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Switchable circular beam deflectors

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Abstract

In this work, we report two types of electrically tunable photonic devices with circularly symmetric polarization independent beam steering performance (beam condensing resp. beam broadening). The devices consist of circular micro grating structures combined with nematic liquid crystal (LC) layers with anti-parallel alignment. A single beam deflector converts a polarized and monochromatic green laser beam (\(\lambda = 543.5\) nm) into a diffraction pattern, with the peak intensity appearing at the third order when \(0 V_\text{pp}\) is applied and at the zeroth order (no deflection) for voltages above \(30 V_\text{pp}\). Depending on the shape of the grating structure (non-inverted or inverted), the deflection is inwards or outwards. Both grating types can be made starting from the same diamond-tooled master mold. A polarized white light beam is symmetrically condensed resp. broadened over \(2^\circ\) in the off state and is passed through unchanged in the on state. By stacking two such devices with mutually orthogonal LC alignment layers, polarization independent switchable circular beam deflectors are realized with a high transmittance (>80%), and with the same beam steering performance as the polarization dependent single devices.

Keywords: beam deflection, liquid crystal, polymer micro structure, soft lithography

(Some figures may appear in colour only in the online journal)

1. Introduction

In recent years, liquid crystal (LC) photonic and optical components with various functionalities, ranging from switchable phase modulators to LC filters, waveguides and beam deflection devices, have attracted a lot of interest due to the large tunable birefringence, low operational voltage, compact volume and good processing compatibility with the current dominant LC display technologies [1–4]. Among those applications, LC beam steering components especially have drawn a lot of attention from both academia and industry, mainly because several novel and innovative applications, such as tunable LC lenticular micro-lenses for autostereoscopic displays, intelligent contact-lenses and glasses, and LC beam intensity distributors for smart luminaires etc, have sprung up in newly emerging markets [5–7]. LC beam steering devices based on gradient refractive index profiles, which are generated by applying different voltages on different strip electrodes, can steer the incident light beam to some extent, but most of them have drawbacks like the serious dispersion and the low deflection efficiency, as well as quite complex driving circuits and interfaces [8–10]. Another kind of LC beam steering technology includes LC devices fabricated by polymerization of photo-curable monomers mixed with LCs and formation of polymer networks with specific patterns by applying gradient electric fields. The issue is that these polymer network patterns are difficult to be accurately defined, which leads to degraded optical performance. Moreover, the sophisticated device processing and high operating voltages further limit their applications [11–13]. The devices based on liquid crystal and linear gratings with size in the range of several microns, show good diffractive beam steering property [14], the possible issue is whether the anchoring effect of only one alignment layer applied on the flat substrate with another bare grating substrate is still valid or strong for larger size micro structures. The structural changes between the planar texture

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or the homeotropic state and the well-oriented and periodic fingerprint texture in cholesteric LCs have supplied other alternative way to implement effective beam steering, and the steering angle mainly relies on the periodicity of uniform fingerprint stripes and the probing wavelength [15, 16].

To manipulate the light beam deflection in a circular way, electrically controllable LC lenses are the most common schemes to realize the focusing and defocusing of the incident light beam. These LC lenses are based on either the aforementioned gradient refractive index effect [17–19] or the alternatively aligned binary LC orientations by the techniques of the photoalignment or other hybrid alignments [20–22]. In this work, we make use of circular micro-gratings (CMGs) with non-reversed and reversed structures which are respectively fabricated by two different soft lithography processes based on the same master mold, combined with nematic LCs to realize electrically switchable circular beam deflectors with beam condensing and beam broadening properties. The LC devices combined with the non-reversed and reversed CMGs can effectively steer the incident light beam inward and outward within a two dimensional plane. The predominant advantage for adopting the CMG structures is that the interface between the CMGs and the LCs is well defined, which is beneficial to achieve the designed optical performance. Furthermore the device processing and the driving connection are relatively simple compared to the aforementioned technical solutions. The two kinds of LC beam deflectors with beam condensing and beam broadening performance are suitable for novel active lighting components, micro-projection displays and innovative photonic beam deflection devices.

