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Field-Induced and Polymer-Stabilized Two-Dimensional Cholesteric Liquid Crystal Gratings

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Field-induced and polymer-stabilized two-dimensional cholesteric liquid crystal gratings

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The authors experimentally demonstrate an electrically switchable gratings based on polymer-stabilized, field-induced two-dimensional square-lattice pattern of a cholesteric liquid crystal. A dependence of the two-dimensional diffraction patterns with the magnitude of applied voltage is observed for before and after the polymer stabilization. The diffraction efficiency reaches 84% calculated for the zero order light intensity at the applied voltage of 0.23 V/μm for a 10 μm thick sample. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2745198]

Optical diffraction gratings play a key role in areas such as multiplexing and processing optical signals (optical interconnection, beam steering, and sensor array interrogation) and protecting vital sensors from hostile radiation.[1–5] Liquid crystals, whose refractive indices can be modulated by external species with a profile, enable the design of very high efficiency switchable phase gratings. Several approaches for liquid crystal gratings have been suggested.[6–10] These strategies involve either the use of patterned alignment layer (or electrode) on substrate sandwiching a low molecular weight liquid crystal, an approach which produces domains of alternating orientation of liquid crystal (LC) optic axis, or the use of polymer-liquid crystal composites, where a controlled polymer-liquid crystal phase separation induces the grating structure. In all those systems, a refractive index gradient is imposed by lithographically (or holographically) patterning the alignment layer/electrode or distribution of liquid crystal droplets with random average director orientation within a polymer binder.[11] In fact, a low-concentration polymer network may also be used in the chiral nematic case to stabilize the grating texture.[12]

Polymer-stabilized cholesteric gratings have become a subject of great attention because of the potential as active diffractive optical elements.[13,14] These gratings, formed by stabilizing the "fingerprint" texture of a cholesteric LC induced in a standard electro-optical cell, can function in either the Bragg or Raman-Nath (phase grating) limits, and are particularly suited for optical beam steering, optical routing, sensors or sensor protection applications requiring operation in transmission, high efficiency, and millisecond response to a low voltage. Two-dimensional (2D) electrically switchable cholesteric gratings may be achieved by applying electric field to a cholesteric at the optimum field conditions (frequency and voltage) and cholesteric pitch to cell thickness ratio.[15,16] However, this type of gratings requires a small bias voltage to achieve the 2D optical pattern-forming state of a cholesteric and thus, it is inappropriate for practical applications. In this letter, we present the fabrication of a 2D electrically switchable diffraction grating using polymer-stabilized 2D pattern-forming state of a cholesteric. The pattern formation in a cholesteric liquid crystal is schematically illustrated. The polymer morphology affecting on the performance of external field on the diffraction patterns is also explored.

The grating sample is prepared with a mixture of nematic LC BL006 (94.4 wt %), chiral dopant R1011 (0.4%), reactive nematic monomer RM257 (5%), and photoinitiator Irgacure 651 (0.2%) in order to obtain a 4π twist for the cholesteric helixes. The mixture is filled into electro-optical cells for homogeneous alignment with 10 μm cell gap by a capillary action. The optical axis of the cholesteric initially twists from bottom to top substrate (planar state), with the helical axis perpendicular to the substrate plane. Applying a square wave voltage across the gap between the substrates reorients the optic axis of the LC perpendicular to the substrates. With the magnitude of the applied electric field at 0.25 V/μm, the cholesteric forms a two-dimensional square-lattice pattern at the condition of high frequency ($\geqslant$1 kHz) electric field and the $d/p \geqslant 2$, where d is the cell thickness and p is the pitch of cholesteric. Photopolymerization of RM 257 was carried out in this pattern-forming state (0.25 V/μm at 1 kHz) using a collimated, unpolarized UV light at 322 nm, 0.72 mW/cm^2 for 30 min.

The field-induced "square-lattice" distortion in cholesteric shown in Fig. 1 has been given a rather different origin as a result of a pure dielectric torque or electric conductivity anisotropy. The latter case produces a periodic distribution of "stored" charge. The variation in orientational order that has been proposed for the square-lattice texture is a simple superposition of orthogonal, one-dimensional undulations of the planar director, each having the same period as the resulting 2D grid. The textures shown were obtained using an initial 4π-twist cell, an alternating field at 1 kHz, and with the optical microscope focus adjusted either toward one of the substrate surfaces [Fig. 1(a)] or in the sample midplane [Fig. 1(b)]. The spatial period of the texture is 20 μm, i.e., the horizontal or vertical distance between bright lines. Also, shifted halfway along the diagonal of the square formed by the bright lines is a second, identical pattern of faint lines. This texture is sensitive to both the magnitude and frequency of the applied voltage.

