Reflective liquid crystal hybrid beam-steerer

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Abstract: We report on efficient optical beam-steering using a hot-embossed reflective blazed grating in combination with liquid crystal. A numerical simulation of the electrical switching characteristics of the liquid crystal is performed and the results are used in an FDTD optical simulator to analyze the beam deflection. The corresponding experiment on the realized device is performed and is found to be in good agreement. Beam deflection angles of 4.4° upon perpendicular incidence are found with low applied voltages of 3.4 V. By tilting the device with respect to the incoming optical beam it can be electronically switched such that the beam undergoes either total internal reflection or reflection with a tunable angle.

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References and links
1. Introduction

In recent years, new ways of steering light electro-optically have been explored. This technique offers several advantages over steering light electromechanically: switching speed, maintenance costs and pointing stability can all be greatly improved. One approach to steering light electro-optically is to use liquid crystals (LCs). They exhibit high birefringence and can be easily switched electronically. Moreover, devices based on LCs can be made with well-established techniques: liquid crystal displays are ubiquitous nowadays and a wide variety of photonic applications of liquid crystals are emerging [1].

Classical beam-steering devices using liquid crystals work by inducing a sawtooth phase profile of either variable pitch or variable blaze. It has been shown that the efficiency of steering to large angles (> 5°) with this classical approach is small (< 60%), mainly due to inherent fringing fields [2]. Modern approaches, such as the liquid crystal polarization grating can steer light to large angles with very high efficiencies (> 99.5%) at the cost of being limited to discrete angles [3–7]. The combination of both, continuous small angle steerers and large angle discrete steerers, addresses the needs for accurate steering over large angles.

Two main types of small-angle continuous beam-steering architectures can be distinguished. The first one is based on patterned electrodes while the second one is based on a hybrid configuration in which an optical substrate, such as glass or a transparent polymer is structured in a periodic grating configuration. The former is also known by other authors as the liquid crystal optical phased array (LCOPA). The patterned electrode configuration suffers from fringe field effects which deteriorate the diffraction efficiency. Extensive numerical simulations of these fringe fields in this configuration have been presented [8, 9]. These simulations revealed that the fringing field broadening effect scales linearly with the LC layer thickness. Numerical simulations have also been used to understand the polarization effects in this type of devices [10].

In the hybrid configuration an optical substrate, such as glass or a transparent polymer, usually index-matched to one of the two LC refractive indices, is structured in a periodic grating configuration. Several researchers have fabricated devices of this kind [11–13]. Computational analyses to obtain the diffraction efficiency for this type of device has been undertaken for a binary grating structure via the rigorous coupled-wave analysis [11]. Recently liquid crystal beam steerers of the hybrid type have been reported and demonstrated, in which the structured polymer layer was formed using soft-embossing, a technique suitable for mass production with roll-to-roll processing [12].

In this article, we study the diffraction efficiency of a hybrid configuration, in which a liquid crystal on top of a blazed grating is electrically switched by means of only two electrodes: one on top of the grating and one on the planar substrate opposite of the grating. Each of the substrates is covered entirely by the electrode. The simulated behavior is compared to the performance of a fabricated, proof of concept device that works in reflection. The use of a metallic reflective layer on top of the structured polymer layer offers two important advantages compared to previously demonstrated devices. First, due to the reflective nature, the steering angle is doubled compared to a transmissive device with identical geometry. Second, due to the fact that the metallic layer is close to the LC layer, the required voltages for operating the device are very low.
2. Device description

The studied beam-steering device consists of a stack of 3 materials: a glass top substrate, a liquid crystal layer and a blazed grating. A cross-section of its structure is shown in Fig. 1. The blazed grating has a blaze angle of $10^\circ$, a periodicity of $\Lambda = 50 \mu m$, and is made of poly(methyl methacrylate) (PMMA), an isotropic medium with a refractive index of $n_{PMMA} = 1.489$ at a wavelength of $\lambda = 633 \text{ nm}$. The PMMA grating is obtained by hot-embossing a PMMA sheet with a brass mold that was manufactured using ultraprecision diamond milling with a cylindrical end-mill [14]. Because of the tool geometry, the two slopes of the grating make a right angle. The molding technique allows for easy replication and upscaling possibilities [15].

