Electrical tuning of refraction in a two-dimensional photonic crystal infilled with a liquid crystal

J.A. Reyes-Avendaño and P. Halevi
Instituto Nacional de Astrofísica, Óptica y Electrónica,
Apartado Postal 51, Puebla, Pue., México 72000,
e-mail: areyes@inaoep.mx

Recibido el 11 de agosto de 2008; aceptado el 24 de noviembre de 2008

We study a novel electro-optic structure with potential applications for ray steering, optical multiplexers, logic gates or switches. Our idea is based on the electrical tuning of refraction in a two-dimensional photonic crystal infilled by a liquid-crystal, with a direct-current electric field applied parallel to the cylinders. Using a two-step homogenization process, we show that, for sufficiently low frequencies, this structure can be represented by two field-dependent effective refractive indices. We demonstrate that the direction of the ordinary and extraordinary refracted rays can be sensitively tuned by varying the magnitude of the applied field.

Keywords: Photonic crystals; liquid crystals; optical properties.

Una nueva estructura electro-óptica con potenciales aplicaciones en el manejo de haces de luz, multiplexores ópticos, compuertas lógicas e interruptores ópticos es estudiada. Nuestra idea se basa en la sintonización eléctrica de la refracción en un cristal fotónico bidimensional infiltrado con cristal líquido y un campo eléctrico de corriente directa aplicado paralelamente a los cilindros. Usando un proceso de homogenización de dos pasos, mostramos que para frecuencias suficientemente bajas, esta estructura puede ser representada por dos índices de refracción efectivos dependientes del campo eléctrico aplicado. Demostramos que es posible sintonizar la dirección de los rayos refractados (ordinario y extraordinario) por medio de una variación en la magnitud del campo eléctrico.

Descriptores: Cristales fotónicos; cristales líquidos; propiedades ópticas.

PACS: 78.20.Bh; 78.20.Ci; 78.20.Fm; 78.20.Jp

In this paper we propose a simple electro-optic device which, for example, could be an element in integrated photonic platforms that incorporate photonic crystals (PCs). Specifically, we consider the electrical tuning of a photonic crystal (PC) infilled with a nematic liquid crystal (NLC). With an electric field applied parallel to the cylinders of a two-dimensional (2D) PC, for sufficiently low frequencies the composite material can be replaced by a uniform, uniaxial optical medium. Taking advantage of this simple description, we demonstrate that the directions of the refracted ordinary and extraordinary rays can be steered by varying the magnitude of the applied field, with up to $\backsim$ 7% change in the angle of refraction.

It seems that the most promising manner of tuning of PCs is based on their infilling by a NLC - tunable by means of pressure, temperature, or an applied magnetic or electric field. As for applications, electric control of the optical response is the most promising. Indeed, the first paper on this subject [1] has motivated many studies of NLC-infilled PCs [2–4]. Now, while several theoretical papers dealt with very large electric fields (above the Freedericksz transition) that have to be rotated with respect to the PC (in order to alter the orientations of the NLC molecules), this scheme proved to be unattractive for experimentation. On the other hand, experimental work with a fixed direction of the field - tuning its magnitude - prospered [3]. Most theoretical papers are concerned with tuning of the photonic band gap (PBG) and the experimental ones with tuning of the reflectance or transmittance. We are aware of only five studies [5, 6] dedicated to the tuning of refraction, and merely one of these [6] is based on NLCs, assuming (cumbersome) rotation of the field or the PC. In this letter we present an explicit simulation of sensitive ray steering, with the magnitude of the field as tuning agent.

In the aforementioned references, the wavelength λ is on the order of the PC lattice constant *a* (PBG region). The frequency region much below the PBG has received much less attention. When $\lambda \gg a$, the structure behaves like a traditional optical element and can be characterized by an effective refractive index n_{eff} . Such *homogenization* of composites has been accomplished for PCs with isotropic ingredients [7–9].

