All angle negative refraction with the effective phase index of −1

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We theoretically studied a left-hand structure based on a two-dimensional (2D) photonic crystal (PC) with a negative refractive index. The propagation of electromagnetic waves in the proposed PC structure is investigated through dispersion characteristic analysis and numerical simulation of field pattern. The designed PC structure can exhibit all angle negative refraction, and the corresponding effective refractive indices along all directions are almost same and close to the ideal value of −1. A flat lens formed from such a PC has been designed and its imaging properties have been investigated systematically.

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The recent discovery of left-hand materials (LHM) with negative effective index over a designed frequency band has attracted increasing interest. In 2000, Pendry[1] proposed that subdiffraction-limited optical resolution could be achieved with a superlens made of an ideal LHM with index $n = -1$. The relevant properties have been observed experimentally at 10.5 GHz[2] in a LHM, showing great potential in the optical regime[3,4].

Another equally important aspect of negative refraction is that under certain conditions, photonic crystals (PCs) can also refract light with a negative refraction angle. Imaging behaviors against negative refraction two-dimensional (2D) PCs slab lens have been found by some authors via numerical simulations and experiments[5,6]. However, the refraction in PCs can be more complicated than in uniform media. A single incident wave can produce multiple refracted Bloch-wave orders, if there are multiple branches of dispersion contours at the same frequency or if the interface is not along major crystal symmetry directions. This results in a scenario similar to simple Bragg scattering in the elementary case of diffraction gratings. Moreover, the presence of strongly scattering crystal structures can modify the dispersion relation of light so much that the shapes of the dispersion contours are far from being circular. The gradient directions on these contours and thus the refraction directions can be very different from those expected in a uniform material. In summary, the candidate PC structures should have three characteristics[7]. First, it should exhibit almost isotropic equal frequency surface (EFS) in a band region with $\vec{v}_{\rm g} \cdot \vec{k} < 0$, where $\vec{k}$ is the wave vector in the first Brillouin zone (BZ) and $\vec{v}_{\rm g}$ is the group velocity. The latter implies $\vec{S} \cdot \vec{k} < 0$, and thus LH behavior. Second, it should guarantee the absence of any higher order Bragg reflections for any incident angle. Finally it should guarantee single beam propagation. The main challenge is to find a structure of all-angle LH negative refraction with the effective phase index $n_{\rm eff} = -1$[1,7].

In this paper, we design an almost ideal structure based on 2D PC. The proposed structure meets almost all the required condition. At a certain frequency the all angle negative refraction with an effective index of −1 can be reached. The flat lens can form both non-near-field image and near-field image. Calculated results show that the traditional limitation can be broken through at the near-field image.

The proposed structure consists of a triangular array of dielectric rods in air, having a dielectric constant $\varepsilon = 12.96$ (e.g., GaAs or Si at 1.55 μm) for the H polarization (the H field is parallel to the rods). The radius of the dielectric rods is $r = 0.45a$, where a is the lattice constant. The plane wave method is used to

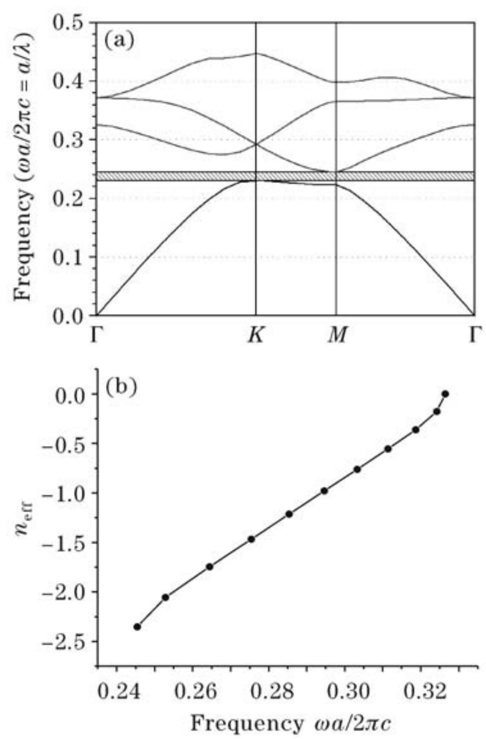

Fig. 1. (a) Band structure of the 2D triangular lattice PC. The radii of the dielectric cylinders with $\varepsilon = 12.96$ are $r = 0.45a$. (b) Effective phase index $n_{\rm eff}$ versus frequency f for the second band along the ΓM direction.

