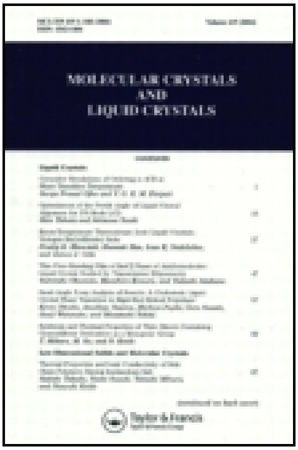


Molecular Crystals and Liquid Crystals

Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/gmcl20

A polarization independent liquid crystal assisted vertical coupler switch

Claudio Gizzi* [a] , Rita Asquini [a] & Antonio D'Alessandro [a]

[a] Dipartimento di Ingegneria Elettronica, Istituto Nazionale per la Fisica della Materia, Università degli Studi di Roma “La Sapienza”, via Eudossiana, Rome, Italy

Version of record first published: 18 Oct 2010

To cite this article: Claudio Gizzi*, Rita Asquini & Antonio D'Alessandro (2004): A polarization independent liquid crystal assisted vertical coupler switch, Molecular Crystals and Liquid Crystals, 421:1, 95-105

To link to this article: http://dx.doi.org/10.1080/15421400490501536

Mol. Cryst. Liq. Cryst., Vol. 421, pp. 95–105, 2004

ISSN: 1542-1406 print/1563-5287 online
DOI: 10.1080/15421400490501536

A POLARIZATION INDEPENDENT LIQUID CRYSTAL ASSISTED VERTICAL COUPLER SWITCH

*Claudio Gizzi**, *Rita Asquini, and Antonio d'Alessandro*
Dipartimento di Ingegneria Elettronica, Università degli Studi di Roma "La Sapienza", Istituto Nazionale per la Fisica della Materia, via Eudossiana, 18-00184 Rome –, Italy

A novel compact cascaded structure suitable for the realization of a 2 × 2 polarization independent integrated optical switch using liquid crystal is reported. The switch consists of a vertical coupler formed by two Ag^+-Na^+ ion-exchanged single-mode channel waveguides diffused in two BK7 glass substrates of a liquid crystal cell. The coupling properties, and thus the switching state (bar or cross), of this structure can be controlled by electrically reorienting the director of the aligned liquid crystal layer. The device was simulated and optimized at $\lambda = 1550\,nm$ by using a beam propagation method algorithm. Calculated crosstalk attenuation and losses of an optimized TE switch with the TE_{00} mode propagating in the input waveguide are 42.5 dB and 0.49 dB respectively with a coupling length of 141 μm. A TM switch, with the TM_{00} propagating mode, exhibits a crosstalk attenuation of 37.7 dB and losses of 1.42 dB with a coupling length of 127 μm. Estimated average crosstalk attenuation and losses of a polarization insensitive cascaded switch are 39.7 dB and 0.93 dB respectively. The evaluated driving voltage magnitude required for the switching operation results below 20 V.

Keywords: ion-exchanged waveguides; liquid crystals; optical switches; polarization independence

INTRODUCTION

Nowadays the terrestrial telecom infrastructure is a mix of physical data channels, with fiber optic cables in the long-haul backbone networks and copper wires used in part of the access networks and "last mile" connections to customers. This structure requires an electrical-optical-electrical conversion of the signal at the nodes of the network and makes

This research has been accomplished within the "GLICROS" INFM project PAIS 2002. The authors thank Dr. Bob Bellini for critically reading the manuscript.
*Corresponding author. Tel.: +39 06 44585436. E-mail: claudio.gizzi@uniroma1.it

the exploitation of the huge bandwidth provided by the optical fibers difficult and expensive. In this context the growing demands of bandwidth for telecommunications justify the considerable research that is devoted to design all-optical routing devices capable of relieving the capacity bottleneck of the conventional network electronic nodes. In fact different technologies, materials and physical phenomena are currently investigated to find out the most suitable ones to build photonic switches such as: thermo-optic switches on either SiO_2/Si [1] or polymers [2], acousto-optic switches on $LiNbO_3$ [3], electro-optic switches on $LiNbO_3$ or polymers [4], Micro-Opto-Electro-Mechanical Systems (MOEMS) on Si [5], bubble switches using SiO_2/Si waveguides [6], liquid crystal spatial light modulators (SLMs), etc.

