

# Photonic band gaps and planar cavity of two-dimensional eightfold symmetric void-channel photonic quasicrystals

Guangyong Zhou<sup>a,b)</sup> and Min Gu<sup>a,c)</sup>

Centre for Micro-Photonics and Centre for Ultrahigh-bandwidth Devices for Optical Systems (CUDOS),  
Faculty of Engineering and Industrial Sciences, Swinburne University of Technology,  
P.O. Box 218, Hawthorn, Victoria 3122, Australia

(Received 3 April 2007; accepted 19 April 2007; published online 15 May 2007)

By using the femtosecond laser induced microexplosion method, high-quality two-dimensional eightfold photonic quasicrystals have been fabricated in a solid transparent polymer material. Multiorder band gaps have been observed in a 25-layer structure with a suppression rate of up to 72% for the fundamental gap. Polarization measurements show that the photonic quasicrystal has a strong anisotropic effect, showing that the transverse electric is the favorite polarization. Fabry-Pérot cavities have been fabricated by removing the central layer of channels. Based on the cavity mode position, the order of the mode and the effective cavity size have been determined.  
© 2007 American Institute of Physics. [DOI: 10.1063/1.2739090]

Photonic crystals (PhCs) have attracted much attention because they are believed to be the basic materials in the next generation communication techniques.<sup>1-4</sup> In a PhC, the dielectric constant is modulated periodically and results in the appearance of energy ranges called photonic band gaps (PBGs) in which the propagation of light is forbidden. If a PBG exists in all incident angles of light, it is called a complete PBG. Although three-dimensional (3D) complete PBG cannot exist in two-dimensional (2D) structures, 2D complete PBG is possible for certain polarized electromagnetic modes<sup>5,6</sup> and such structures can be used for devices such as PhC superprisms,<sup>7,8</sup> waveguides,<sup>9,10</sup> and cavities.<sup>11,12</sup> By employing PhCs with a complete PBG, substantial miniaturization of optical components without severe radiation losses can be achieved. However, to open a 2D complete PBG, the refractive index contrast needs to be larger than 2, which, in fact, rules out the possibility of using polymer materials to fabricate PhCs because their refractive indices are typically lower than 1.7.

Apart from periodic PhCs, another class of structures with quasiperiodic lattice, called photonic quasicrystals (PQCs), has attracted a considerable attention.<sup>13-16</sup> PQCs have neither a true periodicity nor a translational symmetry, but have a quasiperiodicity that exhibits a long-range order and an orientational symmetry. 2D PQCs have high-order rotational and mirror symmetries. Recent studies have demonstrated that 2D complete PBGs can also exist in several quasiperiodic patterns such as fivefold,<sup>17,18</sup> eightfold,<sup>18-21</sup> tenfold,<sup>15,18</sup> and 12-fold.<sup>16,22</sup> Compared with PhCs, PQCs have a smaller threshold value of refractive index to open a complete PBG.<sup>18,19</sup> For example, the threshold value is as small as  $n=1.26$  for an eightfold PQC, which indicates that optoelectronics components based on PQCs may be realized in low refractive index materials such as silica, glasses, and polymers. Most of researches are concentrated on the theoretical simulation and a few on fabrication of structures with dielectric rods in air. No paper has been found to study

the properties of an eightfold PQC with air holes in dielectric matrix.

Recently, we have developed an effective method to fabricate smooth void channels in a solidified polymer material (NOA63, Norland) by using tightly focused femtosecond-pulsed laser light.<sup>23-25</sup> During the microexplosion process, the material is pushed to the surrounding vicinity, generating smooth void channels surrounded by compressed regions with a higher effective refractive index of 1.65 compared with 1.56 of the pure sample.<sup>24</sup> This technique is a one-step approach, which does not require chemical postprocessing, and results in PhCs with a high degree of perfection. Here, we apply this technique to fabricate 2D eightfold PQCs in polymerized NOA63 resin. The polarization dependence, layer number dependence, and planar defects of such PQCs are studied in this letter.