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compute the photonic band structures as well as the EFS of the photonic band structures. Figure 1(a) shows the band structure of the system. The quantity f is the frequency normalized as $\omega a/2\pi c$, where c is the velocity of light. From Fig. 1(a), it suggests that we should focus on the second band in order to study the negative refraction problem of wave propagation in such a PC structure. Figure 1(b) shows the effective phase index $n_{\rm eff}$ versus frequency f for the second band along the ΓM direction. In 2D PCs, $n_{\rm eff}$ had been discussed in detail in Ref. [8]. From Fig. 1(b), we can see that the frequency, which leads to $n_{\rm eff} = -1$, is 0.293.

It has been mentioned above that the candidate structure should exhibit almost isotropic EFS in a band region with $\vec{v}_{\rm g} \cdot \vec{k} < 0$, i.e. $n_{\rm eff}$ must almost be same along all directions. For this reason, the EFS contours in $\vec{k}$ space of the system at several relevant frequencies in the second band are shown in Fig. 2. From Fig. 2, it can be noted that EFS shrinks when frequency increases, so the group velocity is negative. This means that the group velocities are opposite to the phase velocities. The EFS between two frequencies $f = 0.290$ and $f = 0.3143$ is almost isotropic.

In order to test the above theoretical analysis, we perform numerical simulations in the present systems. We employ the finite difference time domain (FDTD) method with the use of perfectly matched layer (PML) boundary condition. A Gaussian source is placed outside the structure to check the negative refraction. The continuous wave (CW) point source of $f = 0.293$ is placed $0.459a$ (1.34λ) away from the lower surface of a ten-layer thick PC slab (non-near-field). The source starts gradually emitting at $t = 0$. Figure 3(a) shows the magnetic field distribution across the PC slab after $t = 263.2t_0$, where $t_0 = a/c$. Clear image is formed away from the upper surface about $4.11a$ (1.20λ). The distance between source and image is just equal to the double thickness of PC slab. Figure 3(b) shows the magnetic field phases of source and image. The source and image have the same phases, which is in agreement with the theoretical expectation of Pendry. In order to further prove the all angle negative refraction with $n_{\rm eff} = -1$, a finite line source is placed at the same position of the point source outside the slab. The incident angles are tilted toward the ΓM direction, which vary from 0° to 75°. The magnetic field phases at the image position of these beams are

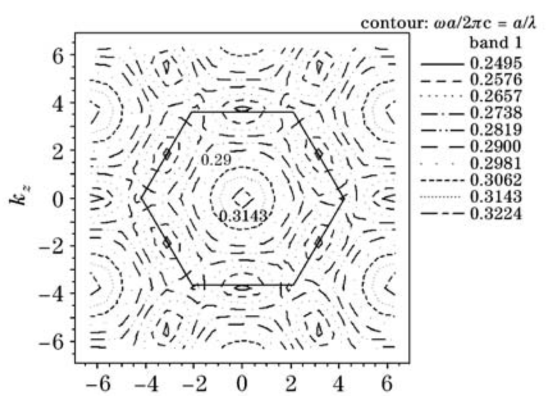

Fig. 2. EFS contours of the system at several relevant frequencies in the second band.

