Non-near-field focus and imaging of an unpolarized electromagnetic wave through high-symmetry quasicrystals

Xiangdong Zhang [1] **, Zhiyuan Li** [2] **, Bingying Cheng** [2] **and Dao-Zhong Zhang** [2]

[1] Department of Physics, Beijing Normal University, Beijing 100875, China,

[2] Institute of Physics, Chinese Academy of Sciences, Beijing, 100080.

zhangxd@bnu.edu.cn

Abstract: The focus behaviors of electromagnetic wave through two-dimensional (2D) high-symmetry photonic quasicrystals (PQCs) have been investigated by using exact multi-scattering numerical simulation. We have found that the high-symmetry PQC flat lenses possess universal feature for non-near-field focus of two kinds of polarized waves. That is to say, the non-near-field focus for two kinds of polarized waves can be realized by using these flat lenses, which are consisting of 12-fold, 10-fold and 8-fold 2D PQCs with the same structures and parameters. Such a superior feature originates from higher rotational symmetry and negative refraction in the PQCs. Thus, potential applications of such a phenomenon to optical devices can be anticipated.

OCIS codes: (260.2110) Electromagnetic theory; (110.2960) Image analysis; (999.9999) Photonic crystals.

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1. Introduction

In recent years there has been a great deal of interests in studying the focus and imaging of electromagnetic wave by using the left-handed material (LHM) or two-dimensional (2D) photonic crystal (PC) flat lens [1-29]. 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 in the case of a parallel-sided slab of material [1, 2]. There are two aspects relating to the focus and imaging. One is position (in near-field region or non-near-field region), and the other is resolution (half maximum width of the focus spot). The position of the focus depends on the effective refractive index of the sample and the homogeneity of the materials, and the resolution depends on the evanescent waves (or resonance transmission). Based on this knowledge, various focus and imaging can be realized. Recently, such image behaviors in the LHM-superlens [3-7] and 2D periodic photonic-crystal-based flat lenses [8-29] have been observed by some numerical simulations and experimental measurements.

In fact, the negative refraction exists not only in the periodic PC, but also in quasi-periodic PC. Recently, such a phenomenon has been demonstrated both theoretically and experimentally [29]. It is interesting that the non-near-field focus and imaging have also been realized by a 2D photonic quasicrystal (PQC) flat lens. However, the above discussions about the negative refraction and the focus of the wave in the 2D PQC only focused on a certain S polarized wave (E polarization mode). From the investigations of the photonic band gaps in some PQCs, we have known that high-symmetry PQCs do have the advantage of supporting absolute gaps (both S wave and P wave) because their high symmetry [30, 31]. It is natural to ask whether or not the non-near-field focus and imaging for two kinds of polarized waves can also be realized by using these high-symmetry PQC slabs with the same structures and parameters? In this paper, we explore the possibility to realize such a focus by using the PQC slabs.

2. System and method

We consider three kinds of the PQC system with 8-fold, 10-fold and 12-fold symmetries. The corresponding PQC structures are shown in Fig. 1(a), 1(b) and 1(c), respectively. In order to gain understanding of the band and gap regions for the electromagnetic waves transport in these PQC structures, we calculate the transmission spectrums. The calculations are performed by using the multiple-scattering method [17, 19]. The results for three kinds of structure are plotted in Fig. 1(d), 1(e) and 1(f), respectively. Solid lines in the figures represent the transmission coefficients of the cases with 7(a) thickness as a function of the frequency for the S

