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PLANAR LC OPTICAL SWITCH FOR OPTICAL COMMUNICATIONS

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Abstract: A planar electrooptical light switch and crossbar interconnection network specifically designed for optical fiber communications is described. It is based on the use of the homogeneously aligned nematic liquid crystals acting as the active elements for light beam splitting and redirecting. Several possibilities based on electrically controlled birefringence in nematic LC are described and the estimate on the dimensional limitations based on the calculations of the electric control field are given. The presented LC optical crossbar can be addressed electrically and can be miniaturized. This makes it particularly interesting anywhere where large number of interconnecting switching of optical light signals is required (i.e. telephone centrals,...)

Planarno tekoče kristalno optično stikalo za optične komunikacije

Ključne besede: Komunikacije optične, stikala optična, LC tehnologije planarne, LC kristali tekoči, LC kristali tekoči nematični, polja električna, količniki lomni, valovodi optični

Povzetek: Opisano je planarno tekočekristalno optično stikalo, ki je posebej primerno za optične komunikacije. Stikalo uporablja homogeno urejeno plast tekočega kristala, ki se mu z električnim poljem lahko spreminja lomni količnik - električno kontrolirana dvolomnost. Opisane so različne možnosti uporabe tega efekta v nematskih tekočih kristalih.Na osnovi izračuna električnega polja znotraj tekočekristalne celice je podana ocena maksimalnih možnih dimenzij takega optičnega stikala. Prednosti tekočekristalnega optičnega stikala so predvsem v majhnih dimenzijah in možnosti električnega krmiljenja z nizkimi napetostmi, zato je posebej zanimiv za uporabo povsod, kjer je zahtevano veliko število optičnih stikalnih elementov (npr. telefonske centrale,...)

INTRODUCTION

A number of different technical solutions using liquid crystals for switching the light signals between different optical fibers has been made so far[1,2,3,4]. They are based on different electrooptic mechanisms in liquid crystals from electrically controlled refractive index variations causing light coupling between optical waveguides[5], total light reflection[6], electrically controlled birefringence and electrically controlled light scattering[7]. Most of these solutions require the use of expensive optic elements (prisms, polarization beamsplitters,..), their construction is nonplanar and they cannot be miniaturized.

In this paper we propose a construction of an LC switching device based on the fact that LC itself can be used as a waveguide as first pointed out by Giallorenzi et al.[9] and later by M.Kawachi et al.[4]. Moreover, using a light, the electrically controlled birefringence of LC can be used to generate electrically induced light guide be-

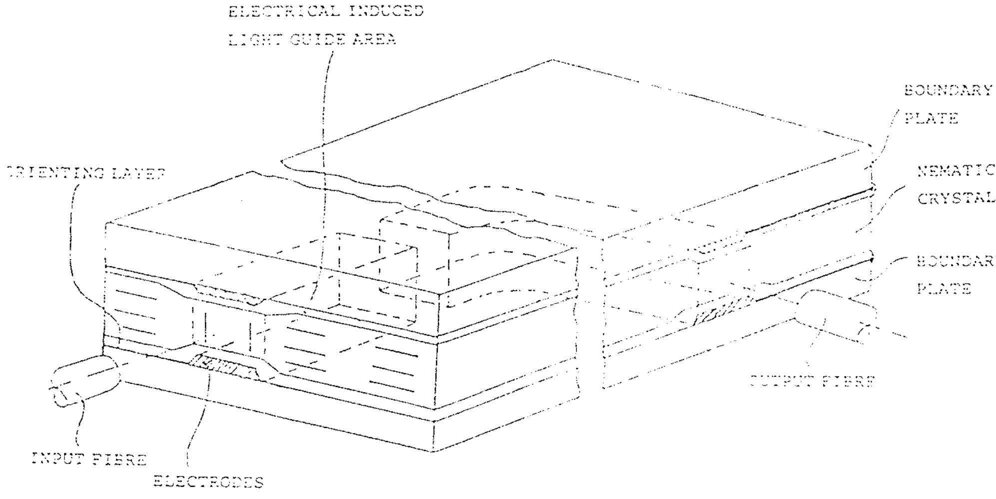


Figure 1: Schematic presentation of the electrically induced optical waveguide in the homogeneously aligned nematic LC

tween the properly shaped electrodes (see Fig. 1) in a standard, homogeneously aligned nematic LC cell.

