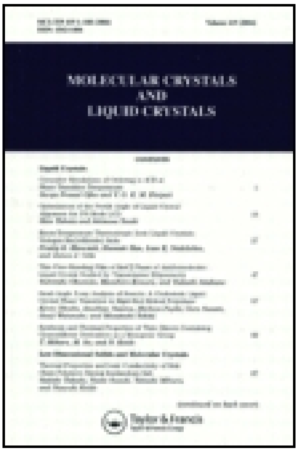

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Modulating light with light: A slab waveguide-liquid crystal device

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Modulating light with light: a slab waveguide-liquid crystal device

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Abstract We present an experiment of modulation of the light propagating in a waveguide-liquid crystal (LC) planar stack, by an external light source. The results confirm that the molecular reorientation in the LC layer, induced by an external optical field, gives rise to a change in the refractive index which in turn modifies the propagation constants of the guided modes, so that the light can be partially leaked off the guide. It is shown how the modulation depends on the physical parameters of the materials and of the light.

Introduction

In the field of integrated optics, liquid crystal based devices have gained an increased interest. Many works, both theoretical and experimental, have appeared in literature, dealing with electrooptical devices and thin-film waveguides in which an LC film is one of the component[1-4]. The reasons for the success of LC materials in the optical devices are quite clear, since they are inexpensive, very easily microintegrated owing to their low viscosity, and overall since they exhibit extraordinary optical properties. On the other hand, a wide diffusion on industrial scale of such devices is, to date, limited by two, not yet solved, major problems: the high light scattering and the slow response time of the

LC. The development of new LC materials, with specific and ever better performances, promise to overcome in the near future these difficulties, opening to them a vast field of application.

One of the fundamental step in integrated optics is to obtain modulation of the light, controlled by weak external fields or, even better, by the light itself. We have recently proposed a planar waveguide with an LC cladding, in which the outgoing light was modulated by the application of an external magnetic field[5]. The basic idea can be briefly summarised: in absence of the external field, the LC is in the alignment imposed by the boundary constraints; with a suitable choice of the refractive indices of all the components we can realise an usual waveguide with the refractive index of the guiding film $n_g > n_s, n_c$; n_s and n_c are the refractive indices of the glass substrate and the LC cladding, respectively. On the application of the external field the LC molecules reorient, in average, to a new direction, resulting in a change of the cladding index n_c, thus the guiding modes propagating in the guide may switch to leaky ones, and the outgoing light intensity is reduced. In this paper we describe a similar device, in which the light modulation is achieved by the action of a second light beam. It is an all-optical device, whose realization and study can, additionally, constitute the first step to the realization of a one-beam nonlinear modulating device. We will show in the following that a strong modulation can be obtained and that the amount of modulation can be controlled by a suitable choice of the refractive indices of the materials.

Theoretical model

A detailed theoretical analysis of the problem is well outside the aims of this work. We will limit ourselves to sketch a reasonable model, in the framework of previously well-stated theories, within which the experimental results could be satisfactory explained. Let us consider a four-layer planar waveguide composed by, in order of stratification, a low-index semi-infinite glass substrate, an high-index film of thickness d, a birefringent LC film of thickness L and a final high-index glass prism. The refractive indices are ordered in the following way: $n_s<n_o<n_g<n_e<n_p$, where n_s is the refractive index of the glass substrate, n_o and n_e are the ordinary and extraordinary indices of the LC film, n_g the index of the guiding film and n_p the index of the glass prism. The z-axis is the direction of stratification and the light propagates in the guide along the x-axis. A schematic representation is shown in Fig. 1. In absence of external fields the LC film is aligned homeotropically, i.e. the average molecular orientation, as usual denoted by the molecular director **n**, which also coincides with the optical axis, is parallel to the stratification direction. The guided light is modulated by a laser beam impinging on a LC sample at oblique incidence as shown in Fig. 1.

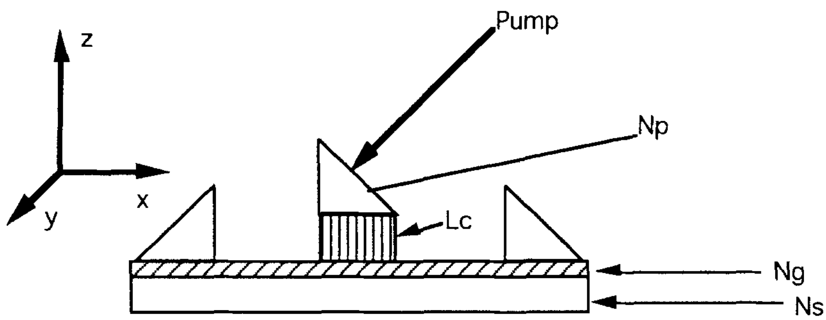

FIGURE. 1 - Schematic representation of waveguide-liquid crystal system; Np, prism index; Ng, waveguide index; Ns, substrate index.

