The disorder effect on the performance of novel waveguides constructed in two-dimensional amorphous photonic materials*

Chen Xiao(陈 笑)† and Wang Yi-Quan(王义全)

College of Science, Minzu University of China, Beijing 100081, *China*

(Received 21 December 2010; revised manuscript received 20 January 2011)

On the basis of two-dimensional amorphous photonic materials, we have designed a novel waveguide by inserting thinner cylindrical inclusions in the centre of basic hexagonal units of the amorphous structure along a given path. This waveguide in amorphous structure is similar to the coupled resonator optical waveguides in periodic photonic crystals. The transmission of this waveguide for S-polarized waves is investigated by a multiple-scattering method. Compared with the conventional waveguide by removing a line of cells from amorphous photonic materials, the guiding properties of this waveguide, including the transmissivity and bandwidth, are improved significantly. Then we study the effect of various types of positional disorder on the functionality of this device. Our results show that the waveguide performance is quite sensitive to the disorder located on the boundary layer of the waveguide, but robust against the disorder in the other area in amorphous structure except the waveguide border. This disorder effect in amorphous photonic materials is similar to the case in periodic photonic crystals.

Keywords: photonic crystal, amorphous photonic material, waveguide, disorder

PACS: 42.70.Qs, 42.82.Et **DOI:** 10.1088/1674-1056/20/7/074211

1. Introduction

Photonic crystals (PCs) named by Yablonovitch[1] and John[2] in 1987 are spatially periodic arrangement of multiple scatters. This kind of artificial material exhibits some unusual physical properties. The primary property is that in the photonic band gaps (PBG) electromagnetic waves cannot propagate in any direction. However, it has been known that if a line defect is introduced into otherwise perfect PCs, the light with frequencies inside the PBG can be well guided along the defect.[3] PC-based waveguides are promising building blocks for the design of optical integrated circuits and all optical ultrasmall devices. Therefore, waveguides, waveguide bends and waveguide intersections constructed in periodic PCs have received intensive and extensive studies.[4−8] On the contrary, no much attention has been paid to the waveguides constructed in amorphous photonic materials (APMs). APM is a kind of dielectric structures with only short-range order and the gap is independent of the incident direction.[9] Hence, compared with its counterpart in periodic PCs, waveguides carved in APMs are much flexible in the connection of optical components within the optical integrated circuits. However, it is impossible for the optical waveguides in APMs. Then the following question arises naturally: How can we take advantage of the isotropy to construct effective waveguides in APMs? Up to now, no one has answered this question either theoretically or experimentally yet. In this article, we propose a novel waveguide in APM by inserting thinner rods in the centre of basic units along a given course, which is similar to the coupled-resonator optical waveguides. Compared with the conventional method by removing a line of cells to construct waveguides, the transmission quality of this novel waveguide is improved significantly.

In practical application, the interface roughness and nonuniformity inevitably occur in the fabrication of PCs, especially when the crystals are of micrometre and submicrometre sizes. The deviation of positions, radii and refractive indexs of inclusions from ideal values can affect the size of a gap considerably and degrade the functionality of a device.[10−12] For periodic two-dimensional (2D) PCs, the effects of various types of disorders on the waveguide performance have been studied in recent years.[13−16] The unifor-

*Project supported by the "985 project" (Grant Nos. 98503-008006 and 98503-008017), the "211 project" of Ministry of Education of China, and the Fundamental Research Funds for the Central Universities of China.

†Corresponding author. E-mail: chenxiao4399@yahoo.com.cn

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mity of the boundary layer of the waveguide is proved to be vital in ensuring the functionality of the waveguide. However, detailed investigation on such a problem in APMs is still lacking. Hence, we consider four different configurations of position disorders in the APM-based waveguide, including disorder spreading over the whole material, disorder only located on the inserted inclusions, disorder confined to the waveguide boundary layer and disorder spreading over the whole except the waveguide boundary layer. The numerical results reveal that the waveguide performance is very sensitive to disorder in the border of the waveguide, but quite robust to the case where the boundary layer is preserved from the randomness.

