Photonic gap in amorphous photonic materials

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Two-dimensional amorphous photonic materials are created, which do not possess any long-range order but have only short-range order. Our calculation of the multiple-scattering method shows that, for *S*-polarized waves, these materials have photonic gap that is independent of incident directions. Even though the detailed structures of amorphous photonic materials are different with each other, they possess a common photonic gap, if only they have the same short-range order. Based on our studies it may be confirmed that, for *S*-polarized waves, the first band gap of photonic crystals comes mainly from the short-range order, while the higher-order band gaps are related to the long-range order. The measured transmission spectrum of an amorphous photonic material agrees perfectly with the calculation.

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Periodic arrayed dielectric materials are viewed as photonic crystals that possess photonic band gaps in which electromagnetic waves cannot propagate in any directions.[1,2] The unusual properties of these photonic crystals have been used to design thresholdless semiconductor lasers, waveguides, filters, optical switch, and all optic devices.[3,4] In the last decade, they had gained more and more attentions and had been studied extensively.

It has been known that either periodic or quasiperiodic photonic crystals can have photonic gaps.[3,5–9] In these crystals both long-range and short-range orders exist. However, for the electronic analogs, only short-range order is necessary for the creation of energy gaps of electrons. Amorphous semiconductors and their corresponding crystalline semiconductors have strong similarities in their electronic structure (both their average gaps and minimum gaps are nearly the same), it is a consequence that these two electronic materials have the same short-range order.[10,11] It has been verified that the random dielectric structures do not possess spectral gap. Recently, Lidorikis *et al.* analyzed numerically the roles of the Bragg diffraction of whole periodic structures and the Mie resonance of a single scatterer.[12] This may be an interesting step to deeply understand the formation of photonic gaps. However, they did not discuss the influence of short-range order. Then the question naturally arises. If a dielectric structure possesses only short-range order, does there exist spectral gap? Yet, no one has answered this question either theoretically or experimentally. Here, we name these dielectric materials with only short-range order as amorphous photonic materials (APM). The study of the APM may reveal what kind of roles the short-range and long-range orders play in the formation of spectral gaps. Motivated by this question, two-dimensional amorphous photonic materials are created, and the multiple-scattering method is used to calculate the electromagnetic propagation in these materials. Calculations show that, for *S*-polarized waves, APM does have spectral gap, and this gap is almost independent of incident directions. Furthermore, the positions and widths of the gaps appearing in different APM's are nearly unchanged, when these APM's have the similar short-range order. Our calculations demonstrate that, for *S*-polarized waves, the first band gap of photonic crystals comes mainly from the short-range order of the dielectric structure, while the higher-order band gaps may be caused by the long-range order. The measured spectrum of an APM agrees perfectly with the calculation.

In the case of electrons, the radical distribution function (RDF) of materials can be served as a criterion to know whether a structure is amorphous solid or not. The RDF $\rho(r)$ is defined as follows. Randomly taking an atom as the origin, $\rho(r)dr$ gives the probability of finding a neighboring atom at a distance between r and $r+dr$. For an amorphous solid, the existence of short-range order is recognized by the presence of the clearly seen first and second peaks in the RDF. On the other hand, the absence of long-range order in amorphous solids manifests itself in that discernible peaks in the RDF rarely occur beyond third-nearest neighbors.[10] Here, we also adopt the RDF to identify our amorphous photonic structures. For two-dimensional amorphous photonic materials, the RDF keeps the first and second peaks, while that of two-dimensional random materials is a linear function of r, $\rho_r(r)=2\pi rn$, where n is an average density per unit area.

Our APM's are created as follows. First, we choice a basic unit, which is a square with a sidelength $a1$, as shown in the inset of Fig. 1. Four dielectric cylinders are placed on its four corners, respectively. Then, a square lattice with lattice constant $a2$ is built. We put the basic unit cells in each lattice point, respectively. An amorphous photonic material is formed by randomly rotating each basic unit against its own center, i.e., the rotating angles of basic units are randomly taken. This is the first model of the APM's. Using this creation method, we can obtain huge amount of APM's, which have different detailed spatial structures, but the same short-range order provided by the basic unit. When $a1=10$ mm, $a2=20$ mm, the pattern of one APM is shown in Fig. 1. Figure 2 is the RDF of the APM. It is clear that the first and second peaks are very narrow and high, and the remainder peaks are wide, low, and much closer to the dotted line, which represents a totally random structure. Therefore, these structures can be considered as amorphous structures. The propagation of electromagnetic waves in these APM's is calculated by the multiple-scattering method.[13,14] We add a wire source at the center of the pattern of Fig. 1 and then

