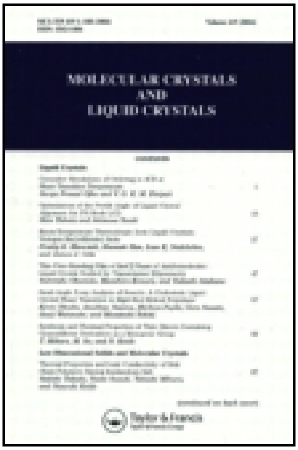

Molecular Crystals and Liquid Crystals
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/gmcl20

Photonics Devices Based on Hybrid Approach Combining Liquid Crystals and Sol-Gel Waveguides

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Version of record first published: 31 Aug 2006

To cite this article: L. Sirleto, G. Coppola, G. C. Righini & G. Abbate (2005): Photonics Devices Based on Hybrid Approach Combining Liquid Crystals and Sol-Gel Waveguides, Molecular Crystals and Liquid Crystals, 429:1, 149-165

To link to this article: http://dx.doi.org/10.1080/15421400590930881

Mol. Cryst. Liq. Cryst., Vol. 429, pp. 149–165, 2005

ISSN: 1542-1406 print/1563-5287 online
DOI: 10.1080/15421400590930881

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A number of integrated electro-optic devices based on hybrid technology combining liquid crystals and sol-gel waveguide are investigated. An integrated electro-optic switch, based on ferroelectric liquid crystal waveguides, is experimentally characterized. Moreover an electro-optical switch and a continuously tunable filter, based on a Bragg grating in planar waveguide with a liquid crystal overlayer, are numerically analyzed. Finally, an optical multimode interference router is theoretically and numerically discussed. The principal advantages of such devices include good performances, low power consumption, low cost and small device size.

Keywords: integrated optics; electro-optic devices; liquid crystal devices; bragg grating; multi-mode interference effect; optical switch; optical tunable filter; routing devices

1. INTRODUCTION

The research on materials for integrated optics is continuously in progress to achieve ever-better performance. In this context, glass-integrated optics has attracted a great interest due to its advantages:

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robustness, appealing optical properties, and compatibility with established silicon manufacturing protocols. Among techniques for fabricating glass integrated optics structures, the sol-gel processing has gained considerable attention in recent years; it is justified by the versatility of process, which allows the production of glasses with largely different physical-chemical properties just by changing the starting solution composition. Thus, it is possible to tune up the refractive index of the produced film over a very large interval; e.g., using silica-titania binary glasses, the refractive index may be varied approximately from 1.5 up to 2.3. This characteristic allows matching the design of the guiding structure to the specific needs of the devices. Other fundamental advantages of the sol-gel process are the relatively low processing temperature, the low cost of production and low-loss connection to single-mode optical fibers [1,2]. The only major disadvantage is the current lack of an operating mechanism for switching and wavelength tuning filtering.

To make compact devices it is desirable to have active control of light over short distances in integrated optical circuits. Liquid crystals have effective electro-optic coefficients orders of magnitude larger than their solid state counterparts [3], due to their anisotropy and large electric-field induced molecular reorientation. These properties, combined with low cost process technology, make liquid crystals interesting as electro-optically active waveguide materials for organic integrated optics, whenever compactness, complexity, and low cost are more important requirements than switching speed. In recent years several authors suggested and demonstrated the possibility of using Liquid Crystals (LC's) materials to control the light propagation in optical guiding devices, as planar waveguides or cylindrical fibers [4–12].

In this paper in order to overcome the lack of mechanism for switching ad filtering in sol-gel waveguide, we propose to combine liquid crystals and sol-gel waveguide. In this approach, electro-optic effects of ferroelectric liquid crystals are used in order to figure out active functions whereas good quality waveguide are realised by sol-gel method.

2. ELECTRO-OPTICAL SWITCHES BASED ON FERROELECTRIC LIQUID CRYSTALS WAVEGUIDES

In order to test electro-optic switch, a particular waveguide structure consisting of a three stage device, having a thin FLC film middle stage and two glass waveguides as other stages, has been designed and realized (Fig. 1). For the fabrication of the electro-optical devices we start with soda-lime glass substrates previously coated with ITO films. First the planar dielectric waveguide was fabricated on the top of the ITO

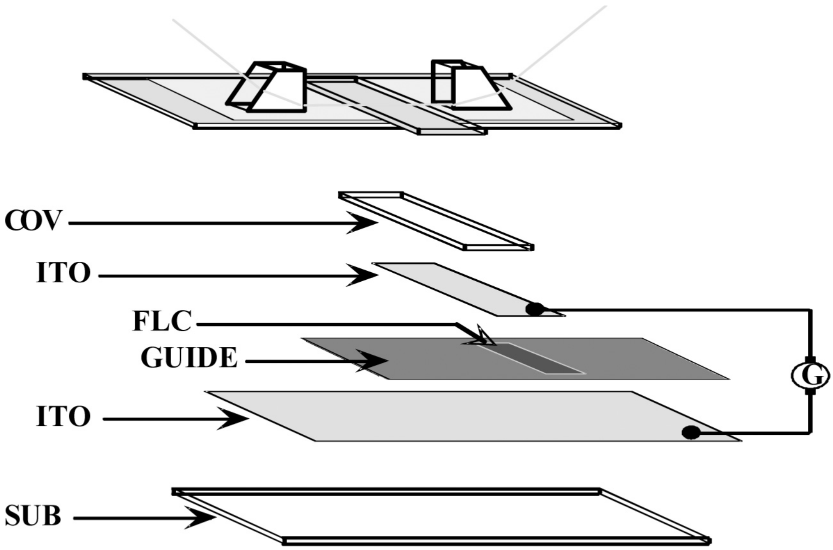

FIGURE 1 Schematic representation of the realized planar waveguide. COV: cover; SUB: substrate; ITO: indium tin oxide; FLC: ferroelectric liquid crystal; G: voltage generator.