Among these technologies, liquid crystals (LCs) have been proven to be promising materials for building reconfigurable optical components needed in all-optical networks (AONs) [7]. A wide variety of datacom applications (optical switching [8–10], filtering [11], variable attenuation [12], polarization control [13], etc.) based either on liquid-crystals or liquid-crystalline composite materials (e.g., polymer dispersed liquid crystals) have been investigated and some of them have been commercialized [14,15]. In particular LC optical switches could offer several advantages over other

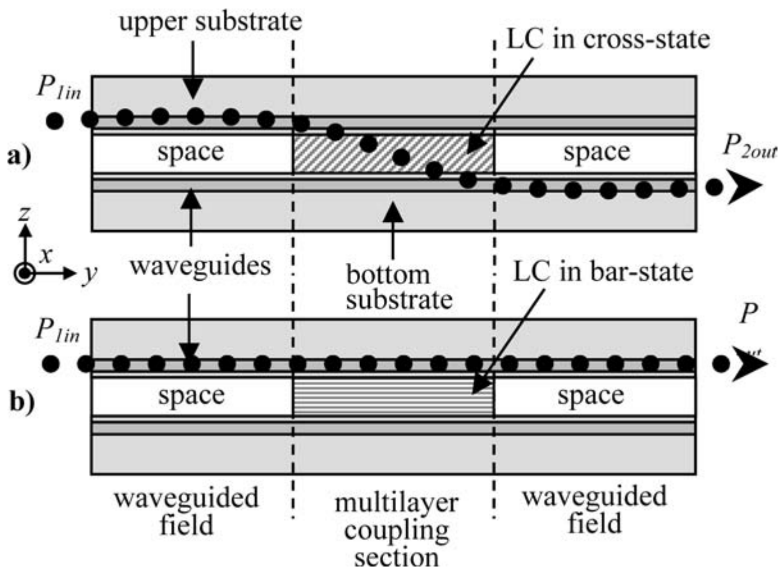


FIGURE 1 Operation concepts of a LC-VC based optical switch. a) cross-state; b) bar-state.

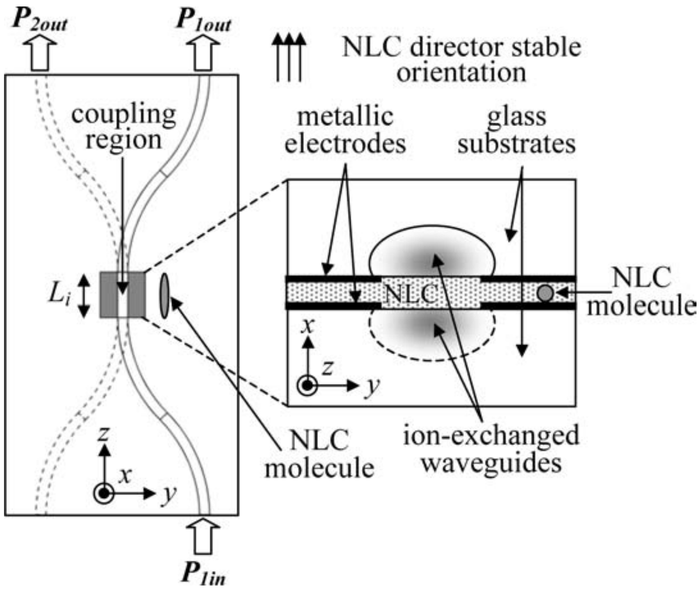


FIGURE 2 Top (left-hand side) and transversal (right-hand side) view of a LC-VC based optical.

technologies: compactness, high birefringence, short switching times (<1 ms) suitable for routing operations, low voltages and power consumption, reliability (no moving parts), versatility (many mixtures and composite materials available), technological know-how and facilities available from the flat panel display industry.

In this paper we report the operation concepts and the design of an integrated polarization independent LC optical switch suitable for all-optical circuit switching applications.