Because of the finite width of the pump beam, the refractive index in the LC layer may depend both on z and on x coordinates, due to the non-uniform orientation of the molecular director[6]. Because of the laser-induced molecular reorientation, the index profile in the LC layer depends also on the light intensity I as a parameter: $n=n(x,z;I)$. In principle, the light field which reorients the LC molecules could be the same field propagating in the guide. The corresponding nonlinear problem must be solved taking into account simultaneously the Maxwell's equations for the propagation of the light and the equations for the response of the medium. In this work, however, we have considered a light field interacting with the

LC molecules and a different one propagating in the waveguide. In this case, the equations for the molecular director can be solved separately, giving the index profile n=n(x,z;I), which must be used to afford the electromagnetic problem. The index n=n(x,z;I) in the LC layer has, in general, a quite complicated dependence on the spatial variables x and z and an exact solution of the electromagnetic problem is possible only numerically, e.g. by means of transform techniques[7] and will be presented elsewhere. Qualitatively, we may imagine the following picture. Suppose the light in the waveguide be linearly polarized along the y-axis, i.e. pure TE modes. In absence of any perturbing field, the LC layer is seen as a uniform layer of index n_o, the molecular director being everywhere parallel to the z-axis. When an intense light field crosses the LC film, in the illuminated region the molecular director reorients and, owing to the strong birefringence, the light propagating in the guide *sees* a different index, approaching n_e as far as the molecular director approaches the y-axis direction. Because $n_e>n_g$, it is clear that for a reorienting light field intense enough, in a given range of the x-axis we reach a condition for which the guided modes switch to leaky modes and a fraction of the guided power escapes through the LC. The actual amount of the light power leaked off the waveguide depends on the values of the indices n_o, n_e, n_g, on the reorientation angle of the molecular director (strictly connected to the intensity of the impinging light) and on the extent, on the x-axis, of the reoriented region (strictly connected to the pump beam waist at the LC film). Even if a quantitative prevision is possible only after a complete numerical analysis, we expect to be able to obtain and control the modulation of the outgoing guided light by proper choice of the material and light parameters.

Experiment

We realized the experimental set-up shown in Fig. 2.

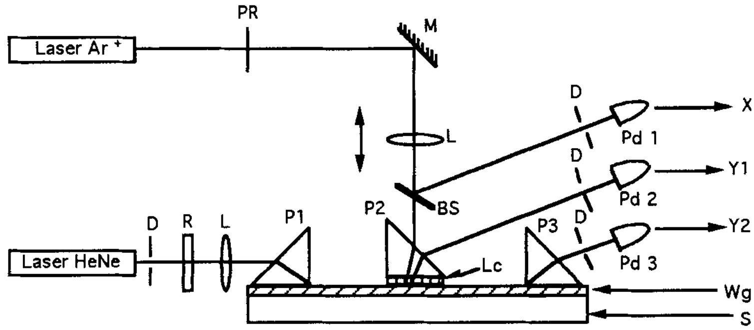

FIGURE 2 - Experimental setup: PR-polarization rotator, M-mirror, L-lens, BS-beam splitter, D-diaphragm, R-λ/2 wave plate, Lc-liquid crystal sample, Wg-waveguide, S-substrate, P1, P2, P3-prisms, Pd1, Pd2, Pd3-photodiodes, X-optical pump signal, Y1, Y2-output channels.

