Optical properties of superlattice photonic crystal waveguides

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We report theoretical investigations of a superlattice photonic crystal (PC) waveguide in which the holes in the PC are infiltrated with an electro-optic medium and alternate rows biased so as to produce a superlattice structure. The three-dimensional simulations fully incorporate the finite thickness of the PC structure and show that the optical properties become strongly dependent on the direction of light propagation. Depending on the degree of index modulation the light experiences switching, out-coupling, or giant refraction and dispersion. © *2004 American Institute of Physics.* [DOI: 10.1063/1.1682678]

Since the proposals by Yablonovitch[1] and John,[2] the prospect of achieving photonic band gap (PBG) by photonic crystal (PC) structures has commanded much attention. However, it is increasingly being realized that in addition to their PBG properties one of the most technologically important properties of PCs is the presence of highly nonlinear and anisotropic dispersion. These effects were proposed by Dowling and Bowden[3] and discovered by Lin *et al.*[4] at microwave wavelengths and soon after by Kosaka *et al.*[5] at optical wavelengths. Additionally, this phenomenon was recently predicted by Park and Summers[6] in two-dimensional (2D) PC slab waveguides with finite thickness, which represent far more realistic structures compatible with conventional lithography-based fabrication. For a Si 2D slab PC, refraction up to 70° was predicted for incident angles less than 7°, and frequency components differing by 3% were separated by 15° much larger than can be achieved with conventional gratings.[6] Recently, Wu *et al.*[7] demonstrated superprism effects in a guided mode and Baba and Matsumoto[8] has predicted that resolutions of ~0.4 nm can be achieved. Self-collimation in these structures has also been investigated theoretically.[9]

The advantages of tunable PCs was first realized by Busch and John,[10] and demonstrated by Yoshino *et al.*[11] and Leonard *et al.*[12] who used the temperature dependence of the refractive index of a liquid crystal (LC) E7, infiltrated into a silica opal and a porous Si PC, respectively, to shift the PBG. Leonard *et al.* also identified the LC mechanism as an escaped-radial alignment of the director, and showed that consequently the tunability was approximately ~60% of the full index change.

We report a theoretical investigation of modulated PC structures realized by infiltrating a PC with an optically active medium, such as an electro-optic or LC material, in which an electric or optical field can induce a large refractive index change, resulting in tunable effects.[13] As recently reported by Scrymgeour *et al.* and Xiang and Fukshima, in lead lanthanum zirconate titanate an index change of 0.12 can be achieved and switched at gigahertz speeds.[14,15] However, these studies were for pure 2D PC structures, disregarding the effect of finite thickness and the resultant constraints by guiding conditions. Conversely, LCs offer much higher index changes ($\Delta n > 0.4$)[16] and, although slower and subject to interface pinning in smaller structures, are suitable for IR applications, because of their high transparency between 400 nm and 12 μm.[17] Also, Khoo *et al.*, has reported LCs that exhibit extremely large photosensitive nonlinearities when excited at 488 nm and that nanosecond response times can be achieved by doping. He also observed that with proper surface preparation the director of the LC molecules aligns perpendicular to the hole wall.[18] An electric field across the LC filled slab, therefore, rotates the director parallel to the hole axis, thus changing the refractive index experienced by the TE-polarized light from 1.7 to 1.5, or visa versa. As described later, the structure investigated in this study has a high aspect ratio of hole diameter to waveguide thickness, ~1.5, thus we believe that the field modulation can be fairly high. A finite element analysis on the field profile confirmed that there is little crosstalk between adjacent electrodes. Additionally, the development of highly birefringent LCs[16] with $\Delta n > 0.4$ strongly suggests that these effects can be demonstrated experimentally, even if the geometry limits the full index change. In this report, we report tunable refraction in 2D slab PCs using LC infiltration and propose the use of superlattice structures that can dramatically increase the tunability.

The simulations were carried out using the finite-difference time-domain (FDTD) method, which explicitly incorporates the effect of finite thickness and the constraints imposed by the guiding conditions.[6,19] The modeled system consists of a triangular array, with lattice constant a, of circular holes filled with an electro-optic material in a Si slab, with hole diameter $0.7a$ and slab thickness $0.5a$. For wavelengths of 500 nm and 1.55 μm, this corresponds to 180 and 560 nm, respectively. The photonic band structures were calculated for refractive index changes between 1.5 and 1.7.

