Appl. Phys. B 81, 465–467 (2005)
DOI: 10.1007/s00340-005-1882-6

Applied Physics B
Lasers and Optics

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Enlargement of complete two-dimensional band gap by using photonic crystal heterostructure

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Received: 8 December 2004 / Revised version: 27 April 2005
Published online: 21 June 2005 •

ABSTRACT A two-dimensional photonic crystal heterostructure, which consists of two photonic crystals of a square lattice of circular columns with reverse dielectric configurations, is proposed. Photonic band gap properties are calculated using a plane-wave method and the transmission spectra are obtained. After optimization, the relative width of the complete band gap reached 13.8% based on the simple unit-cell shape and crystal lattice. The photonic crystal heterostructure opens up new ways of engineering photonic band gap materials and designing photonic crystal devices.

PACS 42.70.Qs; 42.25.Bs

1 Introduction

In recent years, much attention has been drawn towards two-dimensional (2D) photonic crystals (PCs) because they are much easier to fabricate than three-dimensional photonic crystals in the visible and infrared region and have many promising applications, e.g. feedback mirrors, plane waveguides and photonic crystal fibers [1–3]. Since the novel applications of PCs mainly result from the photonic band gap (PBG), crystal structures with a band gap as large as possible are desired.

In the 2D PCs, an electromagnetic wave can be decomposed into the transverse electric (TE) and transverse magnetic (TM) polarization modes. The complete band gap exists only when band gaps in both polarization modes are present and they overlap each other. Physical arguments suggest that connectivity of high-ε regions is conducive to TE gaps, and isolated patches of high-ε regions lead to TM gaps [4]; however, it seems difficult to arrange a crystal structure with both isolated spots and connected regions of high-ε dielectric material. For the square lattice of cylinders, each of the two polarization mode band gaps exist, but there is some discrepancy about whether a complete band gap is present [4–6]. Our calculations for the square lattice of cylinders at the dielectric contrast of 11.4:1 show that both dielectric rods in air and air columns in the dielectric cannot give birth to complete band gaps in any filling fractions. Recently, it was found that symmetry breaking is helpful to obtain a larger complete band gap [6, 7], e.g. two sets of air inclusions and anisotropic inclusions were used. Other 2D PCs with different lattice structure, unit cell or dielectric configuration were also investigated later [8–11]. Very recently, a genetic algorithm was introduced to design a photonic crystal structure with large-width complete band gaps [12], but the complex unit-cell shape makes the structure more difficult to fabricate.

In solid-state physics, it is well known that many novel features for electronic properties appear when two semiconductors form a heterostructure. Recently, one-dimensional and 2D photonic heterostructures were proposed to widen the nontransmission frequency range [13, 14]. In this paper, we will show theoretically that the enlargement of complete band gaps can also be realized by using a 2D photonic crystal heterostructure.

The proposed 2D photonic crystal heterostructure is shown in Fig. 1c, which consists of two photonic crystals with a square lattice of circular columns. The first (denoted as PcA) is composed of dielectric cylinders in air and the second (denoted as PcB) is composed of air cylinders in dielectric. It is noticeable that the structure of PcA favors a TM mode band gap while the structure of PcB favors a TE mode band

