

Variable optical attenuator based on polymer stabilized twisted nematic liquid crystal

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Abstract: A variable optical attenuator (VOA) based on polymer stabilized twisted nematic (PSTN) liquid crystal (LC) is demonstrated. Comparing with the normal twisted nematic LC-based VOA, PSTN exhibits a much faster response time. Moreover, the polymer networks effectively eliminate the backflow effect which exists in the normal TNLC cell. The attenuation mechanism of the PSTN LC was studied. Both polarization rotation and light scattering effects are found to contribute to the optical attenuation. The ratio between these two mechanisms can be adjusted by changing the polymer concentration and polymer network domain size.

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1. Introduction

Liquid crystal (LC) has been widely used in many electrically controlled tunable photonic devices such as spatial light modulator, wavelength filter, variable optical attenuator (VOA), and optical switch. [1-5]. In comparison with the competing micro-electro mechanical systems (MEMS) technology, the LC devices exhibit several advantages, e.g., no-moving-parts, low power consumption, and low cost even in small volume production [4, 5]. A major drawback of the LC based photonic devices is the slow response time [6]. Hence, there is an urgent need to develop fast-response LC devices for the growing photonic applications.

Several approaches have been proposed to optimize the LC response time, e.g., using a high birefringence and low viscosity LC, elevating the operating temperature, or using a stressed LC cell [6, 7]. However, these methods either rely on the new LC materials development or complicate the fabrication process. There have been some reports that the dynamic response can be significantly enhanced by inducing the polymer network into the homogeneously aligned LC to stabilize the material for display applications [8, 9]. As for the TN based LC devices, the situation is more complicated because of the twisted LC distribution. There is a concern if the polymer network can also help the dynamic response in a TN LC cell. To the best of our knowledge, the photonic applications of PSTN have not been reported. On the other hand, in comparison with the homogeneous cell, TN devices exhibit a higher contrast ratio and better spectral, temperature, and manufacture tolerance so that they have been widely used in many commercial products. Therefore, studying the dynamic response of the PSTN cell is fundamentally interesting and practically useful.

In this work, we developed the PSTN LC by doping some bisphenol-A-dimethacrylate (M1) monomer into the nematic LC. The polymer network was formed inside the LC through UV curing. We demonstrated that the polymer network can significantly reduce liquid crystal response time while preserving the desirable polarization rotation effect in the field-off state. Another advantage of the PSTN LC is that the back flow effect is completely suppressed even the applied voltage is as high as $40 V_{rms}$. The physical mechanism responsible for the observed light attenuation in PSTN LC was also studied.

2. Experimental setup and conceptual fundamentals

Figure 1 depicts the schematic diagram of our experimental setup where the ray tracing is modeled by the optical simulation software ZemaxTM. Two polarization beam displacers and a 90° TN cell are sandwiched between two collimators. The light from the input fiber is collimated by the first collimator. When the light comes into the first polarization beam displacer, which is normally a 45° cut birefringence crystal such as YVO₄ or Calcite, the light is separated into the ordinary ray and extraordinary ray, respectively. Because the 90° TN LC acts as a wide-band half wave plate, the polarization states are rotated by 90° , thus the two beams are recombined by the second identical polarization beam displacer and then coupled into the collecting fiber. This is the "on" state of the VOA. When a sufficiently high electric field is applied to the cell, the polarization rotation effect is disrupted. The beams' polarizations retain their original states after passing through the LC cell so that the two beams are further separated by the second beam displacer. As a result, no light is coupled into the collecting collimator. The system now works as the "off" state. Obviously, any arbitrary attenuation level could be achieved by controlling the applied voltage. Normally, the beam displacers and LC cell are tilted by a small angle to avoid the back reflection, which is also illustrated in the diagram.

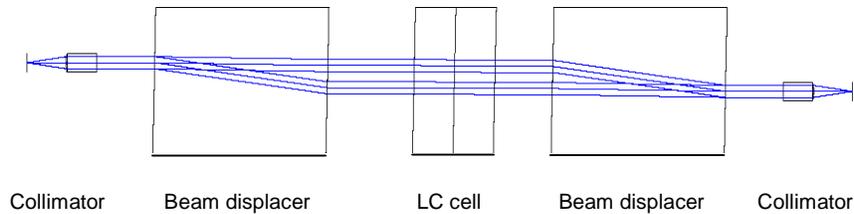


Fig. 1. A TN LC based variable optical attenuator modeled by ZemaxTM optical simulation software.

