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Design, Fabrication, and Characterization of Engineered Materials in the Microwave and Millimeter Wave Regime

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In this paper we present the study of a two-dimensional square-lattice photonic crystal with all-angle negative refraction in its first band. Using this photonic crystal, we designed and fabricated a flat lens functioning as a cylindrical lens, by increasing the vertical dimension of the photonic crystal. Two-dimensional finite-difference time-domain simulation validated negative imaging and sub-wavelength resolution. To perform the experiment, a microwave imaging system was built based on a vector network analyzer. Field distributions were acquired by scanning the imaging plane and object plane. The experiment demonstrated negative refraction imaging in both amplitude and phase, and verified sub-wavelength resolution.

1. Introduction

In 1968, V.G. Veselago argued that if both permittivity and permeability were negative, it follows that the refractive index of a given material would also be negative [1]. Using negative refraction, it was shown to be possible to make a lens with a flat surface. Pendry *et al* [2] studied an interlaced wire structure and concluded that their structure resembled the behavior of a plasma and, as a result, it was possible to achieve negative permittivity in the microwave regime by tuning its period. Based on a similar approach, they proposed another structure made of periodic metal rings and showed negative permeability can also be achieved [3]. Shelby *et al* experimentally demonstrated negative refraction by a structure combining the interlaced wires and the periodic rings [4]. Meanwhile, Notomi [5] studied the dispersion behavior in the vicinity of the photonic band gap and simulated that negative refraction can be also achieved in a dielectric photonic crystal (PhC). Parimi *et al* [6] and Cubukcu *et al* [7] experimentally demonstrated the negative refraction in dielectric PhCs.

Pendry's work sparked a significant interest in negative refraction given its ability to realize the perfect lens [8]. He further explained that negative refraction amplifies evanescent waves and both propagating and evanescent waves contribute to the resolution of the image. Garcial *et al* argued that negative refraction does not make a perfect lens because the finite thickness of a lens prevents the restoration of evanescent waves and perfect focusing [9]. To this end, there are continuing debates over the concept of negative refraction and its utility [10-12]. Despite this ongoing debate, interest in imaging by negative refraction has risen in many areas: material science, RF engineering, optical communication, and medical imaging. A key problem is whether a perfect lens can be achieved by negative refraction. The work contained herein presents our results in this regard.

2. "Flat Cylindrical" Lens

In our work, we use a two-dimensional (2D) PhC to demonstrate imaging by negative refraction. The key distinctions of this work lie in designing the PhC in the first band

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[13], increasing the vertical dimension of the flat lens, and validating the imaging in both amplitude and phase. Although imaging by a flat lens using negative refraction has been demonstrated in 2D PhCs formed by arranging alumina rods in air [14], the phase distribution has not yet been reported. We see this as a very important criterion to actually validating the imaging property. In addition, the assembled "rods-in-air" flat lens is not convenient for fabrication and its small dimension in the vertical direction limit its practical application.

Instead of fabricating holes in a thin dielectric slab or assembling short rods between two metal plates to form a PhC, thereby allowing only single mode on the vertical direction, we increased the vertical dimension of the PhC until this dimension can be treated as infinite to avoid reflection from the vertical facets, as shown in Fig. 1(a). Consequently, a "flat cylindrical" lens is proposed. For designing a planar PhC, a widely used method is to apply an effective index into 2D calculations and simulations. However, the effective index is always smaller than the bulk material refractive index. Thus, a poor index contrast results, which is often a problem for designing a PhC flat lens. In contrast, our approach has the advantage in that a larger index contrast is available as we can apply the bulk refractive index to calculate the equi-frequency contours (EFC) and simulate the behavior of the electromagnetic wave in the horizontal plane (the zero-spatial frequency component) using the 2D finite-difference time-domain (FDTD) method. Theoretically, this approach is a better approximation to the 2D configuration as the device has no limitation in the vertical direction and, consequently, wave propagating on the vertical direction is excluded.

3. Negative Refraction in the First Photonic Band

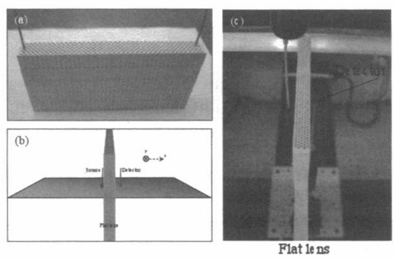

Fig. 1: (a) Picture of the fabricated flat lens. (b) Illustration of the experimental setup. The source is located at x= -1. (c) Picture of the experimental setup.