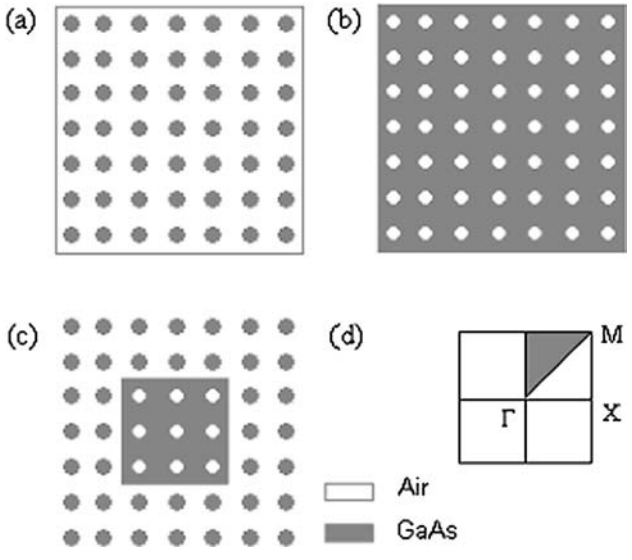

FIGURE 1 Schematic representation for **a** dielectric cylinders in air, **b** air cylinders in dielectric, **c** 2D photonic crystal heterostructure, **d** the irreducible Brillouin zone (light gray) of a square lattice with symmetry points Γ, X and M

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gap. After PcB is embedded into the center part of PcA as a defect, a complete photonic band gap will be expected in the composite structure. The dielectric constants of the constituent materials are $\varepsilon\,\text{air} = 1$ and $\varepsilon\,\text{dielectric} = 11.4$ (ε GaAs at $\lambda \approx 1.5$ um), respectively.

2 Results and discussion

In the present paper, the photonic band structures have been calculated using the plane-wave expansion technique, described in detail in the literature [15–17]. The results were obtained using 625 plane waves. When using 900 plane waves, the five lowest band frequencies for both TE and TM polarizations differed from those calculated with fewer plane waves by a maximum of 0.1%.

Figure 2 shows how the band gaps vary as the radius of the columns changes when $a = b$, where a is the lattice constant of PcA and b is the lattice constant of PcB. The band gaps for the TM mode of PcA and the TE mode of PcB are indicated by the regions with different gray levels. The gap map shows one gap for the TM mode and two gaps for the TE mode in the frequency range displayed. The two overlapped frequency regions (from $0.340(2\pi c/a)$ to $0.498(2\pi c/a)$ and from $0.239(2\pi c/a)$ to $0.364(2\pi c/a)$) will be able to offer a complete two-dimensional photonic band gap as desired.

We choose the upper overlapped frequency regions because the upper TE band gap is larger than the lower one. In Fig. 3, the relative band-gap width, defined as the gap width divided by the mid-gap frequency, is plotted with respect to the radius of cylinders for the upper overlapped frequency regions shown in Fig. 2. For the TM mode, the maximum value occurs when $r = 0.19a$ with a maximum value $\Delta\omega/\omega_0 = 37.8\%$, where $\Delta\omega = 0.138(2\pi c/a)$ and $\omega_0 = 0.365(2\pi c/a)$. For the TE mode, the peak value is $\Delta\omega/\omega_0 = 13.8\%$ when $r = 0.44a$, where $\Delta\omega = 0.061(2\pi c/a)$ and $\omega_0 = 0.442(2\pi c/a)$.

When PcA and PcB have the same periodicity and the relative band gaps of the two modes both reach the maximum value, the mid-gap frequencies of the two modes are different, which means that the overlapping is not optimal. Based on the scaling property of Maxwell's equations, the photonic band frequency is directly related to the lattice constant, so we can improve the frequency-overlapping condition simply by scaling up or down the lattice constant of one Pc. In this work, the lattice constant of PcB is chosen to be $1.212a$, according to the mid-gap frequency ratio $\omega_0/\omega_0' = 0.365/0.442$, where ω_0 and ω_0' are the mid-gap frequencies shown above.

