

Polarization independent beam fanning using a multi-domain liquid crystal cell

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Abstract: Polarization independent beam fanning using a multi-domain liquid crystal (LC) cell is demonstrated experimentally. In the neighboring domains, the LC directors are aligned in orthogonal directions. To prove concepts, two hybrid-aligned LC cells with four and six domains were fabricated. Applying a voltage across the LC layer will change the phase difference between the neighboring domains. When the phase difference is $2m\pi$ (m is an integer), the LC cell will not disturb the incident beam. However, if the phase shift is $(2m + 1)\pi$, the outgoing beam will fan out into several beams; the number of fanout beams is equal to the domain number.

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References and links

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1. Introduction

Liquid crystals (LCs) have been widely used in direct-view [1] and projection displays [2]. In addition to displays, LC is also a useful electro-optic medium for photonic applications, such as fiber-optic variable optical attenuator [3–7], laser beam steering [8–11], adaptive optics

[12], and adaptive-focus lens [13,14], etc. However, most of these photonic devices require a linearly polarized light.

In this paper, we demonstrated a polarization-independent beam fanning using a multi-domain LC cell. In the neighboring domains, the LC directors are aligned in orthogonal directions. To prove concepts, two hybrid-alignment LC cells with four and six domains were fabricated. Applying a voltage across the LC layer will change the phase shift between the neighboring domains. When the phase shift is $2m\pi$ (m is an integer), the LC cell will not disturb the incident beam. However, if the phase shift is $(2m + 1)\pi$, the outgoing beam will fan out into several symmetric beams; the number of fanout beams is equal to the domain number. Such an optical switch exhibits following attractive features: polarization independence, low operating voltage, simple fabrication, and excellent device stability.

2. Device structure and operation mechanism

Figure 1 depicts two device structures with different domains and LC alignments. Figure 1(a) contains four-domain in which the LC directors present a homogeneous alignment, but the LC alignment direction of the neighboring domains is orthogonal. Similarly, Fig. 1(b) consists of six domains. To illustrate the device operation mechanism, let us use Fig. 1(a) as an example. When a collimated laser beam propagates through the LC layer along z -axis (not shown), it will experience a phase shift. For the polarization of the light along x -axis, the phase difference between the neighboring domains is as following:

$$\Delta\phi = \frac{2\pi}{\lambda} d(n_e - n_o) \quad (1)$$

where d is the LC layer thickness, λ is the wavelength of the incident light, and n_e and n_o are the extraordinary and ordinary refractive indices of the LC, respectively. Similarly, for the polarization of light along y -axis, the phase difference between the neighboring pixels is the same as described in Eq. (1). Due to the symmetric LC alignment, device with such an LC alignment is polarization independent.

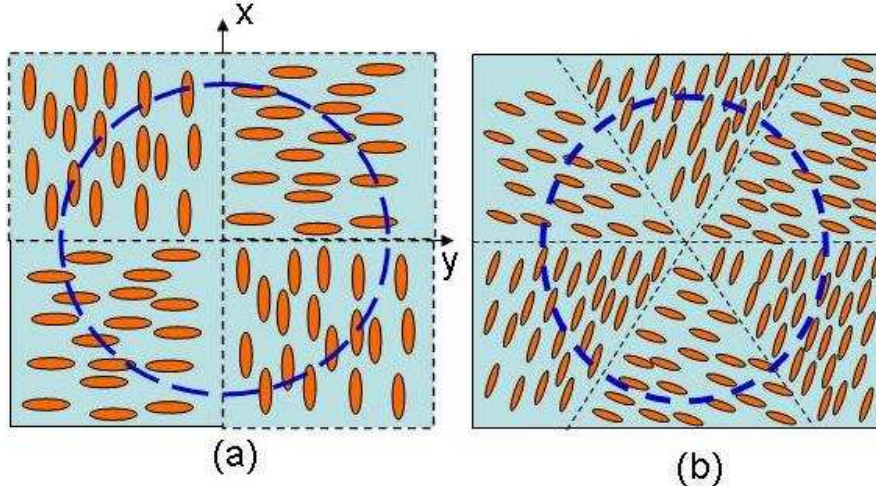


Fig. 1. Device structures with (a) four domains (2) six domains. The LCs in the neighboring domains are orthogonal.

