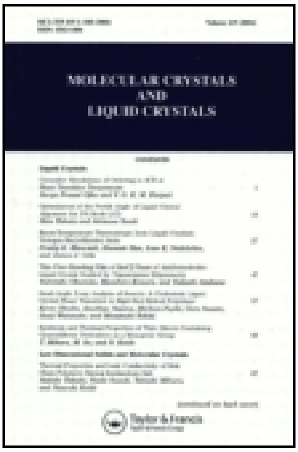

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Electro-Optic Switching in Polymer Waveguide Using Surface Stabilized Ferroelectric Liquid Crystal

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Electro-Optic Switching in Polymer Waveguide Using Surface Stabilized Ferroelectric Liquid Crystal

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A fast electro-optic switching in polymer waveguide has been demonstrated using surface stabilized ferroelectric liquid crystal (SSFLC). In this device, the SSFLC layer is used as the active material with the passive polymer waveguide. The switching time is of the order of several microseconds.

Keywords: ferroelectric liquid crystal, waveguide, polymer waveguide, electro-optic switching, electro-optic effect, SSFLC

1. INTRODUCTION

Electro-optic switching devices of ferroelectric liquid crystals (FLCs) have attracted much attention because of their fast switching speed. So far, various types of electro-optic effects in FLCs have been reported.[1-3] Among them, the surface stabilized ferroelectric liquid crystal (SSFLC) has been studied most extensively because of its high speed response and bistability.[2] However, the application of SSFLC has been limited to flat display panels, and few other configurations of SSFLC have been reported.[4,5] The electro-optic effects in the combination of FLC and optical materials have attracted much interest from practical point of view. For instance, the application of SSFLC to the control of the light in optical waveguides is of potential interest as fast electro-optic switching device for the data processing and communication. In addition, the application of the FLCs with the anomalous behavior to electro-optic devices is effective because of their novel functional properties.

In this paper, a polymer-SSFLC composite for fast electro-optic switching in a waveguide is reported.

2. PRINCIPLE OF DEVICE OPERATION

The SSFLC film is fabricated between one conducting glass plate and a polymer waveguide formed by coating on another conducting glass plate as shown in Figure

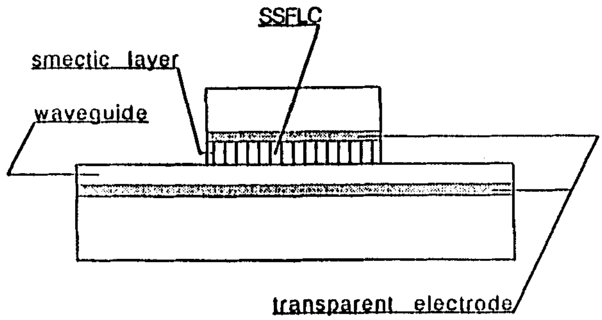

FIGURE 1 Combination of FLC and optical waveguide.

1. In this geometry, the smectic layer was perpendicular to the polymer waveguide. Suppose that a monodomain with a unique optical axis was realized under DC bias field. When the light polarized parallel to the surface propagates in the polymer waveguide, the light sees the refractive index n_e shown by the following equation,

$$n_e = \sqrt{n_{\|}^2 n_{\perp}^2/(n_{\perp}^2 \sin^2\theta + n_{\|}^2 \cos^2\theta)}, \quad (1)$$

where $n_{\|}$ and $n_{\perp}$ are refractive indices of the FLC parallel and perpendicular to the molecular axis, respectively, and θ is the angle between the long molecular axis and the direction of the incident light.

When n_e is smaller than the refractive index of polymer waveguide n_p, the light suffers total internal reflection and propagates in the polymer waveguide. On the contrary, if n_e is larger than n_p, the light cannot be reflected at the polymer-FLC interface and penetrates the FLC film. In other words, when θ is smaller than the critical angle θ_c which is determined by substituting n_p into Equation (1) instead of n_e, the light in the waveguide is not affected by the FLC film. Thus, the light can transmit through the polymer waveguide. This is the on-state (as shown in Figure 2(a)). When θ is larger than θ_c, the light emits out of the waveguide, resulting in the off-state (as shown in Figure 2(b)). The principle of the operation of this device can be explained as follows.

