

# Electrically-switchable, polarization-independent diffraction grating based on negative dielectric anisotropy liquid crystal

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An atomic force microscope is used to scribe polymer-coated substrates to create an electrically-controlled polarization grating. The grating is nondiffracting in the voltage-off state and diffracting in the voltage-on state. Based upon an optical phase difference of approximately  $\pi$  between adjacent pixels, the grating's efficiency is independent of optical polarization and can be prepared for diffraction in either one or two dimensions.

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A number of liquid crystal-based architectures have been proposed for switchable optical gratings [1–9], which can play important roles in optical beam steering and waveguide applications. One class of liquid crystal gratings involves phase separation of a mixture of a liquid crystal and another material, typically a polymer, and exploits the refractive index difference between the background matrix and liquid crystal dopant; such gratings often do not require polarizers. Because liquid crystals are birefringent, another class of gratings that involves a homogeneous liquid crystalline nematic phase often requires the use of a single or a pair of polarizers for operation.

About a dozen years ago Chen, et al suggested an architecture in which hybrid alignment was imposed on a nematic liquid crystal [1]: At one surface the molecules are homeotropically (vertically) aligned, whereas at the other surface the molecules are nearly planar aligned, but with a small pretilt. Additionally, the azimuthal orientation  $\varphi$  of the nearly planar aligned region alternates periodically in position with a period  $P$ , such that  $\varphi = 0$  in one pixel and  $\varphi = 90^\circ$  in the adjacent pixel. Incident light normal to the grating breaks up into ordinary and extraordinary polarizations, with each polarization diffracting sepa-

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rately. For an ideal one-dimensional “square grating” in which the optical retardation  $\alpha$  of one pixel differs by  $\pi$  from the adjacent pixel, the intensities of the  $m^{\text{th}}$  order diffraction peaks are proportional to  $m^{-2}$  for  $m$  odd, and vanish for  $m$  even. Here  $\alpha \equiv \frac{2\pi}{\lambda} \int n_{eff}(z) dz$ , where  $n_{eff}(z)$  is the effective local refractive index for a given polarization eigenmode. Additionally, although the phase difference between the *diffracted* electric fields for the two orthogonal polarization states is  $\pi$ , in principle their intensities are identical and therefore add. Thus, the diffraction intensity profile is independent of polarization. Using semi-transparent indium-tin-oxide (ITO) electrodes, on applying an electric field  $E$  normal to the substrates, the resulting electric torque aligns the positive dielectric anisotropy molecules vertically, i.e., parallel to the field, throughout the bulk, except in a very small region of thickness  $\xi = \sqrt{K/\Delta\chi E^2}$  at the substrate. Here  $K = \sin^2 \theta + \cos^2 \theta$ ,  $K_{11}$  and  $K_{33}$  are the splay and bend elastic constants,  $\theta$  is the polar angle relative to the cell normal, and  $\Delta\chi$  is the electric susceptibility anisotropy. Thus, in the presence of a sufficiently large electric field the optical retardation in adjacent pixels is almost identical, and the diffraction spots nearly disappear. With recent advances in microscopic and nanoscopic control of surface – liquid crystal interactions, we have exploited the ideas of Ref. [1] to construct a prototype grating that transmits in the voltage-off state, diffracts in the voltage-on state, and does not require a polarizer. One advantage of this architecture is that the diffraction peaks vanish completely in the voltage-off state, as the liquid crystal director orientation is everywhere perpendicular to the cell normal. A second advantage is that one can approach saturated planar orientation in the limit of high electric fields.

Two ITO slides were cleaned and spin-coated with the polyimide SE1211 (Nissan Chemical Industries), then baked for 1 hour at a temperature of 180° C. This preparation protocol results in homeotropic alignment of the liquid crystal at the substrate. If baked at higher temperatures and rubbed, we have shown that it is possible to induce a polar pretilt angle as high as 50° off the direction perpendicular to the substrate, i.e., off the vertical direction [10]. Weaker rubbing results in a smaller pretilt angle, and for a rubbing strength  $n_f$  smaller than a critical value  $n_f^0$ , the director remains normal to the substrate. Thus, using the stylus of an atomic force microscope (AFM), the polyimide on one of the slides was scribed weakly over a  $100 \times 100 \mu\text{m}$  square with ten pixels, each  $100 \mu\text{m}$  long and  $10 \mu\text{m}$  wide (Fig. 1a). The odd numbered pixels were scribed unidirectionally parallel to the long axis of the pixels, i.e., along the x-axis, with rub lines spaced 200 nm apart; the even numbered pixels were scribed

along the y-axis, perpendicular to the long axis of the pixels, also with lines spaced 200 nm apart. The opposing substrate was not scribed. The two slides were placed together, separated by a pair of Mylar spacers. Using an interferometric technique, the cell spacing  $d$  was found to be  $(3.0 \pm 0.2) \mu\text{m}$ . The cell was inserted into a temperature-controlled oven and filled with negative dielectric anisotropy liquid crystal ZLI-4330 (Merck) in the isotropic phase, cooled below the nematic – isotropic phase at transition temperature  $T_{NI} = 82^\circ \text{C}$ , and then cooled to room temperature. Since the rubbing strength was sufficiently weak, i.e.,  $n_f < n_f^0$ , the director was oriented homeotropically throughout the cell in the absence of an electric field.