layer, and then a rectangular cell with depth equal to the core thickness is etched in it. The cell is filled with FLC and then covered with a glass plate having the same refractive index as the waveguide substrate. In order to apply the electric field conducting film of ITO was deposited also onto the cover of the cell. In this way one obtains a planar waveguide having a FLC as guiding medium in the central section.

The planar waveguide was fabricated by using sol-gel films, which have been prepared starting from an alcoholic solution (ethanol) of tetraethoxsilane (TEOS) and titanium butilate with 70%/30% relative molar content as precursor of silica and titania, respectively. The films were deposited by dip-coating on soda lime glass substrate in a controlled temperature (30°C) and humidity (30% relative) environment. They were subsequently densified by annealing at 500°C.

The optical characterization of the sample was made first by using the usual dark-line arrangement (i.e. laser light coupling into the guide by an isosceles prism) and later on by loss measurements through the detection of out plane scattered light [13]. Of course the multilayer structure including the ITO film can be significantly affected by the properties of ITO itself: a non negligible decrease of the sample performances can be ascribed mainly to ITO refractive index, which is high (effect on the waveguide modal structure) and may be complex (effect on the waveguide losses). For this reason, when depositing waveguide layers we also used a reference substrate (without ITO coating), in order to compare the guiding properties of the two structures. We checked that usual ITO films of 200 nm thickness drastically changed the guiding properties of multilayer while thinner films of 20 nm have almost negligible effects on the modal structure. Thus, only the latter coatings were used for the realisation of our electro-optical devices [6,7]. The resulting planar waveguide is a step-index layer whose thickness is 0.9 μm, the refractive index of the core in the glass sections is 1.601 and 1.58 at the wavelengths 514 nm and 632.8 nm, respectively. Loss measurements indicated a sufficiently good quality of sol-gel waveguides onto uncoated substrates (with loss below 0.8 dB/cm), while higher losses (up to 2 dB/cm) are caused by the presence of the ITO layer, partly due to its intrinsic absorption.

It is worth noting that inn a uniaxial slab, like a uniformly aligned liquid crystal film, a pure phase modulation of the incident light is obtained only for the extraordinary wave if the optic axis moves in the incidence plane. Generally, in bulk ferroelectric liquid crystals structures an applied electric field moves the optic axis out of the polarization plane, resulting in a polarization modulation rather than a phase modulation. On the contrary, in our geometry, the molecules will be aligned parallel to the confining glass waveguide (book-shelf geometry), so a pure phase modulation is achieved for TE modes, the polarization state being maintained. In fact, applying an electric field between the two ITO electrodes, the LC molecules tilt in the waveguide plane and so does the optic axis of the LC. As a consequence, the FLC refractive index for the case of TE mode is given by:

$$\frac{1}{n_{\mathrm{FLC}}^2(\alpha)} = \frac{\cos^2\alpha}{n_{\mathrm{o}}^2} + \frac{\sin^2\alpha}{n_{\mathrm{e}}^2} \tag{1}$$

where α is the angle between the optic axis of the FLC and the direction of propagation of the light beam in the glass waveguide.

The integrated electro-optic switch has been realized by filling the basin dug out in the glass waveguide with the FLC: SCE10 from BDH. The following values for the ordinary index $n_o = 1.50$ and for the extraordinary index $n_e = 1.67$ have been measured. The alignment of the FLC, planar with molecules parallel to TE polarization, was obtained by evaporating SiO_x at oblique incidence. The cover has been realised depositing a thin film of glass by sputtering on top of a glass substrate, covered with a layer of ITO. The refractive index of sputtering film $n_c = 1.55$ has been chosen in order to obtain intermediate