2. Experimental

The fabrication of the CMG structures on indium tin oxide (ITO) coated glass substrates is a prerequisite for the buildup of the active LC beam deflector. In this study, soft embossing with polydimethylsiloxane (PDMS) molds and ultra violet (UV) curable resins is employed to replicate prefabricated CMGs templates into the UV resin layer on the ITO glass. The reason for adopting this technique is that it is a simple, efficient and low cost process for very fine structure fabrication. Moreover there are plenty of available choices of various UV resins for the CMG replicas. In this work, we developed two techniques to produce the non-reversed and reversed CMG structures based on the same master mold. The master CMG mold which has its steep side outward is made on a 0.5 mm thick PMMA sheet using diamond tooling equipment (Moore Nanotech 350FG). The fabrication of the non-reversed CMG UV replica is illustrated in figure 1. A liquid silicone kit (Sylgard®184, from Dow Corning), consisting of a base and a curing agent mixed in a 10 : 1 weight ratio, is first deposited on top of the master mold, and degased in a vacuum for certain time. Then the sample is baked at 70 °C for 1 h. After peeling from the PMMA master, the PDMS mold is laminated onto the glass substrates coated with UV curable resin layers (NOA74, Norland Products Inc.), followed by an UV irradiation step ($\lambda = 365$ nm, dosage $\geq 4.5$ J cm$^{-2}$) through the PDMS mold. After peeling off the PDMS mold, the optical UV CMGs are formed on the ITO glass substrates.

A technology for reversing the CMG structures with the same master mold, is developed and proposed in figure 2. The basic idea consists of adopting an UV or thermally curable polymer material, which exhibits a large elastic modulus but weak adhesion to the PMMA sheet, to get a reversed CMG structure from the master mold. Subsequently this new polymer mold will act as a new master mold for the optical CMG replication, which is analogous to the aforementioned soft embossing process. The UV curable glue NOA 68 (Norland Products Inc.) satisfies the requirements for the polymer mold well. It is employed to fabricate this reversed mold and the whole process is shown in figure 2. After dispensing the NOA 68 glue on the PMMA master, the glue layer is UV cured (15 mW cm$^{-2}$ and $\lambda = 365$ nm for 5 min) and easily peeled off without any damage due to its proper elasticity and weak adhesion to the PMMA sheet. The Sylgard®184 silicone is then deposited on the polymer mold and thermally cured in the convection oven at 50°C for 24 h, which is lower than the maximum temperature (60°C) that the polymer mold can withstand. After peeling off this PDMS mold which has the same shape as the original PMMA master, it then can be used for the replication of the reversed CMGs on glass substrates using the aforementioned soft embossing process.

The dimensional profiles of both the CMG NOA74 replicas and the PMMA master mold are measured by the Wyko NT3300 surface profilometer, and the results are depicted in

Figure 1. Schematic processing flow of the CMG structures by soft embossing.
figure 3. It is clearly seen that the pitch, the height and the blaze angle of the non-reversed CMG NOA74 replica made by soft embossing closely approximate those of the master grating. Meanwhile, the reversed CMG NOA74 replica made by a slightly complex reverse soft embossing also achieves a similar dimensional accuracy as the conventional soft embossing, but with a reversed CMG structure (now its steep slope is inward). The technology to fabricate the reversed CMGs not only enables to achieve the same dimensions as the master CMGs, but also avoids the costly design and fabrication of a new inverted master mold.

Since the UV cured NOA 74 CMGs cannot withstand temperatures over 90 °C, it is difficult to directly apply a polyimide alignment layer on top of these micro grating structures because usually a thermal curing above 180 °C is required [23]. Moreover, the subsequent rubbing procedure for the LC alignment layer could also damage these circular gratings, thus inducing undesired disclinations and defects in the LC texture [24]. Therefore we have used oblique SiO₂ evaporation, an alternative low temperature technique to generate LC alignment layers. During evaporation, the samples are installed on substrate holders which are oriented at 45° with respect to the incident direction of the SiO₂ beam. This way, SiO₂ layers with a thickness of about 20 nm are formed on both the CMG surface and the counter ITO glass. The two substrates are assembled with a glue gasket to form an empty cell with a gap of 19 μm, and then filled with the E7 LC (Merck) by vacuum filling. Thereby an anti-parallel LC alignment is realized within the component.

