1367-2630/6/1/071.
 - [202] Y. Li *et al.*, 'Orbital Angular Momentum Multiplexing and Demultiplexing by a Single Metasurface', *Advanced Optical Materials*, vol. 5, no. 2, p. 1600502, 2017, doi: 10.1002/adom.201600502.
 - [203] S. Ramachandran and P. Kristensen, 'Optical vortices in fiber', *Nanophotonics*, vol. 2, no. 5–6, pp. 455–474, Dec. 2013, doi: 10.1515/nanoph-2013-0047.
 - [204] K. C. Neuman and S. M. Block, 'Optical trapping', *Rev Sci Instrum*, vol. 75, no. 9, pp. 2787–2809, Sep. 2004, doi: 10.1063/1.1785844.
 - [205] P. A. Prentice *et al.*, 'Manipulation and filtration of low index particles with holographic Laguerre-Gaussian optical trap arrays', *Opt. Express, OE*, vol. 12, no. 4, pp. 593–600, Feb. 2004, doi: 10.1364/OPEX.12.000593.
 - [206] A. Keloth, O. Anderson, D. Risbridger, and L. Paterson, 'Single Cell Isolation Using Optical Tweezers', *Micromachines*, vol. 9, no. 9, Art. no. 9, Sep. 2018, doi: 10.3390/mi9090434.
 - [207] X. Wang *et al.*, 'Enhanced cell sorting and manipulation with combined optical tweezer and microfluidic chip technologies', *Lab Chip*, vol. 11, no. 21, pp. 3656–3662, Oct. 2011, doi: 10.1039/C1LC20653B.
 - [208] Y. Shen *et al.*, 'Optical vortices 30 years on: OAM manipulation from topological charge to multiple singularities', *Light Sci Appl*, vol. 8, no. 1, Art. no. 1, Oct. 2019, doi: 10.1038/s41377-019-0194-2.
 - [209] D. Cojoc, V. Garbin, E. Ferrari, L. Businaro, F. Romanato, and E. D. Fabrizio, 'Laser trapping and micro-manipulation using optical vortices', *Microelectronic Engineering*, vol. 78–79, pp. 125–131, Mar. 2005, doi: 10.1016/j.mee.2004.12.017.

- [210] F. Simoni and O. Francescangeli, 'Effects of light on molecular orientation of liquid crystals', *J. Phys.: Condens. Matter*, vol. 11, no. 41, p. R439, Oct. 1999, doi: 10.1088/0953-8984/11/41/201.
- [211] S. Singh, 'Phase transitions in liquid crystals', *Physics Reports*, vol. 324, no. 2, pp. 107–269, Feb. 2000, doi: 10.1016/S0370-1573(99)00049-6.
- [212] K. Gourley, I. Golub, and B. Chebbi, 'Demonstration of a Fresnel axicon', *Appl. Opt., AO*, vol. 50, no. 3, pp. 303–306, Jan. 2011, doi: 10.1364/AO.50.000303.
- [213] A. Pusenkova, O. Sova, and T. Galstian, 'Electrically variable liquid crystal lens with spiral electrode', *Optics Communications*, vol. 508, p. 127783, Apr. 2022, doi: 10.1016/j.optcom.2021.127783.
- [214] J. Stevens and T. Galstian, 'Electrically tunable liquid crystal lens with a serpentine electrode design', *Opt. Lett., OL*, vol. 47, no. 4, Art. no. 4, Feb. 2022, doi: 10.1364/OL.447853.
- [215] J. Beeckman, T.-H. Yang, I. Nys, J. P. George, T.-H. Lin, and K. Neyts, 'Multi-electrode tunable liquid crystal lenses with one lithography step', *Opt. Lett., OL*, vol. 43, no. 2, pp. 271–274, Jan. 2018, doi: 10.1364/OL.43.000271.
- [216] J. F. Algorri, V. Urruchi, N. Bennis, P. Morawiak, J. M. Sánchez-Pena, and J. M. Otón, 'Liquid crystal spherical microlens array with high fill factor and optical power', *Opt. Express, OE*, vol. 25, no. 2, pp. 605–614, Jan. 2017, doi: 10.1364/OE.25.000605.
- [217] Z. Guo *et al.*, 'Generation of Perfect Vortex Beams With Polymer-Based Phase Plate', *IEEE Photonics Technology Letters*, vol. PP, pp. 1–1, Apr. 2020, doi: 10.1109/LPT.2020.2985745.
- [218] J. Arlt and K. Dholakia, 'Generation of high-order Bessel beams by use of an axicon'. 2000.
- [219] Y. Liu *et al.*, 'Generation of perfect vortex and vector beams based on Pancharatnam-Berry phase elements', *Sci Rep*, vol. 7, no. 1, Art. no. 1, Mar. 2017, doi: 10.1038/srep44096.
- [220] F. O. Fahrbach, F. F. Voigt, B. Schmid, F. Helmchen, and J. Huisken, 'Rapid 3D light-sheet microscopy with a tunable lens', *Opt. Express, OE*, vol. 21, no. 18, pp. 21010–21026, Sep. 2013, doi: 10.1364/OE.21.021010.
- [221] 'Mechanically assisted liquid lens zoom system for mobile phone cameras'. Accessed: Mar. 09, 2024. [Online]. Available: <https://www.spiedigitallibrary.org/conference-proceedings-of-spie/6289/1/Mechanically-assisted-liquid-lens-zoom-system-for-mobile-phone-cameras/10.1117/12.680292.short>
- [222] S. Welch, A. Greenaway, P. Doel, and G. Love, 'Smart optics in astronomy and space', *Astronomy & Geophysics*, vol. 44, no. 1, p. 1.26-1.29, Feb. 2003, doi: 10.1046/j.1468-4004.2003.44126.x.
- [223] M. A. Geday, M. Caño-García, J. M. Otón, and X. Quintana, 'Adaptive Spiral Diffractive Lenses—Lenses With a Twist', *Advanced Optical Materials*, vol. 8, no. 23, p. 2001199, 2020, doi: 10.1002/adom.202001199.
- [224] J. Pereiro-García, 'Chromatic aberration compensation using thin, transparent, large aperture, wide focal range, adaptive liquid crystal lens.', *[In Press]*.

