



Negative Refraction in Gold-Dielectric Nanocomposite Arrays

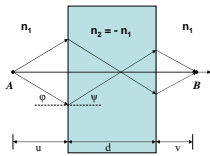
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Introduction

It is well known from electrodynamics that the refractive index n of materials is given by the relationship: $n = \sqrt{\epsilon\mu}$, where $\epsilon > 0$ and $\mu > 0$ are the dielectric constant and magnetic permeability of the material where the electro-magnetic waves propagate. In 1968, Russian Physicist Victor Veselago discovered that if the refractive index of materials was negative then a lot of "exotic" physical phenomena might be observed. For instance, of particular interest was the idea of the "flat superlens" that transforms a 3D point object into a 3D image without distortion. Such a superlens could be implemented by means of a flat lens with negative refractive index [1].



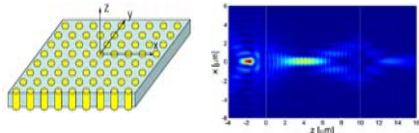
Veselago's flat superlens focuses light from point A into point B. In a negative refraction index material, the propagating light rays bend in opposite direction to that in ordinary materials.

At the time that Veselago's article was published, no material with negative refractive index was known. It was not until 2000, when John Pendry of Imperial College in London suggested that a material with negative refractive index can be created, and that resolutions of the order of a few nanometers across can be achieved for visible light regimes in systems where all dimensions are smaller than the wavelength of light [2]. Pendry also pointed out the link between focusing action and the existence of surface plasmons in wire structures with lattice separation of the order of few millimeters. Such surface plasmons or quanta of resonant collective electron plasma oscillations propagating on the surface of noble metals require $\epsilon < 0$ to exist. In an ideal plasma with resonant frequency ω_{ep} , the dielectric constant is given by the expression:

$$\epsilon = 1 - \frac{\omega_{ep}^2}{\omega}$$

Thus, for $\omega < \omega_{ep}$ (i.e. $\lambda > \lambda_{ep}$), $\epsilon < 0$.

Based on calculations sustained on the Effective Media Theory (EMT), Lu and Sridhar [3] showed recently that a composite metamaterial model consisting of metallic nanowire arrays embedded in a dielectric matrix behaves as a superlens. They found that depending upon the direction of light polarization with respect to that of the nanowires orientation, the model will show two Surface Plasmon Resonant (SPR) modes: one longitudinal and the other transversal. For wavelengths λ larger than that of the longitudinal SPR, the computations show that such a material will exhibit negative refraction index. The modeling results obtained by Lu and Sridhar show that flat superlenses may be produced using metal nanowire dielectric composites.

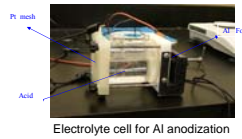


Intensity of the magnetic field in an EMT modeled flat lens imaging system consisting of metal nanorods embedded in a dielectric matrix [3].
 $d = 10 \mu\text{m}$
 $\epsilon_2 = -2.42 + 0.19i$
 $\epsilon_1 = 3.23 + 0.001i$
 $A = 1.55 \mu\text{m}$

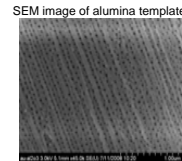
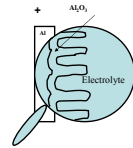
Fabrication nanowire dielectric composites by electrodeposition of Gold in nanoporous alumina templates

The formation of gold nanowires inside the nanoporous of dielectric aluminum oxide templates via electrodeposition of gold is a versatile bottom-up nanofabrication approach that is being intensively investigated in the Nanomanufacturing Lab at NEU [4], [5], [6], [7], [8].

