

Electro-optic guided-wave router using nematic liquid crystals

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An original approach is illustrated and analyzed for the realization of an electro-optic waveguide router to be fabricated by standard liquid crystal technology. The proposed device enables complete switching with modulation voltages as small as 120 mV.

Keywords: guided-wave optics, liquid crystals, electro-optic devices, switching.

Introduction

In recent years a significantly large research activity has been undertaken aiming at the realization of passive integrated optics components for telecommunication networks and internet systems encompassing wavelength division multiplexing protocols [1]. While semiconductors, glass and lithium niobate are the most employed in this field, polymers and liquid crystals (LC) are promising solutions for a wide range of specific problems, and are actually used in thermo-optic and electro-optic elements [2]. Even more than polymers, liquid crystals are rather well known and offer such advantages as a mature technology, low cost, low driving voltages, low losses and wide spectral transparency from the visible to the near infrared [3-4].

In this Communication, we propose and investigate an optical routing/switching element consisting of a bi-modal liquid-crystal waveguide which can be electro-optically controlled and has two outstanding features: (i) its guiding properties depend and rely on the application of an external voltage; (ii) the structure can be driven to route an optical signal towards either of two outputs using a small voltage modulation. The device is based on a version of the well-known Y-junction, as described in [5]: from a two-mode guiding region, two identical mono-mode output branches depart with a small but finite angular separation. When both modes are injected at the input, the corresponding power will couple to one or another output channel depending on their relative phase, as sketched in Fig. 1. When employing an electro-optic dielectric, however, the relative phase and the corresponding interference between the two lowest-order eigenmodes in the bi-modal region can be controlled by varying the applied voltage: one of the two output channels can be preferentially excited as the resulting pattern will exhibit a maximum on the upper or lower portion of the transverse section (Fig. 1). A phase change of π will result, therefore, in complete switching or rerouting of the optical signal.

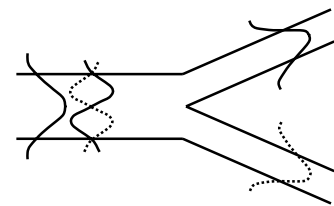


Fig. 1. Sketch of the field distribution due to two superimposed TM guided modes in a 1x2 optical switch encompassing an output Y-junction.

To this extent, we propose to employ electro-optic nematic liquid crystals, in the configuration represented in Fig. 2. A thin layer of nematic liquid crystal is sandwiched between fused quartz substrates with anchoring (Teflon, silica or Nylon) films to enforce a planar molecular orientation, i. e. one with LC molecules parallel to the interfaces. In such ordered form, a nematic LC is a

positive uniaxial ($n_z > n_y$ with reference to Fig. 2). Transparent electrodes, e. g. indium tin oxide films, can be pre-deposited on the same plates to permit the application of an external voltage.

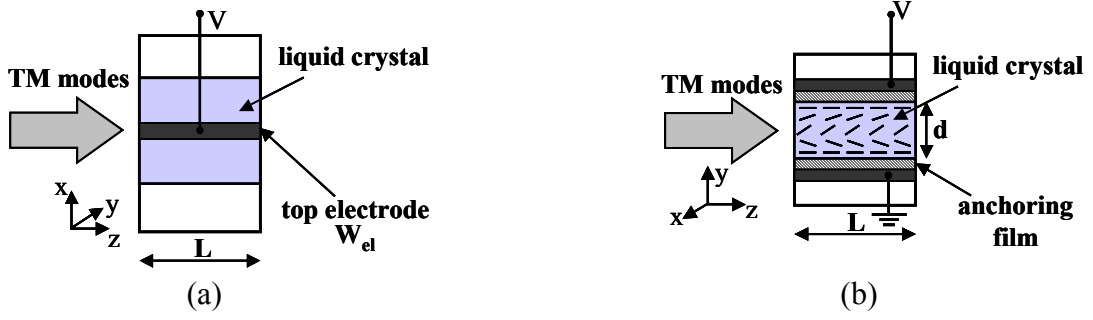


Fig. 2. Top (a) and side (b) views of the proposed nematic LC geometry .

