Influence of line defects on focusing in a two-dimensional photonic-crystal flat lens*

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We investigate in detail the influence of line defects on focusing of electromagnetic waves in a two-dimensional photonic-crystal flat lens. Through simulations, we find that a focusing can always be observed when a line defect in the lens is introduced along the light transmission direction and the width of the line defect is less than $\lambda/2$. However, there appear two focusings when the width of the line defect is more than $\lambda/2$. When the line defect is introduced along the direction perpendicular to the transmission, there is always one focusing.

Keywords: flat lens, line defect, photonic crystal

PACC: 7210F, 4270Q, 4225B

1. Introduction

Left-hand materials (LHMs) and negative refraction have attracted much attention due to their involving some unusual electromagnetic (EM) wave propagation phenomena. Veselago for the first time analysed some interesting and peculiar properties of such materials over 30 years ago,[1] but only recently were these demonstrated experimentally.[2,3] Recently experimental and theoretical work has also indicated that negative refraction phenomena in photonic crystals (PCs) are possible.[4−22] In particular, Luo *et al.* have shown that all-angle negative refraction (AANR) could be achieved at the lowest band of two-dimensional (2D) PCs. The physical principle that allows negative refraction in PCs lies in the spatial dispersion characteristics of wave propagation in a periodically modulated medium, which can be well described by analysing the equifrequency surface (EFS) of the photonic band structures.[23−29] It is well known that negative refraction materials have an important application to 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. 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 a few theoretical and experimental studies on the focusing and the imaging of PC lenses. However, the detailed theoretical and experimental investigations into the influence of defects on focusing of electromagnetic waves are still lacking.[32,33] We have some reports on the study for this case.[34,35] Recently, we investigated the influence of the line defect on focusing. By a finite-difference time-domain (FDTD) simulation, we found that there appears a focusing when a line defect is introduced along the transmission direction in a photonic crystal and the width of the line defect is less than $\lambda/2$. However, there are two focusings when the width is more than $\lambda/2$. There appears always one focusing when the line defect is introduced along the direction perpendicular to the transmission.

The paper is organized as follows. In Section 2 we analyse the band structure, the EFS of periodical structure and the focusing in flat lens without defects. The focusing is discussed when the line defects are introduced along the x or y direction in Section 3. Finally, a summary is given in Section 4.

2. Focusing in photonic crystal without defects

We consider a 2D square lattice of dielectric cylinders with dielectric constant 8.6 and radius 3 mm. The lattice constant of PC is a. The photonic band structure and the EFS contour are crucial for the investigation of negative refraction and focusing effects.

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They are calculated by the FDTD method with a periodic boundary condition, 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 frequency 7.65 GHz for the TM wave is significantly distorted from a circle. It is convex around the M point, which means that the directions of the group velocity ($v_{\rm g}$) and the phase velocity are opposite. The conservation of the plane wave vector in the surface will result in a negative refraction effect in this case. According to the analysis given 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 the TM-polarized wave incident on the ΓM surface at various incident angles will propagate into this crystal on the negative refraction side. In all of our simulations the electric fields are kept parallel to the cylinders, which means that the incident wave is TM-polarized.