Response time is a critical concern for all the LC devices. A fast response VOA leads to a better protection to the optical system. The LC director's field-on response time τ_{on} and the field-off decay time τ_{off} are dependent on the cell gap d , rotational viscosity γ_1 , twist elastic constant K_{22} , threshold voltage V_{th} , and applied voltage V as follows [6],

$$\begin{cases} \tau_{off} = \frac{\gamma_1 d^2}{K_{22} \pi^2} \\ \tau_{on} = \frac{\tau_{off}}{\left(\frac{V}{V_{th}}\right)^2 - 1} \end{cases} \quad (1)$$

From Eq. (1), high birefringence (which implies a thin cell gap) and low visco-elastic coefficient γ_1/K_{22} are helpful for reducing the response time. However, to design a high birefringence LC while maintaining low viscosity is a very challenging task. Furthermore, the twist elastic constant K_{22} , which dominates TN LC's dynamic response, is smaller than the splay (K_{11}) and bend (K_{33}) elastic constants. Thus, the TN cell usually exhibits a slower response time than the corresponding homogeneous or homeotropic cells. Although elevating the driving voltage helps to reduce τ_{on} , the decay time remains basically the same. However, if polymer networks are formed in the LC, the effective elastic constant K is greatly enhanced by the anchoring effect between the LC molecules and polymer networks. Both field-on and field-off response times are improved except that the operating voltage is increased [9]. Related experimental results are shown in the following sections.

3. Experimental results of a TN LC

To characterize the performance of the TN LC-based VOA, an Ando AQ4321D tunable laser working at $\lambda=1.55 \mu\text{m}$ was used as the light source. Its polarization state was randomly controlled by a polarization controller. At first, the LC cell was filled with Merck E45 LC mixture. The birefringence of E45 was measured to be 0.19 at $\lambda=1.55 \mu\text{m}$ and $T=22^\circ\text{C}$. To satisfy the Gooch-Tarry first minimum condition which is $d\Delta n/\lambda = \sqrt{3}/2$ [10], the cell gap is $d = 7.7 \mu\text{m}$.

Figure 2 illustrates the voltage-dependent transmittance measured by a computer-controlled LabVIEW data acquisition and processing system. The measured optical threshold voltage is $1.1 V_{rms}$. As the applied voltage increases, the transmittance decreases. At $V=2.5 V_{rms}$, the measured intensity attenuation reaches 30dB. As the applied voltage is further increased, a better dark state is achieved. The low voltage and high contrast ratio of a TN cell are due to the self-phase compensation effect of the orthogonal surface layers. In the high voltage state, these boundary layers compensate each other. As a result, the dark state voltage is low and contrast ratio is high.

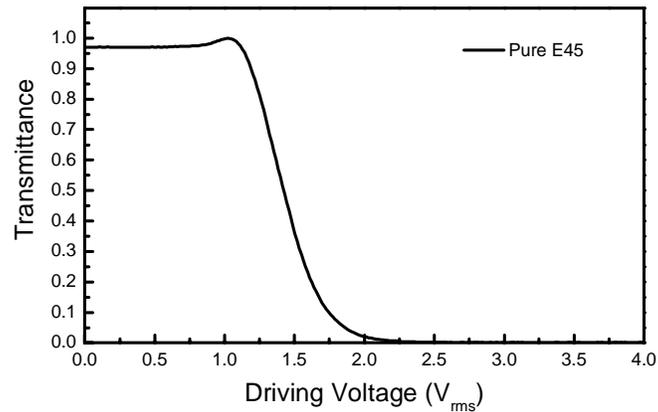


Fig. 2. Voltage-dependent transmittance of a TN LC based VOA. $\lambda=1.55 \mu\text{m}$.

If the applied voltage is suddenly removed, the light signal returns to its maximum value because the LC molecules relax back to their twisted state. In the time domain, the field-off LC decay curves correspond to the rising optical signals in Fig. 3. On the contrary, if the field is suddenly applied, the transmittance is decreased. In Fig. 3, the solid black, dashed red, and the dash-dot blue lines correspond to $V=2.5$, 10, and 25 V_{rms} respectively. At $V=2.5 V_{rms}$, the field-on and field-off optical response times (90-10% transmission change) were measured to be 26.59 ms and 46.37 ms, respectively. With the increase of applied voltage, the field-off response times keep unchanged while the field-on speed becomes faster, as predicted by Eq. (1). At $V=25 V_{rms}$, the field-on process only takes 0.19 ms, which is 140 times faster than that with $V=2.5 V_{rms}$. The detailed results are listed in Table 1, where more data at different voltages are included. However, a severe problem arises during the field-off relaxation process in the high voltage regime. From Fig. 3, a small bump exists in the time dependant transmittance curve when the voltage is removed. The transmitted light bounces to a specific value then decreases to zero and finally recovers to the maximum transmission. This phenomenon originates from the back-flow effect at high driving voltages [11, 12]. The LC directors are reoriented by the hydrodynamic flow at first and then pulled back to their original twisted state. The back flow effect in our VOA emerges at $V=3.7 V_{rms}$ and becomes more pronounced as the voltage increases, as shown in Fig. 3. When the driving voltage is 25 V_{rms} , the optical bounce reaches 9% of the total light intensity with the duration of 40 ms. Back flow severely degrades the VOA's optical performance. The real field-off time should be much longer than the values shown in Table 1. The duration of the back flow should be also counted. As a consequence, simply elevating the driving voltage is not a viable approach to shorten the response time for a TN LC cell.