With reference to the input portion of the proposed switching device (Fig. 1), the electrodes can be patterned in such a way (Fig. 2a) that a channel waveguide is formed in the LC medium only upon the application of a suitable voltage across the cell thickness d . The resulting electrostatic field, in fact, will induce dipoles and a torque on the elongated LC organic molecules, giving rise to their angular reorientation in the principal plane containing their axes and the dominant field component, i. e. the plane (y, z) in Fig. 2b. A voltage-controlled channel waveguide can then be obtained, with degree of confinement and cutoff depending on the external bias at each optical wavelength. In particular, the electrode width can be tailored to allow two-mode guidance in a given wavelength range of operation. Moreover, a slight change in voltage will perturb the phase velocity (i.e., the eigenvalue or effective index) of each of the two eigenmodes, leading to an overall relative phase shift between them upon propagation along z . For two modes interfering in $z=L$ and producing an electric field profile with a maximum on one side of the 2-mode channel, a phase-change of π will switch the output to the other side.

Device design and voltage evaluation

In order to estimate the voltage required to obtain the correct tilt of the LC director $\mathbf{n} = (0, \sin \vartheta, \cos \vartheta)$ in our positive uniaxial and so define a bi-dimensional waveguide, we consider an applied electric field along y axis (Fig. 2b). ϑ is the angle between the director and the z axis. With no voltage applied to the cell, the director $\mathbf{n}(y)$ is uniformly parallel to the z axis ($\vartheta = 0$), because of initial anchoring at top and bottom interfaces (Fig. 2b). A nonzero voltage can then force the elongated LC molecules to re-align and redistribute with their major axis closer to y in order to reduce the field-dipole interaction energy. While such reorientation will not be uniform across the thickness d of the cell due to the anchorage at the boundaries, an index gradient will be induced with a maximum value in $y=d/2$ ($\vartheta = \vartheta_m$), i. e., in the middle of the cell.

The director redistribution comes from elastic and electrostatic energy balance. The voltage needed to induce a particular angle ϑ_m in the middle of the LC cell can be derived by minimizing the total free energy [6-7]:

$$U = \int_0^d (U_{EL} + \Delta U_{EM}) dy \quad (1)$$

with U_{EL} the elastic energy density

$$U_{EL} = \frac{1}{2} \left(k_1 \cos^2 \vartheta + k_3 \sin^2 \vartheta \right) \left(\frac{d\vartheta}{dy} \right)^2 \quad (2)$$

and ΔU_{EM} the change of the electrostatic energy due to the reorientation of the molecular director:

$$\Delta U_{EM} = \frac{1}{2} \frac{D_y^2}{\left(\varepsilon_{\parallel} \sin^2 \vartheta + \varepsilon_{\perp} \cos^2 \vartheta\right)} - \frac{1}{2} \frac{D_y^2}{\varepsilon_{\perp}} \quad (3)$$

D_y being the y component of the displacement field vector, constant throughout the cell. k_1 and k_3 are splay and bend elastic constants of the considered LC, respectively, while ε_{\parallel} and ε_{\perp} are the dielectric constants parallel and perpendicular to \mathbf{n} , respectively. The latter determine the anisotropy $\Delta\varepsilon = \varepsilon_{\parallel} - \varepsilon_{\perp}$. By minimizing the total free energy and imposing boundary conditions with \mathbf{n} parallel to the quartz surfaces in $y=0$ and $y=d$,

$$\begin{aligned} \delta U &= 0 \\ \vartheta(0) &= \vartheta(d) = 0 \end{aligned} \quad (4)$$

we finally get the voltage able to induce the desired director angle ϑ_m :

