Switchable Two-Dimensional Gratings Based on Field-Induced Layer Undulations in Cholesteric Liquid Crystals

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We propose switchable two-dimensional (2D) diffractive gratings with periodic refractive-index modulation arising from layer undulations in cholesteric liquid crystals. The cholesteric cell can be switched between two states: (1) flat layers of a planar cholesteric texture and (2) a square lattice of periodic director modulation associated with layer undulations that produces 2D diffraction patterns. The intensities of the diffraction maxima can be tuned by changing the applied field. The diffractive properties can be optimized for different wavelengths by appropriately choosing cholesteric pitch, cell thickness, and surface treatment. © 2005 Optical Society of America

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Electrically controlled gratings are widely used for beam steering, optical waveguides, and splitting monochromatic beams. With the advent of multibeam devices, they became popular for beam multiplexing. Splitting the beam into a given number of beams by use of a two-dimensional (2D) grating is an efficient way to distribute an optical signal into an array of receivers. Liquid-crystal (LC) devices have great potential as a spatial light modulator. On the other hand, 1D monochromatic beams. With the advent of multibeam devices, they became popular for beam multiplexing. Splitting the beam into a given number of beams by use of a two-dimensional (2D) grating is an efficient way to distribute an optical signal into an array of receivers. Liquid-crystal (LC) devices have great potential as a spatial light modulator. 4 On the other hand, electrically controlled gratings based on periodically patterned electrodes. The unidirectionally buffed streaks. The appearance of this type of defect is associated with layer undulations that produces 2D diffraction patterns. The intensities of the diffraction maxima can be tuned by changing the applied field. The diffractive properties can be optimized for different wavelengths by appropriately choosing cholesteric pitch, cell thickness, and surface treatment. © 2005 Optical Society of America

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We studied the diffraction parameters with a setup consisting of an Ar laser (λ = 488 nm), a polarizer, a
and even diffraction maxima are nonmonotonic functions of the odd and even diffraction orders in the X and Y directions, \( \varphi \) is the angle between the X axis and the vector connecting the zeroth and \( m \)th diffraction maxima, and \( D \) is the distance to the screen.

The diffraction pattern strongly depends on \( d/p \). For cells with \( 2.5 < d/p < 10 \) the intensities of the odd and even diffraction maxima are nonmonotonic functions of \( m_x \) and \( m_y \) [Fig. 2(a)], as in 1D cholesteric gratings.\(^6\) The cells with \( d/p > 10 \) produce diffraction patterns in which the intensities of the maxima monotonically decrease with the increase of the diffraction order [Fig. 2(b)]. Clearly, the odd–even effect is a feature of the 2D gratings with a comparably small number of layers (\( d/p < 10 \)) and is not present for relatively thick samples of \( d/p > 10 \).

To gain insight into the odd–even effect, we use FCPM\(^{10} \) for imaging of the director in the vertical cross sections of cells (Fig. 3). The cholesteric layer that is adjacent to the substrate is not flat, indicating that cholesteric anchoring is finite.\(^{12,16} \) One can distinguish two different types of spatial distortion of the LC director and the average refractive index: one in the bulk region and another at the two surface regions. The modulation of the refractive index scales as \( (\partial u/\partial x)^2 \), where \( u \) is the displacement of layers from their unperturbed flat positions and \( \partial u/\partial x \) is the layers' tilt with respect to the substrate. Therefore the pattern in Fig. 3(a) can be considered qualitatively as comprised of three adjacent parts: two gratings created by the close-to-surface layers with a period of the refractive index of \( L_g = L_u \) and the LC bulk grating with a period of the refractive index.

### Table 1. Materials and Their Electro-Optic Characteristics

<table>
<thead>
<tr>
<th>Nematic Host</th>
<th>Birefringence of Nematic Host, ( \Delta n )</th>
<th>Dielectric Anisotropy of Nematic Host, ( \Delta \varepsilon )</th>
<th>Chiral Dopant, % by Weight</th>
<th>Pitch, ( \mu m )</th>
</tr>
</thead>
<tbody>
<tr>
<td>E7</td>
<td>0.224</td>
<td>13.8</td>
<td>CB15, –2.7%</td>
<td>5</td>
</tr>
<tr>
<td>5CB</td>
<td>0.211</td>
<td>11.5</td>
<td>CB15, –2.8%</td>
<td>5</td>
</tr>
<tr>
<td>ZLI-3412</td>
<td>0.078</td>
<td>3.4</td>
<td>CB15, –3.2%</td>
<td>5</td>
</tr>
<tr>
<td>BL015</td>
<td>0.28</td>
<td>16</td>
<td>ZLI-811, –30%</td>
<td>0.31</td>
</tr>
</tbody>
</table>