LIQUID CRYSTAL ASSISTED VERTICAL COUPLERS (LC-VCs)

Waveguided vertical couplers are very attractive structures for the fabrication of optical switches satisfying some of the requirements needed in AONs [16,17]. The use of LC in conjunction with such structures can provide them the property of reconfigurability needed for the switching operation as experimentally demonstrated in [18].

Figure 1 reports the operation concepts of a liquid crystal assisted vertical coupler (LC-VC) based switch. Two substrates are assembled, separated by spacers and the gap between them is filled with LC. A vertical

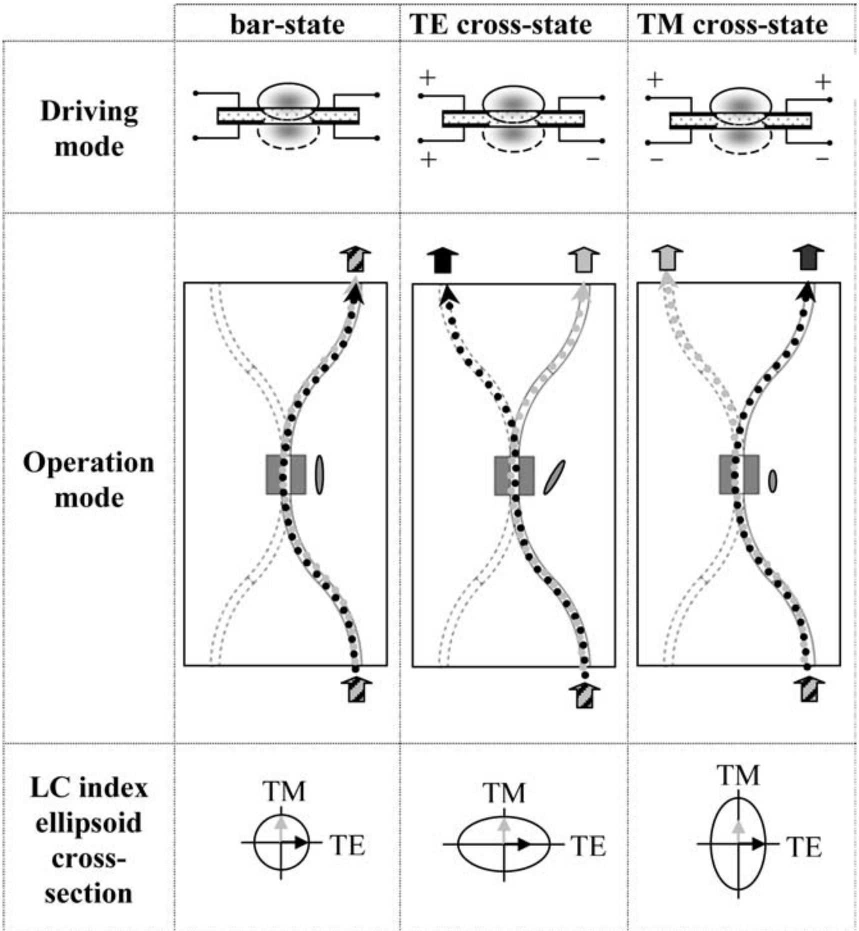


FIGURE 3 Driving, operation modes and corresponding LC index ellipsoid cross-section of the proposed optical switch in bar-state and cross-state for TE and TM polarizations.

coupler is formed by two single-mode waveguides previously diffused onto the internal surfaces of the substrates. The refractive index of the LC can be controlled by means of electrodes (not shown in the figure) in order to enable (cross-state) or to inhibit (bar-state) the coupling between the guided modes of the two waveguides. This device is thus capable of performing an optical switching operation i.e., a transfer of optical power from one channel to another by means of an electrical control signal. The LC refractive index in the two states depends on the director orientation according to the following well-known formulas:

$$n_{LC}^{cross} = \frac{n_e n_o}{\sqrt{n_o^2 \sin^2 \theta_{cross} + n_e^2 \cos^2 \theta_{cross}}}$$
$$n_{LC}^{bar} = \frac{n_e n_o}{\sqrt{n_o^2 \sin^2 \theta_{bar} + n_e^2 \cos^2 \theta_{bar}}} \qquad (1)$$

where θ_{cross}, θ_{bar} are the director angles respect to the z axis and n_{cross}, n_{bar} the refractive indexes of the LC in the two states ($n_{cross} > n_{bar}$).