Figure 2 shows the experimental setup. To simplify discussion while not losing generality, we assume the laser beam is polarized along y -axis. When the collimated laser beam passes through the LC cell, the beam is focused by a convex lens-1 to create interference. Afterwards, the beam is collimated again by a convex lens-2. The output beam is received by a CCD camera. At null voltage ($V = 0$), the phase difference $\Delta\phi$ between adjacent pixels is

constant. As V increases, $\Delta\phi$ decreases. When $\Delta\phi = 2m\pi$ (m is an integer), the beam will not be disturbed by the LC cell. However, when $\Delta\phi = (2m + 1)\pi$ the Gaussian beam will have a maximum destructive interference at the focal point of Lens-1. In this case, the beam will have a maximum energy loss when detected by the CCD camera. Due to the interference, the beam is fanned out into multiple beams, as depicted in Fig. 2(b).

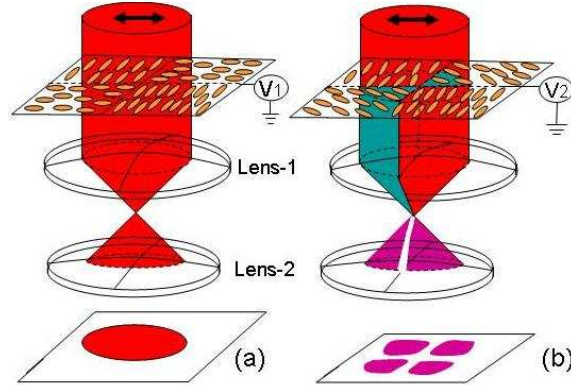


Fig. 2. Experimental set up for observing beam fanning: (a) The beam is undisturbed, and (b) the beam is fanned out into multiple beams.

To prepare the LC cell shown in Fig. 1(a), we coated an ITO (indium tin oxide) glass substrate (2.5 cm x 2.5 cm) surface with a thin polyimide layer and rubbed along x -axis. We then divided the LC layer into 4 domains. To generate the desired homogeneous alignment in four domains would require two rubbing processes. During first rubbing, we covered the two diagonal domains with a thin adhesive tape. The uncovered two domains were buffed along y -axis. After the first rubbing, we removed the protective tape and cleaned the substrate. Ideally the opposite ITO glass substrate should also have the same rubbing patterns as the first one in order to obtain homogeneous alignment. However, this process is rather complicated because it would require a precise alignment to match the domains. Here, we simplified the fabrication process by using homeotropic alignment on the opposite surface. This will result in a hybrid alignment, i.e., one surface is homogeneous and another is homeotropic. Because the LC directors of the neighboring domains are orthogonal and the symmetry of the system remains unchanged, this four-domain LC device is still polarization independent. Using homeotropic alignment on one surface eases the cell preparation, but the tuning range of the phase is reduced. The cell gap was controlled at $d \sim 13.5 \mu\text{m}$. A nematic LC (from L-Display) with $\Delta n = 0.199$ at $\lambda = 589 \text{ nm}$ was injected to the empty cell. To achieve homeotropic alignment, we coated polyimide NS-1211 on an ITO glass surface. The polyimide was baked at 180°C for 1 hr without rubbing treatment. The 6-domain LC cell shown in Fig. 1(b) was also prepared by the similar process. The cell gap was measured to be $\sim 17 \mu\text{m}$.

