Two-dimensional switchable blue phase gratings manufactured by nanosphere lithography

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Abstract: Switchable two dimensional liquid crystal diffraction gratings are promising candidates in beam steering devices, multiplexers and holographic displays. For these areas of applications a high degree of integration in optical systems is much sought-after. In the context of diffraction gratings this means that the angle of diffraction should be rather high, which typically poses a problem as the fabrication of small grating periods is challenging. In this paper, we propose the use of nanosphere lithography (NSL) for the fabrication of two-dimensionally structured electrodes with a periodicity of a few micrometers. NSL is based on the self-assembly of micro- or nanometer sized spheres into monolayers. It allows for easy substrate structuring on wafer scale. The manufactured electrode is combined with a liquid crystalline polymer-stabilized blue phase, which facilitates sub-millisecond electrical switching of the diffraction efficiency at a diffraction angle of 21.4°.

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1. Introduction

Liquid crystal (LC) gratings become more and more popular for developing switchable diffractive optical elements. For example, these gratings find their applications in beam steering devices [1,2], 3D displays [3], optical interconnects [4] and beam multiplexing [5]. LC gratings provide energy-efficient electrical tuning of the diffraction efficiency, since they do not rely on mechanically moving parts.

There exists a multitude of techniques to create LC gratings. A common way is to use periodically arranged electrodes, which induce a periodic refractive index modulation via inhomogeneous electric fields [6]. Other techniques are based on holography, which is used to form a
periodic polymer network in the bulk liquid crystal by photo-polymerization [7] or are applied to create a patterned director orientation on the surface via photoalignment [8–10].

Most liquid crystal gratings use a nematic LC, which usually leads to switching times in the order of 10 ms to 100 ms [11]. A faster alternative is provided by the Kerr effect in blue phase liquid crystals [12–14], which exhibits submillisecond switching times [15–18]. The application of blue phases (BPs) in electrooptic devices has been extensively studied in the last decade. Owing to a cubic superstructure, BPs are isotropic and do not require an alignment layer, which gives them an advantage over nematic liquid crystals. For practical purposes, BPs typically are polymer-stabilized to increase their temperature range [15, 18, 19].

By applying electric fields to the BP an optical anisotropy $\Delta n$ can be electrically induced. The relation between the anisotropy and the applied electric field is accurately described by the extended Kerr model [20]

$$\Delta n(E) = \Delta n_s \left(1 - \exp\left[-\frac{E^2}{E_s^2}\right]\right).$$

(1)

Here, $E_s$ denotes the saturation field and $\Delta n_s$ the saturation birefringence. Both values, $\Delta n_s$ and $E_s$, are usually determined by fitting experimental data to Eq. (1). The electrically induced birefringence leads the blue phase to become uniaxial. The ordinary and the extraordinary refractive indices, $n_o$ and $n_e$, are given by

$$n_e = \bar{n}_{BP} + \frac{2}{3}\Delta n(E)n_o = \bar{n}_{BP} - \frac{1}{3}\Delta n(E),$$

(2)

where $\bar{n}_{BP}$ is the refractive index of the isotropic blue phase at $E = 0$.

Switchable blue phase gratings can be produced with similar methods as nematic gratings (with the exception of photoalignment). Devices based on structured electrodes or holographic methods have been shown to lead to fast tunable diffractive elements [21–24]. The holographic method usually involves a rather delicate setup, while structured electrodes provide a much easier road to BP gratings. However, most of these electrode structures are one-dimensional with large grating periods, which leads to small diffraction angles [25]. Thus, the manufacturing of two-dimensionally patterned electrodes with a grating period of a few microns remains a challenge.

Nanosphere lithography (NSL) provides a solution to this problem. NSL is a convective self-assembly technique [26–28] capable of producing large area structured electrodes with a periodicity on the micro- and nanometer scale [29]. To this end, a monolayer of nanospheres made of poly-styrene (PS) is deposited on the surface in a closely packed layer. The diameter of the spheres determines the grating period and thus the diffraction angle. In order to create the electrodes, the spheres are shrunk by reactive ion etching (RIE), which exposes larger fractions of the bare substrate [30]. The electrode material (metal or metal oxide) is then deposited on the substrate while the shrunk sphere monolayer acts as a shadow mask. Finally, the spheres are removed chemically, which yields the structured electrode. NSL has several degrees of freedom like sphere diameter, shrinkage ratio, substrate material, electrode material and electrode thickness, which makes it a versatile technique for surface structuring.