- [225] D. Werdehausen, S. Burger, I. Staude, T. Pertsch, and M. Decker, 'Flat optics in high numerical aperture broadband imaging systems', *J. Opt.*, vol. 22, no. 6, p. 065607, May 2020, doi: 10.1088/2040-8986/ab8ea2.
- [226] Y. Wang, W. Yun, and C. Jacobsen, 'Achromatic Fresnel optics for wideband extreme-ultraviolet and X-ray imaging', *Nature*, vol. 424, no. 6944, pp. 50–53, Jul. 2003, doi: 10.1038/nature01756.
- [227] 'Achromatic doublet intraocular lens for full aberration correction'. Accessed: Mar. 16, 2024. [Online]. Available: <https://opg.optica.org/boe/fulltext.cfm?uri=boe-8-5-2396&id=362796>
- [228] F. Balli, M. Sultan, S. K. Lami, and J. T. Hastings, 'A hybrid achromatic metalens', *Nat Commun*, vol. 11, no. 1, Art. no. 1, Aug. 2020, doi: 10.1038/s41467-020-17646-y.
- [229] P. Wang, N. Mohammad, and R. Menon, 'Chromatic-aberration-corrected diffractive lenses for ultra-broadband focusing', *Sci Rep*, vol. 6, no. 1, Art. no. 1, Feb. 2016, doi: 10.1038/srep21545.
- [230] T. Zhan *et al.*, 'Practical Chromatic Aberration Correction in Virtual Reality Displays Enabled by Cost-Effective Ultra-Broadband Liquid Crystal Polymer Lenses', *Advanced Optical Materials*, vol. 8, no. 2, p. 1901360, 2020, doi: 10.1002/adom.201901360.
- [231] M. S. Millán, J. Otón, and E. Pérez-Cabré, 'Chromatic compensation of programmable Fresnel lenses', *Opt. Express, OE*, vol. 14, no. 13, pp. 6226–6242, Jun. 2006, doi: 10.1364/OE.14.006226.
- [232] A. Genaro and J. Francisco, 'Adaptive micro-optical phase modulators based on liquid crystal technology', doctoralThesis, 2015. Accessed: Jun. 07, 2023. [Online]. Available: <https://e-archivo.uc3m.es/handle/10016/21765>
- [233] 'Analysis of focus measure operators for shape-from-focus', *Pattern Recognition*, vol. 46, no. 5, pp. 1415–1432, May 2013, doi: 10.1016/j.patcog.2012.11.011.
- [234] Y. Sun, S. Duthaler, and B. J. Nelson, 'Autofocusing in computer microscopy: Selecting the optimal focus algorithm', *Microscopy Research and Technique*, vol. 65, no. 3, pp. 139–149, 2004, doi: 10.1002/jemt.20118.
- [235] Y.-H. Lin, M.-S. Chen, and H.-C. Lin, 'An electrically tunable optical zoom system using two composite liquid crystal lenses with a large zoom ratio', *Opt. Express, OE*, vol. 19, no. 5, pp. 4714–4721, Feb. 2011, doi: 10.1364/OE.19.004714.
- [236] 'Laser Beam Expanders'. Accessed: Oct. 09, 2023. [Online]. Available: <https://www.edmundoptics.eu/knowledge-center/application-notes/lasers/beam-expanders/>
- [237] J. Pereiro-García, O. Blanco-Fernández, Rafael Ramos-Uña, M. Caño-García, X. Quintana, M. A. Geday, 'Tunable magnification and minification zoom system based on liquid crystal spiral lenses', *[In Preparation]*.
- [238] W. Shao, S. Huang, X. Liu, and M. Chen, 'Free-space optical communication with perfect optical vortex beams multiplexing', *Optics Communications*, vol. 427, pp. 545–550, Nov. 2018, doi: 10.1016/j.optcom.2018.06.079.

