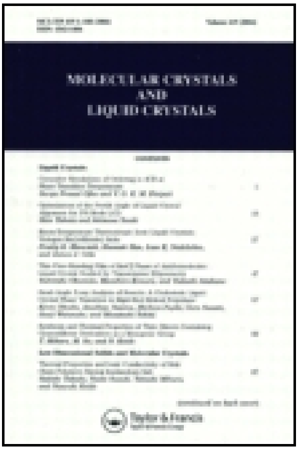

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Fast Electro-Optical Switch Based on a Nematic Liquid Crystal Waveguide

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Fast Electro-Optical Switch Based on a Nematic Liquid Crystal Waveguide

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An integrated electro-optical switch based on a planar nematic liquid crystal waveguide has been realized and tested. We present the experimental results obtained with a three-stage device, having as middle stage a thin nematic LC film and two glass waveguides as other stages. The electro-optical behavior and the response times have been studied for different configurations. The experimental findings show that an additional bias voltage can improve both the transmittivity and the response time of the device (faster than 100 μs), leading to very promising results in the frame of new integrated electro-optical switches. The effect underlying the latter result is not yet understood and probably need some deep insight into liquid crystal physics and into surface interactions. A further analysis is in progress in order to explain an anomalous electro-optical behavior occurred for higher applied voltages.

Keywords: Waveguides; electro-optical switch; liquid crystals

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INTRODUCTION

Light propagation in guiding structures has recently obtained a great deal of attention in the integrated optics field, because the light behavior in electro-optical devices can determinate further improvements in the photonics field.

During last years, several authors suggested and demonstrated the possibility of using Liquid Crystals (LC's) materials to control the light propagation in optical devices as planar waveguides or cylindrical fibers[1-10]. The extreme sensitivity of the optical response of LC's to applied fields, their aptitude to be micromanipulated and their low cost make them particularly attractive in designing components of integrated optics. Since the effective electro-optic coefficients of LC's are orders of magnitude larger than their solid state counterparts, their use as materials for integrated optical modulators is greatly attractive. On the other hand, the use of Nematic Liquid Crystals (NLC's) shows some fundamental limitations on the device performance such as scattering losses and slow response times.

Nevertheless, a first answer to both open questions can be given by using very thin LC films, of the order of 1 μm. For such a thin film, the losses decrease from 20 dB/cm (typical value for film thickness greater than 10 μm) to 2 dB/cm[11-12] and switching times also decrease as the inverse squared thickness, in the limit of validity of the LC's elastic theory. Furthermore, by properly modeling the light propagation in such a device, in view of both material and design optimization, its performances could be pushed to the values requested for practical applications.

In this regard, we have developed recently a theoretical model, which considers the problem of the light coupling among the different sections of a multistage waveguide[13]. This model has been applied for a better understanding of our optical device behavior and its design optimization.

In the present study, we report an integrated electro-optical switch based on a NLC waveguide[14] which exploits the electro-optical properties of NLC's, that is field-induced realignment and consequent refractive index variation. The light propagation in both TE and TM polarization has been analyzed, varying the amplitude of the applied electric field and its frequency.

EXPERIMENT

The manufacture of LC integrated optical devices requires the following steps: a) the choice of the most suitable waveguide fabrication method; b) the design of the guiding structure and of the LC cell that assure the most efficient interaction; c) the design and realization of electrodes.

In order to study light propagation in a waveguide filled with a nematic LC (NLC) material, we designed and realized a planar guiding structure. The planar dielectric waveguide has been realized first, and then a rectangular cell with depth equal to the core thickness is etched in it. The cell is filled with LC and then covered with a glass plate having the same refractive index as the waveguide substrate. The cell's bottom and the top cover have been coated by evaporating SiO_x at oblique incidence in order to obtain the desired planar alignment with the easy axis, which corresponds to the optical axis, perpendicular to the propagation direction.