At the outer edges of the grating area, an elevation in the PMMA substrate and spherical spacers (Micropearl SP-2055 from Sekisui Chemical GmbH) support the top glass substrate at a certain distance, $\max(h_{LC}) = h_{\text{spacer}} + h_{\text{ridge}} = 21.4 \mu m$, from the lowest point of the grating valley. Both the top substrate as well as the slopes of the grating are coated with electrodes. The silver electrode over the grating is deposited by means of e-gun evaporation, paying attention not to heat up the sample so much as to deform the grating. The electrode is made of a 100 nm thick layer of silver that is evaporated on top of a 15 nm thick layer of Chromium.

The nematic liquid crystal mixture E7 is sandwiched between the grating and the planar top substrate. It has an extraordinary and ordinary refractive index of $n_e = 1.730$ and $n_o = 1.519$ respectively at a wavelength of $\lambda = 633 \text{ nm}$.

In conventional cells, both interfaces require alignment layers to obtain a homogeneous and well-defined orientation of the liquid crystal. For our device, we use the photoalignment technique [16] as it is a non-contact process that is well-suited for structured substrates, unlike the rubbing alignment technique. The photoalignment material, PAAD-22 from BEAM Co., was deposited on the substrates and spincoated at 3000 rpm for 60 s. The remaining solvent was subsequently evaporated by placing the substrates on a hotplate for about 3 minutes at 100°C. These substrates were then irradiated by polarised UV light for 5 minutes, using an exposure power density of 15.7 mW cm$^{-2}$. The microscope images shown in Figs. 2(a) to 2(c) illustrate the degree of uniaxial alignment. For Figs. 2(a) and 2(b) the sample was tilted by approximately $18^\circ$, which was necessary to capture the reflected light with the microscope objective, which had a numerical aperture of 0.25. The tilt is evident from the defocussing: only the center part of the images is in focus. Most of the liquid crystal is homogeneously aligned, which is apparent from the overall dark appearance when the alignment direction of the liquid crystal is parallel to one of the polarizers. When the director is at $45^\circ$ relative to the polarizer transmission axes, as in Fig. 2(b), the image should be uniformly bright. This is true for the biggest part of the figure, however some smaller patches vary in intensity compared to their surroundings. This inhomogeneous light intensity can be explained with Fig. 2(d), which shows the PMMA grating imaged from the backside (no liquid crystal), at the edge of the structured region. It indicates that
the surface is not entirely smooth, so that some small patches exist where the metal coating is not perfectly planar. This in turn leads to reflections under different angles and explains the intensity variations shown in Fig. 2(b). Figure 2(c) shows the same sample between crossed polarizers and illuminated by red LEDs in transmissive mode. About 3 sinusoidal variations in the intensity can be distinguished in each grating period. These fringes are the result of linearly increasing retardation, as explained by Haller et al. [17]

![Microscope images of the liquid crystal blazed grating hybrid cell, in absence of a voltage. The sample is imaged using reflected light between two crossed polarizers in (a) and (b). In (a), the sample is rotated such that the director is parallel to the analyzer. As this causes an overly dark image, the lower left region has been digitally enhanced to show the groove direction. In (b), the director is at 45° with respect to both polarizer transmission axes. In (c), the cell is observed in transmission, using light from red LEDs ($\lambda_c = 641$ nm, $\Delta\lambda_{FWHM} = 18.7$ nm) with a magnification twice as large as in (a) and (b). In (d) the cell is imaged from the backside, using the same magnification as image (c).](image)

3. Analytical results for a single period

When a light beam is incident on the device, it will reflect light in a way that is illustrated schematically in Fig. 3. The deviation of the reflected angle as the liquid crystal switches can be calculated analytically when it is assumed that the liquid crystal switches homogeneously over the entire cavity. Using simple considerations of geometric optics and the ray diagram shown in Fig. 3(b), the angle at which light is reflected in the medium surrounding the device, is given by:

$$\theta_o = \arcsin \left\{ \frac{n_{LC}}{n_{env}} \sin \left[ 2\alpha + \arcsin \left( \frac{n_{env}}{n_{LC}} \sin \theta_i \right) \right] \right\},$$

(1)

in which $n_{env}$ and $n_{LC}$ are the refractive indices of the environment and the liquid crystal
respectively. For perpendicular incidence from air \((n_{rm} = 1)\) and with \(\alpha\) small and small enough so that \(\alpha^2 \ll 1\), we may write then for the deviation angle when the refractive index of the LC is modified by applying a voltage that

\[
\Delta \theta_o \approx 2 \times \Delta n_{LC} \times \alpha,
\]

which shows the influence of the parameter \(\alpha\) on the overall deviation angle as a simple multiplication factor.

