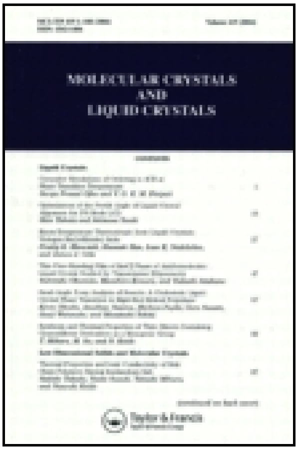

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Experimental Results on a New Integrated Beam Deflector/Switch Based on Liquid Crystals

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Liquid crystals have effective electro-optic coefficients that are orders of magnitude larger than other materials used in integrated optics. A number of integrated optical devices based on these materials have been recently proposed. We have designed and realized an integrated device in a three-stage planar waveguide, having as middle stage a nematic liquid crystal film. We studied the device performance in different geometries using TE polarized light. By a proper choice of the material parameters we measured time responses in the microsecond range. Our experimental results confirm the possibility of employing such a device working as an optical switch and/or beam deflector.

Keywords: Liquid Crystals; optical switch; beam deflector; integrated waveguide; electro-optical device

INTRODUCTION

Optical switching is comprised of the techniques and technologies used to switch or transfer optical signals from one transmission channel to an other while the signals remain in optical form. A wide variety of practical optical switches have been developed using many different physical effects.

Some of the best developed types of optical switch employ liquid crystal (LC) materials due to their extreme sensitivity to applied fields, to their case of micromanipulation and to their low cost. These aspects make them particularly attractive for designing integrated optical components. Since the effective electro-optic coefficients of LC's are orders of magnitude larger than their solid counterparts, their use for integrated optics modulators is also of interest[1-10]. On the other hand, the use of Nematic Liquid Crystals (NLC's) shows some fundamental limitations to the device performance, mainly due to scattering losses and slow response times.

Nevertheless, a first answer to both these problems 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. Switching times also decrease as the inverse of thickness squared, in the limit of validity of the LC elastic theory.

We have designed and realized a particular waveguide structure working as both an optical switch and a beam deflector. In the present paper we report the experimental results of such an integrated electro-optical switch based on a NLC waveguide which exploits the electro-optical properties of NLC's, that is field induced realignment and dynamic scattering. Measurement of the response times and of the output signals as a function of the driving voltage are presented in the case of TE polarization of the incident light.

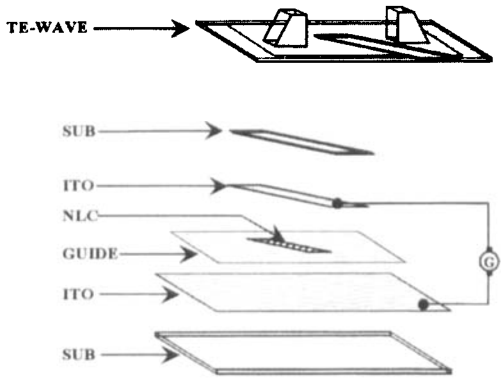


FIGURE 1. Schematic representation of the realized planar waveguide. SUB: substrate and cover; ITO: indium tin oxide; LC: liquid crystal; G: voltage generator.

EXPERIMENTAL

Design and realization of a planar waveguide for electro-optical switching and beam deflection

In order to study light propagation in a waveguide filled with a NLC, we designed and realized the guiding structure schematically shown in Figure 1. The planar dielectric waveguide has been realized using the sol-gel deposition technique[11]. A rectangular cell with depth equal to the core thickness is etched in it with an angle of 21 degrees with respect to the direction of the incident light for the NLC inclusion. (See figure 2). This angle has been chosen considering the refractive indices of the waveguide and the LC, in order to analyze both the transmitted and the reflected states of the incident light. The cell is filled with NLC and then covered with a glass plate having the same refractive index as the waveguide substrate. The bottom and the top cover of the cell have been coated by evaporating SiO_x obliquely in order to obtain the desired planar alignment with the easy axis, which corresponds to the optical axis, perpendicular to the propagation direction.

In order to apply the electric field we used a conducting film of ITO (Indium Tin Oxide) deposited both on the substrate and on the cover of the basin.

In order to limit losses due to light scattering in the NLC, the propagation length in the LC cell has been reduced to a minimum.

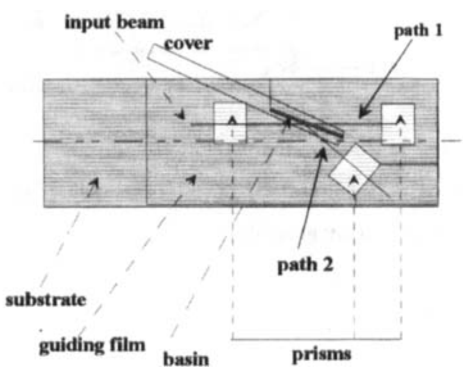


FIGURE 2. Schematic representation of the planar guiding structures showing the prisms for light coupling and decoupling of the transmitted and reflected beams.

