Distributed feedback grating in liquid crystal waveguide: a novel approach

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Abstract: We design a distributed feedback guided-wave device in liquid crystals, utilizing a simple geometry based on electro-optic molecular reorientation in uniaxial nematics. We numerically test the structure and demonstrate an effective Bragg reflector with voltage-tunable resonance.

OCIS codes: (160.3710) Liquid crystals; (130.2790) Guided waves.

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1. Introduction

Nematic liquid crystals (NLC) consist of dielectrically anisotropic molecules in a fluid state; under proper anchoring conditions at the boundaries of a cell, these elongated rod-like molecules tend to align to one another by elastic links, exhibiting a degree of orientational order while lacking positional order. In such state NLC behave as an optically birefringent uniaxial with optic axis along the mean molecular alignment, often described by the director field $\hat{n}(x,y,z)$. [1-2] NLC are transparent from the ultraviolet to the mid-infrared, with very high optical damage; many of them exhibit low refractive indices and large electro-optic response. For the latter reasons, a number of configurations have been proposed and/or demonstrated for the realization of guided-wave devices for optical signal processing, including waveguides, junctions, switches, filters and modulators,[3-12] as well as several configurations for all-optical phenomena and light routing via spatial solitons.[13-18] Particular relevance in this scenario have acquired voltage-tunable geometries which can be adjusted to specific wavelengths in wavelength division (de)multiplexing schemes for optical communications; among them Bragg resonant structures. The latter class of devices, especially in waveguide formats, is prone to the realization of tunable/switchable filters, passive and active cavities, optically bistable gates as well as slow-light elements for storage or nonlinear effects. [19-22]

In this paper we investigate a novel electro-optic distributed feedback waveguide (DFBW) will full adjustability in degree of confinement and Bragg resonance wavelength by an externally applied voltage. We propose and numerically test the operation of this DFBW, demonstrating its operation as wavelength-selective reflector and tunable drop-multiplexer.

2. Basic Physics

In NLC, the bulk alignment of the molecules is not perfectly compatible with the constraints imposed by external fields (low-frequency or static), the latter able to exert a torque through interaction with the electrically induced-dipoles. In practical cases, the consequent change in alignment gives rise to a large electro-optic response in the plane(s) where the director is free to rotate.

Defining $\Delta\varepsilon_{LF} = \varepsilon_{\parallel}^{LF} - \varepsilon_{\perp}^{LF}$ the dielectric anisotropy at low (LF) frequencies, $n_{\parallel}$ and $n_{\perp}$ the refractive indices for field components parallel and orthogonal to $\hat{n}$, respectively, based on the Frank-Oseen model the Gibbs free energy density in NLC media is:[17, 23]

$$F_d = \frac{1}{2}K_{11}(\nabla\cdot\hat{n})^2 + \frac{1}{2}K_{22}(\hat{n}\cdot\nabla\times\hat{n})^2 + \frac{1}{2}K_{33}(\hat{n}\times\nabla\times\hat{n})^2 + F_{field} \quad (1)$$

The first three terms on the RHS of (1) are the energies associated with splay, twist and bend distortions of the molecules, with K_{11}, K_{22}, K_{33} the elastic Frank coefficients and

$$F_{field} = -\frac{1}{2}\langle\mathbf{D}\cdot\mathbf{E}\rangle_{time} = -\varepsilon_0\frac{1}{2}\Delta\varepsilon_{LF}(\hat{n}\cdot\mathbf{E}_{LF})^2 + g \quad (2)$$

the field-matter interaction. We consider the action of a quasi-static electric field of RMS value $\boldsymbol{E}_{LF}$ and g is a director-independent term related to the electrostatic energy density. For positive uniaxials $\Delta\varepsilon_{LF}>0$ and energy minimization implies that the electric torque reorients $\hat{n}$ towards the polarization of the applied field while counteracted by a restoring force owing to the distortion energy. Such mechanism is responsible for a conspicuous electro-optic increase in the extraordinary-wave refractive index $n_e(\theta)$, with $n_e(\theta)^2 = 1/([\cos(\theta)/n_\perp]^2 + [\sin(\theta)/n_\parallel]^2)$ and θ the angle between $\hat{n}$ and the wave vector $\boldsymbol{k}$ of an extraordinarily (*e*-) polarized optical wave or guided-mode (in the presence of transverse confinement).