- [239] A. S. Ostrovsky, C. Rickenstorff-Parrao, and V. Arrizón, 'Generation of the "perfect" optical vortex using a liquid-crystal spatial light modulator', *Opt. Lett., OL*, vol. 38, no. 4, pp. 534–536, Feb. 2013, doi: 10.1364/OL.38.000534.
- [240] J. García-García, C. Rickenstorff-Parrao, R. Ramos-García, V. Arrizón, and A. S. Ostrovsky, 'Simple technique for generating the perfect optical vortex', *Opt. Lett.*, vol. 39, no. 18, Art. no. 18, Sep. 2014, doi: 10.1364/OL.39.005305.
- [241] P. Vaity and L. Rusch, 'Perfect vortex beam: Fourier transformation of a Bessel beam', *Opt. Lett., OL*, vol. 40, no. 4, Art. no. 4, Feb. 2015, doi: 10.1364/OL.40.000597.
- [242] V. V. Kotlyar, A. A. Kovalev, and A. P. Porfirev, 'Optimal phase element for generating a perfect optical vortex', *J. Opt. Soc. Am. A*, vol. 33, no. 12, Art. no. 12, Dec. 2016, doi: 10.1364/JOSAA.33.002376.
- [243] Y. Chen, Z.-X. Fang, Y.-X. Ren, L. Gong, and R.-D. Lu, 'Generation and characterization of a perfect vortex beam with a large topological charge through a digital micromirror device', *Appl. Opt., AO*, vol. 54, no. 27, Art. no. 27, Sep. 2015, doi: 10.1364/AO.54.008030.
- [244] S. Li, M. Liu, X. Li, Z. Ge, and L. Zhang, 'Rapid generation of perfect vortex beam without side lobes', *Modern Physics Letters B*, vol. 32, p. 1850289, Aug. 2018, doi: 10.1142/S0217984918502895.
- [245] Q. Zhou *et al.*, 'Generation of Perfect Vortex Beams by Dielectric Geometric Metasurface for Visible Light', *Laser & Photonics Reviews*, vol. 15, no. 12, Art. no. 12, 2021, doi: 10.1002/lpor.202100390.
- [246] Y. Liu *et al.*, 'Generation of perfect vortex and vector beams based on Pancharatnam-Berry phase elements', *Sci Rep*, vol. 7, no. 1, Art. no. 1, Mar. 2017, doi: 10.1038/srep44096.
- [247] W. Shao, S. Huang, M. Chen, X. Liu, and W. Xie, 'Research of optical vortex's energy efficiency and diffraction angle based on spatial light modulator', *OE*, vol. 56, no. 8, p. 086113, Aug. 2017, doi: 10.1117/1.OE.56.8.086113.
- [248] M. García de Blas, 'Tunable Diffractive Liquid Crystal Photonic Devices', phd, E.T.S.I. Telecomunicación (UPM), 2022. Accessed: May 20, 2024. [Online]. Available: <https://oa.upm.es/72064/>
- [249] E. Otón Martínez, 'Adaptive liquid-crystal phase-only passive devices', phd, E.T.S.I. Telecomunicación (UPM), 2013. Accessed: May 20, 2024. [Online]. Available: <https://oa.upm.es/15838/>

Appendix I: Manufacturing Protocol

All the liquid crystal devices presented in this thesis have been manufactured in the clean room facilities of the Centro de Materiales y Dispositivos Avanzados para las TICs (CEMDATIC), a research center at the Universidad Politécnica de Madrid (UPM). The manufacture of LC cells is sensitive to the contamination of external agents like dust, that can significantly affect the performance of the final device. For this reason, the whole manufacturing process is undergone within this working area where there are cleaning and filtering restrictions as well as special protocols that need to be followed. Once the LC devices are finalized, the characterization and quality testing are carried outside the clean room.

The current CEMDATIC LC devices manufacturing protocols and processes are summarized below. For more detailed information, the reader is referred to the following doctoral theses [193], [248], [249].