The square-lattice texture shown in Fig. 1(d) can function as a two-dimensional phase grating between the "grating-off" [Fig. 1(e)] and "grating-on" states [Fig. 1(f)] with an input polarized light. Various diffraction patterns obtained from the 2D texture prior to polymer stabilization are

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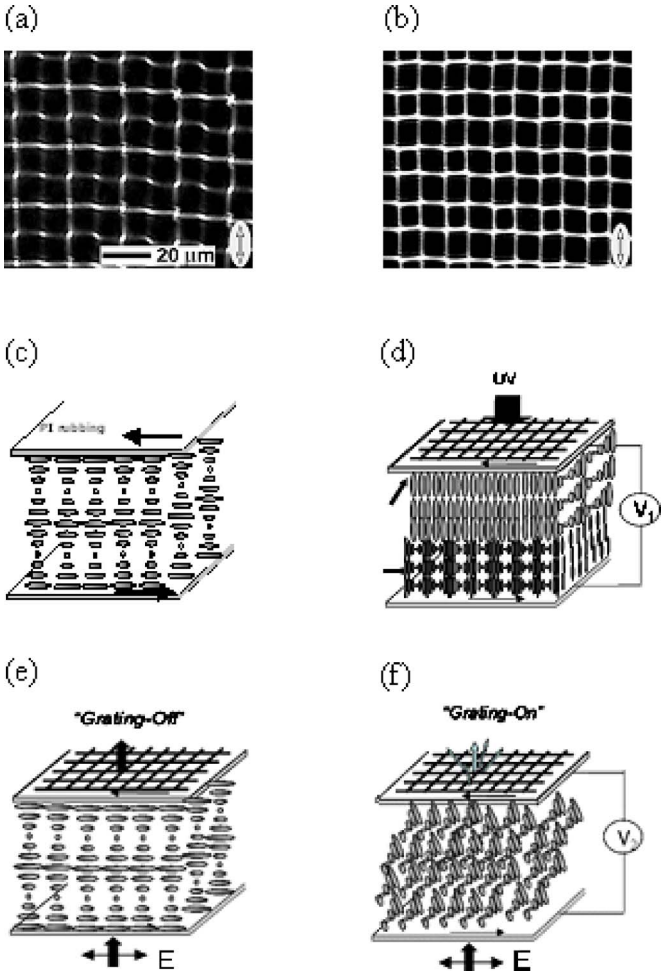

FIG. 1. (Color online) Square-lattice pattern of a cholesteric liquid crystal, induced by applying an alternating electric field (1 kHz, 0.25 V/μm) to the initial 2π-planar state. Polarizing optical micrographs show the square-lattice patterns (a) near the surface and (b) in the middle of the cell, respectively. A cholesteric liquid crystal at planar state (c) and the field-induced 2π helix rotation to form a two-dimensional periodical pattern (d) are illustrated. The "grating-off" (e) and "grating-on" (f) states with input polarized light are schematically presented.

presented in Fig. 2. The diffraction pattern is insensitive to the incident laser light (633 nm) polarization because the cholesteric helix is aligned perpendicular to the surface and the pitch is in infrared spectrum (10 μm). A polarizer was placed at a 90° angle to the figure to reduce the intensity of incident light and no analyzer was used. As the stability of the texture is rather sensitive to the magnitude of the applied field, small variation of the applied field at 1 kHz significantly alters diffracted optical pattern. The weak one-dimensional pattern obtained near the threshold voltage was sensitively transformed to complex two-dimensional patterns by the slight increase in applied field. Since the grating axis is reoriented during the switching between grating "on" and "off" states, the spatial pattern of diffracted spots is also changed. This problem, which seriously hampers device application, is originated from the relatively large value of d/p (i.e., weak surface aligning for pattern orientation).

To solve this postponement of pattern formation problem, uniform texture was formed with great care and stabilized using a low-concentration polymer network. The grating texture fixed by internal network ensures reproducible diffraction pattern during the switching. To achieve this, an

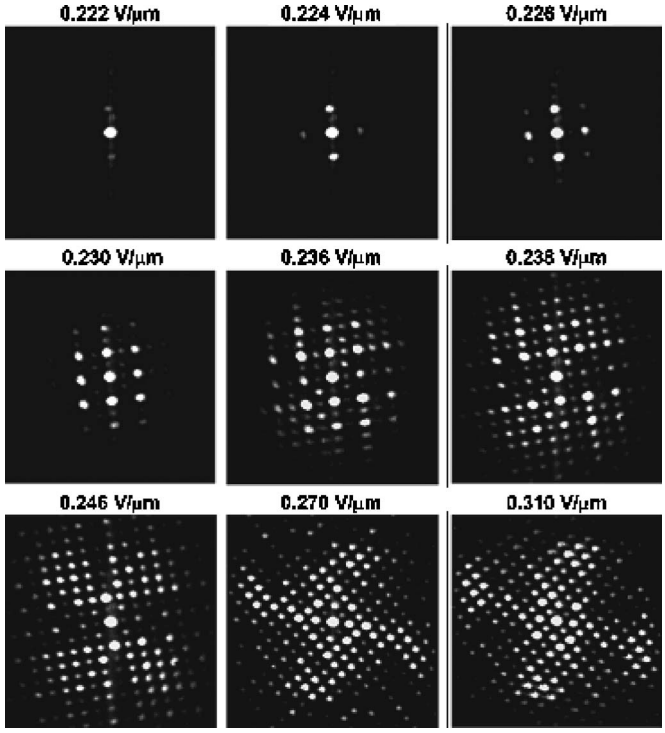

FIG. 2. Optical diffraction patterns obtained by applying various amplitudes of applied electric fields to the cholesteric square-lattice pattern prior to polymer stabilization.

