Optical Characterization of Zero-Index Metamaterials

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BRIEF. We investigated the optical properties of a near-zero index metamaterial and demonstrate that it displays angularly selective transmission.

ABSTRACT. Interest in metamaterials has grown in past years due to the fact that these man-made materials can be constructed such that their optical properties are significantly different than naturally occurring materials. An important property for characterization of these materials is their angle dependent transmission of light. In this project an experimental apparatus was built to examine the transmission through experimentally created materials at varying incidence angles. This apparatus was then used to characterize the angle dependent transmission of a dielectric zero-index metamaterial, demonstrating that the optical properties are in good agreement with the theoretical modeling.

INTRODUCTION.

When electromagnetic (EM) waves interact with a material, the waves can be reflected, absorbed or transmitted through the material. All of these physical phenomena are dictated by the refractive index, which is composed of two parameters, the permittivity, which determines the interaction of EM waves with the electric field of light and the permeability, the interaction of EM waves with the magnetic field of light.

However, man-made composites, deemed "metamaterials", are capable of achieving extreme refractive indices with values both well above and less than unity. A metamaterial is a structured material, which is designed to have unique properties arising primarily from the micro-structure of the material rather than the inherent properties of the base materials [1, 2]. Microstructures are uniform, periodic structures smaller then the intended working wavelength. These structures behave as a homogenous material that can have novel properties.

When electromagnetic waves interact with a material, the waves can reflect, absorb, or transmit through the material. In addition, they can also bend, slow down, or speed up when passing through the material. In naturally occurring materials the value of the refractive index does not fall below unity. Currently, metamaterials with zero and negative refractive indices are under investigation.

A primary aim of metamaterial research is designing structures that have a predetermined response to light. A material with a refractive index less than zero lends itself to several applications such as cloaking [3–5] and a "Super lens" that images at a resolution below the diffraction limit, examples include active visualization of cellular processes such as protein interaction and lipid movement within the cell [6, 7]. Metamaterials that have an index equal to zero have applications that include point source directive emission [8], angular dependent filtration of light[9], and light tunneling through certain metamaterials [10–12].

Current refractive index measurement techniques of metamaterials are limited by their inability to measure the refractive index directly. There are several methods of inferring the refractive index based on measurements. These include the Kramers-Kronig Analysis [13] and ellipsometry [14]. A common problem with these tests is that there is an assumption that only one part of the refractive index varies with wavelength—namely, permeability is not changing—and this assumption cannot be made in the case of metamaterials as both permittivity and permeability vary with wavelength. One possibility to obtain both parts of the index independently is to use the transmission and reflection spectra in conjunction with phase measurements.

The focus of this study was to construct an apparatus that was capable of measuring angular dependence of transmission (Figure 1). In the case of a zero-index metamaterial (ZIM), transmission only occurs for near-normal incidence. Therefore, using this apparatus, it is possible to verify that a material has a zero index based on the angular transmission spectrum. In this study, the experimental measurements are compared to theoretical modeling to infer the refractive index over a range of wavelengths.

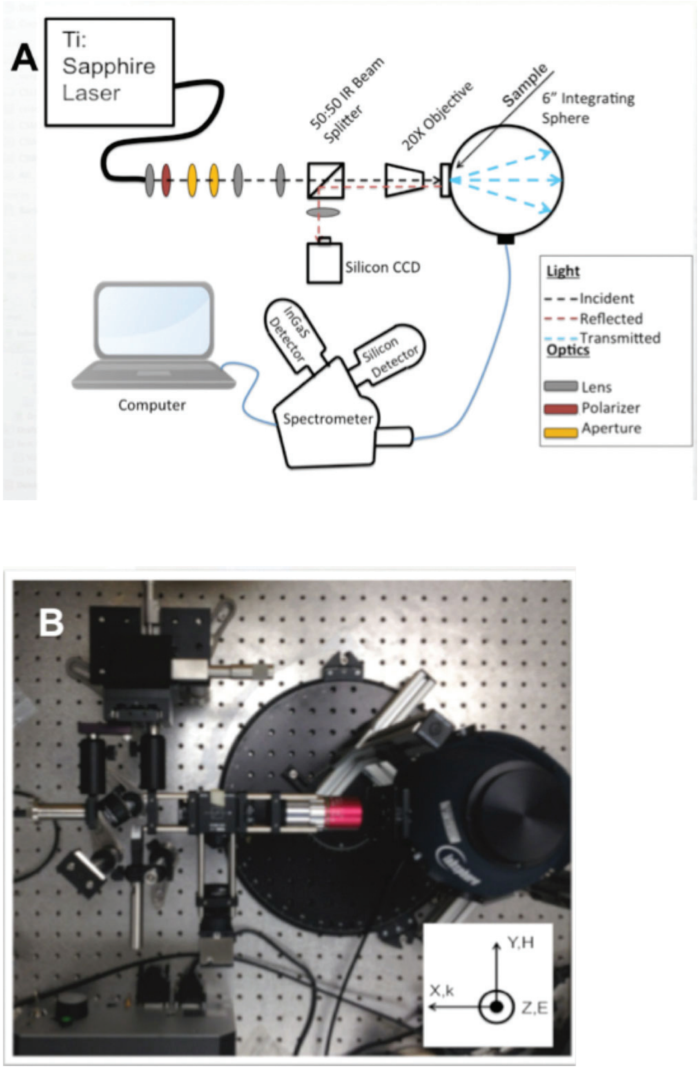

Figure 1. A) Diagram of the integrating sphere and optical components. B) An image of the integrating sphere being used to take transmission measurements.