To design our PhC we used a square-lattice of air holes in dielectric ε=15, with lattice constant a, and hole diameter $2r$=0.70a. The dispersion properties of a similar PhC have been theoretically studied by C. Luo, *et al* [13]. We use the plane wave expansion method to solve for the corresponding eigen frequencies for a given wave vector. Figure 2 shows the equi-frequency contours for the TE modes for the PhC. By observing the EFCs, we can see that all-angle negative refraction in the first band occurs at normalized frequencies ω_n=0.17~0.20 because at these frequencies the EFCs are all-convex. From Maxwell's equations the excited mode will propagate with group velocity $\mathbf{v}_g = \nabla_{\mathbf{k}}\omega(\mathbf{k})$, which means the group velocity is always perpendicular to the EFC. As a result, the group velocity is not opposite to its phase velocity. However, negative refraction still occurs in the first band. C. Luo *et al* attributed this to its *negative-definite photon effective mass.* Figure 3 shows how this occurs in **k**-space: when a light beam is incident from the air into the PhC, the tangential component of the wave vector (phase velocity) is continuous at the interface and the group velocity is perpendicular to the EFC. As a result, k_x component bends to reverse direction and k_y component keeps its direction. The group velocity is only "partially" opposite to its phase velocity. This resembles a birefringent material with n_x<0 and n_y>0. Nevertheless, negative n_x still ensures negative refraction. In addition, the EFCs at ω_n=0.17~0.20 are all-convex, which means the PhC can gather incident beams from all directions to form an image.

Based on these observations, we simulated a flat lens made of this PhC: the hole diameter is $2r$=1.6mm, the lattice constant is a=1.6/0.7=2.3mm, the thickness of the lens is 14.5mm, and the working frequency is f=24.6GHz, which corresponds to normalized frequency ω_n=0.19. The flat lens works in the first band and the optical axis is designed along the (1,1) direction. From the simulated results, we can see that an image is formed by the negative refraction using this flat lens. The lateral size of the simulated image is 9mm or 0.7λ, which confirms sub-wavelength resolution.

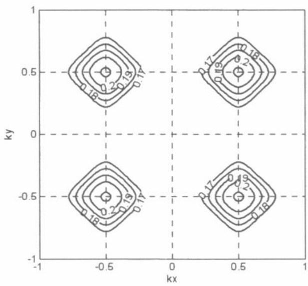

Figure 2. TE mode EFCs of the square-lattice PhC in the vicinity of the first bandgap.

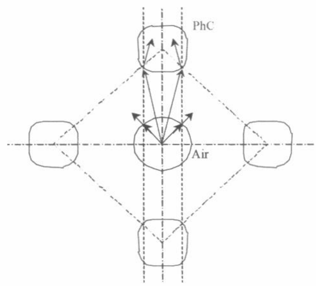

Figure 3. Illustration of propagation of the incident beam and refracted beam in k-space.

4. Experiment

In our work a CNC micro-milling machine was used to fabricate the flat lens. Figure 1(a) shows the fabricated PhC lens. It has the same parameter as the flat lens we simulated. Its dimension in the vertical direction is 63.5mm, which is much larger than the lens thickness.

To characterize its performance we built a microwave imaging setup, as illustrated and shown in Figs. 1(b) and 1(c), based on an Agilent 85106D vector network analyzer, which encompasses a test and measurement capability spanning 45MHz through 110GHz. The source is a dipole antenna connected to the network analyzer, and the detector is another dipole antenna fed back to the network analyzer. The detector is mounted on an X-Y scanner to map the electric field. The field distribution is acquired by scanning the object and image planes. A custom program was developed to synchronize the scanning and measurement using Labview. Once scanning and measurement is completed, we use the S-parameter value, S_{21} in our case, to realize the position as an image. In this case, each pixel in the image corresponds to the S-parameter value at a scanning position. In addition, in the network analyzer the S-parameter is given as complex values, so we can obtain both amplitude and phase distributions.

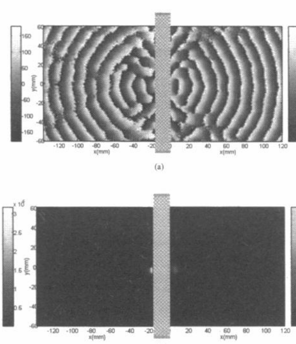

Fig. 4: The measured field distributions at 23.2GHz for the source (left) and the image (right). (a) phase(in degrees) and (b) amplitude. The flat lens (PhC) is depicted between the source and the image

To perform the experiment, we placed the source dipole 1mm away from the lens, with the electric component polarizing along y-axis to stimulate a transverse-electric mode, and mapped the field distribution using the X-Y scanner, meanwhile spanning the frequencies from 22GHz to 26GHz with spacing 0.2GHz. Consequently, we observed good images in the frequency range of 23.2±0.6GHz. Figures 4(a) and 4(b) show the measured phase and amplitude distributions for 23.2GHz. From the amplitude distribution and particularly from the phase distribution, we can see that the wave indeed converges to form an image at 7mm away from the lens at the imaging side, and then diverged into far field. The lateral size of the image is about 10mm, which is 77% of the corresponding wavelength, 13mm. In contrast, it is well known that using a conventional lens it is very difficult to focus light to an area smaller than a square wavelength [8].

5. Conclusions

To summarize, we proposed, designed, simulated, and characterized a flat lens, which works by negative refraction and functions as a cylindrical lens. For the first time, the experiment demonstrated the negative refraction image of a point source in both amplitude and phase. By measuring the image field distribution, we also verified sub-wavelength resolution.

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