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Two-dimensional ring-type photonic crystals in the near-infrared region*

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We propose a ring photonic crystal working in the near infrared region, where the air holes in the background material GaAs are arranged to form a series of rings. We find that the band gaps do not depend on the incident direction, and only a small number of rows are needed to create a frequency gap in the transmission spectrum. The transmission spectra of both P and S polarizations show that there is a complete bandgap in the hexagonal ring photonic crystals and the ratio of gap width to mid-gap frequency is as high as 11%.

Keywords: ring photonic crystals, direction-independent, complete band gap
PACC: 4270Q, 7820P, 7865K

The existence of spectral gap in the electromagnetic wave spectrum opens up many exciting applications, such as waveguides,[1,2] quantum electronic devices,[3] high-Q cavities,[4] laser diodes,[5] optical filter,[6] optical switches,[7] and wavelength division multiplexing (WDM).[8,9] All of these are important in optical communication and other aspects. In the past decades, the periodic photonic crystals (PCs),[10] as well as the quasiperiodic PCs,[11–14] have been extensively investigated. Chan *et al* and Jin *et al* analysed the photonic band gap in two-dimensional (2D) photonic quasicrystals with dielectric cylinders, respectively.[15,16] They found that the quasicrystalline lattice could possess direction-independent photonic band gaps. However, in these systems, there are no complete band gaps for both S and P polarized waves, if a reasonable value of the dielectric constant is taken. The photonic band gap is affected by the structure of the photonic crystals.[17,18] Practically, the PCs made of air holes and high dielectric backgrounds are more suitable for the devices. Zhang *et al*[13] demonstrated that, for a kind of 12-fold symmetric quasicrystal consisting of air holes and dielectric background, a 2D complete photonic gap can appear, but the ratio of gap width to mid-gap frequency is quite small, $\omega_{\rm gap}/\omega_{\rm midgap}$=3%, with a dielectric constant of 11.4 (Fig.6 of Ref.[13]). Here we propose a ring PC, whose band gap is independent of the incident direction, and the corresponding ratio can reach $\omega_{\rm gap}/\omega_{\rm midgap}$=11%.

The 2D ring PC is formed by air holes with circular cross sections and dielectric background. The air holes occupy the vertices of a series of rings, which have different radii, but the same centre, as shown in Fig.1. Assuming the radius of the first ring is R, that of the nth ring is nR and the number of holes in the first ring is m, the number of holes in the nth circular ring is mn, where n and m are positive integers. The ring PC is constituted of 331 air holes, which form 10 circular rows from the centre to the outmost part. The spacing between the neighbouring rows is the same as the radius of the first ring, i.e. 0.4μm, and the radius r of the air hole is 0.18μm. In our simulation, GaAs is selected as a background material, which has a dielectric constant of 11.4.

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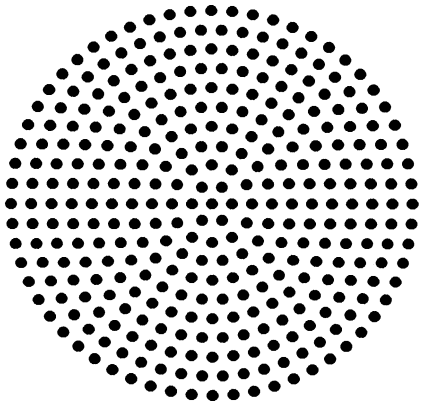


Fig.1. Schematic figure showing the ring arrangement of holes.

We first consider the transverse electric mode (P polarization), where the polarization direction of electric field $\boldsymbol{E}$ lies in the 2D plane. The transmission spectra of the ring PC are calculated with the multiple-scattering method.[19,20] In our calculations, we assume that the incident beam passes through a slit with a width of $4R$, which is located in front of the sample at a distance of $9R$. Figure 2 shows the transmission spectra of the ring PC of P polarization. There is a low transmission range from 1280 to 1800nm with an average transmittance of –49dB. The photonic gap is located between 1300 and 1570nm, and the gap-midgap ratio is 19%. From Fig.2, we can see the effects induced by the disorder at the band edge, especially around 1700nm, where some modes exist, even though the transmittances are quite low. This means that, strictly speaking, the ring PCs possess a pseudogap because of an imperfect periodicity, i.e. within the gap the density of states is very small, instead of zero. The situation is quite similar to the electronic states in quasicrystal and amorphous solids. From the viewpoint of device application the pseudogap plays the same role as the gap. Actually, disorder exists in all real structures. We further calculate the transmission spectra of the ring PC in various incident directions, and the results are shown in Fig.3. It should be noted that the ring structure has a sixfold symmetry, and in each 60° sector the distribution of the holes has a mirror symmetry with respect to the line of 30°. Therefore, for the ring crystals, we need only calculate the transmission at incident angles between 0° and 30°. From Fig.3, it can be seen that the location and the width of the band gaps do not shift as the incident angle varies. The edges of lower and higher frequencies, 1300 and 1570nm, remain unchanged. It may be concluded that, in a 2D ring PC, the band gaps of P polarization are independent of the incident direction. This is an interesting effect, which may have important applications in photoelectric devices.