UV dose of 0.72 J/cm^2 at the wavelength of 322 nm was used to form the polymer network. The optical micrograph of the sample cell after removal of LC is presented in Fig. 3(a). The image taken without analyzer bears two sets of square-lattice pattern with the weak pattern shifted halfway along diagonal to the strong lattices. The square lattice was formed with spatially oriented stripes with approximately 10 μm parallel and perpendicular to the surface alignment direction. The polymer network, in this case, showed very little birefringence under crossed polarizers. As shown in Figs. 3(b) and 3(c), the morphological anisotropy of the network is templated from the spatially ordered LC host. In addition, scanning electron microscopy (SEM) images of the bare polymer network reveal, on both substrates, a square array of polymer bundles with *twice* 10 μm period. This situation is reminiscent of the interdigitation of one-dimensional walls and indicates that mirror symmetry across the sample midplane is also broken. The variation in orientational order that has been proposed for the square-lattice texture is a simple

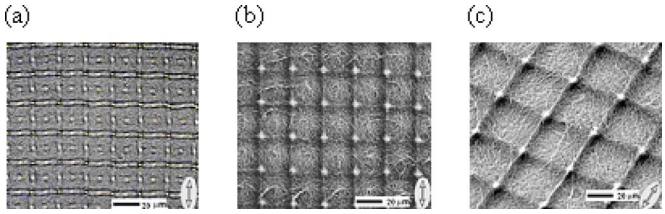

FIG. 3. (Color online) Images are obtained after removal of liquid crystal. (a) The optical image of bare polymer network. No analyzer is used. (b) The SEM image taken from the substrate normal reveals, on both substrates, a square array of polymer walls with a 20 μm period, indicating that the original pattern consists of 20 μm square lattices on each surface shifted halfway along the diagonal with respect to each other. (c) The network structure viewed from glancing angle indicates a superposition of the one-dimensional polymer patterns with a 20 μm period.

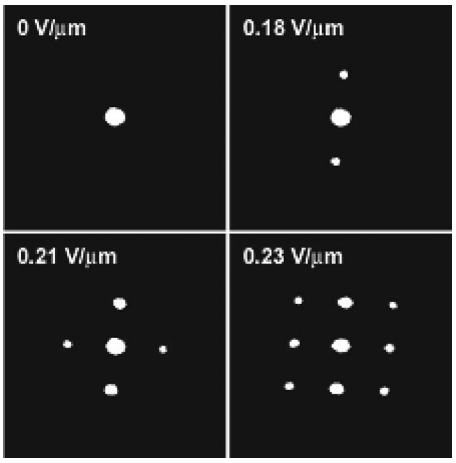

FIG. 4. Cholesteric grating is switched between nondiffracting and two-dimensional diffracting states in response to applied voltage.

superposition of orthogonal, one-dimensional undulations of the planar director, each having the same period as the resulting two-dimensional grid. In a 4π-twisted planar cell, the textural variations between substrates observed in Figs. 1(a) and 1(b) and the SEM results of Figs. 3(b) and 3(c) suggest a more complex superposition involving two square lattices. Each square lattice takes the space approximately half of the cell and with one shifted halfway along the diagonal with respect to the other. In fact, each square-lattice array localized on both substrate surfaces is a superposition of orthogonal one-dimensional stripes with a 20 μm period as clearly seen from the glancing angle [Fig. 3(c)].

The four panels of Fig. 4 show switching for a two-dimensional grating based on the stabilized square-lattice texture of Fig. 3. Three distinct diffracting states with two, four, and eight dominant spots are accessible at relatively low fields of 0.18, 0.21, and 0.23 V/μm, respectively. The diffraction efficiency, in this study, was defined as the ratio of the diffracted light intensity to the total light intensity in all orders. The corresponding diffraction efficiencies are 47%, 68%, and 84%, respectively. In this particular case, a bulk planar diffracting state is no longer stable when the field is removed, but the "memory" effect due to the internal polymer network ensures in each case precise recovery of the distribution of diffracted spots when the field is reapplied.

To conclude, we have demonstrated the 2D electrically switchable cholesteric gratings and the polymer-stabilized cholesteric gratings using field-induced microstructures of pattern-forming states in a cholesteric liquid crystal. The morphology of these microstructures may be fine-tuned to stabilize the basic distortion of the LC optical axis or provide an "internal memory" for the distortion, yet still allow considerable flexibility for electrical switching between various efficient light-diffracting states.

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