MATERIALS AND METHODS.

The near-zero index metamaterial (Figure 2A) consisted of 11 alternating layers of silicon (Si) and oxide with dimensions of 260 nm x 260 nm for the silicon and 340 nm x 260 nm for the oxide. The periodicity of the structure was 600 nm vertically and horizontally. The microstructure arrays that were created were 200 μm x 200 μm in size allowing the unit cells to be smaller then the wavelengths used. The structure was fabricated using low-pressure chemical vapor deposition of the individual layers on a quartz wafer necessary for testing of the integrating sphere apparatus. Once the layers were deposited, reactive ion etching (RIE) was used to etch the silicon and oxide away in order to create the structures seen in Figure 2B. RIE leaves a sidewall angle on the structures that was measured to be a slight 9˚ using a scanning electron microscope (SEM). This small angle does not prevent the material from reaching a refractive index of near-zero as determined by using finite-difference time-domain simulations of the imperfect structure using CST Microwave Studio.

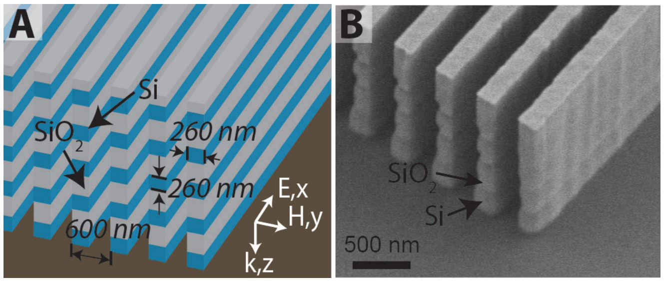

Figure 2. A) Shown is a three dimensional model of the zero-index metamaterial created. B) This is a scanning electron microscope image of the final material. The darker layers are oxide and lighter layers are silicon.

In order to make transmission measurements from 1000-1600 nm, a Labsphere reflection and transmission integrating sphere was used as the collection device. The inside of the integrating sphere was coated with a white diffusely reflecting paint allowing the light to be reflected onto the detector aperture. The light was spatially filtered to fill only a portion of the back aperture of a 20x microscope objective, assuring near-normal incidence on the sample. The small light beam created by the microscope objective was necessary to measure only the metamaterial and not the surrounding substrate. Also, a silicon charge coupled device, CCD, was used to view the light beam's incoming path and determine if it was on or off the metamaterial. A CCD works by converting photons striking the silicon surface to electrons that are then read by the computer. These optical components were installed in a 30 mm cage system and mounted on an XYZ translation stage for ease of focusing and movement (Figure 1A).

When off-normal angle measurements were taken, the integrating sphere was rotated such that the sample did not move in space, but only rotated about the z-axis. The light source used was a titanium (Ti): sapphire tunable laser. The laser cavity was oriented as a ring cavity and pumped at 800 nm. The laser's polarization was flipped 90˚ with a ®^ wave plate and filtered with a 1000 nm long pass filter to insure no 800 nm signal was leaking through and being measured (Figure 1B)

Transmission measurements were recorded using two methods. The first method employed used a spectrometer in order to differentiate the wavelength of light being measured. After the light passed through the sample and the integrating sphere, it was coupled into a fiber and analyzed by an indium gallium arsenide (InGaAs) detector. Additionally, using the tunable Ti: sapphire laser, intensity was measured by an IR photodetector. The energy reading output from this method could then be translated into transmission values. These measurement values were cross-validated with the expected values of a known material, quartz. Experimental transmission through quartz was recorded at several different angles of incidence; these measurements were compared with calculated transmission results using a known refractive index for quartz of 1.54 and the Fresnel equation for multiple internal reflections:

Equation 1

$$\frac{1}{1+\frac{4*\frac{(\sin(\theta_0-\theta_1))^2}{(\sin(\theta_0+\theta_1))^2}}{(1-\sin(\theta_0-\theta_1))^2}*(\sin(2\pi nd*\cos\theta_1/\lambda))^2}$$

where θ = Angle of incidence, θ = angle of refraction, n = refractive index, stet = wavelength, and d = material thickness.

RESULTS.

