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Band gap and wave guiding effect in a quasiperiodic photonic crystal

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A two-dimensional octagonal quasiperiodic photonic crystal composed of alumina cylinders is prepared. The transmission spectra of the quasicrystal are measured in the microwave region for the TM wave. We find that the position and width of the band gap do not depend on the incident direction, while the band structure can appear for quite a small piece of the quasicrystal. Two types of waveguide, a straight guide and a bending guide with two sharp 90° corners, are fabricated by removing three rows of cylinders. The measured transmittances show that the guiding efficiency for both waveguides is high. © *1999 American Institute of Physics.* [S0003-6951(99)04239-4]

Since photonic crystals were proposed more than ten years ago, many theoretical and experimental works have been devoted to this new field and great progress has been made.[1–7] The dielectric or metallic periodic structure gives rise to photonic band gaps, which essentially change the properties of light propagation. A variety of applications, for example thresholdless lasers, microwave antennas, light diodes and all-optical circuits, have been suggested and some already demonstrated.[1–4] Recently, Chan *et al.* calculated the density of state in a photonic quasicrystal instead of in the periodic crystal, and found that there the photonic band gap existed as well.[8,9] Their work shows that a long range periodic order is not a necessary condition for the existence of photonic bands in a two-dimensional (2D) dielectric structure, though it has been known in a one-dimensional Fibonnaci sequence.[10] Meanwhile, investigations also demonstrated that the waveguide in a periodic photonic crystal can guide electromagnetic waves either along a straight path or around a sharp 90° corner with great efficiency.[11,12] A quasicrystal possesses many inequivalent sites, which may result in a more interesting wave guiding effect than in a periodic system. Here we report an experimental study of the band gap in a two dimensional microwave photonic quasicrystal. The measurements show that the band gaps of the 2D octagonal quasicrystal do not depend on the angle of incidence for the TM wave, which coincides very well with the simulation by the multiple scattering method. Furthermore, two types of waveguide, straight and zigzagging bent with two sharp 90° corners, were prepared in the quasicrystal. Both waveguides have very high transmission efficiency within the gap.

The 2D octagonal quasicrystal was constructed by a 23 $\times$23 array of alumina cylinders with a dielectric constant of 8.9, which were placed at each vertex of an octagonal quasiperiodic tiling pattern and embedded in a styrofoam template, shown schematically in Fig. 1. This octagonal quasicrystal pattern is tiled by the squares and rhombuses with an acute angle of 45°, both the squares and rhombuses having the same side length of 9 mm in our experiment. The diameter of the alumina cylinder is 6.12 mm, so the filling fraction of the cylinders is about 49%. The measurements of transmission spectra were carried out in a wide scattering chamber by using an HP8757E scalar network analyzer and HP8364A synthesized sweeper. The scattering chamber was made of two parts, a block with a groove and a cover plate. The block is 270 mm wide and 350 mm long with a groove of width 250 nm and depth 10.16 mm, while the cover plate is 270 mm wide and 350 mm long. The front and back ports of the chamber were each connected to an 8–12 GHz type H trumpet, and then to standard waveguides. The quasicrystal was placed in the middle of the chamber.

The transmission spectrum measured for the normal incident TM wave is shown in Fig. 2(a) (incident angle 0 degree). There is a band gap between 8.9 and 10.5 GHz and the transmittance within this gap is lower than that in the passband by about three orders of magnitude. This is the first gap of the quasicrystal. The transmission was calculated by the multiple scattering approach developed independently by Tayeb *et al.*[13] and Li *et al.*,[14] where a generalized transmission coefficient is defined in terms of the far-field total scattering amplitude. This method is quite suitable for a finite aperiodic structure which consisted of the cylinders with circular cross section. The simulated spectrum coincides very

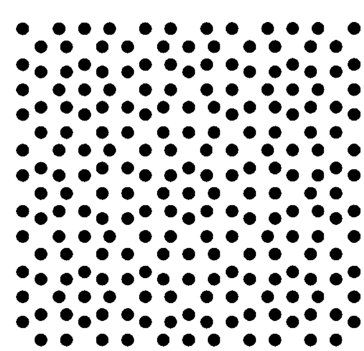

FIG. 1. Schematic of a two-dimensional octagonal quasicrystal.

