

Switchable diffractive cholesteric gratings

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Electrically switchable diffractive gratings based on cholesteric liquid crystals are suggested. An electric field switches the cholesteric cell between three states: two with a uniform in-plane director and one with a periodic in-plane director modulation. The modulated state produces a Raman–Nath diffractive effect. Characteristic time of switching is of the order of 10 ms. Diffractive properties depend on the polarization of the incident beam and the direction of surface orientation. © 1997 American Institute of Physics. [S0003-6951(97)03936-3]

Cholesteric liquid crystals with periodic helical twist of molecular orientation have been used for a long time as materials capable of pronounced Bragg diffraction effects. In recent years interest in these materials has emerged for optical and electro-optical applications, such as low-voltage light modulators,^{1–3} backlight-free displays,⁴ and smart reflectors.⁵

In this letter we suggest electrically switchable cholesteric diffraction gratings of the Raman–Nath (RN) type. RN diffraction in cholesteric liquid crystals can occur when the helix axis is perpendicular to the incident beam direction and when the light wavelength λ , the grating periodicity L , and the grating thickness d , satisfy the condition $\kappa = \lambda d/L^2 \ll 1$ (for Bragg diffraction $\kappa \gg 1$).⁶ Although in principle the possibility of RN diffraction in chiral low concentration structures has been known for years,^{7–10} the experimental realization in cholesterics has been hindered by difficulties in proper alignment. Ideally, the cholesteric layers should be uniform and oriented normally to the bounding planes. To overcome the alignment difficulty we suggest use of the phenomenon of periodic modulation of a cholesteric structure in an applied electric field. The modulations have been observed in wedge-shaped samples¹¹ where they are not uniform and in flat supertwist nematic cells,^{12,13} where they are undesirable. Efforts have been made to eliminate them.^{12,13} For the diffraction effect, on the contrary, the modulated state is needed; therefore the design of the effective supertwist cells and diffractive cells should be different.

In the diffraction device we describe below, the initial field-free state is a planar P state with the helix axis perpendicular to the cell plates. The dielectric coupling of the cholesteric structure with the external electric field creates an in-plane modulated M state. The uniformity and orientation of the modulated pattern is set by surface anchoring that provides unidirectional orientation at both plates. Periodic in-plane modulation of the refractive index results in RN diffraction. The M state can be switched back into the P state at low voltages or into a homeotropic H state at high voltages. In the H state the director is normal to the plates and there is no diffraction.

For the optimal design of the cell (high uniformity of the stripe pattern in the applied field) we used the observations

made by Chigrinov *et al.*¹¹ for wedge-shaped samples. The in-plane orientation of stripes strongly depends on the angle γ between the rubbing directions of the two plates and the ratio d/p , where d is cell thickness and p is the equilibrium cholesteric pitch. For the cell with $\gamma = 90^\circ$, the stripes make an angle 45° or 135° with one of the rubbing directions, depending on the d/p . For $\gamma = 0^\circ$, the stripes can be oriented parallel or perpendicular to the rubbing direction. In the thick part of the wedge ($d/p \geq 2$) the stripes are not uniform and contain numerous defects. Thus to obtain a good grating pattern we used flat cells with $d/p \sim 1$.

Substrates were coated with polyimide SE-610 (Nissan Chem. Ind.) to provide a slightly tilted director orientation (5° – 10° with respect to the substrate). The polyimide layers were rubbed unidirectionally to define an in-plane “easy axis” of the molecular orientation. Depending on the surface treatment and chiral dopant concentration, two types of the cells were obtained: (a) with $\gamma = 90^\circ$ and 270° director twist across the cell; (b) with $\gamma = 0$ (antiparallel rubbing) and director twist 360° . In the experiment we used nematic liquid crystal LC ZLI 5200-000 (E. Merck) with a positive dielectric anisotropy $\Delta\epsilon \approx 5.9$, and refractive indices $n_o \approx 1.494$, $n_e \approx 1.614$ at 20°C for ordinary and extraordinary waves, respectively. The nematic material was doped with the chiral agent CB 15 (EM Industries) to control the ratio d/p . The cells were vacuum filled, and their thickness was $d \approx 5$ – $6 \mu\text{m}$.

The initial structure of the cholesteric cell at $U = 0 \text{ V}$ is planar, the P state, with the helix axis oriented perpendicular to the cell substrates. When the applied field exceeds a threshold voltage U_c (amplitude $U_c = 3.9 \text{ V}$ for a cell with 270° twist and $d \approx 5 \mu\text{m}$, applied voltage frequency $f = 1 \text{ kHz}$), a periodic stripe pattern appears in the plane of the sample, the M state (Fig. 1). Although some dislocations can be noticed, the structure is quite uniform. Stripes are oriented at 45° from the rubbing direction for a 270° cell. For the 360° twist cell we obtained the stripes oriented along the rubbing direction.