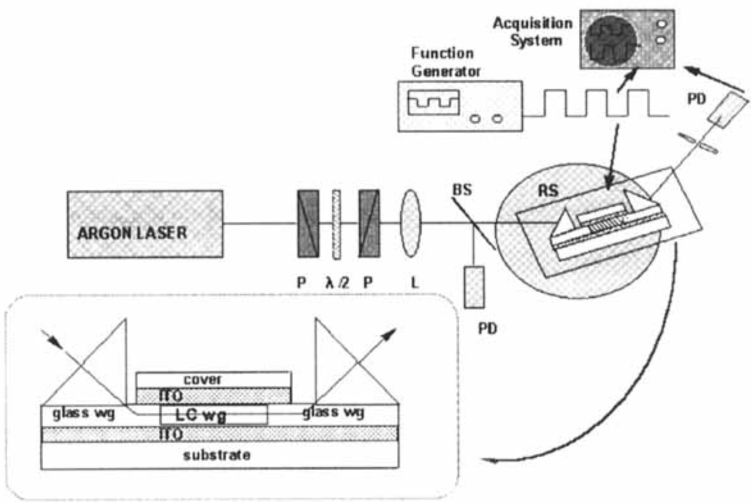


FIGURE 1 Experimental set up. BS=Beam splitter; P=Polarizer; L=Lens; RS=Rotating Stage; PD=PhotoDetector; λ/2= Half-wave retardation plate. Inset: details of the LC waveguide cell.

In order to apply the electric field we used a transparent conducting film of ITO (Indium Tin Oxide) deposited both on the substrate and on the cover of the basin. The waveguide was made by using the sol-gel deposition technique. The final structure is constituted of a three-stage planar waveguide, having the LC cell as middle stage and the two glass waveguides as other stages. The resulting planar waveguide is a step-index bi-modal layer whose thickness is 0.8 μm, the refractive index of the core in the glass sections is n_g =1.601 at the wavelength λ=514 nm. The LC cell, obtained by chemically etching the glass waveguide, has a length of 500 μm along the propagation direction and a depth equal to the thickness of the glass waveguide core. It was filled with the NLC commercially known as TN-3323 provided by ROLIC, whose ordinary and extraordinary refractive indices are n_o = 1.489 and n_e = 1.592 (at λ = 514 nm), respectively.

An electric voltage was applied to the ITO films used as transparent conductive electrodes. The applied voltage was driven by a function generator, which allowed different waveforms, amplitudes and offsets. The experimental set up is shown in figure 1.

The light beam from a CW Ar^+ laser was focused and coupled by means of a high refractive index prism into the glass waveguide. The focal point was chosen in the waveguide but very close to the prism edge to maximize the coupling efficiency and minimize the lateral beam waist in the transversal direction. A system of half-wave retardation plate and polarizer was used in order to select the TM or TE components of the incident light beam. The coupled light propagated directly through the three stages. The light beam was finally decoupled by means of a second prism and detected by a photodiode, whose output was recorded for successive processing or directly displayed on the oscilloscope. The incident light was also recorded for reference; the input power was kept sufficiently low, no more than 90 mW, to avoid a temperature increase in the guide and consequent effects on the coupling efficiency.

The working principle of the device is the following. When the light polarization is parallel to the optical axis in the LC anisotropic stage, the light is guided through the whole device and the switch is in the ON state. Viceversa, when the polarization is normal to the optical axis in the LC stage, then the NLC refractive index is lower than the substrate index and the guiding condition is no more fulfilled: light is leaking off through the cover and the substrate in the LC stage, which thus acts as a shutter between the two glass stages: the switch is in the OFF state. Owing to the fact that the optical axis is determined by the alignment of the NLC molecular director, changing the relative orientation of the light polarization and the optical axis is easily performed by moving the NLC molecules' orientation by means of the applied electric field.