If the polarization of the propagating light is perpendicular to the boundary glass plates of the homogeneously aligned nematic LC (positive dielectric anisotropy!) cell, than the applied electric field between the electrodes on the boundary plates causes, that the refractive index (n_e) of the LC between the electrodes becomes greater than in the area without the electrodes as well as greater than the refractive index of the boundary glass plates. So the conditions for optical waveguiding are met and an electrically induced waveguide is formed within the LC layer between the electrodes. The difference between the ordinary and extraordinary refractive index determines the numerical aperture of this waveguide and imposes the limitations on its maximum curvature.

With the appropriate design of the electrodes different electrooptical switching devices can be made consisting of several electrically induced optical LC waveguide segments. So electrooptical directional elements, crosspoints and even a complex matrix of such switches can be made (see Fig. 2, 3, 6).

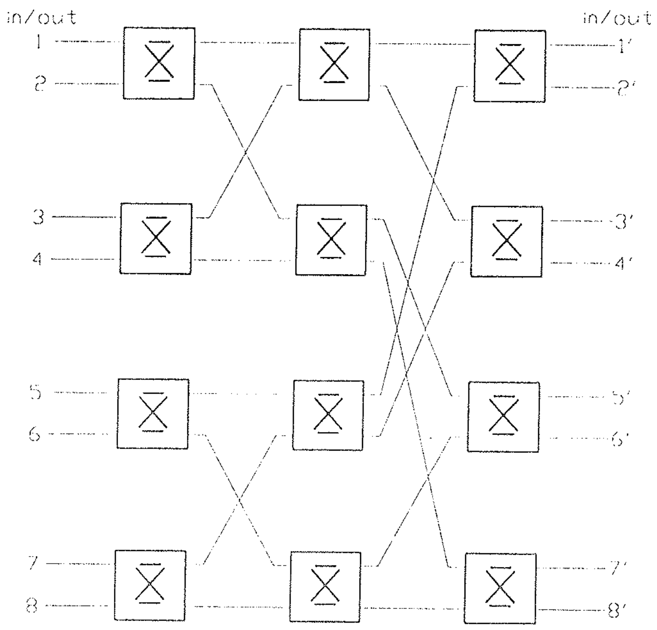


Figure 3: LC matrix 8x8 crossbar switch

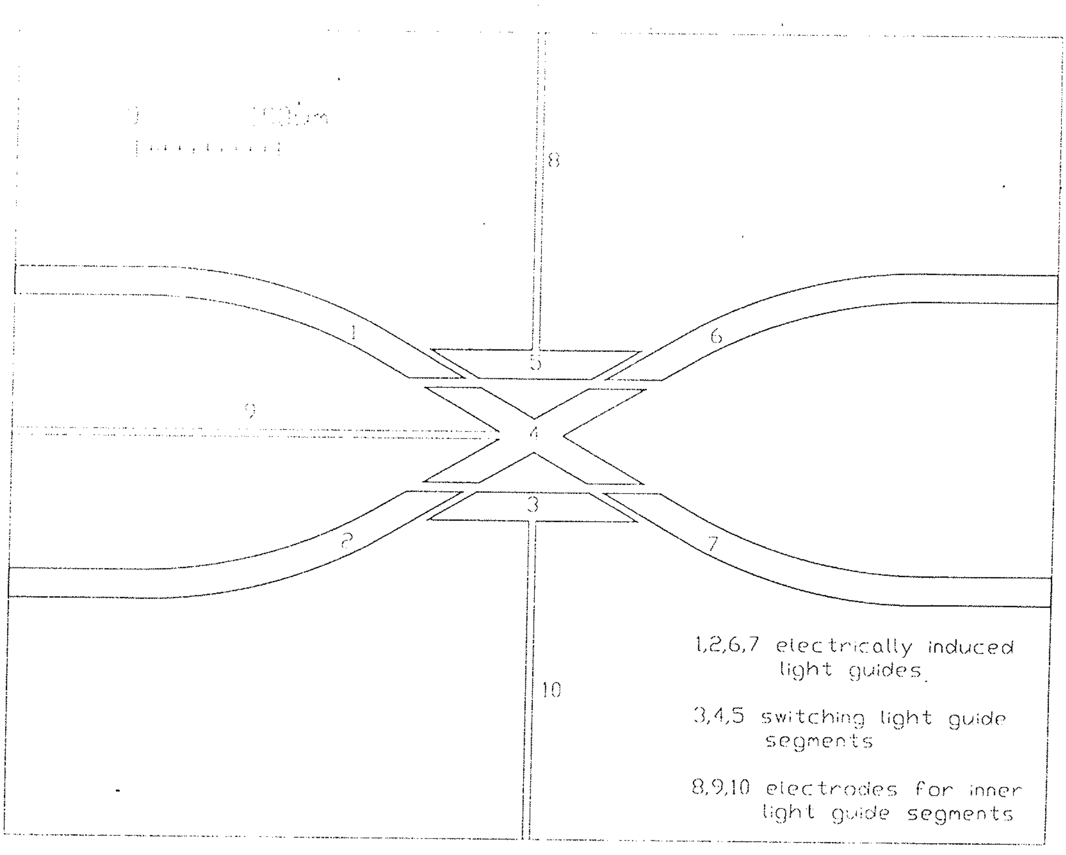


Figure 2: 2x2 Optical cross-bar switch

EXPERIMENTAL

The concept of electrically induced optical waveguide switches was verified by means of different homogeneously aligned LC cells with appropriate electrode configurations. The cells were made in a more less conventional way. ITO covered glass plates were used. After photolithografic formation of the required electrode pattern, the glasses were covered with thin Nylon orienting layer and rubbed to provide for the homogeneous orientation. Ten micron thick cells were made and filled with F.Hoffmann-La Roche nematic liquid crystal ROTN 0530 (n_o=1.513, n_e=1.718). The following electrode patterns were used:

1.Half plane electrodes - determination of the angle of total reflection (see Fig. 4a,b,c)

2.Straight 50-micron wide lines - basic concept of the electrically induced optical waveguide; numerical aperture determination (see Fig. 5)

3.Directional switch (see Fig. 6a,b,c) - evaluation of the switching performances, light losses, etc...

The signal light beam was simulated by a He-Ne laser that was coupled to the LC optical switch by a focusing lens and a precision x-z stage. The traveling of the light signal within the LC optical switch was monitored by observing the light scattered by the order parameter fluctuations under the low amplification microscope by means of the CCD camera coupled to a PC computer.

RESULTS AND DISCUSSIONS

The results of the evaluation of the electrically induced optical waveguide switch concept are shown on figures 4 through 6.