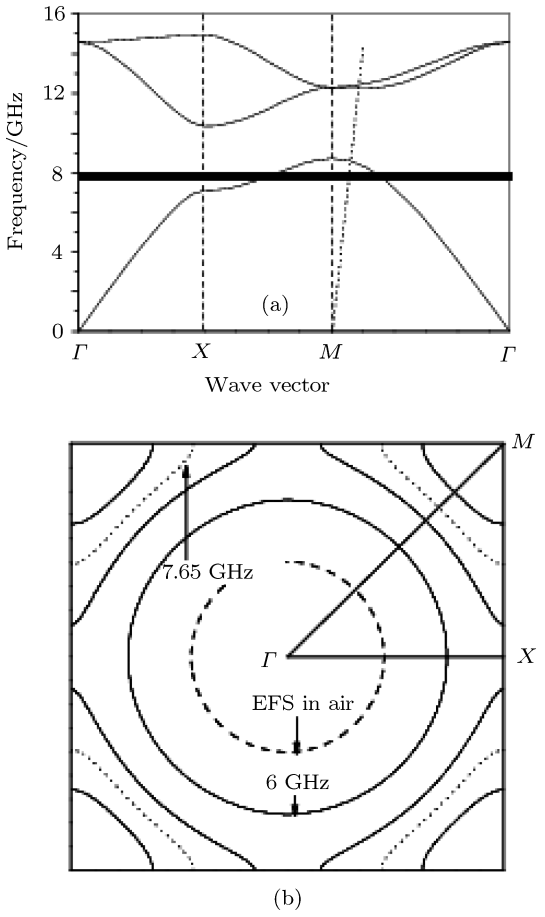


Fig. 1. (a) Theoretical photonic band structure of a square lattice of cylinder for the TM-polarized wave, where the dash line denotes the light line and the shadow area represents the AANR region, and (b) several equifrequency contours for the TM-polarized wave (solid lines) in the first band of 2D PC.

In a way similar to that in Ref. [13], we design a flat lens to realize focusing by using the above PC system. Thus, we take a square slab with a width of $15\sqrt{2}a$ along the x direction.[34] A point source (modulated into a Gaussian distribution) is placed at a distance of $1.0a$ from the left surface of the slab. The frequency of the incident wave is 7.65 GHz. Using the FDTD method, we calculate the propagation of the TM-polarized wave in such a system. One can find a high quality focus to form in the opposite side of the slab. The distance between the focus and the right surface of the slab is about $0.8a$. That is to say, the focus of a point source can be observed at this frequency by such a 2D PC slab.[35]

3. Focusing in PC with a line defect along x or y direction

Now we investigate the effect of a line defect on focusing. We introduce a line defect along the x or y direction by edge dislocation of the structure. It means that a part of dielectric cylinder is moved along the x or y direction when the cylinder coordinate x exceeds a certain value. Firstly, we consider moving along the x direction. The structure of the sample is shown in Fig. 2(a). The arrow represents the direction of motion of the dielectric cylinder. The widths of the line defect are $\lambda/8$, $\lambda/4$, $\lambda/2$ and $3\lambda/4$, respectively. In a way similar to that in the above investigation, we calculate the field distribution when the point source is out of the sample. The results are shown in Figs. 2(b)–2(e). From Figs. 2(b) and 2(c), a high-quality focusing is observed on the right side of the lens when the width of the line defect is less than $\lambda/2$. This is because wave propagation in a photonic crystal can maintain continuity when the wave passes through the position of the defect. However, when the width is more than $\lambda/2$, there appear two focusings as if there were two independent flat lenses, as shown in Figs. 2(d) and 2(e).

Next we study the change along the y direction. When x exceeds a certain value, we move the dielectric cylinder along the y axis as shown in Fig. 3(a). The arrow represents the direction of motion of the dielectric cylinder. The changing values of the dielectric cylinder are $\lambda/8$, $\lambda/4$, $\lambda/2$ and $3\lambda/4$, respectively. We calculate the field distribution when the point source is out of the sample. The point source is placed at a distance of $1.0a$ from the left surface of the slab. The

results are shown in Figs. 3(b)–3(e), respectively. We can see that a high-quality focusing can be observed on the other side of the lens as shown in Fig. 3. For different values, there is always one focusing.

