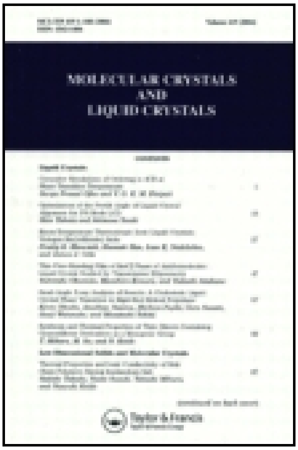

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ALL-OPTICAL SWITCHING IN A LIQUID CRYSTALLINE DIRECTIONAL COUPLER

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Abstract The analysis of a nonlinear directional coupler consisted of an optical fiber and a nematic liquid crystalline waveguide is presented. The nonlinear effect caused by an optically-induced reorientational effect in nematics leads to the bistable behavior. The theoretical model is compared with experimental results.

INTRODUCTION

Although the first observations of liquid crystalline behavior were made in 1888 by Reinitzer and Lehmann, the nonlinear optics of liquid crystals (LCs) have been actively studied for not more than the last twenty years. Early studies have concentrated on the isotropic phase in which LCs reveal a very interesting pretransitional (from isotropic to nematic phase) behavior manifesting itself in great molecular reorientations and macroscopic collective phenomena. In the nematic phase, the correlation among molecules is very strong because of the high anisotropy as well as the collective behavior of the molecules. This is responsible for the fact that LC molecules can easily reorient even with a very low externally applied electric, magnetic or optical fields [1–5].

The use of liquid crystals leads to the numerous nonlinear optical phenomena arising from molecular reorientation or/and thermal effects such as intrinsic

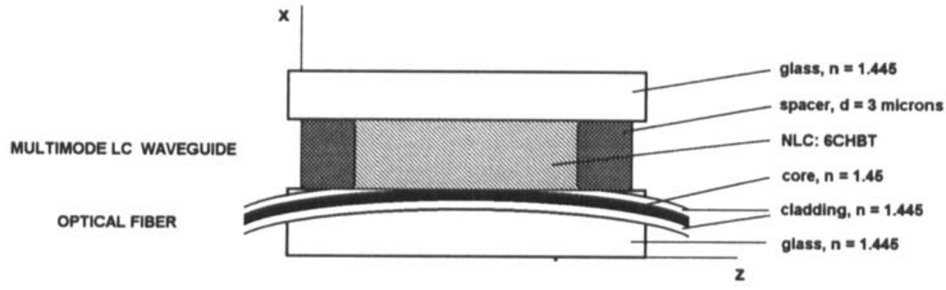

Figure 1: The analyzed configuration of the directional coupler.

bistability, temporal instabilities and stochastic processes for light-induced reorientation, nonlinear phenomena on a surface and on boundaries, fluctuations and nonlinear light scattering at phase transitions. All these optical nonlinear phenomena seem to be very promising in applications to optoelectronic waveguided functional elements[4–8].

Recently[6–8], we presented an analysis of a nonlinear directional coupler in which two planar waveguides were separated by a nematic liquid crystal (NLC) film. We analyzed both homeotropically or planar oriented NLC film subjected additionally external to an electric field at low frequency which enhanced the nonlinear reorientation of liquid crystal molecules. We have also proposed an application of the hybrid aligned nematic film which introduces asymmetry in operation of the directional coupler. It has been shown that all proposed devices allow the low-power all-optical switching.

The paper presents an analysis of a nonlinear directional coupler consisted of an optical fiber and a waveguides made by a NLC film (fig.1.). The nonlinear effect is caused by an optically-induced reorientational effect occurring in nematics and/or thermal effect. The experimental results show an existence of optical bistability in output transmission characteristics. This behavior, not observed in nonlinear directional couplers with Kerr-type nonlinearities, is explained theoretically as a result of orientational effect in NLC.

THEORY

A liquid crystalline layer is assumed to be a lossless planar optical waveguide. These assumptions cause that the guided electromagnetic field is homogeneous in one direction perpendicular to the propagation direction and confined in the second direction. The analyzed NLC layer has a positive optical anisotropy i.e. the extraordinary refractive index of a liquid crystal $n_{\|} = \sqrt{\epsilon_{\|}}$ is greater than the ordinary refractive index $n_{\perp} = \sqrt{\epsilon_{\perp}}$: $\Delta\epsilon = \epsilon_{\|} - \epsilon_{\perp} > 0$. In the analyzed structure (Fig.1) only TM fields (i.e. with nonvanishing E_x, E_z and H_y components of electric and magnetic fields) propagating in z direction and hybrid modes (i.e. with all components of electric and magnetic fields) are allowed. In this paper we limit our discussion to the TM waveguide modes: $\mathbf{E}(x,z,t) = \mathbf{E}(x)\exp(i\omega t - i\beta z)$, where β is a propagation factor. Consequently, the nonvanishing electric field components of the optical wave guided in the waveguide structure are calculated from the Maxwell's equations in the form [9]:

