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Influence on the resolution based on defective NR-PC double flat lens group with Ag for target detection and imaging

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ABSTRACT

In this paper, we employed the dynamic scanning scheme to study the influence on target detection and imaging based on the defective NR-PC double flat lens group with Ag by finite-difference-time-domain method. We firstly deduced the focusing imaging circuit diagram of NR-PC flat lens with the Snell extension law and geometrical optics principle. Numerical simulations indicate that significant enhancement of the scattering signal can be obtained while the NR-PC flat lens is used for target detection and imaging. Then the imaging principle of NR-PC flat lens group is studied. We find that the distance between the two lenses can be adjusted flexibly. What is important, the resolution of target detection is greatly improved when incorporating Ag into the NR-PC flat lens group. In conclusion, our investigation makes the target detection and imaging by NR-PC flat lens come true, and optimizes the performance of small target detection and imaging system.

1. Introduction

Left-handed materials (LHMs) have found many important implications in optical and microwave areas, such as in the area of near-field target detection and imaging [1,2]. The so-called perfect lens made of LHM with no losses is more attractive because of its high focus resolution overcoming the optical diffraction limit [2–4]. And generally, the higher focus resolution yields the better imaging resolution in near-field target detection and imaging [5,6].

Although regarding the flat LHM lens remarkable progress has been made in the area of near-field target detection and imaging [5,6], there is still much uncertainty about whether such materials actually exist in nature. By using a different method, M. Notomi has demonstrated 2D photonic crystals exhibiting negative-index or negative-refraction effects [7]. From their results on the band gap of the equifrequency surface (EFS) in k space we know that negative refraction usually occurs because the size of the contour of EFS in the k space decreases with increasing frequencies. And the contour of EFS up to a certain frequency takes a quasi-circular shape [8], which means that the light propagating in PC is similar to that propagating in the isotropic medium at these frequencies. Thereby an effective negative index of refraction n_{eff} can be used to describe the propagation property of light with frequency falling into a certain frequency spectrum for a given NR-PC, and the NR-PC could be used as a flat LHM, which could be used as a flat lens in near-field target detection and imaging [9,10].

The two-dimensional photonic crystal structure examined in this paper, as shown in Fig. 1(a), is formed by periodically drilling 7 rows (along the Z-axis, that is) of identical air holes with 30 air holes (along the X-axis) in each row in a GaAs matrix with dielectric constant $\varepsilon=12.96$ ($n=3.6$). And the air cylinders take on a triangular array; here the radius of the air cylinders is $0.4a$ (a represents the lattice constant). The effective refractive index of the photonic crystal is calculated with TM mode and is drawn in Fig. 1(b) by using the algorithm in reference of [8]. It is understandable that n_{eff} changes with normalized frequency $\omega=a/\lambda$. From Fig. 1(b), we know that, when n_{eff} takes the value of -1, the corresponding normalized frequency ω is about 0.3068.

In this paper, we mainly discuss the influence on target detection and imaging on the basis of defective NR-PC double flat lens group with Ag. At first, we deduced the focusing imaging circuit diagram of NR-PC flat lens with the Snell extension law and geometrical optics principle. We also discussed the conditions that should meet. According to our results, the refocusing resolution can be improved due to the use of the NR-PC flat lens. Numerical simulations based on the structure shown in Fig. 1(a) indicate that resolution can be greatly enhanced through introducing Ag to the NR-PC flat lens with dynamic scanning scheme. Based on the above study, we replace the single flat lens with NR-PC double flat lens group, which having been introduced Ag. With proper defects, the resolution of target detecting and scanning will be optimized

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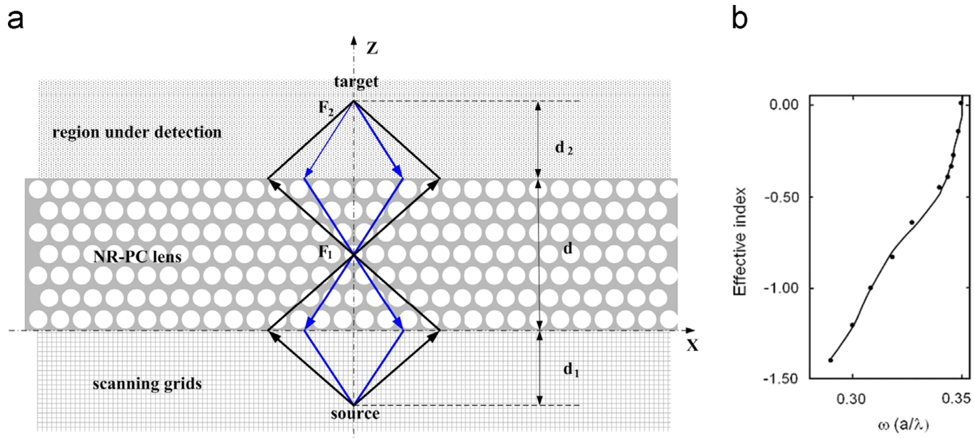

Fig. 1. (a) Target detection and imaging by using NR-PC flat lens and (b) change curve of n_{eff} and ω in the NR-PC lens (for TM mode).

and the distance between the two lenses can be adjusted flexibly. Our studies play an important role in the small target detection and imaging by using NR-PC flat lens.