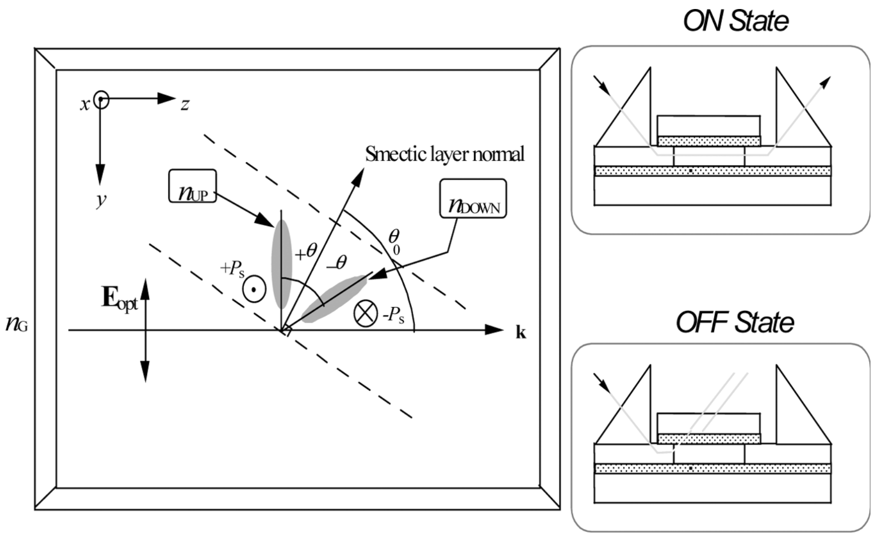

FIGURE 2 Operating principle of switch with FLC as guiding film. k propagation direction of light; E_{opt} field direction of TE mode; θ_0 angle between the smectic layer normal and the direction of propagation; $+\theta$ angle between the smectic layer normal and initial optic axis orientation of FLC; $-\theta$ angle between the smectic layer normal and switched optic axis orientation of FLC; +Ps spontaneous polarization due to initial optic axis orientation of FLC; −Ps spontaneous polarization reversed by the application of applied voltage.

value between the two principal values of refractive index of the utilised FLC.

The optical switching mechanism is the following: the realized alignment means that when switching the FLC between the UP-state and the DOWN-state a TE-polarized light beam traveling in the z-direction sees two different refractive indices. A schematic of this process is shown in Figure 2. In the UP-state, being $\alpha = 90^{\circ}$ the angle between the optic axis of the FLC and the direction of propagation of the light beam in the glass waveguide, the refractive index for TE mode is purely extraordinary ($n_{up} = n_{FLC}(\alpha = 90^{\circ}) = n_e = 1.67 > n_s$ and n_c, where n_c and n_s are the indices of cladding and substrate, respectively, therefore a guided mode is obtained. In the DOWN-state the director is tilted ($2\theta = 60^{\circ}$) with respect to the polarization direction of the light, giving the following refractive index of FLC (seen by Te mode): $n_{down} = n_{FLC}(\alpha = 90^{\circ} - 2\theta) = 1.54 < n_c = 1.55$. At this point the guiding condition breaks down, the light leaks out through the cover and the light power detected after decoupling suddenly drops. The FLC stage acts as a shutter between the two glass stages.

We have realized such an ON-OFF device and the modulation of the output light for the first mode and the second mode is observed while driving the device by a square wave applied voltage. The rise and fall time has been estimated to be $\sim 120\,\mu s$ using a voltage of $Vpp = 45\,V$ at frequency $\nu = 500\,Hz$ in the first waveguide. It is worth noting that the response time could be lowered more than one order of magnitude simply by choosing a faster FLC material.

The extinction ratio between the ON state and the OFF state is 5:1. The very low transmission of the device, a few per cent, and the consequent low extinction ratio are due to two main reasons. The most important is the large mismatch of the refractive indices between the film of the glass waveguide and the FLC at the two interfaces, $\Delta n \approx 0.07$, which causes a large fraction of the input energy to be reflected at the interfaces. The second is the thickness of the FLC waveguide, which actually is larger than designed, i.e. larger than the glass waveguide core and this causes the mode profiles in the two adjacent stages not to overlap properly, yielding a reduced energy transfer.

In our experiment two three-stage structures having the same characteristics were used in the experiment: in the former the alignment of the FLC was obtained onto the cover and the substrate and in the latter only the cover was treated. We obtain the important result that the alignment can be achieved only by treating the cover glass plate. This means that the initial director orientation, hence the refractive index in the ON state, can be changed by simply rotating the cover plate. This is a very important simplification in the sample preparation procedure, allowing one to determine the smectic layer orientation with respect to the polarization vector of the TE-polarized light for optimization purposes, as well as allowing sample reuse in different experiments [6].

3. ELECTRO-OPTICAL SWITCH AND CONTINUOUSLY TUNABLE FILTER BASED ON A BRAGG GRATING IN PLANAR WAVEGUIDE WITH A LIQUID CRYSTAL OVERLAYER

Although intensity-dependent devices can work reasonably well, they experience some disadvantages. For example, in order to get good accuracy and stability these devices need some form of referencing to avoid errors arising from source intensity variations, variable loss in coupling and sensitivity changes in detectors. Some clever

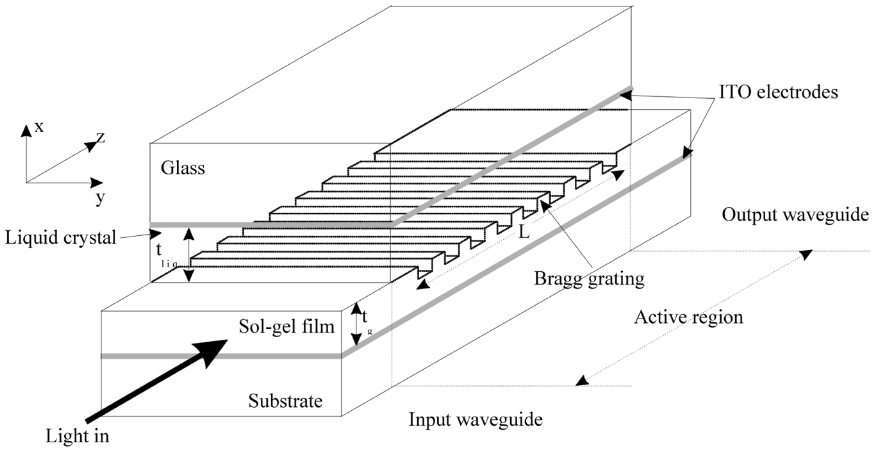

FIGURE 3 Schematic view of the device. t_{liq} = liquid crystal overlayer thickness; t_g = waveguide thickness; L = Bragg grating length.

techniques have been developed to provide referencing but these add to the complexity and cost.

