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Fast switchable grating based on orthogonal photo alignments of ferroelectric liquid crystals

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We demonstrate a fast switchable grating based on ferroelectric liquid crystals and orthogonal planar alignment by means of photo alignments. Both 1D and 2D gratings have been constructed. The proposed diffracting element provides fast response time of around 20 μs, contrast of 7000:1 and high diffraction efficiency, at the electric field of 6 V/μm. The saturated electro-optical (EO) states up to very high frequency ($\approx$5 kHz) are the real advantage of the proposed switchable grating, which opens several opportunities to improve the quality of existing devices and to find new applications. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4737642]

Liquid crystal (LC) gratings have become very important recently, because of their easy tunability with electric field and wide field of application in displays, photonic devices and projection displays, etc.[1] There are three different approaches that underline the most popular methods used for producing the diffractive profile. These are based on: (1) deploying the patterned electrode;[2] (2) defining two or more different alignment regions;[3] and (3) utilizing the intrinsic diffractive properties of LC like cholesteric[4] and ferroelectric liquid crystals (FLC).[5] All of these diffractive LC structures have been extensively documented recently.[1–10]

Most of such gratings are slow and show low diffraction efficiency and low contrast ratio. They also require rather high driving electric field. On the other hand, there are several methods such as the fringe field effect and the guest host effect that have been suggested to increase the speed of the nematic LC devices.[6,7] In these methods, however, the response time is typically limited to 1 ms.

Several efforts to improve the response time are still in progress. Most notably, the polymer-stabilized blue phase liquid crystal that has been proposed last year shows high diffraction efficiency with the response time at about 400 μs but at the expense of high driving voltage.[10] We have recently disclosed a fast switchable grating based on three electrode driving scheme device[2] comprising nematic LC with the response time of 150 μs at the electric field $E = 20$ V/μm.

In an alternative approach that uses the flexoelectric effect in short pitch cholesteric LCs (Ref. 9), the response time is limited to 200 μs. This technology, however, has several material issues and a very complicated fabrication procedure. As a matter of fact, some of the recently proposed diffraction grating elements that show good optical quality combined with fast switching speed generally requires high driving voltages. Due to some fundamental limitations, the latter cannot be reduced much.[11]

FLC diffractive elements have an edge on all of the existing technology because of their fast switching speed and low power consumption. There are, however, a number of problems[5] that considerably complicate deploying FLC as a diffractive element.

There are two known possible approaches to realize FLC diffractive element. The first one uses the diffractive properties of FLC arising from the periodicity of the ferroelectric domains, which strongly depends on the spontaneous polarization, P_s. In this case, high diffraction efficiency can only be achieved in materials with large values of P_s. But, the high P_s is known to produce other defects that have a destructive effect on the quality of the diffractive profile.[12,13]

The second approach, which is based on deploying the striped electrodes, suffers a poor optical quality caused by highly non-uniform electric field. Thus, both of these approaches are not good for the FLC diffractive elements.

In this paper, we suggest an alternative approach to fabricate FLC gratings characterized by high frequency saturated electro-optical (EO) modulation, low driving voltage, high diffraction efficiency, and high contrast ratio. Such gratings are very promising for applications in a variety of fast photonic and display devices.

Alignment of FLC is not a simple technological problem but rather a scientific issue that involves many facts discussed in Refs. 14 and 15. Recently, we have proposed an EO mode (the so-called electrically suppressed helix (ESH) mode) that offers good alignment quality, high contrast ratio, and low driving voltage. The self-diffractive properties of FLC in this EO mode are extremely poor.[15] Nevertheless, owing to the good quality of alignment, we can apply the patterned alignment method to generate the periodic distribution of refractive index and thus the switchable grating.

In this article, we use this method to produce a switchable FLC grating based on patterned alignment domains that provides good optical quality with contrast more than 7000:1 for the first diffraction order and diffraction efficiency about 68%. In addition, since the response time is faster than 20 μs

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at $E = 6\,\text{V}/\mu\text{m}$, it could provide optically saturated EO modulation at high frequency up to 5 kHz.