In this work, we homogenize a 2D PC of cylinders infilled with the NLC 5CB in a silicon oxide (silica) matrix. Here it is important to stress the advantages of silica as host medium, rather than silicon, for example. The free carriers in a semiconductor screen out the applied electric field; this problem can be overcome by a specially designed capacitor, increasing however the complexity of the structure (see the last Ref. 3). In addition, because here PBGs are not of concern, having a low dielectric contrast (between the NLC and the silica glass) actually leads to more sensitive ray steering. The homogenization results in an effective uniaxial medium characterized by two refractive indices: the ordinary n_o and the extraordinary n_e. When an electric field $\mathbf{E}_0$ is applied parallel to cylinder axis $\hat{\mathbf{z}}$, both indices change their values continuously as a function of E_0. As a result, an unpolarized incident beam with $\lambda \gg a$ splits into two refracted beams inside the PC: the ordinary or E mode (with $\mathbf{E}\|\hat{\mathbf{z}}$) and the extraordinary or H mode (with its magnetic field $\mathbf{H}\|\hat{\mathbf{z}}$). As

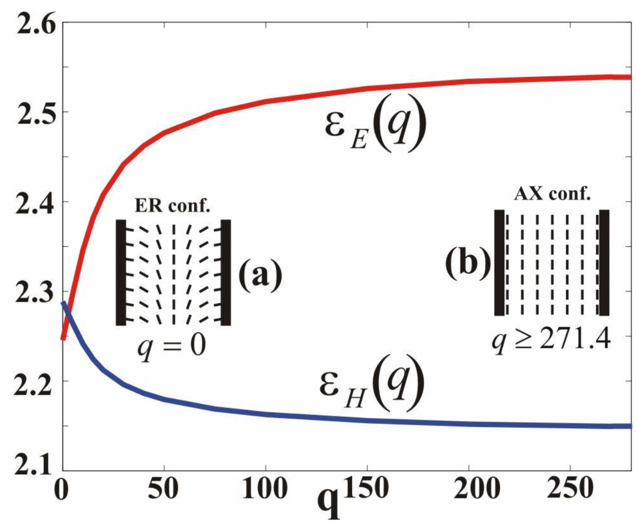

FIGURE 1. Average dielectric constants ϵ_E (ϵ_H) of a nematic liquid crystal cylinder for electric field **E** (magnetic field **H**) parallel to the cylinder, as a function of the electric field parameter q. For $q<271.4$ ($E_0<14V/\mu m$), the NLC molecules adopt the Escaped Radial configuration [inset (a)]. As q increases, the LC molecules gradually align their directors in the $\hat{\mathbf{z}}$ direction until reaching the AXial configuration (inset b) at $q = 271.4(E_0 = 14V/\mu m)$. Here cylinders of radius $R = 0.4\mu m$ are infilled with the NLC 5CB whose dielectric constants in the static (infrared) region are: $\epsilon_O(\epsilon_o) = 7(2.2350)$ and $\epsilon_E(\epsilon_e) = 18.5(2.7889)$ [10] and the elastic constant is $K_{11} = 1.2 \times 10^{-11}N$.

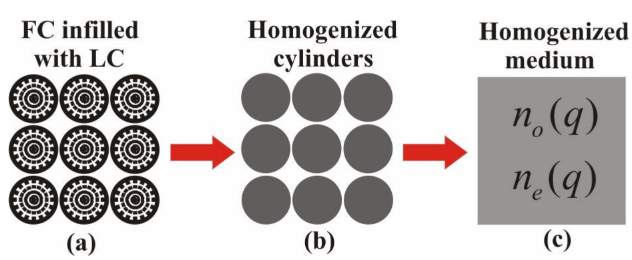

FIGURE 2. PC homogenization process. In (a), the PC is represented by a dielectric tensor for the region inside the NLC cylinders, and a dielectric constant for the host region ($\epsilon_{silica} = 1.96$ in the infrared region [11]). In (b), the structure is simplified, replacing the NLC cylinders by a uniform medium with ϵ depending on E_0 for each polarization. In (c), the PC of two (now uniform) components is replaced by a single uniform medium, characterized by a pair of field-dependent effective indices, corresponding to ordinary and extraordinary modes.

will be made evident below, both angles can be tuned by the applied field E_0 by about $2.3°$ for the E-mode and $1.2°$ for the H-mode.