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 a wavelength of 514 nm. The cell filled with the LC has a length of 0.5 mm along the propagation direction.

Results and Discussion

The experimental set up is shown in figure 3.

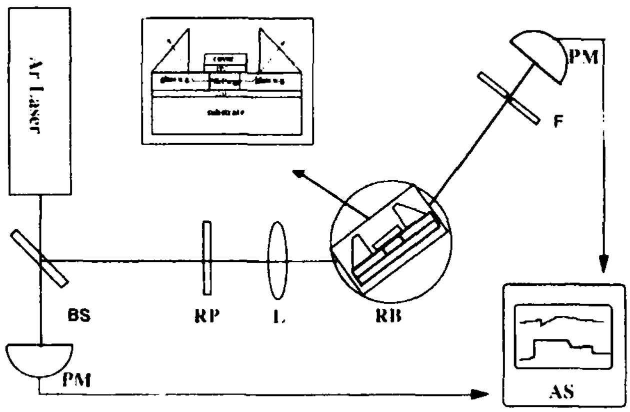


FIGURE 3. Experimental set up. BS = Beam splitter; RP = Polarizer; L = Lens; RB = rotating stage; F = Slit; PM = Power meter; AS = acquisition system.

The light beam from a CW Ar^+ laser (λ = 514 nm) was focused and coupled by means of a high refractive index prism into the glass waveguide. A system of half wave retardation plates and polarizer was used in order to select the TE component of the incident light beam. The coupled light can propagate in two ways: directly through the three stages (path 1 in figure 2) or totally deflected at the first boundary depending on the electric states of the applied film (path 2). In both cases the output light beam was finally decoupled by means of a prism and detected by a photodiode whose output was recorded or directly displayed on the oscilloscope.

An electric voltage was then applied to the ITO films used as transparent conductive electrodes. The applied electric field moves the average orientation of the LC molecules, hence moving the optical axis normal to the polarization direction.

When the light polarization is parallel to the optical axis in the LC anisotropic stage (TE-wave with no applied field in our initial configuration of LC molecules), 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 (TE-wave with applied field), then we are in a total reflection condition: light is deflected at the first boundary in the LC stage, which thus acts as a shutter between the two glass stages. The switch is in the OFF state and the device is acting as a beam deflector.

In order to analyze the electro-optical behavior of our device, we changed the amplitude and frequency of the electric field. In all the tested configurations the field was driven by an applied square wave applied voltage. As a first step, TE-polarized light was used with a driving voltage up to V_{pp}= 2V with a bias of 1V as a function of frequency. Over ν = 10Hz the optical signal was unable to follow the driving field. The results are summarized in figure 4.

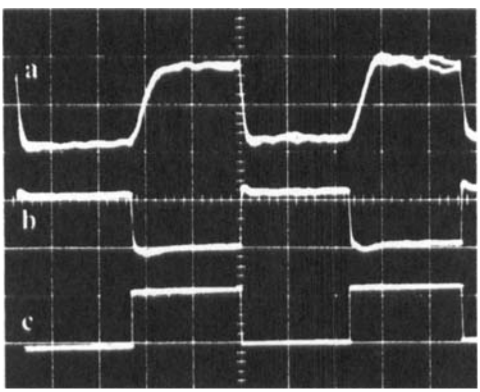


FIGURE 4. Optical response of our guiding device (a is the reflected signal and b is the transmitted one) for TE polarized light. In the lower trace (c) the driving voltage whose frequency is 10Hz is

shown. The time scale is 20ms/div. The output transmitted voltage scale is 0.1 V/div, the output reflected voltage scale is 0.5V/div .

In such a situation, when the applied voltage is lower than a threshold value (approximately 1.5 V), no distortion is induced in the LC molecular director and the TE-mode, i.e. polarization parallel to the optical axis, sees a waveguide with an homogeneous refractive index equal to the extraordinary index of the NLC. Thus, the guiding condition is fulfilled and the optical output is ON.

When the voltage is increased above the threshold, the reorientation of NLC molecules occurs: due to the positive dielectric anisotropy of the considered LC, the molecules are forced to be aligned parallel to the applied electric field direction and the refractive index seen by the TE mode is n_o. In this case, the dominant condition is total reflection; this results in the beam deflection at the first glass-LC interface. As a consequence, the switch (the transmitted signal) is driven to the OFF state. The response times for the transmitted light were estimated to be τ_{ON} = 1.4 ms and τ_{OFF} = 1.5 ms.

Another interesting situation occurred when we applied an additional bias voltage to the square wave. In this case, the optical signal response was able to follow the driving voltage up to a frequency of 100 Hz. The bias voltage value was chosen in order to maximize the contrast ratio and to minimize the response times.

In figure 5 we show the traces on the oscilloscope, for a driving voltage of 4 V at 100 Hz with a constant bias of 3.5 V. The behavior of our device is completely reversed compared to the previous case. In fact, when the field is applied the transmitted and the reflected signals are in ON and OFF state respectively. Thus the underlying electro-optic mechanism could not be the same as previously discussed. The switching time for the transmitted light was measured to be faster than in the previous case and could reach peak performances of τ_{ON} = 400 μs and τ_{OFF} = 750 μs.