Table 1. Comparison of optical response times at different driving voltages.

Voltage (V_{rms})	2.5	3.75	5	7.5	10	15	20	25
Field-on time (ms)	26.59	9.09	4.453	1.81	0.97	0.42	0.23	0.19
Field-off time (ms)	46.37	45.66	45.53	43.68	44.17	42.89	42.98	44.15

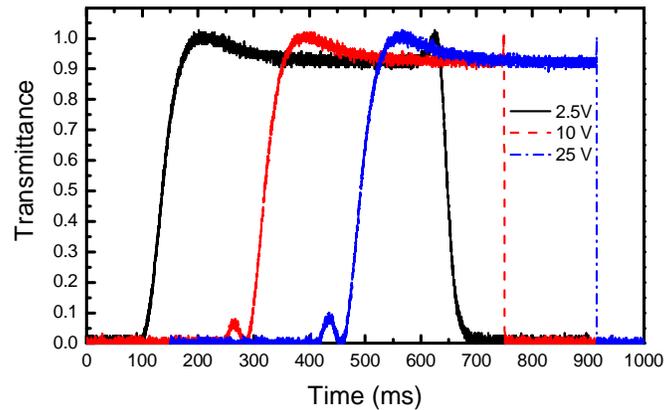


Fig. 3. Time dependent transmittance showing the VOA's dynamic response under different driving voltage. The solid black curve, dashed red curve and dash-dot blue curve correspond to 2.5 V, 10 V and 25 V, respectively.

4. Experimental results of PSTN LC

To fabricate the PSTN LC cell, we first mixed 3 wt% of bisphenol-A-dimethacrylate (M1) monomer into a Merck E45 LC mixture. The photoinitiator was pre-added in the monomer to initiate the UV photo-polymerization process. The LC/monomer mixture was injected into an empty TN LC cell that is the same as what we used in the above experiment. The LC/monomer cell was then exposed under a UV lamp ($\lambda = 365$ nm) with a suitable time and intensity to induce the polymerization. The final PSTN LC cell is highly transparent between the crossed polarizers. It means that the polymer networks still basically follow the same TN LC alignment direction influenced by the surface rubbing effect. At last, the PSTN LC cell was used to replace the normal TN LC cell in the VOA setup for further experiments.

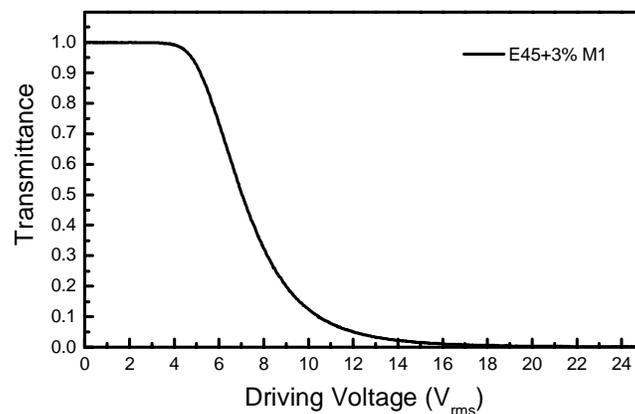


Fig. 4. Voltage dependent transmittance of a PSTN LC-based VOA.

Figure 4 shows the PSTN VOA transmittance as a function of the driving voltage. Under this circumstance, the threshold voltage is increased to $4 V_{\text{rms}}$, which is 3.6 times higher than that of the pure LC. The increased threshold voltage results from the interaction between the LC molecules and the polymer networks. The polymer networks resist the LCs from being reoriented by the electric field so that a higher torque is needed to reorient the LC. As the applied voltage increases, the VOA transmittance decreases, but the attenuation slope is not so steep as that of the pure LC. A 30dB attenuation is obtained at $V=23 V_{\text{rms}}$.

To investigate the dynamic response of the PSTN LC cell, we intentionally turn on and off the applied field periodically at different driving voltages. The relationship between the VOA transmittance and the time gives information about the on and off response times, which are shown in Fig. 5. Here the solid black line stands for $V=20 V_{\text{rms}}$ and the dashed blue lines are for $V=25 V_{\text{rms}}$. Upon comparing them with the $2.5 V_{\text{rms}}$ curve in Fig. 3, both the up slopes and the down slopes are evidently improved. In Fig. 5, the field-on and field-off response times (90-10%) for the $V=20 V_{\text{rms}}$ curve are 0.48 ms and 8.89 ms, respectively. For the $V=25 V_{\text{rms}}$ curve, the times become 0.34 ms and 9.37 ms. As compared to the pure E45 TN cell, the response time improvement is 78X and 5X, respectively. Furthermore, no back-flow effect is found, even if the applied voltage increases to $40 V_{\text{rms}}$. This indicates that the polymer networks have successfully suppressed the unwanted back-flow effect in the PSTN LC cell.