In a recent study [4] we have shown that, when the external electric field is absent, the NLC molecules inside the cylinder adopt the *escaped radial configuration*. In this configuration, the angle θ formed between the NLC molecule axis $\hat{\mathbf{n}}$ (the *director*) and the cylinder axis $\hat{\mathbf{z}}$ increases with the radial distance r. For molecules at the cylinder's center $\theta = 0°$ and, for relatively wide cylinders, θ can reach almost $90°$ for molecules at the cylinder's wall [inset (a) Fig. 1]. The external DC electric field $\mathbf{E}_0$ changes the direction of the NLC molecules, decreasing θ as a function of E. When E_0 reaches a critical value E_c, a phase transition is induced in the NLC. All the NLC molecules in the cylinder are then aligned in the $\hat{\mathbf{z}}$ direction and any E_0 greater than E_c will leave this *axial configuration* unaltered [inset (b) Fig. 1]. In Ref. 4 the cylinder, subject to the applied field $E_0\hat{\mathbf{z}}$, was characterized by a non-diagonal dielectric tensor $\overleftrightarrow{\varepsilon}(r)$ whose elements depend on the angle $\theta_E(r) = (\hat{\mathbf{n}}, \hat{\mathbf{z}})$, as well as on the ordinary and extraordinary dielectric constants $\epsilon_o = n_o^2$ and $\epsilon_e = n_e^2$. Now, when $\overleftrightarrow{\varepsilon}(r)$ is averaged over the cross-sectional area of the cylinder, it becomes diagonal, with the uni-axial structure

$$\langle \widetilde{\varepsilon}_{xx} \rangle = \langle \widetilde{\varepsilon}_{yy} \rangle = \epsilon_o + \epsilon_a \int_0^1 x \sin^2 \theta(x) dx \equiv \epsilon_H(q), \quad \text{(1a)}$$

$$\langle \widetilde{\varepsilon}_{zz} \rangle = \epsilon_o + 2\epsilon_a \int_0^1 x \cos^2 \theta(x) dx \equiv \epsilon_E(q), \quad \text{(1b)}$$

Here, $q = \epsilon_A R^2 E_0^2 / K_{11}$ is a convenient dimensionless field parameter, $\epsilon_A = \epsilon_E - \epsilon_O(\epsilon_a = \epsilon_e - \epsilon_o)$ is the static (optical) *anisotropy*, R is the cylinder radius, K_{11} is an elastic constant of the NLC, and $x = r/R$. Clearly, the optical response of the NLC cylinder is governed by the effective ordinary (extraordinary) dielectric constants $\epsilon_H(\epsilon_E)$ if $\mathbf{H}(\mathbf{E})\|\hat{\mathbf{z}}$ - which justifies the subscript H(E). Fig. 1 shows the variation of $\epsilon_{E,H}$ with q. As this parameter increases, ϵ_E increases from 2.24 to 2.54, while ϵ_H decreases from 2.29 to 2.15, approximately. It is important that, for $q > q_c = 271.4$, ϵ_E and ϵ_H do not change further. Using these ideas, we can represent the PC of NLC cylinders (Fig. 2a) as in Fig. 2b, and the optical response can be calculated as usual for PCs made of homogeneous and isotropic dielectric materials. In Refs. 4 it has been demonstrated that this simple averaging over the cross-sectional area of a cylinder reproduces the exact photonic band structure for 5CB NLC cylinders very well in both a silicon and a silica host. This completes the first step of homogenization.

Next, as mentioned, for $\lambda \gg a$ it is possible to proceed to the second step - complete homogenization of the PC - as indicated in Fig. 2c. For our two-dimensional PC (Fig. 2b), the final value of ϵ_{eff} can be calculated using the methods of Refs. 7 and 8. Both calculations give the same result. For E-polarization, the result of homogenization is simple and yields the effective extraordinary index $n_e(q)$:

$$\langle\epsilon_E(q)\rangle = \epsilon_E(q)(\pi R^2/a^2) + \epsilon_{SiO_2}(1-\pi R^2/a^2) \equiv n_e^2(q). \quad (2)$$

Here a is the period of the square lattice and the expressions in the parentheses are the NLC and silica filling fractions. The formulas for H-polarization, namely $\langle\epsilon_H(q)\rangle \equiv n_o^2(q)$, can be found in the Refs. 7 and 8 and

