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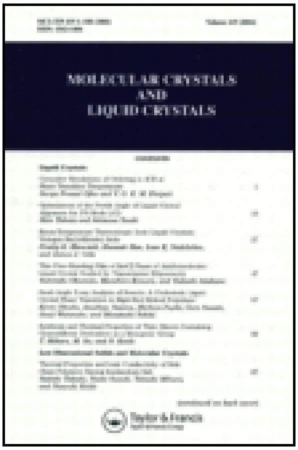

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Electro-Optic Modulation of Light by a Planar Waveguide Based on Ferroelectric Liquid Crystals

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Electro-Optic Modulation of Light by a Planar Waveguide Based on Ferroelectric Liquid Crystals

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We present electro-optic switching from a planar waveguide with a ferroelectric liquid crystal overlayer and discuss the operating principle and the parameters significant for the operation of the device. We have found electro-optic response times of about 20 μs at best as well as a high (5.7%) transmittance in the ON-state of the device. The contrast ratio was 4:1 ON to OFF state.

Keywords: Waveguide; Integrated Optics; Ferroelectric Liquid Crystals; Guided Modes; Radiation Modes; Electro-Optics

INTRODUCTION

In the seventies, a number of studies on nematic liquid crystal waveguides were reported [1-4]. Due to the large scattering losses (>20 dB/cm), though, the interest in this kind of liquid crystal device decreased significantly. During the last decade, however, there has been a revival of the interest in liquid crystal waveguides, mainly due to two reasons: *i)* liquid crystals have large effective electro-optic coefficients as a consequence of collective molecular reorientation; *ii)* it was found that scattering losses could be greatly reduced (down to 2 dB/cm) by using strongly confined systems [5-6] as well as smectic liquid crystals [7]. In particular, the use of ferroelectric liquid crystals in various waveguiding structures has been reported by several authors during the last ten years [8-18]. Also, the use of a pyroelectric liquid crystal polymer (PLCP), based on FLCs, in an m-line study was reported recently [19].

In the present work we have realized a planar glass waveguide with an FLC-overlayer, to give an integrated electro-optic switch with a high transmittance in the ON-state.

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EXPERIMENTAL

The glass waveguide was made by a sol-gel process and deposited on top of an ITO-coated soda-lime glass plate of refractive index 1.51. The ITO-layer was very thin, 35 nm, in order not to disturb the guiding properties of the glass film. The sol-gel film consisted of 70% SiO_2 and 30% TiO_2, giving a refractive index of 1.60 at 632.8 nm. The thickness of the film was 0.9 μm.

A standard ITO-coated glass plate was fixed onto the sol-gel waveguide film at a constant distance as determined by Mylar spacers. The cell thus formed was filled with the ferroelectric liquid crystal ZLI-4237-100 from Merck. See Figure 1. The cover glass plate had a thin layer of polyimide, which had been uni-directionally rubbed in order to determine the alignment of the FLC with respect to the direction of propagation of light in the waveguide. The FLC-alignment was determined only by the polyimide layer of the cover glass plate, as the waveguide film had not been treated with any alignment layer.

The FLC-overlayered waveguide thus formed was mounted in a special support, in which high-index prisms for the coupling and de-coupling of light where held fixed on the waveguide film by mechanical pressure, thus obtaining a thin airgap between the prism and the waveguide film. The light used was that of a HeNe-laser, linearly polarized in the plane of the waveguide film (TE-polarization). The coupling prisms were made of SF6 glass, having a refractive index of 1.7988 at 632.8 nm. The angle between the base of the prism and the interface upon which the light impinged was 56°. The angle of incidence at the prism interface was varied, thus exciting different modes of propagation in the waveguide at the base of the prism. The light exiting from the decoupling prism was monitored by a photodiode. The FLC/waveguide cell was electrically connected in series with a resistance of R=11.4 kΩ, so that the electrical current flowing through the cell during switching could be measured. The applied voltage as well as the current response and the optical response were measured on a Tektronix TDS 430A digitizing oscilloscope and saved on diskette.

The waveguide cell was filled with the liquid crystal in the isotropic phase, then cooled slowly (-2°C/min) down to room temperature without the application of an electric field. Before mounting the FLC/waveguide cell in the laser setup the alignment and the electro-optic switching of the FLC were checked with a polarizing microscope (Olympus BX 60 Pol). The tilt angle of the SmC*-phase at room temperature thus measured was 24°, which corresponds to the specifications of the data sheet of the liquid crystal.