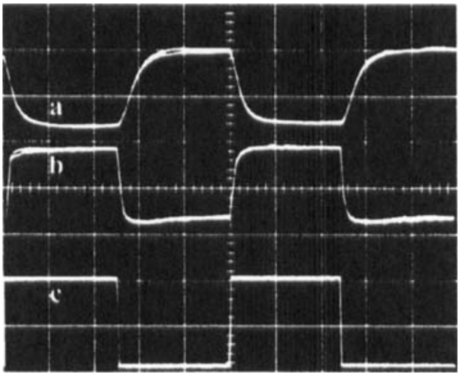


FIGURE 5. Optical response of our guiding device (a is the reflected signal and b is the transmitted one) for TE polarized light. In the lower trace (c) the driving voltage, whose frequency is 100Hz, is shown. The time scale is 2ms/div. The output transmitted voltage scale is 50mV/div, the output reflected voltage scale is 0.5 V/div .

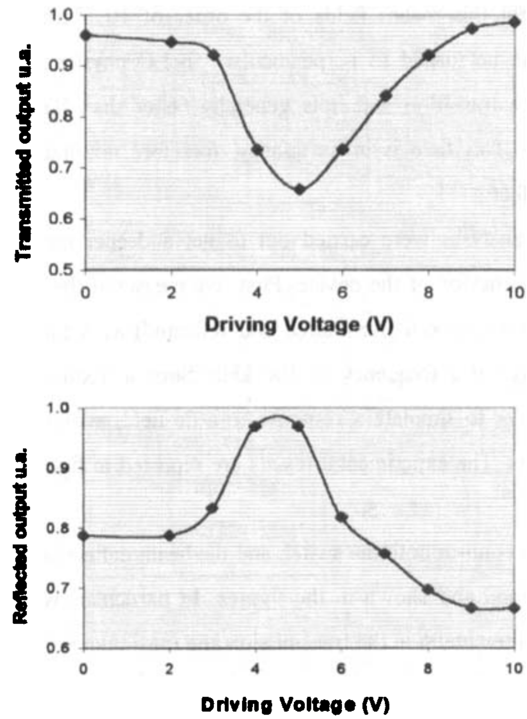
These performances are encouraging; however, we have no precise idea for the moment of the physical mechanism responsible for such behavior. We can be quite sure that a bias field induces a current flow in the LC film, which can in turn give rise to hydro-dynamical instabilities. Several studies have been reported on different regimes of such hydro-dynamical instabilities and on transitions between them, but never, to our knowledge, in very thin films, less than 1 μm thick. An attractive hypothesis, which could account for the improvement of almost one order of magnitude in the response times, is the occurrence of surface transitions in the LC anchoring. The treatment we made to the cell walls produces what is called strong anchoring, which is not supposed 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 field is in its infancy, therefore not much is known about this effect.

Further analyses were carried out to get a deeper insight into the unexplained behavior of the device. First, we measured the amplitude of the output signals (both transmitted and reflected) as a function of the applied voltage at a frequency of 100 kHz. Such a frequency has been chosen in order to simulate a response to a dc field, avoiding undesired current effects. The experimental results are reported in figures 6 (A and B).

The data confirm both the switch and the beam deflection mechanism previously found and shown in the figures. In particular, we notice the existence of a minimum in the transmission and maximum in the reflection for Vpp ≅ 5V, which clearly show the reason of the best performances of the device in terms of contrast ratio and response times for the chosen value of the bias. Without any bias and with applied field up to 8V, in fact we obtained similar results but with less good performances.

Again, the reason for the behavior shown in figure 6 is not clear to us and we can just make hypothesis on the occurrence of surface breaking mechanism. On the basis of simultaneous current measurements, we can further exclude dramatic change in the LC cell resistivity, due for example to dielectric breakdown, since our results give evidence of a linear increase of the current with the voltage, i.e. ohmic regime.



A

B

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

CONCLUSIONS

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

We found that performances of such a device exhibits optical switch and beam deflection with response times of τ_{ON} = 1.4 ms and τ_{OFF} = 1.5 ms for the transmitted light at a frequency of 10 Hz. By adding a constant bias voltage the performances were significantly improved, with response times of τ_{ON} = 400 μs and τ_{OFF} = 750 μs at a frequency of 100 Hz. Our experimental results demonstrate the validity of employing this waveguide structure to realize LC electro-optical switches and/or beam deflectors. A proper study on high voltage (> 5V) induced reorientational mechanism is necessary for a better evaluation of the electro-optical behavior of such a type of device. The anchoring transition which occurs for a driving voltage greater than that necessary to induce Freédericksz transition, requires a further analysis for a better understanding of the relation between the response times and the anchoring of LC molecules in waveguides thick less then 1 μm. Such a study is in progress.

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