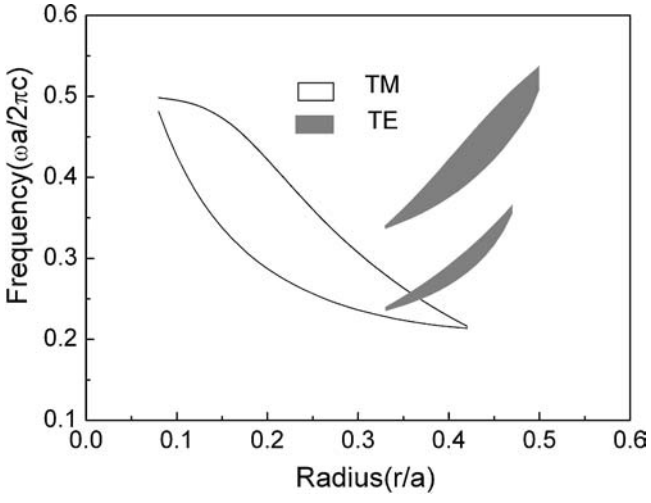

FIGURE 2 Gap map for TM mode of PcA and TE mode of PcB when $a = b$

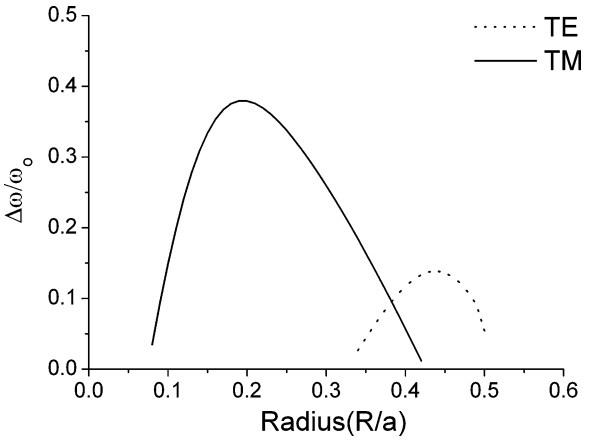

FIGURE 3 Relative band gap as a function of the radius of the rods for TM mode of PcA (*solid line*) and TE mode of PcB (*dotted line*) when $a = b$

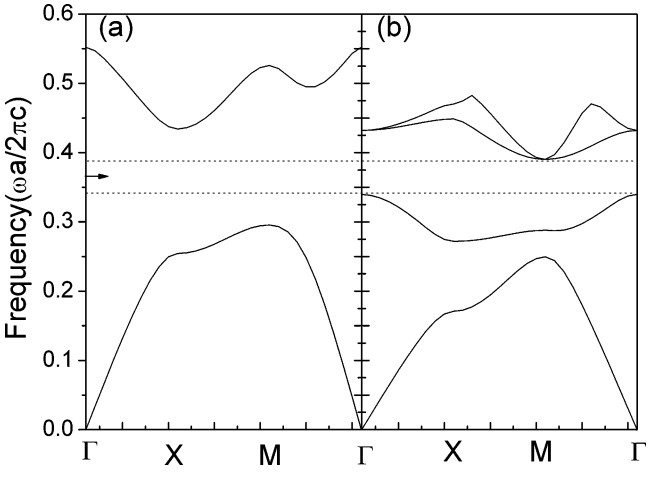

FIGURE 4 Photonic band structure for **a** TM mode of PcA and **b** TE mode of PcB when $b/a = 1.212$. The areas between the *two dashed lines* represent the complete band gap of the heterostructure

Figure 4 gives the photonic band structure calculated for the TM mode of PcA and the TE mode of PcB when $b = 1.212a$. The common forbidden frequency region, from $0.339(2\pi c/a)$ to $0.390(2\pi c/a)$, represents the 2D complete PBG of the heterostructure. Transmission of the two-dimensional photonic crystal heterostructure, calculated by the Translight program [18], is displayed in Fig. 5. The electromagnetic wave propagates through eight rows of dielectric cylinders of PcA and eight rows of air cylinders of PcB at the incident angles of 0°, 45° and 89° (corresponding to ΓX, ΓM and MX directions) in the plane, respectively. The TM mode nontransmission frequency region reads from $0.265(2\pi c/a)$ to $0.426(2\pi c/a)$ while the TE mode nontransmission frequency region reads from $0.347(2\pi c/a)$ to $0.402(2\pi c/a)$. The common nontransmission frequency region, from $0.347(2\pi c/a)$ to $0.402(2\pi c/a)$, is in good agreement with the results of the photonic band structure calculation.