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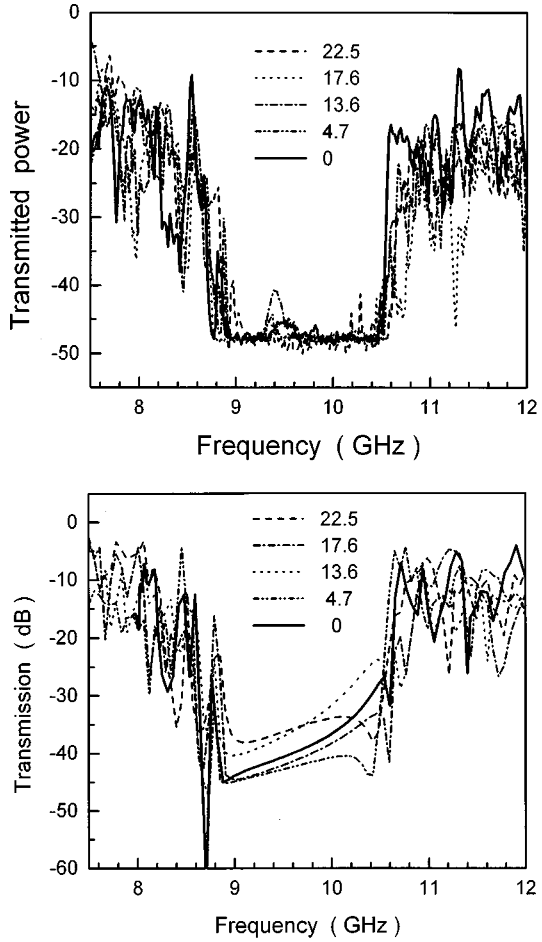

FIG. 2. Transmission spectra between 7.5 and 12.5 GHz for five angles of incidence, namely 0, 4.7, 13.6, 17.6 and 22.5 degrees; (a) measured, (b) calculated.

well with the measurement, see [Fig. 2(b)] (incident angle 0 degree). The transmittance difference between measurement and calculation in the gap region is possibly caused by the limited precision of the calculation. Furthermore, the transmission spectra with different incident directions are plotted in Fig. 2(a). It is quite surprising that the gap position and width, including the lower and higher frequency edges of the gap, do not shift, as the angle of incidence varies from 0° (the normal) to 22.5°. Our quasicrystal has eightfold symmetry, and in each 45° sector the distribution of the cylinders has mirror symmetry with respect to the line of 22.5°. The above experimental result therefore implies that the band gap of an octagonal quasicrystal is independent of the incident directions, i.e., this is a complete gap for the TM wave. Figure 2(b) shows corresponding simulations for the first gap. Because of the limited sweeping range of our microwave sweeper, the transmission spectrum beyond 15 GHz could not be measured. However, the calculation indicates that not only the first gap has such a characteristic, but the higher order gaps are also independent of incident directions. This characteristic is different from the periodic photonic crystals, where a complete gap is determined by the overlap of spectral gaps in all directions. Principally, periodic photonic crystals have a nonspherical first Brillouin zone and then gaps of different directions may appear at different frequencies. To achieve overlap the gap width of each direction should be large enough. This is still a tough requirement.[15,16] However, in the case of quasicrystals this obstacle is naturally overcome.

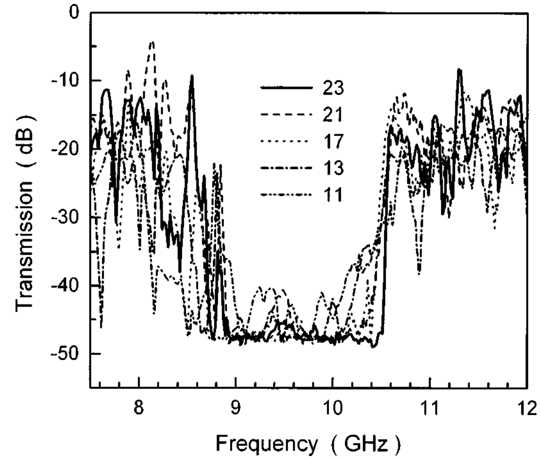

FIG. 3. Transmission spectra for quasicrystals with different numbers of cylinders row, namely, 23, 21, 17, 13, and 11 rows in the incident direction.

Moreover, to know how big the size of the octagonal quasicrystal must be before a photonic band structure can appear, the transmission spectra were measured by removing the cylinder rows simultaneously from the front and back sides of the quasicrystal in the light propagation direction. The results are shown in Fig. 3. As the alumina cylinders were gradually decreased from 23 to 11 rows, the lower frequency edge of the gap remained almost unchanged and its higher frequency edge shifted from 10.5 to 10.3 GHz. The total variation of the gap width was less than 5%. Meanwhile, the transmittances inside the gap varied from the original -50 dB to -40 dB, i.e., the extinction can still reach 25 dB (0.3%). These data indicate that quite a small piece of quasicrystal may possess high reflection in the band gap region.