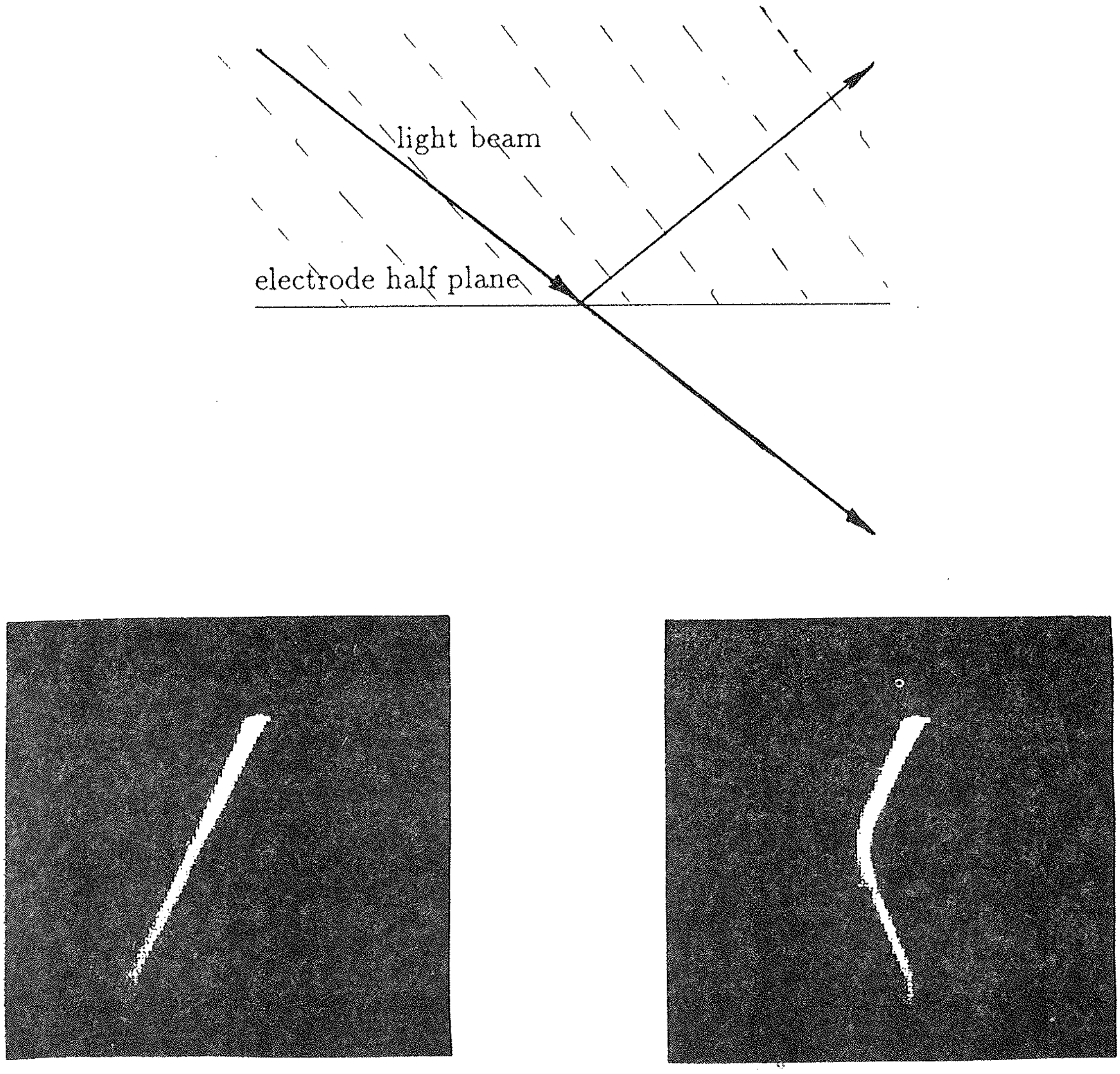


Figure 4: Signal light beam reflection on the electrically induced "refractive index barrier":
a.) Schematic presentation of the light beam and half plane electrodes
b.) Signal light beam propagation without electric field
c.) Signal light beam reflection at the electrically induced refractive index barrier