In this paragraph design and analysis of electro-optical devices based on a Bragg grating integrated on a glass waveguide employing LC as a cover, are presented. The proposed devices have a common structure, which is schematically shown in Figure 3. The refractive indices of the ITO layer and of the glass substrate are $n_{ITO} = 1.9$ and $n_{sub} = 1.516$, respectively. The thickness of the ITO layer is $t_{ITO} = 35\,\text{nm}$, thin enough to have a negligible effects on the modal behavior of the structure. The guiding film could be obtained by using a sol-gel deposition on the thin ITO electrode, whereas a Bragg grating corresponds to the active region. The Bragg grating can be realized on the guiding waveguide surface by means of a holographic exposure followed by a reactive ion etching [14]. In the active region, a LC layer is employed as a cover of the grating. Above this LC a glass layer, coated with an Ito film, is situated (see Fig. 3). Thus the two ITO layers constitute the electrodes where the electric field that induces the refractive index variation of the liquid crystal is applied.

The Bragg grating (BG) exhibits a behavior equivalent to a wavelength-selective mirror, the optical equivalent of a notch filter. Its reflectivity is maximum at the so-called Bragg's wavelength λ_B, which depends both on the physical characteristics of the guiding structure and on the geometrical characteristics of the Bragg grating, i.e.:

$$\lambda_B = 2n_{\text{eff}}\Lambda \qquad (2)$$

where n_{eff} is the effective refractive index of the guided mode and Λ is the grating period. The spectral behavior can be analyzed utilizing a transfer matrix approach [15].

According to Eq. (2), any change of the effective refractive index involves a change in the spectral response of the devices. In our devices, the Bragg grating is over-layered with a liquid crystal film (Fig. 3) and its molecular reorientation can be induced applying an electrical field between the two ITO electrodes. This reorientation implies a change of the refractive index of the cover of the active region and consequently a change of the effective refractive index of the guided mode. According to equation (2), this induces a variation of the Bragg wavelength. Thus in our structures it is possible to vary the Bragg mirror trasmittivity by means of the electro-optic effect in smectic liquid crystals. Moreover, two different configurations can be obtained in dependence of the particular liquid crystal employed as cover of the grating.

The first is an integrated electro-optic switch. In fact, combining a *smectic* C^* liquid crystal [16–18] and the selective properties of the Bragg grating, a variation of the device transmittivity can be achieved. In this kind of devices, the switching of the light intensity is obtained by a shift of the Bragg grating spectral response. Indeed, the device works as a switchable notch filter in the optical domain. This feature allows overcoming the typical problems of intensity dependent devices.

In the latter configuration, the cover of the Bragg grating is a *smectic* A^* [19,21] which enables continuous modulation of the extraordinary refractive index of the LC itself and consequently a continuous variation of the selective properties of devices. This device, therefore, behaves as a tunable notch filter in the optical domain.

3.1. Integrated Electro-Optical Switch

To project a switch with a large contrast between the OFF and the ON state, the demand for a large frequency shift of Bragg's wavelength must be satisfied. In fact, the greater the Bragg wavelength shift is, the smaller is the overlap between the spectral responses of the two states; as a consequence, a high contrast ratio is achievable. The large shift can be obtained choosing a LC with a high birefringence. For these reasons, among the available smectic C^*, the 3M2CP00B Smectic C^* [from Hoechst catalog] has been chosen and the behavior of the switch was simulated considering it as the cover of the active region. This liquid crystal presents an ordinary $n_o = 1.49$ and an extraordinary $n_e = 1.60$ at $\lambda = 632.8\,\text{nm}$. The planar alignment is supposed to have the direction of the grating steps as easy axis (Fig. 4), so