Figure 1(a) shows the sketch of an eightfold PQC with air cylinders in dielectric material where the building tiles are depicted.<sup>18-21</sup> This pattern consists of 33 layers of void channels with a total number of 441. The lattice constant of an eightfold PQC is defined as the length of the side of a square which is also equal to the side of a rhombus, as illustrated in Fig. 1(a). The fabrication setup and blank sample preparation are the same as described elsewhere.<sup>23,25</sup> The

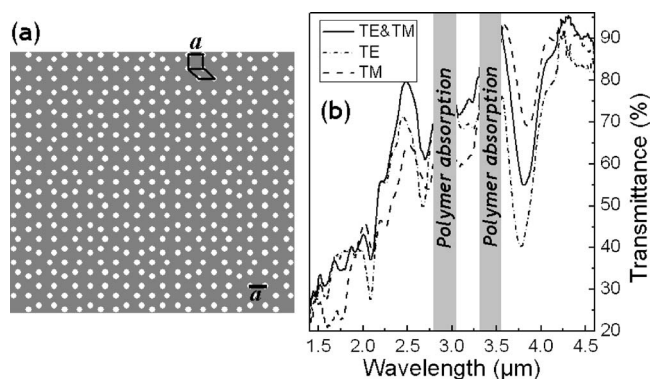


FIG. 1. (a) Sketch of an eightfold PQC with air holes (channels) in a dielectric matrix. (b) Transmission spectra of a 25-layer PQC with a lattice constant of  $1.6 \mu\text{m}$  for different polarizations. The scale bar indicates the lattice constant.

<sup>a)</sup> Authors to whom correspondence should be addressed.

<sup>b)</sup> Electronic mail: gzhou@swin.edu.au

<sup>c)</sup> Electronic mail: mgu@swin.edu.au

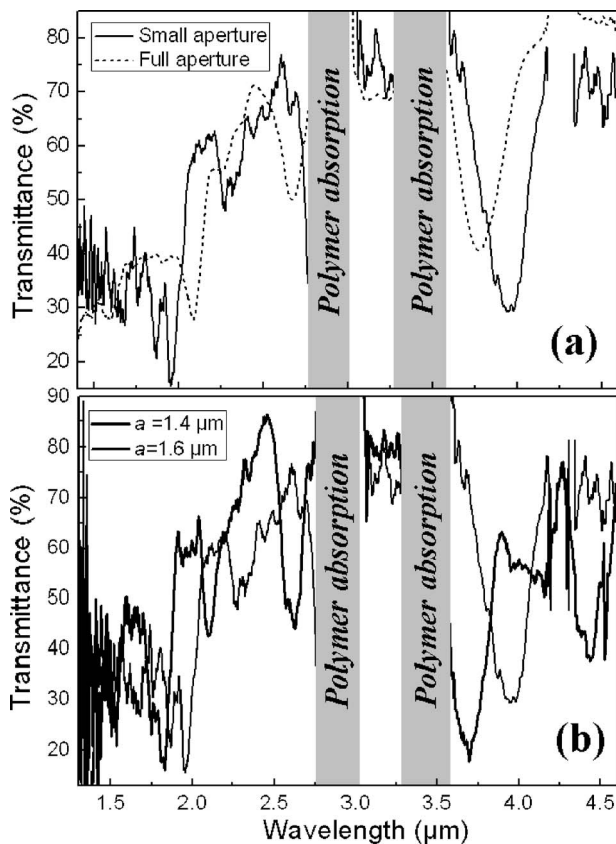


FIG. 2. (a) Transmission spectra of a 25-layer PQC measured with (solid curve) and without (dotted curve) small aperture. (b) Transmission spectra of 25-layer PQCs with different lattice constants.

light power (measured before the back aperture of the objective) of 20 mW and a scanning speed of 500  $\mu\text{m}/\text{s}$  were used, which result in smooth void channels with a diameter of  $\sim 0.6 \mu\text{m}$ .<sup>25</sup> Micron-sized channels with a length of 100  $\mu\text{m}$  were fabricated parallel to the surface. In order to minimize the refractive index induced aberration,<sup>26</sup> all structures were fabricated as close to the surface as possible, with the top layer of 5  $\mu\text{m}$  beneath the top surface of the polymer sample.

Transmission spectra are the best and simplest way to characterize the fabricated PQCs. A Nicolet Nexus Fourier transform infrared (FTIR) spectrometer fitted with a 32 $\times$ , 0.65 numerical aperture (NA) reflective objective (Reflomat, Thermo Nicolet, Madison, WI) was used to measure the transmission spectra. The objective provides an incident hollow light cone with an outer angle of 40° and an inner angle of 15°. The measured transmission spectra are averaged over the angular range from 15° to 40°, corresponding to the propagation angles of approximately 10°–25° inside the sample.<sup>25</sup> The solid curve in Fig. 1(b) shows the transmission spectra of a PQC with 25 layers of void channels. The strong suppression rate of 45% at a wavelength of 3.6  $\mu\text{m}$  and obvious higher-order gaps indicate the high quality of the PQC. Similar to 2D photonic crystal,<sup>25</sup> the photonic band gap of the PQC also has strong polarization dependence. For the transverse electric (TE) polarization where the electric field is perpendicular to the void channels, the suppression rate of the transmission spectra can be up to 60%. While for the transverse magnetic (TM) polarization where the magnetic field is perpendicular to the void channels, the suppression rate is much smaller (30%). One may