With the LC beam steering device between two crossed polarizers of a polarizing optical microscope (POM), it is observed that without applying voltages, an uniform dark field exists within the CMGs area, which indicates that there is a good LC alignment along the predefined direction (marked with a white double arrow in figures 4(a) and (c)). We also observe some bright circular lines in the POM images, which result from the perturbed LC alignment in the vicinity of the peaks and valleys of the CMGs. With a high voltage applied (100 V<sub>pp</sub>), the POM image is mainly divided into two regions.
with slightly different brightness, and a boundary line separating the LC textures is almost perpendicular to the initial LC orientation direction, which exists both in the non-reversed and the reversed CMGs (figures 4(b) and (d)). If we further increase the voltage over 100 V\textsubscript{pp}, the brightness difference of the two regions becomes smaller and smaller. These observations can be explained by the fact that the symmetric CMG structures induce symmetric but slightly non-vertical electric field distributions, resulting in two different areas with opposite tilt angles within the planes that are parallel to the initial LC alignment direction, separated by the boundary line. With a much stronger electric field, the LC molecules realign perpendicularly to the glass substrate, and the boundary line starts to diminish.

3. Result and discussion

3.1. Beam deflection with monochromatic light beam

To fully understand the light beam propagation through the LC-polymer grating, we start this section with a theoretical analysis of a monochromatic light beam traversing the complex LC-polymer grating system, followed by experimental optical characterization and verification with a green laser beam.
3.1.1. Optical analysis of circular LC-polymer grating.

A schematic diagram of the light beam propagation in the LC-polymer grating system is shown in figure 5.

The light ray whose polarization is parallel to the alignment direction experiences the LC extraordinary refractive index \(n_e\), which is larger than that of the circular polymer structure \(n_p = n_o\). Therefore, the LC layer acts as a ‘fixed’ grating with a refractive index of \(n_o\), and the polymer area behaves like a filling material with a refractive index of \(n_o\), which extends to infinity in the direction of \(x\) to temporarily neglect the refraction at other interfaces, such as the glass-air interface. The origin of the coordinate system is set at the center of any random LC grating unit and marked as \(O\), and the grating unit repeats toward the \(z\) axis with a total number of \(N\). \(H(z)\) gives the \(z\) dependent grating height and is given by:

\[
H(z) = (z - jb + \frac{b}{2})\tan \theta_B \quad (j = 0, 1, 2, \ldots (N - 1)) \tag{1}
\]

where \(j\) is the index number of the \(j\)th grating unit, \(b\) and \(h\) are respectively the grating pitch and height, \(\theta_B\) is the blaze angle, and \(\tan \theta_B = h/b\). Here, we first discuss the optical propagation through a single LC-polymer grating unit. Later we will expand on the case for multiple grating units.

Consider a plane and monochromatic light wave \((\lambda)\) incident normally on the surface \(AB\) of the \(j = 0\)th grating unit. Due to the LC grating structure, each point along \(AB\) will have a different phase delay \(\phi(z)\) when arriving at \(AD\), which can be written as:

\[
\phi(z) = k_{nc}H(z) = \frac{2\pi n_{LC}}{\lambda}(z + \frac{b}{2})\tan \theta_B \quad (-b/2 \leq z \leq +b/2). \tag{2}
\]

