Diffractive and Refractive Liquid Crystal Devices based on Multilayer Matrices

Eva Otón, Przemysław Morawiak, Rafał Mazur, Xabier Quintana, Morten A. Geday, José M. Otón,
and Wiktor Piecek

Abstract—Tunable photonic devices based on self-organized materials like liquid crystals are opening new alternatives for photonic applications, especially when several optical functions can be implemented into one device. Beam steering devices based on liquid crystals usually work either as digital beam steerers (phase gratings), or as analog steerers (prisms). Digital steerers move laser beams to fixed positions, however they cannot be tuned continuously. Analog beam steerers produce a continuous angular deviation of laser beams but with very limited deviation angles. In this work we developed a tunable grating-prism, that can work as a prism and as a phase grating at the same time. This combination of refractive and diffractive effects is achieved with multilayer ITO electrode matrices in a liquid crystal device. This solution is completely different from previous approaches, like blaze gratings or Fresnel configurations - the tunability range here is completely continuous, or completely stepped, or a combination of both at the same time - as there are no interpixels or dead areas in the multilayer configuration. The proposed grating-prism is able to deviate a light beam to a large fixed angle by diffraction, and then fine-tune the beam over small angle ranges by refraction. Additionally, the light losses produced by ITO diffraction in conventional liquid crystal gratings are significantly reduced using the multilayer configuration.

Index Terms—Beam Steering, Diffraction Gratings, Liquid Crystals, Liquid Crystal Devices, Prisms, Photonic Devices,

I. INTRODUCTION

LIGHT manipulating devices like tunable photonic devices based on self-organized materials like liquid crystals (LCs) are lately becoming novel unique alternatives for applications in many technological fields. Manufacturing of LC based devices is relatively simple in relation to solutions using other materials. A large number of optical functions can be implemented [1,2] in a single LC-based device. Among them, beam steerers, phase gratings, lenses, optical switches and waveguides [3-6] are of the highest interest.

This work was carried out under POLONEZ programme - National Science Center, Poland - Agreement No. UMO-2016/23/P/ST7/04261 - which has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 665778.

E. Otón, P. Morawiak, R. Mazur and W. Piecek are with the Institute of Applied Physics, Military University of Technology, W. Urbanowicza 2, 00-908 Warsaw, Poland (e-mail: eva.oton@wat.edu.pl).

X. Quintana, M.A. Geday and J.M. Otón are with CEMDATIC, ETSI Telecomunicación, Universidad Politécnica de Madrid, Av. Complutense 30, 28040 Madrid, Spain

Beam steering devices can be roughly split into two categories: analog and digital devices. Analog beam steerers, allow continuous angular variations of the beam propagation direction being deviated by an external driver [7,8] for instance a voltage. Digital beam steerers, on the contrary, switch the light beam between two or more noncontiguous fixed positions [9].

Both, analog and digital beam steerers can be implemented as LC-filled cells. The work principle of the simplest analog beam steerers is equivalent to that of prism refraction: an electric field with a gradient across the device results in a graded reorientation LC molecular director, hence an effective gradient of the effective refractive index observed across the cell. Such medium bends the wave vector of an incident beam towards the region with higher effective refractive index. On the other hand an LC-based digital beam steerer can be implemented e.g. as a phase grating. Phase gratings are diffractive elements, able to generate applied voltage dependent beam deflections to fixed positions.

Majority of LC-based beam steerers proposed in the literature are designed to operate in either digital mode or in analog mode, i.e., as a grating or as a prism-like structure [10-12]. Beam deflections produced by phase gratings are ultimately determined by the electrode spacing of the cell grating. This results in fixed positions of the deviated beam that cannot be tuned continuously. Contrarily, analog beam steerers can fine-tune light beams in a continuous way. The beam deviation is proportional to the LC birefringence and the cell thickness. This effectively results in limitations of analog devices, since the birefringence is limited and thickness can be increased to a certain value only before producing significant losses and rising the LC switching time to unpractical levels. As a consequence, the total deviation angle in analog beam steerers is very limited [12]. The usefulness of LC-based beam steerers could certainly be fostered if a wide range analog control could be achieved.

In this work, we developed a device that can work both as a prism and as a phase grating (i.e., analog and digital beam steering) at the same time. This combination of refraction and diffraction is achieved by using a configuration of multilayer electrodes structure manufactured in stacked ITO layers. Such combined grating-prism structure is able to deviate a driven beam to a relatively large, fixed angle by diffraction, and then, by the driven refraction, the fine-tune the beam over small angle ranges.