$$V_{\vartheta_m} = V_{th} \frac{2}{\pi} \int_0^{\pi/2} \left(\frac{\sqrt{(1 + \kappa\eta^2 \sin^2 \psi)(1 + \gamma\eta^2)}}{\sqrt{(1 - \eta^2 \sin^2 \psi)(1 + \gamma\eta^2 \sin^2 \psi)}} \right) d\psi \quad (5)$$

with:

$$\eta = \sin \vartheta_m, \quad \gamma = \frac{\varepsilon_{\parallel} - \varepsilon_{\perp}}{\varepsilon_{\perp}}, \quad \kappa = \frac{k_3 - k_1}{k_1}$$

and

$$V_{th} = \pi \frac{\sqrt{k_1}}{\sqrt{(\varepsilon_{\parallel} - \varepsilon_{\perp}) \varepsilon_0}}$$

the threshold voltage (Freedericks value) to have a nonzero mid-layer tilt angle ϑ_m . The variable of integration in (5) accounts of the connection between ϑ_m and $\vartheta(y)$, i. e. $\sin \vartheta(y) = \sin \vartheta_m \cdot \sin \psi$, and the integral (5) can be numerically evaluated to yield the voltage required for the desired refractive index n_{LC} and index increase to define a channel waveguide along z .

In our calculations we considered the case of a standard nematic LC, the mixture E7. For the latter material, $k_1=12 \cdot 10^{-12}$ N, $k_3=19.5 \cdot 10^{-12}$ N, $\varepsilon_{\parallel}=19.6$, $\varepsilon_{\perp}=5.1$, $V_{th}=0.96$ V, $\gamma=2.843$ and $\kappa=0.625$. From a standard analysis of dielectric waveguides with a graded index profile, for a thickness $d=1$ μm and width $W_{el}=3$ μm and operating at $\lambda=1550$ nm, a channel waveguide supporting the two lowest-order quasi-TM modes requires a maximum index increase $\Delta n=0.0493$ in $y=d/2$. The corresponding eigenvalues are $n_{eff0}=1.4860$ for TM_{00} and $n_{eff1}=1.4571$ for TM_{01} . This provides $\vartheta_m = 33^\circ$ for $n_{LC} \cong 1.5493$ and, from (5), $V_{33^\circ}=1.257$ V.

Since a change of ϑ_m from 33° to 40° yields $n_{LC} \cong 1.5701$ at $V_{40^\circ}=1.376$ V and the new effective indices $n_{eff0}=1.5007$ and $n_{eff1}=1.4685$, for propagation over a device length $L=233$ μm such variation gives rise to a relative phase shift $\Delta\Phi=\pi$, i.e. what is required to switch output port.

The BPM (Beam Propagation Method) propagation in a 3D structure (3 μm along x , 1 μm along y and 233 μm along z) leads to single-mode light confinement along y and bimodal along x , as shown in Fig. 3. The three cases refer to $\vartheta_m=33^\circ$ in (a), $\vartheta_m=40^\circ$ in (b) and $\vartheta_m=0^\circ$ in (c). It is apparent the peak shift in $z=L$ from the left (Fig. 3a) to the right (Fig. 3b), corresponding to a

voltage variation of 119 mV only. The case of zero applied voltage (Fig.3c) shows the absence of lateral confinement along x: the input beam freely diffracts in the (x,z) plane.

