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Linear optical switching in a FLC/waveguide composite device

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A fast electrooptic modulation in a polymer waveguide using a ferroelectric liquid crystal has been proposed. In this device, the surface stabilized ferroelectric liquid crystal and the soft mode ferroelectric liquid crystal are used as an active material on the passive polymer waveguide, and electrooptic switching is realized by controlling the total reflection at the polymer waveguide–liquid crystal interface. The response time is of the order of several microseconds. The analogue electrooptic modulation in the waveguide is realized using the field induced linear molecular tilt of the electroclinic effect in the soft mode ferroelectric liquid crystal.

1. Introduction

The control of light in a thin dielectric waveguide is required for practical application in areas such as data processing and communication, and various types of devices switching light in the optical waveguide have been demonstrated [1–5]. In particular, the electrooptic effect of liquid crystal is very effective because the magnitude of its refractive index change is larger than that of other solid materials, and the nematic phase has been used for the application of liquid crystals in optical waveguides [3–5]. However, its response speed is relatively slow and is of the order of milliseconds.

The electrooptic effects of ferroelectric liquid crystals (FLCs) have attracted considerable attention because of their fast switching speed. So far, several kinds of electrooptic effects in FLCs have been reported [6–10]. Among them, the surface stabilized ferroelectric liquid crystal (SSFLC) has been studied most extensively for the realization of a high quality, flat display panel because of its high speed response and bistability [7]. Recently, however, other applications of SSFLCs such as spatial light modulators and optical deflectors have also been proposed [11, 12]. We have proposed electrooptic switching in polymer waveguides using SSFLC as an active cladding layer [13].

Electric field induced molecular tilt of the FLC in the smectic A (S_A) phase is well-known as an electroclinic effect [14]. The electrooptic switching using this effect, soft mode ferroelectric liquid crystal (SMFLC), has attracted much attention because of its fast response [10]. In this paper, fast electrooptic response in a waveguide modulator using SMFLC as the active cladding material on the polymer waveguide is proposed.

2. Principle of device operation

The FLC/waveguide composite device proposed in this paper is composed of a polymer waveguide and a FLC layer on top of the waveguide. The FLC layer is

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sandwiched between a conducting glass plate and a polymer waveguide fabricated by coating it on another conducting glass plate, as shown in figure 1 (*a*). In this geometry, the smectic layer was perpendicular to the polymer waveguide (homogeneous alignment).

Suppose that a monodomain with a unique optical axis was realized on the waveguide under DC bias field, as shown in figures 1 (*b*) and (*c*). When light polarized parallel to the surface propagates in the polymer waveguide, the light sees the effective refractive index n_e represented by the following equation,

$$n_e = \frac{n_{\parallel} n_{\perp}}{\sqrt{(n_{\perp}^2 \sin^2 \theta + n_{\parallel}^2 \cos^2 \theta)}}, \tag{1}$$

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

According to equation (1), n_e changes from $n_{\perp}$ to $n_{\parallel}$ as a function of θ. θ_c is defined as the critical angle where n_e coincides with the refractive index of the polymer waveguide n_p. When θ is smaller than the critical angle θ_c, n_e is smaller than n_p and the light suffers total internal reflection at the FLC–waveguide interface. This is the on-state. When θ is larger than θ_c, n_e is larger than n_p and, then, the condition of the total internal reflection

