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Effect of the defect on the focusing in a two-dimensional photonic-crystal-based flat lens*

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We have investigated in detail the influence of defect on the focusing of electromagnetic waves in a two-dimensional photonic-crystal flat lens by using the finite-difference time-domain method. The result shows that many focusings can be observed at the symmetrical positions when a defect is introduced into the lens. Furthermore, the wave-guides in the lens can confine the transmission wave effectively and improve the quality of the focusing.

Keywords: flat lens, defect, photonic crystal
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1. Introduction

Recently, left-handed materials (LHMs) and negative refraction have increasingly attracted attention due to their implication for some unusual electromagnetic (EM) wave propagation phenomena. Veselago[1] for the first time analysed some interesting peculiar properties of such materials over 30 years ago, but only recently did people demonstrate these materials experimentally.[2,3] These materials have many unusual EM properties, such as negative refraction and superlensing effect, inverse Snell law,[4,5] reversed Doppler shift,[6] and reversed Cherenkov radiation.[7] These characteristics open the door for the new approaches to a variety of applications.

Recently experimental and theoretical studies have also indicated that negative refraction phenomena in photonic crystals (PCs) are possible.[8−22] In particular, Luo *et al* [7] have shown that all-angle negative refraction (AANR) can be achieved at the lowest band of two-dimensional (2D) PCs. The physical principle that allows negative refraction in PCs is based on the dispersion characteristics of wave propagation in a periodic modulation medium, which can be well described by analysing the equi-frequency surface (EFS) of the photonic band structures.[23−29] It is well known that an important application of negative refraction materials is making the flat lens.[8] Ideally, such a lens can focus a point source on one side of the lens into a real point image on the other side even for the case of a flat slab of material. It possesses some advantages over conventional lenses. There is no diffraction limit. The imaging behaviours based on the PC have been observed by some numerical simulations[13,15−23,30,31] and experimental measurements.[14,24−26]

There have appeared some theoretical and experimental studies on the focusing and imaging of PC lens. However, detailed theoretical and experimental investigations about the influence of defect on the focusing of electromagnetic waves are still lacking.[32] It is very important to investigate the focusing. In the present, we study theoretically the influence of defect on the focusing in a two-dimensional photonic-crystal flat lens in detail.

The rest of the paper is organized as follows. In Section 2 we analyse the band structure, the EFS of the periodical structure and the focusing in a flat lens without defects. The focusing is discussed when the defects are introduced in Section 3. In Section 4 we study the effect of wave-guide on the focusing. Finally, the conclusion draw from the present study is given in Section 5.

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2. Focusing in PC without defect

We consider a 2D square lattice of dielectric cylinders with a dielectric constant of 8.6 and a radius of 3mm. The lattice constant of PC is a. The photonic band structures and the EFS contours are crucial for the investigation of negative refraction and focusing effect. They are calculated by using the finite-difference time-domain (FDTD) method with periodic boundary conditions, and the results of the TM-polarized EM waves are plotted in Figs.1(a) and 1(b). It can be seen from Fig.1(b) that the contour at a frequency of 7.65GHz for the S wave is significantly distorted from a circle. It is convex around the point M, and this means that the directions of the group velocity and the phase velocity are opposite to each other. The conservation of the surface parallel wave vector will result in the negative refraction effect in this case. According to the analysis approach by Luo *et al*[13] we can obtain an all-angle negative refraction (AANR) region. The shadow in Fig.1(a) represents such a region. In this region, a slit beam of TM-polarized wave incident on the ΓM surface at various incident angles can propagate into this crystal from the negative refraction side. In all of our simulations the electric fields are kept parallel to the cylinders.