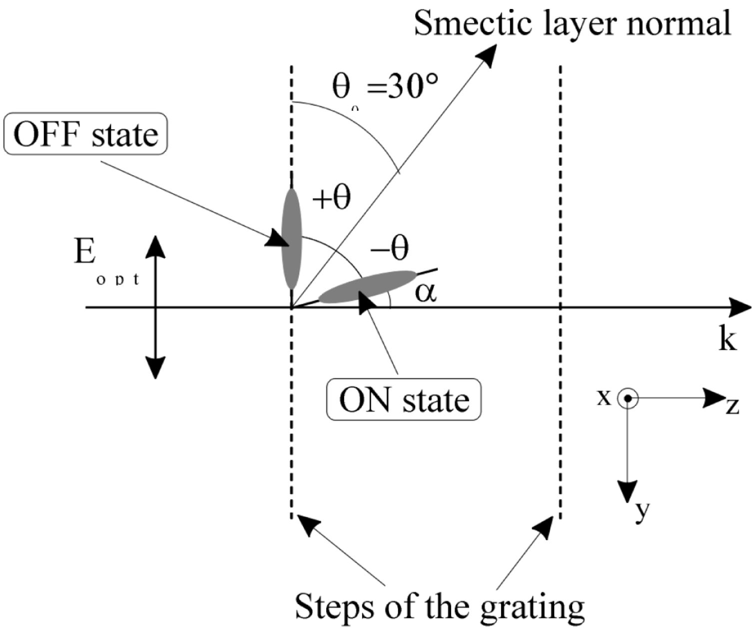

FIGURE 4 Operating principle of the optical switch. k propagation direction of light; E_{opt} field direction of TE mode; $+\theta$ angle between the smectic layer normal and initial optic axis orientation of FLC; $-\theta$ angle between the smectic layer normal and FLC switched optic axis orientation; α angle between the switched optic axis orientation of FLC and the propagation direction.

the smectic layer normal is inclined with respect to the y axis by an angle equal to the tilt angle of the LC ($\theta = 30°$, according to the specifications of the data sheet). The waveguide is characterized by a thickness $t_g = 0.3\,\mu m$ and a refractive index n_{film} of 1.650 at the wavelength $\lambda = 632.8\,nm$.

For TE light propagating through the device, and no applied field, the light polarization is parallel to the optic axis of the liquid crystal over-layer, so that the refractive index perceived by TE mode is purely extraordinary. In this geometry, designing a Bragg grating with a length of $L = 500\,\mu m$, a period Λ of about 200 nm and a depth $a = 50\,nm$, the spectral response of the device, reported in Figure 5 (solid line), is obtained. This state can be considered the OFF state for our switch; in fact a very low transmittivity is obtained at the wavelength λ_0 of the laser radiation and consequently the output light intensity is very low. On application of the electric field with a proper sign, the liquid crystal switches to the other stable state, in which the

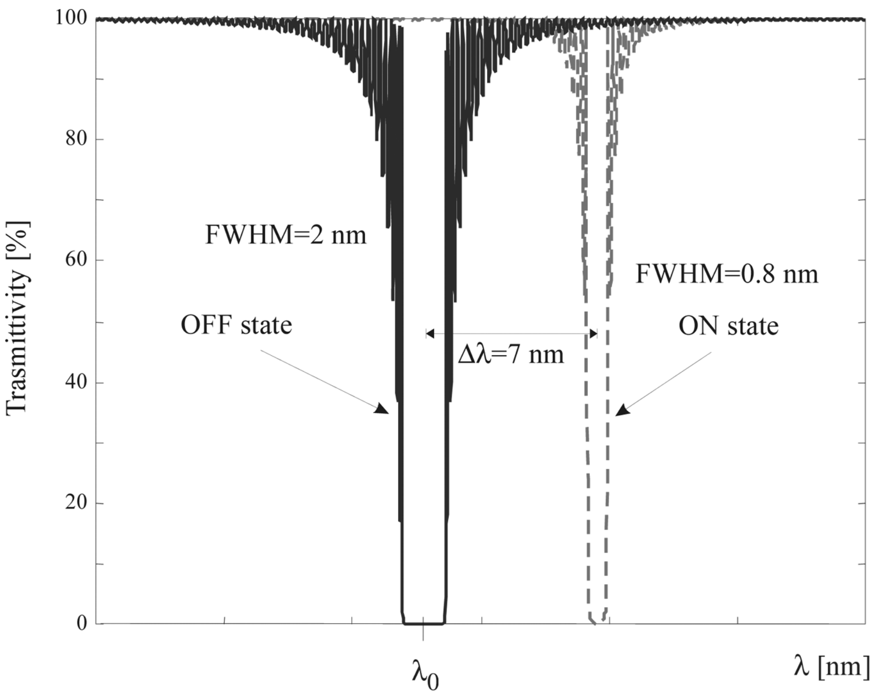

FIGURE 5 Spectral response of the switch in the OFF state (solid line) and in the ON state (dashed line). $\Delta\lambda$ is the frequency shift due to the application of the electrical field. (See COLOR PLATE XII)

optic axis is tilted by an angle of 2θ with respect to the polarization direction of the light (ON state in Fig. 5) On sign reversal of the applied field, the liquid crystal is brought again in its initial configuration, corresponding to the OFF state.

In the ON state $\alpha = 90^\circ - 2\theta$, while in the OFF state $\alpha = 90^\circ$. The spectral response relative to the ON state is shown in Figure 5 (dashed line). It is obviously considered the ON state, because high transmittivity is obtained at the laser wavelength λ_0 and the TE polarized light beam can pass through the device. Thus, if a laser beam at $\lambda = 632.8\,\text{nm}$ is coupled into this device, the optical output would be in its OFF state (i.e. almost zero output intensity signal), or in its ON state, i.e. maximum output intensity signal, according to the sign of the applied field.

The bandwidth (Figure 5) in the OFF is about 2 nm, so no highly coherent sources are required for the right working of the optical switch. Note that the contraction of the bandwidth in the ON state at 0.8 nm, and a frequency shift ($\Delta\lambda = 7$ nm) due to the application of the electrical field, guarantee a negligible overlap factor between the spectral response of the two states, i.e., a very low theoretical crosstalk between channels in an eventual optical communication application. This allows to obtain an optical switch with a large contrast between the OFF and the ON state [10].