2. Design principle of target detection and imaging system based on the NR-PC flat lens

According to the Snell extension law and geometrical optics principle, we can get the negative refraction imaging light path while the point source incidence to the NR-PC flat lens, which is shown in Fig. 2.

Snell (extension) law

$$n_1 \sin\theta_i = |n_{eff}| \sin\theta_r \tag{1}$$

According to the Snell extension law and geometrical optics principle of Fig. 2, we can get: $(n_1 = 1)$

$$SF_1 = \left(1 + \frac{\sqrt{n_{eff}{}^2 - \sin^2\theta_i}}{\cos\theta_i}\right) d_1 \tag{2}$$

$$SF_2 = \left(1 + \frac{\cos\theta_i}{\sqrt{n_{eff}^2 - \sin^2\theta_i}}\right) d \tag{3}$$

where SF_1 represents the distance between the light source S and F_1 in the internal of NR-PC flat lens; SF_2 represents the distance between the source S and F_2 outside of NR-PC flat lens; d represents the width of NR-PC flat lens; d_1 represents the distance between source S and the lower surface of flat lens; d_2 represents the distance between the target and the upper surface of the flat; θ_i and θ_r represent incident angle of and refraction angle, respectively.

When the incident angle is very small, formulas (2) and (3) could be simplified as follows using the paraxial approximation:

$$SF_1 = (1 + |n_{eff}|) d_1 \tag{4}$$

$$SF_2 = (1 + 1/|n_{eff}|) d \tag{5}$$

At the same time, it should meet certain conditions for focusing and imaging by using the NR-PC flat lens:

$$d_1 < d \tag{6}$$

Through simulation, we could get the focusing imaging circuit diagram of NR-PC flat lens, as shown in Fig. 3, which indicates relationship between SF_1, SF_2 and d_1.

From Table 1 and Fig. 3(a)–(c), we could find that the Z coordinate of the internal focus F_1 changes with the flat's position.

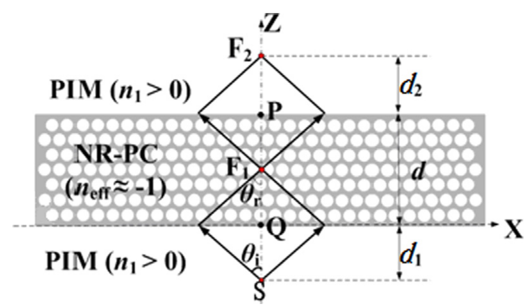

Fig. 2. The focusing theoretical figure of NR-PC flat lens.

That means SF_1 increases with the increase of d_1. It should be noted that the simulation results shown in Fig. 3(c) (it represents the critical state for $d_1 = 6\ \mu m \approx d$) and Fig. 3(d) (no imaging point is formed) illustrates that certain conditions should be meet for focusing. The certain condition is $d_1 < d$.

By further simulation, different SF_1, SF_2 values corresponding to varied d values can be got (while keeping d_1=3 μm), which is shown in Table 2.

Simulation results demonstrate that the point source light could be focused twice by the NR-PC flat lens when $d_1 < d$. The external focus F_2 and SF_2 (the distance between point light source and external focus F_2) are mainly related to the width of flat d. And the internal focus F_1 and SF_1 (the distance between point light source and internal focus F_1) are mainly related to d_1 (the distance between point light source and the lower surface of flat). We also find that SF_2 is related to d (the width of the flat) and SF_1 is related to d_1 (the distance between point light source and the lower surface of flat).

The details discussed above are based on the NR-PC single flat lens. Now we will further study the focusing imaging law of NR-PC flat lens group. The so-called lens group is made up of two or more flat lenses. The lens group (as shown in Fig. 4) discussed in this paper is composed of two identical NR-PC flat lens (as is shown in Fig. 2). d_1 represents the distance between source S and the lower surface of flat A. d_{AB} represents the distance between flat A and flat B. d_2 represents the distance between the target and the upper surface of flat B.

The focusing imaging law of point light source through NR-PC flat lens group (Fig. 4) could be deduced similarly $(n_{eff} \approx -1)$:

$$d_1 + d_{AB} + d_2 = 2d \tag{7}$$

At the same time, it should also meet certain conditions for point source light of incidence focusing and imaging by using the NR-PC flat lens group:

$$d_1 + d_{AB} < d \tag{8}$$