In Ref. 15, it was found that the alignment quality of FLC can be drastically improved provided that the helix pitch, P, is shorter than the cell thickness, d, and the elastic energy of the FLC helix pitch is comparable but necessarily larger than the (polar) anchoring energy coefficient divided by d. Our FLC grating cell has been prepared to meet this condition. The FLC FD4004N (From Dai-Nippon Ink and Chemicals (DIC)) having spontaneous polarization $P_s \approx 61\ \text{nC/cm}^2$ and tilt angle $\theta \approx 22.05^\circ$ was chosen and sulfonic dye SD1 (DIC) was used for the photoalignment.

Interaction of SD1 molecules with a pumping linearly polarized UV light strongly depends on orientation of the azo-dye molecules relative to the polarization vector of the actinic light.[16] Such angular dependence produces the light-induced anisotropy of the orientational distribution of azo-dye molecules that can be described as the photoinduced orientational ordering that can generally occur by a variety of photochemically induced processes. The model describing the light-induced reorientation of azo-dye molecules in SD1 films as rotational Brownian motion governed by the light intensity-dependent mean-field potential was developed in Ref. 16.

The anchoring characteristics of the azo-dye films such as the polar and azimuthal anchoring energies are strongly influenced by the photoinduced ordering. In particular, the easy axis is dictated by the polarization azimuth of the pumping linearly polarized UV light, whereas the azimuthal and polar anchoring strengths may depend on a number of the governing parameters such as the wavelength and the irradiation dose.[17,18]

The exposure of the SD1 substrate by the linearly polarized light with the wavelength 450 nm results in the alignment direction perpendicular to the polarization plane of the incident light. The anchoring energy strength of SD1 layer can be easily controlled by varying the exposure dose.[17,18] The aligning directions of SD1 can also be changed by secondary irradiation with linearly polarized light of the same wavelength but with different polarization azimuth.[19] These features of SD1 enable us to write, erase, and rewrite the alignment with any desirable preferences even with multi domain alignment.

In order to provide the periodic distribution of refractive indexes, the FLC has been aligned in two orthogonal planar alignment regions by mean of two step UV exposures. The exposure energy was fixed at $3\,\text{J/cm}^2$ giving the anchoring energy $4.03 \times 10^{-4}\ \text{J/m}^2$. The cell thickness was maintained at $d = 1.5\ \mu\text{m}$ and the anchoring energy was evaluated using the well known voltage coercivity method.[20]

In the first step of alignment process, the alignment has been made in the one direction and then after the cell was assembled. Then after, the cell has been exposed again through mask with UV light having orthogonal polarization azimuth to the polarization azimuth of the first step exposing light. This technology creates the two alignment domain simultaneously on both aligning surfaces without any mutual shifting. Thus, no precise adjustment is required here for all patterns, which makes the fabrication simple and precise.[1]

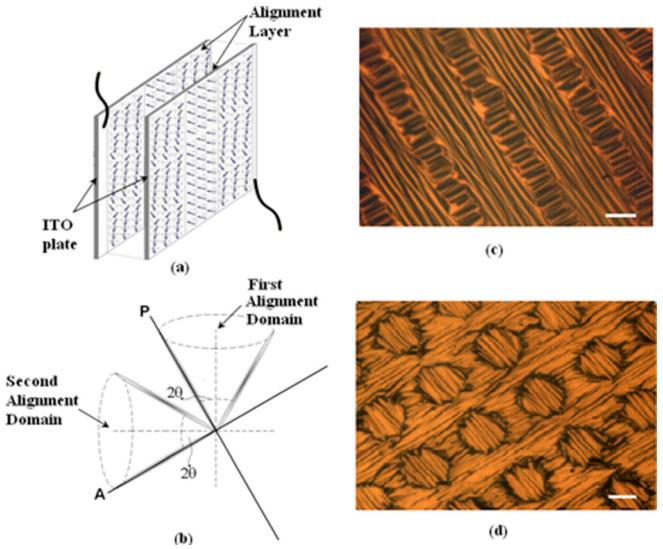

FIG. 1. (a) FLC grating cell with two orthogonally aligned domains where the smectic layer normals arranged to be parallel to the substrate are perpendicular to each other; (b) Orientational structure in the adjacent domains and the geometry of crossed polarizers (P and A stand for the polarizer and the analyzer, respectively); (c)–(d) Optical microphotographs of 1D and 2D FLC gratings taken at $V = 10\,\text{V}$. The length of the white marker is 15 μm.