In Figure 2 the top and transversal structure of a 2×2 LC-VC optical switch made of channel waveguides is reported. Channel waveguides give the switch the ability to be interconnected to form N × N optical switching matrices providing an efficient coupling with optical fibres. The two bent ion-exchanged single-mode channel waveguides overlap to each other in correspondence of the coupling region having length L_i. The LC layer is aligned with the director lying along the z axis direction. Four metallic electrodes are coated beside the waveguides to provide a voltage control of the LC director between them. As shown in the first column of Figure 3, when no voltage is applied both the two polarized components (TE_{00} and TM_{00}) of the input mode experience a "low" refractive index n_o in the coupler gap

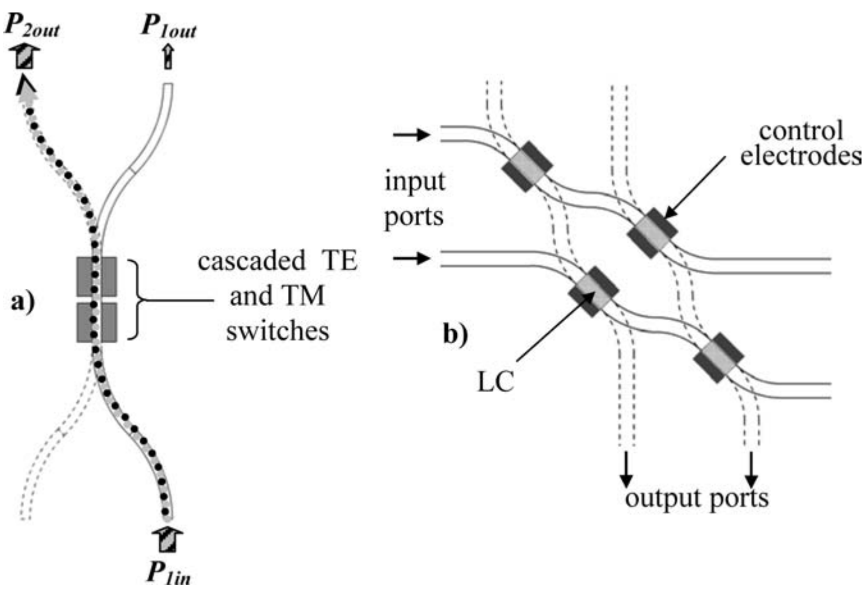


FIGURE 4 a) Cascaded structure of a polarization independent LC-VC based optical switch b) Optical switching matrix fabricated by using LC-VC based switches.

and travel unperturbed along the input waveguide because the coupling with the output one is inhibited. It is also possible to reorient the LC molecules in the *yz* or *xz* plane in order to raise the refractive index experienced by the TE or TM propagating field as sketched in the second and the third column of Figure 3 respectively. These two operation modes can be obtained by applying proper voltage polarities (first row of Fig. 3) to the four electrodes in order to realize a selective coupling of the TE_{00} or TM_{00} mode with the output waveguide. It is clear that in this way the device acts as a waveguided polarization beam-splitter.

A 2×2 polarization independent optical switch can be obtained by cascading the two switching stages (TE and TM) in order to enable the coupling of the two orthogonal polarized modes (Fig. 4a). These structures are suitable for the realization of cross-bar non blocking optical space switching matrices in which LC-VCs are realized and interconnected on the same substrates (Fig. 4b).

Fixed parameters	
waveguide width	$w = 4$ μm
waveguide diffusion lenghts	$h_{diffx} = 1.5$ μm
	$h_{diffy} = 1.5$ μm
waveguide burying depth	$d_{bur} = 1.5$ μm
maximum refractive index gap	$\Delta n_0 = 0.05$ μm
electrodes thickness	$d_{el} = 0.3$ μm

Variable parameters	
LC layer thickness	d_{LC}
angle between LC director and z axis	θ
electrodes separation width	W_{el}
interaction length	L_i