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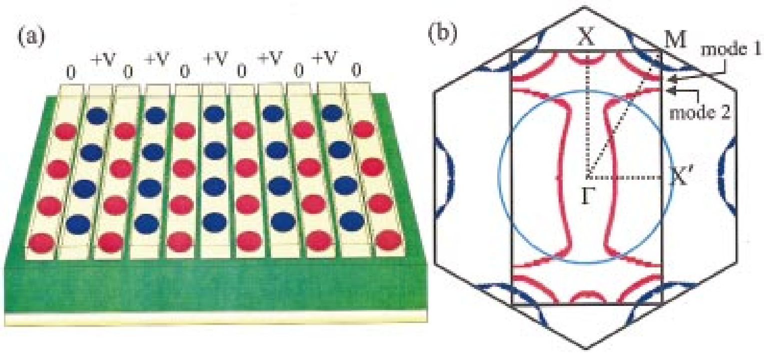

FIG. 1. (Color) (a) Schematic of superlattice PC structure produced by alternating biasing LC-filled holes. (b) Dispersion diagrams for LC infiltrated 2D PC at a normalized frequency of 0.36. Blue curves for unbiased triangular PC; red curves correspond to superlattice created by biasing every other electrode.

Simulations on homogeneous LC infiltrated structures, with an index change of $\Delta n = 0.2-0.4$, show the incident optical beams could be steered over $\sim$5–10°,[13,19] much smaller than predicted by pure 2D modeling studies.[14,15,19] However, the effect of dynamic changes in refractive index can be dramatically increased by selectively biasing the optically active material so that the PC structure can be transformed into a superlattice structure. The proposed superlattice 2D PC structure, shown in Fig. 1(a), is achieved by selectively addressing alternate rows of the LC-filled holes. This modulation creates a superlattice PC in which the additional periodicity superimposed by the index change modifies both the reciprocal lattice space and consequently the photonic band diagram with profound effects on the optical behavior. In the simplest implementation, the bottom electrode is unpatterned, while the top electrodes are linearly patterned to separately bias rows of holes along the Γ-K direction in reciprocal space, as shown in Fig. 1(b). When biased in an alternating fashion, an additional periodicity in refractive index arises along the direction perpendicular to the top electrodes (corresponds to the Γ-M direction in reciprocal space) thereby creating a superlattice PC. The impact is to make some of the k-vectors in reciprocal space equivalent to one another and thus to reduce the size of the first Brillouin zone (BZ), which is known as BZ-folding. In the superlattice structure [Fig. 1(a)] the original hexagonal BZ of the triangular PC is folded into a rectangular BZ, as shown in Fig. 1(b). Due to the symmetry lowering induced by the superlattice, only four of the six M points in the original hexagonal BZ remain equivalent. The other two M points are no longer equivalent to the rest and are folded onto the Γ point in the rectangular BZ of the superlattice. The K points are similarly affected and only two [along the vertical direction in Fig. 1(b)] remain as high symmetry directions. The high symmetry points in the reduced BZ are labeled X and X'.

