Fast-response and high-efficiency optical switch based on dual-frequency liquid crystal polarization grating

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Abstract: A dual-frequency liquid crystal polarization grating is fabricated by photoalignment and demonstrated as an optical switch. A high diffraction efficiency up to 95% is obtained for a single first order with circular incident polarization. Via merely alternating the frequency of applied electric field, the switch On and Off time reach 350 μs and 550 μs, respectively. This work supplies a new design for fast-response and high-efficiency optical switch with the merits of easy fabrication and low power consumption.

OCIS codes: (230.3720) Liquid-crystal devices; (050.0050) Diffraction and gratings; (260.5430) Polarization; (160.5335) Photosensitive materials.

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1. Introduction

Liquid crystals (LCs) are promising candidates for tunable and dynamic optical devices, among which LC switches have sparked significant interests [1]. Optical switches based on the electro-wetting effect were utilized in high ratio optical attenuation [2]. 2D-3D switching displays were realized by nonuniform electric field induced Fresnel lens [3]. See-through displays and smart windows could also be accomplished via LC light shutters driven with crossed patterned electrodes [4]. Besides optical communication and information displays, the LC optical switches have great potentials in photonic applications [5] as well.

Among these LC switches, grating type is widely used [6–8]. To improve the switching responsiveness of such switches, several fast responsive LCs have been employed, such as polymer dispersed LCs [9, 10], blue phase LCs [11–13], dual-frequency LCs (DFLCs) [14, 15] and ferroelectric LCs [16]. However, for traditional binary phase gratings, the maximum efficiency is limited to 40.5%. To further improve the efficiency, the Pancharatnam-Berry (PB) phase can be introduced. PB phase based polarization gratings have already been

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demonstrated in high-efficiency diffractive optical elements [17–20]. Theoretically, the input energy could be 100% diffracted into a single order [21]. For an optical switch, both fast response and high efficiency are vital requirements. Therefore, researches towards the realization of both features in an integral device are of great significance.

Here, we design an optical switch based on the DFLC polarization grating. Its periodically and spatially variant director distributions are accomplished by photo-aligning technique. Through optimizing the cell parameters, the switching On/Off time reaches submillisecond scale via merely alternating the frequency of applied electric field. Moreover, this optical switch still remains the characteristic of high efficiency of polarization gratings. It supplies a practical way towards high-performance optical switch with the merits of easy fabrication and low power consumption.

2. Principles and experiments

Figure 1(a) exhibits the top view of a typical polarization grating. It is featured by periodically and spatially variant optical axes which can usually be realized with LCs. Polarization gratings can locally modify the incident polarization state and result in space-variant output phases. The phase differences caused in this way is the so-called Pancharatnam-Berry phase [22, 23]. The diffraction property of the polarization grating can be obtained by Jones matrix calculation. The LC directors are homogeneous along z axis and obey the following equation in x-y plane: $\alpha(x) = -\pi x/\Lambda$, where Λ is the pitch of the polarization grating. Its transfer matrix is

$$\begin{aligned}\mathbf{T}(x) &= \mathbf{R}(-\alpha)\cdot\begin{pmatrix}\exp(-i\Gamma/2) & 0\\ 0 & \exp(i\Gamma/2)\end{pmatrix}\cdot\mathbf{R}(\alpha)\\ &= \cos\frac{\Gamma}{2}\mathbf{I} - i\sin\frac{\Gamma}{2}\begin{pmatrix}\cos\dfrac{2\pi x}{\Lambda} & -\sin\dfrac{2\pi x}{\Lambda}\\ -\sin\dfrac{2\pi x}{\Lambda} & -\cos\dfrac{2\pi x}{\Lambda}\end{pmatrix},\end{aligned} \tag{1}$$

where Γ is the phase retardation $\Gamma = 2\pi\Delta nd/\lambda$, where Δn is the LC birefringence, d is the LC cell gap, and λ is the free space wavelength. The electric field of the m^{th} diffraction order is

$$\mathbf{D}_m = \frac{1}{\Lambda}\int_0^{\Lambda}\mathbf{T}(x)\mathbf{E}_{\text{in}}e^{-i2\pi mx/\Lambda}\mathrm{d}x. \tag{2}$$