According to the Huygens–Fresnel principle, each point along \(AD\) acts as a secondary coherent light source and emits a circular wavelet in the \(xz\)-plane. \(AB\) is divided into \(M\) sub-sources; a finite segment \((\Delta z_k)\) then consists of \(\Delta z_k M/b\) sub-sources. The contribution to the field intensity at point \(P\) from the \(k\)th segment is accordingly

\[
E_k = \frac{\varepsilon_o}{r_k} \sin(\omega t - k_{nr}r_k - \phi_k) \left(\frac{M\Delta z_k}{b}\right) \tag{3}
\]

where \(\varepsilon_o\) is the sub-source intensity, \(\Delta z_k\) is so small that \(r_k\) and \(\phi_k\) are assumed to be constant for the sub-sources inside it. Suppose that \(AB\) is also divided into \(Q\) segments, so the net field at \(P\) from all \(Q\) segments becomes

\[
E = \sum_{k=1}^{Q} E_k = \sum_{k=1}^{Q} \frac{\varepsilon_o}{r_k} \sin(\omega t - k_{nr}r_k - \phi_k) \Delta z_k \tag{4}
\]

where \(\varepsilon_o\) is the source strength per unit length:

\[
\varepsilon_o = \frac{1}{b} \lim_{M \rightarrow \infty} (\varepsilon_o M). \tag{5}
\]

Assuming that the observation point \(P\) is very far away from these sub-sources along \(AB\) (i.e. \(R \gg h\)), \(\varepsilon_o(z)\) never deviates appreciably from the value \(R\), so that the quantity \(\varepsilon_o M/R\) remains essentially constant for every element \(\Delta z\) within the grating unit \(AB\). Equation (4) is then transformed into an integral:

\[
E = \frac{\varepsilon_o}{R} \int_{-\frac{b}{2}}^{\frac{b}{2}} \sin(\omega t - k_{nr}r - \phi) \, dz. \tag{6}
\]

However, the phase in the integral part of equation (6) is more sensitive and dependent on \(r(z)\), so that a constant approximation for the phase is not justified here. By observing the triangle DCP and applying the cosine law, we obtain

\[
r(z) = R \left[1 + \frac{1}{R^2} \left(\frac{z}{\cos \theta_B}\right)^2 - \frac{2}{R} \left(\frac{z}{\cos \theta_B}\right) \sin(\theta + \theta_B)\right]^{1/2}. \tag{7}
\]

With \(R \gg (z/\cos \theta_B)\) in our case and introducing the Taylor series expansion of a square root to the first order, an approximation of \(r(z)\) is

\[
r(z) \approx R - \frac{z}{\cos \theta_B} \sin(\theta + \theta_B). \tag{8}
\]

Substituting equations (2) and (8) into equation (6), and expanding it with some rearrangement, we get

\[
E = \frac{\varepsilon_o}{R} \int_{-\frac{b}{2}}^{\frac{b}{2}} \sin \left[\omega t - k_{nr}R - k_{nc}\frac{h}{2} + \left[ k_{nc}\sin(\theta + \theta_B) - k_{nr}\frac{h}{b} \right] z \right] \, dz. \tag{9}
\]

To simplify the above equation, let

\[
D = \omega t - k_{nr}R - k_{nc}\frac{h}{2} \tag{10}
\]

\[
A = k_{nr}\frac{\sin(\theta + \theta_B)}{\cos \theta_B} \tag{11}
\]

\[
B = k_{nc}\frac{h}{b}. \tag{12}
\]

By applying the sine of sum identities and integral manipulations, finally we have

\[
E = \frac{\varepsilon_o b}{R} \left(\frac{\sin \beta}{\beta}\right) \sin D \tag{13}
\]

where

\[
\beta = \frac{b}{2} (A - B) = \frac{b}{2} \left(k_{nr}\frac{\sin(\theta + \theta_B)}{\cos \theta_B} - k_{nc}\frac{h}{b}\right). \tag{14}
\]

The irradiance \(I(\theta) = \langle E^2 \rangle_T = \langle \sin^2 D \rangle_T = \langle \sin^2(\omega t - k_{nr}R - k_{nc}\frac{h}{2}) \rangle_T = \frac{1}{2} \) so

\[
I(\theta) = \frac{1}{2} \left(\frac{\varepsilon_o b}{R}\right)^2 \left(\frac{\sin \beta}{\beta}\right)^2. \tag{15}
\]