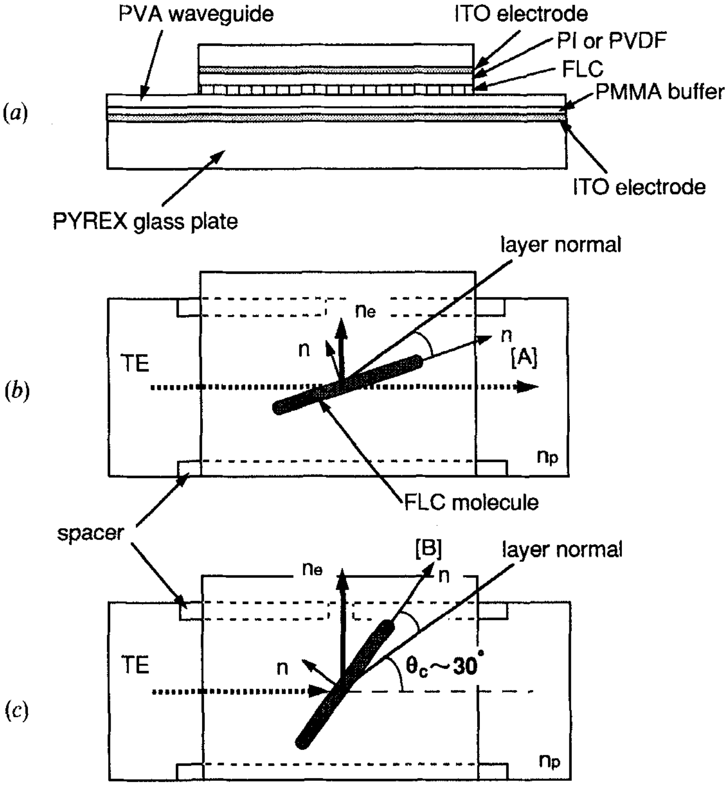

Figure 1. (*a*) Device configuration for studying fast electrooptic switching in the waveguide–FLC composite. (*b*), (*c*) Schematic representations of electrooptic switching in the polymer waveguide using FLC.

at the FLC–waveguide interface is not satisfied. As a result, light is emitted from the waveguide and cannot propagate, resulting in the off-state.

In the fabrication process of the FLC layer, the liquid crystal in the smectic A (S_A) phase aligns itself with the optical axis lying in the direction which makes an angle of θ_c to the path of the incident light in the waveguide, as shown in figure 1. When the molecules are oriented in the direction [A] ($\theta < \theta_c$), as shown in figure 1 (*b*), by the application of the electric field, the condition $n_e < n_p$ is satisfied and the on-state is observed. When the polarity of the applied field is reversed, the FLC molecules are reoriented to the direction [B] ($\theta > \theta_c$), as shown in figure 1 (*c*), resulting in the off-state because $n_e > n_p$. Consequently, the switching of the transmission intensity through the polymer waveguide can be realized [13].

3. Experimental

The liquid crystals studied in this paper are (2*S*, 3*S*)-3-methyl-2-chloropentanoic acid 4′,4″-octyloxybiphenyl ester (3M2CPOOB) and its liquid crystal mixture. The former compound possesses a large spontaneous polarization exceeding 200 nC cm^{-2}. The synthesis and properties of this liquid crystal have been reported previously [15, 16]. The latter compound shows the chiral smectic C (S_C^*) phase in the range from −13 to 49°C and shows the S_A phase in the range from 49 to 63°C.

The lower waveguide 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 a spin coating technique, whose thickness was about 1 μm and refractive index 1·52. The upper substrate was an ITO coated conducting glass plate whose surface was also coated with polymer film to achieve a homogeneous alignment of the FLC. For the alignment of 3M2CPOOB and the liquid crystal mixture, stretched polyvinylidene fluoride (PVDF) film [17] and rubbed polyimide film were used, respectively. The width of the upper substrate with alignment layer was 1 mm. The cell with an appropriate electrode distance fixed with polyethyleneterephthalate (PET) films or polymer beads was constructed using these substrates as shown in figure 1. The cell gap was about 1 to 4 μm.

A He–Ne laser light of 632·8 nm wavelength was coupled to 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 the 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 for the He–Ne laser light. The critical angle θ_c is estimated to be 30·5° from equation (1). Therefore, 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

4.1. *Operation in the S_C^* phase*

Figure 2 shows the typical response waveform of the electrooptic switching device using 3M2CPOOB in the S_C^* phase driven by a rectangular voltage with ±35 V at 10 kHz. The contrast ratio of the transmission intensities in the off- and on-states was about 40. The devices which control light in the waveguide by using liquid crystal as an active material are divided into two types. In one type, liquid crystal constitutes a waveguide itself [3, 4], and in the other type, a passive waveguide is controlled with liquid crystal overlay [5]. The former has a larger loss of transmission light due to Rayleigh scattering. However, the device proposed in this paper is classified in the