The planar waveguide was obtained by sputtering the Corning 7059 on a substrate (50 mm x 18 mm x 1.5 mm) of glass, commercially denoted as SL2. The film thickness was 1.2 μm and the refractive index was n_s=1.5102, for the substrate, and n_g=1.550 for the guiding medium at λ=0.6328 μm. The cover of the guide was realized with a 100 μm thick film of LC sandwiched between the guiding medium and an high-index glass prism (n_p=1.7988 at the same wavelength). The LC was aligned homeotropically with strong anchoring at the walls obtained by coating the walls with a HTAB surfactant. We used three different LC materials: E7 with n_o=1.522 and n_e=1.746, K15 with n_o=1.533 and n_e=1.703 and MBBA with n_o=1.544 and n_e=1.758. All chemicals have been provided by BDH company. A light beam from an He-Ne laser (λ=0.6328 μm) was focused and coupled into the waveguide. The He-Ne polarization direction was tuned to proper TE by a λ/2 plate. The pump beam was provided by a Ar^+ laser (λ=0.5145 μm) sent through the LC film at oblique incidence with the polarization direction lying in the yz-plane. The pump power was changed up to 570 mW. The Ar^+ beam waist at the film location was varied by moving the focusing lens and measured by a camera beam analyzer (Spiricon). Acting on both the laser intensity and waist the optimum condition, maximising the fraction of the guided He-Ne light leaked off, was found. In Fig. 3a and 4a the output power from the guide is reported vs the pump power, for K15 and MBBA respectively.

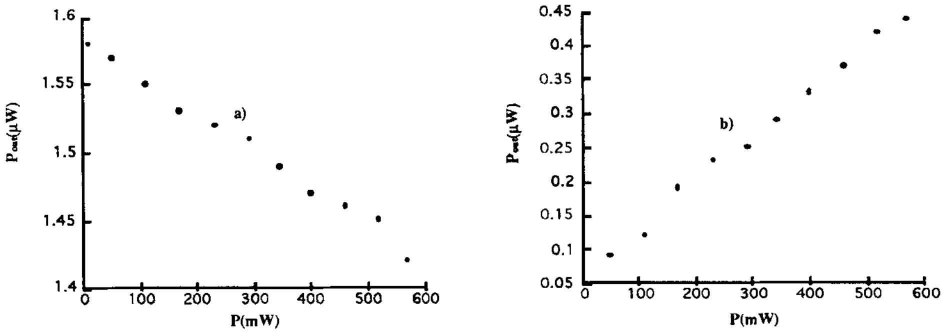

FIGURE 3 - Output light power vs cw Ar laser power; a) from P3 prism, b) from P2 prism. Sample: K15 liquid crystal.

No modulation of the He-Ne light was obtained with E7, because its ordinary index n_0 is too far below n_g. For K15 the optimum beam waist was found to be 540 μm and a maximum modulation of 15% of the guided light was achieved. For MBBA, whose ordinary index n_0 is much closer to n_g, the optimum waist was 570 μm and the outgoing guided light was modulated up to 50%. Fig 3b and 4b show, for K15 and MBBA respectively, the light power leaked through the LC film as a function of the pump power.

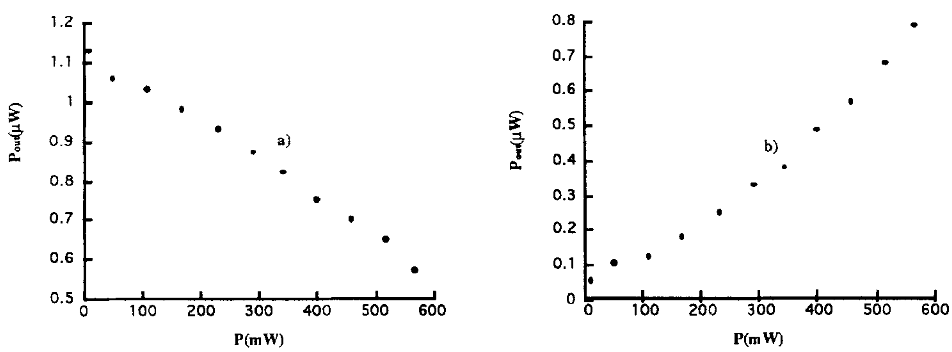

FIGURE 4 - Output light power vs cw Ar laser power; a) from P3 prism, b) from P2 prism. Sample: MBBA liquid crystal.

It is clearly confirmed that the fraction of the light not propagating to the end of the waveguide has leaked off through the LC film. The power balance is not exactly closed because the losses in the guide and the high light scattering in the LC layer.

Conclusion

We have presented an all-optical experiment of modulation of the light propagation in a waveguide by means of a second light source. The device has been realized utilizing LC materials whose convenience in integrated optics has been outlined. A physical picture explaining the observed effects has been given and the way has been indicated to obtain exact numerical previsions. The success of the experiment encourage us to go on in the next step of realizing a nonlinear LC based waveguide in which the reorienting pump beam is the beam propagating in the guide itself.

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