In this paper, we use nanosphere lithography for the creation of a hexagonally patterned gold electrode with a periodicity of 2.1 $\mu$m on microscope slides. After shrinking the spheres to 86% of the initial diameter, the electrodes are generated by physical vapor deposition of a gold layer with a titanium adhesion promoter. Finally, the PS spheres are removed. From the prepared structured electrode, we assemble a blue phase cell with an ITO counter-electrode. The cell is filled with a blue phase and polymer stabilized. We investigate the diffraction pattern and the voltage dependent diffraction efficiency experimentally. We use a semi-numerical model to explain the observed results. Finally, we present results on the polarization dependence and the switching times.
2. Experimental details

2.1. Electrode manufacturing

The preparation of the microstructured electrodes via nanosphere lithography is sketched in Fig. 1(a). Microscope slides are cleaned and pretreated by oxygen plasma (Oxford Instruments PlasmaLab 80 plus) with 2 sccm O₂ and 8 sccm Ar at 0.10 mbar with 50 W RF power for 5 min. Then, polystyrene (PS) spheres with a diameter of 2.1 µm (Thermo Scientific, κ_v < 5 %, 10 wt% solid content in water) are deposited onto the substrate surface by the doctor blade technique [31]. To this end, a 40 µL droplet of the aqueous colloidal suspension is placed onto the surface and moved over it at constant velocity of 110 µm s⁻¹, using a hydrophobic blade at constant velocity. This preparation is performed in air under 50 % relative humidity, while keeping the substrate at an elevated temperature of 26 °C. The slightly elevated temperature is used to ensure repeatable conditions independent of the room temperature. The doctor blade approach gives precise control over the three-phase boundary and leads to a better quality of the monolayer. By this technique, a hexagonally close-packed layer of the PS spheres is obtained [Fig. 1(b)]. From SEM images, we estimate the defect density to be 5 % to 7 %.

In a next step, the spheres of the monolayer are shrunk to 86 % of their initial diameter, in order to expose a larger fraction of the substrate surface [Fig. 1(c)]. This is achieved by oxygen plasma treatment for 14 min under the same conditions as the initial cleaning. The layer of shrunk spheres then acts as a shadow mask for the subsequent metal deposition. Here, 2 nm of titanium are deposited as an adhesion promoter on the surface followed by 10 nm of gold. Both materials are deposited by electron beam evaporation. Finally, we remove the spheres in a tetrahydrofuran bath under ultrasonification and obtain the structured electrodes [Fig. 1(d)].

2.2. Cell assembly

Structured electrodes are assembled together with an ITO counter electrode to a liquid crystal cell [Fig. 2(a)]. The cell thickness d is controlled by the use of glass cylinders with a nominal diameter of 4.5 µm. We fix the cell with UV-curable adhesive Norland NOA 61 by using an UV-LED emitting at 365 nm with an intensity of ~10 mW cm⁻² for 10 min. We determine the final thickness d of the cell by evaluating the Fabry-Perot inference in the visible wavelength.
range with a spectrometer. The measured thickness is \( d = 4.2 \mu m \). Subsequently, the cell is filled with the blue phase material.

![Diagram](image)

**Fig. 2.** (a) Schematic representation of the assembled cell with the structured electrode at the bottom, the ITO counter electrode on top and the blue phase in between. The unit cell of this structure is marked with dashed lines. (b) Magnified unit cell with pitch \( \Lambda \) and cell thickness \( d \).

### 2.3. Blue phase mixture

The blue phase material is prepared by doping the liquid crystalline compounds JC-1041XX (42.5 %, Chisso) and SCB (35.1 %, Merck KGaA) with the chiral dopant ZLI 4572 (9.4 %, Merck). For the polymer stabilization the mesogenic diacrylate RM257 (6.5 %, Merck) and the trifunctional non-mesogenic compound TMPTA (5.6 %, Sigma Aldrich) with a small amount of photoinitiator DMPAP (0.9 %) are added. The mixture is stirred for 24 h in the isotropic state at 65 °C before use to ensure good mixing. This mixture slightly deviates from a well-known blue phase mixture [15], which uses monofunctional EHA instead of TMPTA. In our experiments TMPTA gave more reproducible results during the UV curing process.

We fill the BP mixture in the isotropic state into the prepared cell with the structured electrodes via capillary forces. The sample is slowly cooled down (0.5 °/min) to the BP I phase at 28.0°C. Here it is polymerized with unpolarized light of an UV LED (365 nm) at 1 mW cm\(^{-2}\) for 30 min and at 10 mW cm\(^{-2}\) for additional 30 min as a final cure. This two-step process was employed to ensure that the BP is stabilized in the BP I and there is no transition to other phases.