From equation (15), it is seen that the distribution of the intensity is a sinc squared function of \(\beta\) which is a function of \(\theta\). The intensity distribution has the maximum value when \(\beta\) equals zero, that is
\[ b \frac{k_n \sin(\theta_M + \theta_B)}{\cos \theta_B} - k_{m_c} \frac{h}{b} \] = 0. \tag{16} \]

Noticing that \( \tan \theta_B = h/b \), we obtain
\[ n_p \sin(\theta_M + \theta_B) = n_{LC} \sin \theta_B. \tag{17} \]

Equation (17) is obviously representing Snell’s law, which indicates that for the light propagation within a single LC-polymer grating unit, the position of the maximum intensity can simply be determined by the refraction at the LC-polymer boundary.

For the following part, we extend the optical analysis to multiple LC-polymer grating units. The contribution of the field intensity at point \( P \) from all the grating units is given by
\[ E = C \int \frac{b}{2} F(z) \, dz + C \int \frac{b}{2} F(z) \, dz + \cdots \]
\[ + C \int \frac{(N-1)b}{2} F(z) \, dz \tag{18} \]
where the constant \( C = \varepsilon_0 / R \) is independent of \( z \) over each aperture, \( F(z) = \sin \left[ \omega t - k_{np} z - \phi(z) \right] \) and \( \phi(z) = k_{m_c} H(z) \). Following the same reasoning as in the previous case, \( r_j(z) \) is expressed in the following approximation with respect to \( R_j \).
\[ r_j(z) \approx R_j - \left( z - \frac{j b}{\cos \theta_B} \right) \sin(\theta + \theta_B). \tag{19} \]

With \( R \gg z \), all the grating structures are very close to the origin \( O \), so that we can assume \( \theta_j \approx \theta \). By applying the cosine law to the triangle FCP and introducing the Taylor series expansion of the square root to the first order, we find the following approximation:
\[ R_j \approx R - \frac{j b}{\cos \theta}. \tag{20} \]
Replacing \( R_j \) in equation (19) with equation (20), and putting the expression for \( r_j \) and \( \phi \) into the contribution formula of the \( j \)th LC-polymer grating unit, we obtain
\[ E_j = C \int \frac{b}{2} \sin \left\{ \omega t - k_{np} R - k_{m_c} \frac{h}{2} \right\} \]
\[ + \left( k_{np} \sin \theta - k_{np} \frac{b \sin(\theta + \theta_B)}{\cos \theta_B} + k_{m_c} \frac{h}{b} \right) \phi \]
\[ + \left( k_{np} \frac{\sin(\theta + \theta_B)}{\cos \theta_B} - k_{m_c} \frac{h}{b} \right) \phi \]
\[ \times dz. \tag{21} \]

Applying the sine of sum identities and integral manipulation to equation (21), we arrive at the following equation:
\[ E_j = \frac{b C \sin \beta}{\beta} \sin \left( \omega t - k_{np} R - k_{m_c} \frac{h}{2} + (k_{np} b \sin \theta) \phi \right) \]
\[ \times \left( \frac{1}{2} \frac{b \sin \beta}{\beta} \left( \sin \frac{N k_{np} \sin \theta}{2} \right) \right)^N \tag{22} \]

where \( \beta \) has the same expression as equation (14). Now we need to sum up the contribution from all the LC-polymer grating units, which in turn is written as the imaginary part of a complex exponential:
\[ E = \text{Im} \left[ \frac{b C \sin \beta}{\beta} \sum_{j=0}^{N-1} \left( e^{(i k_{np} b \sin \theta) \phi} \right)^j \right]. \tag{23} \]

Noting that the summation is a geometric series, equation (23) becomes
\[ E = \text{Im} \left[ \frac{b C \sin \beta}{\beta} e^{(i \omega t - k_{np} R - k_{m_c} \frac{h}{2})} \right] \]
\[ \times \left( \frac{1}{2} \frac{b \sin \beta}{\beta} \left( \sin \frac{N k_{np} \sin \theta}{2} \right) \right)^N. \tag{24} \]