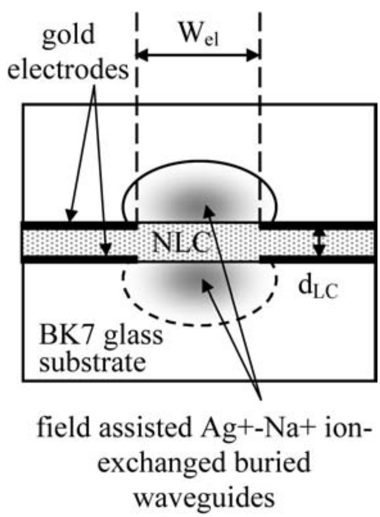


FIGURE 5 Parameters and refractive index distribution of the optical switch structure used in the BPM simulations.

DESIGN AND OPTIMIZATION OF A 2 × 2 LC-VC BASED OPTICAL SWITCH

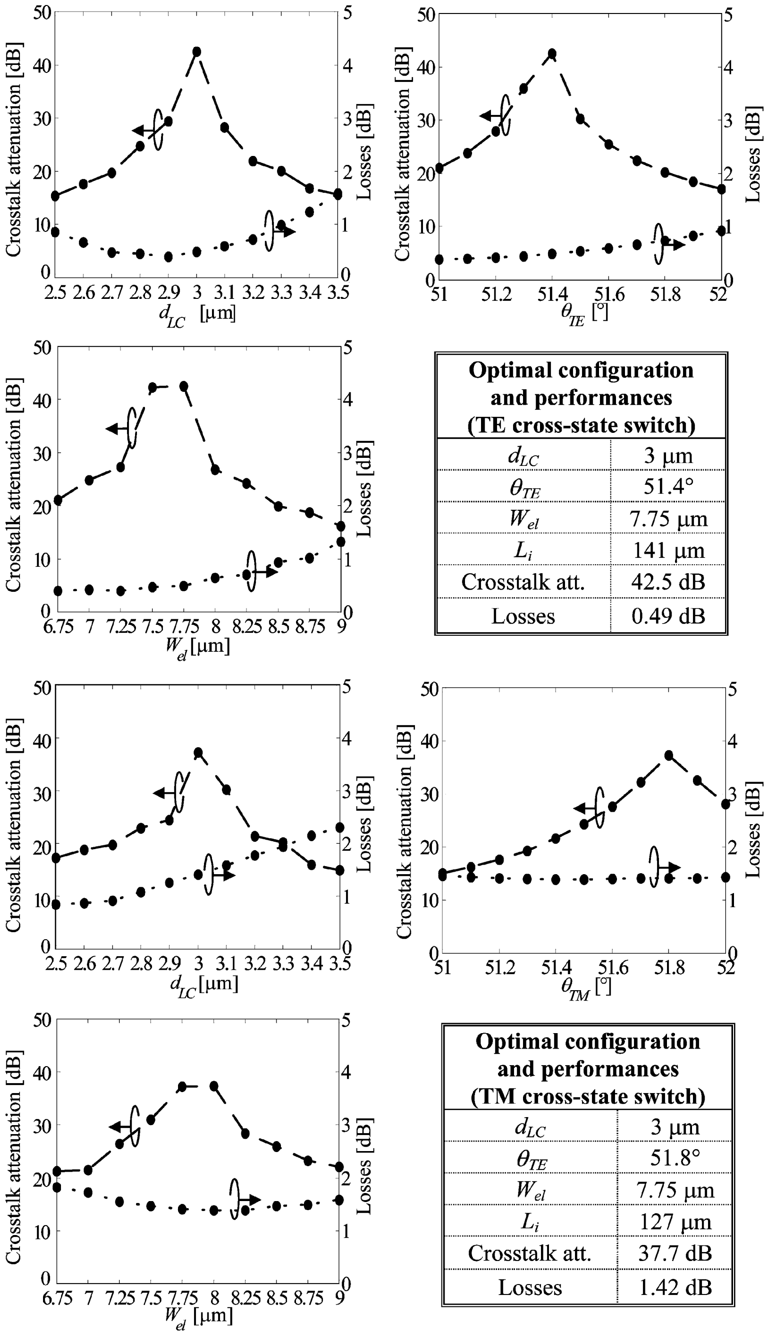
In order to calculate the best performances of the switch, we simulated and optimized the 3D structure of the coupling region in cross-state (Fig. 5) by using a semivectorial BPM (Beam Propagation Method) based software [19]. The LC layer refractive index was considered dependent from the director angle according to Eq. (1). We considered two Ag^+-Na^+ quasi-gaussian shaped buried waveguides diffused in the two BK7 glass substrates by using the field assisted ion-exchange technique [20] having refractive index distribution given by:

$$n(x,y) = n_0 + \Delta n_0 \left\{ \mathrm{erf}\left[\frac{\left(\frac{w}{2}+y\right)}{h_{diffy}}\right] + \mathrm{erf}\left[\frac{\left(\frac{w}{2}-y\right)}{h_{diffy}}\right] \right\} \exp\left[\left(\frac{x-d_{bur}}{h_{diffx}}\right)^2\right] \tag{2}$$

where n_O and Δn_O are the substrate and the waveguide gap refractive indexes, w is the mask opening width, h_{diffx} and h_{diffy} are the tranversal diffusion lengths and d_{bur} is the burying depth whose values assumed in the design are reported in Figure 5. Furthermore we considered an arbitrary NLC mixture, assuming $n_e = 1.6$, $n_o = 1.45$ at 1550 nm. We performed several 3D-BPM simulations ($\lambda = 1550\,\mathrm{nm}$) of the waveguide fundamental mode propagating in the structure varying some other parameters (LC layer thickness, angle θ between LC director and z axis, separation width of the gold electrodes and interaction length). These simulations allowed to fix the variable parameters to obtain the best cross-state performances in terms of crosstalk attenuation and losses:

$$\begin{aligned} \text{Crosstalk att.} &= 10\log_{10}\left(\frac{P_{2out}}{P_{1out}}\right) \\ \text{Losses} &= 10\log_{10}\left(\frac{P_{1in}}{P_{2out}}\right) \end{aligned} \tag{3}$$

Figure 6 reports the optimal variable parameters and performances resulted from the optimization of the TE and TM switches respectively. These performances refer to the propagation of the TE_{00} and TM_{00} fundamental modes in the coupling region. The plots report the crosstalk attenuation and the losses plotted against d_{LC}(LC layer thickness), θ(director angle respect to the z axis) and W_{el} (electrodes separation width) for the optimal switch configuration. The plots relating to the TE switch (Fig. 6) show a peak of the crosstalk attenuation of 42.5 dB and losses of 0.49 dB for $d_{LC} = 3\,\mu\mathrm{m}$, $\theta_{TE} = 51.4$ degrees and $W_{el} = 7.75\,\mu\mathrm{m}$. These three values of d_{LC}, θ_{TE} and W_{el} were then chosen as optimal values.



Optimal configuration and performances (TE cross-state switch)	
d_{LC}	3 μm
θ_{TE}	51.4°
W_{el}	7.75 μm
L_i	141 μm
Crosstalk att.	42.5 dB
Losses	0.49 dB

Optimal configuration and performances (TM cross-state switch)	
d_{LC}	3 μm
θ_{TE}	51.8°
W_{el}	7.75 μm
L_i	127 μm
Crosstalk att.	37.7 dB
Losses	1.42 dB

FIGURE 6 Parameters and sensitivity curves for the TE and TM optimized optical switches.

The plots relating to the TM switch (Fig. 7) have a similar behaviour. The optimal TM switch exhibits crosstalk attenuation of 37.7 dB and losses of 1.42 dB. The two switches are 141 μm (TE) and 127 μm (TM) long respectively.