In optics, a combination “grating + prism”—called a “*grism*”—

is used as an optical element to correct the angular dispersion produced by a grating [13]. Whereas a transmission grating diffracts the light differently depending on the wavelength, the prism attached to the grating completely cancels the chromatic coma, making the light to be split into different wavelengths without changing its overall direction. Grisms are extremely useful in certain applications, for example in astronomy [14], because they allow a camera to be transformed into a spectrograph just by inserting the element in the optical path. The grism, however, is a static optical element where the groove density and the apex angle of the prism are being selected in advance depending on the particular application working at a chosen wavelength. The device proposed here may be used as a tunable grism, for chromatic correction in different scenarios [15].

LC-based devices are especially promising for space technologies where they can be applied in units of pointing and tracking systems as well as for secure inter-satellite or satellite-earth communication systems working at variable wavelengths.

LC-based devices are notoriously designed for avoiding use of mechanical/movable elements. This brings a reduced size and weight and increases significantly the reliability of devices. Moreover, LC-based elements can be controlled at low voltages, decreasing energy consumption and avoiding the use of heat dissipation systems [16].

The unique characteristics of the proposed device may gain interests in LC-based working active optical elements for a broad range of technological fields where light beam signals needs to be carefully handled and tuned. Additionally, the proposed LC-based multilayer device can be used where a chromatic correction in optical and photography systems to correct the rainbow effect.

II. DESIGN AND IMPLEMENTATION OF MULTILAYER ELECTRODE MATRICES ON LC DEVICE

The idea of combining a digital and an analog beam steering comes from the working principles of both devices; the analog beam steerer is formally equivalent to a prism which can be generated as tuned graded index profile, whereas the digital beam steerer device is based on a diffraction grating that can only produce beam deviations on fixed, reasonably large angles. Combining these two modes in the same device results in a versatile beam steerer, where the steering angle can be set off to a large angle and then fine-tuned over a smaller angle range, all together providing analog-like beam deviation over an extended angle domain.

An analog deviation of light beams can be obtained with a structure exhibiting a specially distributed effective refractive index gradient. In a LC device this is achieved when a voltage gradient, applied across an electrode matrix, makes the LCs molecular director to progressively deviate. This obviously results in induction of the effective (for a defined state of polarization of incident light) refractive index gradient (RIG) preferably over the whole device diameter (Fig. 1b). From the optical point of view for the flat wavefront of the incident beam the flat-parallel plate (i.e. LC filled cell of cell gap d) with RIG is equivalent to a prism. A spatially distributed effective optical

thickness $d_{opt}(x)$ of the device $d_{opt}(x) = n_{eff}(x) \cdot d$ can be modified by varying of the applied voltage $U(x)$ distributed along the device. An incoming wavefront experiences a spatial distribution of refractive indices $n_{eff}(x)$ and the wavefront bends by an angle α towards the region with higher index thus the beam is progressively deflected. Increasing maximum and decreasing minimum applied voltage values will broaden the gradient, resulting in larger deviation angles. In practice, the continuity of the beam movement ultimately depends on the applied voltage steps, which should be as small as the electronics and electrode patterning allow. In LC-based beam steerers limitations come among others also from the LC birefringence [17-19] since the maximum gradient of $n_{eff}(x)$ along the device diameter is $\Delta n = n_e - n_o$. This reduces the steering angular range to fairly modest angles, about 1° in regular configurations of the analog LC-based devices.

A digital beam steering can be obtained using a diffraction grating like structure. In a LC device, a matrix of high density interlaced transparent ITO electrodes can produce such grating. By applying increasingly higher voltages on each electrode, the liquid crystal switches on in a stepped orientation profile, i.e. a staircase refractive index profile is obtained (Fig. 1c). The obtained profile is equivalent to a diffraction grating: the grating periodicity can be modified by changing the applied voltage steps. Depending on the driving scheme, these angles can be modified at wish, the widest angle being determined by the electrode resolution and the light wavelength. The grating can be shaped at will in different number of steps. Every group of steps can be driven independently, inducing a total 2π phase delay, so that the following group effectively acts as a piling-up delay, like is observed for well-known Fresnel structure. As the number of grating steps increases, the diffraction efficiency of the first order increases substantially although the deviation angle decreases [20].