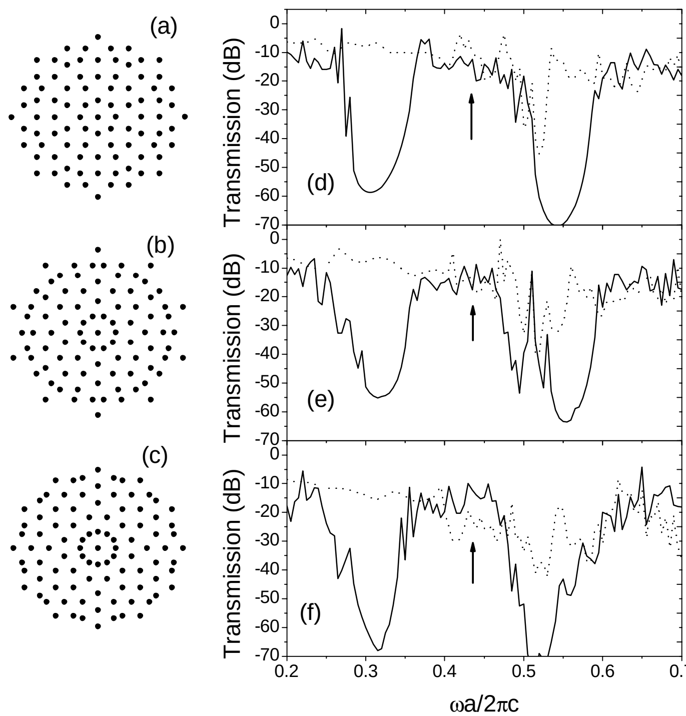

Fig. 1. Schemes of three kinds of PQC structure and the corresponding transmission coefficients as a function of frequency for the PQC slabs consisting of the dielectric cylinders with R=0.35a and $\varepsilon = 8.4$. (a) and (d) correspond to the 8-fold PQC; (b) and (e) to 10-fold PQC; (c) and (f) to 12-fold PQC. Solid lines and dotted lines correspond to the cases of S wave and P wave, respectively.

wave, and dotted lines correspond to those of the P wave. The radii and the dielectric constant of the cylinders are taken as 0.3a and 8.4, respectively. The similar band-gap properties for three kinds of structure are found. The results show two gaps and one band between the frequencies $0.2(2\pi c/a)$ and $0.6(2\pi c/a)$ for the S wave. Because we aim at focus and imaging by using flat lens consisting of the above PQCs, in the following we focus our discussions on

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the band regions.

The properties of wave transport in the periodic PC can well be described by analyzing the equifrequency surface of the band structures. However, such a method is not applicable for the PQC systems, due to the absence of the Bloch theorem. Thus, the study of quasiperiodic composites is much more difficult than that of periodic composites. In this paper, we adopt the multiple-scattering Korringa-Kohn-Rostoker method [17, 19] to perform numerical simulations for wave propagating in these systems.

3. Numerical results and discussion

We first take a 12-fold PQC slab with thickness 11a and width 40a to design a flat lens. A continuous-wave point source is placed at a distance 5.5a (half thickness of the sample)

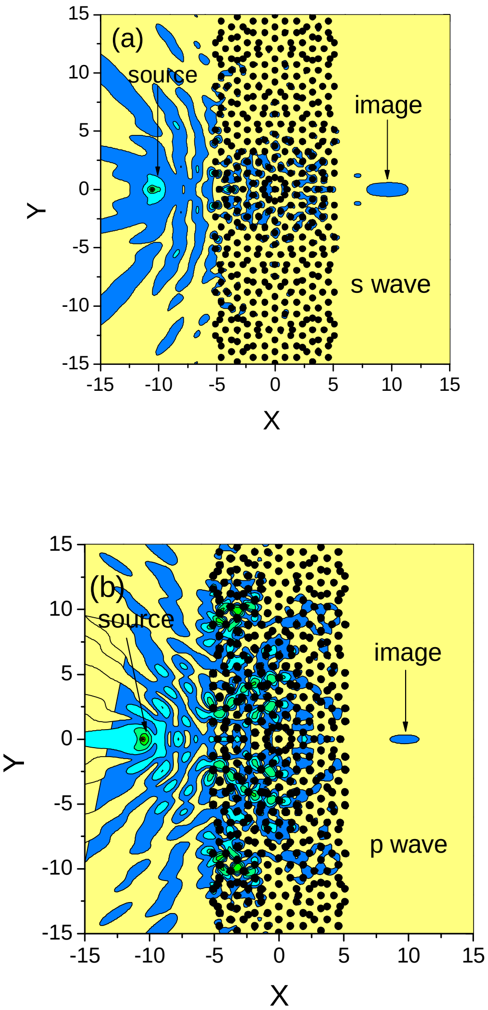

Fig. 2. The intensity distributions of E_z field for S wave (a) and H_z field for P wave (b) of point sources and their images across a 11a 2D PQC slab with 12-fold symmetry at frequency $\omega = 0.4365(2\pi a / c)$. The parameters of cylinders are identical to those in Fig. 1.

from the left surface of the slab. The frequency of the incident wave emitting from such a point source is in the band regions (from ω = 0.35($2\pi c/a$) to ω = 0.48($2\pi c/a$)). Through numerical simulations, we find that the negative refraction and the focusing can appear in a narrow frequency range between $\omega = 0.435$ and $0.439(2\pi a/c)$. However, the focuses at the same position for two kinds of polarized waves occur at ω = 0.4365($2\pi c/a$) [marked by an arrow in Fig. 1(f)]. The results are shown in Fig. 2.