The schematic diagram of the cell structure that illustrates two orthogonal alignment regions and the optical microphotographs is shown in Fig. 1. Fig. 1(a) illustrates two different overlapped alignment regions having mutually perpendicular alignment directions. Fig. 1(b) illustrates the optics of the two alignment domains in between two crossed polarizer with one switching position parallel to either polarizer or analyzer. It can be seen that no diffraction occurs in the dark state when the switching position of the two alignment domain is either parallel to the polarizer or analyzer. However, the diffraction appears for the other switching position where the optic axis for these two domains makes an angle 2θ and $90\text{-}2\theta$ for the polarizer, where $\theta \approx 22.05^\circ$ is the FLC tilt angle.

Figs. 1(c) and 1(d) represents the optical microphotographs of the FLC grating structure for 1D and 2D patterns made through the crossed polarizers at the electric field $E = 6\,\text{V}/\mu\text{m}$. The period of both gratings is $P_g \approx 50\ \mu\text{m}$, which, if necessary, can be reduced down to 1 μm provided that the FLC helix pitch is sufficiently small.[3]

The diffraction profile for 1D and 2D grating is shown in Figs. 2(a) and 2(b), respectively. Fig. 2(c) shows the dark state of the FLC grating, which is the same for both 1D and 2D structures. This figure demonstrates that the good optical quality is combined with the high contrast between diffractive and non-diffractive states. The corresponding intensity profiles are plotted in Figs. 2(d) and 2(e) for 1D and 2D grating, respectively. These figures also illustrate good diffraction efficiency of our FLC grating. In Fig. 3, we present the results for the transmittance of the first diffraction order, which is plotted as a function of voltage in both the bright and dark states. It can be seen that both curves reach the regime of saturation at voltages higher than 2 V. Similar voltage dependence was also observed for the transmittance of the zero order (see insert in Fig. 3). The diffraction efficiency is thus independent of the electric field higher than $1.3\,\text{V}/\mu\text{m}$.

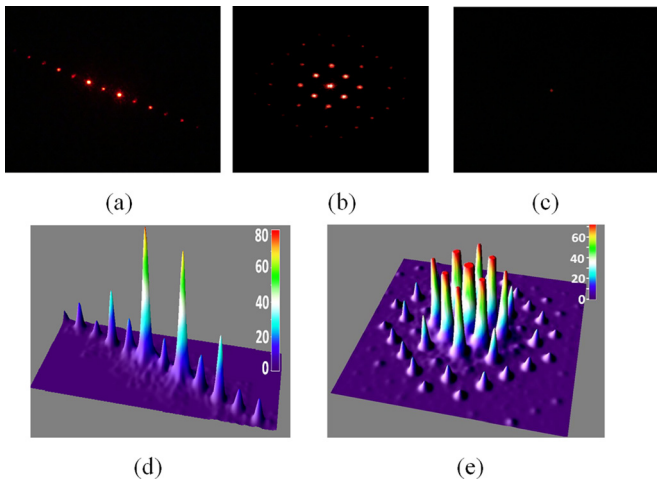

FIG. 2. Diffraction profiles of FLC grating: (a) the diffractive state of 1D grating; (b) the diffractive state of 2D grating; (c) the black state, which is same for both gratings. (d) and (e) Intensity profile measured at the voltage V = 5 V for 1D and 2D gratings, respectively.

