All-Angle Negative Refraction in the Ultraviolet using Three-dimensional Plasmonic Waveguide Metamaterial

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Decades ago, Veselago [1] predicted that a material with simultaneously-negative electric and magnetic polarization responses would yield a "left-handed" (LH) medium in which light propagates with opposite phase and energy velocities - a condition described by a negative refractive index. He proposed that a flat slab of LH material possessing an isotropic refractive index n = -1 could act like an imaging lens when immersed in free space. LH materials are not naturally occurring, and it has only recently become possible to achieve a LH response through metamaterials, electromagnetic structures engineered on sub-wavelength scales to elicit tailored polarization responses. To date, LH responses have typically been implemented using resonant metamaterials composed of periodic arrays of unit cells containing inductive-capacitive resonators and conductive wires having symmetry along two or three axial directions. Resonant metamaterials having centimeter-scale features have achieved negative refractive indices which are isotropic in two [2] or three [3] dimensions at microwave frequencies. Scaling the LH response to higher frequencies, such as the infrared or visible, has been realized by reducing critical dimensions to submicron scales via top-down nanofabrication [4]. This miniaturization has, however, so far been achieved at the cost of reduced unit cell symmetry, yielding a refractive index that is negative along only one axis. Moreover, lithographic scaling limits have so far precluded resonant metamaterials from achieving LH responses beyond the visible [5]. Here, we report the first experimental implementation of a bulk metamaterial with a LH response in the UV [6]. The structure, based on stacked plasmonic waveguides [7], yields an omni-directional LH response for transverse-magnetic (TM) polarization characterized by a refractive index that is negative.

By choosing Ag and TiO_2 as the constituent waveguide materials and engineering the structure to have a refractive index close to -1 over a broad angular range, we achieve Veselago flat lensing in free-space of arbitrarily-shaped two-dimensional objects beyond the near-field. We also demonstrate all-optical switching of the LH response by optically tuning the UV image transferred by the metamaterial flat lens with intensity modulation up to 50%.

Finally, we show that unidirectional transmission of visible light range can be provided by a planar device of wavelength-scale-thickness incorporating diffraction gratings and a passive hyperbolic Ag/SiO_2 metamaterial engineered to display a transmission window for incident electromagnetic waves having specific transverse spatial frequencies. Fabricated devices designed for operation at central wavelengths of 532nm and 633nm, respectively, display broadband, efficient asymmetric optical transmission with maximum contrast ratios exceeding 14dB.

References

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