Figures 2(a) and 2(b) describe the intensity distributions of E_Z field for the S wave and H_Z field for the P wave across such a PQC slab with 12-fold symmetry, respectively. X and Y present vertical and transverse direction of wave propagating. The fields in figures cover $30a \times 30a$ region around the center of the sample. The geometries of the PQC slab are also displayed. One can find that the focuses formed in the opposite side of the slab for two kinds of polarized waves. In particular, their positions are approximately same. They are about at a distance of 5.5*a* from the right surface of the slab. That is to say, the image of point source with unpolarized wave can be realized by 2D PQC slab. A closer look at the data reveals that the half maximum width of the focus spot is about 0.5λ for two kinds of polarized waves. If we change the thickness of the samples, similar features of the focus can also be found.

However, the quality of the focus is related to the interface and the thickness of the slab. Figures 3(a) and 3(b) show that the intensity distributions along the transverse (Y) direction at the image plane for 12-fold PQC slabs with different thicknesses for S wave and P wave, respectively. In fact, various thicknesses mean different interfaces, because the PQCs are different from the periodic structures which possess periodic interface. In previous investigations for the periodic PCs, it has been shown that the image resolutions depend on the interface structures [11, 13, 23-25]. Such a feature can also be observed in the present PQC slabs. Solid lines, dashed lines and dotted lines in Figs. 3(a) and 3(b) correspond to the case of 11a, 9a and 7a thickness, respectively. It is seen that the focus intensities change with the thicknesses of the slabs. For example, if the intensity of the point source for S wave is taken one, the maximum intensity of the focus point is 0.34 for 7a thick lens, it becomes 0.28 for 11a thick lens. At the same time, the image resolutions also vary slightly around 0.5λ half maximum width of the focus spot.

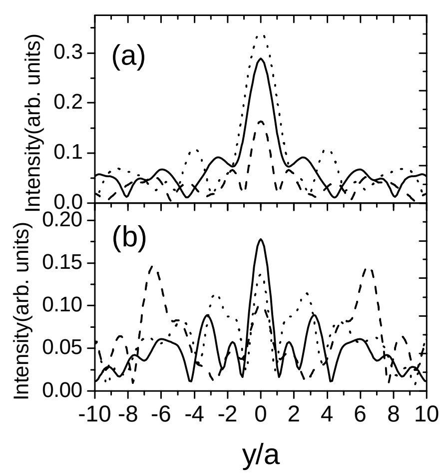

Fig. 3. The intensity distributions along the transverse (Y) direction at the image plane for 12-fold PQC slabs with 11a (solid line), 9a (dashed line) and 7a (dotted line) thickness. (a) S wave; (b) P wave.

