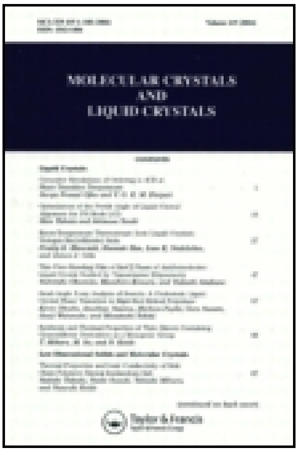

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Switchable Liquid Crystal Polarizer Using Total Internal Reflection

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SWITCHABLE LIQUID CRYSTAL POLARIZER USING TOTAL INTERNAL REFLECTION

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Abstract A switchable nematic liquid crystal (LC) polarizer using the total internal reflection is constructed and its performance characterized. The bandwidth of such a LC polarizer covers the entire visible range. The extinction ratio of the p-wave is found to exceed 10^6. Due to the use of low threshold LC mixture, thin LC layer and high pre-tilt angle alignment layer, the saturation voltage of the LC polarizer is greatly reduced. The switching time of the LC polarizer is about 100 ms at room temperature.

1. INTRODUCTION

Switchable beam splitting polarizer using total internal reflection (TIR) has been demonstrated employing nematic[1-3] and ferroelectric[4] liquid crystals (LCs). The TIR-based LC polarizer exhibits two desirable features: broad bandwidth and high extinction ratio. Owing to the large birefringence of many LC mixtures in the visible spectral region, the condition for total internal reflection to occur is satisfied over the entire visible wavelength. Unlike the polymeric sheet polarizers which utilizes the absorption mechanism, the TIR based polarizer transmits the p-waves and reflects the s-waves of the incoming unpolarized light. The extinction ratio for the p-waves is exceedingly high. However, the required operation voltage for achieving high transmission is somewhat too high ($>50V_{rms}$)[2] and the critical angle for observing total internal reflection is too large ($\theta_c \sim 75^o$)[1-4].

In this paper, we demonstrate a TIR-based nematic LC polarizer with reduced operation voltage and smaller critical angle. Light transmission and polarization behaviors of the LC polarizer are characterized using an incandescent white light and an unpolarized HeNe laser.

2. POLARIZER DESIGN

The LC polarizer we constructed is sketched as shown in Fig.1.

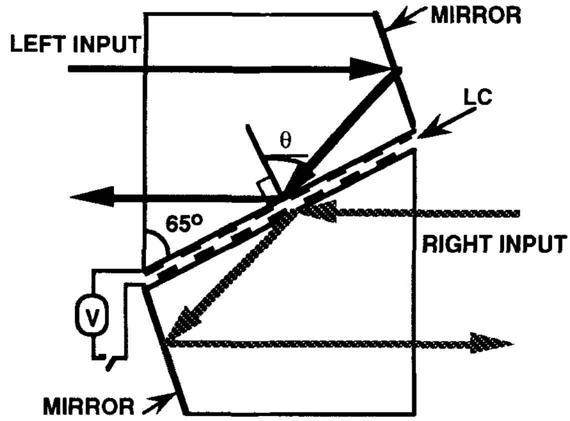

FIGURE 1 Configuration of the TIR-based LC polarizer. The critical angle (θ_c) is designed to be 62°. Light can enter from left or right side as shown.

The light (both left and right) is incident to the prism at the normal angle. This light is then reflected by the mirror to the interface of prism and LC layer. The LC directors are aligned parallel to the prism surface as depicted. At the voltage-off state, the incident angle (θ) exceeds the critical angle (θ_c), thus both s- and p-waves are reflected by the interface.[1] The critical angle is determined by the refractive index of glass (n_g) and the ordinary ray index (n_o) of the LC as:

$$\theta_c = \sin^{-1}(n_o/n_g) \tag{1}$$

From Fig.1, a smaller n_o/n_g leads to a smaller θ_c. The n_o of an LC is primarily determined by the molecular conjugation length and structure.[5] The n_o of many commercially available LC mixtures is around 1.50. It is possible to select an LC mixture with a slightly smaller n_o, however, the small n_o is often associated with a small n_e as well. To ensure the total internal reflection to occur over the whole visible spectral region and at a wide range of operation temperature, we must have a large n_e to satisfy

$n_o<n_g<n_e$ under these conditions. In this work, we have selected a high index glass (SF-10) and a high dielectric anisotropy LC mixture (BL-009 from Merck; its $\Delta\varepsilon$=14.1 at 1 kHz sine wave frequency) for this study. The refractive indices of SF-10 and BL-009 LC mixture are depicted in Fig.2. Using n_g = 1.728, n_o=1.526, and n_e=1.809, θ_c is calculated to be 62°. The angle θ shown in Fig.1 is 65°, which has taken the acceptance angle (3° half angle) into consideration. For application using an incoherent white light, the beam is usually not well collimated and certain divergence angle needs to be considered.