2. Novel waveguides in amorphous photonic materials

The APM is created as follows: First, a basic unit of a regular hexagon with a sidelength $a_1 = 7.13$ mm is built. Six alumina (Al_2O_3) cylindrical inculsions with dielectric constant $\varepsilon_d = 8.6$ and radius $r = 2.8$ mm are located on the corners of a basic unit. Then, the basic unit cells are placed at each square lattice point with lattice constant $a_2 = 20$ mm. Then the APM is formed by rotating randomly each basic cell against its own centre with the rotation angle θ taken randomly from 0° to 360°. The background dielectric constant is $\varepsilon_b = 1.0$. By this creation method, a large number of APMs are obtained, which have different detailed spatial structures, but the same short-range order provided by the basic unit. Figure 1(a) shows one of the APM patterns. In the simulation, an S-polarized slit source with a width of 20 mm is incident on one side and the transmission is measured on the other side. The multiple-scattering method is used to calculate the band structure of AMPs, as well as the transmission of the waveguide.[17,18] Figure 1(b) is the corresponding spectra of energy flux for five APMs by rotating all units randomly. It can be clearly seen that the PBG for different configurations are very smooth without any peak caused by defect modes and a common band gap is found between 7.7 GHz and 9.2 GHz.

A line waveguide is fabricated in the APM, as shown in Fig. 2(a). When the waveguide width is less than $2a_1$, there is no available waveguide mode within the PBG. However, when the width is increased to 25 mm, more than $3a_1$, the waveguide mode begins to emerge. However, the transmissivity of this waveguide in Fig. 2(b) is low, similar to the effect of disorder introduced to the surface layer of the waveguides.[19] Moreover, it is difficult to mark off the waveguide mode from sidebands, which makes it incompatible with the application of components. In order to design more effective waveguides in APMs, instead of removing a row of cylinders to construct low dielectric constant line-defect waveguide, we attempt to insert thinner cylinders with radii 1.5 mm and dielectric constant 8.6 in all centres of basic units along a given path.

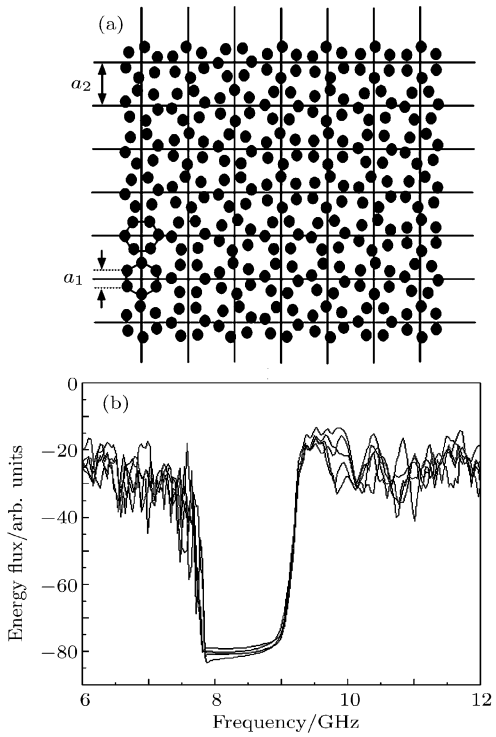


Fig. 1. (a) Schematic scheme of a 2D amorphous photonic structure. By rotating the basic units randomly, periodical structures are transformed to disordered systems. (b) The spectra of energy flux versus frequency for five different amorphous photonic structures constructed by rotating the basic units at some arbitrary angles between 0° and 360°.

Therefore, a high dielectric constant waveguide is formed as plotted in Fig. 3(a). Actually, this structure is quite similar to the coupled resonator optical waveguides (CROWs) in periodic PCs because each basic cell with an inserted thin cylinder can be considered to be a cavity. However, different from CROWs, the coupling between two adjacent basic cells in APMs is various. Based on this structure, the corresponding transmission spectra are illustrated in Fig. 3(b) for five configurations with different rotational randomnesses. The waveguide modes within the band gap are seen clearly. In particular, the transmissivity of waveguide modes is high and is separated from the sidebands, so that the performance of this novel APM-based waveguide is greatly improved.

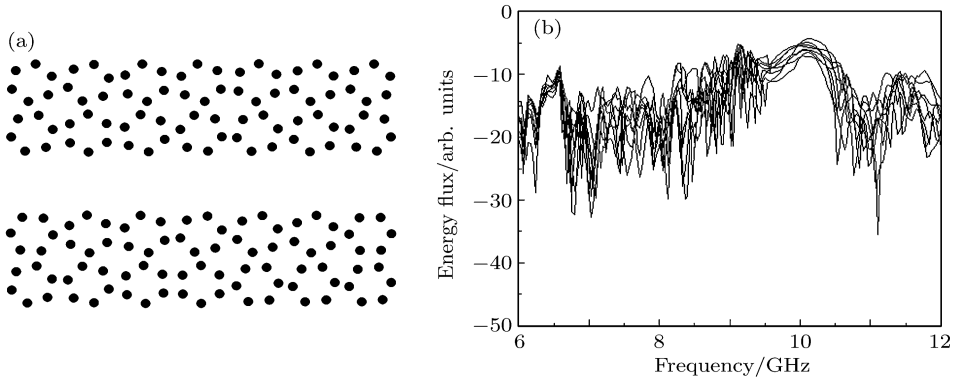


Fig. 2. (a) Schematic scheme of a waveguide fabricated in the amorphous photonic structure. (b) Transmitted energy flux of S-polarized waves guided by a waveguide in amorphous structures. The curves correspond to different spatial configurations by rotating all basic units randomly.