The diffraction efficiency can be denoted as $|\mathbf{D}_m / \mathbf{E}_{\text{in}}|^2$. Thus, we can obtain

$$\begin{aligned}\eta_0 &= \cos^2\frac{\Gamma}{2},\\ \eta_{\pm1} &= \frac{1\pm S_3'}{2}\sin^2\frac{\Gamma}{2},\\ \eta_m &= 0\ (m\neq 0,\pm1),\end{aligned} \tag{3}$$

where S_3' is the normalized Stokes parameter denoting the fraction of incident circular polarization. For left and right circular polarization, S_3' = + 1 and −1, respectively. It can be seen that the polarization grating has only three diffraction orders: ± 1st orders and 0th order. The intensity distribution among the three orders depends on the phase retardation Γ and the incident polarization. By adjusting Γ, switching between 0th and ± 1st orders can be realized. If $\Gamma = \pi$, the incident linearly polarized light will equally diffract to the ± 1st orders. If the input light is circularly polarized, only one first order will be obtained. In this manner, theoretically we can accomplish a 100% diffraction efficiency for a single first order.

For common nematic LCs, the response time of recovering to initial orientation is determined by their intrinsic elastic and viscosity properties, which is usually limited to the

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level of tens of milliseconds. DFLC is a mixture of LCs with opposite dielectric anisotropy [24, 25]. It exhibits a positive dielectric anisotropy ($\Delta\varepsilon > 0$) when frequency f of applied field is below f_c (crossover frequency) while turns to a negative one ($\Delta\varepsilon < 0$) at $f > f_c$. Therefore, electric field facilitates both On and Off switching processes. This property enables the possibility of tuning LC orientations by dual-frequency addressing at a relatively low voltage, permitting a fast switching time down to submillisecond [15, 26].

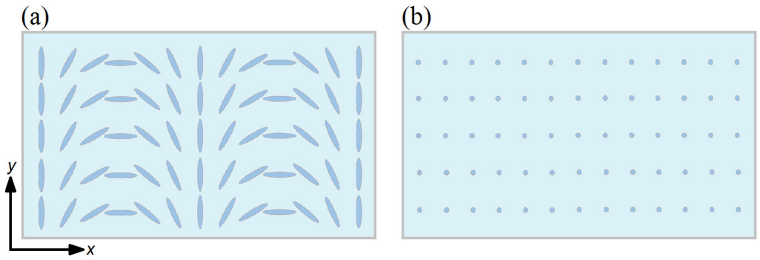

Fig. 1. Top views of the director distributions at (a) On and (b) Off states of the DFLC polarization grating, respectively.

Here, an optical switch is presented based on the DFLC polarization grating. Figures 1(a) and (b) exhibit the top views of its director distributions at On and Off states, respectively. When applied an appropriate electric field with $f < f_c$, the LC directors tend to reorient parallelly to the applied field and the phase retardation approximates zero, resulting in the first order with zero efficiency (*i.e.* Off state). While $f > f_c$, the LC directors tend to reorient perpendicularly to the field, and the light can be totally diffracted into the first orders as the cell gap d is optimized to make the phase retardation satisfy the half-wave condition $\Gamma = (2n + 1)\pi$ (n is an integer). And for circularly polarized incident light, 100% efficiency of single first order can be obtained (*i.e.* On state). Thus a fast-response and high-efficiency optical switch could be realized.

A digital micro-mirror device based dynamic microlithography system [27] is utilized to perform the photo-patterning on a polarization sensitive photoalignment agent, sulphonic azo-dye SD1 (Dai-Nippon Ink and Chemicals, Japan). Indium-tin-oxide glass substrates are spin-coated with 0.5% solution of SD1 in dimethylformamide. 5 μm spacers (to satisfy the half-wave condition for $\lambda = 671$ nm) are spurted over one substrate then the counter substrate is put over it. The assembled cell is sealed by epoxy glue. Afterwards the cell is placed at the image plane of the microlithography system to record the designed patterns. Under UV exposure, the dye molecules tend to reorient their absorption oscillators perpendicular to the light polarization [28]. After an eighteen-step five-time-partly-overlapping exposure [19, 29], a quasi-continuous space-variant orientation of SD1 is carried out. When the DFLC (HEF951800100, HCCH, China. $\Delta n = 0.206$ at $\lambda = 671$ nm) is capillarily filled, a polarization grating is accomplished owing to the excellent fluidity and continuity of LC.