Based on the above two characteristics of the photonic quasicrystal we recognized that it might be more suitable for waveguide applications than periodic photonic crystals, particularly, in the case of a bending waveguide with a sharp corner. Two types of waveguide were prepared in the octagonal quasicrystal. One was a straight-line waveguide made by removing three rows of cylinders in the upper part of the quasicrystal, [Fig. 4(a)]. The width of the guide was 15.7 mm, which was about half a wavelength at the gap center. The second one was a bending waveguide, which consisted of three straight segments connected by two right angle bends, Fig. 4(b). Because of the symmetrical arrangement of the cylinders, the configuration of the first and third segments of the bending waveguide is the same as in the straight waveguide. Therefore, the main difference between our straight and bending waveguides is only in the two sharp corners. The transmission measurement was performed in the same chamber as before, except that at the entrance of the waveguide a slit with a width slightly less than the width of the waveguide was placed. The measured spectra, in Fig. 4(d), indicate a very clear guiding effect in the gap region. Compared with the perfect quasicrystal the transmittance within the gap is now enhanced by more than four orders of magnitude for both waveguides. Outside the gap the trans-

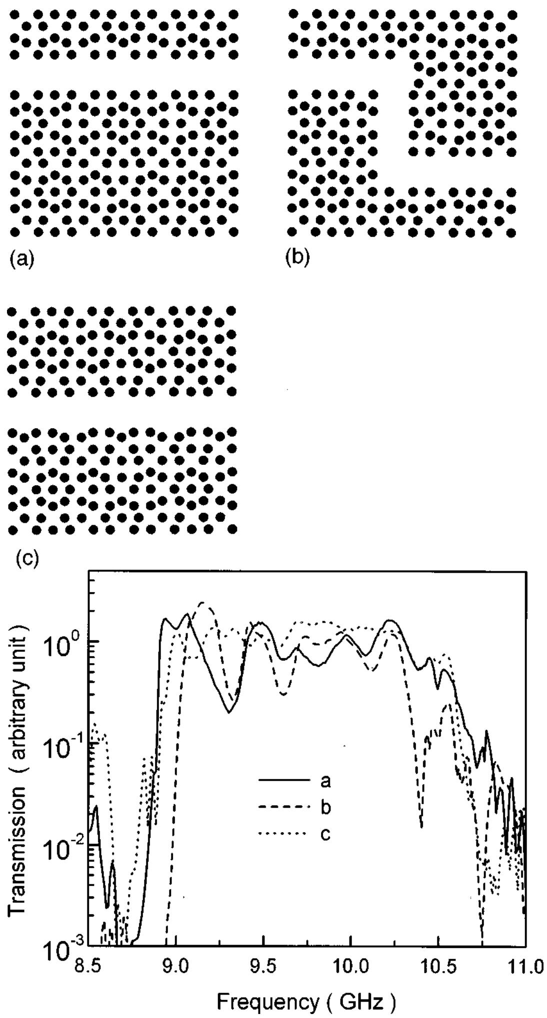

FIG. 4. Schematic of waveguides in the octagonal quasicrystal; (a) straight, (b) bending, (c) another straight, and (d) corresponding transmission spectra.

mittance drops rapidly, because these modes cannot propagate efficiently along the waveguides. However the transmission curve is not so smooth as that in a corresponding periodic crystal. There are some small peaks and dips, especially in the case of the bending waveguide, which might have been caused by the properties of the quasicrystal. The photonic quasicrystal does not possess translational symmetry, so that it has many inequivalent sites. When different rows of cylinders are removed, the interference of scattering waves coming from the remainder cylinders may be quite different. That makes the transmittance frequency dependent. To verify this explanation we prepared another straight waveguide, whose shape was the same as before, but the position in the quasicrystal was changed, as plotted in Fig. 4(c). The corresponding transmission spectrum shows the different aspects. The small peaks and dips appear at other frequencies. This is also the reason why the observed transmittance of the bending waveguide is even higher than the straight one in some frequency regions, which can be seen in Fig. 4(d). The experimental results agree reasonably well with the calculation by the multiple scattering approach. In the simulation the light source was assumed to be a dipole placed at the front of the entrance of the waveguide.

In conclusion, we have demonstrated that direction-independent photonic gaps exist for a TM wave in a 2D octagonal quasiperiodic crystal and only a small piece of the quasicrystal can manifest the photonic band effect. The study of waveguide properties in the quasicrystal show that the transmission efficiency of both straight and bending guides may be high. The variation of the position and width of the waveguide can effectively change the frequency selection of the waveguide.

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