In order to be able to model the blue phase, we investigated the saturation birefringence \( \Delta n_s \) and the saturation field \( E_s \). To this end, we prepared a commercial liquid crystal cell (E.H.C. Japan Cell Co., \( d = 10.4 \mu m \)) with the blue phase mixture and measured the phase change induced by an electric field with a Michelson interferometer. A square voltage with a maximum amplitude of 200 V at 100 Hz was used. By performing a least squares fit of Eq. (1) to the data we find a saturation birefringence of \( \Delta n_s = 0.117 \) and a saturation electric field of \( E_s = 15.6 V \mu m^{-1} \).

### 2.4. Simulations

We model the performance of the device under the application of a voltage by conducting finite element simulations. These give us the electric field distribution in the device, which we then use to calculate the induced birefringence at each point in the cell. We further consider the phase and amplitude modulation by the structured electrodes and use a simple Jones formalism to calculate the evolution of linearly polarized light traveling through the assembled cell. Finally, we obtain the diffraction pattern by employing fast Fourier transform.
The electric field simulations are performed with COMSOL Multiphysics 4.2 [32]. By considering the periodic structure of the cell, it is sufficient to model a hexagonal unit cell [Fig. 2(b)] with the proper periodic boundary conditions. For the simulation, we consider the patterned electrode as flat. The metal covered regions are modeled as perfect electric conductors with a uniform electric potential. Similarly, the counter electrode has a uniform potential based on the applied voltage. We neglect the changing dielectric environment due to the reorientation of the liquid crystal molecules. By this approximation, the electrostatic equations remain linear. Consequently, it is sufficient to simulate the electric field only for one specific voltage; the fields for other voltages then follow from a linear scaling.

With the known electric field inside the cell, the induced birefringence can be calculated using Eq. (1). The optical axis is assumed to be parallel to the direction of the electric field. With the birefringence and therefore the ordinary and extraordinary refractive indices, \( n_0 \) and \( n_e \), we use a simple Jones approach [33] to estimate the accumulated phase change of light under normal incidence traveling through the blue phase layer. This is done by discretizing the unit cell into a regular grid with 75 \( \times \) 75 cells in the \((x, y)\)-plane and 100 layers in the \(z\)-direction. For light polarized within the plane formed by the propagation direction \((z\)-axis\) and the optical axis, an effective refractive index \( n_{\text{eff}} \) is given by

\[
\frac{n^2_{\text{eff}}}{n^2_0} = \frac{n^2_0 n^2_e}{n^2_0 \sin^2(\theta) + n^2_e \cos^2(\theta)}
\]

where \( \theta \) is the angle between the optical axis and the \(z\)-direction.

For the accurate calculation of the diffraction patterns, the phase of light picked up by traveling through the metal electrodes has to be taken into account. Even though the metal layers are only a few nanometers thin, the significant difference in refractive indices compared to the BP leads to a non-negligible contribution to phase and amplitude. The accumulated phase, \( \phi_0 \), due to the structured metal film is given by

\[
\phi_0(x, y) = \begin{cases} 
  d_{\text{Au}} n_{\text{Au}} + d_{\text{Ti}} n_{\text{Ti}}, & \text{on the metal film,} \\
  (d_{\text{Au}} + d_{\text{Ti}}) n_{\text{BP}}, & \text{on the dielectric,}
\end{cases}
\]

where \( d_{\text{Au}} = 10 \text{ nm} \) and \( d_{\text{Ti}} = 2 \text{ nm} \) are the layer thicknesses of gold and titanium and \( n_{\text{Au}} = 0.184 \) [34] and \( n_{\text{Ti}} = 2.704 \) [35] are the refractive indices at 633 \( \text{nm} \). Within the antidots, we approximate the blue phase refractive index by the isotropic index \( n_{\text{BP}} = 1.574 \) in the field-off state. To obtain this value, we measured the refractive index of the unpolymerized blue phase in the isotropic phase and extrapolated to room temperature.