$$\frac{d}{dx}E_z = \frac{i}{\beta}\left[\left(\epsilon_{xx}k_o^2 - \beta^2\right)E_x + \epsilon_{xz}k_o^2 E_z\right], \tag{1}$$

$$\frac{d}{dx}E_x = \frac{\Delta\epsilon}{\epsilon_{xx}}\frac{d\theta}{dx}(E_x \sin 2\theta - E_z \cos 2\theta) - \frac{i}{\beta}\left[\left(\epsilon_{xx}k_o^2 - 2\beta^2\right)\frac{\epsilon_{xz}}{\epsilon_{xx}}E_x + \left(\frac{\epsilon_{xz}^2}{\epsilon_{zz}}k_o^2 - \beta^2\right)\frac{\epsilon_{zz}}{\epsilon_{xx}}E_z\right], \tag{2}$$

where ϵ_{jk} are elements of the electric permittivity tensor in the NLC layer given by:

$$\epsilon = \begin{pmatrix} \epsilon_{\perp} + \Delta\epsilon\cos^2\theta & 0 & \Delta\epsilon\sin\theta\cos\theta \\ 0 & \epsilon_{\perp} & 0 \\ \Delta\epsilon\sin\theta\cos\theta & 0 & \epsilon_{\perp} + \Delta\epsilon\sin^2\theta \end{pmatrix}, \tag{3}$$

and θ is an angle of liquid crystal molecules alignment, and $k_0 = 2\pi/\lambda$. The reorientation angle θ is calculated from the Euler-Lagrange equations which describe minimization of the free energy. For the analyzed configuration the equation takes the form:

$$\frac{d^2\theta}{dx^2}[1 - k\sin^2\theta] - \frac{1}{2}\left(\frac{d\theta}{dx}\right)^2 k\sin 2\theta + \nu[(E_x^* E_z + E_x E_z^*)\cos 2\theta + (|E_z|^2 - |E_x|^2)\sin 2\theta] = 0, \tag{4}$$

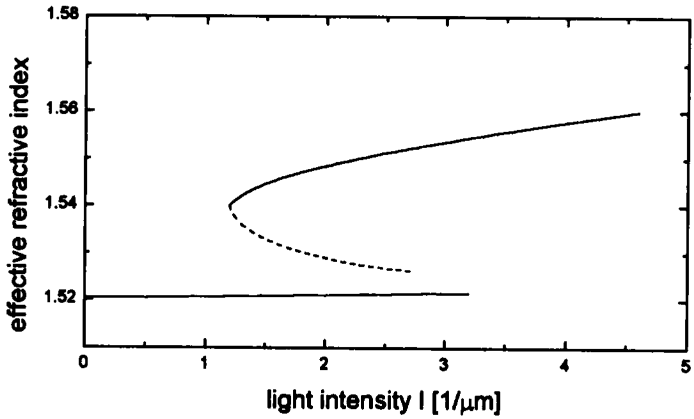

Figure 2: Effective refractive index $N = \beta/k_o$ dependence on the intensity I of light guided in the liquid crystal film.

where ν is a normalizing coefficient: $\nu = \epsilon_o \Delta\epsilon / 4K_{33}$, and $k = 1 - K_{11}/K_{33}$ in the one-elastic-constant approximation ($K_{11} = K_{33}$) is equal to zero ($k = 0$).

The texture of the NLC layer is described by the boundary conditions corresponding to the strong anchoring of nematic molecules at limiting glass surfaces: $\theta(x = 0) = \theta(x = d) = \pi/2$ for the planar orientation and $\theta(x = 0) = \theta(x = d) = 0$ for the homeotropic orientation. Then, for low intensities of the guided light I the molecular orientation is: $\theta(x) = \pi/2$ for the planar orientation and $\theta(x) = 0$ for the homeotropic orientation. For higher intensities, the molecules change their orientation due to the electric field of the electromagnetic wave. This molecular reorientation calculated from eq.(4) with a proper boundary conditions leads to a change in the local electric permittivity tensor (3), which simultaneously modifies the electromagnetic fields. This feedback between the molecular reorientation and electromagnetic field is responsible for the existence of a few solutions for the same values of a guided light power[10].

Fig. 2 presents the values of the effective refractive index $N = \beta/k_o$ versus the guided light power in the liquid crystalline waveguide $I = \nu \int_{-\infty}^{+\infty} |E_x(x)|^2 dx$. The planar orientation and the waveguide parameters corresponding to that used in experiments (fig.1) were taken into calculations. For the 6CHBT nematic liquid crystal, the light intensity $I = 1\mu m^{-1}$ corresponds to the light power $\sim 50mW$. This is a multimode waveguide and for the first mode (with higher effective refractive index) the hysteresis with two stable solutions is obtained. The third mathematical solution in between (dotted line) is unstable.