Or equivalently,
\[ E = \frac{b C \sin \beta \sin(\alpha \alpha)}{\sin \alpha} \sin \left( \frac{1}{2} \frac{b \sin \beta}{\beta} \right) \sin \left( \frac{2 k_{np} \sin \theta}{2} \right) \]
\[ + (N - 1) \frac{b \sin \theta}{2} \right) \tag{25} \]

where
\[ \alpha = \frac{k_{np} b \sin \theta}{2}. \tag{26} \]

The irradiance \( I(\theta) = (E^2)_r \) is then
\[ I(\theta) = \frac{1}{2} \frac{b \sin \beta^2}{\beta^2} \left( \sin \frac{\beta}{\sin \alpha} \right)^2. \tag{27} \]

From equation (27) it is seen that the sinc squared function acts as an envelope modulation to the diffraction pattern. The maximum intensity is found when \( \sin(\alpha \alpha) = \sin \alpha = N \) and \( \sin \beta / \beta = 1 \), that is when
\[ n_p b \sin \theta_m = m \lambda \quad (m = 0, \pm 1, \pm 2 \cdots) \tag{28a} \]
\[ n_p \sin(\theta_M + \theta_B) = n_{LC} \sin \theta_B. \tag{28b} \]

Equations (28a) and (28b) show that the light propagation through the LC-polymer grating system satisfies both the diffraction equation and Snell’s law. The principal maxima occur at angles \( \theta_m \) and \( m = 0, \pm 1, \pm 2 \cdots \) represent the indices for different diffraction orders. The maximum peak intensity appears on one of the diffraction orders, which is determined by using Snell’s law at the LC-polymer grating boundary. Note that other refractions are occurring at the polymer-glass-air interfaces. They act as prisms that shift the whole envelope of the diffraction pattern to a certain angle, but the angular distance between two adjacent diffraction orders remains the same.

3.1.2. Laser beam steering performance. The LC devices with non-reversed and reversed CMG structures are characterized with a green laser beam (\( \lambda = 543.5 \) nm, Model 1652, JDS Uniphase). Since the single LC device is polarization dependent, a polarizer whose polarization axis is parallel to the initial LC alignment is employed in the optical setup. The optical steering patterns are projected on a screen (the interval between the sample and the screen \( L = 27.5 \) cm), and captured by an image camera (Nikon 1 J2). The results are shown in figure 6.
It is observed that without applying any electric field, both the LC device with non-reversed CMGs and the one with reversed CMGs have similar diffraction patterns. According to equation (28a), with similar physical parameters of the CMGs and LCs, it is concluded that the two LC devices would have the similar distribution of the diffraction orders. The calculated angular difference between the 1st order and the 2nd order with equation (28a) is 0.44°, close to the measured value (0.6° ± 0.1°). The maximum intensity and the subsidiary maximum intensity respectively appear on the 3rd order and the 4th order for both of the two circular LC beam deflection devices, as shown in figures 6(a) and (c). Furthermore, the measured angular position of the 3rd order where the maximum intensity peak is located is 1.8° ± 0.3°. In appearance, the diffraction patterns for the two LC devices with non-reversed and reversed CMGs look similar, but the distributed intensities at different orders for each device are quite different, e.g. the measured diffraction efficiency of the 3rd order for the two LC devices is about 30% and 45%, respectively. From equation (28b), we know that the location of the maximum intensity peak is determined by Snell’s law at the LC-CMGs boundary and the glass-air interface, from which the calculated angular position for the maximum intensity is 2.2°. The experimental values closely approximate the theoretical ones using the aforementioned theory. The highly directional and coherent laser beam with 3 mm in diameter first converges in front of the beam condensing device (∼1.4–40 mm between the sample and the converging point), then it starts diverging, and undergoes an approximate trace as the light beam passing through the beam broadening device, leading to the similar order location of the two maximum peaks in the far field region. With a strong electric field (100 Vpp), most of the LC molecules are realigned parallel to the electric field, and the refractive index difference between the LC layer and the CMGs becomes rather small, so that the major light intensity shifts back to the original beam position. The zeroth orders of the LC devices with non-reversed and reversed CMGs with Vapp = 100 Vpp take up about 36% and 52% of the original beam intensity, respectively. Due to the slightly imperfect refractive index match, there are still visible diffraction patterns observed in figures 6(b) and (d). With an even higher voltage of 200 Vpp, the diffraction efficiency of the zeroth order for the two LC devices is respectively increased to 53% and 55%. This means that some inconformity exists between the two kinds of LC devices at moderate applied voltages possibly due to the different LC response behavior and different CMG structures.