Analogously, the metal films influence the amplitude of the optical field due to reflection and absorption. We take this into account by using a transmission coefficient \( t \) for the electric field, which results from reflection and material absorption

\[
t(x, y) = \begin{cases} 
  (1 - r)t_0, & \text{on the metal film,} \\
  1, & \text{on the dielectric,}
\end{cases}
\]

where \( r \) is the reflection coefficient on incidence on the metal film and \( a \) the normalized absorption due to traveling through the material given by \( t_0 = \exp(-\kappa_{\text{Au}} k_0 d_{\text{Au}}) \exp(-\kappa_{\text{Ti}} k_0 d_{\text{Ti}}) \). Here, \( k_0 \) is the modulus of the vacuum wavenumber. \( \kappa_{\text{Au}} = 2.326 \) [34] and \( \kappa_{\text{Ti}} = 3.1038 \) [35] are the imaginary parts of the refractive index of gold and titanium, respectively.

Using the Jones calculus, we obtain the complex electric field vector \( E_{\text{out}} \) after passing through the BP cell by

\[
E_{\text{out}}(x, y) = t(x, y) J(x, y) E_{\text{in}},
\]

where \( E_{\text{in}} \) is the electric field vector of the incident plane wave and \( J(x, y) \) is the unitary Jones matrix.
From the simulations and the experiments we find that the polarization of the incoming and outgoing light are basically identical (> 99.8%). Thus it is possible to represent the relation between \( E_{\text{out}} \) and \( E_{\text{in}} \) as scalars:

\[
E_{\text{out}}(x, y) = t(x, y) \exp[-i\Delta\phi(x, y)] E_{\text{in}},
\]

Here, \( \Delta\phi(x, y) = \phi(x, y) - \min[\phi(x, y)] \) is the phase after traveling through the sample, from which a global phase is subtracted.

3. Results and discussion

3.1. Diffraction efficiency

We illuminate the prepared blue phase sample cell with a HeNe laser (633 nm) at normal incidence, the structured electrode is facing the laser. About 10% of the incoming intensity is reflected and \( \sim 72\% \) is transmitted. The remainder is either absorbed or arbitrarily scattered. Figure 3(a) shows the image of the diffraction pattern displayed on a screen in the field-off state. We measured the diffraction angle between the incident beam and the first order diffraction to be 21.4°. This diffraction in the field-off state is caused by the structured metal film, which induces a phase and amplitude mask as described above. The off-state diffraction can be reduced by using ITO as an electrode material. We determine the diffraction efficiency \( \eta \) by summation of the intensities of the six first order diffraction peaks and dividing by the overall intensity of the zeroth and first order. Hence, we neglect higher diffraction orders. In the field-off state \( (V = 0 \text{ V}) \), this leads to \( \eta(V = 0 \text{ V}) = (1.7 \pm 0.1)\% \).

![Diffraction pattern on a screen caused by the structured electrodes sample at a distance of 36.4 cm in the field-off state.](image)

Figure 3(b) shows the voltage dependent diffraction efficiency on increasing and decreasing voltage. We limit the voltage to 100 V in order to avoid disruptive discharges, which we observed in other samples. At first on increasing voltage we find an increasing diffraction efficiency, which reaches a maximum of \( (3.4 \pm 0.2)\% \) at 62 V. For voltages beyond 62 V, the diffraction efficiency decreases. On decreasing voltage, the sample exhibits a hysteresis, which shifts the diffraction maximum to about 45 V. Hysteresis is often observed in polymer-stabilized BP I systems [36]. Starting and endpoint after multiple cycles to 100 V and back are identical, thus the sample does not show any memory effects.

In order to investigate the appearance of the maximum in efficiency in more detail we performed simulations of the electric field distribution inside the sample cell [Fig. 4(a)]. In Fig. 4(b)
we visualize the simulated electric field inside a unit cell within a \((x, z)\)-cut plane for a voltage of 100 V. We observe that the strongest electric field is found close to the bottom electrodes. The weakest field is in the center of the unit cell. With increasing distance from the structured electrodes at the bottom, the field inhomogeneity decreases rapidly. About 1 \(\mu\)m away from the electrodes, the field appears completely homogeneous, thus only a small part of the cell contributes to the \((x, y)\)-dependent phase change. Due to the cell design with the structured electrode on the bottom and ITO counter-electrode on the top, most of the electric field is facing along the \(z\)-direction [black arrows in Fig. 4(b)]. In fact, within the section show in Fig. 4(b) only \(\sim 7\%\) of the absolute field squared points along the \(x\)-direction and less than 0.1 \% point along the \(y\)-direction. Further, due to the almost circular structure of the unit cell, the electric field components perpendicular to the \(z\)-axis are almost completely radially polarized.