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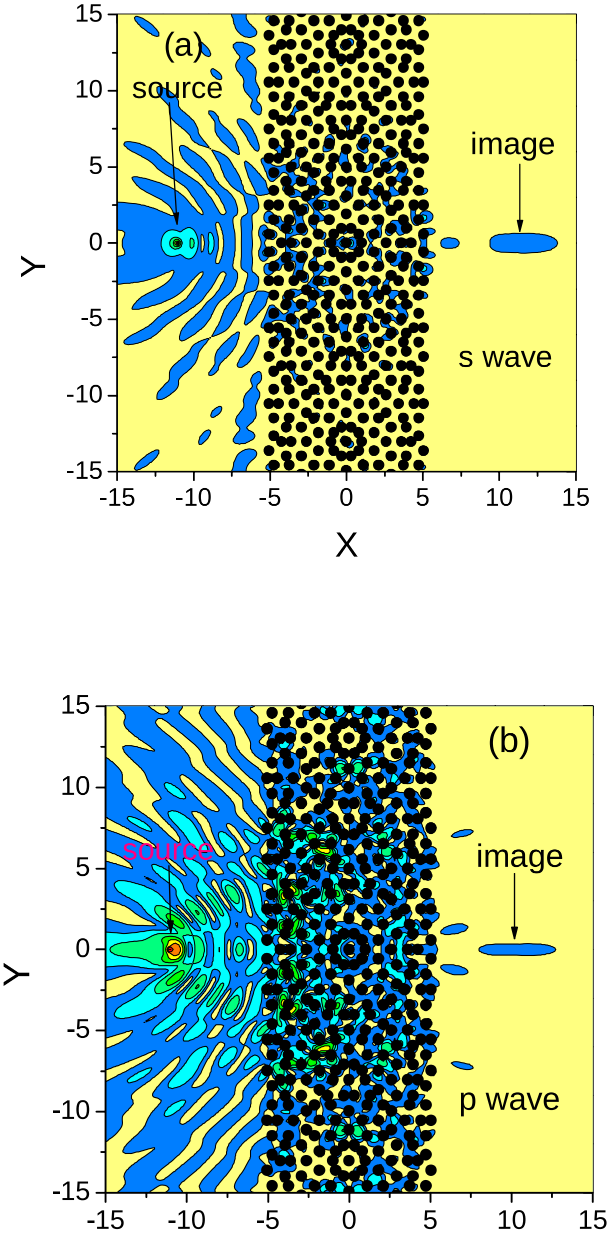
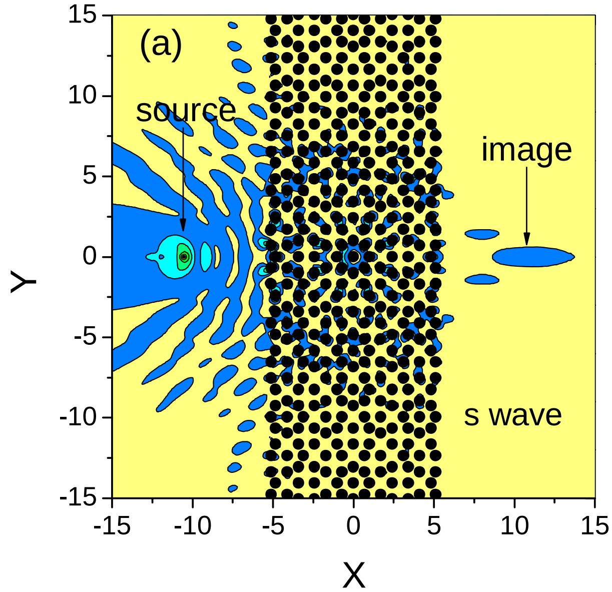


Fig. 4. The intensity distributions of E_Z field for S wave (a) and H_Z field for P wave (b) of point sources and their images across a 11a 2D PQC slab with 10-fold symmetry at frequency $\omega = 0.4367(2\pi a/c)$. The parameters of cylinders are identical to those in Fig. 1.



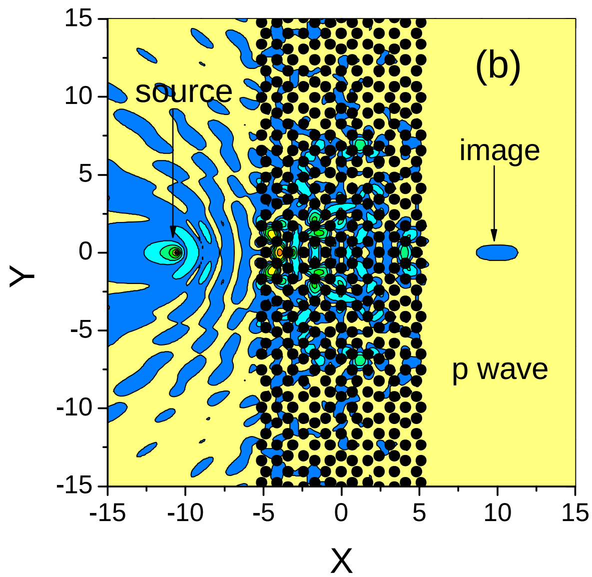


Fig. 5. The intensity distributions of E_Z field for S wave (a) and H_Z field for P wave (b) of point sources and their images across a 11a 2D PQC slab with 8-fold symmetry at frequency $\omega = 0.436(2\pi a / c)$. The parameters for cylinders are identical to those in Fig. 1.