The observed bistability of the guided mode appears for thick waveguides and for large differences of refractive index between waveguiding core and surrounding media. The analyzed bistable phenomena is due to the collective behavior of NLC molecules and the interactions between the NLC molecules and glass plates. Therefore it can be recognized as a global nonlinearity dependent on the electromagnetic field values at the whole waveguide cross-section. Contrary, a thermal nonlinearity has different properties. Since the electromagnetic field in this case changes only locally the values of $\epsilon_{\|}$ and $\epsilon_{\perp}$, the local nonlinearity is similar to the generalized form of the Kerr-type nonlinearity: $\epsilon(x) = \epsilon_L(x) + \epsilon_{NL}(|E(x)|^2)$ .Consequently, the thermal nonlinearity of a liquid crystal medium placed in the waveguide core would be responsible only for the single state solution for a given mode without any bistable behavior[11].

The analyzed directional coupler configuration (see Fig.1) is composed of two waveguides separated by a dielectric film. In the directional coupler, the light guided by the first waveguide is tunneling through the evanescent field to the second waveguide. This interaction between two waveguides is described by the coupled mode equations for the complex amplitudes of the waveguide modes A_j [12]:

$$i\frac{dA_j}{dz} = \beta_j A_j + \kappa_{jl} A_l, \qquad (j \neq l) \tag{5}$$

where κ_{jl} is a coupling coefficient dependent on the separation d and j, l denote the waveguide modes. The used in eq.(5) amplitudes are connected with the light intensity guided by the separated waveguides $I = |A|^2$.

In the case of generalized Kerr-type nonlinearity both propagation factor β and coupling coefficient κ_{jl} in eq.(5) are continuous functions of the light intensities $|A_j|^2$. Then the light transmission between two waveguides is dependent on input light intensity but without any hysteresis[13]. To obtain hysteresis (the optical bistability) the optical feedback is necessary. Such a feedback can be supported by an optical

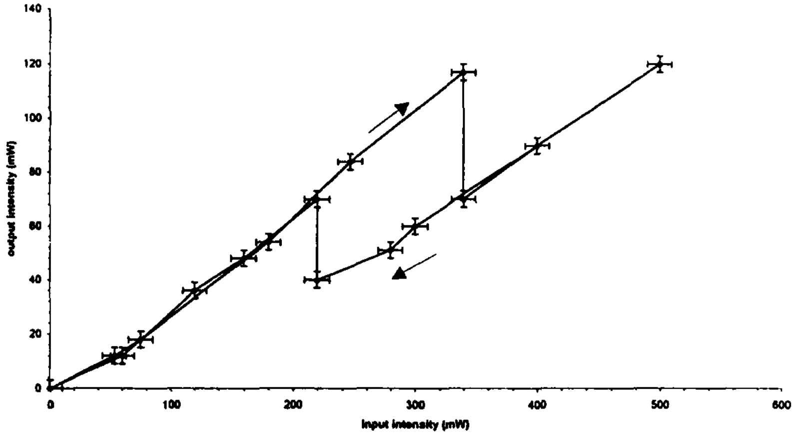

Figure 3: Output characteristics of the analyzed directional coupler obtained for argon laser ($\lambda = 514nm$) and 6CHBT liquid crystal film.

nonlinearity in the case when the propagation factor β exhibits two-stable values at the same intensities of light guided in the waveguide. Then the directional coupler transmission characteristics can be bistable. Therefore the reorientational effect in the NLC layer can be responsible for the bistable behaviour in the directional coupler.

EXPERIMENTAL

In the experiment we have used the directional coupler composed of a single-mode optical fiber SM-600 (core $n = 1.45$, cladding $n = 1.445$) manufactured by UMCS-Lublin, Poland and a 6CHBT nematic liquid crystal. For the wavelength used (Argon laser l=514nm) the SM-600 fiber guides two lowest-order linearly polarized spatial modes LP_{01}, LP_{11} and polarization of light in optical fiber was changed by the all-fiber polarization controller.

The NLC ($n_e = 1.68$, $n_o = 1.51$ at $20°C$) was placed between two polished silica blocks ($n = 1.445$) separated by $3 - \mu m$ Mylar spacers. The homeotropic orientation on the separated glass layers was imposed by an appropriate surface treatment with the surfactant CTAB. The SM-600 fiber was located into the lower silica block (Fig.1) which has been polished close to the fiber core. The coupling coefficient for the obtained half-coupler was 85% for an overlay with the refractive index equal to the effective refractive index of the fiber (immersion oil $n_D = 1.47$ at 20^oC).

A typical directional coupler performance obtained in the experiment is presented in Fig.3. The obtained hysteresis loop was checked for bistability and repeatability in every cycle. A contrast of bistability, equal to 41.4% of output intensity (measured on the end of the fiber), has been obtained for the $340mW$ light intensity of the argon laser.

To conclude, we have obtained experimentally for the first time the bistable operation of the directional coupler between the optical fiber and the liquid crystalline waveguide . The optical bistability phenomena is explained as a result of the orientational nonlinearity in nematic liquid crystalline film.

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