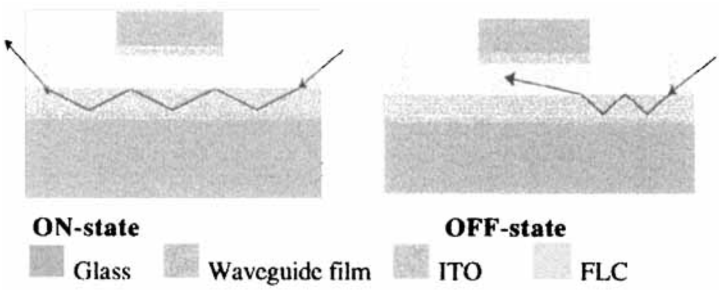

FIGURE 1 Waveguide device, consisting of a sol-gel glass waveguide film, an FLC-overlayer, and a cover and cladding layer of soda-lime glass.
See Color Plate XIII at the back of this issue.

PRINCIPLE OF DEVICE OPERATION

The fundamental principle of operation governing of the device is as follows. When the effective refractive index N_m, associated with a mode propagation constant β_m, propagating in the waveguide film is greater than the refractive index n_{FLC} of the liquid crystal the condition for total internal reflection at the interface is satisfied – *i.e.*, the light continues to propagate in the glass waveguide film without significant energy losses, thus resulting in the ON state of the device. See Figures 1-2. Inverting the sign of the electric field, the optic axis of the FLC in the plane of the waveguide cell is switched through twice the tilt angle (48°) resulting in a change of the refractive index of the liquid crystal layer. In this situation, the effective index N_m is now less than n_{FLC}, thus no longer satisfying the condition for total internal reflection at the waveguide/FLC-interface. As a result, a substantial part of the energy of the propagating mode goes into the FLC-layer, thus diminishing the intensity of decoupled light impinging on the photodiode and resulting in the OFF-state of the device. See Figures 1-2. The refractive index of the ferroelectric liquid crystal for the case of TE-modes is given by

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$$\frac{1}{n_{\mathrm{FLC}}^2(\alpha)} = \frac{\cos^2\alpha}{n_o^2} + \frac{\sin^2\alpha}{n_e^2}, \tag{1}$$

where α is the angle between the optic axis of the FLC and the direction of propagation of the light beam in the glass waveguide.

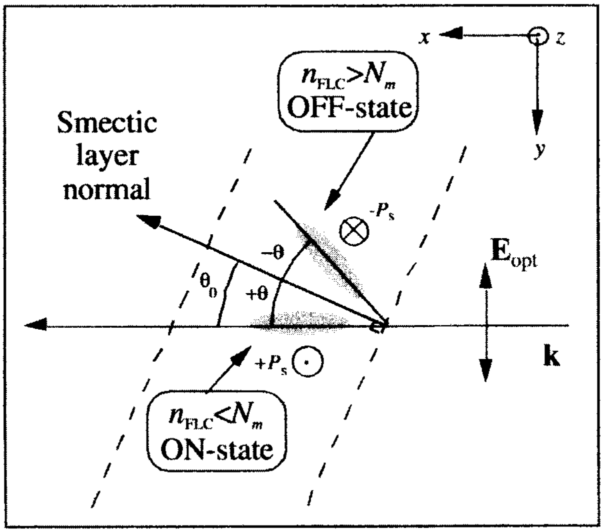

FIGURE 2 Operating principle of the FLC/waveguide device. See Color Plate XIV at the back of this issue.

RESULTS

The waveguide film was first characterized with respect to its TE-mode structure for the case without liquid crystal on top. The values of the effective refractive indices are obtained from the angles of incidence upon the coupling prism for which light waveguiding is obtained, according to:

$$N_m = n_p \sin\left(\phi + \arcsin\left(\frac{\sin\theta_{i,m}}{n_p}\right)\right) \tag{2}$$

where n_p is the refractive index of the prism, ϕ is the prism angle and $\theta_{i,m}$ is the angle of incidence upon the prism with respect to the normal of the prism/air interface. As a comparison, the TE-mode structure for the

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case without liquid crystal was calculated analytically for a 3-layered asymmetric waveguide stack according to:

$$\frac{2\pi d}{\lambda}\sqrt{n_g^2-N_m^2}-\arctan\sqrt{\frac{N_m^2-n_s^2}{n_g^2-N_m^2}}-\arctan\sqrt{\frac{N_m^2-n_c^2}{n_g^2-N_m^2}}=m\pi \quad (3)$$

where n_s, n_g and n_c are the refractive indices of the substrate, glass waveguide film and the cladding or cover layer, and d is the thickness of the glass waveguide film. The experimental and calculated results for the case without liquid crystal are shown in Table 1.

