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Mechanically tunable photonic crystal structure

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We report a tunable nanophotonic device concept based on flexible photonic crystal, which is comprised of a periodic array of high-index dielectric material and a low-index flexible polymer. Tunability is achieved by applying mechanical force with nano-/microelectromechanical system actuators. The mechanical stress induces changes in the periodicity of the photonic crystal and consequently modifies the photonic band structure. To demonstrate the concept, we theoretically investigated the effect of mechanical stress on the anomalous refraction behavior and observed a very wide tunability in the beam propagation direction. This concept provides a means to achieve real-time, dynamic control of photonic band structure and will thus expand the utility of photonic crystal structures in advanced nanophotonic systems. © *2004 American Institute of Physics*. [DOI: 10.1063/1.1823019]

Recent developments in photonic crystals (PCs) have clearly demonstrated the possibility of generating, manipulating, processing, transmitting and detecting light in compact and highly integrated nanoscale structures.[1] These devices hold high promises for providing the breakthroughs needed for the next-generation photonics technology. However, although many device schemes have been developed by extensive theoretical and experimental works, most of them are based on "passive" PC structures designed to perform certain functions without any means of external control. A crucial innovation needed to fully exploit the unique optical properties of PCs is the ability to dynamically control or tune the photonic band structure and consequently their optical properties. There have been some efforts to achieve tunability by using electro-optic materials which change their refractive indices in response to external electric field. Busch and John predicted the tunability of photonic band structure by infiltrating liquid crystal (LC) into an opal structure.[2] This work was soon followed by experimental demonstration of temperature tuning of photonic band gap in LC infiltrated PC structures.[3,4] More recently, two-dimensional (2D) modeling studies showed wide tunability of the super-prism effect in 2D PCs infiltrated by LC and lead lanthanum zirconium titanate ($\mathrm{PbLaZrTiO_3}$, PLZT).[5,6] However, a more rigorous three-dimensional (3D) simulation taking explicitly into account the finite thickness of the slab PC structure predicted that tunability is limited due to the small attainable changes in the refractive index of LC.[7] In order to expand the tunability, Park and Summers recently reported a superlattice PC structure in which LC is used to change both the refractive index and periodicity.[8] While these recent developments are encouraging, it is clear that there exists a fundamental limitation on achievable tunability due primarily to the small attainable changes in refractive index. For LCs, the attainable change in refractive index is typically ~15% and, for PLZT, it is even smaller.

In this letter, we report a fundamentally different approach to achieve tunability. Our structure named flexible photonic crystal is comprised of a periodic array of high-index dielectric materials embedded in a flexible polymer film such as poly-dimethylsiloxane (PDMS) and polyimide. Flexible polymers have refractive indices typically around 1.5 whereas the high-index materials such as silicon possess $n > 3.0$. Therefore, the system exhibits a high-index contrast, leading to the formation of photonic bands. The structure is then subject to an external mechanical force by a silicon or metallic nano-/microelectromechanical system (NEMS/MEMS) actuator that stretches and releases the flexible polymer. Application of mechanical force results in physical changes in crystal structure to which the photonic bands are extremely sensitive. This approach can therefore produce much greater tunability than what is possible in the structures involving electro-optic materials. The device concept is schematically shown in Fig. 1.

To demonstrate the tunability achievable in flexible PC, we performed theoretical investigations on the effect of mechanical force on optical beam propagation. PCs are known to exhibit anomalous refraction behavior due to the highly nonlinear and anisotropic dispersion characteristics. This unique phenomenon was first discovered by Lin *et al.*[9] at microwave wavelengths and soon after by Kosaka *et al.*[10] at optical wavelengths. Additionally, this phenomenon was also

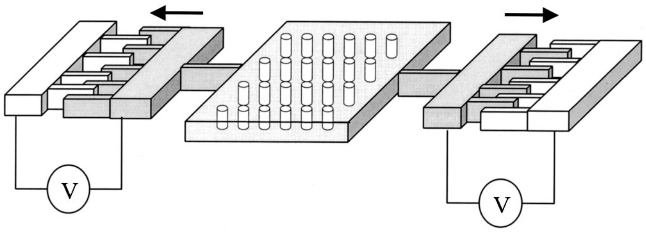

FIG. 1. Schematic diagram of flexible photonic crystal structure controlled by a pair of NEMS/MEMS actuators. The flexible photonic crystal is composed of Si pillars (white cylinders) embedded in a flexible polymer film. The actuators are made of metal or silicon.