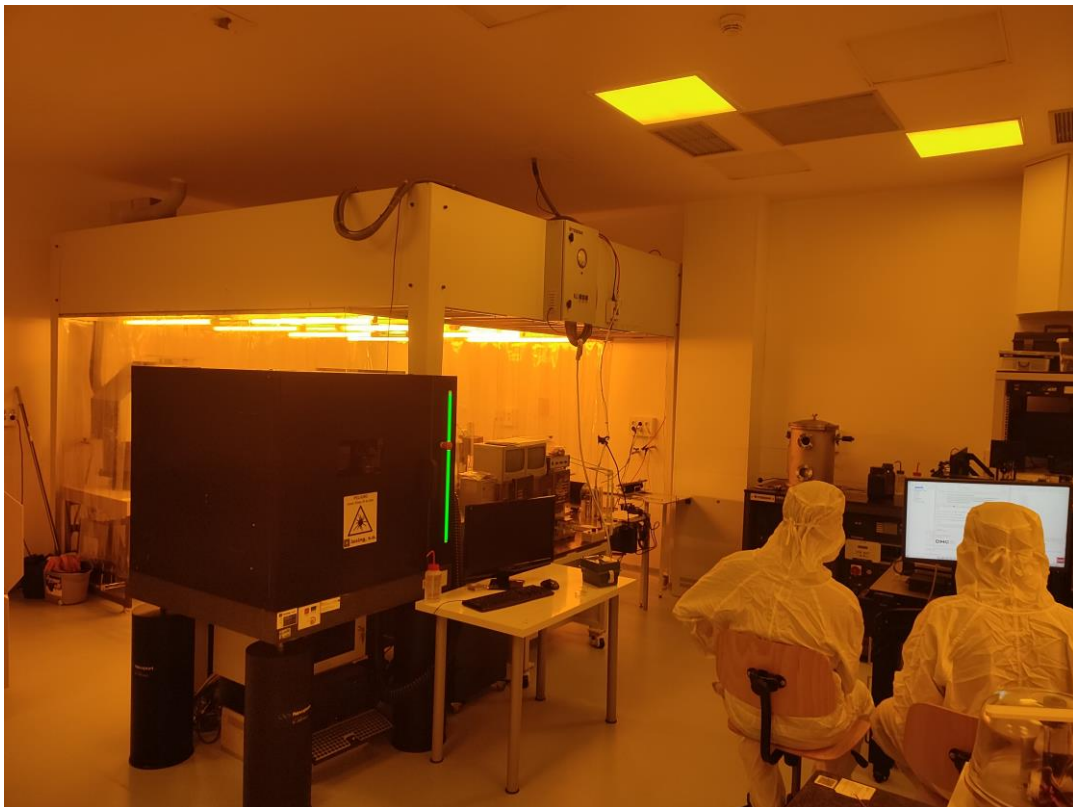


Figure A.1: CEMDATIC clean room facilities.

A.1 Substrates preparation

As described in Chapter 3: Experimental, the LC devices developed in this thesis are based on a sandwich-like structure. Two ITO-coated glass substrates enclose the LC in the middle. These commercial glass substrates need to be cut, ITO side down, to the required dimensions. For this purpose, an in-house developed cutting machine is employed where multiple cutting lines can be programmed.

Once the substrates have the tailored dimensions, a cleaning process is required to get rid of undesired particles. First, glass shards that may have arisen from the cutting process are removed using a brush to avoid them scratching the ITO surface. Then, a cleaning protocol is followed to remove any desired dust or any organic particles:

1. Initial soft rubbing with a clean room cloth and acetone: 1 min.
2. Acetone bath: 1 min.
3. Isopropanol bath: 1min.
4. Immerse the substrates in deionized water: 1 min.
5. Ultrasonic bath in deionized water: 30 min.
6. Dry the samples with pressurized nitrogen.
7. Remove the remaining humidity by putting the substrates in the oven 30 mins at 200 °C.

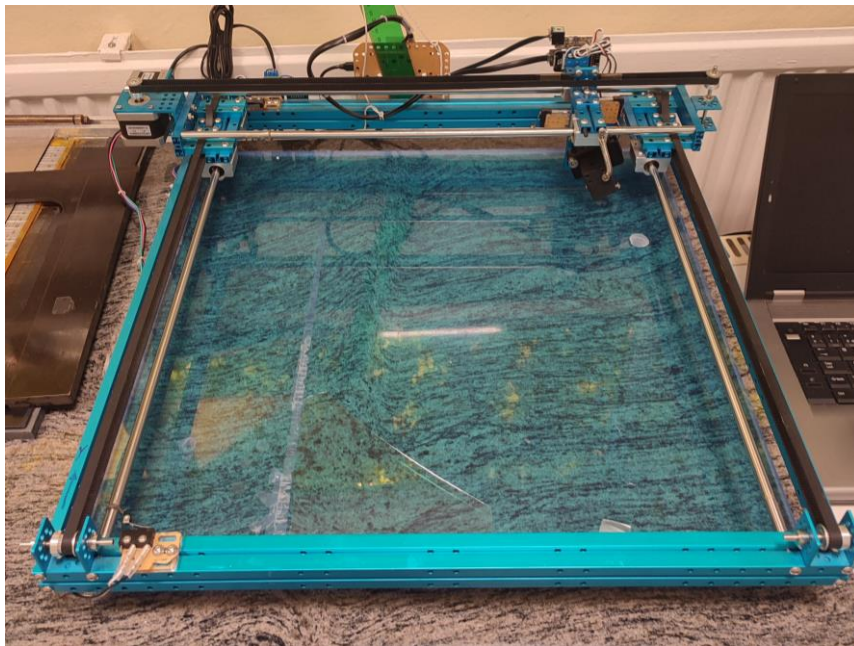


Figure A.2: Glass substrates cutting in-house developed system.

A.2 Electrode patterning

One of the ITO planes is going to act as a homogeneous counter electrode; thus, no patterning is required. However, the other ITO plane has electrodes with a certain geometry dependent on the desired device to be manufactured.