3. Results and discussion

We first inspected the LC alignment of the four-domain LC cell using an optical microscope. The cell was placed between two crossed linear polarizers with the rubbing direction of one domain along the polarizer's transmission axis. As shown in Fig. 3(a), all the four domains appear dark. This implies that the axis of each domain is either parallel or perpendicular to the optic axis of the polarizer. By rotating the cell 45° all four domains appear bright, as Fig. 3(b) shows. When the cell was rotated by 90° , the four domains become dark again, as shown in Fig. 3(c). Such results indicate that the principal axes of the neighboring domains are indeed perpendicular, and the LC presents a hybrid alignment.

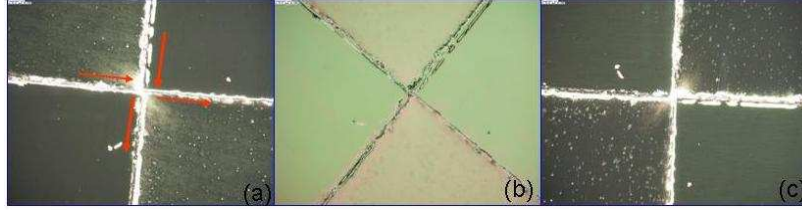


Fig. 3. Microscope photos of the 4-domain LC cell between crossed polarizers at (a) 0° , (b) 45° , and (c) 90° . The red arrows denote the rubbing direction on the surface of one substrate

Figure 4 shows the measured voltage-dependent transmittance of one domain at $\lambda = 633$ nm. The cell was placed between crossed polarizers. The diameter of the beam was ~ 5 mm. The rubbing direction of the domain was oriented at 45° with respect to the optic axis of one polarizer. As expected, the hybrid alignment exhibits no threshold voltage. From Fig. 4, the total phase shift is calculated [15] to be $\Delta\phi \sim 4.27\pi$. It is enough to provide more than 2π phase shift between neighboring domains with a relatively low operating voltage.

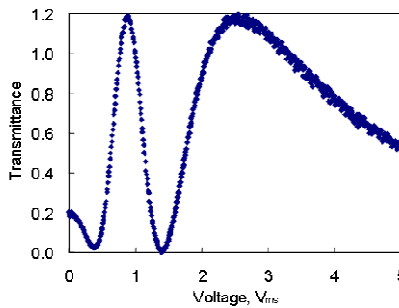


Fig. 4. Voltage dependent transmittance of one domain of the 4-domain LC cell. $\lambda = 633$ nm.

To characterize the optical switching behaviors of the LC cell, we used the experimental setup shown in Fig. 2 to measure the beam intensity distribution. The focal length of lens-1 was 150 mm (SPX046, New Port) and lens-2 was 50.2 mm (KPX082 New Port). The LC sample was placed at ~ 50 mm before lens-1. The distance between lens-2 and lens-1 was about 200 mm. A CCD camera was set ~ 100 mm behind lens-2. An unpolarized He-Ne laser was used as the light source. The two-dimensional (2D) intensity profiles were recorded by the CCD camera at different voltages. Results are shown in Fig. 5.

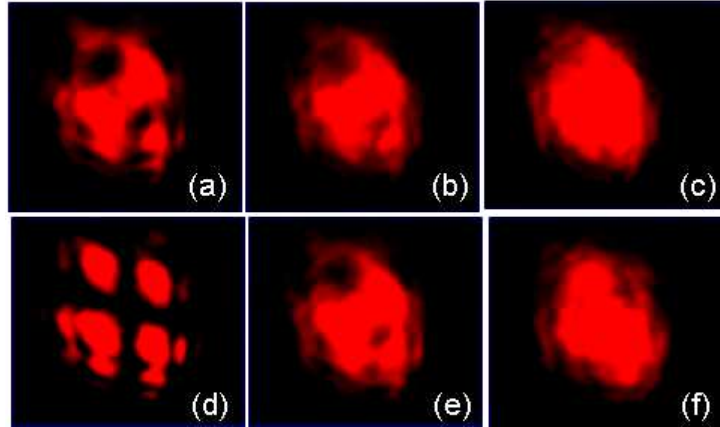


Fig. 5. Intensity profiles of a laser beam modulated by the four-pixel LC cell under different voltages. (a) $V = 0$, (b) $V = 0.32 V_{\text{rms}}$, (c) $0.45 V_{\text{rms}}$, (d) $0.88 V_{\text{rms}}$, (e) $1.25 V_{\text{rms}}$, and (f) $1.50 V_{\text{rms}}$.