Figure 1(b) shows two dispersion curves calculated at a normalized frequency ($\omega a/2\pi c$) of 0.36, the first for an unbiased triangular LC infiltrated PC, and the second for a superlattice created by biasing every other electrode. The two dispersion curves exhibit distinctly different shapes as a consequence of the refractive index change and the BZ-folding. In interpreting this data, attention must be paid to the major difference between a 2D PC slab and a pure 2D or 3D PC, which is the imposition of the guiding condition represented by the cutoff circle. Only modes outside the circle are guided within the slab while those inside radiate into the surrounding media. Once the dispersion curve is obtained, one can determine the light propagation direction as the group velocity is given by the gradient of $\omega(\mathbf{k})$ curve. According to the boundary condition at the interface dictating that the tangential component of the k-vector must be conserved, the allowed k-vectors having the same tangential component as the incident wave are found from the dispersion curve. Then, the refracted light propagation direction is determined by taking the gradient at the allowed k-points, which is the normal direction to the dispersion curve pointing toward the direction of increasing frequency. Examination of the dispersion curves show that the optical properties become critically dependent on the direction of light propagation. For light incident along the Γ-X' direction [perpendicular to the top electrodes, Fig. 1(a)], the dispersion curves for the triangular PC and superlattice do not exhibit a significant difference in their curvatures and thus the refraction properties are similar to the case of uniform biasing. However, there is a major difference in that BZ-folding transfers the originally guided modes of a triangular PC into the radiation regime in the superlattice. Thus, along the Γ-X' direction, one achieves switching between guided and radiation modes for modest changes in refraction angles. Conversely, along the Γ-X direction, corresponding to light propagating parallel to the top electrodes, the unbiased triangular PC exhibits a stop band and thus does not support any modes. However, when the electrodes are switched on in an alternating manner to create a superlattice PC, BZ-folding brings in allowed modes along the Γ-X direction, as shown in Fig. 1(b). Thus, along the Γ-X direction, one may switch between two states where light is allowed to propagate with modest refraction or all of the incident light is back reflected. A more complicated behavior occurs along the Γ-M directions, which make an angle of 30° with the top electrodes. As shown in Fig. 1(b), the superlattice possesses three allowed modes along the Γ-M direction but only two are guided modes lying outside the cut-off circle. The outermost mode (mode 1) exhibits a curvature similar to that of the triangular PC. Thus, for this branch, we expect only modest changes in the refraction angle. Figure 2 shows the refraction angles calculated by numerically evaluating the curvatures. As shown, the outermost branch exhibits $\sim$10° changes in refraction angle for very small incident angles ($\theta_i < 2°$) and reaches a refraction angle of almost 50° for $\theta_i = 12°$ beyond which the mode ceases to exist. The other guided mode (mode 2) exhibits a fundamentally different curvature. At small incident angles, the refraction angle has its maximum of 47° and decreases with increasing incident angle. This

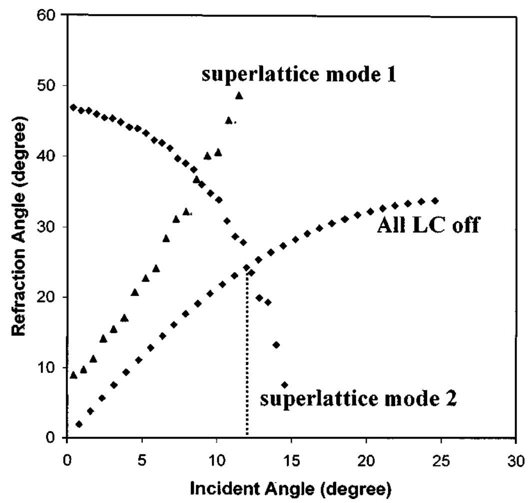

FIG. 2. Calculated refraction for an unbiased PC and for the superlattice structure created by biasing every other electrode. The incident angle is measured from the Γ-M direction.

behavior is completely opposite to the triangular PC, which exhibits small refraction effects at low incident angles. Therefore, by preferentially coupling to this branch, light incident along the Γ-M direction may be electronically, or optically, scanned over very large angles: up to 47°. Furthermore, for incident angles greater than 12°, the outermost branch no longer exists, resulting in a single-mode regime where the superlattice exhibits refraction angles smaller than the triangular PC. In this single-mode operation, the largest achievable difference in refraction angle was approximately 20° at an incident angle of 15°.

In summary, we have proposed a 2D superlattice PC that has unique directional properties. In this structure, electro-optic materials are incorporated into the PC so that an external field, by changing the refractive index values, creates an additional periodicity in the waveguide structure. The resulting superlattice exhibits light propagations extremely sensitive to the refractive index changes because of BZ folding. For a simple biasing scheme in which alternating electrodes along the Γ-K direction are switched on and off, one may achieve switching, out-coupling, and beam steering over a wide range of angles. For an index change of $\Delta n = 0.2$, light traveling parallel to the superlattice modulation can be switched on/off, and in a perpendicular direction can be switched from the guided to out-coupled state. For propagation at an angle of 30° to the modulating electrodes, a large variation in refraction up to 47° was achieved. The demonstration of dynamically tunable giant refraction creates an additional tool to manipulate light and opens possibilities of realizing, among others, optical switches, routers or modulators in a compact, highly-integrated design.

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