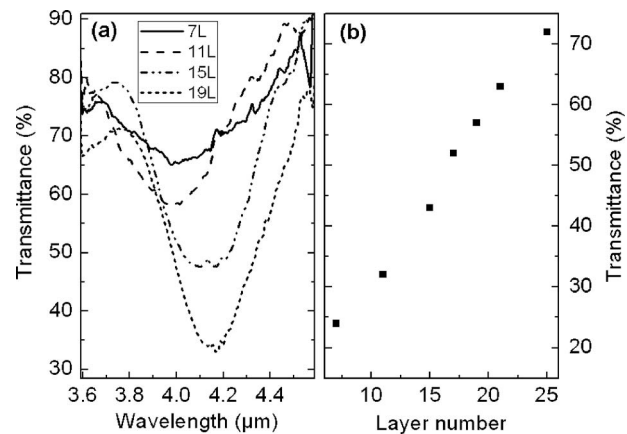


FIG. 3. (a) Transmission spectra of the main gap for different layers of PQCs. (b) The dependence of the suppression rate as a function of layer numbers for an eightfold PQC.

use the strong polarization dependence to design and fabricate a microsized polarizer which may be used in all-optical chips.

To reduce the angle of incidence, a small off-centered aperture corresponding to a half angle of 5° was placed in front of the FTIR objective. By tiling the sample perpendicular to the incidence light cone, a near-zero degree angle of incident was achieved.<sup>27</sup> The solid curve in Fig. 2(a) shows the transmission spectra after the use of a small aperture of the same PQC as the one in Fig. 1. Compared with the one measured without aperture (dotted curve), the suppression rate of the fundamental gap increases from 60% to 72%. Apart from the fundamental gap, the suppression rates of some smaller drops at shorter wavelengths in the transmission spectra also increase. There is only a tiny dip at 2.2  $\mu\text{m}$  without the aperture but it increases to 15% with the aperture. Another feature is that there is clear shift for all gaps/drops but not with the same trend. The fundamental gap shifts from 3.77 to 3.95  $\mu\text{m}$  (180 nm) after the use of the aperture. The drops at 2.2 and 2.75  $\mu\text{m}$  (fall within the absorption band of the polymer) also shift to longer wavelengths. However, the drop at 2.15  $\mu\text{m}$  shifts to a shorter wavelength (1.95  $\mu\text{m}$ ). Compared with a 2D PhC in the same material,<sup>25</sup> a 2D PQC has a much completed transmission spectral structure. The possible reason is that the PQC has two different layer spacings between two adjacent layers whereas the PhC only has one layer spacing. Such an abundant spectral structure may enable people to develop a device which can operate at different wavelengths simultaneously.

In order to study the layer dependence of the band gap, PQCs with different layers of channels were fabricated. Figure 3(a) shows the transmittance spectra of PQCs with various layers of void channels measured with the small aperture. In a PQC with seven layers of channels, a clear suppression ( $\sim 24\%$ ) can be observed [Figs. 3(a) and 3(b)]. By increasing the layer number, the suppression rate increases dramatically. For a 25-layer structure, the normalized suppression rate is up to 72%. Although further increasing the layer number can still increase the suppression rate, the increased thickness makes the fabrication process difficult because the slight refractive index mismatch between the polymer (1.56) and the immersion oil (1.52) introduces a strong aberration for a high NA (1.4) objective.<sup>26</sup>

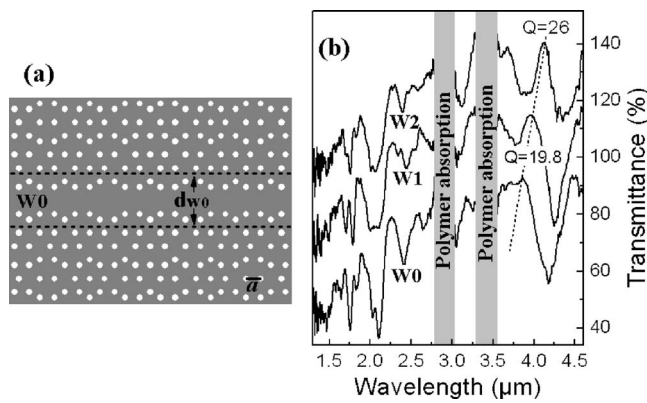


FIG. 4. (a) Sketch of a planar cavity after removing the central layer of channels. (b) Transmission spectra of PQC with different sizes of planar cavities. The scale bar indicates the lattice constant.