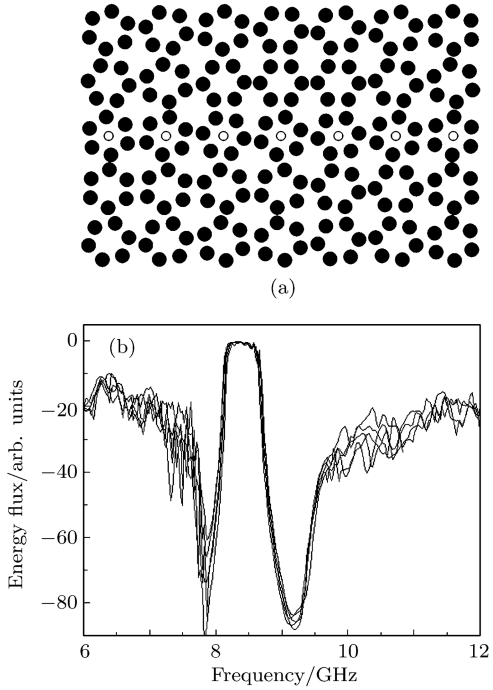


Fig. 3. (a) Schematic scheme of a novel waveguide constructed in amorphous photonic structures by inserting thinner cylinders with radius 1.5 mm and dielectric constant 8.6 in the centre of basic units along a given path. (b) Transmitted energy flux of S-polarized waves guided by this waveguide in amorphous structures. The curves correspond to different spatial configurations by rotating all basic units randomly.

3. Disorder effect on waveguide modes in APMs

The influence of disorder on the transmission of waveguides in PCs is an important issue for manufacturing practical devices. In general, there are three kinds of disorder in PC structures: cylinder position displacement, cylinder radius variation and varied dielectric constants of cylinders.[20] It has been known that the transmission properties of periodic PC-based waveguides vary with different types of disorder. However, detailed investigations of such a problem in APMs are still lacking. Therefore, we consider the case of cylinder site randomness and introduce it into APM. The disorder degree can be modulated by controlling the positional derivation of cylinders within a range of $[-\mathrm{d}r, \mathrm{d}r]$.

First, we introduce disorder into all cylinders and calculate the transmitted energy fluxes with the disorder degree $\mathrm{d}r = 0.5$ mm and 1.0 mm. Figure 4 shows that with the increase of the disorder degree, both the transmissivity and bandwidth of waveguide modes begin to fluctuate remarkably, which causes the deterioration of the transmission quality. However, only from the results above, it is hard to conclude which part of the disordered APM plays a major role in affecting the performance of waveguides. Therefore, we further consider the randomness into three parts of APM: the disorder only confined to the inserted cylinders (type I), the disorder spreaded over all cylinders except the inserted rods and those on the waveguide boundary layer (type II) and the disorder only distributed on the waveguide boundary layer (type III). Figures 5 and 6 indicate the waveguide modes that are quite insensitive to types I and II, although the disorder degree is increased to 1.5 mm. However, when the disorder is introduced into the border of waveguides, Fig. 7 shows a noticeable change in the transmissivity and bandwidth of waveguide modes, especially for large disorder degree. It leads to a detrimental effect on the performance of waveguides. Therefore, we can conclude that although the disorder has been taken into the whole APM in Fig. 4, the disorder only located on the boundary layer of the waveguide is actually the dominant cause in ensuring the functionality of the waveguide in APMs. This property is similar to the case in periodic PCs.

