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Polarization-independent and submillisecond response phase modulators using a 90° twisted dual-frequency liquid crystal

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A polarization-independent phase modulator using a 90° twisted dual-frequency liquid crystal (DFLC) is demonstrated. In addition to being polarization independent, such a phase modulator exhibits many other advantages such as being scattering-free and having large phase change, low operating voltage, and submillisecond response time. Using a 15 μm transmissive DFLC cell, the phase shift achieves 1π at $\lambda = 633$ nm and the applied voltage is lower than 25 V_{rms}. Potential applications of such a phase modulator for laser beam steering, tunable-focus lenses, and switchable two-dimensional/three-dimensional liquid crystal displays are foreseeable. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2219998]

Phase-only modulation is particularly attractive for laser beam steering,[1,2] spatial light modulators,[3] tunable-focus lenses,[4] and switchable two-dimensional (2D)/three-dimensional (3D) displays.[5] Various materials and methods have been investigated for phase modulators. Among them, liquid crystal (LC) is the most promising candidate material because its effective refractive index is electrically controllable. However, most of the LC phase modulators are polarization dependent. Several approaches, e.g., microstructure rubbing process,[6] nanosized polymer-dispersed liquid crystal (nano-PDLC),[7–9] voltage-biased PDLC (Ref. 10) and polymer-stabilized cholesteric texture,[11] and double-layered homogeneous LC cell[12] and LC gels,[13] have been developed for overcoming the polarization dependence problem. Each approach has its own pros and cons. However, two general problems in these approaches are the need for a high operating voltage (>100 V_{rms}) and the small phase change ($\ll 1\pi$). Thus, their applications are limited to microphotonic devices.

In 1988, Konforti *et al.* reported the phase-only modulation behavior of a 90° twisted nematic (TN) LC.[14] In 1991, Patel reported that the Fabry-Perot filter using a 90° TN LC is polarization insensitive when the applied voltage is ~ 3 times greater than the threshold voltage.[15] Based on this property, in this letter we demonstrate a fast-response polarization-independent phase modulator using a 90° twisted dual-frequency liquid crystal (DFLC). A phase change of more than 1π can be obtained at $\lambda = 633$ nm using a DFLC mixture developed in our laboratory, designated as UCF-4, in a 15 μm LC cell gap. The physical properties of UCF-4 are listed as follows: $n_o = 1.497$, $\Delta n = 0.286$ at $\lambda = 633$ nm, $\Delta\varepsilon = +5.97$ at $f = 1$ kHz and -3.53 at $f = 30$ kHz, and the crossover frequency is $f_c = 11$ kHz at 23 °C. By applying overdrive and undershoot voltages, submillisecond response times in both rise and decay periods are obtained. Compared to the above mentioned methods, the fabrication process of our TN cell is quite straightforward and, moreover, the twisted DFLC cell is scattering-free and its operating voltage is relatively low.

In experiment, we filled an empty twisted cell with UCF-4 in an isotropic phase. The inner surfaces of the glass substrates were covered by a thin indium tin oxide (ITO) electrode and then overcoated with a thin polyimide layer. The two substrates were rubbed in orthogonal directions. We measured the voltage-dependent transmittance (*V-T*) curve of the 90° twisted DFLC cell sandwiched between two crossed polarizers at different β, where β is the angle between the polarizer's optic axis and the front rubbing direction of the LC cell. To avoid complexity, in Fig. 1 we only plot the *V-T* curves for $\beta = 0°$ (also known as *e* ray), 45°, and 90° (*o* ray) as examples to illustrate the electro-optic properties of the twisted DFLC cell. When the applied voltage reaches the Freedericksz transition threshold (V_{th}) of ~ 1.5 V_{rms}, the transmittance of the LC cell starts to change and oscillate for the cases of $\beta = 45°$ and 90°, but the *o* ray remains unchanged until 2.7 V_{rms}, which corresponds to the optical threshold (V_{op}).[14] The transmittance for all the different linearly polarized lights becomes zero when the applied voltage is above ~ 5.5 V_{rms}.

In the $V_{th} < V < V_{op}$ region, the LC directors start to tilt while retaining the uniform twist. Such molecular tilt decreases the effective birefringence of the LC layer. As a result, the propagation of the incident light except for the *o* ray is affected by the decreased phase retardation of the LC. Therefore, the transmittance for *e* ray and $\beta = 45°$ lights var-

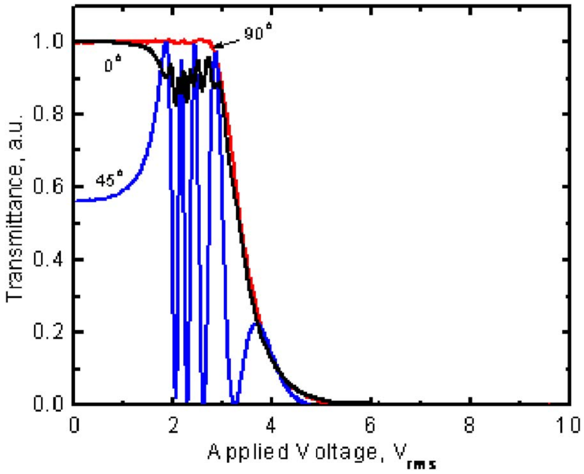

FIG. 1. *V-T* curves of the twisted DFLC sandwiched between two crossed polarizers.