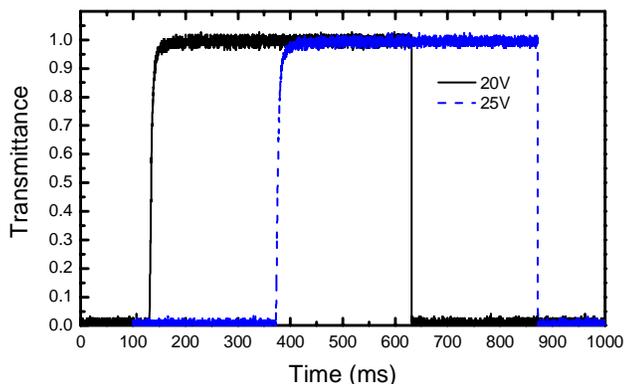


Fig. 5 Time dependent transmittance of a PSTNLC based VOA under different driving voltages. The solid black curve and the dashed blue curve correspond to 20 V and 25 V, respectively.

In a polymer stabilized liquid crystal, the LC molecules are anchored by the polymer networks. As a result, the elastic constant is increased which, in turn, leads to a faster rise and decay times, and a higher threshold. However, a precise mathematical model is difficult to develop because of the complicity of the composite material system. Thus, here we only give the experimental results of the PSTN VOA.

In the PSTN cell, it is not yet completely clear how the polymer networks are actually cross-linked. Based on the results shown in Fig. 4, in the voltage-off state the LC directors retain their twist alignment and the PSTN cell is still highly transparent. In a voltage-on state, the polymer networks resist LC molecules from being reoriented by the electric field. As a result, the microdomains are formed. If the microdomain size is comparable to the incident laser wavelength, the polymer networks would scatter light [13] Figure 6 shows the measured light scattering loss for the PSTN LC cell used in the VOA experiments. An unpolarized $1.55 \mu\text{m}$ laser and an InGaAs photodiode act as the light source and detector, respectively. From Fig. 6, the maximum light scattering loss amounts to $\sim 18\%$ of the optical power at $V \sim 9 V_{\text{rms}}$. This phenomenon is very interesting, which means that both light scattering and polarization rotation contribute to the optical attenuation of the PSTN VOA. The ratio between these two

mechanisms is dominated by the size and concentration of the polymer network, which can be controlled by the monomer concentration and the curing process [14]. We believe that this should be the first report of this kind of hybrid mode VOA.

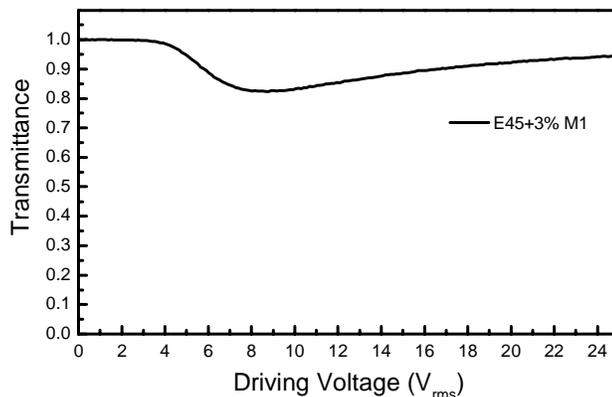


Fig. 6. The measured light scattering of a PSTN LC cell as a function of the applied voltage.

To further improve the VOA's response speed, one could use a thinner gap PSTN LC cell because the response time is proportional to the square of cell gap. However, a higher birefringence LC is required in order to satisfy the Gooch-Tarry first minimum condition. A recent report shows that birefringence up to 0.45 is achievable [15], thus it is possible to further improve the response time of the PSTN LC-based VOA. The demonstrated VOA is just a simple example using the new PSTN LC cell. Our results could also apply to other TN LC-based photonic devices that require a faster response.

5. Conclusion

We proposed a hybrid mode VOA based on the PSTN LC. Both light scattering and polarization rotation effect contribute to the optical attenuation. In comparison with the normal TN LC-based VOA, the PSTN LC significantly improves the optical response speed. At $V=25 V_{rms}$, the field-on and the field-off response times are reduced by 78X and 5X, respectively, without noticeable back-flow effect. The polymer networks approach can be extended to other TN LC-based photonic devices.

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