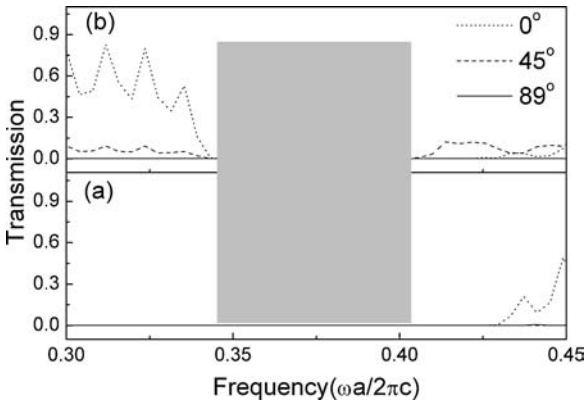

FIGURE 5 Calculated optical transmission of the 2D photonic crystal heterostructure at different incident angles when $b/a = 1.212$. The *dotted*, *dashed* and *solid lines* stand for 0°, 45° and 89° incident angles; **a** and **b** represent the transmissions of TM and TE modes, respectively. The computational program is available from Andrew L. Reynolds, University of Glasgow, UK

The efficiency of photonic crystals is mainly determined by the photonic band gap width. The absolute gap width of the heterostructure is $0.051(2\pi c/a)$ and the relative width reaches 13.8%, which is nearly 2.7 times larger than the best value $[0.0188(2\pi c/a)]$ obtained for the single square lattice of cylinders [6], nearly 1.4 times larger than the maximal value $[0.035(2\pi c/a)]$ found for a square lattice of anisotropic inclusions [7], approximately the same as the maximal value $[0.0548(2\pi c/a)]$ obtained in a symmetry-reduced square lattice by using two sets of air inclusions [6], less than the band gap $[0.076(2\pi c/a)]$ obtained in a structure formed by connecting dielectric rods with veins [11] and less than the band gap $[0.157(2\pi c/a)]$ obtained in a structure designed by a genetic algorithm [12], but considering the complex structure or unit-cell shape in Refs. [6, 7, 11, 12], our structure has an obvious advantage from a fabrication point.

It is worth noting that the complete photonic band gaps obtained with the composite heterostructure discussed here differ from the ones obtained with a single photonic crystal. In the heterostructure, the polarization band gaps were obtained separately with an independent photonic crystal. With the wide complete band gaps and extra ability to control TE and TM polarizations separately, some novel photonic crystal devices with special properties will be innovated, e.g. designing the shape of PcB deliberately or introducing defects in PcB. This heterostructure, therefore, could have potential applications ranging from photonic crystal fibers to optical microcavities. In addition, as the inevitable compromise which comes from two polarization band gaps' opposite requirements on the dielectric configuration when demanding that a single-crystal structure with complete band gaps is avoided, a much larger complete photonic band gap will be expected by designing specific structures with adequately large band gaps for one polarization and overlapping them properly using the heterostructure.

3 Conclusion

In this paper, we have proposed a two-dimensional photonic crystal heterostructure which consists of two reverse dielectric configuration photonic crystals with a square lattice of circular columns. The composite structure enlarges the photonic band gap substantially, and holds the advantage of easy fabrication. Furthermore, the TM mode and the TE mode band gaps are obtained from two PCs independently, which bring flexibility in the work to obtain a complete 2D PBG. The photonic crystal heterostructure, therefore, opens up new ways of engineering photonic band gap materials and designing photonic crystal devices.

ACKNOWLEDGEMENTS One of the authors (D.D. Wang) would like to thank Ph.D. Z. Wang sincerely for helpful discussions. This work was supported by the School Foundation of Beijing Jiaotong University (DXJ02006) and the Doctor Innovation Foundation of School of Science, Beijing Jiaotong University.

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