

In-plane and out-of-plane band-gap properties of a two-dimensional triangular polymer-based void channel photonic crystal

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The in-plane and out-of-plane band-gap properties of two-dimensional triangular void channel photonic crystals fabricated by femtosecond laser drilling in a solid polymer material were characterized for transverse electric (TE) and transverse magnetic (TM) polarization illumination. For a 24 layer structure stacked in the Γ - M direction, the fundamental stop gap resulted in the suppression of infrared transmission of as much as 96% for TE- and 85% for TM-polarized incident light. The midgap wavelength for the TM polarization was longer by 2.5% than that for the TE polarization. Increasing the angle of incidence for both the in-plane and out-of-plane cases shifted the stop gap to short wavelengths for both TE and TM polarizations. The experimental results allowed for the estimation of the cross section of void channels and the effective refractive index of the polymer after the fabrication. © 2004 American Institute of Physics.

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Photonic crystals have become a more and more interesting research area in optics and photonics since they can be used as basic materials in the next generation of communication techniques.¹⁻⁴ Two-dimensional (2D) photonic crystals are important because they can be fabricated relatively easily^{5,6} and result in devices, such as waveguides⁷ and channel drop filters,⁸ which can be part of an all-optical chip. Although complete photonic band gaps cannot exist in low index contrast structures, 2D band gaps are possible for certain polarized electromagnetic modes, and such structures can be used for devices such as photonic crystal superprisms^{9,10} or waveplates.¹¹⁻¹³ Semiconductor lithography is generally used to fabricate 2D photonic crystals. However, this fabrication method is complicated and the generation of high-quality photonic crystals with depth of numerous wavelengths is not trivial. Another effective method to generate low index contrast 2D photonic crystal structures is based on etching cylindrical holes into glass.¹⁴⁻¹⁶ Recently, we have developed a method to fabricate photonic crystals in a solid polymer material, which is based on the generation of submicron-size void channels using tightly focused femtosecond-pulsed laser light.^{17,18} The technique is a one-step approach, which does not require chemical postprocessing, and results in photonic crystals with a high degree of perfection. Here, we apply this method to the fabrication of 2D triangular lattice photonic crystals. In this letter, the dependence of the photonic band-gap properties on the in-plane and out-of-plane angles of incidence is investigated for both

transverse electric [(TE) electric field perpendicular to the void channels] and transverse magnetic [(TM) magnetic field perpendicular to the void channels] illumination.

The upper-right-hand side part of Fig. 1 schematically shows the triangular structure used in this work as well as the first Brillouin zone. The irreducible part Γ - M - K - N - O - Γ is also indicated. The structure consists of 24 layers of void channels stacked in the Γ - M direction with an in-plane spacing of $\delta x = 1.5 \mu\text{m}$ and a layer spacing of $\delta z = 1.3 \mu\text{m}$. The void channels are slightly elongated in the z direction with a ratio of the long axis to the short axis of roughly 1.5.¹⁷ The light penetrates through the photonic crystal from above for both the fabrication process and the infrared transmittance spectrum measurements. Experimental setup and blank sample preparation are the same as described

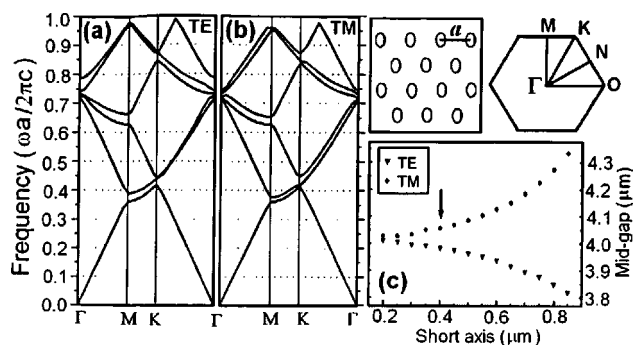


FIG. 1. TE mode (a) and TM mode (b) photonic band structure between Γ - M and Γ - K directions. Midgap wavelengths as a function of the short axis of channels for TE and TM modes (c). The upper-right-hand side part shows the schematic diagram of the 2D structure and the first Brillouin zone with its irreducible part Γ - M - K - N - O - Γ .

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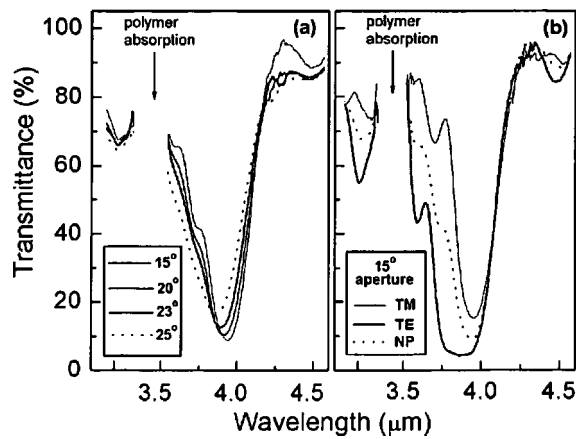


FIG. 2. (a) Infrared transmission spectra of the triangular 2D photonic crystal for different incident light cone sizes. (b) Transmittance spectra for TE-, TM-, and nonpolarized illumination for the smallest aperture.

in our previous papers^{17,18} except that an Olympus 100 $\times$, numerical aperture (NA) 1.4 oil immersion objective was used. The 2D structures with the total size of 80 μm $\times$ 80 μm were fabricated parallel to the surface of the polymer film with the top layer 5 μm below the surface.