In this thesis Direct Laser Writing (DLW) is employed for the electrode patterning by ITO laser ablation. As the substrates are already coated with ITO, this technique does not require any previous treatment and can be directly applied to the cleaned glass substrates. Another advantage of this technique is that the patterned design can be easily modified from one batch to another by software, without needing any mask replacement.

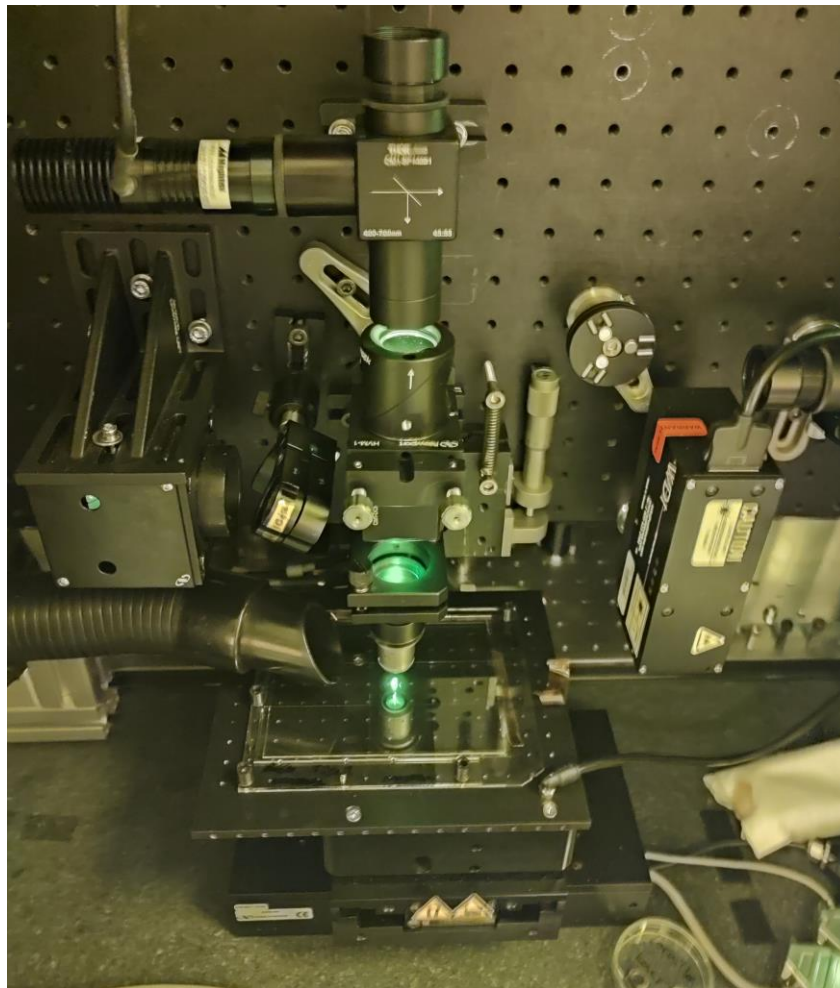


Figure A.3: Direct laser writing system at the CEMDATIC clean room.

The DLW system (Lasing S.A.) employed in this thesis core elements are a UV laser and a CNC controlled stage. The laser is a Nd-YAG tripled laser with an output power of 300 mW working at an optimized frequency of 50 kHz. The laser wavelength is 355 nm with a pulse width lower than 15 ns and an optimum driving current of 5.2 A. After configuring the desired design, the cleaned substrates are placed in a holder with the ITO sided facing downwards to perform back-scribing ablation.

A.3 Surface treatment

After the ablation, substrates are cleaned again following the previous presented cleaning protocol. Then, a surface treatment is applied using an ultraviolet oven (UVO) cleaner (Jelight Company). This process helps to remove any remaining organic molecules that can contaminate the final device. Additionally, this treatment makes the surface more hydrophilic, enhancing the homogeneity of the latter spin coated depositions. Substrates are placed in the UVO cleaner with the ITO side facing upwards during 30 minutes.