Naively, one might want to increase the angle \(\alpha\) to obtain a larger deviation angle. There is a limit to this however: as Fig. 3(b) shows, the exitance angle is larger than the incidence angle. By increasing \(\alpha\), the beam will eventually reach the critical angle, \(\theta_o = 90^\circ\), at which total internal reflection (TIR) occurs. For the refractive indices of the liquid crystal E7, 1.730 and 1.519, this already happens at \(\alpha_c = 17.7^\circ\) and \(\alpha_c = 20.6^\circ\) respectively. By using \(\alpha = 17.6^\circ\), the grating structure might be optimized, as the deflection angle could become as large as \(24.6^\circ\), based merely on Eq. (1) and the refractive indices of E7 mentioned earlier. However, the magnitude of the partial reflections from the inner media to the environment would be close to 100%, so while this scenario would be more ideal for obtaining a larger deflection angle, it will reduce the amount of reflected power. A blaze angle of \(10^\circ\) ensures that we remain below the total internal reflection threshold, while preserving a moderate amount of power in the reflected orders. It would lead theoretically to a deviation angle of \(5.0^\circ\), assuming the refractive index of the liquid crystal is uniform and equal to one of the two aforementioned values. It is still possible to reach the TIR-condition by increasing the angle of incidence however, which will be discussed later.

Note that in this discussion we have neglected the influence of the periodicity of the grating structure. The immediate influence of this parameter is given by the grating equation,

\[
\Lambda (\sin \theta_o + \sin \theta_i) = m \lambda,
\]

in which \(\Lambda\) is the period of the structure, \(\lambda\) the wavelength of light and \(\theta_i\) and \(\theta_o\) respectively the angle of the incident and outgoing beams relative to the grating normal, also indicated in Fig. 3. \(m\) is an integer that determines the order number. The grating equation prevents light from being deflected over a continuum of angles in the proposed device. Instead, it will be diffracted to discrete orders, that are close to the angle given by Eq. (1).
4. Simulation

We have modeled the device’s beam-steering functionality by numerically simulating the switching of the liquid crystal when a potential difference between the two electrodes is applied. These simulations are carried out by minimizing the free energy of the system incorporating the full Q-tensor representation of the LC by the Finite Element Method [18]. In [19], Yeh and Gu list the liquid crystal parameters used for the electric simulations: $\varepsilon_\perp = 5.1$, $\varepsilon_\parallel = 19.6$, $k_1 = 11$ pN, $k_2 = 10.2$ pN, $k_3 = 16.9$ pN. Interpolation from the unstructured mesh onto a rectangular grid and conversion of the Q-tensor to the director is performed for post-processing and visualization. The results of two such simulations are visualized in Fig. 4. It shows the director profile within the cavity, together with the equipotential lines. It is clear from Fig. 4(b) that the non-planar profile of the grating causes a laterally varying electric field that is strongest at the peak of the grating. A non-negligible lateral component in the neighbourhood of the steep sidewall of the grating is present. In this region polarization rotation can be expected, as the polarized light experiences both indices of a birefringent medium. At the end of section 3, it was mentioned that the periodicity of the grating would prevent continuous beam-steering. We now see that as $\Lambda$ becomes smaller, the influence of the lateral component will become more important too, which would lead to more polarization rotation.

![Fig. 4. Simulated director profile and equipotential lines for two electric potential differences between the electrodes (thick, black lines). Initial alignment of the LC molecules is along the grating grooves, i.e. perpendicular to the plane of this figure. The black dots and rods in (a) and (b) represent the projection of the liquid crystal director on the plane of these cross-sections. In (a), the voltage between the electrodes is $V = 0.8$ V, in (b) ($V = 7.7$ V). Periodic boundary conditions are used on the left and right sides, Dirichlet boundary conditions on the electrodes.](image)

To study the diffraction efficiency of this tunable grating, the director profile obtained from the Finite Element simulations is used as the input to Lumerical FDTD Solutions (version 8.12.631), a commercial-grade simulator based on the finite-difference time-domain method. In the optical simulation, the power in the reflected diffraction orders at 633 nm is calculated, relative to the power of the incoming source. The polarization of light perpendicularly incident on the structure is along the grooves and hence along the director when no potential is applied. The boundary condition at the top of the simulation region is a perfectly matched layer and at the sides it is periodic (Bloch). A simulation returns the normalized power in each of the diffraction orders, which are given by the grating equation [Eq. (3)].