3. Results and discussions

Figure 2(a) shows the calculated director distribution of a polarization grating. The color from blue to red indicates the directors varying from 0 to π continuously. The obtained DFLC polarization grating is observed under a polarized optical microscope and the micrograph is shown in Fig. 2(b). The continuous change of the brightness gives a vivid exhibition of the space-variant directors. The bright domains correspond to regions with LC directors around 45° with respect to the polarizer or analyzer, whereas the dark domains correspond to regions with LC directors approximately parallel to the polarizer or analyzer. The bright-to-dark alternates twice along with the director turning through π, leading to a denser grating under the microscope. When rotating the sample, the bright and dark domains interconvert gradually, confirming the continuous varying of the director. This reveals that the designed director distribution is accurately transferred into the DFLC cell. When 671 nm linearly polarized laser passes through the sample, the diffraction pattern is captured by a CCD

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camera. As shown in Fig. 2(c), only first orders exist and zeroth order is highly suppressed, indicating the half-wave condition is perfectly satisfied here ($\Gamma = 2\pi\Delta nd / \lambda = 3\pi$).

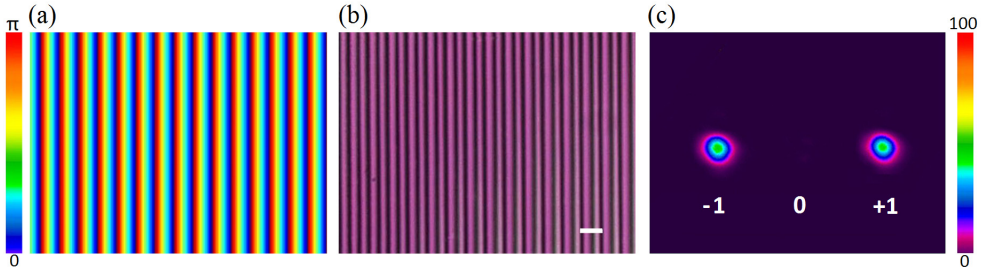

Fig. 2. (a) Theoretical director distribution of polarization gratings. (b) The micrograph of a DFLC polarization grating with crossed polarizers. Scale bar: 50 μm. (c) Diffraction pattern captured by CCD without applied field for linearly polarized incident light.

A major challenge of DFLC devices is noticeable dielectric heating effect originating from the applied high frequency, which in turn causes the crossover frequency to drift [30, 31]. Precisely controlled operation temperature can make them work well [32]. We measured the frequency dependent dielectric index in our experiments. The crossover frequency f_c = 40 kHz. The dielectric index approaches maximum at 65 kHz [33]. Therefore, at the selected frequency, fast response is achieved with comparatively low thermodielctric effect.

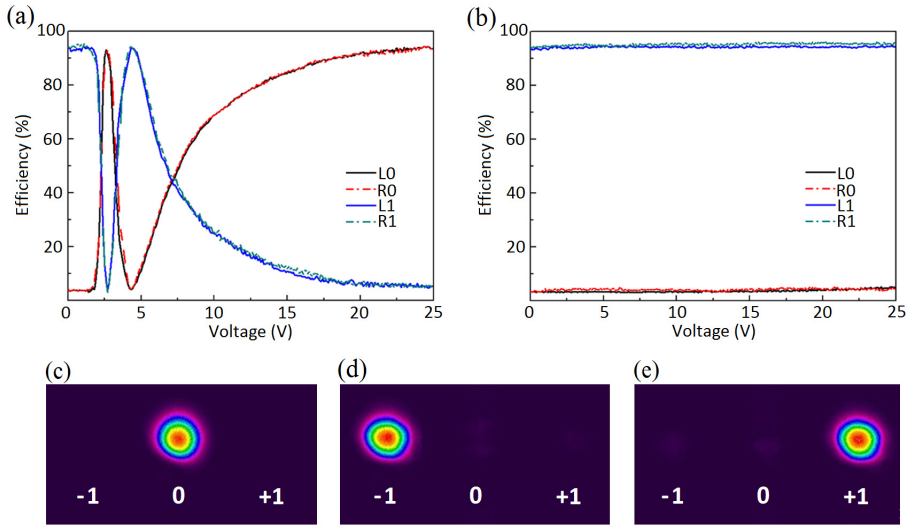

Fig. 3. Voltage dependent efficiency curves of circularly polarized incident light at frequencies of (a) 1 kHz and (b) 65 kHz, respectively. Diffraction patterns of (c) Off state and On states of (d) right (R) and (e) left (L) incident circular polarization.

