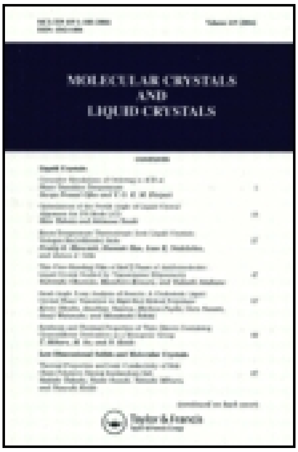

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LIQUID CRYSTALLINE DIRECTIONAL COUPLER WITH ASYMMETRICAL NONLINEARITY

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Abstract The analysis of a nonlinear directional coupler consisted of two planar waveguides separated by a nematic liquid crystal is presented. The nonlinear effect is caused by an optically-induced reorientational effect occurring in hybrid aligned nematics. The asymmetrical configuration causes the nonreciprocity in switching characteristics of the directional coupler.

INTRODUCTION

Over the past decade, nonlinear guided-wave devices have been extensively studied because of their potential applications in all-optical data processing and high speed communication systems [1]. Current research effort has focused considerable attention on highly efficient nonlinear materials of potential use in nonlinear guided-wave devices. Liquid crystals, because of the high anisotropy as well as the collective behavior of molecules under any external field are unique nonhomogeneous anisotropic objects for nonlinear optics. The use of liquid crystals leads to numerous nonlinear optical phenomena arising from molecular reorientation or/and thermal effects [2-6] such as intrinsic 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.

Recently [7], we presented an analysis of a liquid crystalline nonlinear directional coupler in which two planar waveguides were separated by a homeotropically oriented nematic liquid crystal (NLC) film and initial results were limited to a TE-polarized electromagnetic wave under the one-elastic constant approximation. A more advanced and developed analysis of a nonlinear planar waveguide and a nonlinear directional coupler with a homeotropic or planar-oriented NLC was presented in Ref. [8] in which classical geometries of the light-induced Fredericks transition (LIFT) corresponding to three basic deformations (*splay, twist*, and *bend*) occurring in a NLC were analyzed and an influence of a d.c. external electric field enhancing the action of the optical field was discussed.

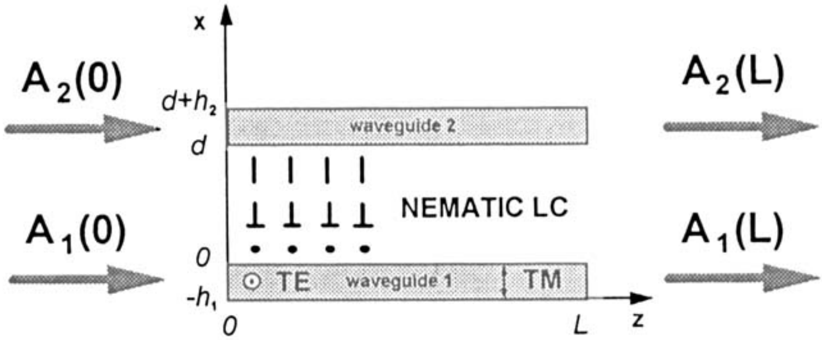

Figure 1: The analyzed configuration of the directional coupler with a hybrid aligned nematics.

It is commonly known that there is usually a threshold value of the optical field for the LIFT (the same is valid for the classical Fredericks transition). However, it was demonstrated [9] that the threshold disappears for the hybrid aligned nematic (HAN) cell. The HAN cell consists of two glass walls which induce, respectively, homeotropic and planar orientations and the cell has focused very recently growing interest due to its potential displays and nonlinear optics applications [10].