In a practical application, a combined LC grating-prism should be able to display both refraction and diffraction effects simultaneously (Fig. 2, top) since the driving voltage distribution can be combined with both schemes. An essential requirement for this device would be to induce a graded refractive index profile in the LC, while at the same time, to switch selectively part of the electrodes in order to induce a diffraction grating. These two features, however, are not compatible in a traditional single layer electrode matrix like those based on indium tin oxide (ITO) coatings in LC displays.

The multilayer electrode matrix proposed in this work allows using combined voltage signals. Figure 2 (bottom left) depicts the proposed design of the matrices. The multilayer matrix is made of a first set of electrodes, an isolating layer and a second set of electrodes developed onto the same substrate. The first ITO electrode matrix is produced by photolithography on an ITO-coated glass substrate. A set of parallel electrodes is created, their width being the same as the interpixel gaps. An isolating layer, required to separate both electrode matrices, is at that point evaporated onto the first set of electrodes. Eventually a second ITO layer is deposited on the isolating layer, and a second photolithographic process is performed on this second ITO layer. The second photolithography creates

another set of electrodes over the gaps of the first set, resulting in two identical electrode sets seamlessly interlaced to each other. Finally the substrate is assembled into a glass cell, filled with an appropriate liquid crystal mixture and wired. The detailed manufacturing protocol is described in the part of this paper entitled Methods.

A collateral advantage of this structure is that it reduces significantly the typical light losses caused by the diffraction of ITO electrodes. Indeed, both pixels and interpixels are the same size, both electrode matrices overlap, there are virtually no interpixels or dead areas.

III. RESULTS

The manufactured LC devices were characterized when working either as a pure grating or as a pure prism, and, finally, as a combined grating-prism.

A. Liquid crystal grating-prism working as a pure grating

The LC grating-prism can work as a pure diffraction grating by addressing one electrode matrix only. Since pixels and interpixels of each matrix have the same size ($7\mu\text{m} + 7\mu\text{m}$), a simple diffraction grating can be obtained addressing the whole electrode matrix with the same applied voltage. A binary grating is obtained, the generated diffraction pattern reaching the maximum deflection angle for a blaze grating. Figure 3a shows a micrograph of the liquid crystal switching profile for a binary grating, as seen between crossed polarizers. The stripe width is $7\mu\text{m}$.

Addressing the device in pure grating mode, the transmission levels for 0th, 1st and 2nd orders were measured, using the same methods as described in a more detailed study performed in a previous work [21]. Transmission levels vary when increasing voltage to saturation one. 0th order decreases to its minimum while 1st order increases to its maximum. 2nd order remains approximately constant over the whole voltage range. The optimum working voltage can be determined from transmission levels when the 1st order reaches its maximum transmission. The average optimal working voltage for the maximum 1st order efficiency with maximum deflection angle for binary grating was set to $V_d = 3.5 \pm 0.2\text{V}$.

In some cases, the 1st order transmission levels did not decrease when applying voltages higher than the optimal voltage, V_d . This is probably caused by a fringing effect; most likely, a fraction of the liquid crystal located on non-switched electrodes is partially switched on, as it is affected by the surrounding applied electric field. For this reason, the second electrode matrix was ground connected ($V = V_g$), avoiding fringing and induced charges as well (Fig. 3b).

Fig. 3c shows the reconstruction of the spatial power distribution of the measured wavefront profile in 3D, when the cell is working at the optimal voltage: 0th order power decreases and the beam power is deflected to the 1st order; the relative intensities show the efficiency of the diffraction grating. The generated diffraction pattern is shown in Fig. 3d, although the light intensities in the photo are misleading since the detector was oversaturated. Note that higher diffraction orders (2nd and 3rd in the Figure) are also present. The cell thickness was set by

taking into account that the device needs to work both as a grating and as a prism. For a phase grating, the 1st order reaches its maximum transmission, when phase delay equals π , so that the 1st order shows and the 0th order vanishes. This occurs for a relatively small cell gap of $d \approx 2\mu\text{m}$ which is too thin to produce reasonably large steering angles when the device is working as a prism. However, increasing thickness induces scattering losses from the liquid crystal, as well as other diffraction effects when thickness becomes larger than the grating pitch. As a result, the cell thickness was set to $14\mu\text{m}$, as a trade-off between the grating and the prism working modes.