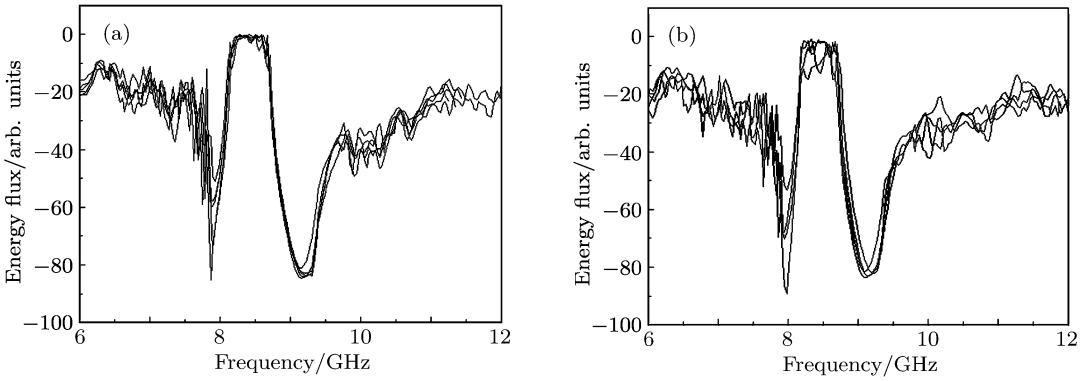


Fig. 4. Transmitted energy flux of S-polarized waves versus frequency in the presence of the randomness in the whole amorphous photonic material within the disorder range: (a) dr = 0.5 mm, (b) dr = 1.0 mm.

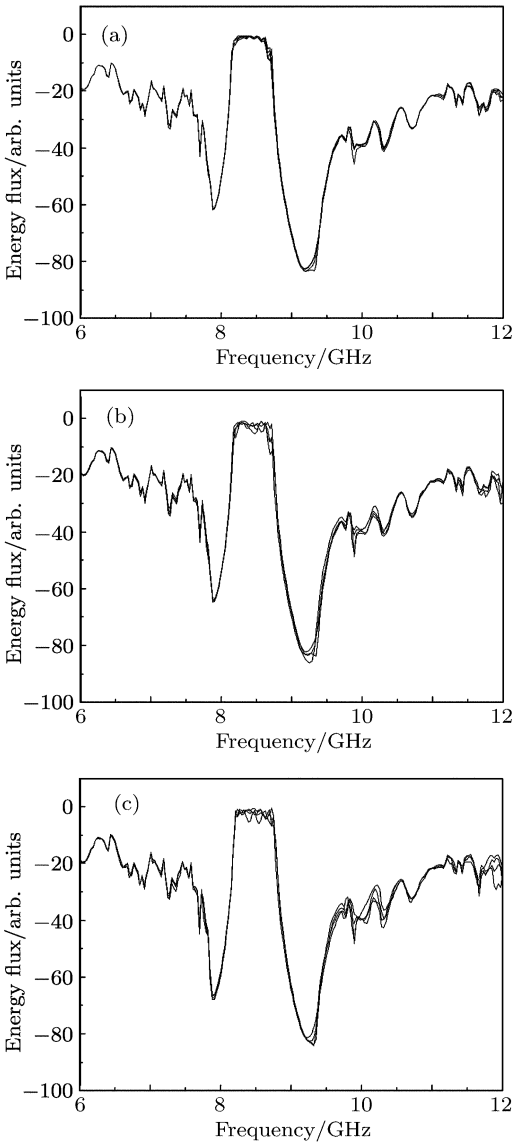


Fig. 5. Transmitted energy flux of S-polarized waves versus frequency with the randomness only confined to the inserted cylinders. The disorder ranges are (a) dr = 0.5 mm, (b) dr = 1.0 mm and (c) dr = 1.5 mm, respectively. The lines correspond to different configurations within the disorder range.