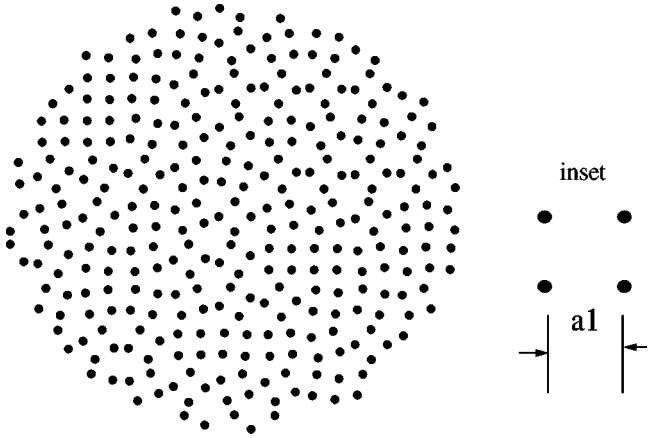

FIG. 1. Schematic of an amorphous photonic structure. The method is as follows. First, a square with a sidelength $a1 = 10$ mm is chosen to be a basic unit, as shown in the inset. Four dielectric cylinders are placed on its four corners, respectively. Then, a square lattice with lattice constant $a2 = 20$ mm is built, while we put the basic unit cells in each lattice point, respectively. An amorphous photonic material is formed by randomly rotating each basic unit against its own center, i.e., the rotating angles of basic units are randomly taken.

total output energy flux is detected at the round of the pattern. What we can obtain now is not a transmission spectrum in a certain direction, but a total radiation power as a function of frequency, which is equivalent to the density of states.[6] The radiation power spectrum can determine the full gap as well as the defect mode. Its validity has been proved.[15] For the disordered systems the average of different configurations should be taken into account. In this radiation power approach the configuration average has been carried out, because the effects caused by different incident

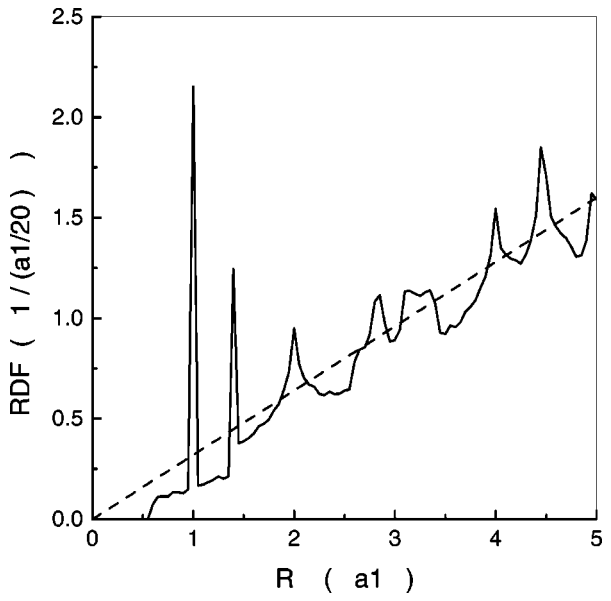

FIG. 2. The RDF of an amorphous photonic structure plotted in Fig. 1. The dotted line represents the RDF of a complete random structure.

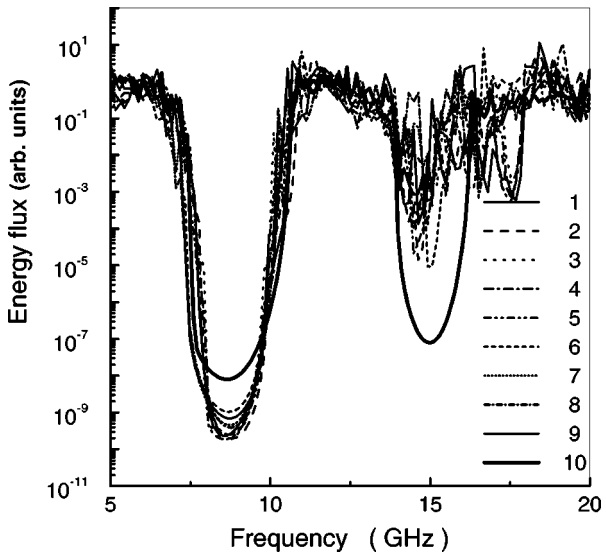

FIG. 3. The spectra of energy flux vs frequency for nine different amorphous photonic structures constructed by the same square unit, where $a1 = 10$ mm, $a2 = 20$ mm, $r = 2.5$ mm, and the dielectric constant of cylinder ϵ_a and background ϵ_b are 12.0 and 1.0, respectively. The thick line denodes the spectra of energy flux vs frequency for the corresponding periodic photonic crystal.