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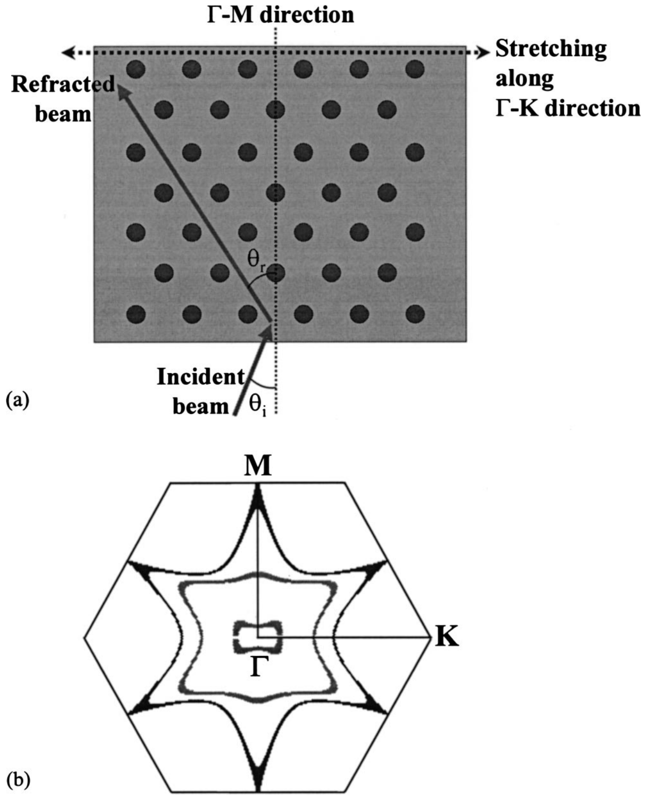

FIG. 2. (a) Schematic diagram of triangular PC structure of Si pillars (dark circles) in a PDMS film (light background). (b) Dispersion curves of perfectly triangular (outer curve), 5% stretched (middle curve), and 10% stretched (inner curve) PCs calculated for a normalized frequency of 0.39. The hexagon is the first Brillouin zone boundary.

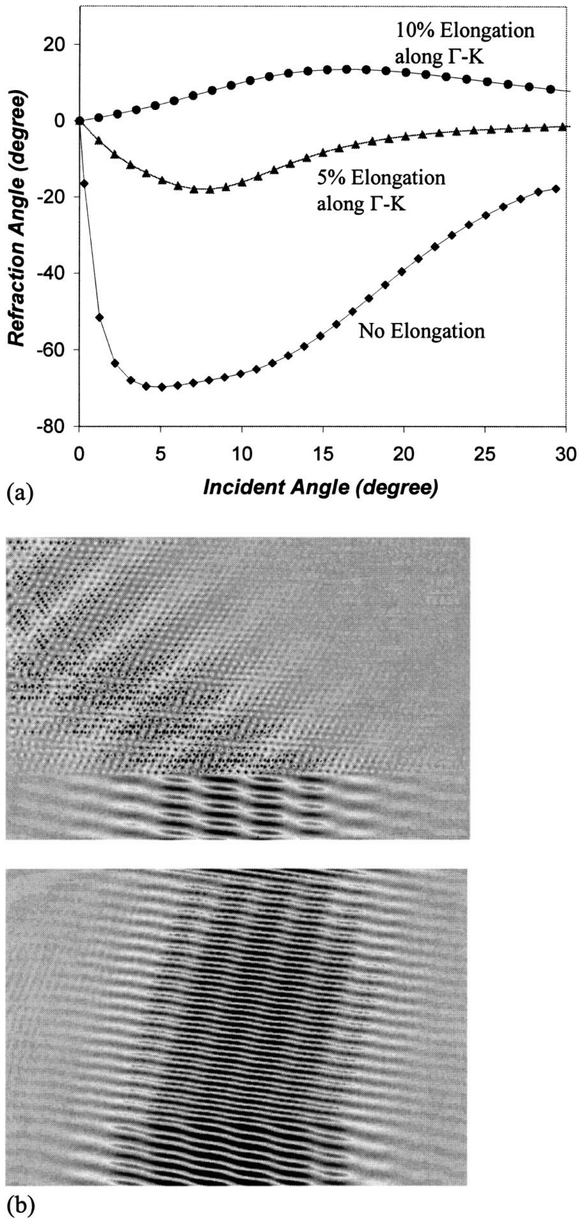

FIG. 3. (a) Refraction angles calculated from the dispersion curves in Fig. 2(b). Angles are measured from the Γ-*M* direction, as indicated in Fig. 2(a). (b) FDTD simulations showing the refraction of a Gaussian beam incident on the perfectly triangular PC (upper panel) and 10% stretched PC (lower panel). The incident beam was launched from the bottom and the flexible PC structures were placed in the upper region of the computational domain with the same orientation shown in Fig. 2(a). The incident angle was 12° for both cases.

predicted by Park and Summers[11] in 2D PC slab waveguides with finite thickness, which represent the realistic structures compatible with conventional lithography-based fabrication technique. For a Si 2D slab PC, a refraction angle up to 70° was predicted for incident angles less than 7°, and frequency components differing only by 3% were separated by 15°, much larger than what is achievable with conventional gratings.[11] These effects have recently been demonstrated experimentally in a GaAs-based 2D slab PC structure by Wu, Mazilu, and Krauss.[12]

For numerical modeling, we used the plane-wave method[13] and finite-difference time-domain (FDTD) method[14] to calculate photonic band structures, equi-frequency dispersion curves and refraction angles, and also to directly visualize the propagation of an optical beam. The test structure we modeled is comprised of a triangular array of silicon pillars embedded in PDMS. The dielectric constants of silicon and PDMS were set to be 12 and 2.4, respectively. The pillar diameter was $0.6a$ where a is the lattice constant, i.e., the center-to-center distance between two adjacent pillars. The structure was discretized into a numerical grid with 15–32 points per lattice constant. For the calculation of photonic band structures and equi-frequency dispersion surfaces, the computational domain contained only one unit cell with periodic boundary conditions. For beam propagation simulations by the FDTD method, we modeled a large structure enclosed by perfectly matched layer absorbing boundary condition.