The dependences of the diffraction efficiency (η) on the applied voltages (V) for circularly polarized incident light at frequencies of 1 kHz and 65 kHz are studied respectively. Here, η is defined as the intensity ratio of the objective order to the total transmitted light. Figure 3(a) reveals the η-V curves of the 0th and ± 1st at 1 kHz. Γ decreases gradually towards zero as the tilting angle of the DFLC changes from 0° to 90° along with the increasing of V. Correspondingly, the ratio of energy distribution between 0th and 1st varies. As expected, η remains the same value as the DFLC orientations keep unchanged at 65 kHz, as shown in Fig. 3(b). Comparing the curves in Figs. 3(a) and 3(b), at 2.6 V_{rms} and 25 V_{rms} with frequency of 1 kHz, the diffraction is highly suppressed and only the 0th order can be clearly observed (Off state) as exhibited in Fig. 3(c). For the same voltage at 65 kHz, the 0th order is highly

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suppressed and a single first order is observed for a given incident circular polarization (On state). Figures 3(d) and 3(e) exhibit the cases of right and left incident circular polarization, respectively. η of first order up to 95% is obtained. Therefore, keeping these voltages, the switching On/Off could be realized via merely alternating the frequency.

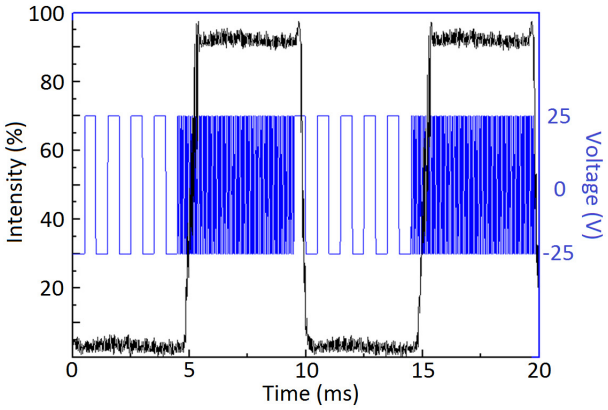

Fig. 4. Switch performance of the sample (black line) and the applied signals (blue line).

As a key parameter, the switching time is measured. Since larger voltages fasten the response, the switching performance at 25 V_{rms} is characterized. As illustrated in Fig. 4, a 25 V_{rms} signal is utilized with frequency alternating between 1 kHz and 65 kHz, lasting for 5 ms each. Submillisecond switching has been achieved, with measured On and Off time (defined as the duration time that intensity changes from 10% maximum to 90% maximum and reverse) of 350 μs and 550 μs, respectively. Further improvement could be accomplished by increasing voltages or reducing the cell gap. Due to the residual phase at Off state, η cannot be reduced to zero at this condition. The extinction ratio could be improved by further increasing the applied voltages. By introducing phase compensation, the issue could be satisfactorily addressed [34]. Though simple periodical gratings are demonstrated here, optical elements with more complicated structures could also be realized via similar strategy, for instance, Fresnel lens [35], optical vortex [36, 37] or Airy beam generators [29].

4. Conclusions

In this work, we have demonstrated a fast-response and high-efficiency optical switch based on DFLC polarization gratings via a dynamic photo-patterning technique. The switching is realized on single first order by alternating the frequency of certain applied electric field. The diffraction efficiency up to 95% is obtained for circularly polarized incident light. The switching On and Off time reach 350 μs and 550 μs, respectively, both of which are in the submillisecond scale. This work supplies a practical approach for designing fast-response and high-efficiency optical switch with the merits of easy fabrication and low power consumption.

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