The electro-optic director distortion in a coordinate system *xyz* can be modeled by means of a standard variational approach in elevation θ and azimuth ρ of $\hat{n}(x,y,z) \equiv [\sin\vartheta, \cos\vartheta\cos\rho, \cos\vartheta\sin\rho]^T$, writing the Fréchet derivatives of total energy F_d:

$$\begin{cases} \dfrac{\partial F_d}{\partial \vartheta} - \displaystyle\sum_{j\in(x,y,z)} \dfrac{\partial}{\partial j}\dfrac{\partial F_d}{\partial \vartheta/\partial j} = 0 \\ \dfrac{\partial F_d}{\partial \rho} - \displaystyle\sum_{j\in(x,y,z)} \dfrac{\partial}{\partial j}\dfrac{\partial F_d}{\partial \rho/\partial j} = 0 \end{cases} \tag{3}$$

and coupling system (3) with the Poisson equation to account for the applied electric-field distribution. Most NLC are positive uniaxials ($n_\parallel > n_\perp$) with birefringence $n_\parallel - n_\perp \geq 0.2$. In bulk, optical plane eigenwaves with wavevector $\boldsymbol{k}||\boldsymbol{z}$, i. e. $\boldsymbol{E}=\boldsymbol{A}exp(ikz)$, have extraordinary (*e*) and ordinary (*o*) components with linear polarizations lying in the plane defined by $\hat{n}$ and $\boldsymbol{z}$ or $\hat{n}$ and $\boldsymbol{y}$ normal to it, respectively. Low amplitude field components orthogonal to $\hat{n}$, below the optical Fréedericks transition, can be assumed not to induce molecular reorientation.

Neglecting bending effects (i. e., assuming $K_{11}=K_{22}=K_{33}=K$),[1] the variational derivative of the free-energy density yields:

$$K\nabla^2{}_{xy}\theta + \frac{1}{2}\varepsilon_0\Delta\varepsilon_{LF}\left|E_{LF\,x}\right|^2\sin 2\theta = 0 \tag{4}$$

being E_{LFx} the *x*-component of the applied electric field $\boldsymbol{E_{LF}}$. The static field distribution $\boldsymbol{E_{LF}}$ can be calculated from Maxwell divergence equation in terms of the voltage V:

$$\frac{\partial}{\partial x}\left[\left(\varepsilon_\perp + \Delta\varepsilon_{LF}\sin^2\theta\right)\frac{\partial V}{\partial x}\right] + {n_o}^2\frac{\partial V}{\partial y} = 0 \tag{5}$$

with $\boldsymbol{E_{LF}} = -\nabla V$. Finally, the refractive index experienced by a TM-polarized wave is $n = \sqrt{n_\perp^2 + (n_{//}^2 - n_\perp^2)\sin^2\theta}$. Equations (4-5) with Maxwell equations describe light evolution in voltage biased NLC.

3. DFBW structure

The device we propose and investigate is based on a simple sandwich structure with a film of liquid crystals and a proper electric polarization. Figure 1 is a schematic three-dimensional drawing of the integrated distributed feedback waveguide. The structure consists of a planar glass (or other low-index transparent substrate) cell with an external voltage (i.e. LF field) applied to the NLC layer by a set of top and bottom transparent electrodes. The elongated (ellipsoidal) molecules represent an ideal (distortion-free, disclination-free) liquid crystal in the nematic phase, with director $\hat{n}$ along their major axes and parallel to $\boldsymbol{z}$ in the absence of bias. The NLC layer is assumed to be of thickness and refractive index able to support the propagation of transverse-magnetic (TM) guided waves in the planar slab. The two-dimensional optical confinement is ensured via a graded-index channel by a suitable voltage applied between the finite-width (along $\boldsymbol{y}$) top electrode and the ground plane at the opposite boundary. The top electrode is also periodic along $\boldsymbol{z}$, in order to define the one-dimensional photonic lattice entailing Bragg reflection via distributed feedback. The design parameters for a given wavelength of operation and NLC, i. e. electrode overall width, periodicity and duty-cycle along $\boldsymbol{z}$ and layer thickness along $\boldsymbol{x}$, have to be selected in order to achieve high coupling between the TM optical field and the induced Bragg grating over a finite propagation distance. The periodic modulation in refractive index n_e produces a phase-modulation on the

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guided TM eigenmode of the voltage-defined channel waveguide; in this limit, it can be studied by the usual coupled-mode-theory approach.

We considered the standard nematic liquid crystal E7 (supplied by Merck), with elastic constants $K_{11} = 12$ pN, $K_{22} = 7.3$ pN, $K_{33} = 17$ pN, $\varepsilon_{\perp} = 7$, $\varepsilon_{//} = 20$, $n_{\perp} = 1.50$, $n_{\|} = 1.689$. Planar

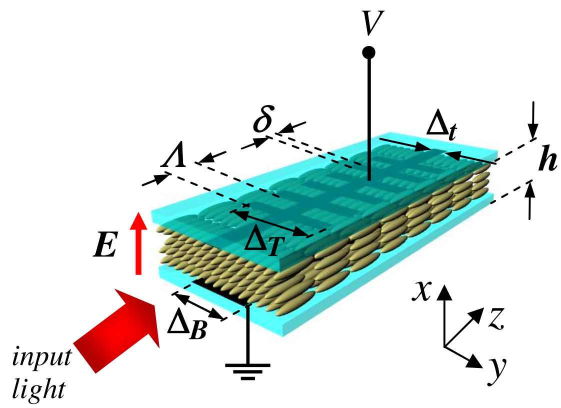

Fig. 1. Schematic drawing of the DFBW structure with planarly anchored NLC.