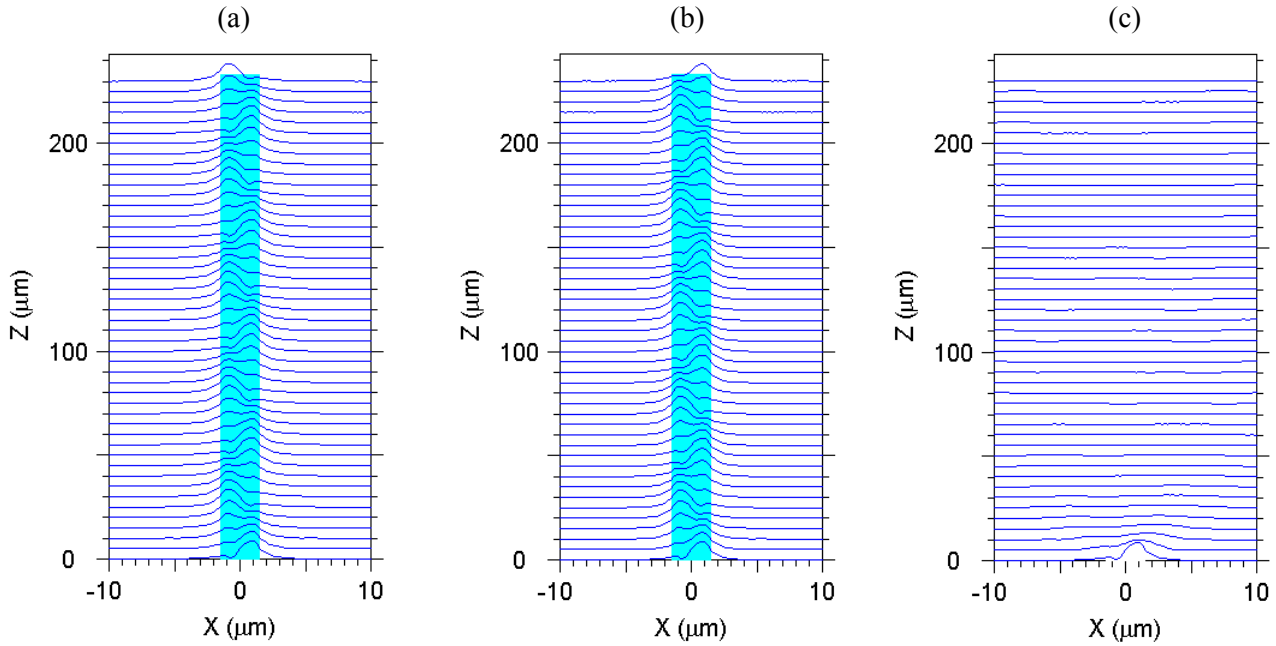


Fig. 3. Propagation of the electric field along z for a device length $L = 233 \mu\text{m}$ and $\vartheta_m = 33^\circ$ (a), $\vartheta_m = 40^\circ$ (b) and $\vartheta_m = 0^\circ$ (c). The shaded area in (a) and (b) indicates the LC area reoriented by the bias.

The output light intensity $z = L$ is plotted in Fig. 4, to emphasize the lateral shift of the peak on either side of the waveguide output facet.

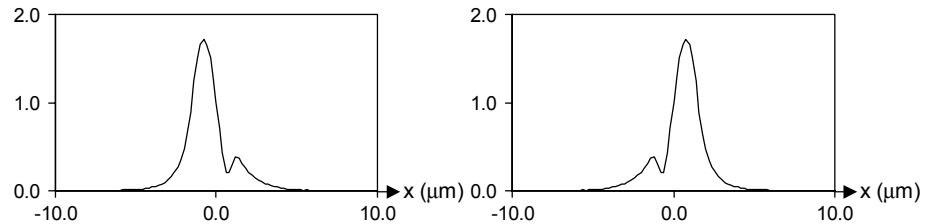


Fig. 4. Output intensity (arbitrary units) versus x for applied voltages differing by 119 mV.

Conclusions

A novel liquid crystal channel waveguide structure has been proposed and analyzed. In this electro-optically controlled device, an applied voltage lower than 1.5 V can provide lateral confinement of the signal, whereas its increase of about 119 mV can switch the light output between two different positions. The investigated geometry allows the realization of a versatile and fully electro-optic Y-junction switch, which can be optimized for operation at any wavelength of interest by acting on the bias.

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