At $V = 0$, some holes appear in the spot, as Fig. 5(a) shows, because the phase shift between the neighboring domains is 4.27π . As the applied voltage increases, the phase retardation decreases. At $V = 0.32 V_{\text{rms}}$, the holes almost disappear as shown in Fig. 5(b). When the voltage is increased to $0.45 V_{\text{rms}}$ which corresponds to $\Delta\phi \sim 4\pi$ from Fig. 4, the holes disappear completely (Fig. 5(c)) and the laser beam is not disturbed while traversing thru the LC cell. At $V = 0.88 V_{\text{rms}}$ (corresponding to $\Delta\phi \sim 3\pi$ from Fig. 4), the beam is dissected into four parts with a wide black cross through the center, as shown in Fig. 5(d). This pattern originates from the destructive interference of the laser beam modulated by the LC cell. Continually increasing the voltage will show a periodic beam modulation. The beam spot at $V = 1.25 V_{\text{rms}}$ is similar to that at $V = 0.32 V_{\text{rms}}$, while the beam spot at $V = 1.5 V_{\text{rms}}$ is the same as that at $V = 0.45 V_{\text{rms}}$. Moreover, we can conclude from Fig. 5(f) that the phase difference between the neighboring domains is 2π . From Fig. 5, when the LC cell is driven between $0.45 V_{\text{rms}}$ to $0.88 V_{\text{rms}}$, the intensity of the Gaussian beam at the center area can be switched from maximum to minimum. Thus, the LC cell can function as an optical switch.

To further analyze the beam performances, we converted the images shown in Figs. 5(c) and 5(d) to 3D intensity profiles and results are given in Figs. 6(a) and 6(b), respectively. The diameter of the beam was measured to be ~ 5 mm. The beam intensity was very strong which saturated the CCD camera. In Figs. 6(a) and 6(b), the peaks present almost the same light intensity. The dissected peaks imply that the phase difference in these areas is $\sim 3\pi$.

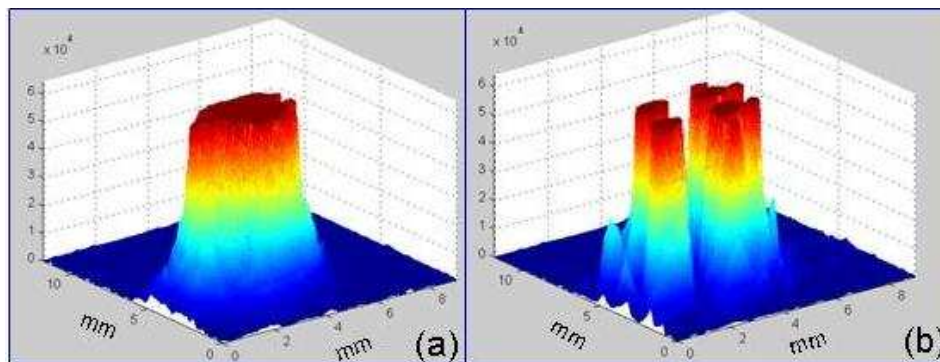


Fig. 6. 3D intensity profiles of a laser beam passing thru the 4-domain LC cell at (a) $V = 0.45 V_{\text{rms}}$ and (b) $V = 0.88 V_{\text{rms}}$.