![Fig. 4. (a) Three dimensional representation of the unit cell used for calculating the electric fields. The red area marks the \((x, z)\)-cut plane. (b) Distribution of the absolute electric field within the \((x, z)\)-cut plane. The surface plot is scaled logarithmically. (c) Induced birefringence \(\Delta n(E)\) in the \((x, z)\)-cut plane for different voltages.](image)

With the known electric field, the local electrically induced birefringence can be calculated using Eq. (1). The results for different voltages are plotted in Fig. 4(c). At \(V = 0\) V (not shown) there is no birefringence as the blue phase remains isotropic and there is no diffraction caused the BP. For increasing voltage, the induced birefringence is highest closely above the electrodes and homogenizes quickly for increasing \(z\)-values. For small voltages, the birefringence roughly follows the electric field because in the regime \(E \ll E_s\) the relation \(\Delta n \propto E^2\) holds.

The most interesting information is that for high voltages \((V > 80\) V\) the birefringence across the whole cell is driven into saturation in accordance with Eq. (1). In terms of the diffraction efficiency this means that it will decrease because the variation in phase across the cell, which is picked up by the light travelling through the cell, is flattened out. The ‘extreme’ example for \(V = 1000\) V (i.e. \(E \gg E_s\)) illustrates this most clearly as nearly the complete cell has reached the saturation birefringence \(\Delta n_s = 0.117\). Consequently, a cell with a homogeneous birefringence
will show no contribution of the BP to the diffraction, which explains the occurrence of a maximum in diffraction efficiency presented in Fig. 3(b) and the further decrease for high voltages.

3.2. Polarization dependence

The above arguments ignore the fact that the optical axis is not constant within the cell. For a more quantitative analysis we used the Jones formalism to calculate the accumulated phase picked up by light which travels through the sample. Figure 5(a) shows the phase profile for light with a polarization parallel to the x-axis. Similar to what we observed for the induced birefringence [Fig. 4(c)], the variation in phase across the cell first increases with increasing voltage, but beyond 80 V these variations slightly decrease.

![Phase profiles of the optical field after passing through the sample for different voltage](image)

In Fig. 5(b), the phase profile for light polarized at an angle of $\psi = 30^\circ$ with respect to the x-axis is shown for $V = 100$ V. The profile looks almost identical to the profile at $\psi = 0^\circ$, which is a consequence of the almost circular geometry.

For a direct comparison between the theoretical and experimental results, we measured the diffraction efficiency for each spot separately and precisely controlled the polarization with respect to the orientation of the structured electrode. We calculated the theoretical diffraction patterns by fast Fourier transform based on the simulations of the unit cell. The experimental and theoretical results are shown in Fig. 6.

In the polarization resolved measurements, two sets of curves are found for the experimental and the theoretical results. These two sets are characterized by different diffraction efficiencies. In the case of $\psi = 0^\circ$ [Fig. 6(a) and 6(c)], spots 1 and 4 show higher diffraction intensities than the spots 2, 3, 5 and 6. The latter set of spots exhibits a more pronounced maximum, which appears at lower voltages, compared to the former set. For the $\psi = 30^\circ$ [Fig. 6(b) and 6(d)], the spots 1, 3, 4 and 6 are grouped together exhibiting higher efficiencies than the spots 2 and 5.

There is a good qualitative agreement between the experimental results and the theoretical prediction. This includes the grouping into two sets, the trend of each of the curves and the comparison of diffraction efficiencies for the different states of polarization. However, the
Fig. 6. Diffraction efficiencies for first order diffraction spots: (a, b) experimental, (c, d) theoretical from fast Fourier transform. The efficiencies are labeled according to the inset in (a). The insets in (a) and (b) show the real space structure with the corresponding plane of polarization (POP). The experimental curves are only shown for increasing voltage. (a, c) x-polarized light, i.e. $\psi = 0^\circ$ (s. inset). (b, d) Polarization tilted by 30° with respect to the x-axis. The insets in (c) and (d) show the calculated diffraction patterns, the arrows indicate the polarization.

Absolute efficiencies are underestimated by the theory. This may be attributed to the simplicity of the model. The strong fields occurring at the edges of the electrodes may cause a phase transition from the blue phase to nematic phase, which shows higher birefringence.

In general, the polarization dependence and the grouping of the spots seem to originate from the hexagonal arrangement as the phase profile for the unit cell is almost identical for 0° and 30° [Fig. 5].

From the calculated diffraction patterns we find a diffraction angle of 20.5°, which is a little smaller than the angle of 21.4° obtained in the experiment.