RESULTS AND DISCUSSION

In order to analyze the electro-optical behavior of our device, we changed the polarization states, the amplitude and frequency of the electric field. In all the tested configurations the field was driven by a square wave applied voltage. As a first step, we sent into the device TM-polarized light with a driving voltage up to V_{pp}= 6V at increasing frequencies. Over ν = 100Hz the optical signal was no more able to follow the driving field. The results are reported in figure 2.

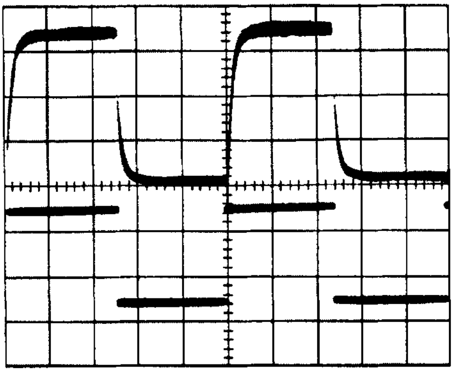


FIGURE 2 Optical response of our guiding device (upper trace) for TM polarized light. In the lower trace is shown the driving voltage whose frequency is 100Hz. The time scale is 2ms/div; The output voltage scale is 50 mV/div.

In such a situation, when the applied voltage is lower than a threshold value (approximately 1.5 V_{pp}), no distortion induced in the LC molecular director appears and the TM-mode, i.e. a polarization normal to the optical axis, sees a waveguide with an homogeneous refractive index equal to the ordinary index of the NLC. This index value is lower than the cover and substrate one, thus the guiding condition is not fulfilled and the optical output is OFF.

When the voltage is increased above the threshold, the reorientation of NLC molecules occurs: for positive dielectric anisotropy, the molecules are forced to be aligned parallel to the applied electric field direction and the refractive index seen by the TM mode becomes the extraordinary index, n_e. In this case, the guiding condition is fulfilled and furthermore, because of our choice of material's parameters, there is a good index matching ($n_e \cong n_g$) of the indices among the three stages of the device. This results in low reflection losses at the glass-LC interfaces and highly transmitted light, so that the device is driven to the ON state. The response times were estimated to be τ_{ON} = 600μs and τ_{OFF} = 400 μs.

It is worth noting, that an estimate of the time response of the molecular switching process based on the LC elastic theory[15] gives a value of about 0.6 ms, which is consistent with our findings for the switching on time but higher than those for the switching off. This fact can be explained, considering that even a small change in the refractive index of the guiding medium can lead to dramatic changes in the mode distribution and a consequent dramatic increase of the reflection losses. Due to the high birefringence of the LC materials, $\Delta n \sim 0.2$, such a small index variation can occur well before the molecular reorientation process is completed.

The other configuration we studied is a TE wave which propagates in the NLC waveguide: a driving voltage of 6 V_{pp} at a frequency ν = 100 Hz was applied to the electrodes. The experimental results are reported in figure 3.

Contrary to the case of TM mode, now when the electric field is in the low state, the optical signal is in ON-state, and when the electric field is in the high state the device switches to the optical OFF state. The response times measured in this situation are τ_{ON} = 600 μs and τ_{OFF} = 500 μs. As expected, apart the exchange between the ON and the OFF states, the main features remained unchanged.

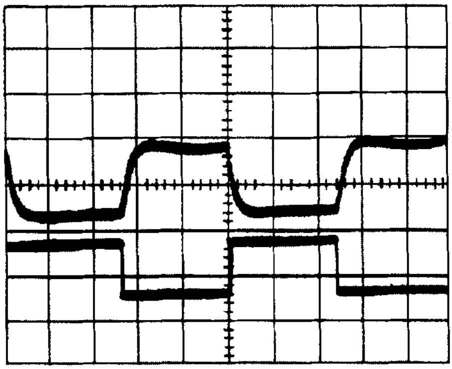


FIGURE 3 Optical response of our guiding device (upper trace) for TE polarized light. In the lower trace is shown the driving voltage whose frequency is 100Hz. The time scale is 2ms/div; The output voltage scale is 1 V/div.

