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Switchable liquid crystal grating with sub millisecond response

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In present article, we disclose a fast switchable grating based on nematic liquid crystals. A fine striped electrode has been exploited to generate the grating profile and a driving scheme to drive the grating cell has also been proposed, which enable us to drive the cell up to very high frequency (~ 2 kHz) with evident saturated optical states. The response time for the first order diffracted beam, at the electric field of $10 \text{ V}/\mu\text{m}$, is less than $100 \mu\text{s}$ and optical contrast is higher than 400:1. Thus, the proposed LC grating could find application in several advance electro-optical devices. © 2012 American Institute of Physics. [<http://dx.doi.org/10.1063/1.3693601>]

Liquid crystals (LCs), because of their easy tunability by electric and magnetic fields, became one of the very important elements in various photonic devices. Switchable grating is one of these elements which has been studied broadly.^{1–5} Recently, several types of switchable gratings have been proposed. To construct a grating profile, periodic refractive index change of LC is necessary which can be generated by three basic approaches. First, by exploiting striped electrodes to generate periodic electrical field distribution and locally control of the director profile for uniformly aligned LCs.^{6,7} The other is to directly guide the initial LC directors to realize periodic refractive index profile through patterned alignment layers^{8,9} or holographic recording in polymer dispersed LC.^{10,11} However, these grating are very slow with the response time in the range of few ms,^{6–11} while the latest technologies demand fast electro-optical (EO) elements.¹² Another class of LC gratings that uses the natural ability of materials such as cholesteric and ferroelectric LCs (FLC) to form a periodic bulk structure,^{14–16} some of the cholesteric LC gratings offer good optical characteristics; however, the response time is limited to the ms range and required very high driving voltages. The FLC can be a potential candidate, because of the fast response time and less driving voltages, but due to some fundamental problems (viz., geometry defects, shock problem, poor contrast, etc), it is very hard to develop a real device.^{5,13}

On the other hand to increase the speed of the nematic LC devices, several methods, viz., fringe field effect, guest host effect, etc, have been proposed so far but the response time is typically limited to 1 ms.^{17,18} However, recently, Morris *et al.* have disclosed a fast switchable grating based on polymer stabilized short pitch chiral LC.¹⁹ The characteristic switching time for this grating is $600 \mu\text{s}$, whereas the required electric field is around $20 \text{ V}/\mu\text{m}$, which is relatively high. Another approach to speed up such devices has been proposed by Carbone *et al.* by utilizing the flexoelectric effect of short pitch cholesteric LC.²⁰ The response time is limited to $200 \mu\text{s}$; however, this technology has several material issues and very complicated fabrication procedure. Therefore, in this article, we present a relatively simple and faster LC device that manifests saturated EO modulation up

to very high frequency (~ 2 kHz) and, thus, could find application in several fast photonic and display devices.

The switching dynamics for planar aligned nematic LCs in terms of response time ($\tau_{0.9-0.1}^{\text{on}}$) and relaxation time ($\tau_{0.1-0.9}^{\text{off}}$) can be defined as¹³

$$\tau_{0.9-0.1}^{\text{on}} = \frac{\gamma d^2}{\frac{|\Delta\epsilon|V^2}{4\pi} - K\pi^2}, \quad \tau_{0.1-0.9}^{\text{off}} = \frac{\gamma d^2}{K\pi^2}. \quad (1)$$

Here, γ is rotational viscosity, $\Delta\epsilon$ is dielectric anisotropy, K is the elastic constant, and V is the voltage applied to the cell, while d represent the LC layer thickness. Thus, by decrease in γ , d and increase in $\Delta\epsilon$ and K can reduce both times. However, the optimization of these parameters is a critical issue of material science. On the other hand, the $\tau_{0.9-0.1}^{\text{on}}$ response time is usually fast and can be controlled by the electric field.^{13,21} Thus, if we restrict ourselves to the response time only then the resulting device could be very fast. Therefore, in this article, we present a switchable grating based on fine striped three-electrode structure and a driving scheme to reduce the relaxation time. The features of two EO modes have been combined in the proposed structure that offers the simultaneous application of vertical and horizontal electric fields on planar aligned nematic LCs. Thus, both the switching times, i.e., $\tau_{0.9-0.1}^{\text{on}}$ and $\tau_{0.1-0.9}^{\text{off}}$, can be controlled by the electric field.

For this purpose, a very fine ITO pattern has been designed and the cell structure for one period of the cell is shown in Fig. 1. On one substrate (bottom), the ITO was patterned similar to in plane switching (IPS) substrate with the electrode width and gap between two electrodes of $2 \mu\text{m}$,¹⁸ whereas continuous ITO has been used for the other substrate. Thus, the proposed structure is termed as three electrodes (A, B, and C in Fig. 1(a)), but to switch different periods, number of the patterned electrode can be increased; a simple example for this has also been discussed in the article. The planar aligned LC cell of thickness $1.5 \mu\text{m}$ has been prepared by the photoalignment of sulfonic dye SD1 (Dai-Nippon Ink and Chemicals (DIC)) with alignment direction perpendicular to the IPS strips. Afterwards, the positive LC A0138 (DIC) was filled into the cell by the capillary action.