Light from a He-Ne laser at wavelength  $\lambda = 633 \text{ nm}$  passed through a light chopper; a polarizer oriented at an angle  $\beta$  with respect to the x-axis; a lens of focal length  $f = 73 \text{ mm}$ ; and the sample, which was located a distance approximately equal to  $f$  behind the lens. The position of the lens was adjusted so that the diameter of the beam at the sample was just under  $100 \mu\text{m}$ . A photodetector, apertured with a  $100 \mu\text{m}$  pinhole, was placed a distance 12 cm behind the sample on a microtranslation stage. The detector output was fed into a lock-in amplifier referenced to the light chopper frequency, and the output from the lock-in amplifier was computer recorded. In the absence of an applied voltage the nematic director is homeotropic and spatially uniform. Figure 2a shows the intensity of light for polarizer angle  $\beta = 90^\circ$  when the sample was heated to  $40^\circ \text{C}$ ; the profile is similar for all angles  $\beta$ . The absence of first or higher order diffraction peaks demonstrates virtually perfect transmission in the voltage-off state, independent of polarizer angle  $\beta$ . At small nonzero voltages no diffraction peaks were visible, as the liquid crystal director orientation remained homeotropic. Above the Fredericksz threshold voltage  $V_{th}$  [11], however, diffraction peaks became visible: For  $V > V_{th}$  the tendency of the negative dielectric anisotropy liquid crystal molecules to orient perpendicular to the electric field wins out over the elastic energy associated with nonuniform alignment. Figure 1b shows schematically the director orientation through the cell's cross-section. Notice that the liquid crystal director remains *approximately* normal at the substrates, with a small pretit determined by the magnitude of the applied field and by the local rubbing direction ( $\varphi = 0^\circ$  in the odd numbered pixels and  $\varphi = 90^\circ$  in the even numbered pixels). For distances  $\gtrsim \xi$  from the substrates, the director is oriented perpendicular to the electric field. For polarization orientation  $\beta = 0^\circ$ , the pixels alternate from an extraordinary to an ordinary

to an extraordinary.... refractive medium, giving rise to the symmetric diffraction pattern in Fig. 2b obtained with an applied voltage  $V = 40$  V at  $T = 40^\circ$  C. For polarization  $\beta = 90^\circ$ , the pixels alternate from an ordinary to an extraordinary to an ordinary.... refractive medium, in principle giving rise to the same diffraction pattern, as seen in Fig. 2d. Finally, for polarization  $\beta = 45^\circ$ , the light breaks into two eigenmodes (one at  $\beta = 0^\circ$  and one at  $\beta = 90^\circ$ ), each diffracting independently and resulting in the pattern in Fig. 2c. These data clearly show that the grating efficiency is independent of optical polarization. For  $V = 40$  V, we found maximum diffraction efficiency  $e$ , defined as the ratio of the the integral under the two  $m = 1$  peaks divided by the total integrated intensity, to occur at  $T \approx 40^\circ$  C, where  $e = 0.44$ ; these are the results shown in Figs. 2b, 2c, and 2d. We note that the width of the diffraction peaks is due largely to the limited number of spatial periods illuminated by the beam, as well as the small angle associated with the focused beam. Although we have chosen to demonstrate proof-of-concept for the grating by writing a single, spatially limited but high precision, diffraction pattern, other techniques such as photolithographic, ion beam, or massively-parallel rubbing tips, may be used to scale up the design to create much larger gratings.