directions have been included. To make sure that the dip existing in the radiation power spectrum represents a full gap we further simulated the spectrum in nine different spatial configurations. Figure 3 shows nine spectra lines for the *S*-polarized wave (the direction of electric field is the same as the axis of cylinders), corresponding to nine APM's constructed by the above procedure, respectively. Here the dielectric constants of the cylinders ϵ_a and background ϵ_b are 12.0 and 1.0, respectively, and the radius of the cylinder r is 2.5 mm. In the calculation altogether 75 unit cells are used. It is clearly seen that the transmission dips, which are as deep as 10^5 , of all the nine curves are very smooth without any peak caused by the defect modes. A common photonic gap between 7.6 and 10.1 GHz can be found for all the nine APM's. This means that there is a full photonic band gap for this kind of APM. However, there is no other gap in the higher-frequency region. These results reveal that, if the basic unit does not change, no matter what the structure of these amorphous photonic materials varies, there exists a common gap in these amorphous photonic materials for *S*-polarized waves. When the basic unit does not rotate, the structure becomes a square photonic crystal with lattice constant of 10 mm. If the parameters of the square photonic crystal are chosen to be the same as the APM's, this periodic crystal has not only the first band gap between 7.54 and 10.5 GHz as shown in Fig. 3 by a thick line, but also the higher-order band gaps, such as the second band gap between 14.0 and 16.1 GHz. Furthermore, the gaps of these APM's overlap quite well to the first band gap of the corresponding crystalline photonic crystal. The only difference is that there are no higher-order gaps in the APM's. Based on the above studies, we find that, for *S*-polarized waves, only short-range order of photonic structure is necessary for the formation of the first band gap, while the high-order gaps are strongly

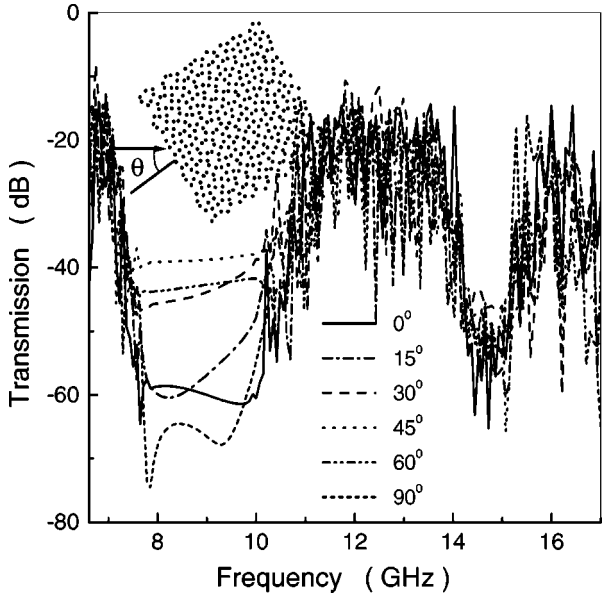

FIG. 4. The transmission spectra of the amorphous photonic material with various incident angles. The photonic structure is shown in the inset. The size of the APM is 200×200 mm, where, $a1=10$ mm, $a2=20$ mm, $r=2.5$ mm, $\epsilon_a=12.0$, and $\epsilon_b=1.0$. The calculations are carried out at six angles between $0°\sim90°$. It can be seen that the gap position is independent of incident angles.