In the fabrication process of SSFLC, the liquid crystal in the smectic A phase aligned itself with the optical axis lying in the direction which makes an angle of θ_c to the path of incident light in the waveguide, as shown in Figure 2. When the molecules are oriented in the direction [A] ($\theta < \theta_c$), as shown in Figure 2(a), by the application of the electric field, the condition $n_e < n_p$ is satisfied and the high transmission intensity through the waveguide is observed. When the polarization of the applied field is reversed, the FLC molecules are reoriented to the direction [B] ($\theta > \theta_c$) as shown in Figure 2(b), resulting in the low transmission state because of $n_e > n_p$. Consequently, the switching of the transmission intensity through the polymer waveguide can be realized.

3. EXPERIMENTAL

The liquid crystal studied in this paper is (2S, 3S)-3-methyl-2-chloropentanoic acid-4′,4″-octyloxybiphenyl ester (3M2CPOOB). This liquid crystal possesses large spon-

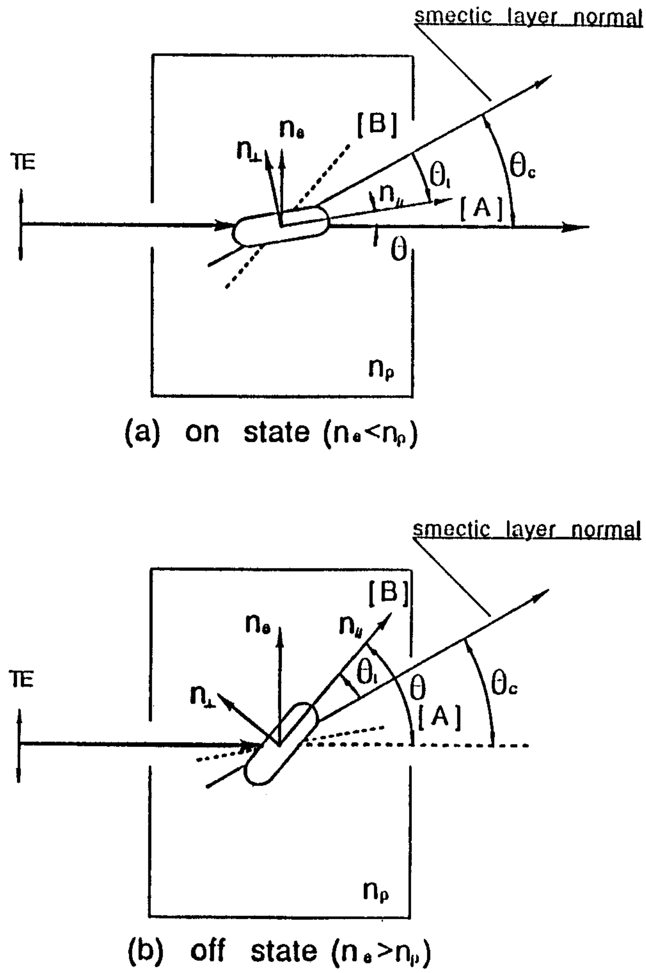

FIGURE 2 Schematic representations of electro-optic switching in polymer waveguide using FLC.

taneous polarization exceeding 2×10^{-7} C/cm^2. The synthesis and properties of this liquid crystal have been reported previously.[6,7] The product was purified by recrystallization from hexane.

The configuration of the electrically controlled polymer waveguide is shown in Figure 3. The lower substrate was an In-Sn oxide (ITO) coated conducting PYREX glass plate with a refractive index of 1.47. The waveguide of polyvinylalcohol (PVA) was coated by the spin coating technique, whose thickness was about 6–7 μm. The upper substrate was ITO coated conducting glass plate whose surface was coated with stretched PVDF film of 1 μm thickness to achieve a homogeneous alignment of FLC.[8] The cell with an appropriate electrode distance fixed with polyethyleneterephthalate (PET) sheets was constructed utilizing these substrates. The cell gap was 4 μm. The cell was filled with the liquid crystal by capillary action, and the realization of the excellent alignment of the SSFLC was confirmed by microscopic observation.