Our test structure was found to exhibit anomalous refraction behavior at a normalized frequency $(\omega a/2\pi c)$ of 0.39. The equi-frequency dispersion curve for the unstressed triangular PC (outer curve) shown in Fig. 2(b) has a star-like shape, exhibiting sharp inflection points along the high symmetry directions, Γ-*M* and Γ-*K*. These inflection points represent regions where strong variation in the light propagation direction is expected. We then proceeded to model the system under mechanical stress, which lowers the crystal symmetry and consequently yields a strong modification of the dispersion surface. When the PC is uniformly stretched along the Γ-*K* direction, as indicated in Fig. 2(a), the dispersion curve becomes consequently distorted as shown in Fig. 2(b). It is evident that the dispersion curves are extremely sensitive to the mechanical deformation, especially along the horizontal direction (Γ-*M* direction) normal to the direction of mechanical force. As shown, the dispersion curves along the

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Γ-*M* direction become flattened significantly as the PC is stretched along the Γ-*K* direction. This results in a very large change in the refraction behavior for optical beams propagating near the Γ-*M* direction. Since the group velocity is defined as the gradient of dispersion surface in *k* space, we can estimate the refraction angles from the curvature of the equi-frequency dispersion curve.[11] The calculated refraction angles are shown in Fig. 3(a). All three cases exhibit unconventional refraction behaviors, deviating strongly from Snell's law. The perfect triangular lattice exhibits giant negative refraction in which the refraction angle reaches ~70° for an incident angle as small as 5°. As the PC is mechanically stretched, however, due to the flattening of the dispersion curve, the refraction angle decreases dramatically and varies only little as the incident angle is changed. Furthermore, for the case of 10% stretching, it no longer exhibits negative refraction but the normal refraction behavior. The differences in refraction angles between the perfect triangular lattice and 10% stretched crystal reach more than 75° for a fairly wide range of incident angles between 5 and 15°. This analysis based on the equi-frequency dispersion curves was further confirmed by the beam propagation simulation using the FDTD method. The real space simulation by FDTD shows the actual beam path from which the refraction angles can be measured directly. Our FDTD simulations yielded the results that are consistent with the analysis based on the equi-frequency dispersion curves. Figure 3(b) shows two simulations done for perfect triangular lattice and 10% stretched crystal with a Gaussian beam incident with an angle of 12°. The incident Gaussian beam was launched from the bottom of the computational domain and the flexible PC structure was placed in the upper region with the same orientation shown in Fig. 2(a). The large difference in refraction angles between the two cases is clearly shown.

It is emphasized that such a large change in refraction angle is achieved with a very small mechanical deformation. When designed for the communication wavelength of 1.54 μm, the pillar-to-pillar distance, *a*, is 0.6 μm and a 10% change is a mere 60 nm per unit cell. A larger stretching could, of course, induce an even greater change in refraction behavior but one must also consider fatigue and elasticity limit of the polymer. We performed finite element modeling and confirmed that, up to 10% stretching, the polymer would be stretched uniformly with its displacement linearly proportional to the applied mechanical force. Another important consideration that needs to be made is the Poisson ratio of the flexible polymer. PDMS has a very large value of Poisson ratio approaching nearly 0.5. This means that a 10% stretching along the Γ-*K* direction will result in a simultaneous reduction in film thickness by 5% or 15 nm in our test structure. Fortunately, the photonic band structure is not very sensitive to the slab thickness, as it is concerned primarily with the light propagation along the slab. Thus, such small changes in thickness will not significantly affect the light propagation characteristics. Finally, we point out that the tunability of the anomalous refraction behavior is not limited to one particular direction and similar behaviors have also been observed for stretching along the Γ-*M* direction. This result demonstrates that mechanical tuning of PCs' optical properties is a broadly applicable concept.

In summary, we reported a tunable photonic crystal structure, the flexible photonic crystal, that can be controlled by a NEMS/MEMS actuator. Due to the sensitivity of photonic band structure to the physical changes in crystal structure, a very large tunability can be achieved. Also, the device structure is compatible with the lithographic fabrication technique and is therefore perfectly fitting for monolithic integration with other semiconductor-based opto-electronic devices. To demonstrate the tunability, we carried out theoretical investigations on the effect of mechanical stress on anomalous refraction. A 10% stretching along the Γ-*K* direction yielded a change in refraction angle as large as 75°, clearly showing the potential for optical beam steering device. By providing real-time control over the unique optical properties of PC structures, the flexible photonic crystal will serve as a platform for nano-scale photonic devices such as optical switches, routers and modulators.

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