B. Liquid crystal grating-prism working as a pure prism

When applying a voltage gradient ΔV_a to the device placed between crossed polarizers, an interference pattern becomes visible. The interference pattern fringes correspond to consecutive delays of $\pi, 2\pi, 3\pi \dots$ (each fringe shows one color) and can be modulated by modifying the working voltage range. The applied voltage gradient is set within the limits of threshold voltage and saturation voltage, where the actual reorientation of the liquid crystal indicatrix occurs. Also, when possible, the device working range is set in a voltage zone where the refractive index variation is approximately linear. The active area of the devices is 0.7cm^2 . For higher applied voltage gradients, the interference fringes become too close to each other, so that interference patterns could not be observed with the naked eye: the voltage range tests were then performed under a polarizing microscope. The beam deflections were measured with laser sources of 3 wavelengths ($R = 640\text{nm}$, $G = 532\text{nm}$, $B = 453\text{nm}$).

Upon increasing the voltage gradient, the number of interference fringes increases. The fringes become thinner and closer to each other (Fig. 4a). The closer the fringes are, the steeper the birefringence gradient is, and consequently the wider the steered angle becomes. Figure 4b shows the spatial distribution of voltage gradients in the cell.

The spot deflection follows an approximately linear trend when increasing the voltage gradient, as shown in Figure 4c. Both the device and the target were placed sufficiently far apart, so that angle variations become small enough to be equivalent to spot position shifts. Maximum beam deviations were found for shorter wavelengths, since the device optical function is a refractive element: $\theta_a = \pm 0.29^\circ$ (@640nm), $\theta_a = \pm 0.35^\circ$ (@532nm), and $\theta_a = \pm 0.40^\circ$ (@453nm).

Figure 4d shows photographs of a 453nm laser spot upon increasing the applied voltage gradient. Figure 4e is the spatial power distribution of the measured wavefront profile reconstructed in 3D for the three laser sources mentioned above: without applied voltage (OFF), and then the maximum deflection that was achieved when using red, green and blue laser sources respectively. At the maximum applied voltages, the spot shows a sequence of small spots next to the main one. These spots are attributed to small parasitic interference fringes that become too close together upon voltage increasing, affecting the beam wavefront. The effect is not as pronounced as Figure 4d might suggest, as the camera detector was oversaturated. The measured relative intensities were found to

be 7-8% at most with respect of the main spot. The light sensor that was used in the measurements of wavefront deviation was less sensitive for shorter wavelengths. For that reason the reconstructed wavefront profiles measured with the blue laser source tended to show noisier profiles.

C. Liquid crystal grating-prism combined: diffraction + refraction

The combined LC grating-prism is able to generate both optical functions, refraction and diffraction. The proposed multilayer electrode matrix allows using combined voltage signals which are, in fact, applied to different layers. A V_g voltage is applied to one electrode matrix that generates the binary grating producing the diffraction pattern. Meanwhile, a voltage gradient ΔV_a is applied to the second electrode matrix to generate the prism profile. The first matrix is then addressed with a slightly different voltage gradient, that maintains the binary grating, and at the same time, generates a new graded profile, overall producing the grating-prism refractive index profile, (Fig. 5a). Macroscopically, the active area shows a strongly colored interference pattern like the pure prism optical function, as shown in Fig. 5b (top). The fringes are too close to each other to be seen by the naked eye. A closer inspection, using a polarizing microscope, confirms the presence of a binary grating. Figure 5b, (bottom), shows that the electrodes are being switched alternatively. The micrograph shows the binary grating generated in the electrodes (white thin stripes), while the general color change (wide bands) corresponds to two different interference fringes.

While the grating function, V_g , is kept fixed, the prism function ΔV_a is modulated to fine-tune the grating. Figure 5c shows the measurements taken on the 1st diffraction order and Figure 5d is the 3D spatial power distribution of the wavefront. The deflected angle produced by the grating alone was 1.80° (@453nm), while the refractive fine-tuning of the 1st order reached a maximum additional angle of $\pm 0.27^\circ$. Indeed, the fine-tuning works in both directions: depending on the direction the voltage gradient is applied, the spot can be tuned closer or farther away from off-state position. In total the 1st order of diffraction can be fine-tuned over a range of 0.54° .

As in the previous case, some small spots showed up next to the 1st order of diffraction at the highest applied voltage. However, light losses –4% in total– were lower than for the pure prism working mode.