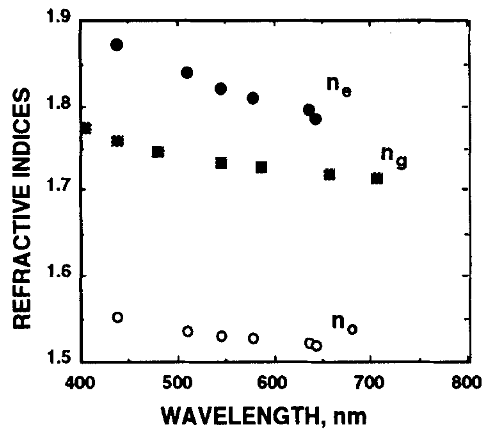

FIGURE 2 Wavelength-dependent refractive indices of the SF-10 glass and BL-009 LC mixture at T=20°C.

3. ELECTRO-OPTIC PROPERTIES

In the voltage-on state, the LC directors are reoriented by the electric field to be nearly perpendicular to the interfaces. Under this circumstance, the condition of TIR for the p-waves (linearly polarized in the plane of incidence) fails; the light leaks through the LC layer and is reflected by the second mirror as depicted in Figs. 3a and 3b. On the other hand, the s-waves (linearly polarized normal to the plane of incidence) still sees n_o and is reflected from the interface.

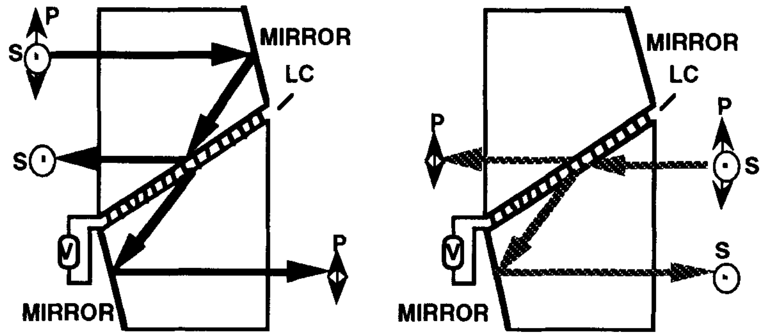

FIGURE 3 LC polarizer at the voltage-on state. (a): left input channel and (b): right input channel. P and S stand for the p- and s-waves, respectively.

4. EXPERIMENT

We have measured the voltage-dependent transmission, extinction ratio, and switching time of the LC polarizer under an incoherent white light and a coherent HeNe laser illuminations.

4.1 White Light Experiment

A xenon lamp was used as the light source for this white light experiment. The beam diameter was condensed by a pair of lenses to about 1.5 cm. The left input scheme (Fig.3a) was used for all the measurements described below. Similar results were obtained using the right input scheme.

Voltage-dependent white light transmission (T) and reflection (R) is shown in Fig.4. At the voltage-off state, the incident light is totally reflected at the interface resulting in no transmission. As voltage exceeds 1.5 V_{rms}, the light transmission increases and then gradually saturates. Beyond 30 V_{rms}, only a small increase in transmission is observed. Normally, in the devices employing total internal reflection, the required operation voltage is quite high (~50 V_{rms}) because the mechanism involved is the refractive index change occurs near the glass and LC interfaces.[2] These boundary layers are extremely difficult to be reoriented by the electric field.

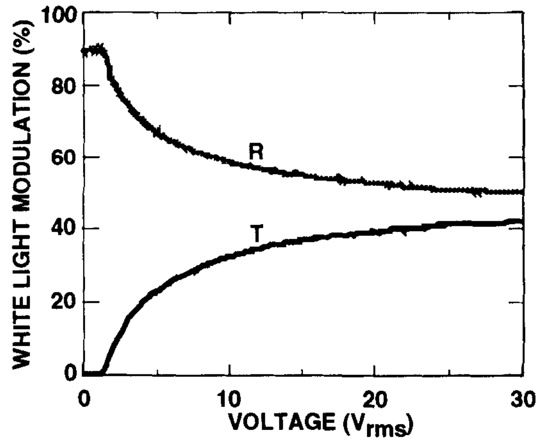

FIGURE 4 Voltage-dependent reflection (R) and transmission (T) of the LC polarizer under white light illumination.