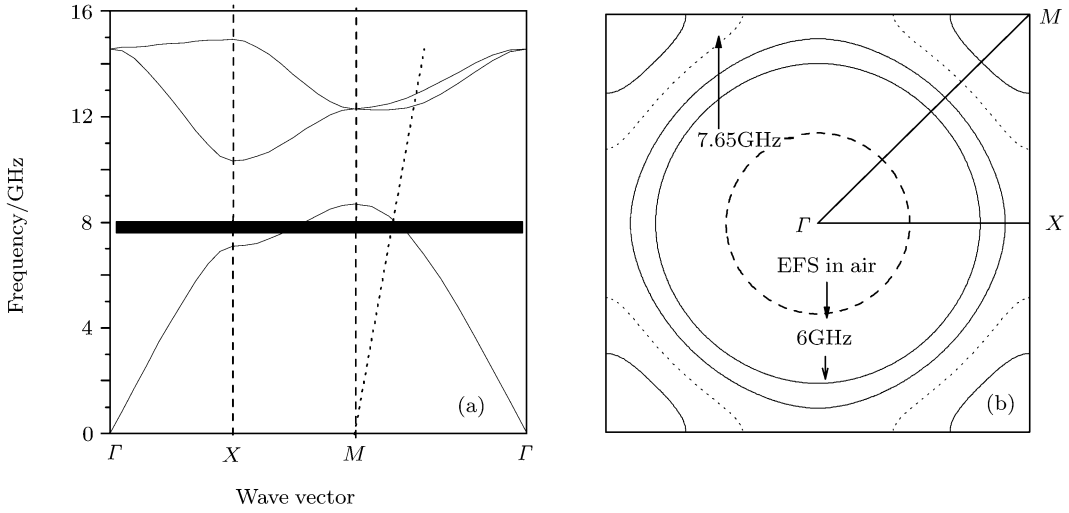


Fig.1. Theoretical photonic band structure of a square lattice of cylinder for TM-polarized wave (a) where the light line is shown by the dashed line and the shadowed area represents the AANR region, and several equi-frequency contours for TM-polarized wave (solid lines) in the first band of the 2D PC (b).

In a way similar to that in Ref.[13], we can design a flat lens to realize the focusing by using the above PC systems. Thus, we take a square slab with each side length of $15\sqrt{2}a$ as shown in Fig.2(a). A continuous-wave point source is located at a distance of $1.0a$ from the left surface of the slab. The frequency of the incident wave emitting from such a point source is 7.65GHz, chosen to lie within the region where the absolute all-angle negative refraction may occur (see Fig.1(a)). Using the FDTD method, we investigate the propagation of the TM-polarized wave in such a system. The result is plotted in Fig.2(b). One can find a high-quality focusing formed on the opposite side of the slab. The distance of the focusing from the right surface of the slab is about $0.8a$. That is to say, the focusing of a point source can be observed at this frequency by such a 2D PC slab. The physical reason can be understood from the analysis by Luo *et al.*[13] Furthermore we locate the point source at the centre of the sample. We can observe high-quality focusings along other directions. It is proved that the sample can focus in many directions.

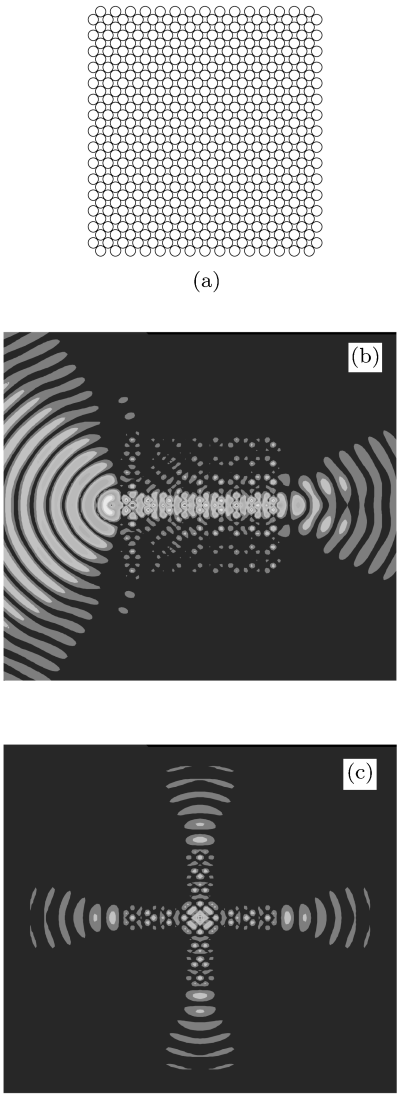


Fig.2. Structure of the flat lens (a), where the holes represent dielectric cylinders, the field distribution for the point source located outside of the lens (b), and the field distribution for the point source at the centre of the lens (c).