3.2. Continuously Tunable Filter

To prove our device to be suitable for a wavelength division multiplexing (WDM) application, the previous liquid crystal material is substituted by a commercially available BDH764E [from BDH catalog], having the ordinary and the extraordinary refractive index respectively equal to $n_o = 1.50$ and $n_e = 1.65$ at the wavelength $\lambda = 1.55\,\mu m$ and a maximum value of the tilt angle $\theta_{max} = 10°$ [22]. Planar alignment with the smectic layer normal tilted of an angle θ_{max} with respect to y direction is assumed (free state, in Fig. 6).

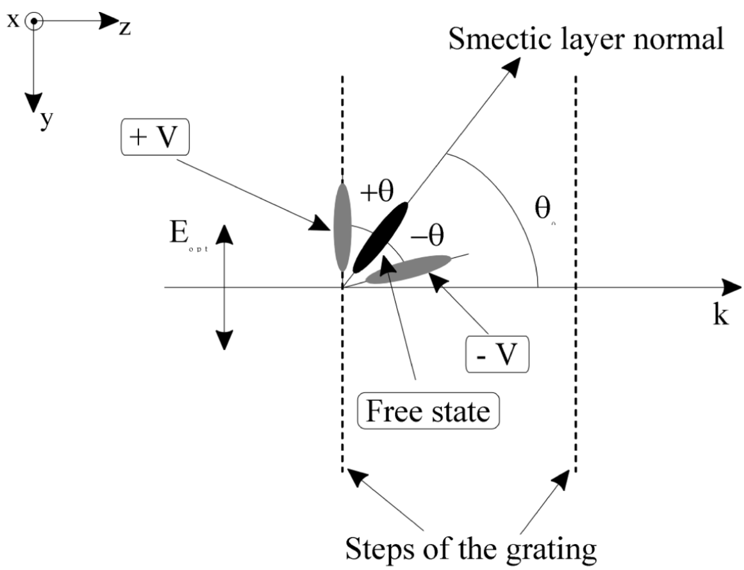

FIGURE 6 Operating principle of the tunable optical filter. k propagation direction of light; E_{opt} field direction of TE mode; $+\theta_o$ angle between the smectic layer normal and propagation direction of light; $+\theta$ angle between the smectic layer normal and optic axis orientation of FLC obtained applying a voltage +V; $-\theta$ angle between the smectic layer normal and optic axis orientation of FLC obtained applying a voltage −V.

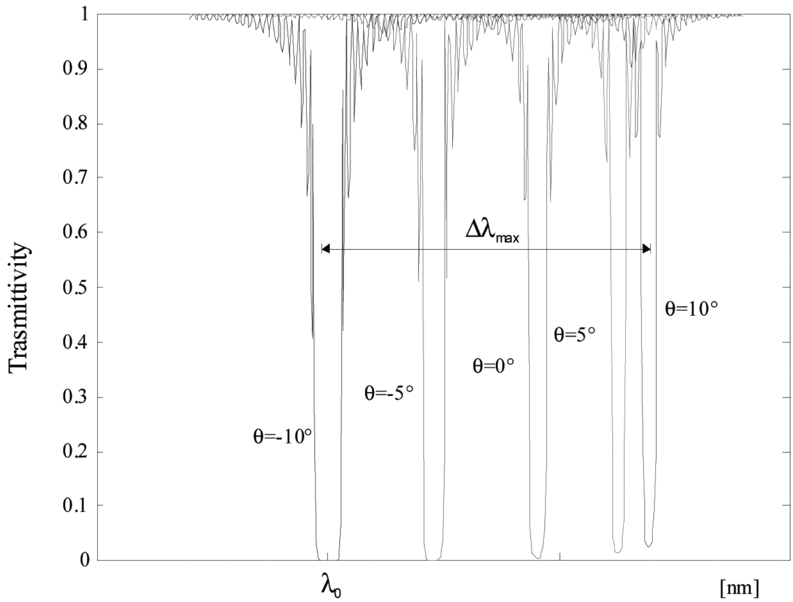

FIGURE 7 Spectral response of the tunable filter for different tilt angle. (See COLOR PLATE XIII)

To guarantee the single mode behavior, the thickness and the refractive index of guiding layer are 1.4 μm and 1.67 respectively; moreover, the simulated Bragg grating has a length of 5000 μm and a depth of 50 nm. According to Eq. (2), the period of the grating is $\Lambda = 471$ nm, which permits to use less demanding technological processes compared to the already-mentioned devices working in the visible range.

An applied voltage, continuously varying between V_{max} and $-V_{max}$ allows to obtain a tilt angle between $+\theta_{max}$ and $-\theta_{max}$, hence a continuous variation of the refractive index of the liquid crystal over-layer on top of the BG is achieved according to Eq. (2). This variation implies a continuous shift of the Bragg reflectivity peak. Figure 7 reports the variation of the grating spectral response for five tilt angles. This kind of device enables us to select a specific wavelength between those falling in the range covered by $\Delta\lambda$; in other words, if a broad band optical signal is coupled into the device, a selected narrow band signal can be extracted the device's output. This is the essential feature required to realize a tunable wavelength filter for the wavelength division multiplexing (WDM) technique at the wavelength range of optical communication systems ($\lambda = 1.55$ μm) [10].