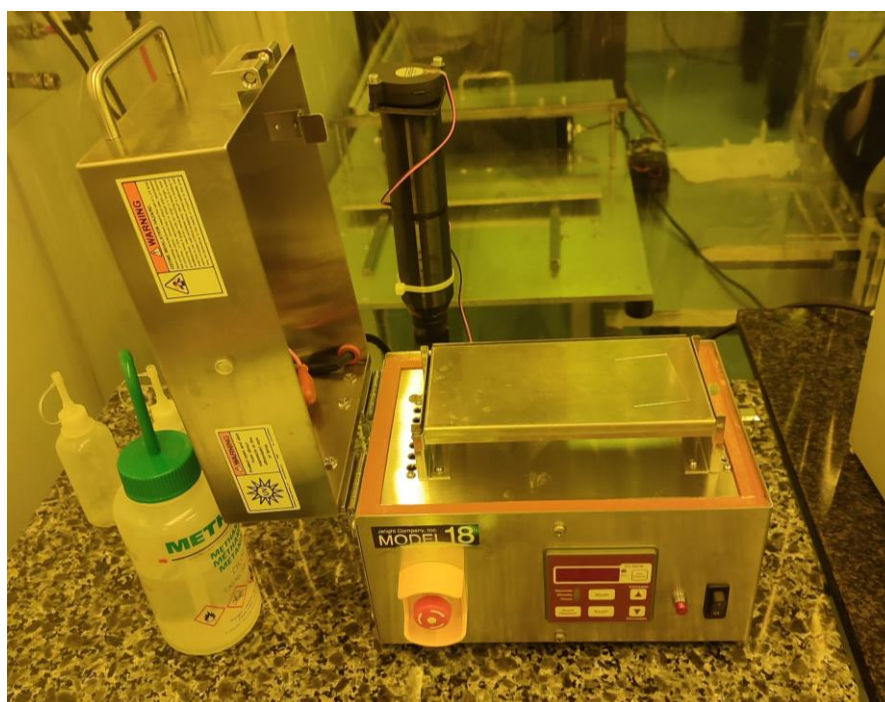


Figure A.4: UVO cleaner employed to perform surface treatment.

A.4 Alignment layer deposition and rubbing

Alignment layers are deposited over the ITO to ensure a preferred LC switching plane. The devices presented in this thesis use polyimide as alignment layer deposited by spin coating process:

1. The polyimide mixture is removed from the refrigerator 30 minutes before use to allow it to slightly temper.
2. Polyimide is deposited over the substrate using a syringe equipped with a 0.45 μm particle filter.
3. Substrates are spun at 2500 *rpm* for 30 s.
4. The substrates are placed on a preheated hot plate at 150 °C for 2 minutes. This prebake process induces a slow evaporation of the polyimide mixture solvents to minimize the appearance of bubbles.
5. Polyimide layer is cured in a preheated oven at 180 °C for 45 minutes.
6. Removing the cured polyimide from the contact areas and rubbing as described below.



Figure A.5: Glass substrate on the spin coating machine.

After polymerizing the alignment layer, it is manually removed from the counter electrode contact areas (polyimide acts as an electrical insulator) using a rubber eraser. The preferred switching plane direction is induced by performing a rubbing technique. This process is carried out employing an in-house developed machined composed of a rotating motorized cylinder covered by a velvet cloth. The roll height needs to be adjusted to ensure that the pressure over the substrates is not too high, which is generally done using visual inspection on dummy samples with an identical substrate height. The substrate is placed in the stage with the alignment layer side facing upwards and the cylinder rotation is started. The stage is slowly moved across the machine to perform the rubbing. Both substrates are rubbed and mounted in opposite directions to produce an anti-parallel configuration. Lastly, substrates are blown with a filtered nitrogen gun to remove any particle deposited over the surface.

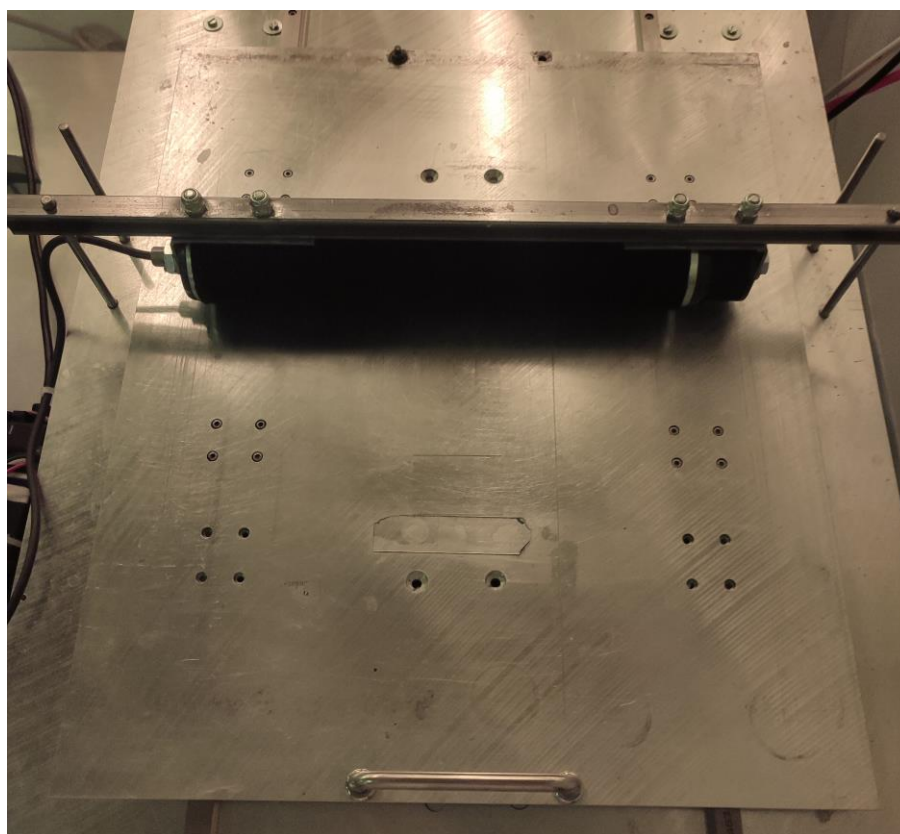


Figure A.6: Rubbing machine composed of a rotating cylinder lined with velvet cloth.