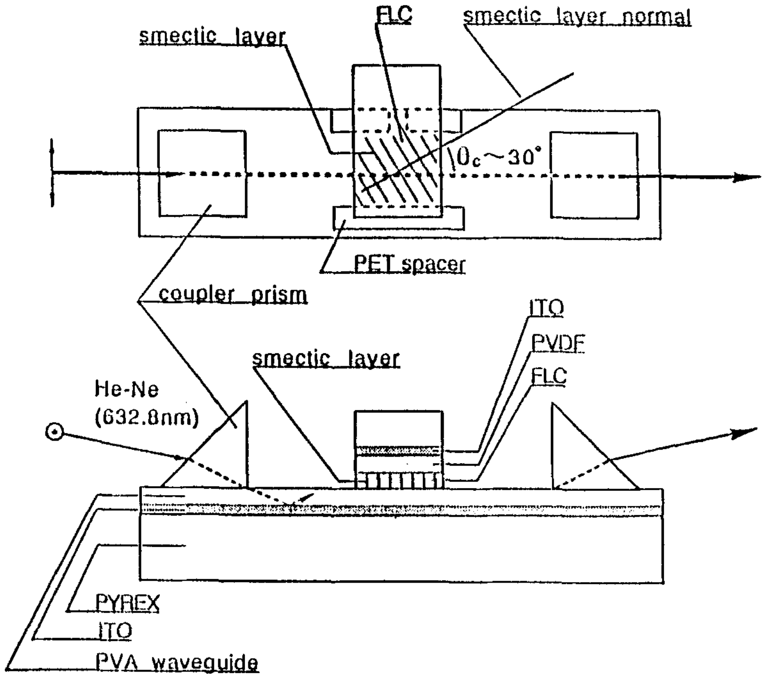

FIGURE 3 Experimental configuration for studying the fast electro-optic switching in polymer-SSFLC composite.

A He-Ne laser light (632.8 nm) was coupled into the polymer waveguide by a prism coupler having a refractive index of 1.78. The polarization of the incident light was parallel to the plane of the waveguide. The refractive index of polymer waveguide n_p was 1.52, while the liquid crystal had a parallel index $n_{\parallel}$ of 1.60 and a normal index $n_{\perp}$ of 1.49. The critical angle θ_c is estimated to be 30.5° from Equation (1). The direction of the smectic layer normal was chosen to make an angle of 30° to the direction of the incident light.

4. RESULTS AND DISCUSSION

Figure 4 shows the typical switching waveform driven by a rectangular voltage with ±35 V at 10 kHz. The contrast ratio of the transmission intensities in the off- and on-states is about 40. The devices which control light in the waveguide by using liquid crystal as the active material is divided into two classes. In one type the liquid crystal constitutes the waveguide itself,[9,10] and in the other type a passive waveguide is controlled with liquid crystal overlay.[11] The former has large loss of transmission light due to Rayleigh scattering. However, the device proposed in this paper is classified in the latter, and liquid crystal is used as active substrate material with the polymer waveguide. Therefore, the transmission loss is very low in the on-state.