We have simulated the power in the orders for a range of voltages. The simulation results are visualized in Fig. 5, which illustrates the voltage-dependent beam-steering behavior of the LC hybrid blazed grating device. Figure 5(a) shows how the beam jumps from one order to the next as the voltage increases. It also shows the total deflection angle for 633 nm light: without potential applied, most of the light is reflected under an angle of $-36.5^\circ$ and $-37.4^\circ$ in air, which correspond to the 47th and 48th diffraction order respectively, according to Eq. (3). For
comparison, the absolute value of the angle predicted by the geometric optics formula of Eq. (1) is 36.3°, very close to these orders and the small difference might be explained by diffraction of the wave as it propagates past the peak of the grating. At a potential difference of 1.0 V the steering becomes visible as the liquid crystal reorients. This is evident from the intensity redistribution in the figure: as the potential increases, the angle to which most of the beam power is diffracted is reduced, bringing it closer to the grating normal. The reason for this is that the effective refractive index of the liquid crystal is reduced as the director tilt is increased. The maximum deviation angle for an applied potential of 10 V is 4.4°, only taking into account the light being diffracted into the 47th and 42nd order. This value is close to the value calculated earlier in section 3 and the small difference can be explained by the discrete nature of the diffraction orders and the inhomogeneity of the refractive index in the LC region. Figure 5(b) shows the same data in a more detailed representation. At 3.4 V, the power in the 42nd order reaches 50% of its maximum value, which is reached at 6.5 V. At each voltage, the sum of the power in diffraction orders 42 to 48 (inclusive) is about 60% of the incident power. At 0 V, the reflected power in all orders is 88% of the incident plane wave, 7% of which is specular reflection, 64% is in the 7 orders shown in Fig. 5(b). That means that 12% is lost due to absorption in the silver electrode or to light that is totally internally reflected due to the increase of the angle $\beta + 2\alpha$ (using the labeling from Fig. 3) upon each successive round trip in the LC layer. An anti-reflection coating and a better reflector could be used to improve the diffraction efficiency.

Fig. 5. Simulated power in the diffraction orders of the hybrid blazed grating for 633 nm light. The graph in (a) shows the beam deflection behavior, while finer details are apparent from the representation in graph (b). The normalization of the intensity is with respect to the incident light.

5. Measurements and discussion

Now we compare the functionality of the fabricated device with the simulations discussed previously. To that end, the output of a HeNe-laser is directed perpendicularly to the grating substrate. Only the polarization component parallel to the grooves is considered, by having the beam pass through a properly aligned polarizer before incidence. A digital camera records the intensity of the different reflected orders. Two examples of this are shown in Fig. 6.

We have recorded the diffraction pattern for a range of voltages between 0.1 V and 10.0 V. We visualize this dataset by integrating the power in the different orders. In this way, the two-dimensional images are reduced to a one-dimensional dataset, which is shown in Fig. 7.

Comparison of Fig. 7 to the simulations from Fig. 5(a) shows good agreement in the tunable deflection angle, although the majority of the power at 0 V in Fig. 7 is in the 48th order, not the 47th as predicted by the simulations. Measurement of the power in the 48th order at 0 V
Fig. 6. Recorded laser diffraction pattern of the hybrid blazed grating at two different voltages. The location of the beam incident on the reflective grating, relative to the reflected beam, is indicated in the figure, as well as the order number, \( m \) from Eq. (3).

Fig. 7. Evolution of the diffraction pattern of the hybrid blazed grating as a function of the voltage applied between the two electrodes. Each vertical slice shows the diffraction pattern at a specific amplitude of an applied 1 kHz square wave electric signal. The deflection angles relative to the grating normal, which is parallel to the incident laser beam. The dataset to the left shows the evolution for unpolarized reflected light, whereas the dataset to the right displays the result from having another polarizer between the reflective grating and the detection screen.

shows 15.2 mW. Relative to the incident power of 86.1 mW, that is 17.7 \%, not too far below the 22.6 \% predicted by the simulation for that order and shown in Fig. 5(b). The fabricated device is slightly transparent, because the silver layer is not thick enough: 3 \% of the incident laser light is transmitted. Further comparison between the experiment and the simulations shows that there is a small difference in threshold voltage. The biggest discrepancy between the two figures is found in the diffraction order that is most strongly excited at larger voltages: for the experiment, this is the 43rd order, whereas in the simulation it is the 42nd. We believe this is due to small variations in the manufacturing process that lead to an error in the estimated height of the liquid crystal region, which would influence the electric field over the LC.

