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Subwavelength imaging by a flat cylindrical lens using optimized negative refraction

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We experimentally demonstrate subwavelength imaging by a “flat cylindrical” lens using negative refraction. A two-dimensional photonic crystal whose dispersion at the second band provides group velocity opposite to the phase velocity for electromagnetic waves is employed to realize the flat lens, and the working frequency is chosen so that the effective refractive index is approximately equal to −1.0. Experiment demonstrated the imaging of a point source in both amplitude and phase in the millimeter-wave regime. By measuring the field distributions in the object plane and image plane, we observed amplification of evanescent waves and subwavelength size image. The image of two incoherent sources with subwavelength distance showed two resolvable spots, which served to further verify subwavelength resolution. © 2005 American Institute of Physics. [DOI: 10.1063/1.2035317]

All naturally occurring materials obey Snell’s law with positive refractive indices. However, it has been shown recently that some artificially prepared metamaterials and photonic crystals (PhCs) exhibit negative refraction. Negative refraction can achieve imaging with planar surfaces allowing for the creation of flat lenses. Moreover, these flat lenses are expected to exhibit superresolution because they can potentially overcome the diffraction limit. Negative refraction by PhCs was theoretically investigated by Notomi and then experimentally demonstrated in microwave regime by Cubukcu et al. and Parimi et al., and recently in near-infrared regime by Berrier et al. Imaging with a flat lens using negative refraction was demonstrated in a two-dimensional (2D) PhC formed by arranging alumina rods in air and also in our work. In both cases, PhCs operate at the first band and effective refractive indices (ERI) were not specified and varied for different incident angles. However, index matching and aberration pose problems in negative refraction imaging if the ERI is anisotropic and different than −1.0. When the index of refraction is isotropic and equal to −1.0, low reflection occurs at the free-space/lens boundary for all incident angles. This low back-reflection allows for efficient collection of light emanated from the source—a particularly important feature when evanescent waves, which decay rapidly, are to be captured to allow for subwavelength imaging. Subwavelength resolution has been predicted theoretically, and verified experimentally by one-dimensional intensity profile along lattice position. However, the results presented in Ref. 10 are obtained using a photonic crystal working in the first band, where phase velocity is not opposite to group velocity. Therefore, in this work, we provide full 2D field distribution of the image, in both amplitude and phase using a recently developed millimeter-wave imaging system, thereby confirming faithful imaging of a point source and subwavelength resolution. The advances of this work lie in designing the PhC to achieve all-angle negative refraction with the ERI=−1.0, demonstrating the imaging in both amplitude and phase, and validating subwavelength resolution in the millimeter-wave regime.

2D PhCs are often fabricated by drilling holes in a thin dielectric slab or assembling short rods between two metal plates, where the vertical dimension of PhCs is restricted to allow only a single mode. Strictly speaking, these PhCs should be more accurately referred to as planar PhCs. In planar devices, electromagnetic waves propagate in a similar way as in 2D devices, but with a smaller propagation constant. Typically, an effective index method is employed to study them numerically, which allows for the reduction of this inherently three-dimensional (3D) problem to a 2D model. However, the effective index is always smaller than the bulk material refractive index. Thus, poor index contrast results, which is often a problem when designing PhC flat lenses. In our work, we take the opposite approach: We increase the vertical dimension of the PhC until this dimension can be treated as infinite and the reflection in vertical direction can be ignored. As a result, a flat lens functioning as a cylindrical lens, namely “flat cylindrical lens,” is developed. This approach has the advantage in that larger index contrast is available because we can use the bulk refractive index, instead of the effective index, to obtain the photonic band structure and simulate the behavior of the electromagnetic wave in the horizontal plane, i.e., for $k_z=0$. Theoretically, this approach is a better approximation to the 2D configuration as the device has nearly no limitation in the vertical direction, and the wave propagating in the vertical direction is excluded.