Figures 1(a) and 1(b) show the calculated band structures of the 2D triangular photonic crystal along the edge of the Γ - M - K - Γ directions in the first Brillouin zone as determined by an eigenvalue analysis (BandSOLVE, RSoft Design Group, Ossining, NY). For consistency with experiments, an effective refractive index n_{eff} of 1.606, a short axis of 0.4 μm , and long axis of 0.6 μm were used for the calculations. Due to the low refractive index contrast, there is no complete 2D photonic band gap for either TE or TM polarizations. However, wide TE and TM stop gaps do exist in certain directions. As seen from the band diagrams, the TE stop gaps are wider than the TM gaps between the Γ - M and the Γ - K directions, and the central wavelength of the main gap for the TE mode is shorter than that for the TM mode. For both polarizations, the main stop gap positions shift to shorter wavelengths when the incident beam rotates from the Γ - M to the Γ - K direction.

Infrared spectra were measured using a Nicolet Nexus Fourier transform infrared (FTIR) spectrometer fitted with a 32 $\times$, NA of 0.65 reflective objective (Relechromat, Thermo Nicolet, Madison, WI), which provides an incident hollow light cone with an outer angle of 40 $^\circ$ and an inner angle of 15 $^\circ$. The measured transmission spectrum averages over the angular range from 15 $^\circ$ to 40 $^\circ$, corresponding to propagation angles of approximately 10 $^\circ$ -25 $^\circ$ inside the sample. Figure 2(a) shows FTIR spectra of the 2D photonic crystal when the maximum angle of incidence is confined to 15 $^\circ$, 20 $^\circ$, 23 $^\circ$, and 25 $^\circ$ by a circular aperture introduced after the objective. The fundamental gap shifts to shorter wavelengths and the suppression of IR transmission decreases for larger apertures due to averaging of band gap effects over a larger range of angles. The smallest aperture size, corresponding to a maximum angle of incidence of 15 $^\circ$, resulted in a suppression of transmission of 88%. Figure 2(b) shows the transmittance spectra for TE-, TM-, and nonpolarized light illumination when the smallest aperture size is used.¹⁹ The fundamental gap for the TE polarization is wider and deeper than that for

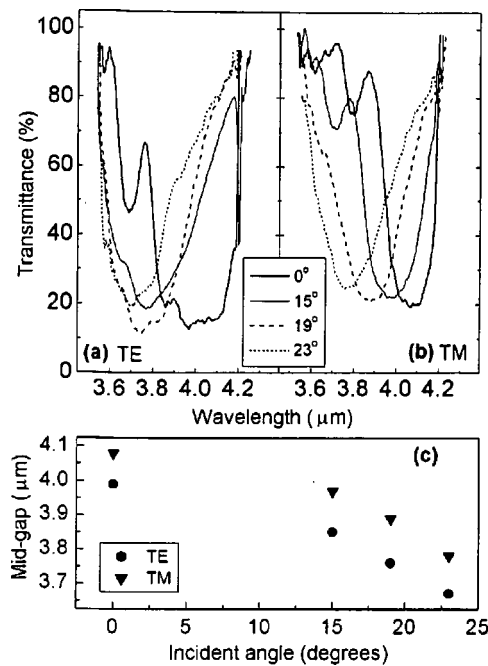


FIG. 3. TE (a) and TM (b) transmittance spectra of the 2D void channel photonic crystal at different in-plane directions of light incidence and dependence of the midgap wavelength on the angle of incidence (c).

the TM polarization with suppression of infrared transmittance as large as 96% and 85% for the TE and TM cases, respectively. This phenomenon is consistent with the band structure calculations. Physically, a stronger suppression can be achieved if more layers of channels are stacked.