Initial tests of the integrating sphere on quartz were conducted to calibrate the integrating sphere, an important step to show the apparatus worked correctly. Tests were done with both a spectrometer and a photodetector in order to determine which collection method was more accurate. Since this apparatus was designed to experimentally measure angularly selective transmission, accurate transmission measurements are crucial. Table 1 shows the experimental differences between the measured and expected transmission values through quartz at several angles of incidence. At 0°Δ, 15°Δ, and 30°Δ, transmission values through quartz were 92.9%, 92.8%, and 93.5%, respectively. Both measurement techniques were within 3.5% of the expected values; however, when using the photodetector there were fewer measurement anomalies (measurement errors due to mechanical problems) in the data. Measurement errors could originate from coupling issues into the spectrometer as light is focused down onto the entrance slit. The importance of this test was to show that the measurements taken with our experimental apparatus accurately reflects the light transmission through the sample. Due to its higher accuracy, the photodetector was primarily used for the metamaterial measurements along with illumination from the Ti: Sapphire laser.

Table 1. Transmission values of light through quartz were taken using two measurement devices. The experimental error is shown as percent differences from the calculated transmission values of a quartz wafer with refractive index 1.54.

	Percent Error	Percent Error	Percent Error
	0^0	15^0	30^0
Spectrometer Values	0.50%	3.50%	0.80%
Photodetector Values	1.00%	1.10%	0.50%

Simulation results for the ideal metamaterial, as seen in Figure 3A, were simulated using finite-difference time-domain software to acquire the expected transmissions between 1200 nm and 1600 nm for varying angles of incidence. Figure 3A shows that for normal incidence light, there is broadband transmission, but as the angle of incidence increases transmission decreases. This is expected because one important parameter of a zero-index metamaterial is directive transmission, meaning the material should only transmit light at normal incidence. Experimental results are shown in Figure 3B. The curves shown represent transmission at varying wavelengths and angles of incidence. At all four wavelengths tested there is significant transmission when normal incidence is maintained; however, at high angles of incidence a decrease in transmission is evident. Past 20 degrees the metamaterial did not transmit light, which was expected because the transmission through a near-zero index metamaterial is angular dependent.

DISCUSSION.

This project had two purposes. The first was the creation of a device that could measure transmission at variable incidence angles, and second the optical characterization of an experimentally created near-zero index metamaterial. The apparatus designed to measure transmission consisted primarily of a light source, an integrating sphere, and a photodetector. An integrating sphere was chosen as the testing apparatus because of its capabilities to capture both specular and diffuse transmission from a sample. This is important because a metamaterial can scatter much of the light that is transmitted through. The apparatus was tested and calibrated using quartz, with a known refractive index, because the expected transmission could be calculated with the Fresnel equations. After this calibration was complete an experimentally created material was tested in this device and the transmission spectra were analyzed to determine if the material did have a near-zero refractive index.

In conclusion, an integrating sphere system for experimentally measuring transmission and reflectance of light through metamaterials as a function of wavelength and incidence angle was created. Upon calibration with quartz, a substance with a known refractive index, it was determined that this apparatus was successful at measuring the complete transmission, both spectral and diffuse, of materials. The lack of intensity in the 1000-1400 nm wavelength range

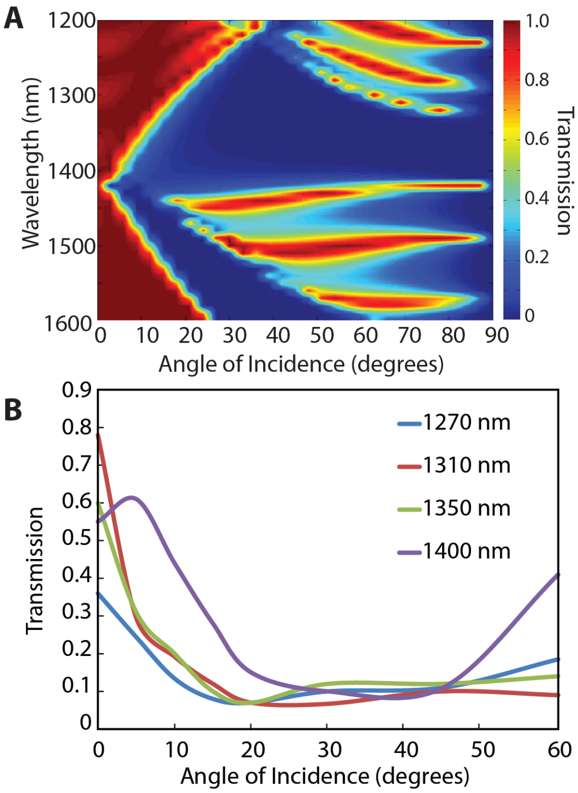

Figure 3. A) A graph of simulated transmission through the metamaterial at varying incidence angles. B) Experimentally measured transmission through the zero-index metamaterial.

and lack of definition in the spectra were two challenges in this setup; however, both of these issues were addressed by implementing a tunable laser in combination with a photodetector to look at specific regions of the spectra at varying incidence angles. With this modification, the apparatus successfully measured the complete transmission spectra of metamaterials and could be utilized for other small area samples. Future experiments with this device and other optical analysis will lead to the verification of an all-dielectric near-zero index metamaterial in the optical/infrared frequency, the first in this range. The apparatus constructed in this project is another way of measuring both spectral and diffuse transmission of a material, which is one way to characterize optical materials.

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