3.2. Beam deflection with collimated white light

To characterize the circular LC beam deflection devices with a white light beam, two diaphragms with an aperture diameter of 8 mm and an interval of 2.5 cm are put in front of a white LED light source to get a collimated white light beam. The light beam passes a polarizer with polarization axis parallel to the LC alignment direction. Square waveform voltages with $f = 1$ kHz and different amplitudes are applied between the two ITO electrodes, and the distance between the sample and the screen is $L = 19.5$ cm. The plots of the intensity distribution at varied applied voltages for the two types of circular beam deflectors are shown in figure 7. It is observed that there are multiple intensity peaks in each curve, but the maximum peak is still discernible, and used to derive the two points whose intensity values are half of this maximum peak, leading to the full width at half maximum (FWHM) for each curve with different voltages. It is seen in figure 7 that at low applied voltages, the FWHM of the beam spot is small (9.3° at Vapp = 0 Vpp), and the device delivers the maximum peak intensity ($I_{\text{max}} = 427$ au). Upon an increase of the applied electric field, the size of the beam spot starts to increase, while the intensity decreases, and the beam condensing process is shown in figures 8(a)–(c). Above Vapp = 40 Vpp, the beam state is saturated, reaching a FWHM of 13.1° ± 0.1° and a peak intensity of 320 ± 5 au. Conversely, the device behavior shown in figure 7(b) is completely opposite: it exhibits the maximum FWHM value (16.6° ± 0.3°) and the minimum peak intensity (238 ± 2 au) at lower applied voltages and reaches the minimum FWHM (12.5° ± 0.2°) and the maximum peak intensity (337 ± 2 au) for voltages above Vapp = 30 Vpp, and figures 8(d)–(f) show the beam broadening performance with different voltages.

Without applied voltage, the linearly polarized light beam experiences the extraordinary refractive index $n_e$ of the liquid crystal E7 ($n_e = 1.7394$, $n_p = 1.5224$ at $\lambda = 589$ nm), which is substantially larger than that of the CMGs ($n_p = 1.52$), hence, light deflection occurs at the LC-CMGs boundary. The
equivalent LC grating profile resulting from the quiescent LC orientation is reversed with respect of that of the CMGs. Therefore, the LC device with non-reversed CMGs tends to deflect the incident light beam inward, while the one with reversed CMGs deflects the light outward. Moreover, this polarized light beam always undergoes a transition between

Figure 7. Plots of the intensity distribution versus the viewing angle for a single LC beam deflection device with (a) non-reversed CMGs and (b) reversed CMGs by applying different voltages (the plot of FWHM versus applied voltage is shown in the inset).

Figure 8. Collimated white light beam steering of a single LC beam deflection device with a polarizer: (a) $0 \text{ V}_{pp}$, (b) $10 \text{ V}_{pp}$ and (c) $50 \text{ V}_{pp}$ for a single LC beam condensing device; (d) $0 \text{ V}_{pp}$, (e) $10 \text{ V}_{pp}$ and (f) $50 \text{ V}_{pp}$ for a single LC beam broadening device.
two different refractive indices at the LC-CMGs boundary in a fashion that is circularly symmetric around the center point of the structure. As a result, the incident beam is condensed circularly by the device with non-reversed CMGs (acting as a LC beam condensing device). Conversely, the light beam passing through the device with the reversed CMGs is circularly expanded to some extent (LC beam broadening device). With a high voltage of $100 \text{V}_{pp}$ applied, most of the LC molecules within the component realign parallel to the electric field which is approximately normal to the glass substrates. The LC layer and the CMGs now have a very similar refractive index and behave like an optically uniform medium for the linearly polarized light, so that the size and shape of the beam passing through the device are left almost unchanged. From the FWHM difference between the low applied voltage and the high voltage, the steering angle is estimated to be $2^\circ$ for the LC beam condensing device, and $2.1^\circ$ for the LC beam broadening device, both of which are very close to the value calculated using Snell’s law ($2.2^\circ$).