The paper presents an analysis of a nonlinear directional coupler consisted of two planar waveguides separated by a NLC film. The waveguides act as two specially prepared glass walls which impose, respectively, homeotropic and planar orientations of the NLC. Hence, the waveguides and the NLC film form a hybrid aligned nematic cell. The nonlinear effect is caused by an optically-induced reorientational effect occurring in nematics. The results obtained are applied to analyze the action of a nonlinear directional coupler. It is shown that the characteristics of the analyzed liquid crystalline coupler are different to characteristics obtained for the symmetrical configurations. The proposed directional coupler with the HAN can be applied as a logical gate for signals incoming from various waveguides.

THEORY

Let us consider a step-index single-mode 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 cover of the waveguide consists of a NLC layer with a positive optical anisotropy (i.e. the extraordinary refractive index of a liquid crystal $n_{\|}$ is greater than the ordinary refractive index $n_{\perp}$: $n_{\|} > n_{\perp}$). A transversal component of the electric field of the optical wave guided in the waveguide structure is given by [11]:

$$E(x,z) = \Psi(x)\exp(-ik_0 n_{eff} z), \tag{1}$$

where $k_0 = 2\pi/\lambda$, n_{eff} is an effective refractive index of the guided mode, and $\Psi(x)$ is a waveguide mode field profile. The intensity of light guided by the analyzed structure is defined as follows:

$$I = \sqrt{\frac{\epsilon_0}{\mu_0}} \int_{-\infty}^{+\infty} \Psi^2 dx.$$

The reorientation angle θ of the liquid crystal molecules is calculated from the Euler-Lagrange equations which describe minimization of the free energy. For the analyzed configuration the equation take the form:

$$\frac{d^2\theta}{dx^2}[k \sin^2\theta + 1] + \frac{1}{2}\left(\frac{d\theta}{dx}\right)^2 k \sin 2\theta + \nu\Psi^2(x) \sin 2\theta = 0, \tag{2}$$

where for TM polarized light $k = K_{33}/K_{11} + 1$, and for TE-polarized light $k = K_{11}/K_{33} + 1$, and ν is a normalizing coefficient defined by the formula:

$$\nu = \frac{(n_{\|}^2 - n_{\perp}^2)\epsilon_o}{4K}, \tag{3}$$

where K is the elastic constant $K = K_{11}$ for TM and $K = K_{33}$ for TE polarization. In the one-elastic-constant approximation $K_{11} = K_{33}$ and then $k = 0$.

Since the HAN cell is described by the boundary conditions corresponding to two different regimes of interactions between nematic molecules and limiting glass surfaces. The angle θ at the boundaries is written as: $\theta(x = 0) = \pi/2$ and $\theta(x = d) = 0$ and for low intensities of the guided light I and for the one-elastic-constant approximation the reorientation of nematic molecules is linear: $\theta = \pi x/2L$. However, for higher intensities molecules reorient due to the electric field of the electromagnetic wave. This molecular reorientation calculated from eq.(2) with a proper boundary conditions leads to changes in the local electric permittivity:

$$\epsilon = \frac{n_{\perp}^2}{\cos^2\theta + (n_{\perp}/n_{\|})^2 \sin^2\theta}. \tag{4}$$

The analyzed directional coupler configuration (see Fig.1) is composed of two single-mode waveguides separated by a nematic film in the HAN geometry. In the directional coupler, the light guided by one 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_1 and A_2:

$$i\frac{dA_1}{dz} = \beta_1 A_1 + \kappa A_2$$

$$i\frac{dA_2}{dz} = \beta_2 A_2 + \kappa A_1 \tag{5}$$

where κ is a coupling coefficient dependent on the separation d and β is a guided mode propagation factor. For a small perturbation, the propagation factor β has a form [11]:

$$\beta_l = k_0 n_{eff}^{(l)} + \delta\beta_l \tag{6}$$

where $l = 1, 2$ and the nonlinear propagation factor changes are equal to:

$$\delta\beta_l = \frac{1}{2n_{eff}^{(l)}} \frac{\int_0^d \delta\epsilon \Psi^2(x)dx}{\int_{-\infty}^{+\infty} \Psi^2(x)dx} \tag{7}$$

where $\delta\epsilon$ is a difference between the electric permittivity (4) for the light intensity $I = 0$ and for the considered value of the light intensity. Note, that due to the asymmetry in the HAN the $\delta\beta$ dependence on light intensity I is different for both waveguides. Therefore, following the ref.[13], it is convenient to calculate the asymmetry coefficient:

$$\eta = \frac{\delta\beta_1 - \delta\beta_2}{\delta\beta_1 + \delta\beta_2} \tag{8}$$

which defines the asymmetry in nonlinearity caused by the light guided by both waveguides.

