All-angle Negative Refraction and Active Flat Lensing in the Ultraviolet

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Predictions of unique and potentially useful properties, such as a negative refractive index, have triggered a quest to implement left-handed (LH) media under the form of artificially engineered structures known as metamaterials. Here we report the first experimental implementation of a bulk metamaterial with a LH response in the ultraviolet (UV). The structure, shown in Fig. 1a, is based on stacked coupled plasmonic waveguides[1] and exhibits an all-angle refractive index close to –1. Figure 1b displays the cross section of a metamaterial structure formed of three unit cells of sputter-deposited, alternating layers of Ag and TiO_2, to a total thickness of 450 nm. An optically-opaque Cr film was deposited on top of the metamaterial slab followed by focused-ion-beam (FIB) milling of a 600-nm-wide rectangular opening to define an aperture for refraction experiments. For TM-polarized light illumination at λ_0=364nm, we observe negative power refraction of the UV beam over a broad range of incident angles (Fig. 1c).

Based on the all-angle negative refraction achievable with this metamaterial, a Veselago flat lens of thickness 450 nm was fabricated. Optical characterization of image projected by the metamaterial when the object apertures are illuminated at normal incidence with circularly-polarized UV light of wavelength 364nm, demonstrates flat lensing beyond the near field (Fig. 2(a)). In addition, we demonstrate that the intensity of an UV image transferred by the metamaterial flat lens can be dynamically varied by illumination of the exit surface of the lens with a pulsed pump beam tuned above the bandgap of TiO_2 (E_{BG} = 3.65 eV). The corresponding intensity modulation contrast $\gamma = (I_{OFF} - I_{ON}) / I_{OFF}$, displays a quasi-linear dependence on pump-beam intensity, increasing to a value $\gamma \sim 50\%$ at the maximum explored pump intensity below damage threshold for the sample (Fig. 2(b)). The fabrication-friendly planar architecture of this metamaterial shows promise for building large-area, left-handed optical elements for manipulating light beyond the visible.

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[1] Verhagen, E., Waele, R. D., Kuipers, L. & Polman, A. *Phys. Rev. Lett.* **105**, 223901 (2010).

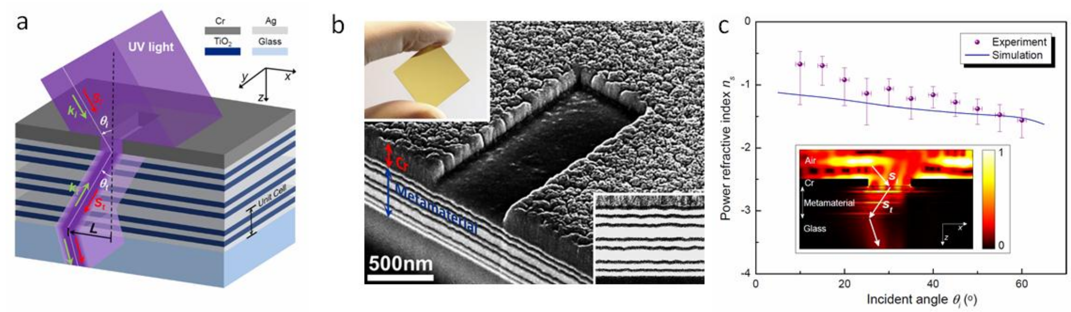

Figure 1:(a) Schematic of negative refraction of UV light from air into a coupled plasmonic waveguide metamaterial formed by three vertically-stacked MDMDM unit cells and coated with a beam-defining mask consisting of a rectangular aperture in an opaque Cr film. (b) Scanning electron microscope (SEM) image of fabricated refraction-experiment sample, showing beam-defining aperture, and sectioned by FIB milling to reveal the internal metamaterial structure. Left inset: Picture of glass slide uniformly coated with 450-nm-thick metamaterial. Right inset: magnified cross-section of metamaterial layers. (c) Experimentally-derived and FDTD-simulated values of power refractive index, n_S, as a function of incident angle θ_i, for TM-polarized light. Inset: FDTD simulated profile of the time-averaged Poynting-vector, for the aperture-bearing metamaterial illuminated at $\theta_i = 40^\circ$.

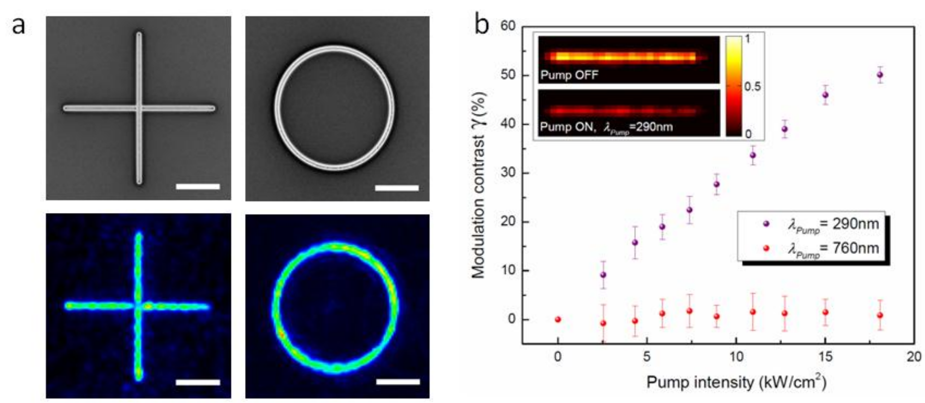

Figure 2:(a) Top: SEM images of slit apertures located on the metamaterial flat lens surface forming, respectively, cross and ring objects. Bottom: Corresponding images produced by the flat lens under illumination with circularly-polarized UV light, as recorded by the optical microscope. (b) Intensity modulation contrast γ as a function of pump intensity at wavelength of 290nm (purple dots) and 760nm (red dots). Pump pulse length = 150 fs, repetition rate = 80 MHz. Error bars: standard deviation for repeated measurements. Inset: recorded intensity profiles of slit image with pump off (top) and pump on (bottom, pump intensity: 18kW/cm^2).