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Three Dimensional Optical Metamaterial Exhibiting Negative Refractive Index

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Supplementary Information

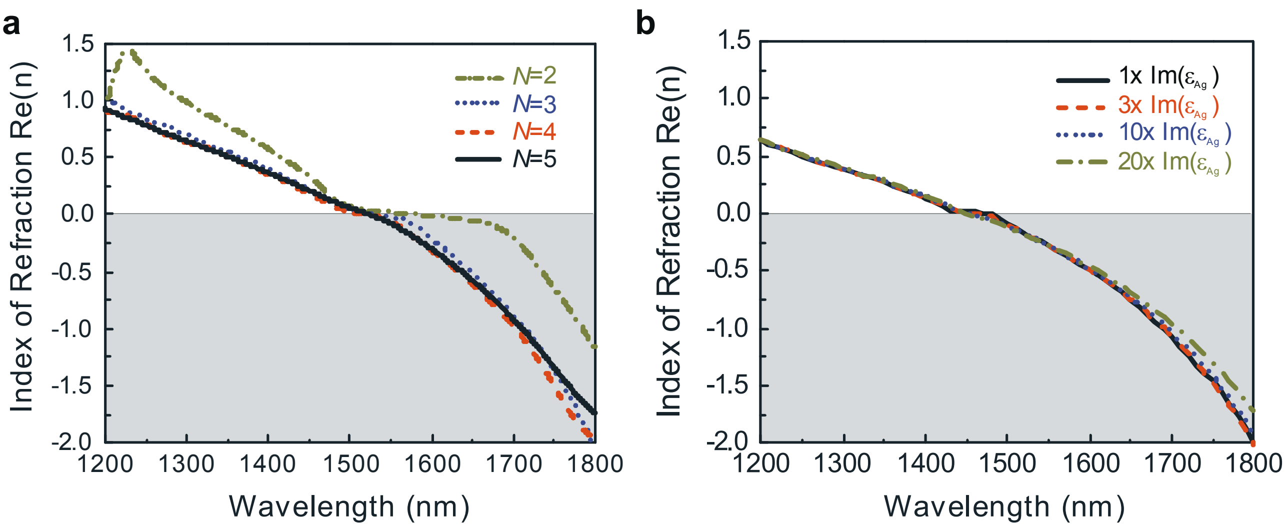

Figure S1. The refractive index of the fishnet metamaterials for different numbers of layers and material loss. (a) The refractive index for different number of functional layers along the propagation direction. One important feature of metamaterials is the consistent refractive index profiles for different thicknesses. The effective refractive index was found by calculating the complex transmittance and reflectance and solving for the Fresnel equation: $\cos(nkd) = (1 + t^2 - r^2)/2t$. It is obvious that the refractive indices for the different thicknesses are in good agreement. This also gives rise to a smooth wave front for the light exiting the prism. (b) We show that the material loss does not significantly affect the dispersion (ω vs. k) of the cascaded fishnet metamaterial. For demonstration, we calculate the dispersion curves of the fishnet structure with the same geometry as the one we fabricated, but for different scattering frequencies of the metal, ranging from 1x to 20x of the fitted scattering frequency to the experimental data obtained by Johnson and Christy ($\gamma_0 = 0.018$ eV). RCWA was used to obtain the dispersion curve and thus index of refraction by calculating the eigenvalue of the transfer matrix of a single unit cell along the direction of propagation. It is seen that the dramatic increase of the material loss does not make a dramatic effect on the refractive index, a feature characteristic of the left handed transmission line. This explains why the measured refractive index is very close to the numerical results, though the transmission for a ten functional layer fishnet metamaterial is 4 times lower than that of the simulation. The calculation verifies the robustness of this design for achieving negative index.

Methods

In the numerical studies of the 3D fishnet metamaterial, with the exception of Fig. 3c and 4d-e, we utilized a rigorous coupled wave analysis (RCWA) which expands the electromagnetic field into a number of diffraction orders and matches the boundary conditions at each interface. Figure 3c and 4d-e were calculated with commercial finite difference time domain software (CST Microwave Studio). In all calculations the intrinsic losses of the metal are included.

The multilayer stack was deposited by electron beam evaporation of alternating layers of 30 nm silver (Ag) and 50 nm magnesium fluoride (MgF_2). The final stack consisted of 21 layers with a total thickness of 830 nm resulting in 10 *functional* layers. The unit cell of the fishnet structure, as shown in Fig. 1a, is designed to have a negative refractive index in the telecommunication wavelength range around 1.5 μm. Two different configurations of the fishnet samples were fabricated on the multilayer stack. Samples of the first configuration consist of 22 by 22 in-plane fishnet unit cells and were used for the characterization of the transmittance. The unit cell dimensions of the fishnet patterns, as well as a SEM image and a cross-section view (inset), are shown in Fig, 1a and Fig. 1b, respectively.

Samples of the second configuration, which were used to measure the refractive index, consist of a prism fabricated on the multilayer stack, with the number of functional layers ranging from 1 on one side, to 10 on the other side. The prism was formed by etching the film at an angle β with respect to the film surface using FIB. The exact angle was measured with an atomic force microscope, and was found to be slightly varied for different samples. A 10 by 10 fishnet pattern was subsequently milled in the prism, the SEM image of which is shown in Fig. 2a.

In the experimental setup (see Fig. 2c) light from the optical parametric oscillator (OPO) was focused onto the prism using an achromatic lens (lens 1) while the second lens (lens 2) was placed at its focal position. An Indium Gallium Arsenide (InGaAs) infrared camera was placed at the focal position of lens 2 allowing the light passing through the sample to be imaged at the Fourier plane in a $2f$ configuration. The position of the beam at the second lens's focal distance (f_2) was used to calculate the angle of refraction. Due to limited camera imaging area, only the zero-order Fourier image was recorded. To obtain the absolute angle of refraction, a window with an area equal to that of the prism was etched through the multilayer stack to serve as a reference. The window's Fourier image was measured at all wavelengths, giving a reference position corresponding to a refractive index of 1. The centers of the beam spot for both the window and prism samples were determined by fitting the intensity with a 2D Gaussian profile and the total beam shift (δ) at the position of the second lens was calculated by taking the difference in the beam spot centers. Consequently, the angle of refraction at the surface of the prism (α) is given as:

$$\alpha = \beta - \tan^{-1}(\delta / f_2) \qquad (1)$$

where f_2 is the focal distance of the second lens (refer to Fig. 3c). Snell's law ($n = \sin\alpha / \sin\beta$) was used to calculate the real part of the refractive index of the sample. The imaginary part of the refractive index of the sample was obtained from transmittance and reflectance data acquired with a 21 layer sample of the first configuration (as described above) using the relation: $\mathrm{Im}(n) = (\lambda / 4\pi d)\ln((1-R)/T)$ where λ, d, R and T are the wavelength, sample thickness, transmittance and reflectance, respectively.