4. OPTICAL MULTIMODE INTERFERENCE ROUTER BASED ON A LIQUID CRYSTAL WAVEGUIDE

The operation of optical MMI devices is based on the self-imaging principle. It can be stated as follows: *Self-imaging is a property of multimode waveguide by which an input field profile is reproduced in single or multiple images at periodic intervals along the propagation direction of the guide* [23–26].

The device may be built in silica-titania glass, by using a sol-gel deposition on a glass substrate (See Figure 8). The refractive index of glass substrate is $n_{sub} = 1.516$. It is covered with an indium tin oxide (ITO) layer. The thickness and the refractive index of the Ito layer are $t_{ITO} = 20\,\text{nm}$ and $n_{ITO} = 1.9$, respectively. The refractive index of guiding film is $n_{film} = 1.670$ at the wavelength $\lambda = 1.55\,\mu\text{m}$. On the surface of the active region a thick layer of smetic A^* liquid crystal is placed. This in turn is covered by a glass substrate, coated with ITO layer. Finally, the output Y-branch is realized by two S-bend waveguides, which are able to select one of the two output states of the active region. Both the waveguides of the branch are designed to sustain only the fundamental mode.

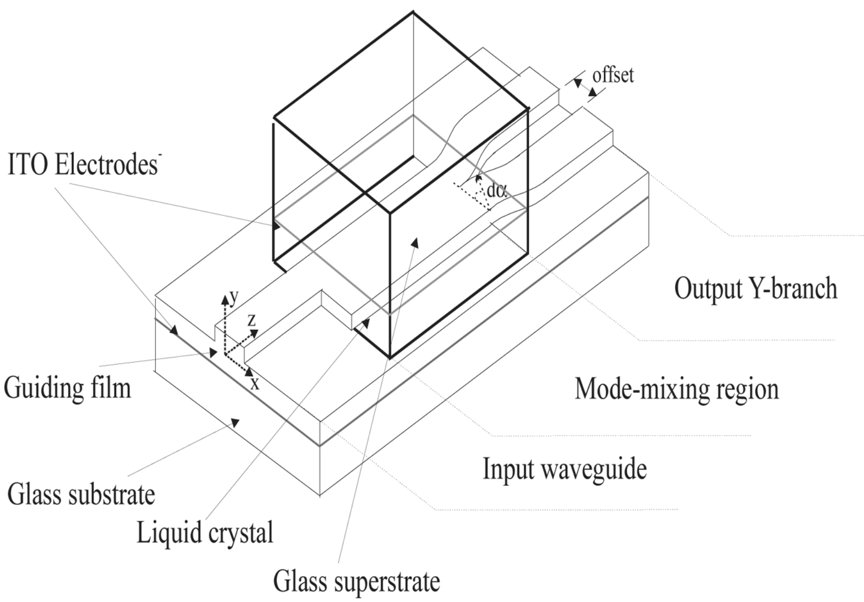

FIGURE 8 Schematic top view of the device.

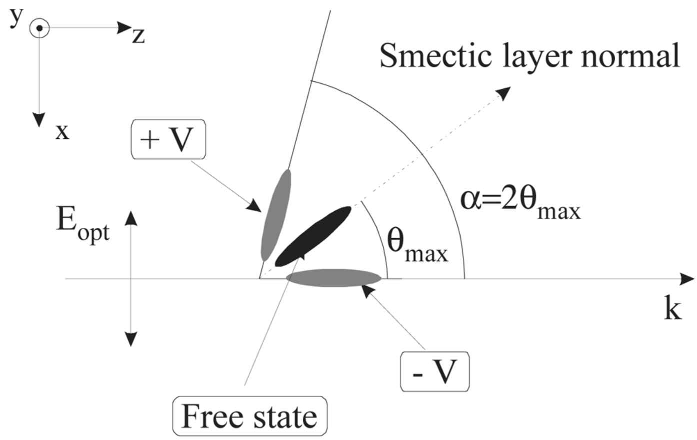

FIGURE 9 Operating principle of the LC/router.

The working principle of device is as follows: the fundamental (the quasi TE_{00}) mode coming from the input waveguide excites both the fundamental mode and the first higher order mode in the active region, namely the quasi TE_{00} and TE_{01} modes, respectively. These two modes spatially interfere upon propagation in the active region, leading to a localized output power emerging on one of the two output sides (*self-imaging principle*). The length of the active region is designed to ensure that an additional π phase shift, between the two propagating modes in the active region, allows steering the light on the other side of the output. The desired phase shift is reached by means the molecular reorientation of liquid crystals over-layer, induced by an electrical field. The change in the refractive index of the liquid crystal implies a change of the propagating characteristics (effective refractive indices) both of the fundamental mode and of first higher mode travelling in the active region. So the light can be steering between the two outputs sides of the Y- branch, simply switching the sign of electrical field applied on the liquid crystal.