3.3. Switching speed

Finally, we investigated the switching times [Fig. 7] of the device, which are expected to be fast due to the properties of the blue phase. Both, the switching on and switching off times, are clearly in the submillisecond region. For the switching on process, we determined 113 $\mu$s for the switching on and 105 $\mu$s for the switching off as time constants by fitting an exponential function to the experimental curves. The switching times are in good agreement with previous measurements [15].
3.4. Comparison to other techniques and possible improvements

The advantage of our approach over many other techniques is the use of self-assembly which basically allows for the fast creation of grating periods down to the wavelength of visible light on large areas. This leads to large diffraction angles, which is difficult to achieve with existing techniques. However, the applicability of NSL to larger grating periods is limited because the self-assembly of spheres becomes more difficult for diameters larger than 5 µm.

An established manufacturing technique for liquid crystal gratings is POLICRYPS [37]. This method utilizes the phase separation of liquid crystals and monomers under photopolymerization by a holographic setup. POLICRYPS leads to high diffraction efficiencies of up to 98%. However, standard POLICRYPS gratings are one-dimensional, higher dimensional gratings can be produced but require an elaborate holographic setup [7].

There exist only a few other methods for switchable two-dimensional gratings. One of them is based on the formation of undulation in chiral nematics, which leads to a square-type diffraction pattern [38]. However, such gratings are rather slow, which limits their applicability. A more recent technique employs the interference of circularly polarized light of opposed handedness to produce periodical alignment patterns on the substrates [10]. This approach requires careful alignment of the substrates in order to produce the desired director field. And the switching times have not been investigated so far.

Thus, using NSL for 2D structured electrodes remains a viable candidate for switchable 2D grating, yet the main challenge is the low diffraction efficiency. There are multiple improvements which can be applied. On the one hand, the geometry of the structured electrodes can be optimized to have thinner fillets or larger grating periods. The latter is realized by employing spheres with a larger diameter, which in turn lowers the diffraction angle. Both will lead to a larger penetration depth of the field inhomogeneity. On the other hand, the employed blue phase mixture can be improved to exhibit a larger saturation birefringence. At the same time, a lower saturation field will decrease the voltage needed to operate the device.

From our simulations, we can estimate the effect of these measures on the diffraction efficiency. Reducing the fillet size leads to an increase of diffraction efficiency about 15%. Using spheres with a diameter of 5 µm leads to an increase by a factor of 2.5. The sphere size cannot be increased arbitrarily because the self-assembly process becomes more difficult for larger spheres. Finally, a blue phase mixture with a saturation birefringence of ~0.2 roughly doubles the efficiency. These effects cumulate to a factor of about 6, which would lead to an overall efficiency of roughly 10% for the first diffraction order. Choosing a nematic LC over a blue phase would be a more drastic
approach to increase the accessible birefringence at voltages under 10 V. But this would come at
the cost of slower switching speeds and the need of alignment layers.

4. Summary and conclusion

In summary, we prepared a blue phase grating based on periodically structured electrodes made
via nanosphere lithography (NSL). NSL is a self-assembly process, which can be used to create
a hexagonally patterned conducting shadow mask. We used the structured electrode together
with an ITO counter-electrode to assemble a blue phase liquid crystal grating and measured the
efficiency. Due to the grating period of 2.1 µm, the grating reaches a high diffraction angle of
21.4°. The average diffraction efficiency exhibits a maximum at 62 V and then decreases with
increasing voltage.

We give a qualitative explanation for the appearance of the observed maximum by simulating
the induced birefringence based on the extended Kerr model. These simulations show that for
high voltages the birefringence across the whole cell is driven into saturation, which homogenizes
the phase profile of the cell and decreases the efficiency.

Based on calculations of the birefringence and the Jones formalism, we obtained the diffraction
patterns by fast Fourier transform. These theoretical results and the experimental data revealed a
polarization dependence of the diffraction efficiency of the individual first order diffraction spots.
Theoretical and the experimental diffraction curves show good qualitative agreement.

Finally, the time constants for electrooptic switching were found to be 115 µs and 105 µs for
switching on and off, respectively.

In conclusion, the fabrication of an optical element by means of nanosphere lithography shows
encouraging results. The grating exhibits polarization dependent effects based on the hexagonal
structure of the electrodes. The usage of a liquid crystal blue phase leads to submillisecond
switching times. The low diffraction efficiency remains a challenge. We presented several ideas
on how to improve the efficiency by optimizing the electrode geometry and the blue phase
material.

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