To realize a polarization independent circular LC beam steering component, we stack two of the single circular LC beam deflectors together, with their LC alignment direction perpendicular to each other. Figure 9 shows the white light beam steering performance of the polarizer-free circular LC beam condensing and broadening devices. An unpolarized white light beam can always be decomposed into two polarized beam components with mutually orthogonal polarization direction, which are respectively along the two LC alignment directions. Each of these two light beams experiences a deflection within its corresponding LC layer as described above but is unaffected by the other layer. Hence the unpolarized light beam is circularly deflected inward and outward by about $2^\circ$ at $V = 0 \text{V}_{pp}$ as respectively shown in figures 9(a) and (d). It is also observed that dispersion appears around the edges of the two deflected circular beam spots by the two different double crossed LC beam steering devices, as well as for the two single beam steering devices shown in figure 8. This phenomenon is mainly due to the aforementioned wavelength dependent diffraction (equation (28a)) by the periodic grating units, and the refraction (equation (28b)) by the linear slope of each LC-grating unit whose refractive indices are also dispersive. By applying $\text{V}_{pp} = 100 \text{V}_{pp}$, the LC molecules within both devices reorient parallel to the strong electric field, and the unpolarized light beam sees an optically uniform system, whereby no deflection occurs, as shown in figures 9(b) and (e). Since all the photographs were taken with the same exposure conditions, we can see that the beam spots (the intensity and the size) of the double crossed LC beam

Figure 9. Collimated white light beam steering of double crossed LC beam deflection device without a polarizer: (a) $V = 0 \text{V}_{pp}$ and (b) $V = 100 \text{V}_{pp}$ for double crossed LC beam condensing device; (c) original beam spot pattern; (d) $V = 0 \text{V}_{pp}$ and (e) $V = 100 \text{V}_{pp}$ for double crossed LC beam broadening device.
deflectors at $V = 100 \ V_{rp}$ slightly deviate from the original beam spot shown in figure 9(c). The reason is that due to the strong surface anchoring effect, there is a small fraction of the LC molecules at the interface between the LC layer and the CMGs which do not exactly follow the electric field direction, resulting in locally nonuniform LC orientations, in addition to the disclinations in the LC textures shown in figures 4(b) and (d). Both factors contribute to a small amount of light scattering during the light beam propagation, inducing a slight difference in the beam spot patterns. The corresponding transmittance of the two circular LC beam steering devices is respectively measured to be (83 ± 5)% and (88 ± 5)% compared to the original beam intensity.

4. Conclusion

Circular switchable beam condensing and beam broadening devices are realized by respectively using non-reversed and reversed circular micro-gratings (CMGs) combined with liquid crystal (LC). The two kinds of CMGs are fabricated by different soft lithography processes based on the same diamond tooled master mold. Both beam deflectors demonstrate similar diffraction patterns in which for green laser light the peak intensity appears at the 3rd order in the off state, while it moves to the zeroth order at high voltages. The behavior is consistent with the diffraction equation as well as Snell’s law. Polarization independent LC beam deflectors are realized by stacking two single LC devices with mutually crossed alignment layers. They can deflect a white light beam symmetrically inward/outward over $\pm 2^\circ$ with high transmittance ($> 80\%$). These circularly switchable LC beam deflectors could be used in novel luminaries, short-distance projection displays, switchable photonic diffusers and condensers, and so forth.

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