D. Reduction of light losses due to the ITO diffractive electrodes

The multilayer matrix configuration offers an additional advantage. Thin matrices of electrodes are responsible for light losses solely produced by diffraction caused in the ITO pixel/glass interpixel gap. When both pixels and interpixels are the same size, the two electrode matrices can overlap with each other completely, and the active area virtually becomes a solid ITO pixel with no interpixels or dead areas. As a result, the characteristic light losses that the ITO electrode matrix produces by diffraction are avoided.

A number of devices were prepared with the same features

as the multilayer devices, but having only one set of electrodes, which essentially produces a diffraction grating. Light losses were measured in both monolayer and multilayer devices when working as diffraction gratings and in off-state as well: electrodes were addressed from one side only in multilayer electrodes to produce the same binary grating as the one resulting in monolayer devices. Light output efficiency was measured in all devices as the average of the power measured in both 0th and 1st orders (Figure 6). Light losses were reduced for the multilayer devices, an average of 14-16% in off-state, and 17-18% in on-state at the optimal working voltage for a binary grating.

IV. DISCUSSION

The idea behind our device makes it a multipurpose beam steerer that is capable of manipulating light beams in different modes. However, the combination of both diffraction and refraction effects simultaneously makes the proposed device different. The working principle offers advantages, as the light power can be selectively deflected to fixed positions and then adjusted by fine-tuning for applications needing precise beam handling and control. Moreover, not only the device offers new functionalities for communication systems, but it could also become a full-range steerer, where the 1st diffraction order can be fine-tuned to the point of “jumping” to the next order. This function can be achieved by increasing the maximum deviation angle and the range (fine-tuning) the device can reach so, in fact, both diffractive and refractive beam steerer types would be enhanced by increasing the maximum deviation angle.

Increasing maximum deviation angles is possible by increasing the phase delay or reducing the pixel size. However, as mentioned above, increasing the phase delay by increasing the devices thickness would introduce light losses from the liquid crystal – and would increase the switching times and the birefringence of liquid crystals mixtures can be only increased to a certain limit, too. By reducing the pixel size, which is usually a limiting factor in traditional photolithography, the diffraction efficiency is reduced, because a fixed space (interpixel) must be kept between every two pixels, ultimately resulting in an inactive or dead area. In the proposed multilayer matrices the interpixel area is not needed, since adjacent pixels can be placed in two independent layers, thus pixel size could be further reduced, reaching up to twice the resolution of current devices. Moreover, by reducing the active area size as well, the voltage gradient used for generating the prism function would become steeper, and thus the refractive index variation – and therefore the beam deflection– would increase.

An upgrade to the proposed design would be including a second set of electrode matrices in the opposite substrate. Further photolithographic processes would be needed, and this time the electrodes would be placed perpendicular to the first set to obtain a grating-prism that can move light beams in 2D.

Some applications could greatly benefit from the proposed optical functions. In particular, in spectroscopy, gratings are widely employed, but most spectrometers work using reflection gratings; just in recent years transmission gratings have experienced some developments [13]. A transmission grating

coupled with a prism–direct-vision grism– implemented in a spectrometer becomes a simple spectral separation element [22]. Yet, most grisms solutions are fixed to provide an in-line viewing for a single wavelength. Our device offers the possibility of tuning the optical function to the desired wavelengths for the user, depending on the object of interest. For instance, it can be used to resolve the spectral lines of many astronomical objects without affecting the optics of the telescope [23].

Indeed, as longer wavelengths are more diffracted but less refracted and vice versa, the grating-prism could be driven in a kind of inverse mode. By coupling diffraction and refraction functions, the device could be also optimized to correct the rainbow effect in the whole deflection angle range to be implemented as a pure white light beam steerer.

V. METHODS

A. Device manufacturing

The proposed multilayer device was manufactured using high resolution photolithography and sputtering techniques for achieving the multilayer structures. The device is made up of two ITO coated ultraflat glass substrates assembled in a sandwich-like cell and filled with liquid crystal. One substrate contains the multilayered high-density electrode matrix, the other substrate is a solid ITO backplane.

The generation of the electrode pattern of such an elevated number of electrodes required the elaboration of a specific LabView based program, capable of generating a script for AutoCAD depicting each individual electrode. The pitch of the electrodes in the active area is $14\mu\text{m}$ with a symmetric pixel width and interpixel gap of $7\mu\text{m}$ each. At the two “fanouts” the 248 electrodes were joined into one continuous electrode spanning $3\times 30\text{mm}$ (Fig. 7a). The proposed multilayer design uses two sets of electrodes, which makes a total of 496 electrodes for the active area. The design of the electrode matrix was prepared in a chrome coated glass substrate for the photolithographic mask.