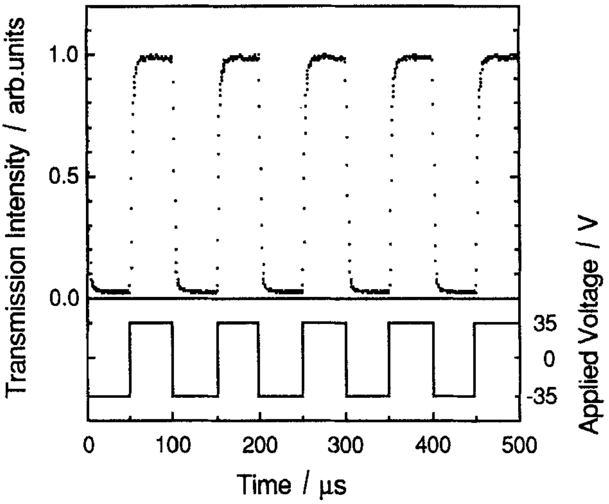

Figure 2. Typical switching waveform of the electrooptic switching device using 3M2CPOOB in the S_C^* phase driven by a rectangular voltage with ±35 V at 10 kHz.

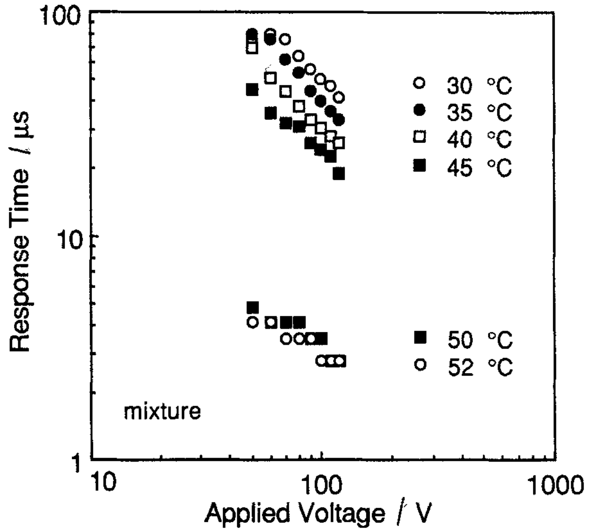

Figure 3. Voltage dependences of the response time of the electrooptic switching device using the liquid crystal mixture as a function of temperature.

latter, and liquid crystal is used as cladding material with the polymer waveguide. Therefore, the transmission loss in the on-state is very low. It is clear from figure 2 that the output optical signal can respond well to the input signal. The response times of these switchings were very short and were both about several microseconds.

4.2. *Operation in the S_A phase*

Figure 3 shows the voltage dependence of the response time of the waveguide switching device as a function of temperature using the liquid crystal mixture which shows the ferroelectric phase at room temperature. The response time decreases with