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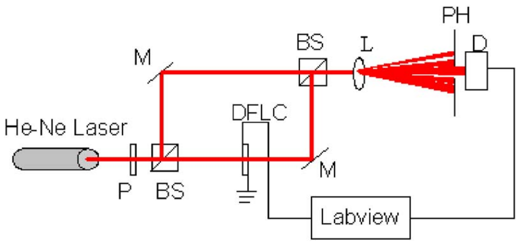

FIG. 2. Experimental setup for measuring the polarization-independent phase shift. P: polarizer, M: mirror, BS: beam splitter, PH: pinhole, L: lens, and D: detector.

ies with the applied voltage. For the *o* ray, since the Mauguin condition ($d\Delta n \gg \lambda$) for the polarization rotation effect still holds, such molecular tilt does not affect the *o* ray propagation. Therefore, the transmittance of the *o* ray is barely changed. In the $2.7 < V < 5.5$ $\mathrm{V_{rms}}$ region, the twist in the LC bulk is broken so that the Mauguin condition is no longer satisfied. Further decrease of the effective birefringence leads to the decreased transmittance for all the different polarized incident lights including the *o* ray.

In the $V > 5.5$ $\mathrm{V_{rms}}$ region, the bulk LC directors are reoriented almost perpendicular to the substrates by the electric field. In a 90° TN cell, since the two boundary layers are orthogonal, the respective phase retardations of the two boundary layers compensate each other. If the incoming linearly polarized light is an *e* ray to the front surface, it will behave like an *o* ray to the rear surface, and vice versa. In this case, the LC cell functions as an isotropic media, which means that there is no phase retardation in the LC cell and that the LC cell is independent of polarization. Since there is no phase retardation in the LC cell, the incident linearly polarized light keeps its original polarization state after traversing through the cell but is blocked by the crossed analyzer. Therefore, the transmittance vanishes at $V > 5.5$ $\mathrm{V_{rms}}$.

Although the TN LC cell does not exhibit phase retardation at $V > 5.5$ $\mathrm{V_{rms}}$, the effective refractive index of the LC still varies due to the further increased voltage because more LC directors can be tilted farther as the voltage increases. As a result, the residual phase change can still be observed and this phase change is polarization independent. Usually, the phase retardation of a LC cell can be measured by sandwiching the cell between a pair of crossed or paralleled polarizers. To measure the polarization-independent phase change, however, the above mentioned method is not viable since the transmittance is either dark or bright at $V > 5.5$ $\mathrm{V_{rms}}$. Under such a circumstance, the interference method must be employed.

In our experiment, we used the Mach-Zehnder interferometer, as shown in Fig. 2, to measure the phase change. The beam from an unpolarized He–Ne laser was expanded and collimated and then split into two beams by a beam splitter. The 90° twisted DFLC was placed in one of the arms. These two beams are recombined by another beam splitter. A lens was placed behind the beam splitter to project the interference fringes to a screen. A photodetector was placed behind the lens to capture the transmitted intensity with respect to the applied voltage. In front of the photodetector, a pinhole was used to allow only a single interference fringe to pass through.

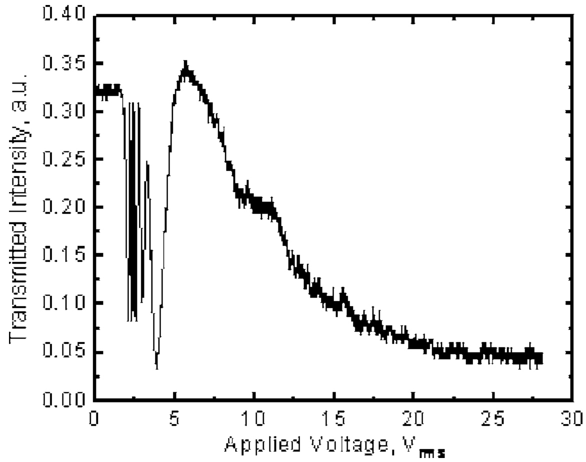

FIG. 3. The detected intensity of the interference fringe with the applied voltage.

