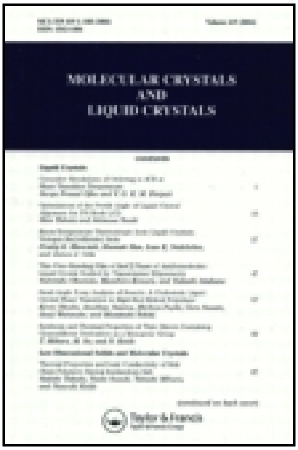

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Design of an Ultrashort Directional Coupler with an SSFLC Coupling Layer

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A design of a vertical directional coupler, operating at the wavelength λ= 632.8 nm, is presented. The coupler consists of a layer of the Hoechst ferroelectric liquid crystal mixture FELIX-M4851-025, homogeneously aligned and sandwiched between two single mode ion-exchanged BK7 glass waveguides. The design of the directional coupler was carried out by using the beam propagation method, taking into account also teflon alignment layer and ITO electrode contributions. Given the FLC mixture refractive indices, n_e= 1.611 and n_o= 1.466 at λ= 632.8 nm and T= 25 °C, calculations show that less than 60 μm coupling length, with an extinction ratio higher than 21 dB can be obtained by using single mode waveguides with a refractive index change at the surface Δn= 0.013, an FLC layer 2 μm thick, and cone axis tilted by about 19° from the propagation direction of the lightwave.

Keywords: surface stabilised ferroelectric liquid crystals; optical switches.

INTRODUCTION

Directional couplers are basic components for building optical switching matrices. Lithium niobate has been employed to build large optical switching systems based on guided wave directional couplers with an active length of 6.7 mm and coupling length of about 3 mm [1].

Calculations by using beam propagation method (BPM) show that much shorter coupling lengths, less than 100 μm, are feasible in vertical directional couplers when a surface stabilised ferrolectric liquid crystal (SSFLC) layer is used as coupling intermediate layer between two guiding layers [2].

Clark and Handschy demonstrated experimentally a vertical directional coupler consisting of an SSFLC cell, whose surfaces were ion-exchanged glass waveguides [3]. In that device, FLC molecules are rotated by applying an electric field which induces a change of the refractive index of the coupling layer: it can be either lower than that n_s in the waveguide substrate, in case of bar-state, or slightly higher than the refractive index at the surface $n_w=n_s+\Delta n$ of the waveguides, in case of coupling (cross-state). However that very first demonstration of an SSFLC directional coupler required too much high voltage, about 1 kV, to be driven and employed multimode waveguides which are not preferred in optical communications applications.

Vertical directional couplers using nematic liquid crystal as active coupling layer have been also demonstrated both theoretically [4] and experimentally [5]. In a planar configuration, light path in a polymer waveguide can be switched towards either of two distinct output ports by means of total internal reflection by changing refractive index of a nematic liquid crystal used as overlayer [6].

Ferroelectric liquid crystal are preferred for optical switching because of two main advantages: faster switching and bistability. FLC molecules can be switched in microseconds and bistability gives the possibility to make electro-optical switches with memory, which implies that these devices require application of electric field only to change switch state but no applied electric field is required to hold any switch state. Large electrooptical switch matrices using liquid crystals can be built by using a mature technology mostly already developed to make flat panel displays.

In this paper an ultrashort vertical directional coupler consisting of two ion-exchanged single mode waveguides separated by a thin FLC layer, is designed by using the BPM. After a description of device structure, light propagation is simulated to find the FLC orientation and waveguide characteristics in order to get highest waveguide coupling in the shortest length. Moreover, ITO electrodes and alignment layers influences on device performance are taken into account to evaluate device performance.

DEVICE STRUCTURE AND ITS WORKING PRINCIPLE

The longitudinal section of the directional coupler proposed in this paper is sketched in Fig. 1, where z is the direction of propagation. In a prototype under construction, the two slab waveguides are obtained in BK7 glass substrates by ion-exchange in melted $NaNO_3$:KNO_3:$AgNO_3$ at a temperature T= 385°C and for a time t= 10 min. Polytetrafluoroethilene (PTFE or better known as teflon) is used as alignment layer easily deposited by hot friction [7] while the electrodes are made of ITO. The FLC mixture is FELIX-M4851-025 by Hoechst and it is sandwiched between the two waveguides as in a standard SSFLC cell. The working principle of such a device, described in [3], is based upon the idea of changing the SSFLC layer refractive index by electrooptic effect, as sketched in Fig. 2 where refractive index profiles and thickness of the guiding layers are reported.