An important feature of the electrode design is that the voltage gradient, caused by a coupling of the current and the ITO resistivity, is generated outside the active area, thus preventing ohmic heating of the liquid crystal.

Obtaining such high-resolution matrices superimposed on a single substrate proved to be a fairly delicate process, that ultimately required an optimization of the fine resolution photolithographic process.

The photolithographic process was modified from the previously reported fine resolution protocol [24] in the following steps: the photolithographic process was performed on ITO coated glass substrates using photoresist S-1805G2 (Microresist). Developing was performed using a 0.4% solution of NaOH for 15 seconds, and for the etching process the substrates were immersed in an in-house prepared acidic mixture for 1 minute. Both first and second ITO layers were prepared using this high resolution photolithographic protocol.

After the first high resolution photolithographic process was performed obtaining the first electrode matrix, a vacuum

chamber was used for the evaporation of SiO_2 and ITO layers. The chamber was equipped with: Telemark 264 electron gun/quartz crystal microbalance (QCM) for evaporation rate control and layer thickness, a heating system for regulating the temperature of substrates, gases dosing system for oxygen pressure application and especially designed masks for shaping of the layers. A 300 nm thick SiO_2 layer was employed as isolating layer to separate the two ITO matrices. The evaporation process was carried out under 5×10^{-5} mbar oxygen pressure at 200°C substrate temperature. In these processes, special masks for layers shaping were used to provide access to the electrodes. Subsequently, a second ITO transparent layer with thickness of 25nm was deposited onto the SiO_2 layer. The ITO deposition process was carried out at 250°C substrate temperature, under oxygen pressure (7×10^{-5} mbar).

Then the second photolithographic process was performed on the top ITO layer. The most delicate step of the entire manufacturing process is the alignment of the mask for the second electrode matrix with respect to the first one. Both matrices need to be perfectly aligned, within a nanometer precision, in order to ensure good optical performance without any unwanted secondary diffraction effects or additional light losses. Figure 7b shows the precise alignment process between the electrode mask and the first set of electrodes underneath. The mask aligner system used for second photolithography is from Midas System (MDA400).

Once the second electrode matrix was obtained, alignment layers were deposited onto the substrates to induce homogeneous alignment (i.e., parallel to the substrates) on the liquid crystal molecules. Next, the substrates were assembled into cells, using $14\mu\text{m}$ spherical spacers, filled with a nematic liquid crystal mixture with a relatively high birefringence (MDA-98 – $\Delta n=0.266$), and sealed with NOA-81 adhesive (Norland Optical Adhesive) to conform the final device.

B. Device characterization

The optical set-up used to measure the grating-prisms devices consisted of: 3 wavelength laser source with maximum output peak of 2mW and output wavelengths: R= 640nm, G= 532nm, B= 453nm, a scanning slit optical beam profiler (BP104-VIS, 400-1100nm, $\varnothing 10\mu\text{m}$ – $\varnothing 4\text{mm}$ Beam ThorLabs). The beam profiler analyzes the beam quality and the spatial power distribution, of both X and Y beam profiles. Additionally, a 1/2.5” CMOS sensor with $2.2\mu\text{m}\times 2.2\mu\text{m}$ pixel size was used to capture the deflecting output light and by means of a software reconstruct the spatial power distribution of the wavefront in 3D.

