Negative refraction and slab imaging of photonic crystals

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Dielectric negative-index photonic-crystal slabs can form images with subwavelength resolution.

Imaging using lenses with curved surfaces is a common experience in our daily life, as for example when we use digital or cellular-phone cameras or overhead projectors. However, the imaging properties of such conventional lens systems are limited by aberration and diffraction. Careful optical design can significantly reduce the former, but not the latter, because it is due to the fundamental nature of light, which blurs the image of a geometrical point object into a finite-sized spot.

In 2000, John Pendry performed insightful simulations showing that a perfect lens could be realized in the form of a thin planar slab with refractive index $n = -1$. When light is refracted in a direction opposite to that of conventional refraction, the process is termed negative refraction as illustrated in Figure 1. Materials that can display a negative index include metals, silicon carbide, some polymers and dyes, as well as more versatilely engineered metamaterials and photonic crystals (PhCs).

PhCs are nanostructured materials in which a periodic variation of the dielectric constant results in a photonic band gap. Those made from dielectric materials are particularly well-suited for optical imaging since there is little or no material loss. However, the negative refraction and imaging mechanisms of PhCs differ from those of metals and metamaterials.

Since PhCs are periodic structures, electromagnetic Bloch modes that consist of an infinite number of wavevectors can form in the photonic lattice. Therefore, the light-lattice interaction is governed by diffraction, scattering, reflection, and resonance effects, which makes analytical methods generally impractical to characterize their imaging properties. Bloch wave propagation studies have shown that the effective index of refraction, $n_{\text{eff}}$, can be extracted from band structures. It is negative at the second band because the group velocity (i.e. the speed at which a pulse propagates in a PhC and equal to the energy velocity in periodic media) moves towards the scattering center $\Gamma$.

Although $n_{\text{eff}} = -1$ can be obtained, light behavior is not the same as in left-handed materials.

To systematically investigate the imaging properties of PhCs, we have performed a series of simulations using the finite-difference time-domain (FDTD) method applied to 2D hexagonal-lattice PhC slabs with 3–12 rows of holes in a dielectric material. Our results showed that $n_{\text{eff}} = -1$ for operation at a normalized frequency of 0.3. Figure 2 shows the instantaneous field of a three-row slab imaging for a point object positioned on the left side of the slab. The image distance is an approximately negatively linear function of the object distance in the regime where the latter is less than or equal to the slab thickness, $d$, in agreement with the Veselago relation. From the linear object-image relation of the finite-sized slab, we extracted the $n_{\text{eff}}$ values, which always had an absolute value smaller than the 1 calculated for the infinite structure. This is reasonable, since a finite-sized structure displays weak light-lattice interactions. A Fourier analysis of the image intensity distribution showed that the image contained larger wavenumbers than the largest propagating wavenumber, implying that evanescent waves contribute to image formation. The resolution could reach 0.39λ for a 10-row slab with adequate fine tuning. In addition, we showed

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that the object must contain sufficient transversal wavevectors in order to be focused to an image. We also noted that the linear object-image relation may fail when evanescent waves dominate imaging.\footnote{5}

The finite-sized slab has a limiting value for aperture size that effectively limits the highest achievable resolution. This is due to the weak light-lattice interactions of large transversal wavevectors and to the impact of diffraction causing the waves with the larger transversal wavevectors to leak out from the slab without contributing to image formation. Thus, increasing slab aperture does not lead to higher resolution beyond this limiting value.

Interface modification and optimization can lead to increased image intensity, but image distance is also modified as a result of surface diffraction. In addition, it was recently reported that wavefronts have a positive phase evolution inside a PhC\footnote{6}, and that the phase-related refractive index was positive\footnote{7} and associated with the main wavevectors.\footnote{6,\footnote{7}} This explains why negative-index PhCs differ from left-handed materials. However, it is the fundamental wavevector in the first Brillouin zone that determines the direction of the refracted light.

This subwavelength imaging behavior predicts promising advances in such areas as optical data storage, photolithography, bio-sensing, and nano-integrated photonic circuits.

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References