θ_i	N_m (exp.)	N_m (calc)	Output intensity
0.74°	1.4985	–	Strong
2.68°	1.5169	1.5165	Strong
11.11°	1.5904	1.5774	Weak

TABLE 1 Experimental and calculated TE-modes of the sol-gel glass waveguide. The parameters for the calculation are: $n_s = 1.51$, $n_g = 1.60$, $n_c = 1.00$, $d = 0.9\mu m$

According to the calculation there should only be two modes in the waveguide, while three modes are observed. However, one of the experimentally observed modes has an effective index value which is lower than the substrate index and thus occurs for a very small angle of incidence with respect to the normal of the air/prism interface. This would be consistent with a substrate mode (radiation mode), for which the effective index satisfies the condition

$$n_c \le N_m < n_s. \quad (4)$$

For the other two modes that are found experimentally, the one at the smaller angle of incidence is found to have an N_m-value equal to that calculated for the second mode ($m = 1$) according to Eq. (3) above. The mode at the larger angle of incidence, however, has an N_m-value which is different from, although in the vicinity of, that calculated for the first mode ($m = 0$). Another discrepancy between what is expected and what is observed is that the intensity of the decoupled light is much less for what apparently seems to be the first mode than for the second mode. In spite of these discrepancies, however, the best interpretation of the TE-mode structure of the glass waveguide is that of having a weak-intensity

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first mode, a strong-intensity second mode, and a (strong-intensity) substrate mode.

Given the findings for the blanc waveguide as described above, we chose to utilize what we presume to be the second mode of the waveguide for the electro-optic switching with the ferroelectric liquid crystal, *i.e.*, the mode whose effective index value is $N_m = 1.517$. This mode on one hand corresponds to the calculated result and on the other hand has a high output intensity. The transmittance for this mode in the blanc (without FLC overlayer) waveguide in terms of the light intensity through the decoupling prism with respect to the light intensity incident upon the coupling prism was about 5%.

The rubbing direction on the polyimide-coated glass plate was chosen such that the smectic layer normal would make an angle with respect to the propagation direction of the light beam equal to the SmC*-tilt angle. In this way, for one of the stable states, the TE-polarized light beam in the glass waveguide propagates with the ordinary refractive index of the liquid crystal layer on top of the film. In the polarizing microscope we could confirm that this alignment was actually obtained. The refractive indices of the FLC are $n_e = 1.65$ and $n_o = 1.51$ at the HeNe-laser wavelength, giving the FLC index values of $n_{FLC}(E<0) = 1.583$ and $n_{FLC}(E>0) = 1.51$ according to Eq. (1), where the sign of the applied electric field was correlated to the optic axis orientation in the FLC/waveguide cell by inspection in the polarizing microscope.

The TE-mode structure for the waveguide with the FLC was found to be significantly different from that of the waveguide without the FLC-layer. In particular, the previously observed mode at small incidence angle could no longer be observed, supporting the interpretation of it being a substrate mode; with the FLC-overlayer, condition (4) for radiation modes no longer holds. However, with the FLC-overlayer a mode at incidence angle 2.58° was found, equivalent to an effective index of $N_m = 1.516$, coinciding with that of the second mode of the blanc (without FLC overlayer) waveguide. This mode was found to switch upon application of the electric field. Figure 3 shows the electro-optic response of the FLC/waveguide cell in terms of the optical transmission of the output guided light. It was found that the ON-state occurs for positive polarity of the applied electric field ($n_{FLC} < N_m$) while the OFF-state occurs for negative polarity ($n_{FLC} > N_m$), as expected. The transmittance in the ON-state was found to be 5.7% while that in the OFF-state was 1.4%, giving a contrast ratio of 4:1. The response times were found to be asymmetrical, *i.e.*, the optical fall time is much shorter than the optical rise time.

In Figure 4 the optical rise and fall times as measured in the guided-wave configuration as well as in the polarizing microscope are shown as a function of the applied voltage. The ON-OFF switching is a fast process, going down to about 20 μs at elevated voltage.