A planar microcavity in PhCs (Refs. 11, 12, and 27) is an important defect category which may be a key component in the photonic chips. By removing the central layer of void channels from the PQC, a Fabry-Pérot resonator was fabricated, named as W0, as shown in Fig. 4(a). In contrast with the periodic PhC lattice, the walls of the waveguide are not flat with the maximum and minimum widths of 2.26 and 3.2  $\mu\text{m}$  at different positions. By shifting the top part of the PQC upward by 0.2 and 0.4  $\mu\text{m}$ , cavities with different cavity sizes can be obtained, named as W1 and W2, respectively. Figure 4(b) shows the transmission spectra of the PQC with different planar cavities measured with the small aperture. For the cavity W2, a clear cavity mode can be observed at 4.11  $\mu\text{m}$  inside the band gap (the top curve). As it locates at near the center of the band gap, the strong reflection from two parts of the PQC makes the cavity mode strong and sharp with a quality factor ( $Q$  factor) of 26. For cavity W1 with a smaller cavity spacing, the cavity mode shifts to a shorter wavelength of 3.95  $\mu\text{m}$  (the middle curve). As the reflection reduces for a wavelength away from the gap center, the  $Q$  factor reduces to 19.8 for W1. For W0 with a further reduced cavity spacing, the cavity mode shifts to 3.79  $\mu\text{m}$  which locates at the edge of the band gap (the bottom curve). Based on the positions of modes in different cavities, we can calculate the order of the mode and the effective width of the cavities. For a simple Fabry-Pérot étalon, the following relationship holds:

$$m\lambda = 2nd \cos \theta_{\text{FP}}, \quad (1)$$

where  $\lambda$  is the central wavelength of a cavity mode, the integer  $m$  is the order of the cavity mode,  $\theta_{\text{FP}}$  is the internal light propagation angle, and  $n$  and  $d$  are the refractive index and the effective spacing of the cavity, respectively. After the use of an aperture,  $\theta_{\text{FP}}$  is reduced to  $\sim 5^\circ$  and therefore  $\cos \theta_{\text{FP}} \sim 1$ . Based on Eq. (1) and the central wavelength of W1 and W2, the order of the cavity mode can be expressed as

$$m = \frac{2n(d_{\text{W2}} - d_{\text{W1}})}{\lambda_{\text{W2}} - \lambda_{\text{W1}}} = \frac{2 \times 1.56 \times 0.2}{4.11 - 3.95} \approx 4. \quad (2)$$

So the effective cavity spacing can be calculated as  $d_{\text{W0}} = 5.04 \mu\text{m}$ ,  $d_{\text{W1}} = 5.06 \mu\text{m}$ , and  $d_{\text{W2}} = 5.08 \mu\text{m}$ . Compared with the physical widths of the cavity, 2.36 and 3.2  $\mu\text{m}$  for W0, the effective width is almost doubled, which means that

the effective reflection surfaces are not at the walls of the cavity but at a position inside the PQC. The effective cavity for the W0 cavity is illustrated in Fig. 4(a). This is because the reflection needs to be built up through interference after a couple of layers of voids.

In summary, high quality 2D eightfold PQC with void channels in a dielectric matrix have been fabricated by using a femtosecond laser-induced microexplosion method. Polarization measurements show that the suppression rate is much bigger for TE modes than TM modes. The suppression rate of 72% has been achieved for a PQC with 25 layers of void channels. Planar cavities have been fabricated by removing the central layer of channels. Infrared transmission measurements revealed a pronounced cavity mode which is explained by using a simple reflective surface Fabry-Pérot model. Our results suggest that an eightfold PQC and related microdevices may play an important role as periodic PhCs would do.

The work is supported by an Australian Research Council (ARC) Discovery Project Grant (DP0665868) and the ARC Centre of Excellence for Ultrahigh Bandwidth Devices for Optical Systems (CUDOS) (CE0348259).