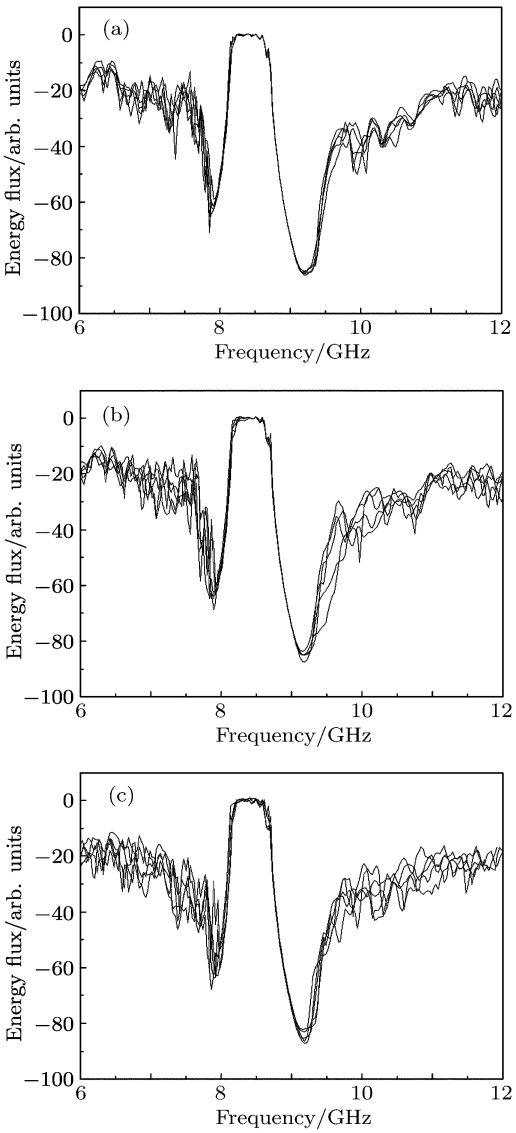


Fig. 6. Transmitted energy flux of S-polarized waves versus frequency with the randomness introduced to all cylinders except the inserted rods and those on the boundary of waveguides with (a) dr = 0.5 mm, (b) dr = 1.0 mm and (c) dr = 1.5 mm, respectively. The lines correspond to different configurations within the disorder range.

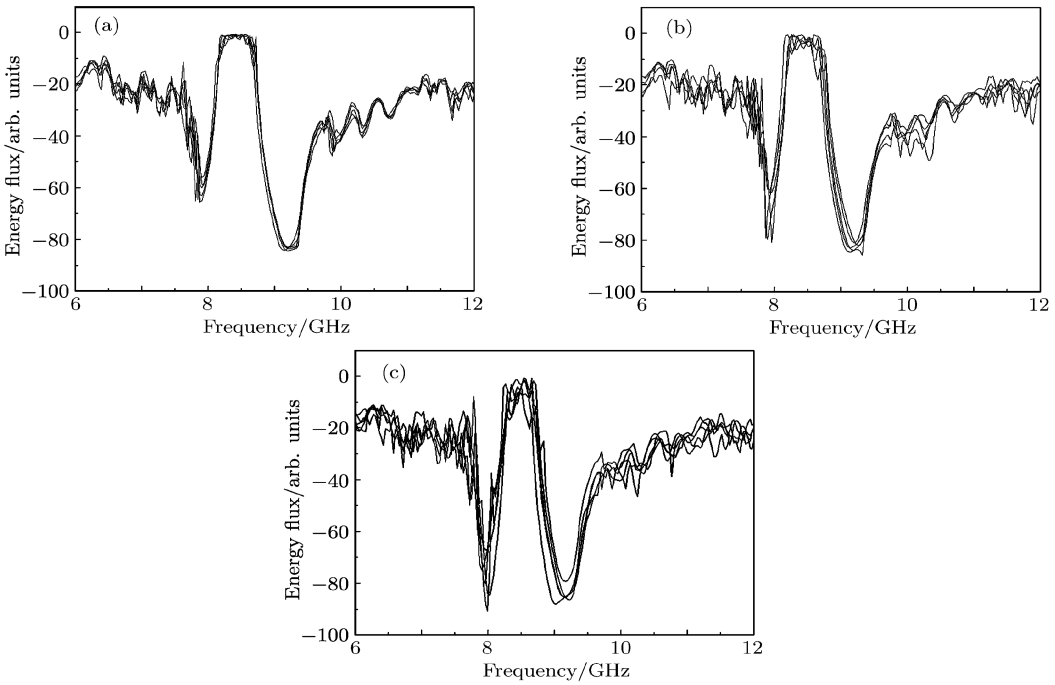


Fig. 7. Transmitted energy flux of S-polarized waves versus frequency with the randomness introduced to those cylinders on the boundary layer of waveguides with (a) dr = 0.5 mm, (b) dr = 1.0 mm and (c) dr = 1.5 mm, respectively. The curves correspond to different configurations within the disorder range.

4. Summary

On the basis of two-dimensional amorphous photonic materials, we design a novel waveguide in amorphous structure by inserting thinner rods in each centre of the basic hexagonal units along a given path. Compared with the conventional waveguide by removing a line of rods from photonic crystals, the transmission quality of the waveguide modes, including the transmissivity and bandwidth are improved significantly. Then, we introduce the positional disorder into amorphous photonic materials and find that the performance of waveguides degrades with the increase of the disorder degree. Furthermore, among the disorders located on different parts of amorphous structure, it is found that the uniformity of the microstrcture in the border of waveguides plays a primary role in affecting the waveguide modes. These results may be helpful in the fabrication of waveguides in amorphous photonic materials.

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