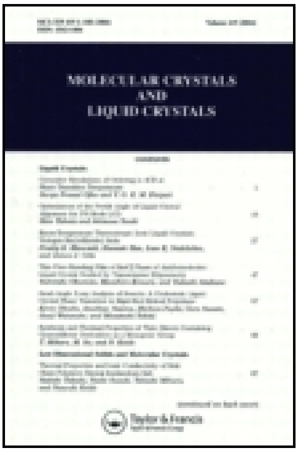

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Experimental Results on the Light Propagation in a Nonlinear Waveguide with Nematic Liquid Crystal: Hybrid Alignment Case

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EXPERIMENTAL RESULTS ON THE LIGHT PROPAGATION IN A NONLINEAR WAVEGUIDE WITH NEMATIC LIQUID CRYSTAL: HYBRID ALIGNMENT CASE.

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Abstract The light propagation in a LC nonlinear planar waveguide is studied for both TE and TM polarization states of incident light. Two different nematic liquid crystal samples were employed with hybrid alignment in a special guiding structure *ad hoc* realized for this work. The experimental results show that the guided modes are affected by the incident light power. In particular, the power exchange of the propagating light between different modes was studied in detail.

INTRODUCTION

Despite of the strong light scattering, which is the main source of losses in liquid crystal (LC), thin structures of liquid crystal materials, such as slab waveguide, have been proposed to implement electro-optical or all-optical integrated devices.[1-5] The main advantages of using LC into integrated structures are due to their low viscosity, allowing their insertion into microdevices, and their large optical nonlinearity which may be useful to obtain optical bistability at low light power rates. All-optical devices are particularly fascinating as compared to hybrid ones, where external fields are needed to change the refractive index of the medium, because they simplify manufactory operations, avoiding outer components. Laser beam induced light modulation in a slab waveguide of liquid crystal has been recently reported.[6] This was achieved by using an external laser beam to change the refractive index of the LC layer, acting as cover of the optical waveguide. Even more attractive could be the realization of a full nonlinear LC waveguide device where the field inducing the LC index change is the guided light itself. A theoretical model of such a device, is under way and will be presented elsewhere. It is clear from now that, from these calculations, it emerges not only the possibility to nonlinearly modulate the guided light but also to obtain other nonlinear optical effects such as self-trapping and bistability.[7] Nonlinear optical propagation in cylindrical waveguide with LC core was recently studied both theoretically[8] and experimentally in isotropic phase.[9] In this work we present what we believe to be the first experimental study of nonlinear planar waveguide, where the core was a LC material in nematic phase. We decided to use a hybrid alignment, to avoid the occurrence of Optical Fréedericksz Transition (OFT) so that nonlinear optical phenomena could be observed even at low light intensity.

EXPERIMENT

Sample preparation

The guiding structure, shown in Fig. 1, was specially designed and realized in order to study the light propagation in a waveguide filled with a nematic LC material.

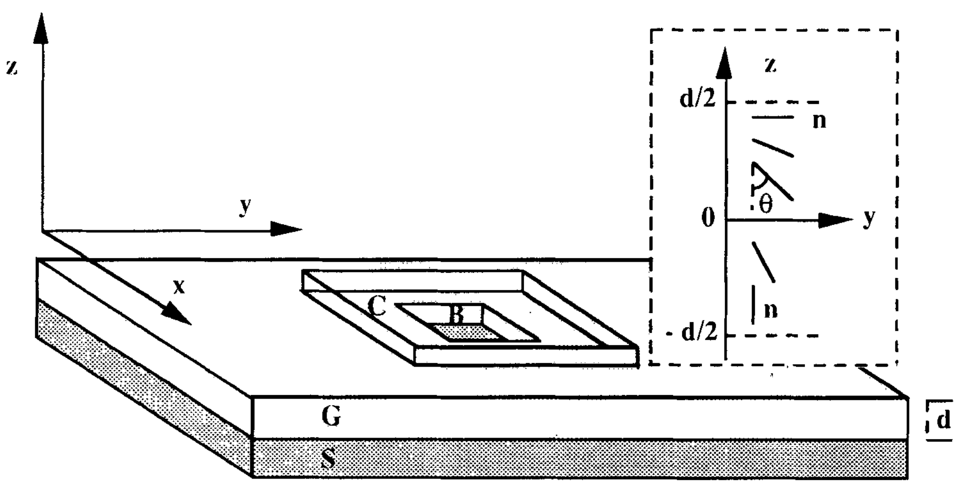

FIGURE 1 Scheme of the used planar waveguide with basin containing liquid crystal. G: Guide; S: Substrate; B: Basin; C: Cover; d: 3.8 μm waveguide thickness and basin depth; **n**: molecular director.