In the classically analyzed nonlinear directional couplers, the Kerr-type nonlinearity has the form $\beta_l = k_0[n_{eff}^{(l)} + \alpha_l \nu I]$. Then the equations (5) for $\alpha = const$ and $\kappa = const$ are analytically solvable in terms of Jacobi elliptic functions [12-13] and the asymmetry coefficient is independent on light intensity.

RESULTS AND CONCLUSIONS

Results presented in Figures 2-4 have been obtained for the TE-polarized waves in the planar waveguide structure with $n_f = 1.74$, $n_c = 1.52$, $n_s = 1.72$ (see Fig. 1) and for the wavelength $\lambda = 1.06\mu m$. The waveguide thicknesses $h_2 = 2.0\mu m$ and $h_1 = 1.67\mu m$ were taken to obtain the same values of the effective refractive indices $n_{eff}^{(1)} = n_{eff}^{(2)}$ for the HAN thickness $d = 2\mu m$. The nematic liquid crystal chosen for the calculations was PCB (nematic range from $21°C$ to $35°C$) characterized by refractive indices $n_\perp = 1.52$, $n_\parallel = 1.72$, and by one elastic constant of the order 10^{-12}N.

Fig. 2 present variations of the nonlinear propagation factor changes $\delta\beta/k_0$ (defined in the equation (7)) plotted against the guided light intensity for both waveguides and for three values of nematic film thickness: $d = 1\mu m$, $d = 2\mu m$ and $d = 4\mu m$. The nonlinear changes in the propagation factor $\delta\beta$ are higher in the waveguide '1' than in the waveguide '2' for TE-polarized waves. This is caused by the fact, that the molecular alignment at the boundary of the waveguide '1' imposed by planar anchoring fulfills the requirements of free energy minimization. Consequently, the evanescent electromagnetic field penetrating the medium easily reorients bulk molecules. The same behavior will be observed for the TM-polarized waves in the waveguide '2'. Contrary, the reorientation effect of the electromagnetic field is much smaller in the case, when the TE (TM) wave tends to reorient the molecules in the vicinity of the waveguide '2' ('1').

This asymmetry in optical nonlinearity is clearly visible in Fig.3 where the asymmetry coefficient η (defined in (8)) instead of being equal zero (as in the sym-

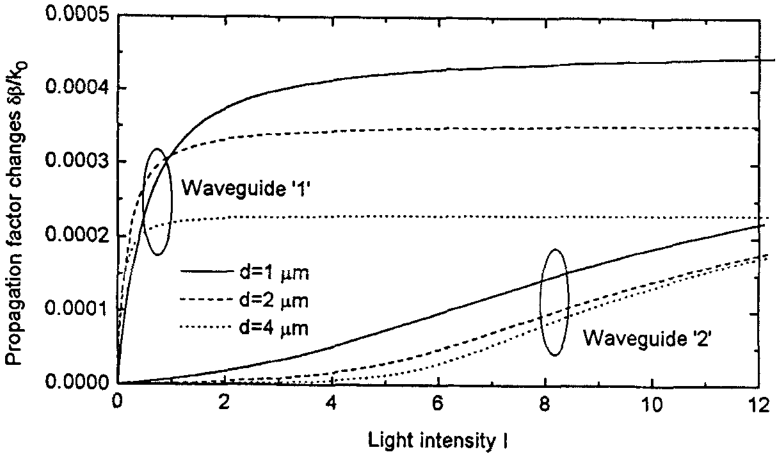

Figure 2: Changes in nonlinear propagation factor $\delta\beta/k_0$ (defined in the equation (7)) plotted against the guided light intensity for both waveguides and for three values of nematic film thickness: $d = 1\mu m$, $d = 2\mu m$ and $d = 4\mu m$.