For the diffraction studies a He–Ne laser beam ($\lambda = 633 \text{ nm}$) was directed through a linear polarizer whose orientation was controlled by Newport rotary stage 495. The polarized beam was incident normally to the cell. The diffracted light intensity was measured by a photodetector for each of the different locations of diffraction maxima.

Figure 2 shows a diffraction pattern at $U = 4.2 \text{ V}$ for the light polarized along the rubbing direction of the front plate

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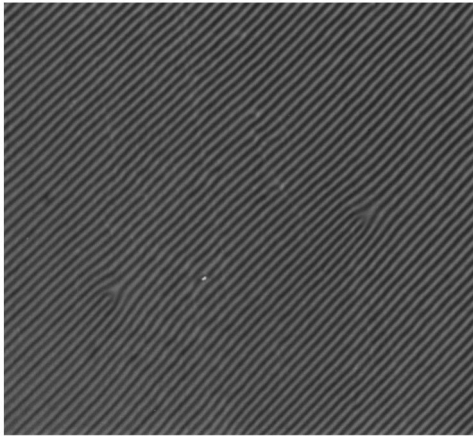


FIG. 1. Microscopic picture of the stripe domains in the 270° cell, applied voltage $U=4.2$ V. The distance between two consecutive stripes is $L/2 = 6.6 \mu\text{m}$.

of a 270° cell. There is no analyzer in the system. The diffraction pattern is rather unusual. First, the strongest maxima are the second-order ones. The measured diffraction angle for the second maximum is approximately 5.5° . Two first order maxima are visible, but they are much weaker (10–20 times). Higher order (3,4,...) maxima are hard to detect when the voltage is close to U_c . However they appear as the field increases. Odd order diffraction maxima are significantly weaker than even ones, and their intensity depends strongly on the angle of incidence.

Voltage dependencies of the diffraction intensities for the zeroth and second two maxima (combined) are shown in Fig. 3. The voltage scan rate was $+1$ mV/s. Incident light is polarized along the rubbing direction of the front plate. Two voltage regions should be considered separately. In the region from $U_c = 3.9$ V to $U \approx 4.5$ V the diffraction pattern is stable. Switching by voltages higher than $U > 4.5$ V gives unstable patterns with moving dislocations. The diffraction pattern slowly evolves and shows significant scattering.

The second mode of diffraction switching is the transition from the H state at high applied voltages ($U \geq 10$ V) to the M state ($4 \text{ V} < U < 4.4 \text{ V}$).

To define the diffraction grating response time we mea-



FIG. 2. Diffraction pattern at $U=4.2$ V for a 270° cell; diffraction angle is 5.5° for the intense second order maxima.

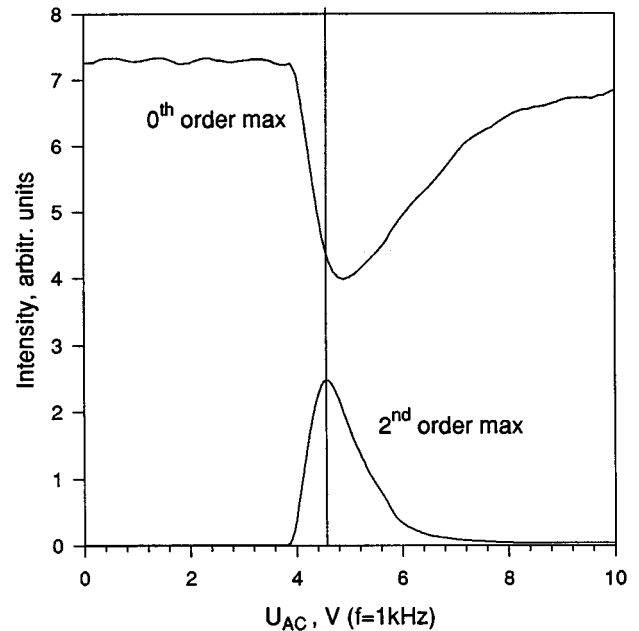


FIG. 3. Voltage dependence of diffraction intensity for zeroth and combined two second order maxima for 270° twist cell.

sured the intensity of the second maximum as a function of the applied electric field. Voltage steps of amplitude $U = 3.6$ V and offset voltage $U_{\text{off}} = 0.6$ V were applied. The growth and decay time Δt (measured when the intensity changed to 90% from the initial value) is approximately 20–30 ms.

The diffraction efficiency depends on the direction of incident light polarization. Results for the second maximum for 270° and 360° cells are presented in Fig. 4. No analyzer is present. Polarizer orientation is measured with respect to the stripe orientation in the cell.