We first realized a dielectric multimode waveguide, obtained by sputtering glass on glass, and having refractive indices of core and substrate n_g=1.555 and n_s=1.520, respectively at the wavelength λ=514 nm.

In such a guide was then dug a little basin 1 mm long, 10 mm wide and having d=3.8 μm depth equal to the thickness of the waveguide core. The basin was filled out with nematic material and then covered with a glass plate having the same refractive index of the waveguide substrate.

The basin bottom and the top cover were previously coated with proper surfactants in order to obtain hybrid alignment of the LC molecules: homeotropic anchoring at the basin bottom and planar anchoring at the glass cover.

In this way, we obtained a d thick planar waveguide having a nematic LC as guiding medium, in which the optical axis, in the absence of applied external field, passes from $\theta = 0$ at $z = -d/2$ to $\theta = \pi/2$ at $z = d/2$, (see Fig. 1).

In order to couple and decouple the laser beam, we used two prisms with refractive index n_p=1.798.

In our experiment we used two different nematic materials (both supplied by MERCK): E7 with ordinary and extraordinary refractive index n_o=1.522 and n_e=1.746, and K15 with refractive indices no=1.533 and n_e=1.703, respectively. The two materials exhibited a similar qualitative behaviour, but the use of K15 sample gave more efficient guided light propagation because of the better index matching between the glass waveguide and the LC one, with consequent decrease of the scattering losses. The proper choice of waveguide-LC index matching is very critical. Indeed, passing from $\Delta n=n_g-n_o=0.33$ for E7 to $\Delta n=0.22$ for K15, led to output signals ten times greater.

Measurements

The experimental apparatus is shown in Fig. 2. A retardation plate $\lambda/2$ was used to vary the light polarization of the cw Ar laser at λ=514 nm. A lens (focal length f=75.6 mm) focused the light beam into LC. The guide was placed on a rotating base to select the guided modes. A translation stage was used to send the guided beam into different paths: one entirely included in the glass waveguide, and the other passing through the LC waveguide. In this way we were able to compare the signals obtained from the light travelling in and off the LC waveguide. The measurements were made, using the incident angle onto the coupling prism, the light polarization and the input power, as external control parameters. In each case, the power coupled into a selected mode of the glass guide is redistributed in all modes available at output, which, owing to their different propagation constant, are spatially separated.