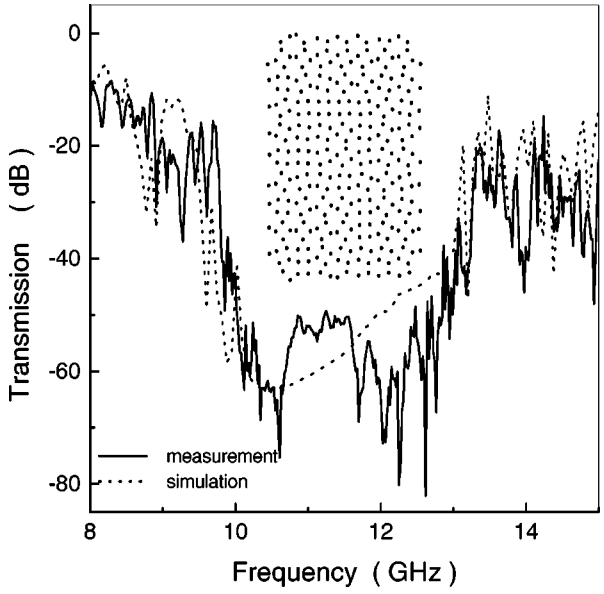

FIG. 5. The comparison between measured and calculated transmission spectra for the amorphous photonic material fabricated by the first method and shown in the inset, where $a1=10$ mm, $a2=20$ mm, $\epsilon_a=8.4$, and $\epsilon_b=1.04$.

related to the long-range order. Once the long-range order no longer exists, the high-order gaps disappear. This also agrees with the previous works on the photonic gaps in slightly disordered photonic crystals, where the higher-order gaps disappear soon with the increase of disordered degree.[16,17] Furthermore, the photonic gap of these APM's is independent of incident direction. Figure 4 gives the transmission spectra for six different incident directions, all of the six spectra show the same gap between 7.5 and 10.1 GHz. This may be caused by the fact that the dielectric distribution of APM's is isotropic. In the range of 14 to 15 GHz, a second gap seems to be seen. However, in the transmission spectrum of this gap, many peaks, i.e., defect modes exist. That means that this is not a real gap. Furthermore, from Fig. 3, we can also find that even one configuration of the sample seems to possess a second gap, but if the average of different configurations of the sample is taken into account, the second gap disappears. For a *P*-polarized wave, there is no clearly seen photonic gap in the APM.

An amorphous photonic material was also built according to the above method, which is shown in the inset of Fig. 5, where $a1=10$ mm and $a2=20$ mm. 289 dielectric cylinders are imbedded in a polystyrene foam template. In the incident direction there are eight rows of unit cell. The dielectric constants of the cylinders and template are 8.4 and 1.04, respectively. The set of measurement has been described in detail elsewhere.[8,18] Here, we just give a simple description. We measure the transmission spectrum in a wide scattering aluminum chamber by using Hewlett Packard 8510C Vector Network Analysis System. The chamber is composed of a wide waveguides of 250 mm wide and 300 mm long, and two H-type 8-12 GHz trumpets that are connected to the back and front ports of the wide waveguides, respectively. The amorphous photonic material is placed in the middle of the wide waveguides scattering chamber and a slit source is used. The transmission spectrum is measured under *S*-polarized wave normal incidence, as shown by the solid line in Fig. 5, where the dotted line gives the simulated spectrum. Both spectra show the same photonic gap between 10.0 and 13.0 GHz. The agreement between the simulation and measurement is very good. This is the experimental evidence that APM possesses a photonic gap.

In the above APM, only one unit cell, a square, is used. Now, we apply two unit cells, square and triangle, to form another kind of APM. Both of these two units have the same sidelength $a1$, as shown by the insets 1 and 2 of Fig. 6. There each dot indicates a dielectric cylinder. Then a square

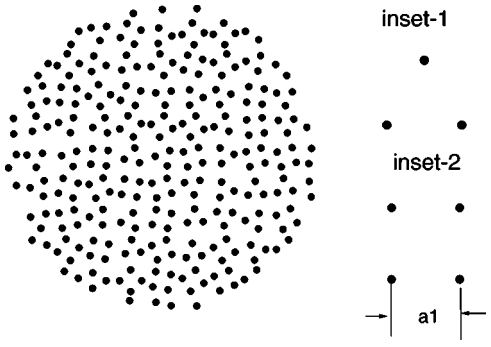

FIG. 6. Schematic of another amorphous photonic structure. Here we apply two unit cells, square and triangle, to form this kind of APM. Both of these two units have the same sidelength $a1=10$ mm, as shown in insets 1 and 2. Then a square lattice with lattice constant $a2=10$ mm is produced. Finally each lattice point is randomly replaced by any one of the basic units, and these units are rotated randomly around their own centers, respectively.