One way to reduce the peak intensity of the incident beam is to divide the LC cell into more domains. Figure 1(b) shows the 6-domain structure. We used the same experimental

setup to characterize the beam fanning of the 6-domain LC cell. By controlling the applied voltage, we can split one beam into 6. Figure 7(a) shows the outgoing beam profile at $V = 0.65 V_{\text{rms}}$. In this case the beam passes through the cell without disturbance. Figure 7(b) shows the beam profile at $V = 1.3 V_{\text{rms}}$, where the beam was dissected into six spots.

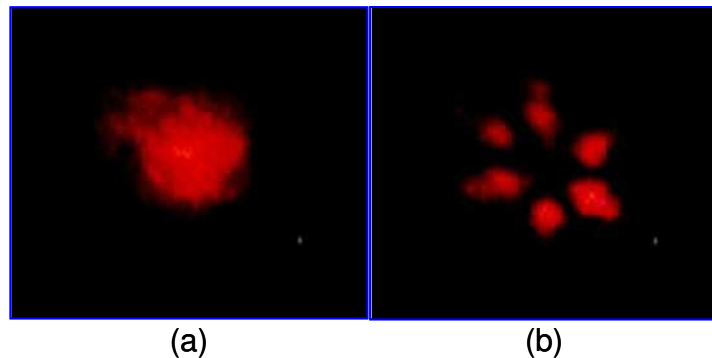


Fig. 7. 2D intensity profiles of the beam modulated by the six-domain LC cell at (a) $V = 0.65 V_{\text{rms}}$ and (b) $V = 1.3 V_{\text{rms}}$.

The response time of such an optical switch is determined by several parameters, such as cell gap, visco-elastic coefficient, anchoring energy, bias voltage, and applied voltage [16,17]. To improve the switching speed, a bias voltage $V = 1.6 V_{\text{rms}}$ ($f = 1 \text{ kHz}$) was applied to the cell. This bias voltage also functions as the switch-on voltage. To switch off the beam, a square voltage burst at $V = 3 V_{\text{rms}}$ was applied to the cell. During switching operation, we could visually observe the switching states. A movie showing the dynamic switching was recorded in Fig. 8. Using an oscilloscope, the measured rise time was measured to be $\sim 24 \text{ ms}$ and decay time $\sim 46 \text{ ms}$ at the room temperature ($\sim 23^\circ\text{C}$). The response time can be shortened if a high birefringence and low viscosity LC [18] is employed.

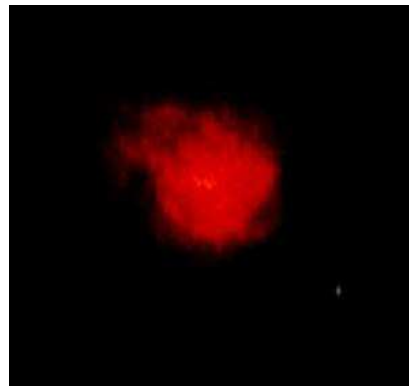


Fig. 8. Beam switching dynamics of the 6-domain LC cell. (Media 1)

From Figs. 5(d) and 7(b), we find that the number of the fanout beams is equal to the domain number of the LC cell. Thus, we could increase the number of fanout beams by making more domains. To fabricate an LC cell with more domains, we have to use the photolithographic method in order to precisely create the desired molecular alignment within each domain. Such an LC cell can also function as a polarization converter which turns the fundamental linearly polarized (LP) mode to a higher order LP mode. Because the higher order LP mode cannot propagate in a single-mode fiber, this kind of device can be used as an optical fiber switch.

5. Conclusion

We have demonstrated a beam fanning device using multi-domain LC structure. The optic axes of the neighboring domains are orthogonal. The number of the fanning beams is equal to the number of domains. A device with more domains will present a higher optical switching performance, but its fabrication process is more sophisticated. Our LC cell presents several attractive features: easy fabrication, low operating voltage, polarization independent, and video rate response time, and good mechanical stability. Potential applications of this device for optical fiber switch, mode converter, and optical sensing are foreseeable.

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