Although the averaged transmission spectra already indicate strong stop gap effects, it is necessary to investigate the in-plane (i.e., the plane of incidence perpendicular to the void channels) angle dependence of the transmittance spectra which is important if 2D photonic crystals are used as a chip device. To this end, a small off-centered aperture corresponding to a half angle of 5 $^\circ$ was placed in front of the FTIR objective, resulting in angles of incidence of 15 $^\circ$, 19 $^\circ$, and 23 $^\circ$ by adjusting its position. By contrast, the illumination in the Γ - M direction (i.e., the 0 $^\circ$ angle of incidence) was achieved by tilting the sample perpendicular to the resulting incidence light cone. Figures 3(a) and 3(b) show the TE and TM in-plane transmittance spectra at various angles of incidence. The angle dependence of the midgap wavelength for both modes is plotted in Fig. 3(c). Increasing the angle of incidence (i.e., moving from the Γ - M direction toward the Γ - K direction) shifts the TE and TM gaps to short wavelengths. Moreover, the stop gaps for the TE mode are much wider than those for the TM mode. These phenomena are consistent with our band structure calculations as well as the observations on channel-type photonic crystals in glass.^{14,15}

Now let us turn to the out-of-plane (i.e., the plane perpendicular to the periodic plane which contains the Γ - M direction) TE and TM transmission spectra at various angles of incidence, as shown in Figs. 4(a) and 4(b). The dependence of the midgap wavelengths on the angle of incidence is shown in Fig. 4(c). Similar to the in-plane features, increasing the angle of incidence leads to a gap shift to shorter wavelengths for both TE and TM polarizations, which is in

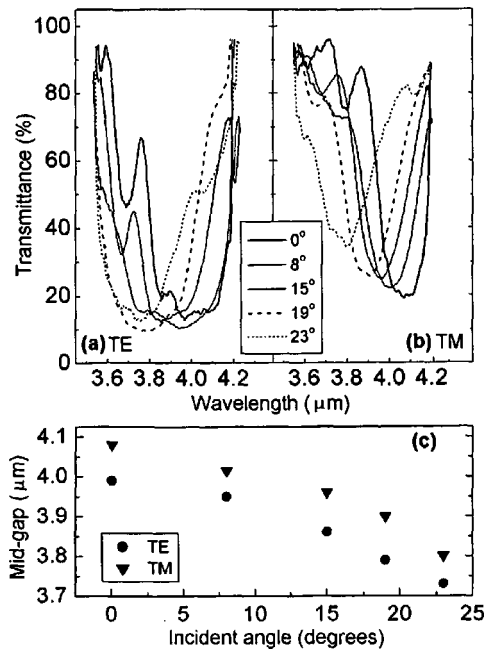


FIG. 4. Transmittance spectra of the 2D photonic crystal for TE-polarized (a) and TM-polarized illumination (b) at different out-of-plane directions of light incidence. The dependence of the midgap wavelength on the angle of incidence is given in (c).

agreement with the results reported by Foteinopoulou¹⁶ and Rosenberg.²⁰

As pointed out in our previous papers,^{17,18} the generation of void channels in solid polymer material results in compressed material regions of several hundred nanometers surrounding the channels as well as an increase of the effective refractive index n_{eff} of the polymer material due to its compression.¹⁸ The exact measurement of the void channel cross section A is not trivial because the structure is embedded in the polymer material. However, A and n_{eff} satisfy the Bragg condition:¹⁸

$$m\lambda_{\text{gap}} = 2\delta z \sin \theta n_{\text{avg}} = 2\delta z \sin \theta \left[n_{\text{eff}} - \frac{A}{\delta z \delta x} (n_{\text{eff}} - 1) \right], \quad (1)$$

where m is the order of the gap, n_{avg} is the average refractive index of the photonic crystal, and θ is the angle between the incident beam and the scattering plane. Equation (1) allows for the determination of the average refractive index and, hence, provides a way to derive A and n_{eff} from the experimental in-plane TE and TM transmittance spectra by comparison with the band structure calculations. From Fig. 3, we take the average of the mid-gap wavelengths for the TE (3.99 μm) and TM (4.06 μm) modes at perpendicular (0°) incidence as the gap position λ_{gap} to estimate $n_{\text{avg}} = 1.547$. For a given value of A , the effective refractive index n_{eff} is determined by Eq. (1). A series of band structure calculations was done for various values of A and n_{eff} . Figure 1(c) presents the dependence of the calculated TE and TM midgap wavelengths on the channel cross section A in the Γ - M direction. The difference between the TE and TM gap wavelengths increases with the channel cross section. A comparison of the measured TE and TM midgap wavelengths in the Γ - M di-

rection with the calculated ones reveals that the best-fitting length of the short axis is 0.4 μm as marked in Fig. 1(c). Using the result, the effective refractive index n_{eff} is calculated to be 1.606 from Eq. (1). We also point out that the variation of the channel cross section A and of the orientation of the noncircular channels with respect to the lattice structure allows for the optimization of the gap/midgap ratios.²¹

In summary, 2D triangular photonic crystals have been fabricated in a solid polymer material by femtosecond laser drilling of void channels. TE mode band gaps were found to be wider and located at shorter wavelengths in comparison with TM mode gaps, consistent with calculations. Upon rotation of the incident beam from the Γ - M direction toward the Γ - K direction, the stop gaps shift to short wavelengths, and a similar angle dependence is observed for out-of-plane light incidence. The polarization- and angle-dependent transmittance spectra provide a way to estimate the void channel cross section and the effective refractive index. Our results demonstrate that the 2D void channel polymer photonic crystals can be potential polarization-sensitive elements in a photonic chip.

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