This phenomenon can be explained based on a simple EO model describing the FLC grating in the geometry of crossed polarizers. For a plane wave ($\lambda \approx 632$ nm) normally incident on the domain with the helix axis directed along the x axis (the z axis is normal to the cell) and the FLC director $(d_x, d_y, d_z) = \cos\theta x + \sin\theta c$, where $c = \cos\phi y + \sin\phi z$ is the c-director, the transmission matrix can be written in the following form:

$$T = R(\psi)\begin{pmatrix} t_e & 0 \\ 0 & t_o \end{pmatrix}R(-\psi), \quad t_{o,e} \approx \exp(in_{o,e}h), \qquad (1)$$

where $h = 2\pi d/\lambda$; $n_e^2 = [(1-d_z^2)/\varepsilon_{//} + d_z^2/\varepsilon_\perp]^{-1}$ $(n_o^2 = \varepsilon_\perp)$ is the refractive index of extraordinary (ordinary) wave; $\psi = \arg(d_x + id_y)$ is the azimuthal angle of optical axis; and R(ψ) is the 2×2 rotation matrix. Our grating can be regarded as a binary FLC grating with the director rotated by $\pi/2$ about the z axis in the adjacent domains and the transfer matrix

$$T_g = p(y)R(-\pi/2)\cdot T \cdot R(\pi/2) + (1-p(y))T, \qquad (2)$$

where $p(y)$ is the P_g-periodic diffraction profile function characterized by the Fourier coefficients $c_n = r\exp(i\pi nr)\,\mathrm{sinc}(\pi nr)$ and the first domain fraction ratio $r = P_1/P_g$. In the crossed polarizer geometry, the transmittance coefficients of the diffraction orders are given by

$$T_n = T_{xy} \times \begin{cases} (2r-1)^2, & n = 0, \\ 4r^2[\mathrm{sinc}(\pi nr)]^2, & n \neq 0, \end{cases} \qquad (3)$$

where $T_{xy} \approx \sin^2(\delta/2)\sin^2[2(\psi+\theta)]$, $\delta = \Delta n h$ is the phase retardation and $\Delta n = n_e - n_o$ is the birefringence. When the azimuthal angle of FLC director ϕ varies from $\phi = 0$ $(\psi = \theta)$ to $\phi = \pi$ $(\psi = -\theta)$, the transmittance coefficient T_{xy} decays to zero, so that the grating is in the non-diffractive state at $\phi = \pi$.

In the low-voltage limit, Eq. (3) can be used in combination with the measured values of the zero-to-first diffraction order ratio, $T_0/T_1 \approx 0.11$ and the first order transmittance, $T_1 = 0.27$, to estimate the first domain fraction, $r \approx 0.6$ $(P_1 \approx 30\,\mu\mathrm{m})$, and the zero-voltage birefringence $\sqrt{\varepsilon_{//}} - \sqrt{\varepsilon_\perp} \approx 0.14$. We can now apply the formula $\cos\phi = \tanh(\tau_0 - f_E/f)$, where $f_E = P_s V/(\gamma d)$ and γ is the rotational viscosity for reorientation of the smectic cone, derived by assuming the ESH mode has surface stabilized ferroelectric liquid crystal (SSFLC)-like viscosity-limited dynamics,[21] to describe the voltage dependence of FLC director angle, ϕ. The theoretical curve presented in Fig. 3 was computed at $\gamma \approx 0.35$ Pa s and $\cos\phi_0 = \tanh(\tau_0) \approx 0.98$.

The results on the dynamics of the FLC grating are shown in Fig. 4. The electric field dependence of the response time of the first diffraction order is similar to the one for the planar aligned FLC cell. It reaches the maximum value at the critical field of unwinding and decreases when the electric field further increases.