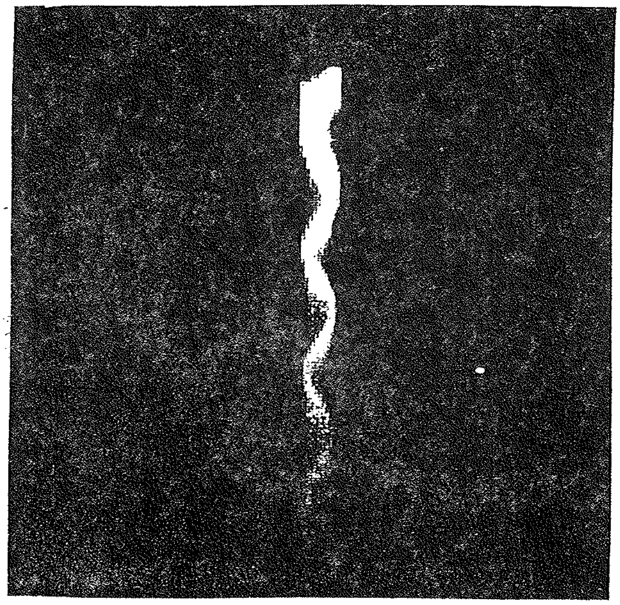


Figure 5: Electrically induced optical waveguide: the signal light beam is traveling along 50 μm wide straight LC waveguide. Since the incidence angle is different from zero but smaller than the one determined by the angle of total reflection, the light beam is reflected back and forth, but stays within the waveguide.

In order to evaluate the limitations and performances of this optical signal switching concept, a detailed computer analysis of the average refractive index variations based on the computer simulation of the nematic director fields within the LC optic waveguide switch was made. The refractive index was calculated for the birefringent medium according to the formula:

$$n_{ef}(\Theta) = \frac{n_e n_o}{\sqrt{n_o^2 + \left(n_e^2 - n_o^2\right)\sin^2\Theta}}. \qquad (1)$$

The nematic director fields were obtained as a result of the numerical solution of the relaxation equation for the director fields:

$$\gamma\frac{\partial}{\partial_t} n_i = k\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}\right) n_i + \Delta\varepsilon E_i \sum_{j=1}^{3} E_j n_j + \lambda n_i\,, \qquad (2)$$

where E is the electric field, Δε dielectric anisotropy and λ is a normalization constant.