A.5 Spacers and silver conductive paste deposition

Both the LC cell homogeneity and thickness are crucial for the proper performance of the devices. The LC cells must have enough thickness to produce a 2π phase delay. The desired thickness is ensured by depositing silica spacers of known dimensions:

1. Silica spacers are mixed with ethanol/acetone in a concentration of $0.1 \frac{mg}{ml}$.
2. The suspension is placed in an ultrasonic bath for 15 minutes to avoid spacer-aggregation.
3. The suspension is deposited using a pipette over the treated substrates and are spun at 1500 *rpm* for 30 *s*.

Once the spacers have been deposited and the solvents evaporated, silver conductive paste drops are deposited within the polyimide-free areas to ensure electrical connection between substrates once the cell is assembled.

A.6 Cell assembly and filling

The two glass substrates are mounted with the ITO layers facing inwards. Once they are properly aligned their position is fixed with clamps. The clamps are distributed to ensure a homogeneous thickness across the cell. Adhesive (Araldite) is applied onto three edges of the cell to leave one side open used to introduce the LC material.

The filling process is performed in a system composed of a vacuum chamber, a hot platform and a moving stage:

1. The cell is attached to the moving stage with kapton tape with the open slit pointing downwards.
2. The crucible is filled with the LC material and placed on the hot platform.
3. The vacuum pump is turned on as well as the heating system. The vacuum is applied for 1 hour to remove the air contained in the cell and dissolved in the LC
4. The cell is moved towards the crucible until the slit is immersed in the LC. The cell is kept in this position for 1 hour to ensure the homogeneous filling of the cell.
5. Once the filling is completed, the vacuum pump is turned off and the valve is slowly opened.
6. The slit is sealed with Araldite adhesive and left to dry. If there is excess of LC over the edges, it can be cleaned with a clean room cloth and acetone.

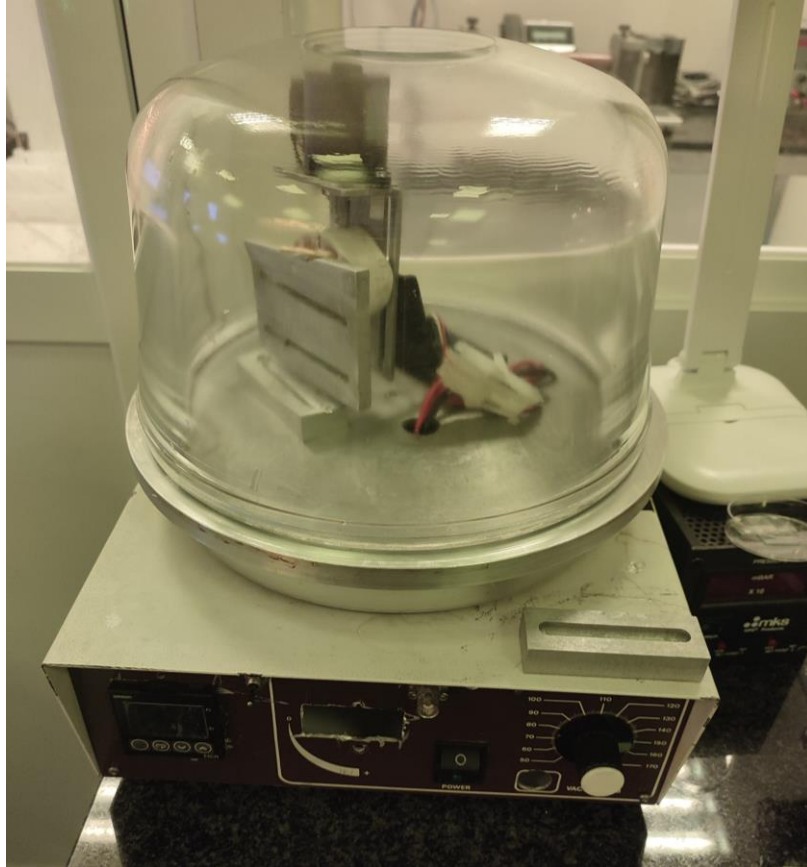


Figure A.7: Liquid crystal cell filling system.