FIG. 1. (Color online) (a) Fabricated “flat cylindrical” lens. (b) Illustration of the experimental setup. The source is located at $x=0$. (c) Picture of the experimental setup.
Figures 1(b) and 1(c) show our experimental setup. The source is a dipole antenna connected to the output of a vector network analyzer, and the detector is another dipole antenna fed back to the network analyzer. The detector is located at the same horizontal plane as the source and mounted on an XY scanner to map the electric field. We placed the source dipole 6 mm away from the lens, with the electric component pointing along the z-axis to excite transverse magnetic (TM) modes. A triangular-lattice PhC, the flat lens, was fabricated in a low loss material with a dielectric constant 20. The diameter of the holes is 2r=1.6 mm and the lattice constant is a=2.3 mm. The thickness of the lens is 11.9 mm, while its vertical dimension is 63.5 mm, which is much larger than the vertical dimension of the second band and the light cone. As shown in Fig. 2, the second band is curved downward. As a result, the group velocity, $v_g = \nabla k \cdot \omega(k)$, is opposite to the phase velocity and negative refraction ensues. In our work, we focused on the intersection of the second band and the light cone. In order to see that region clearly, we projected the second band in the vicinity of the intersection into a series of equifrequency contours, as shown in Fig. 2(b), where we can see that the intersection occurs at $\omega_0=0.236$. Since the contour of $\omega_0=0.236$ is approximately circular, we can treat it as another isotropic medium with $\text{ERI}=-1.0$. The magnitude of ERI comes from the equifrequency contour radius ratio to that of the light cone, while the “−” sign is attributed to the opposite directions of the group velocity and the phase velocity.

To test the performance of the lens, we built a millimeter-wave imaging setup based on an Agilent 85106D vector network analyzer. Two dipoles were placed along the z-axis, working as the source and the detector, respectively. The detector is mounted on an XY scanner to map the electric field. The field distribution is acquired by scanning the object plane and image plane point by point. In the network analyzer, the S parameter is given as a complex value, so we can obtain both amplitude and phase distributions, which is difficult for near-infrared or visible light measurement.

In our experimental investigations, we mapped the object and image field distributions using the XY scanner, while covering the frequencies from 31.0 GHz to 33.0 GHz with spacing 0.1 GHz. As a result, we were able to reconstruct images in the frequency range of 31.5±0.4 GHz. Figures 3(a) and 3(b) show the measured phase and amplitude distributions for 31.5 GHz. This frequency is the highest among the experiments demonstrating negative refraction in the microwave regime.

To avoid clutter, we only depicted the first two equifrequency contours close to the intersection between the second band and the light cone. As shown in Fig. 2, red circles are equifrequency contours and green is the light cone for $\omega_0=0.236$. To illustrate the equifrequency contours, we chose the normalized frequency $\omega_0=0.236$ corresponds to $\tilde{f} = \omega_0 c/\lambda = 31.0$ GHz for our fabricated structure.
waves, which indicates that the reflection from the lens is very small. This phenomenon was only observed in a small frequency range when $\text{ERI}=1.0$ (for finite flat lens, its thickness also affects transmission). High transmission at large incident angles, in turn, improves the imaging resolution.

In order to confirm subwavelength resolution, we need to know the magnification of the imaging system in addition to the image feature size. Therefore, to further validate subwavelength resolution, we employed two $z$-polarized dipole sources from two different vector network analyzers with $d_z=6$ mm and aligned the sources on the $y$ axis $5$ mm (0.51\mu m) away from each other. We balanced the powers of the sources and repeated the scanning in the image plane. During the scanning, we alternately used the network analyzers to measure the field at each position. Figure 4(a) shows the image we obtained at that plane. It shows two resolvable spots $5.2$ mm apart, which is $0.53\mu m$. Further analysis of this image indicates that the resolution is better than that number [Fig. 4(b)], i.e., dipole sources less than $0.5\mu m$ apart should be resolvable. This result, combined with the result shown in Fig. 3, confirms that subwavelength imaging is achieved for an object containing subwavelength feature size. Thus, the lens is capable of subwavelength imaging from both viewpoints of the object and of the image.

To summarize, in this letter, we revisited the concept of 2D PhC and realized a flat lens functioning as a cylindrical lens. The lens was designed to work by ideal negative refraction and the experiment showed not only negative refraction imaging in both amplitude and phase, but also verified subwavelength resolution, amplification of evanescent waves and excellent index match.

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15We use Cartesian coordinates with the origin at the source. $x$ axis coincides the optical axis, whereas $y$ and $z$ axes represent the horizontal and vertical directions, respectively.