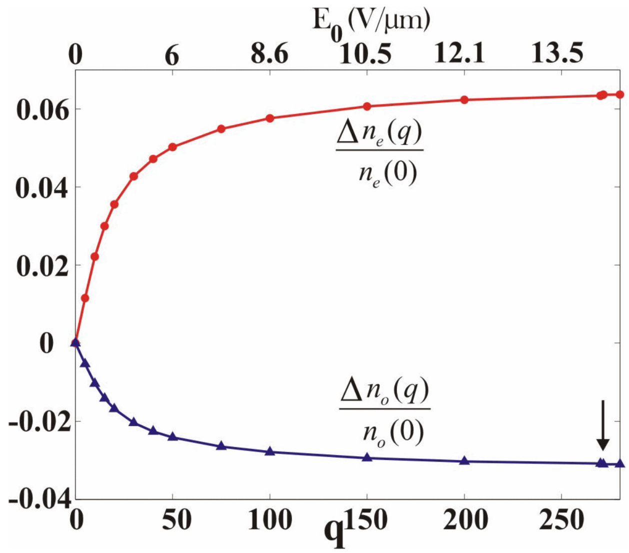

FIGURE 3. Relative changes of the effective refractive indices of a two-dimensional PC of NLC cylinders in a silica matrix, as the applied electric field changes from zero beyond its critical value; see top coordinate $E_0 (in V/\mu m)$ for our chosen parameters. The PC lattice constant is $a = 0.85\mu m$ and $R = 0.4\mu m$. As q increases, the ordinary (extraordinary) refractive index decreases (increases) up to a limiting value for $E_0 = 14V/\mu m$, indicated by the arrow. For any q beyond this value, both indices remain unchanged. Both curves are well fitted up to q = 100 (the most significant interval for tuning) by series of the form $\Delta n(q)/n(0) = \sum_{n=0}^{5} a_n q^n$. The coefficients for the ordinary (extraordinary) mode are a_0=0.00015(0.00031), a_1=−0.001301(0.002813), a_2=$2.83\times10^{-5}(-6.544\times10^{-5})$, a_3=$-3.03\times10^{-7}(7.819\times10^{-7})$, a_4=$1.338\times10^{-9}(-4.333\times10^{-9})$, a_5=$-1.116\times10^{-12}(8.231\times10^{-12})$.

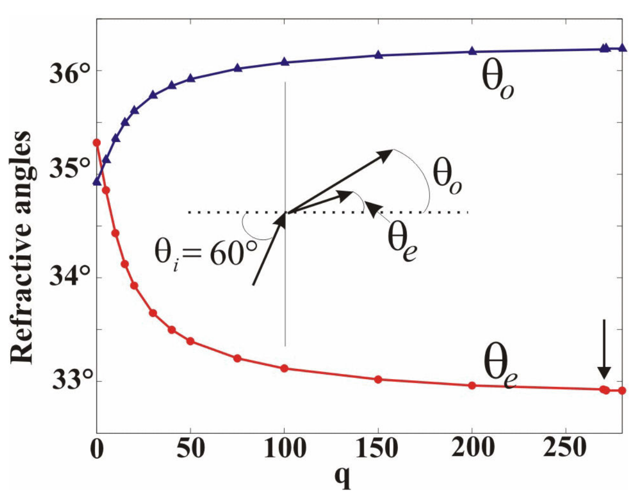

FIGURE 4. Angles of refraction for ordinary and extraordinary rays in the homogenized medium. As q increases, the angle between the refracted beams increases until a phase transition occurs in the LC, as indicated by the arrow.

provide the effective ordinary index $n_o(q)$. The fractional changes of these indices,

$$\frac{\Delta n_{o,e}(q)}{n_{o,e}(0)} = \frac{n_{o,e}(q) - n_{o,e}(0)}{n_{o,e}(0)}, \qquad (3)$$

are plotted in Fig. 3.

It is observed that the applied electric field can tune the effective index by up to $\sim 6\%$. Here it is important to note that the larger changes occur for modest values of the applied electric field ($E_0 \leq 5V/\mu m$), and it is not necessary to reach the phase transition at ($E_0 = 14V/\mu m$) to get a significant tuning. Finally, in Fig. 4 are shown the variations of the refraction angles, for both the ordinary and extraordinary rays, considering an angle of incidence $\theta_i = 60°$. An unpolarized beam incident at the PC, with its saggital plane perpendicular to the cylinders, will split into the ordinary and the extraordinary beams. As the applied field increases, θ_o increases and θ_e decreases, reaching saturation at the phase transition.