Maximum diffraction efficiency and elimination of even order diffraction peaks can be accomplished ideally when the optical phase retardation  $\alpha$  differs by  $\pi$  from one pixel to the next. The effective local refractive index  $n_{eff}(z)$  depends on both applied voltage and temperature. Figure 3, for example, shows the intensity of the  $m = 1$  peak as a function of voltage at  $T \approx 40^\circ$  C. The initial slow rise is due to the nonzero Freedericksz threshold voltage  $V_{th}$ . At higher voltages the intensity, and thus the diffraction efficiency, continues to rise, although the onset of asymptotic behavior becomes apparent at the highest voltages applied. We have chosen to perform our experiments at an applied voltage of  $V = 40$  V, as higher voltages would have degraded the cell over long periods of time. Let us estimate the retardation difference  $\Delta\alpha$  between adjacent pixels in our  $d = 3.0 \mu\text{m}$  cell at the temperature of maximum efficiency,  $T \approx 40^\circ$  C. As determined with Abbe refractometer,  $n_e - n_o \approx 0.133$ , where  $n_o$  and  $n_e$  are the ordinary and extraordinary refractive indices, respectively. For finite applied voltage the director orientation varies from planar in the bulk part of the cell to approximately vertical at the substrates over a small distance  $\xi$  near each of the two substrates (Fig. 1b). For  $K \sim 1 \times 10^{-6}$  dyn [11] and  $\Delta\chi \sim 0.13$  [12], we find  $\xi \sim 0.1 \mu\text{m}$  at this voltage. These surface layers have the effect of reducing the retardation difference  $\Delta\alpha$

between adjacent pixels, resulting in  $\Delta\alpha \sim 3.7$ . This is larger than  $\pi$ , which would suggest that maximum efficiency should be achieved at higher temperatures, where the birefringence is smaller.

But several other factors enter the picture. The energy cost associated with elastic distortions have the effect of homogenizing the director orientation. At the rubbed surface the azimuthal director orientation  $\varphi$  does not change abruptly by  $90^\circ$  at the pixel boundaries, but rather varies smoothly over a distance  $L \sim K/W$ , where  $W$  is the (temperature dependent) quadratic anchoring strength coefficient associated with orientational deviations from the rubbing direction.  $W$  depends upon both temperature and polar tilt angle, and typically is of order  $10^{-3}$  to  $10^{-1}$  erg cm $^{-2}$ . Thus, the width  $L$  of the boundary between the pixels can be as small as  $0.1 \mu\text{m}$  or as large as  $10 \mu\text{m}$ , although polarized microscopy examination of the cell indicates that  $L \sim 1 \mu\text{m}$ . This washing out of the boundary has a profound influence not only on the conditions of maximum grating efficiency, but also on the absolute efficiency of the grating. It also explains in part the large central peak for  $m = 0$ . Additionally, twist elasticity tends to homogenize the azimuthal orientation as one moves away from the rubbed substrate, and thus drives the grating away from the ideal one-dimensional “square grating” condition. This effect can be mitigated in two ways: First, a higher birefringence liquid crystal may be used in conjunction with a thinner cell, thereby reducing the effects of twist elasticity and reducing the homogenization effect away from the rubbed substrate. Second, one can use two rubbed surfaces aligned in register, which would promote the desired azimuthal orientations at both substrates and reduce the homogenization effect by a factor of approximately two. These are issues to be addressed in the optimization of the grating.

Finally, we note that two-dimensional gratings also are possible. Figure 4a shows a photograph of the diffracted light from a checkerboard writing pattern. Note that the bright main beam is blocked. Figure 4b shows the diffracted light from the writing pattern in Fig. 1a.

The proposed grating has the advantage of a nearly perfectly nondiffracting voltage-off state and the ability to saturate the alignment in the voltage-on state. Unfortunately, this architecture, as do all nematic architectures that rely on the spatial variation of the director in a homogeneous phase, suffers from elastic effects that tend to drive the director orientation away from the desired profile. Nevertheless, the simple fabrication for large

sized gratings, along with its polarization-independent character, makes this an attractive alternative for one or two dimensional switchable gratings.

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FIG. 1: a) Front view: schematic diagram of rubbing pattern on one substrate. Each pixel is  $10 \mu\text{m}$  wide, and  $\varphi$  represents the azimuthal rubbing direction ( $0^\circ$  or  $90^\circ$ ). b) Side view: (cross-section) of cell.  $\xi$  represents the electric field coherence length, such that the director in the bulk is approximately  $\perp \vec{E}$  for distances from the substrates  $> \xi$ . Note that figure does *not* show the azimuthal homogenization of the director away from the rubbed substrate.

FIG. 2: a) Intensity vs. angle for  $E = 0$ . Only the central peak,  $m = 0$ , is present. b, c, and d) Intensity vs. angle for three different orientations  $\beta$  of the polarizer. Temperature  $T = 40^\circ \text{C}$  and applied voltage  $V = 40 \text{ V rms}$ . Efficiency  $e$  is independent of  $\beta$ . Note the decrease of the central peak  $m = 0$  intensity from the field-off case (a) due to diffraction, especially into the  $m = 1$  peaks.

FIG. 4: a) Diffracted light for two-dimensional checkerboard pattern ( $m = 0$  central peak is blocked out). Notice the presence of weak higher order peaks. b) Diffracted light for the one-dimensional pattern (see Fig. 1a), with central peak blocked out.

FIG. 3: Intensity vs. applied voltage for  $m = 1$  diffraction peak at  $T = 40^\circ \text{C}$ .