To simulate the router working, a commercially available *smectic* A^* liquid crystal (BDH764E [from BDH catalog]) has been considered as cover of the active region [22]. A planar alignment with the smectic normal layer tilted of an angle equal to θ_{max} with respect to z direction (free state in Fig. 9) has been supposed. By applying an electric field, the LC molecules tilt in the plane of waveguide (the x-z plane as depicted in Fig. 9) letting the angle between the average molecular optic axis and the incident beam direction θ to change. In this way, being the molecules being aligned parallel to the confining glass waveguide and

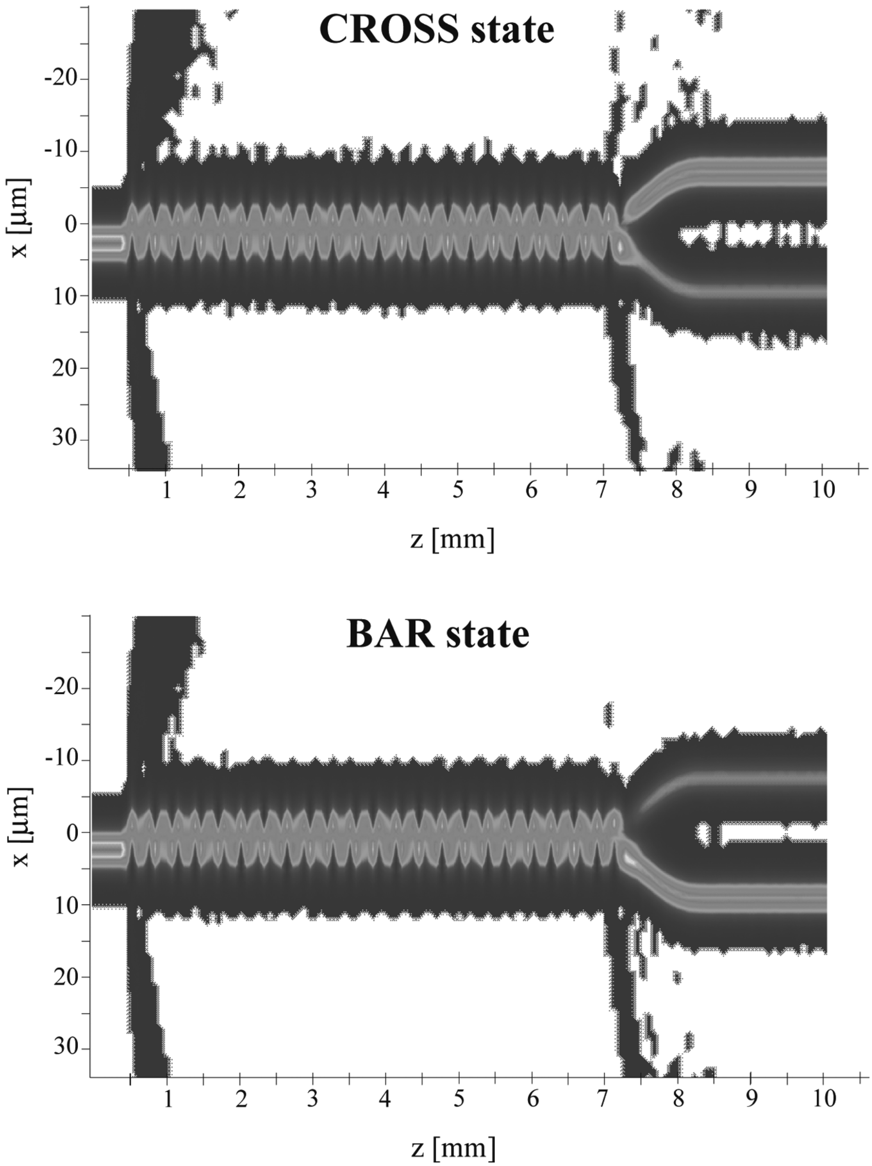

FIGURE 10 Beam propagation inside the device in *cross* and *bar* state. (See COLOR PLATE XIV)

referring to a TE mode as input field, the electro-optic effect turns into a modulation of the LC extraordinary refractive index and the output polarization is still linear. In particular, by applying the following voltage values: V_{max} and $-V_{max}$, tilt angle $+V_{max}$ and $-\theta_{max}$ are achieved. As a consequence the following values for the refractive index of the liquid crystal over-layer, according to Eq. (1), are obtained: $n_{LC}(\alpha = 0) = n_o$ or $n_{LC}(\alpha = 2 \cdot \theta_{max})$, depending on the device working condition (the *cross* and the *bar* state respectively). The length L needed to guarantee the additional π shift, in order to steer the light on the other side of the output Y-branch, is of about 7200 µm. In Figure 10 the spatially interference upon propagation in the active region is shown in both cross and bar states. For the proposed configuration a crosstalk of -12.0 dB has been estimated both in *CROSS* and *BAR* state [11].

CONCLUSIONS

In this paper, a number of integrated electro-optic devices based on hybrid technology combining liquid crystals and sol-gel waveguide are investigated.

An integrated electro-optic switches based on ferroelectric liquid crystal waveguides is experimentally characterized. Even if its performances are not so good, a numbers of interesting indications about devices optimization and practical applications are provided. Moreover numerical results regarding electro-optical switch, continuously tunable filter and optical multimode interference router, prove promising performances.

Some interesting extensions are also possible, for example joining the structures of first proposed switch and of devices based on Bragg grating, a Fabry-Perot cavity could be figure out. Moreover the 1×2 structure could be extended to $1 \times N$, in fact a smectic A^* enables a continuous reorientation so numbers of intermediate position could be considered in order to figure out N out ports.

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