Al anodization: Nanoporous aluminum oxide templates are generated by DC anodization of commercially available Al foil in an acidic electrolyte [9]. The preparation of nanoporous alumina template does not require sophisticated instrumentation, however the electrochemical processes taking place during anodization are complex. When an anodic voltage is applied, a barrier layer of aluminum oxide forms on the surface of the aluminum foil and the electrical current circulating across the electrolyte solution decays. Further anodization results in the formation and propagation of nano traces on the barrier oxide that in turn give rise to the nanoporous structure and the increase of the electrical current [10]. Pore parameters such as diameter and length can be controlled by adjusting the anodization conditions. Pore dimensions in the range of 4 to 100 nm and higher, and pore lengths on the order of hundreds of nanometers up to several microns are commonly obtained. Membrane thickness in the range from 10 to 100 μm with pore densities as high as 1011 pores / cm^2 , can be obtained. In this work, templates with pore diameter $\sim 12 \text{ nm}$ were fabricated by anodization of Al in 15% sulfuric acid at 10 V, and templates with pore diameter $\sim 35 \text{ nm}$ were fabricated by anodization of Al in 3% oxalic acid at 40 V. The time of anodization was 30 minutes which produces templates with thickness around 4 microns.

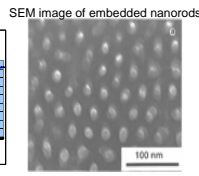
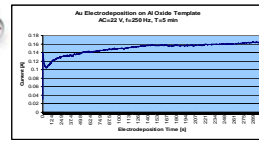
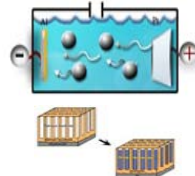


Electrolyte cell for Al anodization



SEM image of alumina template

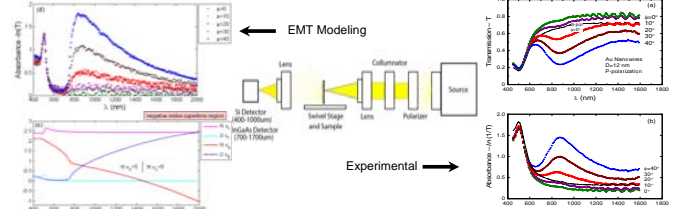
Gold electrodeposition on nanoporous Al templates: Metal nanowires are synthesized inside the templates by means of AC electrodeposition. In our experiment we synthesized Au nanowires. To do this, an aqueous solution consisting of HAuCl_4 (1g/l) and boric acid (4g/l) was used as electrolyte, and voltages of 22 V with frequency 250 Hz were applied. The unanodized Al layer below the pores was removed using a mercury chloride solution. This procedure rendered a dielectric template consisting of embedded Au nanowires. From the information on wire dimensions and pore parameters, the fill factors (ratio of metal versus dielectric) can be calculated.



SEM image of embedded nanorods

Nano-optic spectral characteristics of gold-dielectric nanocomposites

Transmission spectra from the nanowire dielectric composites for varying angles of light incidence with respect to the long axis of the wires were obtained. The spectra were obtained for both P- and S-polarized waves over the wavelength range 300 – 1600 nm. For the P-polarized wave, the magnetic field is perpendicular to the wire axis, while for the S-polarized wave, the electric field is perpendicular to the wire axis. The optical absorbance, $-ln(T)$, was computed from the optical transmission T .



The transmission spectrum for S-polarized light shows a minimum at $\sim 500 \text{ nm}$ and is independent of the angle of incidence and polarization. This corresponds to an absorbance peak arising from the transverse plasmon mode. For P-polarization, besides the 500 nm peak of the transverse plasmon, a spectral absorbance peak for the longitudinal plasmon in the range 845 – 875 nm is observed. This longitudinal resonance is strongly dependent on the incident angle. The experimental results are in good agreement with the absorbance calculations obtained by modeling [3]. From the graphs it can be seen that for wavelengths $\lambda > 1450 \text{ nm}$ the gold nanowire dielectric composite will behave like a negative index medium.

Summary

Anodization of aluminum and electrodeposition of metal nanowires in nanoporous alumina templates is a non-complex and non-expensive method of producing nanowire dielectric composites. The physical dimensions of the nanowire dielectric composites can be controlled by adjusting the fabrication parameters. Theoretical and Experimental results show that nanowire dielectric composites may work in negative refraction index regime, which makes them optimal for being used in different nanotechnology applications. Particularly in nano-optics, nanowire dielectric composites may be useful to produce flat lenses or superlens imaging devices.

Acknowledgments

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