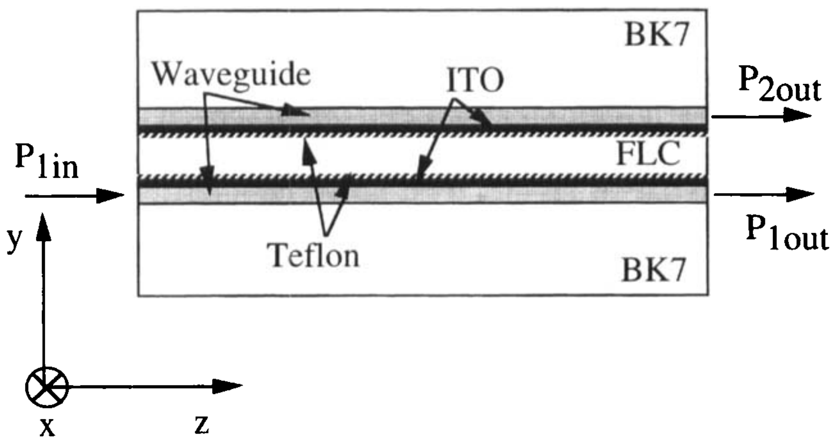

FIGURE 1 Directional coupler structure.

In the bar-state, the SSFLC refractive index is lower than that in the substrate hence the waveguides are not coupled and input optical power remains in the input waveguide. In the cross-state, the refractive index of the SSFLC layers is higher than that of the core of the coupled waveguides and optical power is transferred from one waveguide to the other one through the SSFLC layer. In this device configuration only TE polarized light can "see" refractive index change when electric field is applied to the SSFLC cell.

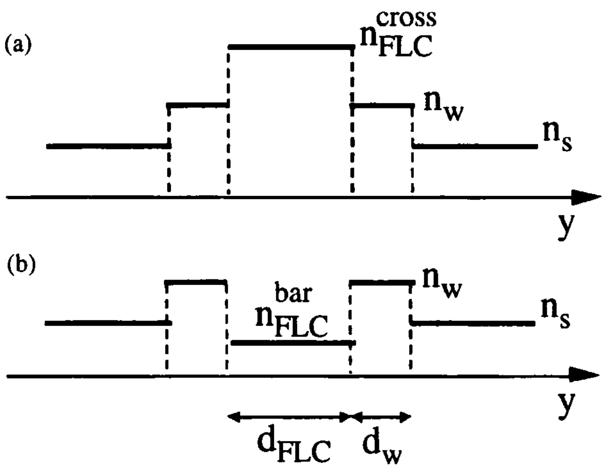

FIGURE 2 Refractive index profile of the directional coupler in the cross-state (a) and in the bar-state (b).

DEVICE DESIGN

BPM simulations were carried out in order to compute the values of refractive indices of the waveguides and the FLC layer to get the maximum extinction ratio ER defined as ER = $10 \cdot \mathrm{Log}_{10}[\max (P_{2out}/P_{1out})]$, where P_{2out} and P_{1out} are the output optical powers from waveguide 2 and from waveguide 1, respectively, as showed in Fig. 1. In the BPM simulations the typical graded-index profile of ion exchanged waveguides was approximated by a step index profile by assuming as waveguide thickness the depth from substrate surface at which $\Delta n = n_w - n_s$ is decreased by 1/e. Typical single mode waveguides are about 1.2 μm deep. Furthermore, at first in the BPM simulations ITO and teflon influences were neglected and taken into account only after finding the optimal refractive indices of the guiding layers.

Extraordinary and ordinary FLC refractive indices, measured by Hoechst at 25 °C and λ= 589 nm are n_e= 1.638 and n_o= 1.483 respectively. Since measurements at λ= 632.8 nm are not available, variations of refractive index versus wavelength were estimated by using a Cauchy dispersion formula reported in [8]. Simple calculations give n_e= 1.611 and n_o= 1.466 at λ= 632.8 nm. The FLC thickness has been fixed at 2 μm in order to obtain a good surface stabilised FLC cell. An important design parameter is also the FLC smectic cone orientation, or equivalently the orientation of the normal to the smectic layers, with respect to the lightwave direction of propagation z, defined by the angle α as sketched in Fig. 3, where 2θ is the smectic cone angle, which is 52° wide at 25°C for the mixture M4851-025.