3. Focusing in PC with point defect

Now we investigate the effect of defect on the focusing. Above all we introduce one defect into the centre of the sample. It means that the four cylinders around the centre are taken out as shown in Fig.3(a). In a similar way to the one used in the above investigation, we first calculate the field distribution when the point source is outside the sample. It can be seen from Fig.3(b) that the wave changes its transmission direction when it arrives at the position of the defect. Interestingly, we observe the other two focusings in other directions. There is also a focusing in the transmission direction, but the quality of the focusing degrades. It means that the defect can cause many focusings of the lens. The result also demonstrates that both the negative refraction effect and self-collimation effect are important for the focusing of the lens. The reason is that the photonic crystal possesses a four-fold symmetry. When the wave arrives at the position of defect, the focusings appear at other symmetrical position because of the holdback of defect. To further support our observation, we locate a point source at the centre of the sample. Figure 3(c) shows the simulation result. Four high-quality focusings are observed at the four symmetrical positions.

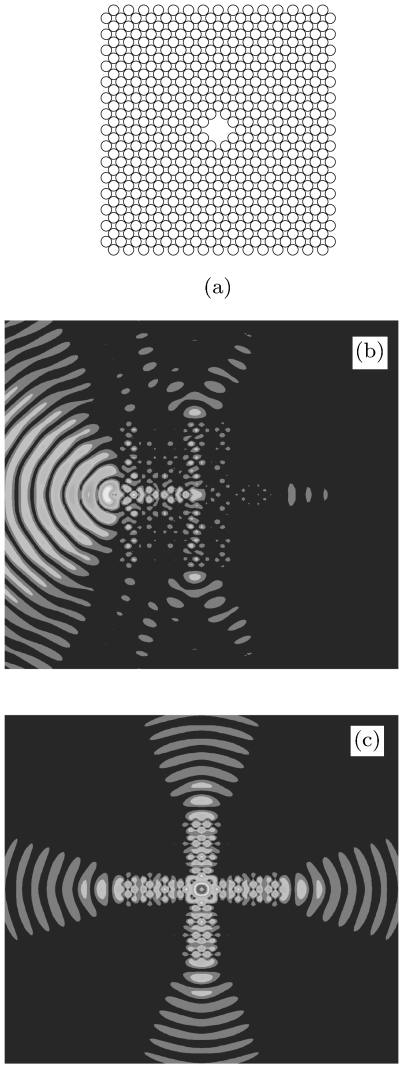


Fig.3. Structure of the lens with a defect (a), the field distribution for the point source located outside the lens (b), and the field distribution for the point source at the centre of the lens (c).

Since the wave does not transmit at the position of defect, we consider introducing four defects as shown in Fig.4(a). We calculate the field distribution when the point source is outside the lens as shown in Fig.4(b). We also observe the focusing in the other directions. When the transmission source is located at the centre of the sample in Fig.4(c), we find that all the energies are located at the centre of the sample. The lens does not focus in any direction. It is also proved that the defect can confine the transmission of the wave effectively.

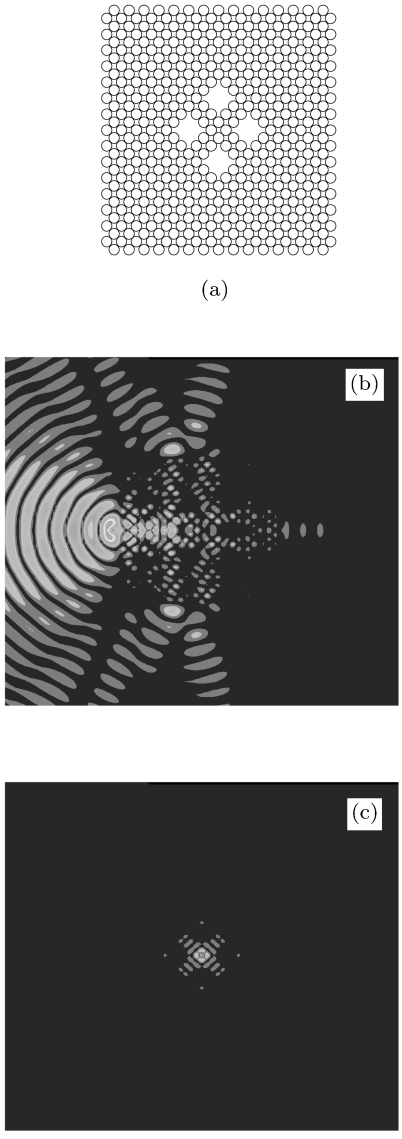


Fig.4. Structure of the lens with four defects (a), the field distribution for the point source located outside the lens (b), and the field distribution for the point source at the centre of the lens (c).