The appearance and polarization properties of a diffractive pattern in cholesteric cells show that the director distri-

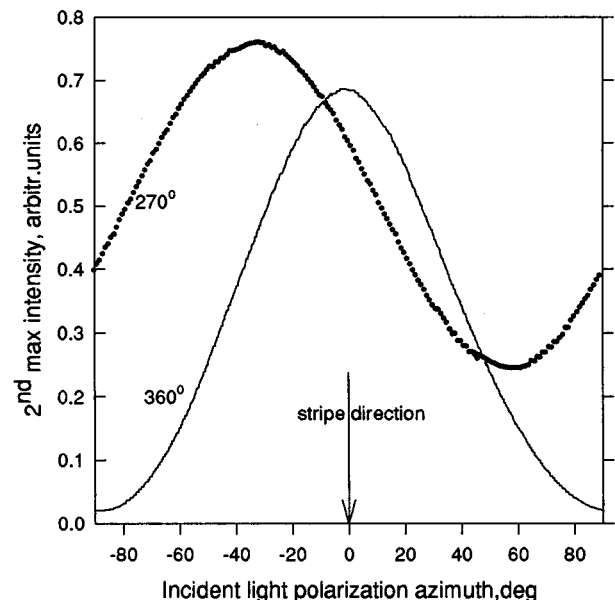


FIG. 4. Diffraction intensity vs direction of the incident light polarization for 270° and 360° cells ($U=4.2$ V).

bution in the cell is rather complicated. We will compare our results with theoretical predictions of the diffraction of a cholesteric layer with no surface influence.^{9,10}

Let us consider an ideal cholesteric layer and light propagating normally to the helix. For the polarization perpendicular to the helix axis, the refractive index is a periodic function of coordinate x along the helix axis. For the polarization along x axis the refractive index is $n = n_0 = \text{const}$. Such a layer represents a polarization-sensitive phase grating: only the component of electric field vector that is perpendicular to the helix axis is diffracted. The diffraction condition is given in general by

$$m\lambda = L \sin \theta, \quad (1)$$

where m is the diffraction order, θ is the corresponding diffraction angle, and L is the grating periodicity.

We note two main differences between what was observed in the diffraction pattern in our experiment and that theoretically predicted for an ideal cholesteric:^{9,10}

- (1) The maximum efficiency of diffraction is (not necessarily) for the light that is polarized parallel to the stripes (see the data for 270° twist cell, Fig. 4). This fact clearly indicates that in the M state there is still some director rotation between the plates that changes the state of light polarization. This rotation is controlled not only by the molecular twist and field but also by the surface anchoring that should be taken into account for an adequate theoretical model.
- (2) For an ideal cholesteric, theory predicts only even diffraction orders corresponding to the optical periodicity $p/2$. The directions $\theta = \pm 5.5^\circ$ of $m = \pm 2$ maxima fit well (Eq. (1)) with $\lambda = 633$ nm and $L = 13.2$ μm . Even diffraction orders correspond to the spatial harmonic with the periodicity $L/2 \approx 6.6$ μm . This periodicity is the distance between two consecutive bright or dark stripes in Fig. 1. The dislocation structures with Burgers vector clearly equal to L (Fig. 1) confirm that the real periodicity of stripes is L rather than $L/2$. This conclusion is also supported by polarizational microscopy observations with a quarter wave plate: The interference colors are different for the i th and $(i+1)$ th stripes but are the same for i th and $(i+2)$ th stripes. This means that the in-plane director orientation in two consecutive stripes is different. Qualitatively it can be understood as the consequence of undulation of pseudonematic layers in the cell.

A peculiar feature of the diffraction is that the higher-order maxima are visible only at relatively high voltages. This feature might be related to two mechanisms. The first is the appearance of additional spatial harmonics when the field increases (the phenomenon is well established for ideal helical structures in the normal field¹⁴). Secondly, the depth of optical modulation in the plane of the cell depends on the applied voltage, causing the change of the effective thickness (Δnd) of the phase grating.

The unique polarization properties of the diffraction can be understood as a consequence of the diffraction in the anisotropic phase grating with index ellipsoid variation in-plane and normal to the plane of the grating.¹⁵ The diffraction pattern and properties can be used to obtain the parameters of the spatial molecular orientation in the cell by assuming some director distribution model, as was done in Ref. 15. Because the phenomenon of the in-plane modulated cholesteric structure is practically impossible to describe analytically, numerical calculations are in progress to model the real director field and diffraction properties.

The measured response times (~ 20 ms) are in good agreement with the well-known estimate of the relaxation time of the helical structure $\tau \sim \gamma_1 D^2 / 4\pi^2 K$, where D is the characteristic length of the system (in our case $D \approx d \approx p$), γ_1 is the viscosity coefficient, K is an effective elastic constant.^{2,14} With typical $\gamma_1 \approx 200$ mPas, $K \approx 10^{-11}$ N and $D \approx 5$ μm one gets $\tau \approx 20$ ms. A faster response time could be achieved by reducing the cell thickness and pitch.

To conclude, we demonstrated that a modulated cholesteric structure in an applied field could be used as a switchable diffraction grating. The optical response times are of the same order as the switching times in twisted nematic displays (~ 20 – 30 ms). Polarization dependence of the diffraction properties clearly shows that the surface alignment significantly influences the cholesteric structure; the latter cannot be considered as an ideal helix. Further studies of the role of system parameters (birefringence, elastic constants, dielectric anisotropy, cell thickness, pitch, etc.) should be performed to optimize the diffraction characteristics.

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