In order to generate the switchable grating profile in the cell, both vertical and in-plane electric fields have been applied. The driving scheme is shown in Fig. 2. Curves a, b,

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FIG. 1. (Color online) (a) Detail description of one period of the used three-electrode LC cell. A, B, and C are the electrodes where the electrode width and gap for B and C is $2\ \mu\text{m}$. (b) represents the simulated LC director profile of the dark state where 10 V of electric field is applied on the top electrode, i.e., A. (c) The LC director profile when alternate electric field has been applied between B and C.

and c represent the electric fields applied to A, B, and C electrodes, respectively; Fig. 2(d) represents the EO response of the cell under crossed polarizers. To provide the vertical electric field, electrodes B and C were set to be at the same potential and the electric field was applied between the top and bottom substrates, so the LC cell shows dark state. However, for the in-plane electric field, the electric field has been applied between B and C electrodes while the top electrode was grounded and, thus, LC cell represents the bright state. The LC director profile in the dark and bright state with the above mentioned driving scheme has been simulated by LCD master and presented in the Figs. 1(b) and 1(c), respectively, which reflects that the dark state is sufficiently dark. On the other hand, when in-plane electric field is applied, the LC molecules between the in-plane electrodes switches very

fast to the planar orientation. However, the region just above electrodes remains vertical, which creates the periodic variation of the refractive index and, thus, generates the diffraction grating profile that has been discussed in the following paragraph.

A linearly polarized green laser ($\lambda = 543.8\ \text{nm}$) was used to generate the diffraction pattern in the far field at a distance of 25 cm from the sample. Fig. 3 represents the intensity profile of the diffraction pattern at the electric field of 10 V. When the in-plane electric field has been applied, the clear diffraction pattern appears (Fig. 3(a)), whereas no diffraction has been observed (Fig. 3(b)) on the application of the vertical field. To elaborate the phenomenon, the surface intensity profile of the cell has been plotted in the Fig. 3(c) that reveals the grating profile for the bright state, while for the

FIG. 2. (Color online) Schematic diagram describing the driving scheme. (a) The conventional electric field for top electrode, (b) and (c) are the electric field applied to the in-plane electrodes. (d) represents the EO response of the first order diffraction pattern.

FIG. 3. (Color online) The intensity profile along the diffraction pattern at electric field of 10 V. (a) and (b) represent optical photographs of the cell under crossed polarizer in bright and dark states, respectively. (c) shows the surface intensity profile of the cell in the bright state, while (d) and (e) show the diffraction pattern in bright and dark states, respectively.

FIG. 4. The applied voltage dependency of the response time at the fixed frequency of 500 Hz. Inset shows the EO response of the grating cell at the applied voltage of magnitude 20 V and frequency 1.5 kHz.

black state, it is perfectly flat. Thus, the diffraction profile can be switched by applying alternative vertical and in-plane electric fields. The diffraction profiles with the in-plane and vertical fields have been shown in Figs. 3(d) and 3(e), respectively. The optical contrast ratio for the first order diffracted beam, at the electric field of 10 V, is 400:1, whereas the total diffraction efficiency is 21%. The contrast ratio and the diffraction efficiency can further be improved at higher electric field and by optimizing the LC and cell parameters.

Fig. 4 reveals the response time dependencies on the applied voltages at a frequency of 500 Hz. Both the response times decrease at the higher electric fields. The $\tau_{0.9-0.1}^{on}$ and $\tau_{0.1-0.9}^{off}$ at the electric field of 10 V/ μm are 95.6 μs and 151 μs , respectively. This behavior can be explained on the basis of Eq. (1). The solid lines in the Fig. 4 represent the best theoretical fits of the Eq. (1). The $\tau_{0.9-0.1}^{on}$ is greater than the $\tau_{0.1-0.9}^{off}$, the electrode gap can be attributed for this behavior because the electrode gap for the vertical field is 1.5 μm , while for the in-plane field, it is 2 μm . The electrode gap can be optimized for the better performance for different applications.

The response time is around 150 μs that gives us an opportunity to drive the proposed grating at very high frequency. The inset of the Fig. 4 shows the EO response for the first order of the diffracted beam at 1.5 kHz, which manifests saturated optical states even at higher frequencies. This fast EO response makes this technology to be applicable for wide range of tunable photonic and other EO elements, viz., tunable grating, optical interconnects, beam steering devices, optically addressed spatial light modulator (SLM), etc.

Another advantage of this method is the switch-ability of grating periods. By increasing the number of electrodes on the IPS patterned electrode, one can have several grating periods. An example with three IPS electrodes has been shown in the Fig. 5(a). The first two consecutive electrodes have been kept at the same potential, while it is different for the third electrode. The director profile of bright (diffractive) state under this condition has been shown in Fig. 5(b), which

FIG. 5. (Color online) The diffraction intensity profile, when the electric field is applied between electrodes C and D. (a) The cell structure with three bottom electrodes (i.e., B, C, and D), (b) shows the director profile of the LC, and (c) the optical photographs of the diffraction pattern.

reveals the grating period of 16 μm . On the other hand, the director profile for the black state is the same as discussed earlier. Fig. 5(c) shows the diffraction intensity profile for the grating with 16 μm . Therefore, increment in the number of electrodes may offer higher number of grating periods.

In summary, we presented an amplitude LC grating cell based on fine periodic patterned ITO micro-channels on one substrate and continuous ITO on the other substrate. This structure gives us an opportunity to apply alternative vertical and in-plane electric fields that create diffraction grating profile only in the bright state while no diffraction exists in the dark state. The proposed structure in association with the proposed driving scheme offers very fast switching speed for both $\tau_{0.9-0.1}^{on}$ and $\tau_{0.1-0.9}^{off}$, which allows us to operate such nematic LC devices up to a very high frequency (~ 2 kHz) with evident saturated optical states. Further improvement in the LC and cell parameters can improve the diffraction profile. Thus, this technology can find application in high-resolution 2D or 3D displays, optical shutters and photonic devices, and very promising for applications, demanding sub-millisecond timescales.

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