Another interesting situation arose when we applied an additional bias voltage, a constant offset, to the square wave in both TE and TM case. In both cases, the optical signal response was able to follow the driving voltage up to a frequency of 1kHz.

In figure 4 we report the traces shown at the oscilloscope, for a driving voltage of 6 V_{pp} at 1 kHz superimposed to a constant bias of 6 V for a TM-wave.

Even if the behavior appears to be similar to the previous case, the quantitative results are quite surprising, and the underlying electro-optic mechanism could not be the same as previously sketched.

First of all, the presence of such an intense bias should reorient almost completely the LC molecules and the additional square wave field should very little modify the reorientation. Following the previously given explanation, the device should stay always in its ON state exhibiting no switching. What is actually observed is quite different. While the modulated electric field is in the low state, the device is ON. But when the electric field is in the high state a very low light transmitted is observed, so that the device is OFF. The switching time

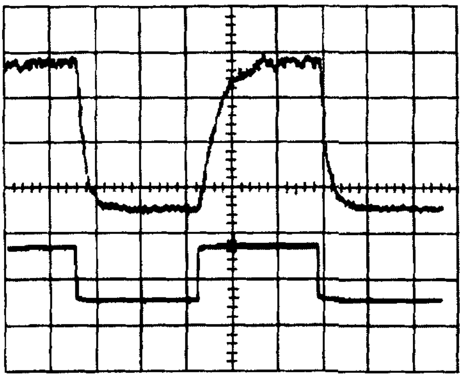


FIGURE 4 The optical switching for the TM light propagation driven at a frequency of 1kHz (upper trace). The driving voltage is shown in the lower trace. The time scale is 200μs/div.

was measured to be always faster than in the previous case and, depending on the driving and bias field values, up to peak performances of τ_{ON} = 80μs and τ_{OFF} = 40 μs (see figure 4). These performances are certainly appealing, however we have no precise idea for the moment of the physical mechanism responsible for such behavior. We can suppose that such a static field induces a current flow in the LC film, which can in turn give rise to hydro-dynamical instabilities. Several studies have been reported on different regimes of such hydro-dynamical instabilities and on transitions between them, but never, at our knowledge on very thin films, less than 1 μm.

Furthermore, an attracting hypothesis, which could account for the improving of almost one order of magnitude in the response times, is the occurrence of surface transitions of the LC anchoring. The treatment we made to the cell walls is producing what is called strong anchoring, which is supposed not to be changed by external fields. However, if the field is strong enough, and for SiO_x treatment this means fields of the order of 10 V/μm, the planar alignment can be turned to perpendicular: in LC physics this effect is called surface transition and it is generally faster than bulk molecular reorientation. This is a frontier field and not much is known about this effect. In order to verify the relevance of these effects for the experimental findings of our switching device a much deeper insight into the physics of these phenomena is required.

The last configuration we studied is a TE wave which propagates in the LC waveguide, with a bias voltage: a driving voltage of 5 V_{pp} at a frequency ν = 1kHz, superimposed to a bias voltage of 5 V was applied to the electrodes. The experimental results are reported in figure 5.

Contrary to the previous case, when the electric field is in the low state, the optical signal is in its OFF-state, and when the electric field is in the high state the device switches to the optical ON state. The response times measured in this situation are τ_{ON} = 80μs and τ_{OFF} = 60 μs. We must note in this geometry that, during the reorientation process, the optical axis is driven out of the propagation plane of the light. For this reason, hybrid modes are propagating in the LC stage, giving rise to a change in the polarization state of the output light, which was always TM polarized. As in the previous case, a reasonable explanation of these results is not at the moment available. However, they look attractive