![Image](image-url)
of $L_g = L_n/2$. The two surface gratings are shifted by $L_n/2$ with respect to each other and separated by a distance of $-\Delta d$ along the $Z$ axis. The resulting diffraction pattern is a superposition of diffraction effects caused by the three stacked gratings and can be described with Eqs. (1) and (2). The diffracted beams labeled $b$ [Fig. 2(a)] are caused by modulation of the refractive index in the bulk with a period of $L_n/2$ and the beams labeled $s$ [Fig. 2(a)] are caused by modulation of the refractive index close to surfaces with period $L_u$. When $d/p$ is large, the contribution from the regions close to the surfaces is negligible compared with the modulation of the refractive index in the bulk of the cell, and the diffraction maxima caused by the close-to-surface layers are not observed [Fig. 2(b)]. Thus the alternation of strong- and weak-intensity maxima in the diffraction pattern is caused by the surface confinement, similar to the case of 1D gratings.\(^6\)

When the applied voltage is changed, the layer undulations become more or less pronounced and, as a consequence, the depth of the modulation of the effective refractive index changes too. Therefore the intensities of the high-order maxima can be controlled with the voltage (Fig. 4). Importantly, the performance of the gratings was found to be practically polarization independent and the relative intensities of the diffraction maxima did not change much after the linear polarization state was switched between the two orthogonal directions (up to 5%) or the polarization was changed from linear to circular (up to 10%). The diffraction pattern is stable in a wide voltage range. For example, 55-\(\mu\)m-thick cells with an E7 + CB15 mixture of $p$ = 5 \(\mu\)m produce the diffraction pattern within a voltage range of $U = 12$–25 V in which one can control the intensities of the high-order maxima.

Depending on parameter $\kappa = \lambda d/L_g^2$, one can distinguish the Raman–Nath ($\kappa \ll 1$) and Bragg ($\kappa > 1$) types of diffraction.\(^{18}\) In the case of thick cholesteric cells with $d \gg \xi$ and $L_g = L_n/2$, assuming elastic constants for a 5CB matrix ($K_{22} = 3$ pN, $K_{33} = 10$ pN), one obtains $L_g = 1.1(pd)^{1/2}$ and $\kappa_{\text{thick}} \approx 0.9\lambda/p$. In the thin cells with $d \approx \xi$ and $L_g = L_u$ we find $\kappa_{\text{thick}} = 0.2\lambda/[p(d + 2\xi)]$. The layer undulations can be used as gratings of both types.\(^{18}\) The conditions for the Bragg diffraction are achievable, especially with small $p$ and $\lambda$ in the infrared region. For example, for $p = 0.31 \mu$m and $\lambda = 3 \mu$m one obtains $\kappa_{\text{thick}} \approx 9$, which corresponds to the Bragg diffraction regime. In the opposite limit a thin grating with $d = 12.5 \mu$m and $p = 5 \mu$m produces diffraction in the Raman–Nath regime at $\lambda = 0.488 \mu$m and $\kappa_{\text{thick}} \approx 0.012$.

To conclude, we have demonstrated that the layer undulations in the cholesteric cells can be used as switchable weakly polarization-dependent 2D diffraction gratings of both Raman–Nath and Bragg types. The periodic structure of the layer undulations and corresponding spatial modulation of an average refractive index in the plane of a cell allows us to produce diffraction patterns with a square-type arrangement of diffraction maxima. The spatial periodicity of the diffraction pattern can be changed and adjusted for different wavelengths by use of cholesterics of different pitch and by confining them into cells of different thicknesses. The intensities of the diffraction maxima can be continuously tuned by the applied voltage; the grating can be switched between the diffraction and no-diffraction states by use of pulses of ac voltage.

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References

15. B. I. Senyuk, I. I. Smalyukh, and O. D. Lavrentovich, are preparing a paper titled “Undulations of lamellar liquid crystals in cells with finite surface anchoring.”