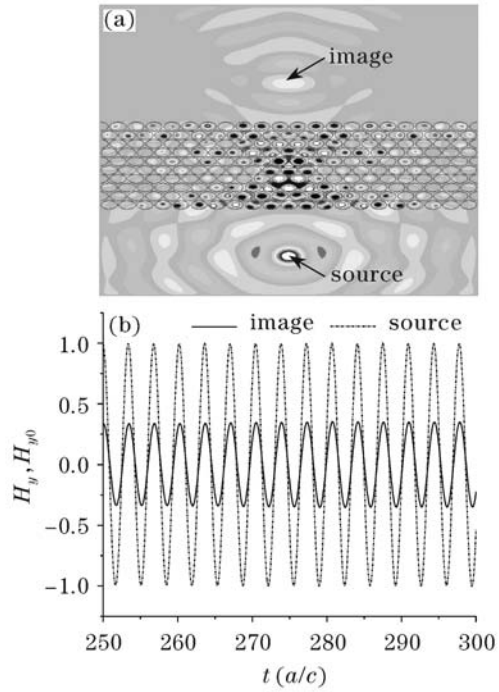

Fig. 3. (a) Simulated magnetic field distribution of a point source located at 1.34λ from the 10-layer slab; (b) magnetic field phases of source and image, where H_{y0} is the magnetic field amplitude of source.

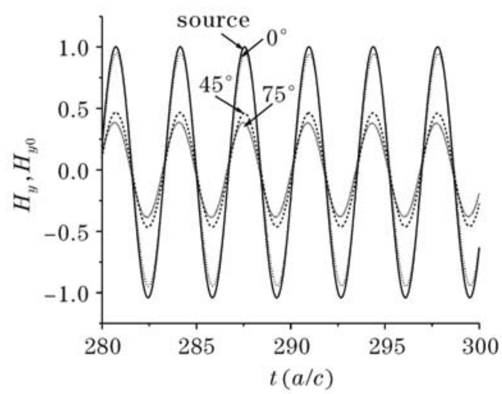

Fig. 4. Magnetic field phase of source and magnetic field phases of various incident beams at the image position, where H_{y0} is the magnetic field amplitude of source.

consistent with the phase of source, as shown in Fig. 4. It suggests that our designed PC lens restores the phases of the transmitted propagating waves. The designed PC lens has characteristic of a LHM lens with an effective refractive index of $n_{\rm eff} = -1$, and the conventional refraction law of wave beam for focusing and imaging is satisfied fairly well.

In the following, we consider the near-field image. We take a slab of the sample with two-layer thickness. A CW point source with $f = 0.293$ is placed at a distance $0.883a$ (about 0.26λ) from the lower surface of the slab. The results of magnetic field pattern across the slab sample are plotted in Fig. 5 after $t = 243.5t_0$. One can find quite a high quality image in the opposite side of the slab. By plotting the light intensity across the image as shown in Fig. 6, we find that the spatial resolution in this case,

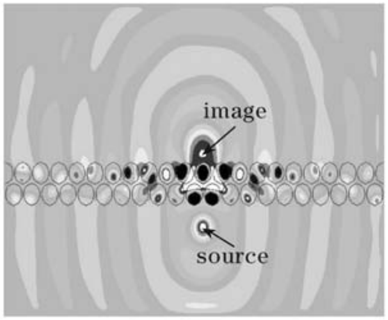

Fig. 5. Simulated magnetic field distribution of a point source located at 0.26λ from the 2-layer slab.

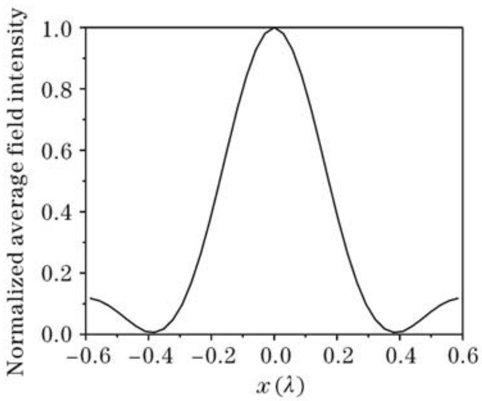

Fig. 6. Normalized average field intensity along the x direction at the image plane.

as measured by the transverse half width of the central peak, is about 0.36λ.

In conclusion, special 2D PC structure is designed. The proposed structure can exhibit all angle negative refraction. Whether dispersion characteristic analysis or numerical simulation of field patterns can both prove the effective phase indexes along all directions close to -1. A lens has been formed based on this PC structure. The image properties are studied in non-near field and near field. And these should be valuable for realistic negative-refraction superlens design.

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