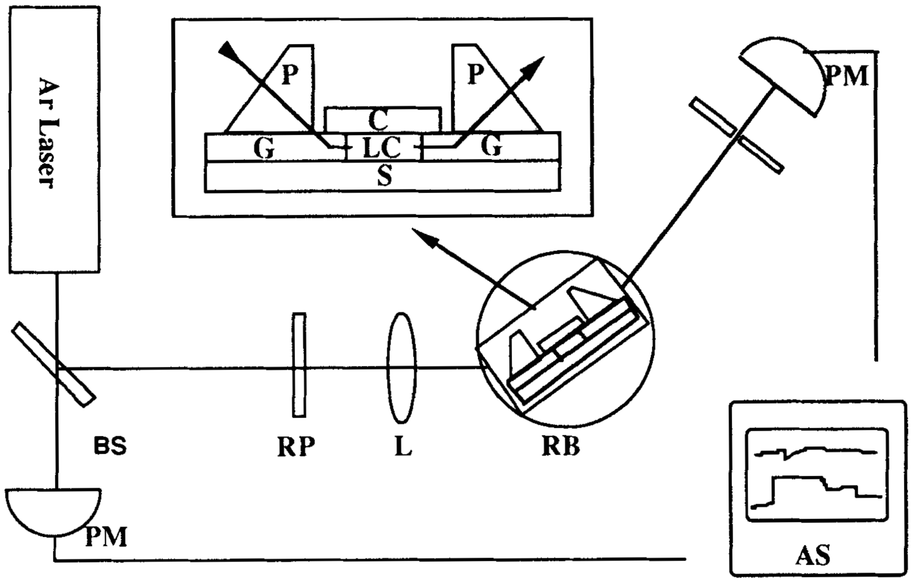

FIGURE 2 Experimental set-up. BS: Beam Splitter; RP: Retardation Plate; L: Lens; RB: Rotating Base; PM: Power Meter; AS: Acquisition System; P: Prism; C: Cover; G: Guide; LC: Liquid Crystal sample; S: Substrate.

Results

All measurements were made by exciting only the first fundamental mode of the glass waveguide.

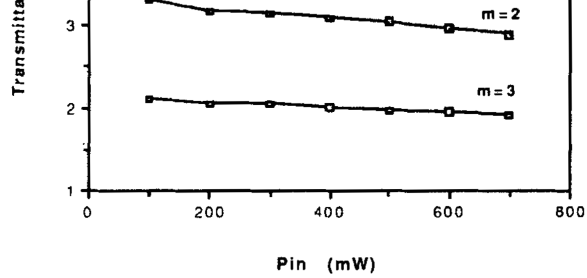

FIGURE 3 Transmittance T_m of the first three TM-modes propagating out of basin as a function of the incident power.

For simplicity only results concerning K15 nematic LC are reported here.
The transmittance $T_m = P^{out}/P^{in}$ for the first three output TM-modes as a function of the incident power, when the light is propagating out of the LC-filled basin, is reported in Fig. 3

In spite of the fact that the light propagates in glass only, the overall transmittance T_m for each guided mode decreases slightly as the laser incident intensity increases. We ascribe this behaviour to the already known lowering of coupling efficiency due to the small change in the air-gap of the prism and coupler because of laser heating.[10,11]

The same measurements were repeated with the laser beam travelling in the LC. The propagating light *sees* the refractive index ranging between n_o and n_e. In Fig. 4 we report the transmittance T_m of the first three guided TM-modes as a function of the input power.

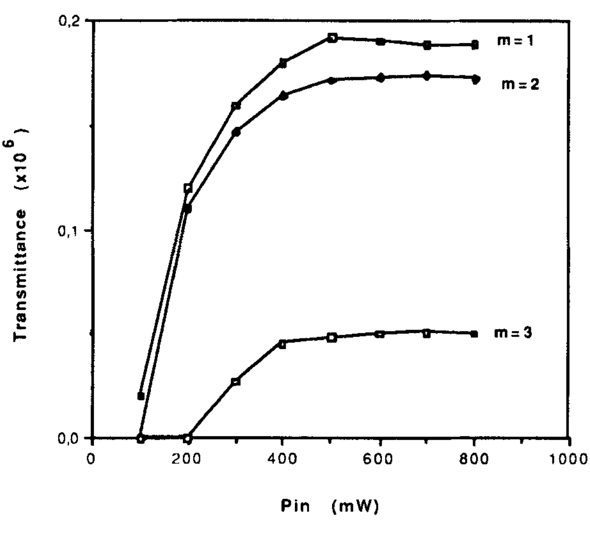

FIGURE 4 Transmittance T_m of the first three TM-modes propagating in LC as a function of the incident power.

The large increasing of T_m with increasing laser power is evident. This could be due to the decreasing of loss-scattering, because of the attenuation of molecular thermal fluctuations in the presence of the laser beam,[12] as well as to a better overlapping between the glass and LC waveguide mode profiles. The nonlinear optical behaviour of the LC waveguide is better demonstrated considering the fraction R_m of output power in the m-th mode. In Fig. 5 R_m is reported versus total incident power. We checked that

R_m are independent of the laser beam power, when the light propagates just in the glass waveguide.

On the contrary, as shown in Fig. 5, when the laser beam propagates in LC-filled basin, the fraction R_m changes as a function of the input power.