REFERENCES

- [1] Z. He, Y.-H. Lee, F. Gou, D. Franklin, D. Chanda, S.-T. Wu, "Polarization-independent phase modulators enabled by two-photon polymerization," *Opt. Express*, vol. 25, no 26, pp. 33688-33694, 2017, 10.1364/OE.25.033688.
- [2] N. Hasan, A. Banerjee, H. Kim, C.H. Mastrangelo, "Tunable-focus lens for adaptive eyeglasses," *Opt. Express*, vol. 25, no 2, pp. 1221-1233, 2017, 10.1364/OE.25.001221.
- [3] E. Otón, E. Netter, T. Nakano, Y.D. Katayama, F. Inoue, "Monodomain blue phase liquid crystal layers for phase modulation," *Sci. Rep.* vol. 7, 44575, 2017, 10.1038/srep44575.
- [4] J.M. Oton, E. Oton, X. Quintana, M.A. Geday, "Liquid crystal phase-only devices," *J. Mol. Liq.*, vol 267, pp. 469-483, 2018, 10.1016/j.molliq.2017.10.148.
- [5] J.F. Algorri, N. Bennis, V. Urruchi, P. Morawiak, J.M. Sánchez-Pena, L.R. Jaroszewicz, "Tunable liquid crystal multifocal microlens array," *Sci. Rep.* vol. 7, 17318, 2017, 10.1038/s41598-017-17688-1
- [6] J. Albero, P. García-Martínez, N. Bennis, E. Otón, B. Cerrolaza, I. Moreno, "Liquid crystal devices for the reconfigurable generation of optical vortices," *J. Lightwave Technol.*, vol. 30, no 18, pp. 3055-3060, 2012, 10.1109/JLT.2012.2211567.
- [7] X. Wang, X. Huang, Z. Huang, L. Wu, J. Shang, Q. Qiu, S. Wu, "Nonmechanical infrared beam steering using blue addressed quantum dot doped liquid crystal grating," *Nanoscale Res. Lett.*, vol. 12, no 1, pp. 36-39, 2017, 10.1186/s11671-016-1816-8.
- [8] E. Oton, A. Carrasco-Casado, R. Vergaz-Benito, J.M. Oton, J.M. Sanchez-Pena, X. Quintana, M.A. Geday, "2D tunable beam steering - Lens device based on high birefringence liquid crystals," in *Proc. ICSOS*, Santa Monica, CA, USA, 2011, 10.1109/ICSOS.2011.5783671
- [9] H. Chen, G. Tan, Y. Huang, Y. Weng, T.-H. Choi, T.-H. Yoon, S.-T. Wu, "A low voltage liquid crystal phase grating with switchable diffraction angles," *Sci. Rep.*, vol. 7, 39923, 2017, 10.1038/srep39923.
- [10] X. Shang, J.-Yi Tan, O. Willekens, et al. "Electrically controllable liquid crystal component for efficient light steering," *IEEE Photon. J.*, vol. 7, no 2, 2015, 10.1109/JPHOT.2015.2402592.
- [11] J. Yan, Y. Li, S. T. Wu, "High-efficiency and fast-response tunable phase grating using a blue phase liquid crystal," *Opt. Lett.*, vol. 36, no 8, pp. 1404-1406, 2011, 10.1364/OL.36.001404.
- [12] E. Otón, W. Piecek, P. Morawiak, L.R. Jaroszewicz, Z. Raszewski, R. Dabrowski, R. Mazur, "Analog, polarization insensitive, tunable beam steering device based on short pitch cholesteric liquid crystals," at the *4th Workshop on Liquid Crystals for Photonics*, Hong Kong, 2012.
- [13] D.J. Schroeder, *Astronomical Optics*, 2nd ed., New York, USA: Academic Press Inc., 1987, pp. 402-405.
- [14] D.A. Ludovici and R.L. Mutel, "A compact grism spectrometer for small optical telescopes," *Am. J. Phys.*, vol. 85, no 11, pp. 873-879, 2017, 10.1119/1.5000801.
- [15] Y. Feng, P.A. Dalgarno, D. Lee, Y. Yang, R.R. Thomson, A.H. Greenaway, "Chromatically-corrected, high-efficiency, multi-colour, multi-plane 3D imaging," *Opt. Express*, vol. 20, no 18, pp. 20705-20714, 2012, 10.1364/OE.20.020705.
- [16] E. Hällstig, J. Stigwall, M. Lindgren, L. Sjöqvist, "Laser beam steering and tracking using a liquid crystal spatial light modulator," *Proc. SPIE*, vol. 5087, pp. 13-23, 2003, 10.1117/12.486892.
- [17] Z. Raszewski, W. Piecek, L. Jaroszewicz, E. Nowinowski-Kruszelnicki, P. Perkowski, L. Soms, R. Dabrowski, J. Kedzierski, M. Olifierczuk, M. Mrukiewicz, E. Miszczyk, P. Morawiak, R. Mazur, K. Kowiorski, "High birefringence liquid crystals mixtures and their selected applications," *Adv. Mat. Res.*, vol. 909, pp. 12-18, 2014, 10.4028/www.scientific.net/AMR.909.12.
- [18] R. Dąbrowski, P. Kula, J. Herman, "High birefringence liquid crystals," *Crystals*, vol. 3, no 3, pp. 443-482, 2013.
- [19] D. Węglowska, P. Kula, J. Herman, "High birefringence bistolane liquid crystals: synthesis and properties," *RSC Adv.*, vol. 6, no 1, pp. 403-408, 2016, 10.3390/cryst3030443.
- [20] N. Bennis, M. A. Geday, X. Quintana, B. Cerrolaza, D.P. Medialdea, A. Spadlo, R. Dąbrowski, J.M. Otón, "Nearly-analogue blazed phase grating using high birefringence liquid crystal," *Opto-Electron. Rev.*, vol. 17, no 2, pp. 112-115, 2009, 10.1364/OE.18.017498.
- [21] E. Oton, D. Poudereux, X. Quintana, J.M. Oton, M.A. Geday, "Design, manufacturing and characterisation of a liquid crystal based blaze grating for space applications," in *Proc. OPTOEL*, Santander, Spain 2011.
- [22] Q. Yang, W. Wang, "Compact orthogonal-dispersion device using a prism and a transmission grating" *J. Eur. Opt. Soc. Rapid. Publ.* vol.14, no8, 2018, 10.1186/s41476-018-0077-9
- [23] P. A. Oesch, G. Brammer, P. G. van Dokkum, et al., "A remarkably luminous galaxy at Z=11.1 measured with Hubble Space Telescope Grism Spectroscopy," *Astrophys. J.*, vol. 819, no 2, pp. 129-140, 2016, 10.3847/0004-637X/819/2/129.
- [24] E. Oton, "Adaptive Liquid-Crystal Phase-Only Passive Devices," Ph.D. dissertation, CEMDATIC, Technical University of Madrid, Spain, 2013.