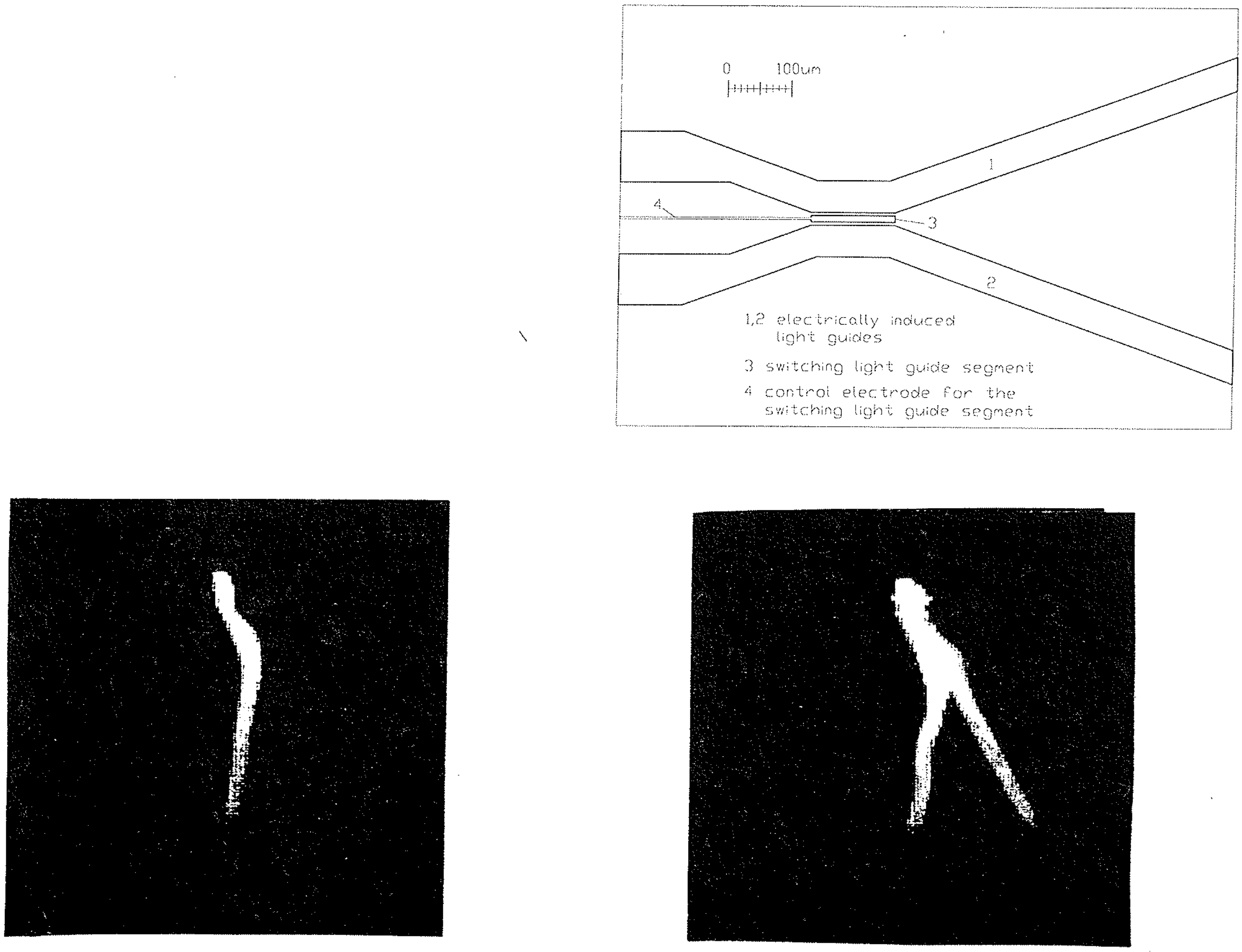


Figure 6: LC optical directional switch:
a.) Schematic presentation of the electrode pattern
b.) Signal light beam propagation with the switching segment turned off
c.) Signal light beam propagation with the switching segment turned on

This relaxation equation was coupled to the equation for the electric field:

$$E= -\mathrm{grad}V;\ \mathrm{div}(\underline{\varepsilon}(x,y)\ \mathrm{grad}V(x,y)) = 0, \qquad (3)$$

where:

$$\underline{\epsilon} = \begin{bmatrix} \epsilon_{\perp} + \Delta\epsilon n_x^2 & \Delta\epsilon n_x n_y \\ \Delta\epsilon n_x n_y & \epsilon_{\perp} + \Delta\epsilon n_x^2 \end{bmatrix}$$

in LC and $\underline{\varepsilon} = \varepsilon_0$ outside.

Assuming strong anchoring conditions at the boundary surface, this relaxation equation was solved numerically using SOR method (Simultaneous over-relaxation)(10). The results for a segment (Fig. 7) between two parallel electrically induced wave guides are shown on the Fig. 8 and Fig. 9.