Figure 3 is the plot of the *V-T* curve detected by the photodetector. The variation of the transmitted intensity with the applied voltage corresponds to the change of the LC's effective refractive index and consequently the phase of the LC cell. As seen in Fig. 3, the phase of the LC cell starts to change when the applied voltage reaches ~1.5 $\mathrm{V_{rms}}$ and gradually saturates as the applied voltage exceeds 20 $\mathrm{V_{rms}}$, at which point all the LC directors are reoriented along the electric field. According to the two-beam interference principle, the normalized transmittance (T) of the interference fringe has the following relationship with the phase difference (δ):

$$T = \frac{1+\cos(\delta)}{2}. \tag{1}$$

We can convert the *V-T* curve into a *V*-phase curve from the following equation:

$$\delta = \cos^{-1}(2T-1). \tag{2}$$

Figure 4 shows the measured voltage-dependent phase shift of the twisted DFLC cell at $\lambda = 633$ nm. From the above description, we know that the phase change becomes polarization independent only when the applied voltage exceeds 5.5 $\mathrm{V_{rms}}$. From this sample, a polarization-independent phase change of about 1π was obtained for the voltage swing from 5.5 to 25 $\mathrm{V_{rms}}$. For laser beam steering using an optical phased array, 2π phase change is required. To achieve a 2π

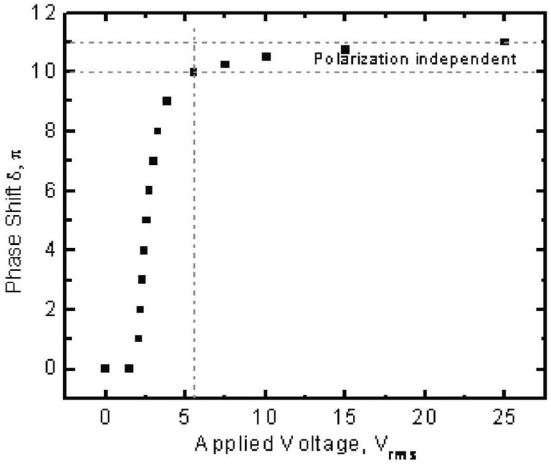

FIG. 4. Voltage dependent phase shift of the twisted DFLC cell. Cell gap $d = 15$ μm and $\lambda = 633$ nm.

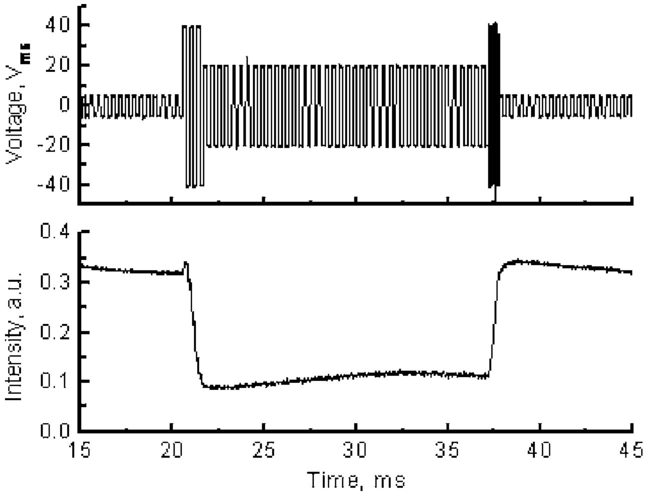

FIG. 5. The measured response time of the 15 μm twisted DFLC using overdrive and undershoot driven methods. (a) Rise time ~0.6 ms and (b) decay time ~0.7 ms at T~23 °C.

phase change, we could increase the birefringence of the DFLC material or use the reflective mode. In the reflective mode, the incoming laser beam traverses the cell twice and the phase change is doubled.

Response time is another important concern for practical applications. Because of a relatively thick cell gap (~15 μm) involved, the response time is quite slow when using the conventional driving method. For instance, for a 15 μm 90° TN cell using a commercial Merck E7 LC, the rise time is 9.7 ms and decay time is ~803 ms by switching the voltage between 0 and 20 V_{rms}. However, with a biased voltage, which is used to ensure that the phase change is polarization independent, the response time can be significantly improved. For example, by switching the voltage between 5.5 and 20 V_{rms}, the rise time is decreased to ~1 ms and decay time to 17 ms for the E7 cell. Using the dual-frequency driving scheme, the corresponding response times are ~2 and 2 ms for the DFLC cell. These response times can be further improved by using the overdrive and undershoot voltage wave forms during low- and high-frequency periods.[16] Figure 5 shows the results when the employed low and high frequencies are 2.5 and 30 kHz, respectively. The measured rise time is ~0.9 ms and decay time is ~0.8 ms at room temperature (~23 °C).

In summary, we have demonstrated a polarization-independent and fast-response phase modulator using a 90° twisted DFLC cell. The phase change becomes polarization insensitive when the applied voltage exceeds 5.5 V_{rms} and an ~1π polarization-independent phase change at $\lambda = 633$ nm is obtained using a 15 μm cell. To achieve 2π polarization-independent phase change, we could use a reflective device. By incorporating the overdrive and undershoot voltage methods, we obtained submillisecond response times. In addition to the large phase change and fast response time, the device is free from light scattering and its operating voltage is relatively low (<25 V_{rms}). All these advantages make this approach very promising for many applications including laser beam steering and microlens arrays.

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