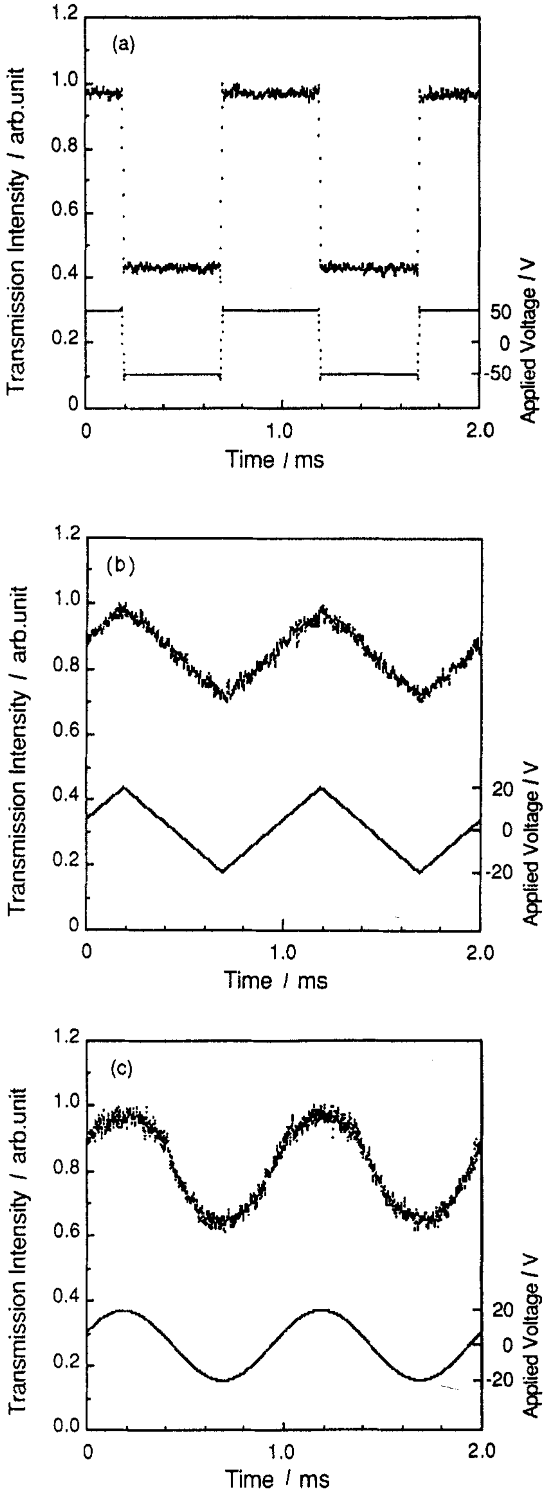

Figure 4. Typical switching waveforms of the electrooptic switching device using the liquid crystal mixture in the S_A phase driven by (*a*) rectangular, (*b*) triangular and (*c*) sinusoidal wave voltages.

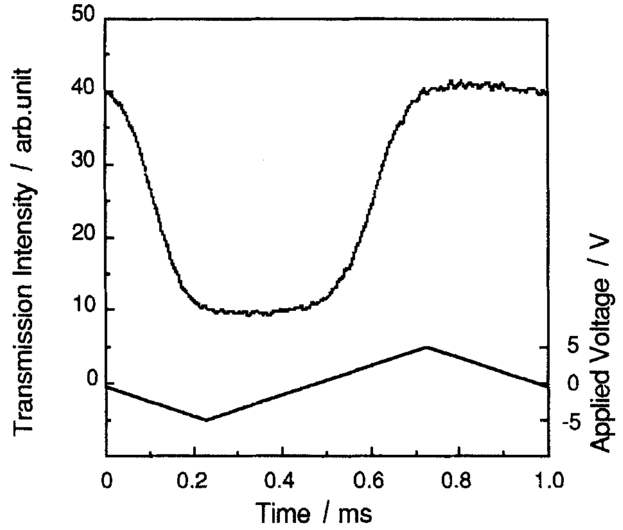

Figure 5. Typical switching waveform of the electrooptic switching device using the liquid crystal mixture ($T_c - T = 4°C$) in the S_C^* phase driven by a triangular wave voltage.

increasing voltage. It should be noted that the response time abruptly changes between 45°C and 50°C. This temperature corresponds to the phase transition point between the S_A and S_C^* phases, T_c, and this fast response is observed in the S_A phase. In the S_A phase, the electrically induced tilt angle in proportion to the magnitude of the applied electric field, i.e. the electroclinic effect, is observed [14] and the response time of this effect is very short [10]. The waveguide device studied in this paper requires switching of the FLC director across θ_c. That is to say, if the direction of the smectic layer normal made an angle of θ_c to the light path, then switching can be realized even at small tilt angle such as induced tilt angle in the S_A phase. Therefore, the fast response just above T_c shown in figure 3 seems to be due to the electrically induced tilt of the molecular direction in the electroclinic effect.

In the S_A phase, the induced tilt angle of the electroclinic effect is in proportion to the applied electric field. Therefore, in the geometry of the waveguide switching device studied in this paper, the angle θ between the molecular long axis and the direction of the incident light changes linearly with the applied electric field. In other words, n_e continuously changes with the change of the applied voltage. Therefore, it may be expected that the transmitted light intensity changes in proportion to the applied electric field.

Figure 4 shows typical waveforms of the response of this device to the triangular and sinusoidal waves of the applied voltage at 50°C ($T - T_c = 1°C$). It is found that an analogue electrooptic modulation in the waveguide is realized in the S_A phase.

On the other hand, figure 5 shows the response of this device to the triangular voltage wave in the S_C^* phase. The analogue response of the light intensity cannot be observed in the S_C^* phase because of the bistability of the molecular orientation.

5. Conclusions

A fast electrooptic switching and modulation in the polymer waveguide using the control of total reflection by ferroelectric liquid crystal was proposed. In this device, liquid crystal was used as a cladding material with the polymer waveguide, and the transmission loss in the on-state was low. Fast switching of the order of several microseconds was provided. In the S_A phase, the analogue electrooptic modulation in the waveguide was realized, which had not been observed in the S_C^* phase due to the bistability of the molecular orientation.

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