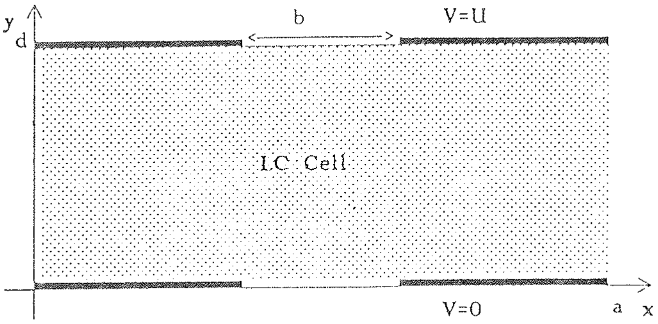


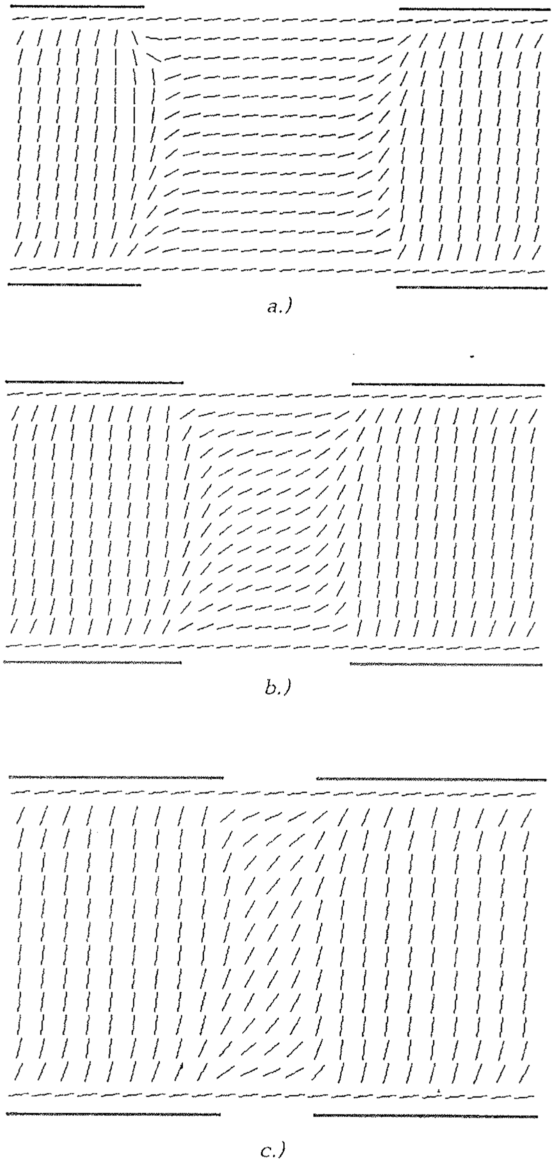
Figure 7: Shematic presentation of the waveguide segment

These results, which are also well confirmed by the experimental data (see Fig 4, 5, 6), clearly show, that:

1. The electrically induced waveguides are well separated if the electrode distances are more than two LC cell gaps apart. In this case one cannot expect much of the crosstalk between them.

2. If the electrodes are closer than one LC cell gap apart, the light signal passes from one waveguide to another almost without any light loss.

3. The switching waveguide segments of the LC light switch have to be wider than two LC cell gaps and should be located closer than one cell gap to assure good switching.


a.)

b.)

c.)

Figure 8: Plot of the director fields for different spacing of the electrodes:
a.) spacing is equal to four LC cell gap
b.) spacing is equal to two LC cell gaps
c.) spacing is equal to one LC cell gaps

The anisotropy of the refractive index (n_e -n_o) in modern nematic LC materials can be as high as ≈ 0.25. This imposes a limit to the maximum curvature of the electrically induced optical waveguides. So an optical crossbar switch (Fig. 2) has to be ≈ 200 μm long. Since order parameter fluctuations in nematic LC are causing relatively strong light scattering (light loss!), the area of the total optical switching array is limited to 600x600 μm. This means that the 8x8 switch array (Fig. 3) is the maximum, that one can expect from the nematic optical switches as described in this paper.

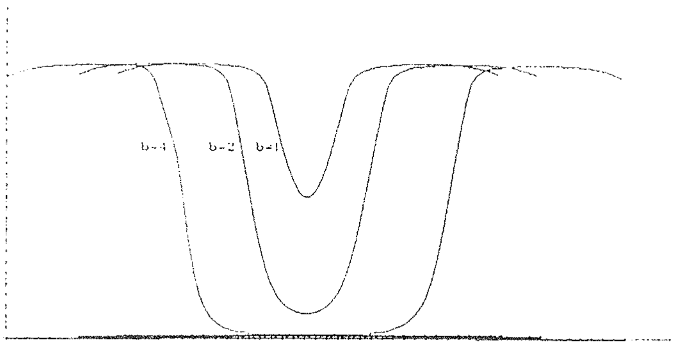


Figure 9: *Plot of the refractive index between the electrodes for different electrode spacings (b): b=1 LC cell gap, b=2 LC cell gaps, b=4 LC cell gaps*

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