Large Area Negative Refractive Index Structures at Optical Frequencies Using Nanoimprint Lithography

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After negative refractive index structures were originally proposed as a flat lens by Victor Veselago in 1968 [1], scientists reached a theoretical roadblock. Electrical polarizations causing a negative permittivity (ε) typically occur at high frequencies while magnetic resonances leading to negative permeability (μ) occur at lower frequencies. However, recent research into metamaterials and advances in lithography have paved the way for sub-micron structures where simultaneously $\varepsilon<0$ and $\mu<0$ becomes attainable at certain resonant frequencies in the visible spectrum. The existence of negative refractive index structures further hints at possible structures with a zero/near-zero index of refraction. In either case, such metamaterials could find numerous applications in optics including LEDs, waveguides, and the so-called "superlens" [2].

While surface plasmon resonance is readily attainable in the visible, the magnetic response is much harder to reach at optical frequencies. By exploiting planar split-rings arrays fabricated by e-beam lithography, magnetic resonance has been demonstrated near 100 THz frequency [3]. However such an approach is not scalable to large areas for practical applications. Also it is very challenging to reduce the feature size further in order to push the magnetic resonance to the visible band. In addition, the planar split-ring structures cannot produce magnetic resonance for light with normal incidence.

In this work, we propose and demonstrate vertically oriented split-ring arrays (Fig. 1a) to address the aforementioned issues. Utilizing nanoimprint lithography, we have fabricated numerous preliminary grating structures with a 220 nm period by imprinting a resist-coated glass with a SiO_2 mold, followed by an etch of the residual layer and a further etch into the glass sample. After liftoff two shadow evaporations were performed at a specific angle to produce the desired vertical split-ring structure (Fig.1b). Such a system acts as an inductive-capacitive circuit with transverse magnetic fields inducing current in the ring causing an opposing magnetic field and thus a negative permeability. Simulations and measured transmission data are consistent as shown in Fig. 2. Our simulation shows that simultaneous negative ε and μ, and therefore negative refractive index, can be achieved in certain frequency range (Fig. 3). At some frequency, the effective refractive index is zero.

[1] V.G. Veselago, *Sov. Phys. Usp.* **10**, 509 (1968).

[2] Vladimir Shalaev, *Nature Photonics* **1**, 41, 2007.

[3] S. Linden, C. Enkrich, M. Wegener, J. Zhou, T. Koschny, and C. Soukoulis, *Science* **306**, 1351 (2004).

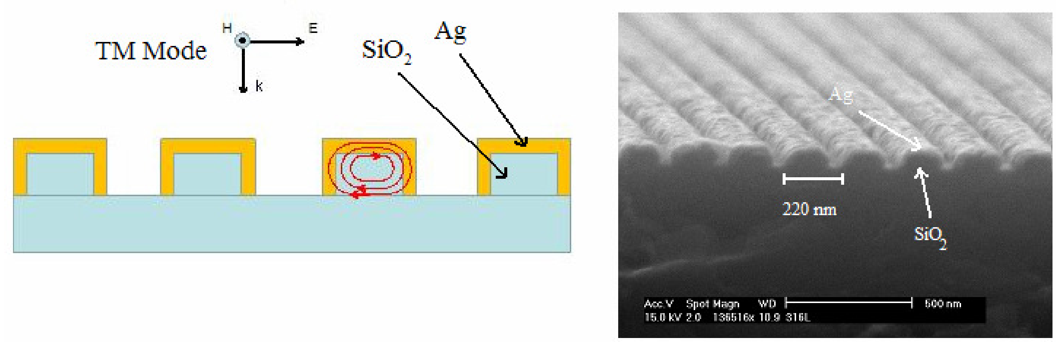

Fig. 1 Schematic of vertically oriented split-ring structure showing H-field induced current path in the split-ring (left) and SEM image of fabricated split-ring structure with 220 nm period, 130 nm linewidth, 50 nm depth, and 20 nm Ag thickness.

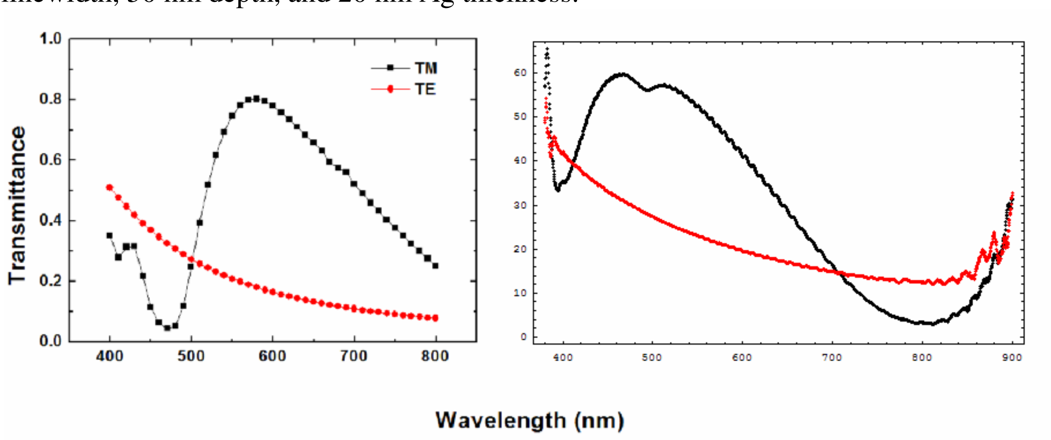

Fig. 2. Simulated (left) and measured (right) transmittance versus wavelength data for TM and TE modes for the proposed and the fabricated split ring structures.

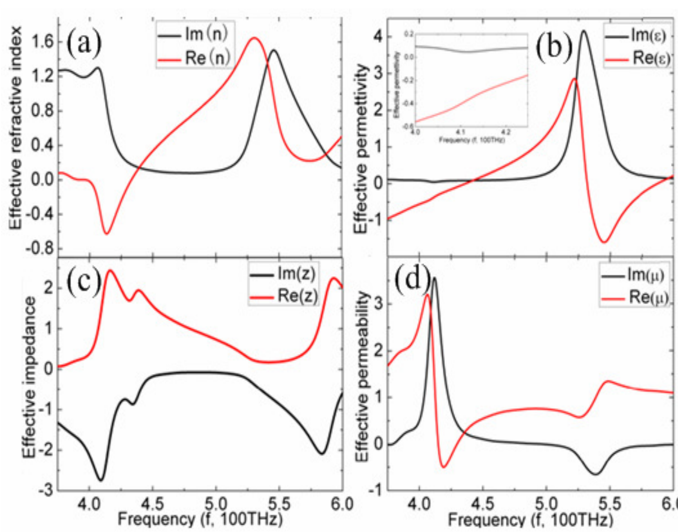

Fig. 3. Simulated effective index, impedance, permittivity and permeability as a function of frequency. The effective refractive index is negative in certain frequency range.