

Optical Negative Refraction in Bulk Metamaterials of Nanowires

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Metamaterials are artificially designed subwavelength composites possessing extraordinary optical properties that do not exist in nature. They can alter the propagation of electromagnetic waves, resulting in negative refraction (1), subwavelength imaging (2), and cloaking (3). First reported at microwave frequencies by using metamaterials made of an array of split ring resonators and metallic wires (4), negative refraction has been observed in two-dimensional (2D) photonic crystals into the infrared (IR) region (5–8) and in surface plasmon waveguides at visible frequencies (9). In both cases, negative refraction is constrained in two dimensions and is limited to a narrow band of frequencies. An indirect observation of negative refraction in the mid-IR region was also reported in a semiconductor multilayer structure (10). Creating bulk metamaterials that exhibit negative refraction for visible light remains a major challenge because of substantial resonance losses and fabrication difficulties. Recent theoretical studies suggest that metamaterials consisting of metal wire arrays exhibit an optical response at frequencies far away from resonances (11, 12), in which electromagnetic (EM) waves propagating along the nanowires exhibit negative refraction at a broad frequency band for all angles (13). Moreover, the material loss is much lower than traditional metamaterials with similar functionality.

We report observations of negative refraction in bulk metamaterials composed of silver nanowires with separation distance much smaller than the wavelength at optical frequencies (Fig. 1A). A porous alumina template was prepared by electrochemical anodization (14), into which silver nanowires were electrochemically deposited. A 1- μm -wide slit, etched through a 250-nm-thick silver film coated on the metamaterials, was

illuminated by a collimated diode laser beam at different incident angles (see left side of Fig. 1A). The transmitted light was mapped by scanning a tapered optical fiber at the bottom surface of the metamaterial. The results are shown in Fig. 1, B and C, for incident light at wavelengths of 660 nm and 780 nm, respectively. When the incident angle is 30°, the transmitted beam is shifted to the left for transverse magnetic (TM)-polarized light, which corresponds to the negative refraction. The subwavelength composite forms an effective medium with opposite signs of electrical permittivities along and perpendicular to the wires (9). The hyperbolic dispersion enables negative light refraction even though the phase velocity remains positive (10, 13, 15). Conversely, the transverse electric (TE)-polarized light undergoes positive refraction. Figure 1D shows the dependence of refraction angles on a range of incident angles at 780 nm. The group refractive indices of the metamaterial are shown to be -4.0 and 2.2 for TM and TE light, respectively. The phase

refractive index of the metamaterial remains positive, in contrast to that of left-handed metamaterials (1, 4). For normal incidence, the light intensity only decays $\sim 0.43/\mu\text{m}$ in the medium at 780-nm wavelength, showing loss a few orders of magnitude lower than that of single-layer metamaterials reported at the same wavelength (16). Further calculations show that the negative refraction in this nanowire composite exists for longer wavelengths and also does not depend on the orientation of the nanowire lattice.

Because the dielectric response in this metamaterial does not require any resonance, the negative refraction has low loss and occurs in a broad spectral range, for all incident angles, making it an intrinsic optical response of the underlying metamaterials. Moreover, such bulk metamaterials can support propagating waves with large wave vectors that are evanescent in air or dielectrics, enabling manipulation of visible light at subwavelength scale. This can substantially affect applications such as waveguiding, imaging, and optical communication.

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Materials and Methods

Fig. S1

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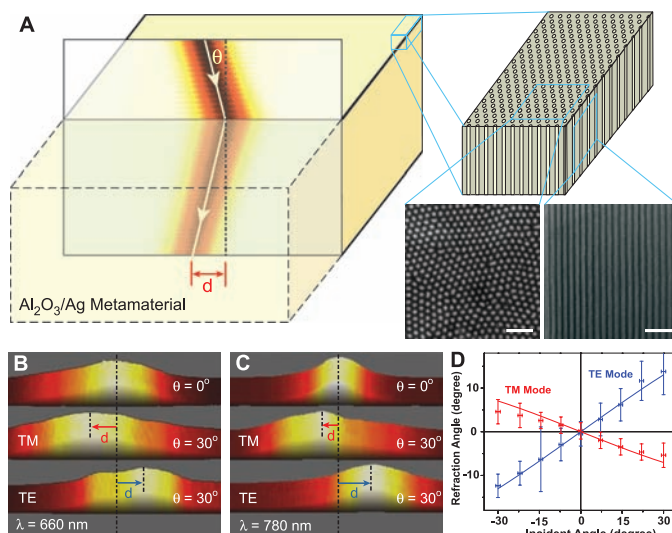


Fig. 1. Negative refraction in bulk metamaterial at visible frequencies. **(A)** (Left) Schematic of negative refraction from air into the silver nanowire metamaterials. (Right) Nanowires embedded in an alumina matrix, as well as scanning electron microscopy images showing the top and side view of the nanowires (60-nm wire diameter and 110-nm center-to-center distance). The scale bars indicate 500 nm. **(B)** Measured beam intensity at the existing surface of the metamaterial slab at the wavelength of 660 nm **(B)** and 780 nm **(C)**. The lateral displacement (d) of TM polarized light shows the negative refraction in the metamaterial at both wavelengths, whereas TE light undergoes positive refraction. The horizontal sizes of **(B)** and **(C)** are 5 μm and 12 μm , respectively. **(D)** The dependence of refraction angles on incident angles and polarizations at 780-nm wavelength. The negative refraction occurs for broad incident angles. The experiment data agree well with calculations (solid curves) using the effective medium theory. The sample thicknesses in **(B)** and **(C)** are 4.5 μm and 11 μm , respectively.