Electromagnetic behavior of metamaterials and nanostructures at optical frequencies

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Recently, metamaterials with negative index of refraction have been demonstrated for microwave electromagnetic (EM) radiation. It has been anticipated in 1950-60s by Pafomov and Veselago that negative refraction should occur in homogeneous media with simultaneously negative dielectric permittivity and magnetic permeability, $\varepsilon<0$, $\mu<0$. It has been speculated by Pendry (2000) that the ideal Veselago lens can produce and image beyond the limits of geometrical optics. We explore this possibility theoretically and experimentally. We find a strong effect of surfaces on resolution limit and nontrivial relation of subwavelength imaging to EM "softness" of the lens [1]. We have designed the metamaterial by means of FDTD modeling, which is a stack of metallic films with periodic hole arrays separated by dielectric layers (called "fishnet", FN) to work at IR wavelengths λ=1.5-1.7 μm, and fabricated a few samples by nanoimprint lithography[2], Fig.1a,b. The FN transmission and reflectance characteristics of the samples have been measured by laser spectroscopic ellipsometry and showed unambiguously that the FN supports the "backward" waves and have overall negative index of refraction at IR frequencies, Fig.1c.

We have achieved optical modulation of the effective refractive properties of a "fishnet" metamaterial with a Ag/Si/Ag heterostructure in the near-IR range and the associated fast dynamics of negative refractive index was studied by pump-probe method. Photo excitation of the amorphous Si layer at visible wavelength and corresponding modification of its optical parameters is found to be responsible for the observed modulation of negative refractive index in near-IR.

We have also studied the possibility of forming the isotropic 3D negative index material from an assembly of Ag nanoparticles [3]. It appears that various open- and close-packed structures exhibit "soft" electromagnetic response and extraordinary transmission at certain wavelengths that much exceed the period of the structures. It appears that various nanoparticles assemblies are close to having negative index but remain "positive". They are discussed from a perspective to be used as "transparent metals".

Recently, large interest is being generated by application of plasmonic metamaterials for sensors, e.g. surface enhanced Raman, and improving an extraction efficiency of LEDs. These topics will also be touched upon.

References

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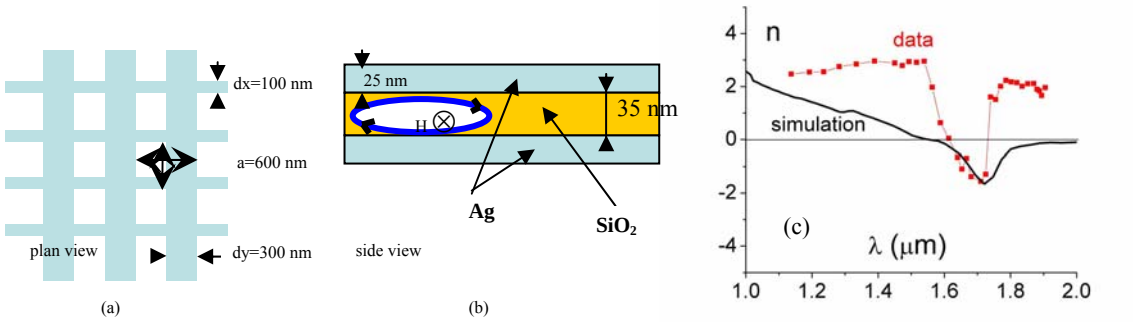

Fig. 1. Schematic of the "fishnet" metallic trilayer structure (25nm Ag layers and 35 nm spacer SiO_2 layer): plan view (a) and side view (b). (c) Negative index n at λ≈1.7 μm extracted from the spectroscopic data (dots), and simulation (solid line) are in fair agreement.

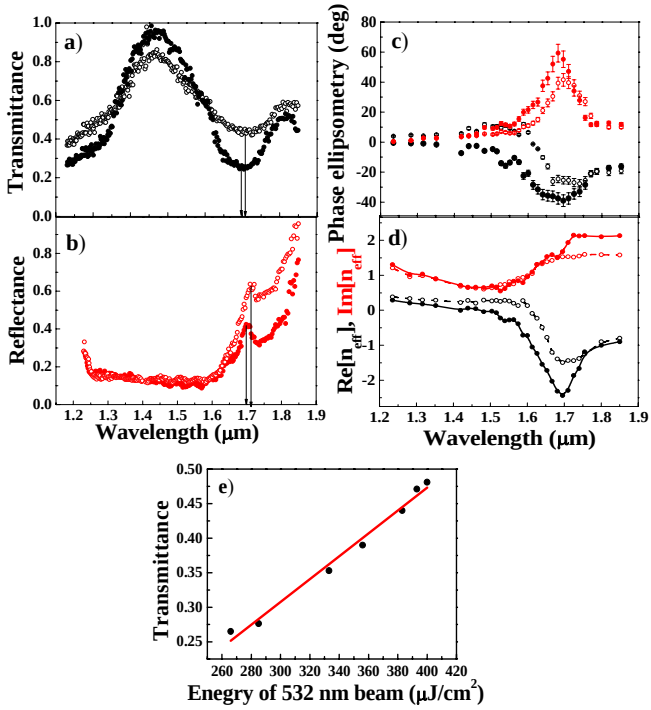

Fig. 2. (a) Transmittance and (b) reflectance spectra from the "fishnet" structure without pump (black dots) and with a pump fluence of 320 μJ/cm^2 (open black dots) at zero pump-probe time delay. (c) Phase difference spectra for transmitted and reflected light without the pump (black and red dots, respectively) and with the pump (open black and red dots, respectively). (d) Real and imaginary parts of the refractive index deduced from experimental data without the pumping (black and red dots, respectively) and with the pumping (open black and red dots, respectively). (e) Variation of transmittance at the magnetic resonance as a function of the pump fluence.