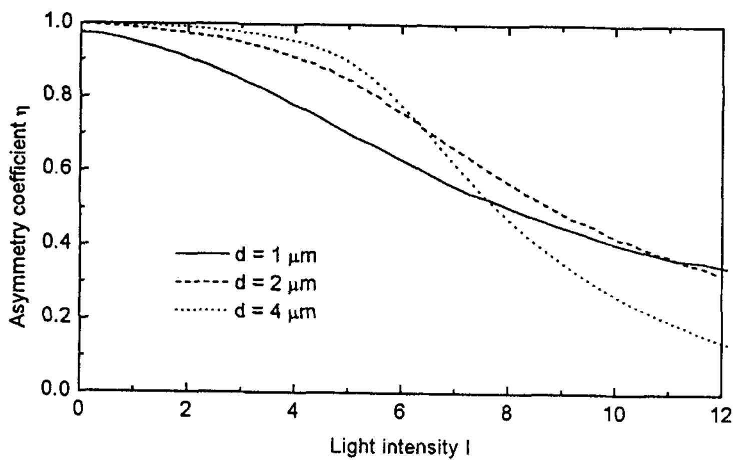

Figure 3: Asymetry coefficient η defined in (8) *vs.* the guided light intensity, for the thicknesses: $d = 1\mu m$, $d = 2\mu m$ and $d = 4\mu m$ of the HAN cell.

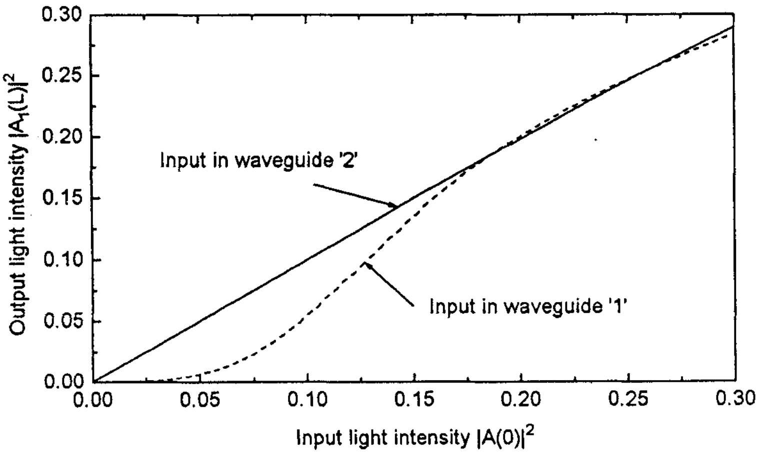

Figure 4: Output characteristics of the analyzed directional coupler with asymmetrical nonlinearity. ($d = 2\mu m$).

metrical case) is close to one, for low intensities of guided light. Note, that there is no threshold value for the nonlinear effect in both cases.

Fig. 4 presents the output light intensity in waveguide '1' vs. the input light intensities in waveguide '1' and waveguide '2' for the directional coupler structure. The light transmission from waveguide '2' to waveguide '1' (defined as $|A_1(L)/A_2(0)|^2$) is almost independent on the input intensity (in a range of light intensities under consideration). Contrary, due to the strong nonlinear effect for light injected to waveguide '1' the observed output light intensity at waveguide '2' decreases for higher intensities. It means that for certain values of input light intensities light is outgoing only from waveguide '1' independently to which waveguide light was initially launched. This phenomenon is of particular interest from the all-optical signal processing and computing point of view.

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