anchoring (e.g. by mechanical rubbing of a thin Nylon6 coating spun on the two plates) was assumed at the glass interfaces, with a pre-tilt of ≈1° to substantially eliminate the Fréedericks threshold. We assumed cladding and substrate in borosilicate D263, with refractive index ≈ 1.516 at λ = 1550 nm. The transparent electrodes were in 100 nm thick Indium Tin Oxide, with real and imaginary refractive index components equal to 1.3 and 0.1, respectively.[24]

For single-mode operation at λ ≈ 1550 nm we considered an NLC thickness h = 1 µm. The ground electrode was a straight stripe along z, of width $\Delta_B = 0.5$ µm. The top electrode encompassed a thorough stripe of width $\Delta_t = 0.1$ µm and a central periodic symmetric comb-structure with pitch $\Lambda = 0.5$ µm and duty-cycle 3:20 in order to achieve Bragg resonance with an effective periodic modulation of the waveguide, despite the inherent non-locality in the electro-optic response. Each transverse segment of the top electrode was $\Delta_T = 3$µm wide (along $\boldsymbol{y}$) and extended along z for δ = 75 nm.

4. Numerical design and analysis

We employed the finite element method, first solving the Poisson equation and then injecting the solution in the Frank-Oseen model Eqns. (1)-(2) to obtain the director distortion. An iterative algorithm provided a minimum of the energy (1), yielding in turn the distributions of the optic axis $\hat{n}$ and the electric field. The result was thus the map of the NLC elevation ξ and azimuth ρ and, subsequently, the transverse profile of the refractive index n_e for TM light polarization, the one undergoing two-dimensional confinement and Bragg reflection between the LF-voltage biased electrodes. Calculated E7 director elevation and azimuth in a cross section under one of the Δ_T -wide ribs or the Δ_t-wide central stem are shown in Fig. 2 for an applied voltage of 3 V. The corresponding extraordinary index distributions n_e are in Fig. 3.

The modal analysis was performed accounting for the two-dimensional graded index profile obtained from voltage-driven reorientation. Figure 4 displays the guided-wave funda-

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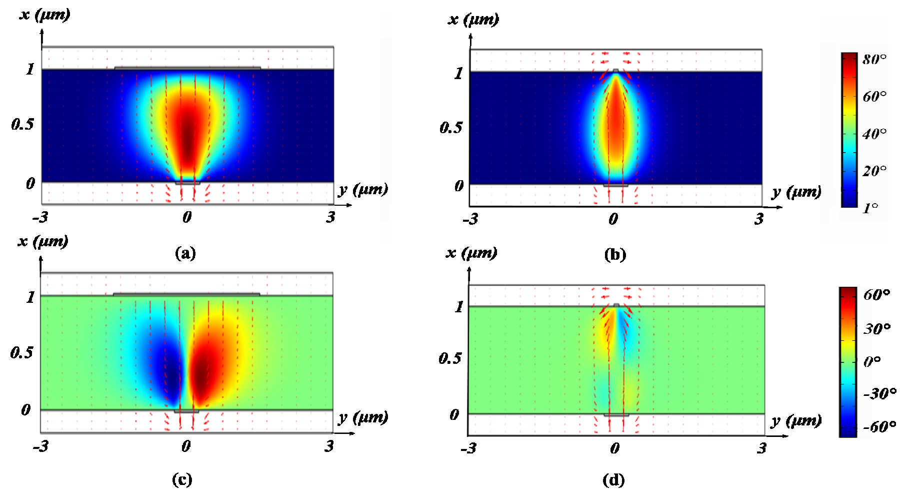

Fig. 2. Distribution of the molecular director for an applied voltage of 3V and corresponding electric field distribution (red arrows): (a) Elevation and (c) twist under the wide ribs of the top electrode; (b) elevation and (d) twist under the central stem of the top electrode, respectively.

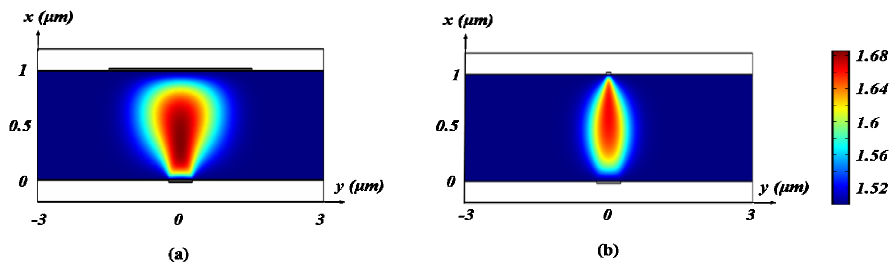

Fig. 3. Refractive index profile for TM polarized light, corresponding to the reorientation in Fig. 2 under (a) the wide ribs or (b) the central stem, respectively.