The above results are found in the 12-fold PQC. If we replace the 12-fold PQC slab by 10-fold or 8-fold PQC slabs, similar phenomena can be observed. Figures 4(a) and (b) describe the intensity distributions of E_Z field for the S wave and H_Z field for the P wave of the point sources and their images across 11a 2D PQC slab with 10-fold symmetry, respectively. Here the frequency of incident wave emitting from the point source is ω = 0.4367(2$\pi c/a$) [marked by an arrow in Fig. 1(e)], which is a little different from the case of Fig. 2. The size of the slab and the distributions of the field are identical to those in Fig. 1. As seen from the figures, the focus positions for two kinds of polarized waves are still approximately same. The corresponding results of the PQC with 8-fold symmetry are plotted in Figs. 5(a) and 5(b). The similar non-near-field focus for the S wave and the P wave at ω = 0.436(2$\pi c/a$) [marked by an arrow in Fig. 1(d)] are observed again.

Our calculated results indicate that the high-symmetry PQC slabs possess universal feature for the non-near-field focus of two kinds of polarized waves. That is to say, the flat lenses consisting of 12-fold, 10-fold and 8-fold 2D PQCs all can focus the unpolarized wave emitting from a point source at the approximately same frequency. The origin of such a superior feature can be understood from the following two aspects. First, the appearance of the focus through the high-symmetry PQC can be understood similar to the cases in the periodic PCs [29]. The focus principle of electromagnetic wave through the flat slabs consisting of the periodic PCs is due to the negative refraction and complex Bragg scattering effects, which can be described in terms of the equifrequency surface of the band structures [8-25]. Strictly speaking, the equifrequency surface and the band structures in PQCs do not exist due to the absence of the Bloch theorem. However, recent experiments [32] had shown that analogous concepts to Bloch-like functions and Bloch-like states in the periodic structures can be applied approximately to some quasicrystals. This means that the complex Bragg scattering effects still exist in some PQCs. Thus, the existence of the negative refraction and the focus for the electromagnetic wave in PQC slabs becomes understandable.

In addition, the high rotational symmetries, which the high-symmetry PQCs possess, play important role for such a non-near-field focus. Although the non-near-field focus for the unpolarized wave can also be realized by periodic PCs [28], it can only be realized at some cases under complex designing. It is very difficult to construct a flat lens by using pure dielectric cylinder of periodic structure to realize the non-near-field focus for two kinds of polarized waves, but it is easy to complete it by high symmetry PQC slabs as has been shown. This is because that the position of the image depends on the homogeneity of the materials. In general, the homogeneous dispersion can be obtained easily in the high-symmetry structures. However, the highest level of symmetry that can be found in the periodic lattice is only six. In contrast, the high geometric symmetry of PQCs can reach 8, 10 and 12. The motivation for using these high-symmetry PQCs is to maintain the periodic scattering of light while reducing the orientational order of the system so that it is more isotropic around the symmetric point. This makes the high-symmetry PQCs possessing some superiority to realize the non-near-field focus of unpolarized electromagnetic wave.

We would like to point out that the PQCs are not better than the periodic PC in all aspects. The focus through the flat lens consisting of the periodic PC can be realized by a point source placed at any position along Y direction. However, for the PQC lens, the best focus is that the point source is placed at the axes which pass through the high-symmetry points such as Y=0. Once the point sources depart from the axes, the focusing effects degrade.

This is because the focuses of the field around the symmetric center (also the center of the slab) are related to the high rotational symmetric structure. If the point source departs from the axes, the high-symmetry along X direction for such a source will lose. Thus, the focus will become worse.

4. Conclusion

In summary, based on the exact multi-scattering numerical simulation, we have investigated the focus behaviors of unpolarized wave by using 2D high-symmetry photonic quasicrystal flat lens. Some universal features for the non-near-field focus of two kinds of polarized waves have been found. The non-near-field focuses for two kinds of polarized waves at the same structures and parameters have been realized by these flat lenses consisting of 12-fold, 10-fold and 8-fold 2D PQCs. In addition, our PQC structures are composed of pure dielectric materials and therefore are less absorption. Therefore, our results can all be generalized to any range of the frequency, and can be applied in a range of optical devices.

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