Fig. 1 – (a) Basic scheme of a LC beam steerer set-up. (b) Analog beam steerer scheme: a voltage gradient is applied across the electrode area producing a refractive index gradient, hence an upcoming wavefront bends towards higher refractive indices. (c) Digital LC beam steerer design: different voltages are applied to the electrodes to produce a periodical profile; a diffraction pattern is obtained

Fig. 2 – (Top) Scheme showing the LC refractive index $n_{eff}(x)$ distribution across the device simulated in a grating and in a prism. The combination of both creates a grating-prism where a laser beam can be deflected to a large angle and then fine-tuned (bottom right). (Bottom left) Design of the multilayer matrix: the two electrode matrices are isolated from each other; therefore they can be independently driven.

Fig. 3 – (a) Micrograph of the active area when the LC switching profile exhibits a binary grating. (b) Scheme of the signals applied to the device for generating a binary grating. (c) 3D spatial power distribution of the measured wavefront profile: without applied voltage ($V = 0V$), all the light power is in the 0^{th} order (left);

when applying a voltage ($V=V_d$), part of the light power is transferred to the 1st order (right), (d) photographs of the diffraction pattern produced by the LC binary grating, with $V=0V$ (top) and $V=V_d$ (bottom).

Fig. 4 – (a) Pictures of active area while applying a voltage gradient: an interference pattern shows up, its fringes becoming closer to each other as the voltage increases. (b) Spatial distribution of voltage gradients for generating a prism function. (c) Beam deviation for increasing voltage gradients; the laser spot follows an approximately linear trend. (d) Pictures of beam steering for increasing voltage gradients (@453nm). (e) 3D Spatial power distribution of the measured wavefront profiles: without voltage (OFF), and maximum deflection achieved for red, green and blue laser sources (R= 640nm, G= 532nm, B= 453nm).

Fig. 5 – (a) Scheme of voltage signals applied to the device for generating a combined grating-prism function, (b) Pictures of the active area when the combined voltage signals are applied: an interference pattern shows up (top), upon closer inspection the grating function can be seen in the micrograph (bottom); the change in color corresponds to two different interference fringes. (c) Measurements of beam deviations in the 1st diffraction order, upon increasing the applied voltage gradient (prism function) for fine tuning, and (d) 3D spatial power distribution of the measured 1st order upon increasing the voltage gradient.

Fig. 6 – Output light power measured for both monolayer and multilayer electrode devices: light efficiency significantly improves for multilayer devices.

Fig. 7 – (a) High resolution electrode matrix design. The inset shows a close-up of the electrodes. (b) Precision alignment of the electrode mask for the second photolithography (bright stripes) with the first electrode matrix underneath (grey stripes).