4. Focusing in PC with waveguide

To test the above theoretical analysis, we adopt a wave-guide in the lens. We first consider W1 wave-guide, which is formed by a line of missing cylinders. The structure is displayed in Fig.5(a). Firstly, we investigate the case in which the point source is located outside the sample as shown in Fig.5(b). We find that the lens has a high-quality focusing. But at other positions outside the wave-guide there also exists the transmission wave. To test this result, we locate the point source at the centre of the sample. Figure 5(c)

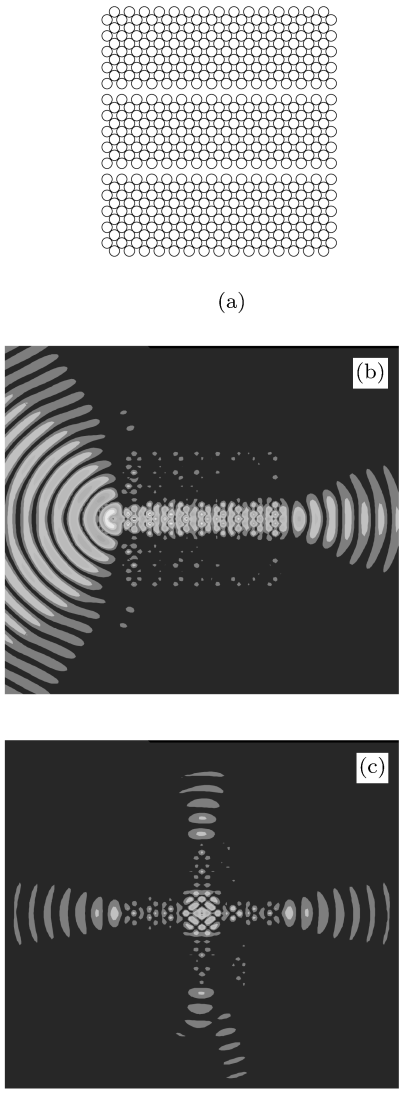


Fig.5. Structure of the lens with W1 wave-guide (a), the field distribution for the point source located outside the lens (b), and the field distribution for the point source at the centre of the lens (c).

shows there appear four focusings at four symmetrical positions. It is proved that W1 wave-guide does not confine enough the transmission wave. The EM does not attenuate totally when it traverses the W1 wave-guide. Secondly, we take out two lines of cylinders (W2 wave-guide) as displayed in Fig.6(a). We carry out the same simulation. The field distributions are shown in Figs.6(b) and 6(c). We can observe that the transmission wave is confined completely into the region between the two wave-guides. In the other directions there appears no transmission wave. When the point source is located at the centre of the lens, there remain only two focusings. Moreover, the qualities of the focusings have been improved.

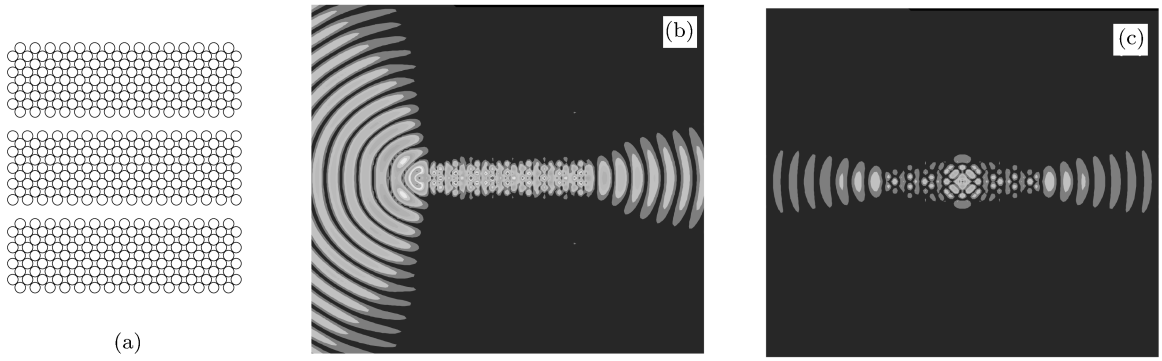


Fig.6. Structure of the lens with W2 wave-guide (a), the field distribution for the point source located outside the lens (b), and the field distribution for the point source at the centre of the lens (c).

5. Conclusion

Using the numerical simulations based on the finite-difference time-domain method, we study the effect of defect on the focusing of lens that is built by a square lattice of dielectric cylinders. We find that the lens with defects can focus in many directions. When the wave-guides are introduced, the transmission wave is confined effectively within this region.

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