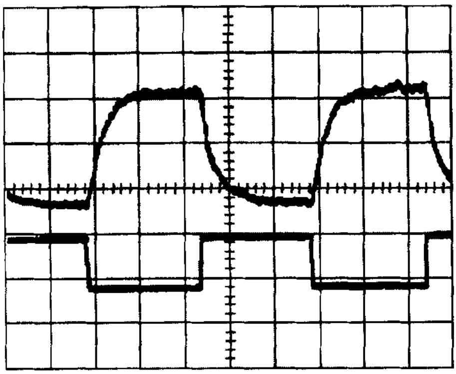
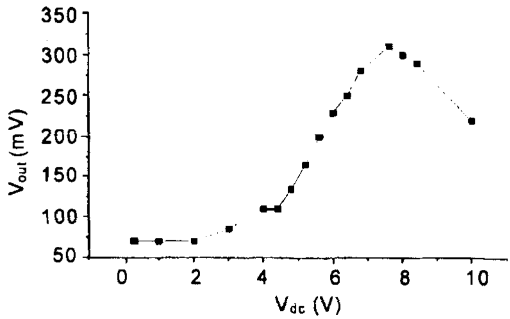


FIGURE 5 The optical switching for the TE light propagation driven at a frequency of 1kHz (upper trace). The driving voltage is shown in the lower trace. The time scale is 200μs/div.

in themselves for the potential applications and also they are opening a number of questions involving fundamental aspects, both theoretical and experimental, of the liquid crystal physics.

In order to investigate this effect an analysis on the working of the device has been made considering the amplitude of the transmitted signal as a function of the applied voltage at a frequency of 100 kHz, greater enough to avoid any possible real-time following of the molecular director. Such a high frequency field has been preferred to a static voltage in order to avoid undesired current effects. The experimental results are reported in figure 6 (curves A and B). The data confirm the switch mechanism previously found for both TM and TE polarization of the incident light and shown in the photos, even if an explanation of the inversion of the signals remains to be found.



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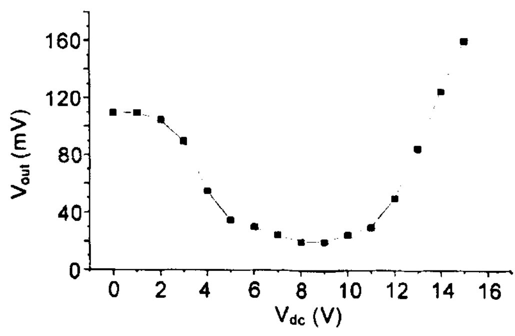

B

FIGURE 6 Transmitted optical response for TM-light (A) and for TE-light (B) of our guiding device as a function of the driving voltage at a frequency of 100 kHz.

CONCLUSION

We have presented experimental results on the light propagation in a planar device constituted of a three-stage planar waveguide. This device exploits the well known electro-optical properties of nematic LC but also exhibits interesting behavior related to not yet understood effects.

According to the expected behavior, for both light polarizations, up to a critical value of the applied voltage, the light switch works as reported in table 1 with the relative response times.

	Driving voltage	Output signal	τ
TE	ON	OFF	500 μs
	OFF	ON	600 μs
TM	ON	ON	600 μs
	OFF	OFF	400 μs

TABLE 1 Response times values for the two polarization states considered.

Above the critical voltage, we noticed an anomalous response, which contrasts with the phenomenological behavior of such a LC switch device. Due to the presence of a constant bias voltage, the switch regime of our device should be never reached; on the contrary, unexpectedly, the device still works as a switch with faster response time as reported in table 2.

Our experimental results demonstrate the validity to employ such a waveguide to design fast integrated LC electro-optical devices.

Further investigations not only on this device but also on fundamental aspects of liquid crystal physics are suggested by this study.

	Driving voltage	Output signal	τ
TE	ON	ON	80 μs
	OFF	OFF	60 μs
TM	ON	OFF	40 μs
	OFF	ON	80 μs

TABLE 2 Response times values for the two polarization states considered above the critical voltage.

Acknowledgements

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