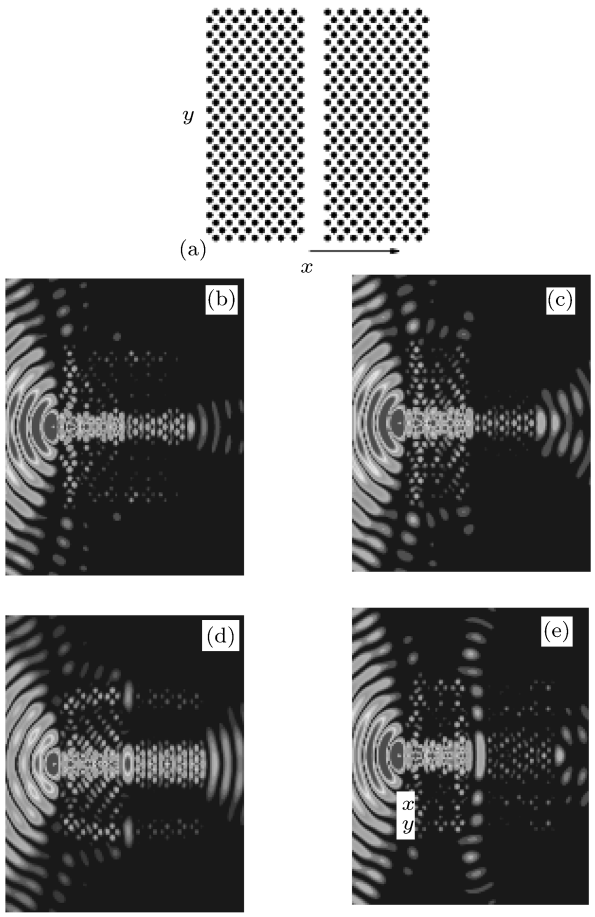


Fig. 2. (a) Structure of the line defect along the x direction, where the arrow represents the direction of motion of the dielectric cylinder and field distributions calculated for different widths of the line defect: $\lambda/8$ (b), $\lambda/4$ (c), $\lambda/2$ (d) and $3\lambda/4$ (e).

As is well known, the wave propagation inside a photonic crystal can be amplified with Bloch eigenfunctions which are periodic in space and time. When the line defect is introduced along the y direction (perpendicular to the propagating direction), the existence of the defect exerts little influence on wave propagation. Therefore, a high-quality focusing can always survive. However, when the line defect is along the propagating direction, the scattering from the line defect will inevitably deteriorate the quality of focusing, more or less depending on defect width. When the defect width is less than $\lambda/2$, the scattering from the defect is minor. Thus the focusing effect is preserved. When the defect width is larger than $\lambda/2$, the scattering becomes intense, and we can observe two focusings, as if a single flat lens became two lenses.

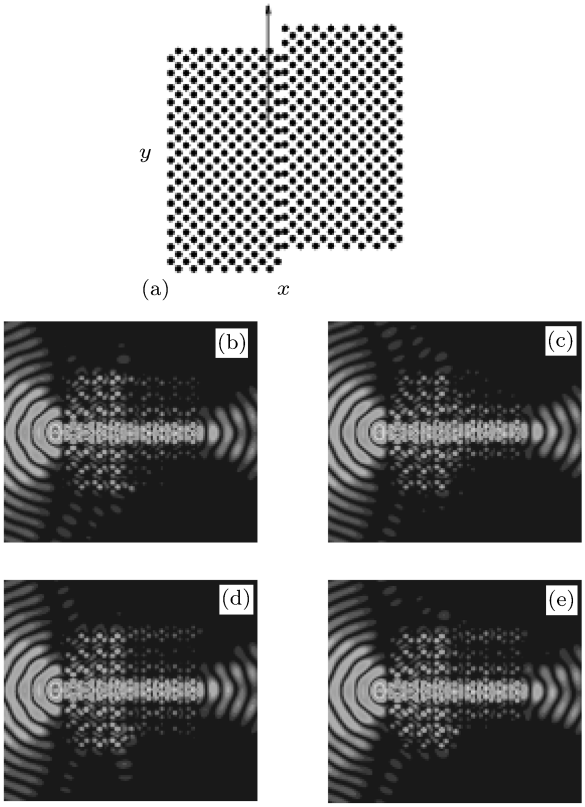


Fig. 3. (a) Structure of the line defect along the y direction, where the arrow represents the direction of motion of the dielectric cylinder, and the field distributions calculated for different widths of the line defect is shown: $\lambda/8$ (b), $\lambda/4$ (c), $\lambda/2$ (d) and $3\lambda/4$ (e).

4. Summary

By the finite-difference time-domain method, we investigated the focusing of a flat lens in a two-dimensional photonic crystal with a line defect. We find that there is a focusing in the x direction when the line defect in the lens is introduced along the x direction and the width of the line defect is less than $\lambda/2$. This is because the continuity of the electromagnetic wave can be maintained when the wave passes through the line defect. However, there are two focusings when the width is more than $\lambda/2$. When the line defect is introduced along the y direction, one focusing is always observed.

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