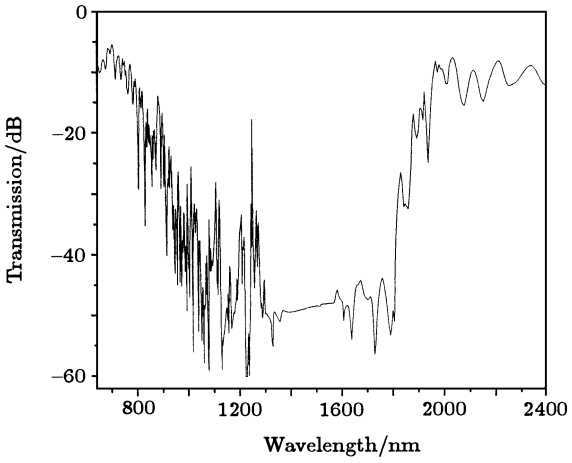


Fig.2. P polarization transmission spectra for the ring photonic crystal.

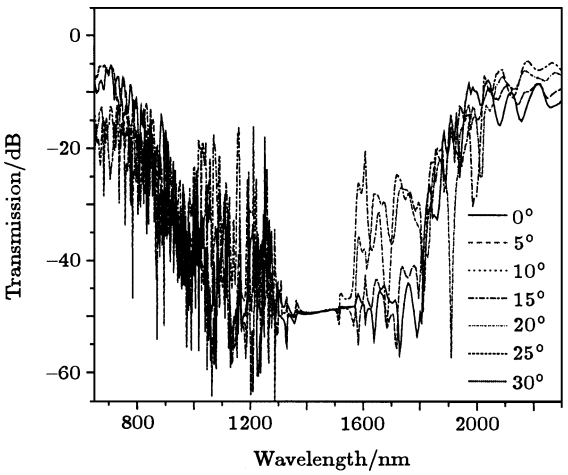


Fig.3. P polarization transmission spectra at various incident angles for the ring photonic crystal, namely 0, 5, 10, 15, 20, 25, 30°.

It has been demonstrated that a periodic 2D PC or a 2D quasi-period crystal with a few rows of dielectric column or air column in the incident direction can still have a photonic band gap.[14] We subtract the rows from the outmost part, and calculate their transmission spectra, as shown in Fig.4. As the air holes are gradually decreased from 11 to 7 rows, the lower and higher band gap edges and the band gap widths remain almost unchanged. Meanwhile, the transmittance inside the gap varies from the original –54dB to –31dB. In the last case, with 7 rows of holes, the crystal is very small, with radius of only about 5.6μm, but it still has a band gap effect.

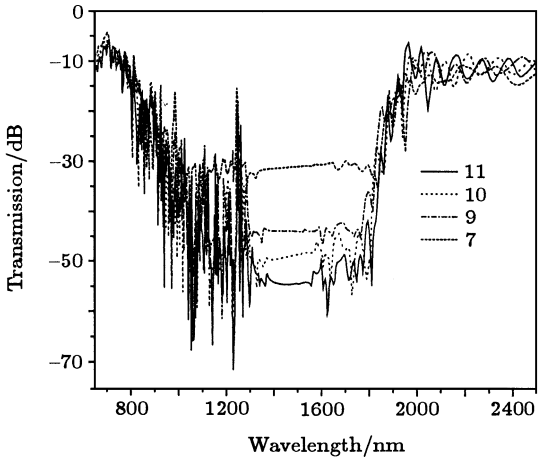


Fig.4. Transmission spectra for the ring crystals with different numbers of holes row for hexagonal ring crystal, namely 11, 10, 9 and 7 rows.

From the above calculated result, we know that there is a direction-independent band gap for P polarization. Then we consider the S polarization incidence to judge whether the P polarization photonic band gap overlaps with the S polarization band gap, i.e. whether there is a complete band gap. The crystal we used now is a 7-row ring crystal, and the dielectric constant of the background and the radius of the first ring are the same as previous ones. When the filling fraction is small, we do not find the overlapping of the P polarization gap with the S polarization gap. As the ratio r/R reaches 0.4, a complete gap is found. The transmission spectra of the PC with r/R=0.475 for both P and S polarizations are shown in Fig.5. The overlapping gap is in a range from 1450 to 1620nm, which just involves the optical communication wavelength 1550nm. The maximum gap–midgap ratio is about $\omega_{\rm gap}/\omega_{\rm midgap}$=11%. Then the complete band gap is much larger than that in quasiperiodic PC. By using the e-beam or ion-beam lithography, such a ring structure may be fabricated.

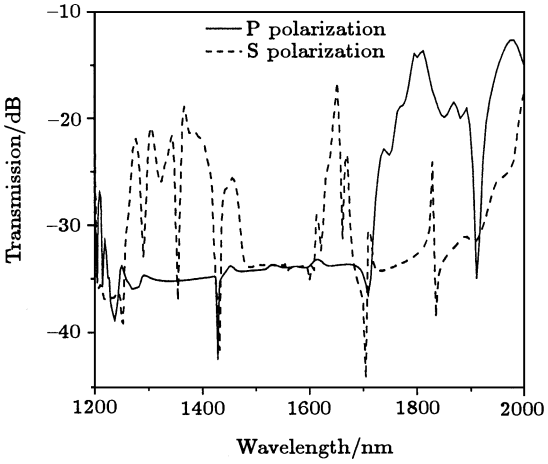


Fig.5. Transmission spectra for the ring crystal with different air hole radius r, the solid line is P polarization the dotted line is S polarization; the radius of the first ring R=0.4μm, and r/R=0.475.

In summary, 2D air-hole ring PCs have been investigated by the multiple-scattering method. We find that these PCs have direction-independent band gap. When the filling fraction is large enough, a wide complete band gap emerges covering the wavelength of optical communication. Therefore, these ring PCs may have some important applications in photoelectric devices.

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