Remark that Fig. 7(b) shows the experimental results when another polarizer, whose transmission axis is parallel to the first, is inserted in the path of the reflected beams. Comparison of this figure to Fig. 7(a) shows that at low voltages most of the light undergoes no polarization rotation, but at intermediate to high voltages a larger amount of polarized light is converted to light of the perpendicular polarization. The reason for this can be explained with Fig. 4(b): starting from intermediate voltages, the director tilts upwards, but because of the lateral component of the director, polarization rotation occurs. The small angular difference of 0.1° in the lower diffraction orders of Fig. 7(b) compared to the angles of the same orders in Fig. 7(a) is due to beam displacement as it passes through the 2 mm thick polarizer. Note that the simulation result of Fig. 5(a) shows the evolution of the diffraction pattern for unpolarized light, similar to Fig. 7(a).
6. On-off steering with totally internally reflected light

The reflective blazed grating can be used in a way that allows it to be switched electrically between a state where it reflects incident light and one where light is totally internally reflected. To this end, consider Fig. 3(b) again. When s-polarized light is incident on the grating it first refracts at the air-glass interface. Because of the chaining property of Snell’s law at parallel interfaces, the angle $\beta$ can be calculated. The same goes for $\theta_o$. For some angles $\theta_i$, light will be totally internally reflected after passing through the liquid crystal layer. This TIR-condition is given by $\theta_{i,TIR} = \arcsin\left(n_{LC}\sin\left(\arcsin\left(n^{-1}_{LC}\right) - 2\alpha\right)\right)$, with $n_{LC}$ the effective refractive index experienced by light as it propagates through the liquid crystal medium.

Using the ordinary and extraordinary refractive indices of E7 given earlier, we find that when no voltage is applied, light would be totally internally reflected when $\theta_{i,TIR0} = 26.2^\circ$, whereas if the liquid crystal would be fully switched, $\theta_{i,TIR\infty} = 31.4^\circ$. This means that when $26.2^\circ \leq \theta_i < 31.4^\circ$ light is totally internally reflected when no voltage is applied and is reflected in a similar way as discussed earlier when the effective refractive index is decreased to some threshold by applying an electric potential over the liquid crystal layer.

For this application we have tilted the cell so that the grating normal makes an angle of $(26.6 \pm 0.1)^\circ$ relative to the incoming beam. At this point, the diffraction orders with most intensity have just disappeared from the $180^\circ$ field-of-view in front of the reflective grating, as shown in Visualization 1, which also includes the dynamic behaviour due to on-off switching.

In a similar way as before, we obtain a dataset from the diffraction patterns at different voltages, which is shown in Fig. 8(a). Below the threshold of 1.2 V, there is no light visible on the detection screen. In this TIR-state, light eventually reaches the side edge of the grating and is scattered at the glue boundary that holds the two substrates together, as shown in Fig. 8(b). As the voltage increases, the effective refractive index of the LC decreases and the beam that propagates through the liquid crystal layer is no longer totally internally reflected: the diffraction pattern becomes pronounced again. The power in the diffraction order that makes the second smallest angle to the device surface is measured at 8.1 % of the incident power when the device voltage is at 3.5 V. When the voltage is switched off, less than 0.1 % is measured at that same position.

![Fig. 8](image)

Fig. 8. Left: experimental results of the light reflection to different angles as a function of applied voltage. The grating is tilted with respect to the incident beam at an angle of $(26.6 \pm 0.1)^\circ$. Right: photos of the cell, when the applied voltage is 0 V (top) and 10 V (bottom). The process of tilting the cell and its influence on the diffraction orders is shown in Visualization 1, which also includes the dynamic behaviour due to on-off switching.
7. Conclusion

We have studied the spatial evolution of the diffraction pattern of a blazed grating with small blaze angle as a function of the voltage that is applied over the liquid crystal layer that is sandwiched between this grating and a planar glass top substrate. Both our simulation results and experimental results show a tunable deflection of the beam over 4.4° for light perpendicularly incident on the grating, by applying a few volts. These low switching voltages could not have been obtained if the electrode had been below the blazed grating as the PMMA layer would screen most of the applied voltage. We have also used this device as a way to switch light electronically between a state where light is totally internally reflected and scatters at the edge of the cell and a state where light is reflected from the device and the reflection angle can be tuned over approximately 10°. Such switching behaviour could be of interest for emergency lighting applications, that can switch between an illumination state and a scattering state.

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