We have combined the following three methods together to obtain the low operation voltage: (1) low threshold voltage LC mixture, (2) thin LC layer, and (3) large pre-tilt angle. The LC mixture used for this experiment has a relatively large dielectric anisotropy so that its threshold voltage is quite low. Although thin LC layer (5-μm) has nothing to do with the threshold voltage, it helps to lower the saturation voltage. Another important factor for reducing the saturation voltage is to increase the pre-tilt angle of the LC layers. We found the new high-tilt polyamic acid (from Du Pont) produces a large (~10°) pre-tilt angle. As a result, the saturation voltage is reduced significantly.

The transmitted p-wave is linearly polarized with an excellent polarization purity. However, the reflected beam is mixed with s- and p-waves. At a voltage below threshold, the ratio of the s and p wave intensity (s/p) is unity indicating that both s and p-waves are equally reflected at the prism-LC interface. This ratio increases linearly as the applied voltage exceeds the threshold, as shown in Fig.5. As voltage increases, more p-wave is transmitted resulting in an increased s/p ratio in the reflected beam. At high voltage regime, all the p-wave is transmitted (as shown in Fig.4) through the prisms. Thus, the reflected beam contains only s-wave.

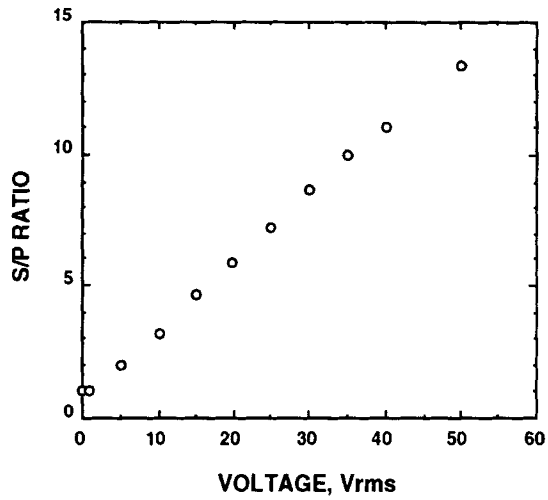

Fig.5 The s/p intensity ratio of the reflected light. The threshold voltage of the LC polarizer is 1.5 V_{rms}.

4.2 HeNe Laser Experiment

The electro-optic response of the LC polarizer was characterized using an unpolarized HeNe laser (λ=633 nm) as well. Results are slightly different from those of using an incoherent xenon lamp. Fig.6 shows voltage-dependent light transmission of the LC polarizer using a HeNe laser. As the voltage exceeds the threshold, the transmitted p-wave exhibits an oscillatory behavior and gradually reaches a stable state. This phenomenon was also observed by previous authors.[1,2] No such oscillation is observed (Fig.4) when an incoherent white light source was employed. On the other hand, the s-wave is always reflected, independent of the applied voltage.

It deserves a special mention that the extinction ratio of the transmitted p-wave is exceedingly high. Switching the LC polarizer from 0 to 20 V_{rms}, the extinction ratio is found to be greater than 10^6:1.

The switching time of the LC polarizer was measured using both white light and a HeNe laser. Results are of course similar except for the oscillatory spikes for the coherent light. It is well-known that the rise time depends on the applied voltage; the higher voltage leads to a faster rise time. The rise time of the LC polarizer is 3 ms and decay time of about 100 ms at room temperature (23°C). Operating the device at an elevated temperature would greatly reduce the decay time.[5]

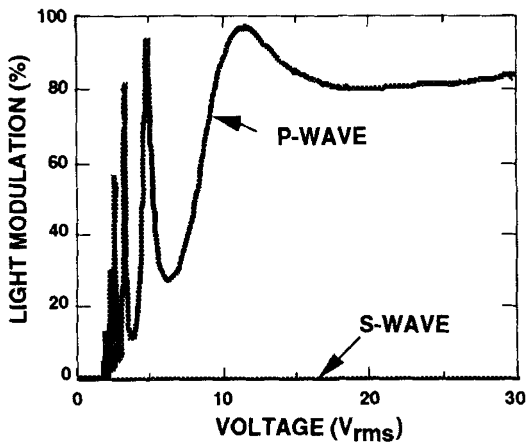

FIGURE 6 Voltage-dependent transmission of the p- and s-waves of the LC polarizer.

5. CONCLUSION

We have demonstrated a LC polarizer using the total internal reflection mechanism. Its bandwidth covers the entire visible range. The extinction ratio higher than 10^6:1 was measured for the transmitted p-waves. The lower operation voltage is achieved by using a LC mixture with low threshold voltage, a thin LC layer and a high pre-tilt angle alignment layer. The response time of the LC polarizer is about 100 ms. A faster response time can be obtained by using a lower viscosity material or operating the polarizer at an elevated temperature.

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