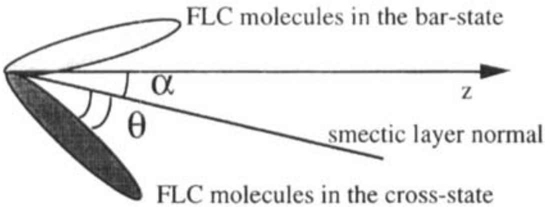

FIGURE 3 Top view of the FLC molecules orientation with respect to the propagation direction z, both in the bar-state and cross-state.

The refractive indices in both states are reported below:

$$n_{FLC}^{bar} = \frac{n_e \cdot n_o}{\sqrt{n_o^2 \cdot \sin^2(\alpha - \theta) + n_e^2 \cdot \cos^2(\alpha - \theta)}}$$
$$n_{FLC}^{cross} = \frac{n_e \cdot n_o}{\sqrt{n_o^2 \cdot \sin^2(\alpha + \theta) + n_e^2 \cdot \cos^2(\alpha + \theta)}} \qquad (1)$$

Several simulations were carried out and Fig. 4 reports ER versus n_w for four different values of n_{FLC}^{cross}, 1.528, 1.533, 1.538 and 1.543 corresponding to α = 17° , 19°, 21° and 23°, respectively and θ=26°. The highest extinction ratio, 31.4 dB, is obtained for n_w=1.533, n_{FLC}^{cross} = 1.538 with a coupling length of about 50 μm. Since waveguide substrate has a refractive index n_s= 1.515, unfortunately, simple ion-exchange technique can not give low-loss single mode waveguides with refractive index change at the surface Δn= 0.018. In general the ER maximum value is obtained for the optimal difference of the refractive index of the FLC layer and refractive index of the core of the waveguides. Furthermore the maximum of ER increases with n_{FLC}^{cross} and also shifts towards higher waveguide refractive indices, up to about α=21°, then it starts to decrease. For n_{FLC}^{cross}=1.528 a second maximum occurs for higher values of n_w and in that case the directional coupler can be studied with the classic coupled mode theory, both in the bar and cross-state, since it is $n_{FLC}^{cross} < n_w$.

Single mode waveguides were obtained by an ion-exchange performed at 385 °C for 10 min in a mixture of $NaNO_3$:KNO_3:$AgNO_3$ generated as follows: initially a mixture of $NaNO_3$:KNO_3 50 % weigth/weigth is made, then the final mixture is made by adding 0.7 mole % $AgNO_3$. A refractive index change at the surface Δn =0.013 has been assumed, since a waveguide refractive effective index n_{ef}= 1.528 was experimentally measured by standard prism coupling technique. According to Fig. 4, n_w= 1.528, with n_{FLC}^{cross}= 1.533 for α= 19°, which can be obtained very simply during teflon layer deposition, gives ER equal to about 21.7 dB. It must be observed that it is θ= 26° only when electric field is applied, but since θ relaxes down to about 8° (about 1/3+1/4 of θ= 26°) when electric field is removed, α= 37° must be chosen in order to get again the same value for ER and L_c also for memorized states. In fact, in this case according to (1), it is still $\alpha+\theta$ = 45°, hence n_{FLC}^{cross}= 1.533 and $\alpha-\theta$ gives $n_{FLC}^{bar} < n_s$, which implies no coupling between the two waveguides in the bar-state.

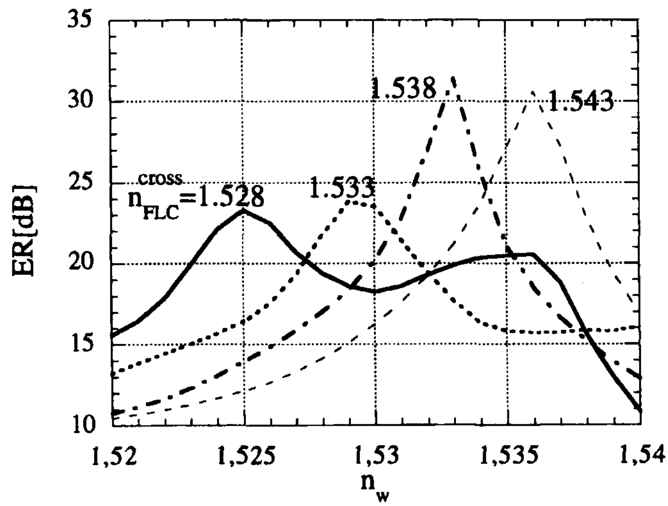

FIGURE 4 Extinction ratio (ER) versus waveguide refractive index, n_w, for four values of FLC refractive index, 1.528, 1.533, 1.538 and 1.543 corresponding to α= 17°, 19°, 21° and 23°, respectively.