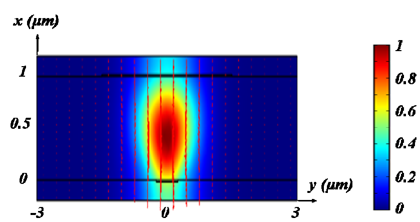

Fig. 4. Quasi-TM mode profile of an electrically assisted NLC waveguide: the color map shows the normalized power flow, the arrows indicate the electric displacement under the Δ_T-wide rib.

mental mode profile at 1550 nm with an effective index $n_{TM00} \approx 1.56$.

For a "reduced" DFBW with 4 periods in the top electrodes, Fig. 5 shows the calculated refractive index modulation "seen" at 100 nm below the top electrode by the TM_{00} mode propagating along the axis z for various applied voltages. Clearly, the effectiveness of the Bragg filter depends on the total number of periods. Significant modulation is observed for V in the range 2.5-3 V. For V= 3V an index contrast ≈0.015 is obtained, whereas it decreases to 0.008 for V=2.5 V. In the same interval single mode propagation is ensured. The asymmetry versus z is caused by the initial 1° pretilt, but it does not affect the device operation.

Finally, using coupled-mode theory we computed the DFBW reflectivity for a given number of periods and index modulation depth. The grating length and index contrast also

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affect the reflectivity full-width at half maximum (FWHM). Figure 6(a) shows the filter reflectivity calculated at V=3V. Bragg FWHM and device length to achieve 100% reflection were 0.38 nm and 5 mm, respectively.

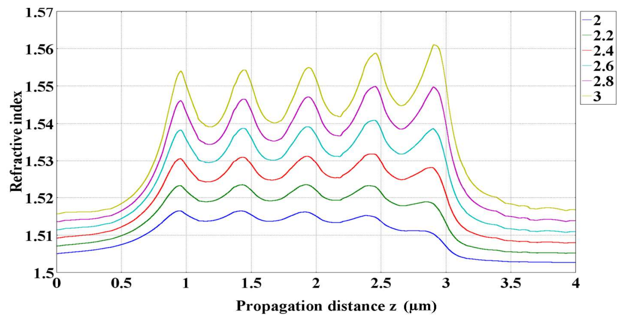

Fig. 5. Refractive index profile 100nm below the top electrode for various biases and TM-polarized light.

Finally, we tested the voltage adjustability of the filter within the range of single mode operation, in order to demonstrate electro-optic wavelength tunability of this Bragg reflector. To this extent, we superimposed a small control voltage on a bias lower than nominal. Figure 6(b) displays the DFBW tuning versus voltage.

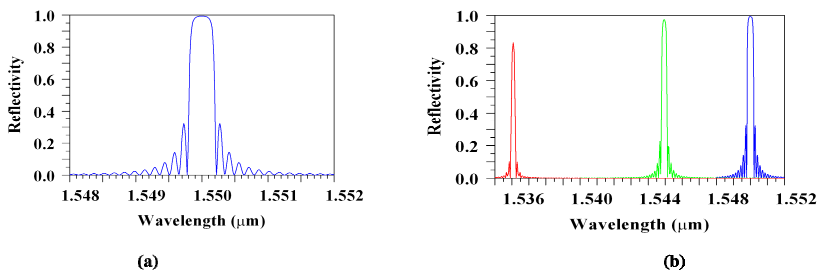

Fig. 6. (a) The DFBW spectral response in reflection. The peak is 99% and the FWHM is 0.38nm. (b) DFBW reflectivity for various voltages: 3V (blue), 2.8V (green), 2.5V (red). Peak values (FWHM) are 83% (0.23nm), 97% (0.32nm) and 99% (0.38nm) from left to right, respectively.

5. Conclusions

We have proposed, modelled and numerically tested a simple distributed feedback waveguide which, realized with nematic liquid crystals, can be electro-optically tuned versus wavelength in a large spectral range. The simple design, the technologic maturity of liquid crystals and their optical properties make this Bragg device an effective one for dense wavelength division multiplexing, filtering and switching, provided crosstalk is minimized through sidelobe suppression, for instance via apodization of the electrode pattern or applied bias. In terms of realization, phase mask techniques or electron beam lithography are widely available and could easily be employed to define the structure. We anticipate the experimental demonstration of Bragg gratings based on this approach and their applications to other areas of investigation, including gap solitons and slow-light via reorientation in NLC.

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