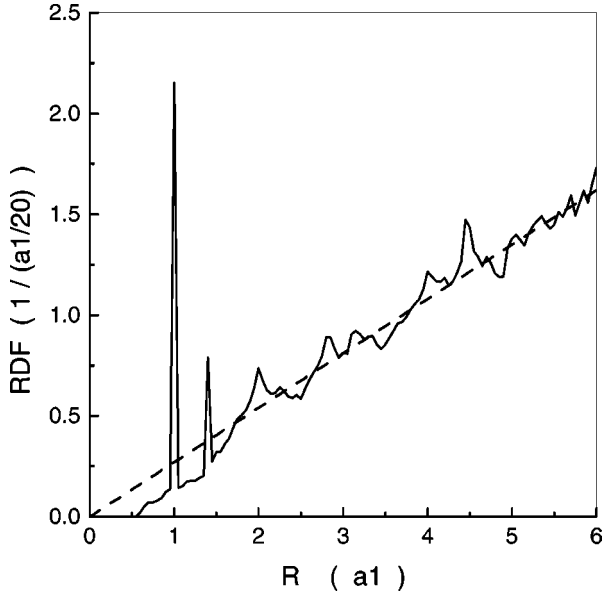

FIG. 7. The RDF of the amorphous photonic structure plotted in Fig. 6. The dotted line represents the RDF of a complete random structure.

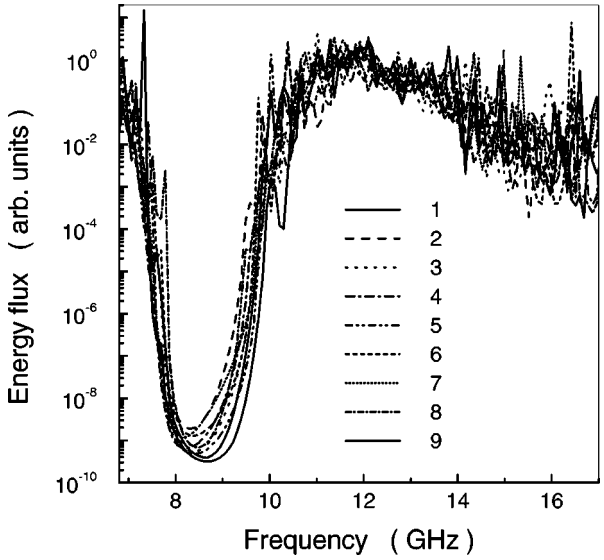

FIG. 8. The spectra of energy flux vs frequency for nine amorphous photonic structures constructed by two unit cells. Here, $a1 = 10$ mm, $a2 = 20$ mm, $r = 2.5$ mm, $\epsilon_a = 12.0$ mm, and $\epsilon_b = 1.0$.

lattice with lattice constant $a2$ is produced, each lattice point is randomly replaced by any one of the basic units, and these units are rotated randomly around their own centers, respectively. One of such APM structure is shown in Fig. 6. In principle, the disordered degree of this kind of the APMs should be larger than the first one. It can be seen from the RDF of this structure, which is shown in Fig. 7, where $a1 = 10$ mm and $a2 = 20$ mm. The first and second peaks are clearly seen, while the higher peaks are not discernible. Here the dielectric constants of the cylinders and background are 12 and 1, respectively, and the radius of the cylinders is 2.5 mm. When an *S*-polarized wave wire source is located in the center of the APM's, we calculate the spectra of energy flux vs frequency for nine APM's constructed by the second method, respectively. The results are plotted in Fig. 8. Even though there exists a trivial difference at low and high gap edges among these spectra, the center frequency of the gap are the same. A common photonic gap between 7.78 and 9.49 GHz is found. In this case, the gap width is a little bit smaller than that constructed by the first method. It is expected that if more totally different basic units are taken, i.e., the disordered degree of the dielectric structure increases, the gap width will shrink. A dielectric structure with infinite different basic units corresponds to a complete disordered structure, where a photonic gap will disappear.

In conclusion, two-dimensional amorphous photonic materials are built by two different methods. The radical distribution function is served as a criterion to identify whether a structure is an amorphous structure. Both simulations by the multiple-scattering method and experiment show that there exists a common photonic gap in various amorphous photonic materials built by the same method for *S*-polarized waves. Their gap is isotropic, i.e., independent of incident directions. However, there is only one gap existed for APM, no high-order gaps can be found. Furthermore, we also find that, under *S*-polarized waves, the first gap of the periodic photonic crystal overlaps with the common gap of the corresponding APM's. This is an evidence that only short-range order is necessary for the formation of the first band gap, while the higher-order band gaps are completely dominated by the long-range order. Our results show a deeper analogy between electronic solids and photonic materials. Further investigations might be helpful for fully understanding the generation mechanism of photonic gaps. On the other hand, compared with photonic crystals, these amorphous photonic materials are easily fabricated, and conveniently applied in practice.

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