Fig.5 reports coupling length and ER versus α, for θ= 26°, with n_w= 1.528. It can be seen that a coupling length L_c=61 μm, at which the maximum light intensity is transferred to the other waveguide, is obtained for α= 18° with ER= 23 dB. Fig. 5 shows that for α>18° a shorter coupling length can be obtained by paying in terms of reduction of extinction ratio. In particular it is L_c= 55 μm with ER= 22 dB for α= 19°(n_{FLC}^{cross} = 1.533).

Fig. 6 shows the evolution of TE electric field intensity normalized to the input peak value along the directional coupler both in the bar-state (Fig. 6a) and in the cross-state (Fig. 6b) for n_w=1.528, n_{FLC}^{bar} = 1.466 and n_{FLC}^{cross}= 1.533, d_w=1.2 μm and d_{FLC}= 2 μm.

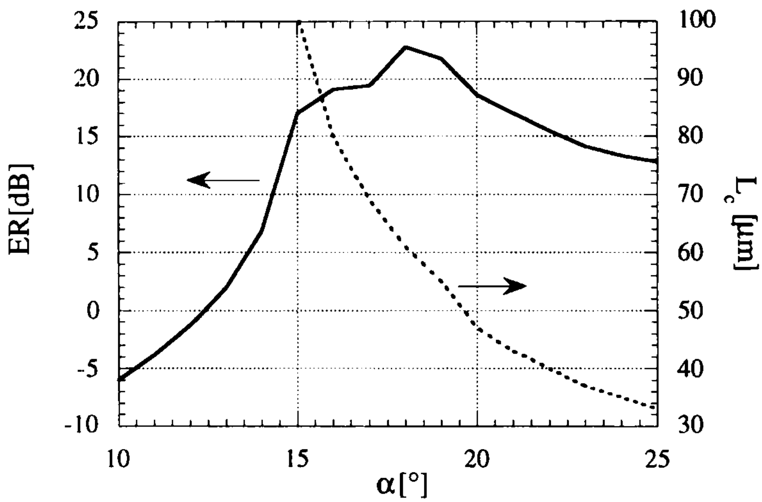

FIGURE 5. Plots of extinction ratio and coupling length versus α for n_w=1.528 and θ= 26°.

INFLUENCE OF ALIGNING LAYER AND ELECTRODES

ITO layer used to make electrodes affects device performance because of light absorption. Calculations of ER, scattering losses and coupling length have been carried out for ITO thicknesses of 50 Å, 100 Å, 150 Å and 200 Å, including a teflon layer of 500 Å, which is a typical thickness of hot friction deposited layers [7].