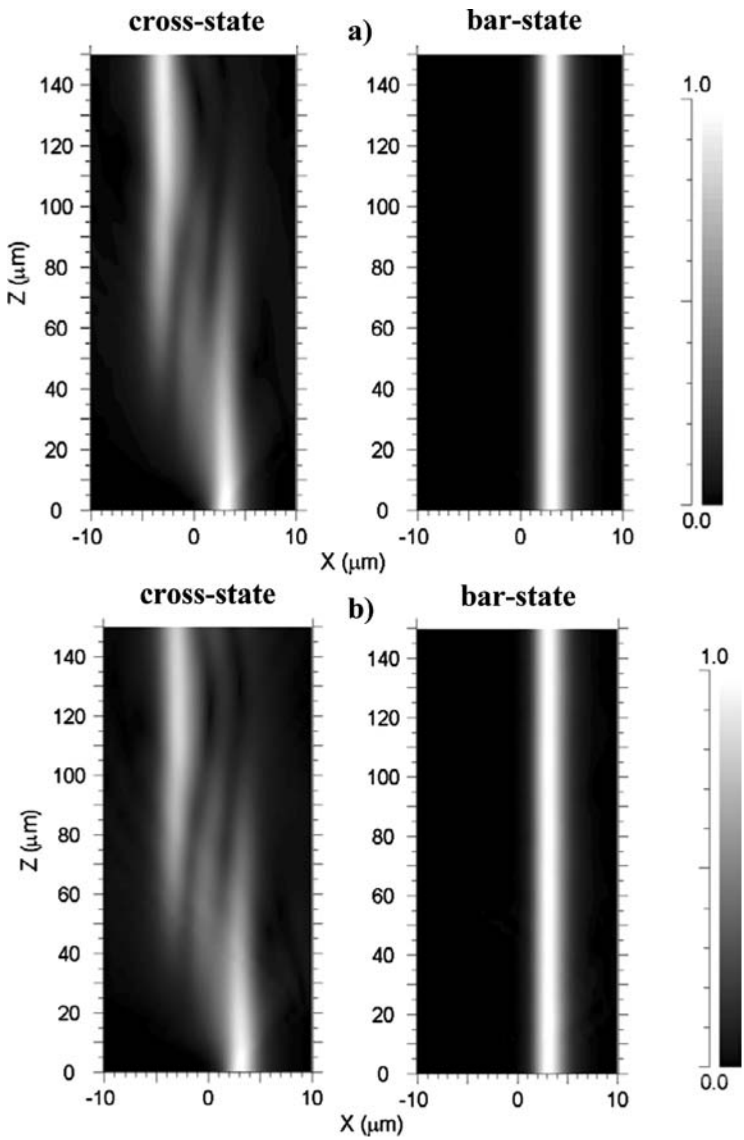


FIGURE 7 a) Contour map of the TE_{00} mode propagating in the TE optimized switch b) TM_{00} mode propagating in the TM optimized switch.

Figures 7a and 7b report the simulation of the propagating fundamental modes in these optimized structures.

From the results of the simulations of the TM and TE optimized switches it is possible to estimate the performances of the polarization independent switch. By considering ideal bar-states we obtained a crosstalk attenuation of 39.7 dB and losses of 0.93 dB. These average values refer to the situation in which the input power P_{1in} is equally divided between the TE_{00} and TM_{00} modes.

We carried out numerical simulations to calculate the director field of the LC crystal layer in the cross-state. This allowed us to evaluate the voltage amplitude required for the switching operation of the optimized device. The numerical algorithm was based on the minimization of the free energy inside the cell [21]. An E7 LC mixture was considered. We found a required driving voltage of about 14 V and 6 V for the TE and TM switches respectively.

CONCLUSIONS

An innovative vertical coupler based structure of a polarization independent LC optical switch to be used for the realization of optical routing components, working at 1550 nm, has been proposed and optimized. The device is realized by using the low-cost technology of liquid crystals and ion-exchanged glass waveguides. The BPM simulations of a 141 μm-long structure working with TE polarized guided optical field show that is possible to achieve very good performances at $\lambda = 1550$ nm in terms of crosstalk attenuation (49.5 dB) and losses (0.49 dB). The TM optimized counterpart (127 μm long) exhibits crosstalk attenuation and losses of 37.7 dB and 1.42 dB respectively. The average performances of a polarization independent switch, obtained by cascading the two optimized structures, resulted in a crosstalk attenuation of 39.7 dB and losses of 0.93 dB. The evaluated driving voltage required for the switching operation using an E7 LC mixture resulted in about 6 V and 14 V for the TE and TM switch respectively.

This switch is well suited for the realization of optical space cross-bar switching matrices in which the LC-VCs are realized and interconnected by using bent waveguides.

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