Summarizing, we have calculated the refractive angles for light incident at a 2D PC, employing a two-step homogenization process. The first step leads to the effective dielectric constants $\epsilon_E(q)$ and $\epsilon_H(q)$ that characterize the NLC cylinders for a given external field E_0, and the second completes the homogenization, representing the entire NLC-infilled PC with an effective index for each polarization. Because of the uniaxial nature of the homogenized medium, the incident electromagnetic wave splits into two beams. The refractive angles of these (ordinary and extraordinary) rays can be continuously varied up to $\sim 6\%$ in comparison to the fieldless case (for $\theta_i = 60°$). The second step of homogenization requires that $\lambda \gg a$, that is, the linear region of the PC's band structure, where $\omega \simeq kc/n_{o,e}(q)$. This implies, typically, the infrared regime. If the PC is placed in a capacitor of width $\sim 15\mu m$, efficient tuning could be achieved with voltages up to about 70 V. The method described could be used for ray steering, for example employing a PC prism as proposed in Ref. 7. Another potential application is based on a PC lens, as suggested in Ref. 9, now with the possibility of tuning the lens's focus. Further applications to be considered are optical multiplexers (where the electromagnetic wave path can be selected by external agents), optical logic gates or optical switches.

Acknowledgements

The authors would like to thank J. A. Reyes-Cervantes for helpful interaction. This work was partially supported by the CONACYT project SEP-2004-C01-46425. Also, J. A. R.-A. wishes to acknowledge support by CONACYT of his graduate studies.

1. K. Busch and S. John, *Phys. Rev. Lett.* **83** (1999) 967.

2. S.W. Leonard *et al.*, *Phys. Rev. B* **61** (2000) R2389; K. Yoshino, Y. Shimoda, Y. Kawagishi, K. Nakayama, and M. Ozaki, *Appl. Phys. Lett.* **75** (1999) 932; D. Kang, J.E. Maclennan, N.A. Clark, A.A. Zakhidov, and R.H. Baughman, *Phys. Rev. Lett.* **86** (2001) 4052; G. Mertens, T. Röder, R. Schweins, K. Huber, and H.-S. Kitzerow, *Appl. Phys. Lett.* **80** (2002) 1885.

3. Y. Shimoda, M. Ozaki, and K. Yoshino, *Appl. Phys. Lett.* **79** (2001) 3627; D. McPhail, M. Straub, and Min Gu, *Appl. Phys. Lett.* **86** (2005) 051103; M. Haurylau, S.P. Anderson, K.L. Marshall and P.M. Fauchet, *Appl. Phys. Lett.* **88** (2006) 061103; and references therein.

4. P. Halevi, J.A. Reyes-Avendaño, and J. A. Reyes-Cervantes, *Phys. Rev. E* **73** (2006) 040701R; J.A. Reyes-Cervantes, J.A. Reyes-Avendaño, and P. Halevi, *Opt. Commun.* **281** (2008) 2535.

5. David Scrymgeour, Natalia Malkova, Sungwon Kim, and Venkatraman Gopalan, *Appl. Phys. Lett.* **82** (2003) 3176; Sibei Xiong and Hiroshi Fukshima, *J. Appl. Phys.* **94** (2003) 1286; Wounjhang Park and Jeong-Bong Lee, *Appl. Phys. Lett.* **85** (2004) 4845; Liang Feng *et al.*, *Phys. Rev. B* **71** (2005) 195106.

6. H. Takeda and K. Yoshino, *Phys. Rev. E* **67** (2003) 056607.

7. P. Halevi, A.A. Krokhin, and J. Arriaga, *Phys. Rev. Lett.* **82** (1999) 719, and references therein.

8. A.A. Krokhin, P. Halevi, and J. Arriaga, *Phys. Rev. B.* **65** (2002) 115208; P. Halevi and F. Pérez-Rodríguez, *Proc. SPIE* **6320** (2006) 63200T; and references therein.

9. P. Halevi, A.A. Krokhin, and J. Arriaga, *Appl. Phys. Lett.* **75** (1999) 2725.

10. Iam-Choon Khoo and Shin-Tson Wu, (World Scientific 1993).

11. I.H. Malitson, *J. Opt. Soc. Am. A.* **55** (1965) 10.