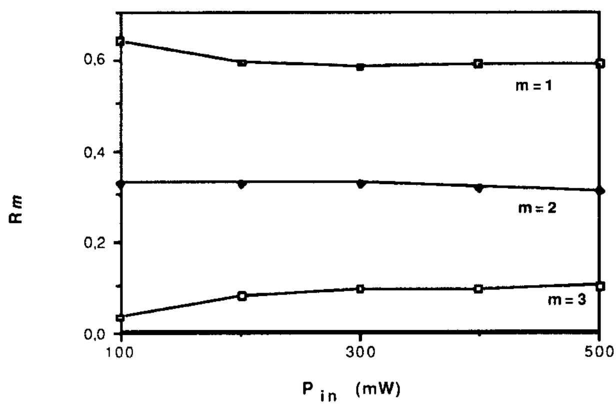

FIGURE 5 Distribution R_m of the output power fraction on the first three modes for TM polarization as a function of the incident power.

The most evident variations of R_m are obtained at low input power. We ascribe this behaviour to a laser-induced reorientation leading to a change in the index profile of the LC waveguide. As a consequence, the LC guide symmetry is modified and the relative distribution of energy among the modes of the output glass guide too. As expected for hybrid alignment, the phenomenon has no threshold.

The same measurements were repeated for TE polarization of the incident wave, where a threshold behaviour is expected. In this case the detected output signals are significantly higher because of the better index matching in the unperturbed state. The guided light, in fact, sees an uniform index distribution $n=n_0$ in the LC medium. Off guide constant behaviour of R_m is confirmed also in TE case. When the laser beam propagates into the LC and the input power is above a critical threshold value, a change is observed in the transmittance of the first three modes as the incident power is increased.

This is shown in Fig. 6. It is remarkable the occurrence of two distinct thresholds, indicated by the arrows in the figure. The first one is the threshold for the OFT, where the reorientation appears. At this point power is exchanged between the fundamental mode and the third excited mode of the glass waveguide.

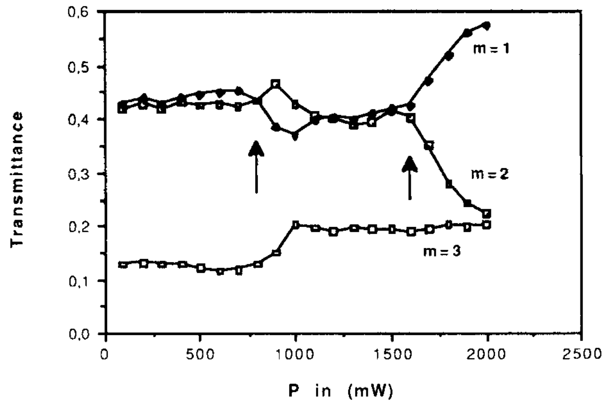

FIGURE 6 Transmittance of the first three modes as a function of the incident power for TE polarization. The critical powers are: P_1=0.8 W, and P_2=1.6 W.

At the second critical power a much more evident exchange is observed between the first and second mode.

This is due to the fact that at low power the optical reorientation is confined in the central part of the medium and it is almost symmetric. This allows energy exchange between first and third mode, having the same parity. At higher power the reorientation zone enlarges and it is no more symmetric because of the different conditions at boundaries so that energy is now exchanged between modes having different parity.

Finally, we estimated the reorientation time that, in the case of TE polarization of the incident wave, appears longer (6 sec.) than the TM polarization one (3sec.). This is expected because the LC response times scale in the two geometries as $k_{33}/k_{22} \cong 2$ for K15.

CONCLUSION

In this work we studied the light propagation in a LC-filled nonlinear planar waveguide. Several nonlinear optical effects have been observed. For TM polarization, no threshold is found and optical reorientation can be induced even at low laser power, yielding large increase of the waveguide transmission with increasing guided power. Moreover nonlinear power exchange between first and third mode has been observed. For TE polarization, no optical nonlinearity is observed below the critical threshold of 800 mW, where power exchange between first and third mode is set up. At a second higher threshold (≅1600 mW), on the contrary, very strong cross-talk is observed between first and second mode. This is made possible in our system because of the not symmetric LC anchoring at the waveguide boundaries.

It is also remarkable that the LC film thickness of 3.8 μm used in this experiment, is much lower than the one used till now to study the laser-induced optical reorientation in nematic films.

We believe that these results could be of some interest in developing new integrated optical devices.

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