In a conventional SSFLC flat switching device, the contrast ratio generally de-

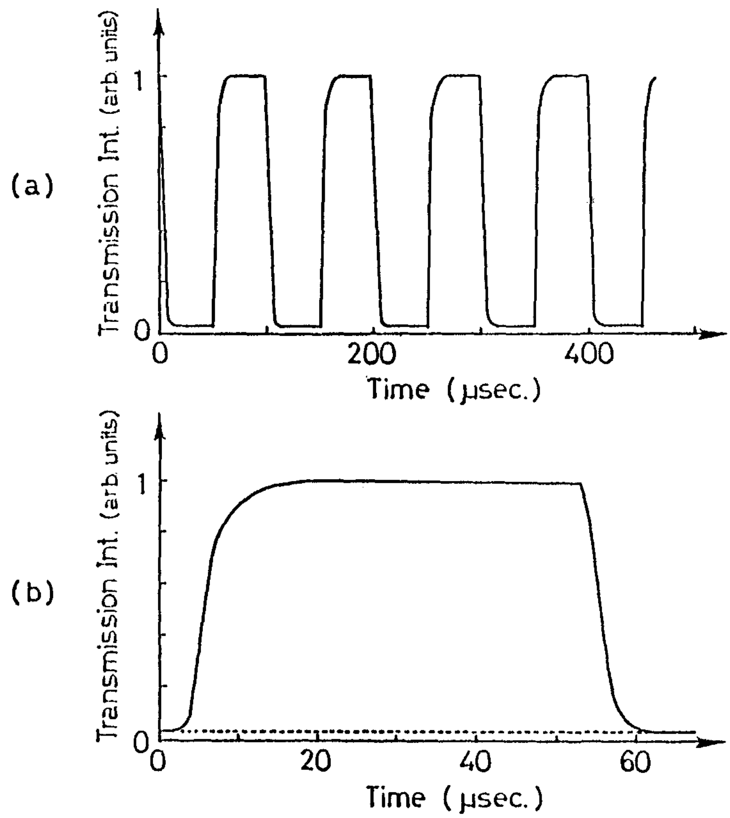

FIGURE 4 Typical switching waveforms driven by rectangular voltage with ±35 V at 10 kHz.

pends on the tilt angle, and thus is sensitive to temperature. On the other hand, this waveguide device requires the switching of director of FLC across θ_c. That is, if the direction of the smectic layer normal makes an angle of θ_c to the light path, the switching can be obtained even at small tilt angle. Therefore, the electro-optic switching does not markedly depend on the magnitude of the tilt angle. The contrast ratio is dominated by the transmittance in the polymer waveguide and the leakage of the scattering light in the liquid crystal. Therefore, the contrast ratio of this device is hardly influenced by the variation of the temperature.

It is clear from Figure 4 that the output optical signal can respond well to the input signal. The optical rise and fall waveforms of the transmitted light in the magnified scale are also shown in Figure 4(b). The response times of these switchings are very short and are both about several μs.

Figure 5 shows the voltage dependence of the response time. The response time is defined as the time required for switching from 10% to 90% of the transmission change. The response time of switching from on- to off-states (closed circles) decreases with V^{-1} in a relatively higher voltage range. This relation agrees with the simplest theoretical estimation of the switching time in a bulk sample. On the other hand, the response from off- to on-states is anomalous. That is, the response time increases with the applied voltage (open circles). In the case of this config-

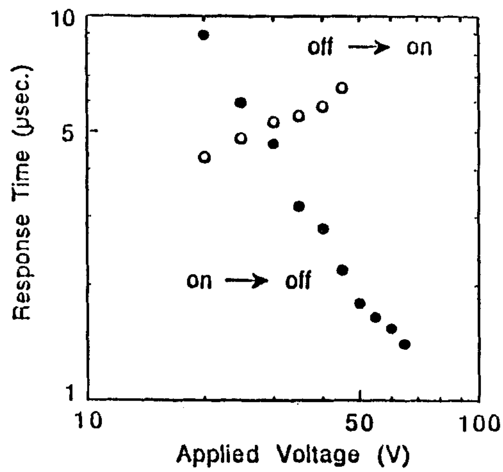

FIGURE 5 Voltage dependence of the response time to the application of rectangular voltage at 10 kHz. Closed and open circles represent responses of on- to off-states and off- to on-states, respectively.

uration, in the off-state the dipole moment orients from PVDF to PVA substrates, and in the on-state, the dipole orients in the opposite direction. The orientation to PVA may be favorable compared with that to PVDF. The cause of this anomalous dependence is not clear, but the asymmetry of the substrates or the space charge in the thick polymer waveguide may play an important role. In fact, the influence of the charge in the alignment or insulator layers is one of the most important problems in the SSFLC flat panel. That is, the anomalous response of the on to off switch seems to be not intrinsic, but extrinsically originated from the dipole and space charge effect, etc. This anomaly should be also related with dielectric anomaly in this polymer-SSFLC system. It should be also mentioned that this anomally is expected to be suppressed by an appropriate choice of polymers.

The driving applied voltage is relatively high, because the effective distance between electrodes is fairly thick. However, the voltage can be lowered by the reduction of the thickness of waveguide and FLC layer.

5. SUMMARY

A fast electro-optic switching device in polymer waveguide using the control of total reflection by ferroelectric liquid crystal was proposed. This device had a high contrast ratio of transmitted light intensities of on- and off-states. In this device liquid crystal was used as active substrate material with the polymer waveguide, and the transmission loss in the on-state was low. The fast switching of the order of several microseconds was provided.

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