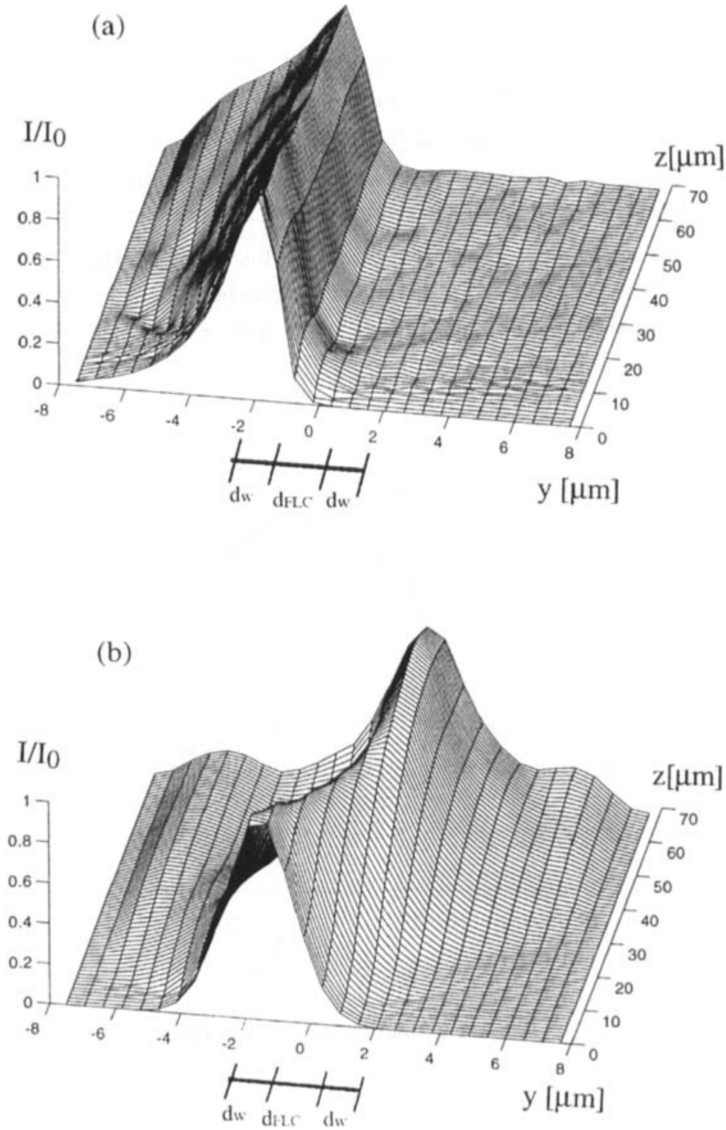

FIGURE 6. Evolution of TE electric field along the directional coupler with d_{FLC}= 2 μm, d_w= 1.2 μm and n_w=1.528: (a) bar state with n_{FLC}^{bar} = 1.466 and (b) cross-state with n_{FLC}^{cross}= 1.533 (α= 19°).

In these calculations, whose results are reported in Table 1, experimental optical waveguide refractive index has been employed, n_w= 1.528, and n_{FLC}^{cross} = 1.533. Moreover a complex refractive index of ITO n_{ITO}= 1.9+i0.075, measured by ellipsometry on sputtering deposited layers, and a refractive index for teflon of about 1.51 have been considered in the calculations. Table 1 shows that L_c, at which the maximum optical power is transferred to the other waveguide in the cross-state, is slightly different from L_{max} defined as the length at which maximum ER occurs. This mismatch between L_c and L_{max} is caused by scattering of light at the interfaces. However maximum ER, higher than 18 dB, is obtained after a propagation length shorter than 60 μm even for ITO 200 Å thick. Although the results reported in Table 1 include teflon contribution in the calculations, its influence can be neglected. Furthermore optical measurements on waveguides coated with teflon showed no variation of refractive effective index and losses, because teflon refractive index is very close to the substrate index. In the last column of Table 1 attenuation increases with ITO thickness, as expected, because of light absorption. Therefore an ITO layer not thicker than 200 Å is suggested for device realisation.

Table 1 Influence of ITO on coupling length L_c, extinction ratio at L_c, maximum extinction ratio with relative length L_{max} and attenuation in the cross-state for n_{FLC}^{cross}= 1.533 (α= 19°), n_w=1.528, n_{ITO}= 1.9+i0.075, n_{teflon}= 1.51 (500 Å).

ITO thickness [Å]	L_c [μm]	ER (at L_c)[dB]	Maximum ER [dB]	L_{max} [μm]	Attenuation at L_{max} [dB]
0	56	18.3	19.9	53	1.4
50	55	21.9	22.7	54	2.9
100	46	18.3	23.8	54	4.3
150	46	18.9	21.1	50	5.7
200	45	16.4	17.9	47	6.7

CONCLUSIONS

A directional coupler with coupling length shorter than 60 μm has been designed by using BPM technique. Given the FLC mixture, ion-exchanged single mode glass waveguides have been fabricated with calculated optical characteristics and orientation of the smectic FLC layers with respect to the propagation direction. Simulations show that ER higher than 30 dB and L_c of about 50 μm can be obtained, provided that waveguide with Δn=0.018 are feasible. In particular with FLC 4851 025 by Hoechst, a coupling length not higher than 60 μm has been found for waveguide refractive index change at the surface Δn=0.013, experimentally obtained in BK7 glass by ion-exchange performed at 385 °C for 10 min in a mixture of $NaNO_3$:KNO_3:$AgNO_3$ and SSFLC smectic layer normal tilted by 19° respect to propagation direction. Teflon alignment layer influence on device performance is negligible due to its refractive index very close to that of BK7. Coupling length less than 60 μm and extinction ratio higher than 20 dB have been computed even when ITO electrodes are used, provided that their thickness is not higher than 150 Å. Such short coupling length and high extinction ratio are promising features to build large optic switch matrices with high scale of integration.

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