A.7 Cell flex connector attachment

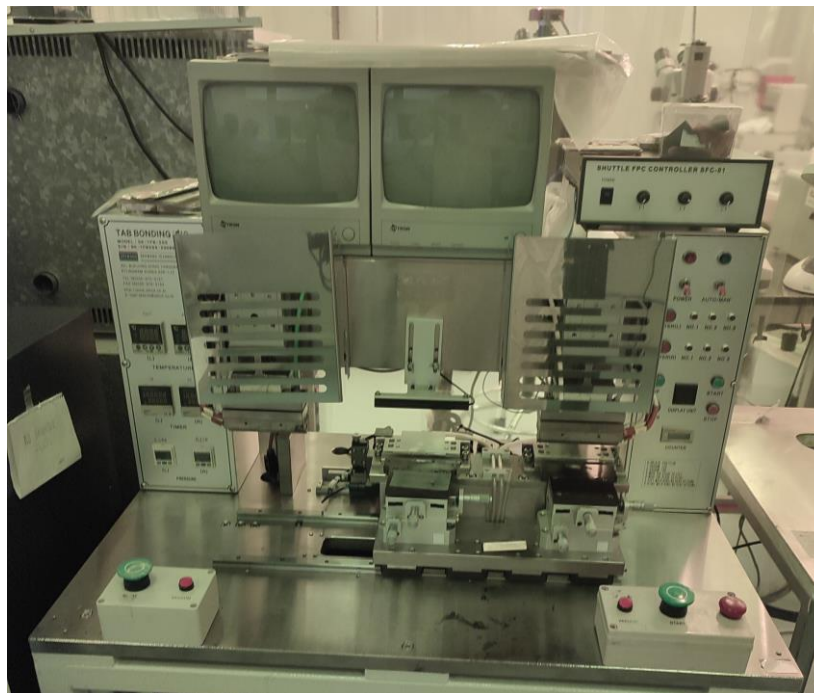


Figure A.8: Bonding system at the CEMDATIC facilities.

A flex connector is employed to connect the cell patterned electrodes with the driver output signals. The attachment of this connector is the device manufacturing process last step. The connectors are made up of 80 different conductors having $500\ \mu\text{m}$ width and a pitch of $1\ \text{mm}$. These connectors have been in-house designed and are manufactured by an external PCB manufacturer using a flexible polyimide substrate. Both ends of the connectors use standard golden finger finishing but only the one that is attached to driver has structural reinforcements.

This connector is attached to the cell using an anisotropic conductive adhesive film (Hitachi) and a bonding system following the next procedure:

1. Cured polyimide is removed from the cell connector area using a rubber eraser.
2. The protective film of one of the sides of the anisotropic adhesive is manually removed. Then, the anisotropic conductive film is placed over the cell polyimide-free area.
3. To enhance the attachment of the adhesive to the substrate, an initial bonding is performed at $120\ ^\circ\text{C}$ and $0.15\ \text{bar}$, for $19\ \text{s}$.
4. The remaining protective film is removed and the connector is carefully placed following the alignment marks assisted by microscope cameras and linear positioners.
5. The connector is attached to the cell using the bonding head at $330\ ^\circ\text{C}$ and $0.40\ \text{bar}$, for $19\ \text{s}$.
6. A protective kapton film is placed over the connector to enhance the attachment between the cell and the connector.

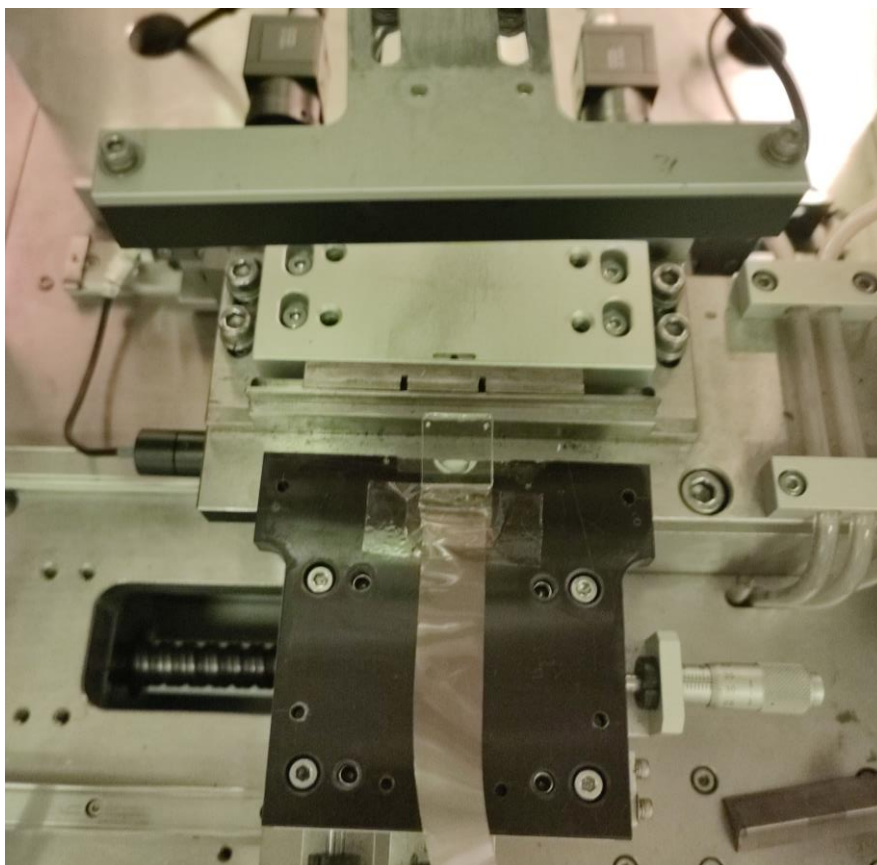


Figure A.9: Finished device after the connector attachment process.