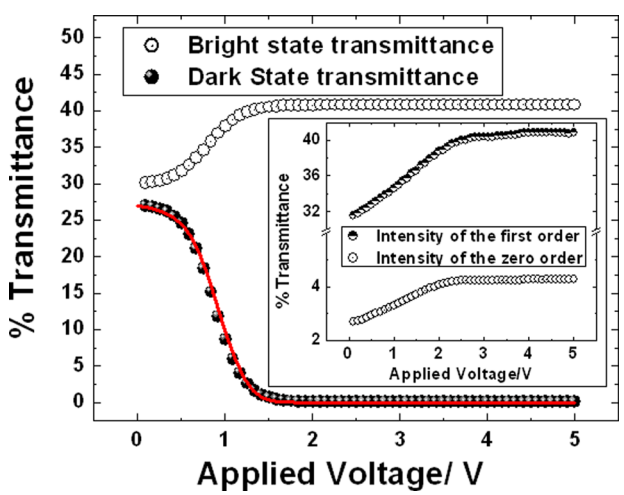

FIG. 3. Electric field dependence of the transmittance for the first diffraction order. Insert shows the bright state transmittance of the first and zero diffraction orders as a function of voltage. Solid line represents the curve computed from Eq. (3).

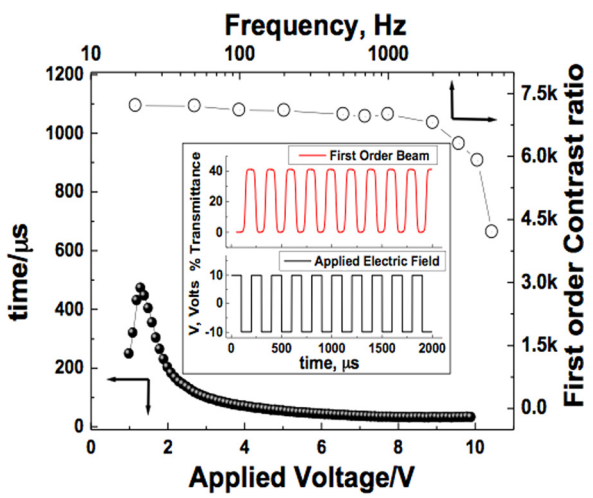

FIG. 4. Voltage dependence of the response time at driving frequency of 500 Hz (solid circles) and frequency dependence of the first order contrast ratio at the fixed applied voltage V = 10 V (open circles). Insert shows time dependence of the applied voltage (bottom) and the EO response of the first diffraction order (top) at the wavelength $\lambda = 632$ nm and at the operational frequency $f = 5$ kHz.

At the electric field of 10 V, the response time is about 20 μs. Such fast response time enables us to drive the device up to very high driving frequency $f = 5$ kHz. Insert in Fig. 4 presents the EO response of the first diffraction order measured at frequency of 5 kHz. It is clearly characterized by the optically saturate bright and dark states with high contrast.

Since the contrast ratio for FLC cell with ESH mode is typically very high, similarly high contrast has been observed for the first diffraction order. The contrast ratio for the first order (i.e., the ratio of the I_{max}/I_{min} for the first order) is more than 7000:1 at the electric field of the 6 V/μm.

As is expected, the contrast ratio decreases in the high frequency region because the period has to be long enough to reach the optically saturated state. The response time of our grating is 20 μs and, therefore, the contrast ratio does not show a pronounced decrease up to the frequency of 2 kHz. Even though it is considerably reduced at higher frequencies, the contrast ratio for the first diffraction order is 4200:1 at $f = 5$ kHz.

In conclusion, we have used the patterned photoalignment method to produce both 1D and 2D switchable FLC binary gratings with the two orthogonally aligned domains. It is found that these gratings combine good optical quality with very fast dynamical response at very low driving voltage. The experimental data were theoretically interpreted based on a simple phenomenological model. A more comprehensive analysis can be performed using the polarization-gratings approach developed in Ref. 22. Thus, the proposed grating have extreme potential for application in many devices, e.g., projection displays, micro-displays, beam steering devices, and other photonic and adaptive optic elements like optical interconnect. However, several restrictions on the FLC, photoalignment material, and alignment process make this technology little bit difficult and further research is required to make this technology simpler. Moreover, the hysteresis in FLC's is another issue that affects the optical quality, although the ESH mode is characterized by very small hysteresis and can be suppressed by choosing the optimized material parameters.[15]

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