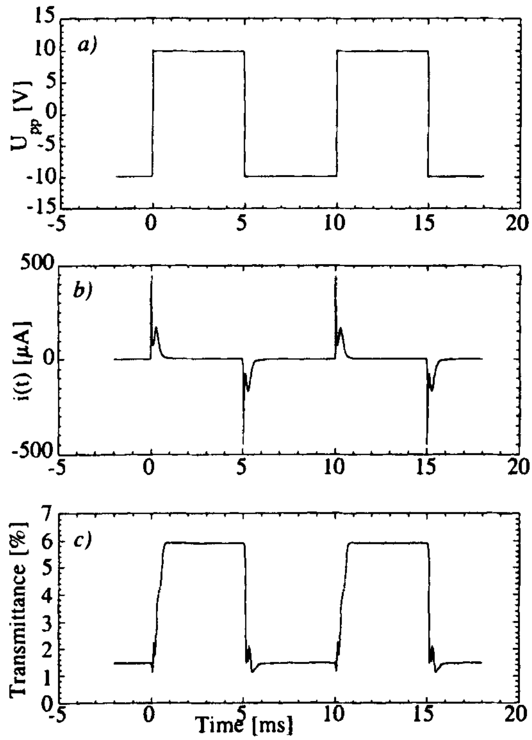

FIGURE 3 The electro-optic response of the FLC/waveguide device

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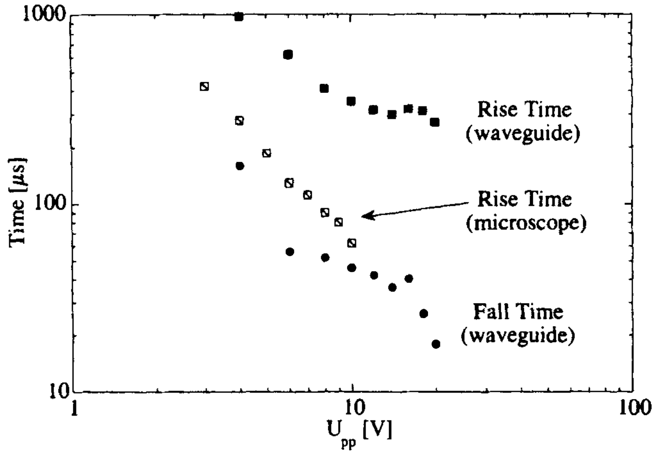

FIGURE 4 The optical rise and fall times measured in the guided wave configuration and rise times measured in the polarizing microscope.

DISCUSSION

When the device is in the ON-state almost all of the energy of the light propagating in the glass waveguide passes through the region with the FLC-overlayer. This is evidenced by the fact that the overall transmittance of the entire device (including the coupling prisms) is in the range of 5-6% in the ON-state of the FLC/waveguide device *as well as* in the waveguide without the FLC-overlayer. When the FLC/waveguide device is in the OFF-state, however, there is still an overall transmittance of 1.4% of the whole device (causing a low contrast ratio of 4:1). In other words the light is not completely leaked out of the device and lost. This cannot be understood if the FLC is considered as a cladding layer, as was done in [14]. Rather, what we have is a 4-layer structure, consisting of a substrate (the glass plate of the waveguide), a cladding (the cover glass plate) and *two* guiding layers (the sol-gel waveguide and the FLC), since the refractive index of the cover glass plate (the cladding) is smaller than the refractive index of the FLC. For this reason, the light energy which goes into the FLC when the device is in the OFF-state is still reflected at the FLC/cover glass interface and therefore does not leak out of the device. Another way of saying this is that when the FLC is in its high-index state (so that $n_{FLC} > N_m$) the 4-layer system supports several modes, of which some may have an electric field distribution in the sol-gel layer that overlaps to some extent with the electric field

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distribution of the mode that enters from the part of the waveguide without the FLC-overlayer. Therefore, part of the incoming energy is transferred through the FLC-overlayered region of the waveguide even in the OFF-state. In fact, numerical simulations showed that this is actually the case in our device. The detailed numerical analysis will be presented elsewhere. In order to increase the contrast ratio of the device it is necessary to use a high-index cover plate, so that the light energy in the OFF-state leaks out of the device.

The response time of the FLC/waveguide device is fundamentally determined by the time for the cone switching of the molecules. However, from an optical point of view, when going from the OFF to the ON state, the transmittance shows some oscillations until the time is reached when the maximum of the current peak occurs and then starts to increase significantly. This would suggest that it is *after* this time that the condition $n_{FLC} < N_m$ for total internal reflection at the waveguide/FLC-interface is reached, resulting in the confinement of the propagating mode in the sol-gel layer. That is, the increase of transmitted energy occurs during the latter, slower part of the molecular switching. When going from the ON to the OFF-state, however, the condition for total internal reflection at the waveguide/FLC-interface is lost more quickly, since the optical change now occurs in the beginning of the cone switch. Therefore, the rise time is longer than the fall time.

CONCLUSIONS

We have demonstrated electro-optic switching in an FLC-overlayered waveguide and analyzed the experimental results. We have found asymmetric switching times, of which the fall times can be as short as 20 μs. Work in order to optimize the performance of the device is currently underway, in particular with respect to the contrast ratio. The detailed numerical analysis of the FLC/waveguide behavior will be presented elsewhere.

Acknowledgments

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