- <sup>1</sup>S. John, Phys. Rev. Lett. **58**, 2486 (1987).
- <sup>2</sup>E. Yablonovitch, Phys. Rev. Lett. **58**, 2059 (1987).
- <sup>3</sup>S. Y. Lin, J. G. Fleming, D. L. Hetherington, B. K. Smith, T. Biswas, K. M. Ho, M. M. Sigalas, W. Zubrzycki, S. R. Kurtz, and Jim Bur, Nature (London) **394**, 251 (1998).
- <sup>4</sup>Z. Y. Li and Z. Q. Zhang, Phys. Rev. B **62**, 1516 (2000).
- <sup>5</sup>S. Fan, P. R. Villeneuve, J. D. Joannopoulos, and H. A. Haus, Phys. Rev. Lett. **80**, 960 (1998).
- <sup>6</sup>M. Qiu and S. He, J. Opt. Soc. Am. B **17**, 1027 (2000).
- <sup>7</sup>S. Y. Lin, V. M. Hietala, L. Wang, and E. D. Jones, Opt. Lett. **21**, 1771 (1996).
- <sup>8</sup>H. Kosaka, T. Kawashima, A. Tomita, M. Notomi, T. Tamamura, T. Sato, and S. Kawakami, Phys. Rev. B **58**, R10096 (1998).
- <sup>9</sup>Woo Jun Kim and John D. O'Brien, J. Opt. Soc. Am. B **21**, 289 (2004).
- <sup>10</sup>Andrei Faraon, Edo Waks, Dirk Englund, Ilya Fushman, and Jelena Vučković, Appl. Phys. Lett. **90**, 073102 (2007).
- <sup>11</sup>M. M. Beaky, J. B. Burk, H. O. Everitt, M. A. Haider, and S. Venakides, IEEE Trans. Microwave Theory Tech. **47**, 2085 (1999).
- <sup>12</sup>H. B. Sun, V. Mizeikis, Y. Xu, S. Juodkazis, J. Y. Ye, S. Matsuo, and H. Misawa, Appl. Phys. Lett. **79**, 1 (2001).
- <sup>13</sup>W. Man, M. Megens, P. J. Steinhardt, and P. M. Chaikin, Nature (London) **436**, 993 (2005).
- <sup>14</sup>B. Freedman, G. Bartal, M. Segev, R. Lifshitz, D. N. Christodoulides, and J. W. Fleischer, Nature (London) **440**, 1166 (2006).
- <sup>15</sup>M. Notomi, H. Suzuki, T. Tamamura, and K. Edagawa, Phys. Rev. Lett. **92**, 123906 (2004).
- <sup>16</sup>M. E. Zoorob, M. D. B. Charlton, G. J. Parker, J. J. Baumberg, and M. C. Netti, Nature (London) **404**, 740 (2000).
- <sup>17</sup>P. Guyot, P. Kramer, and M. de Boissieu, Rep. Prog. Phys. **54**, 1373 (1989).
- <sup>18</sup>M. Hase, H. Miyazaki, M. Egashira, N. Shinya, K. M. Kojima, and S. Uchida, Phys. Rev. B **66**, 214205 (2002).
- <sup>19</sup>J. Romero-Vivas, D. N. Chigrin, A. V. Lavrinenko, and C. M. Sotomayor Torres, Opt. Express **13**, 826 (2005).
- <sup>20</sup>S. S. M. Cheng, L. M. Li, C. T. Chan, and Z. Q. Zhang, Phys. Rev. B **59**, 4091 (1999).
- <sup>21</sup>Y. S. Chan, C. T. Chan, and Z. Y. Liu, Phys. Rev. Lett. **80**, 956 (1998).
- <sup>22</sup>Y. W. Wang, X. Hu, X. Xu, B. Cheng, and D. Zhang, Phys. Rev. B **68**, 165106 (2003).
- <sup>23</sup>M. J. Ventura, M. Straub, and M. Gu, Appl. Phys. Lett. **82**, 1649 (2003).
- <sup>24</sup>M. Straub, M. Ventura, and M. Gu, Phys. Rev. Lett. **91**, 043901 (2003).
- <sup>25</sup>G. Zhou, M. J. Ventura, M. Straub, M. Gu, A. Ono, S. Kawata, X. Wang, and Y. Kivshar, Appl. Phys. Lett. **84**, 4415 (2004).
- <sup>26</sup>D. Day and M. Gu, Appl. Opt. **37**, 6299 (1998).
- <sup>27</sup>M. J. Ventura, M. Straub, and M. Gu, Opt. Express **13**, 2767 (2005).