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### Title

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# Fabrication and Optical Measurements of Nanoscale Meta-Materials: Terahertz and Beyond

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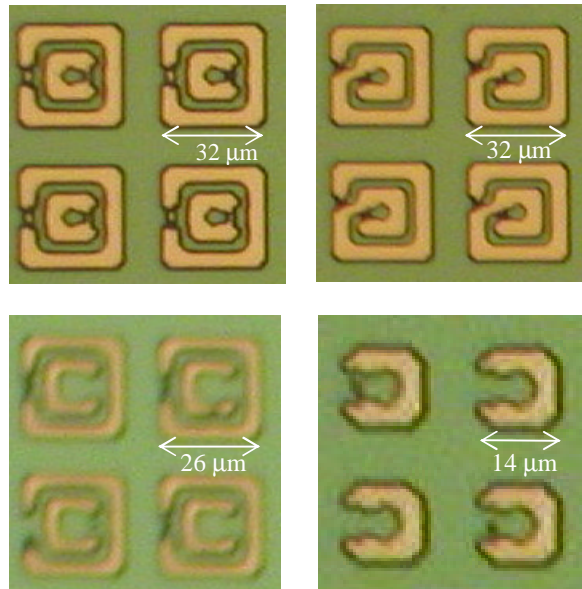
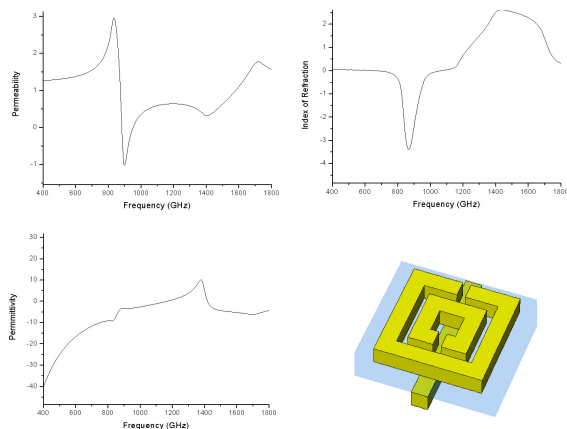
## Introduction

Recently, artificial meta-materials have been reported [1] that have a negative index of refraction, which allows a homogeneous flat slab of the material to behave as a “perfect” lens [2], possibly even creating sub-diffraction limited focusing. These novel artificial materials have numerous potential applications in science, technology, and medicine [3], especially if their novel behavior can be extended to the technologically critical near-infrared and visible region.

The meta-materials consist of split-ring resonators which provide a negative  $\mu$ , and metal strips which provide a negative  $\epsilon$ . First steps towards scaling the dimensions of these meta-materials have been recently taken with the fabrication of split ring resonator structures showing magnetic resonances at about 1 THz [4] and 100 THz [5] frequencies.

## Simulations

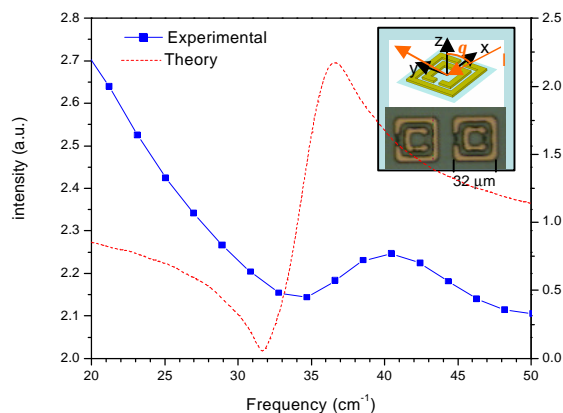
We employ sophisticated computer codes to simulate the magnetic and electric responses of a wide variety of test structures as a function of frequency to help understand how to optimize the design of meta-materials for negative index of refraction properties. (examples are shown in Figure 1, below). We then use the results of these simulations to first fabricate appropriate meta-materials, and then to compare with our measured optical responses.



## Micro-fabrication

We have also begun the micro- and nano-fabrication of these meta-material structures using gold on thin SiN windows (see examples of split ring resonators and spirals above Figure 2, with dimensions as indicated). The SiN substrate is thin enough (100 nm) that these are nearly free-standing structures allowing us to fully characterize the index of refraction properties as a function of wavelength using ALS Beamlines 1.4.2, 1.4.3, 1.4.4, and 7.2.1.

In order to understand the resonance properties of those resonators, we measured the far-infrared (THz) spectral response of these meta-materials. The samples are measured in reflectance geometry with a variable angle of incidence between 5 and 80 degrees. A wire-grid wide-band polarizer is placed before the sample to ensure a polarized beam because the metamaterials are bianisotropic. By adding an additional polarizer after the sample as an analyzer, we can determine all the optical parameters such as complex permeability and permittivity. We also use Beamline 1.4.4's infrared imaging

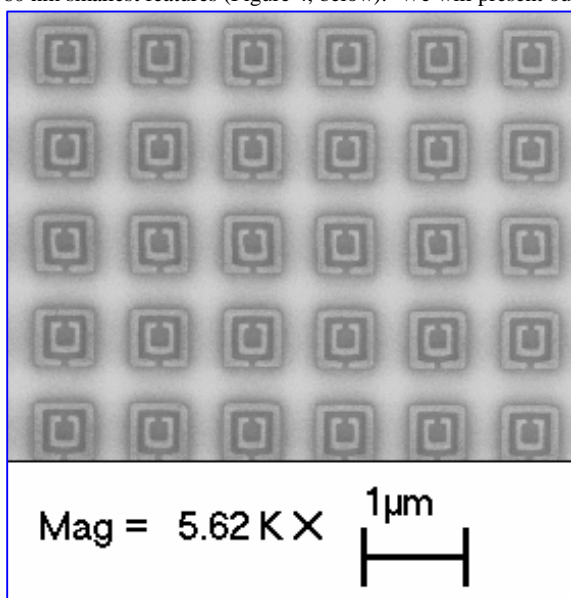


microscope to determine the spectral response as a function of position on the micro-fabricated structures.

Figure 3 (above) shows an example of the measured and simulated magnetic resonance from the double split ring resonator pictured in the inset. The observed resonance frequency at  $\sim 37 \text{ cm}^{-1}$  ( $\sim 1.1 \text{ THz}$ ) is well predicted by the electromagnetic transient simulations. The configuration of the incidence beam and sample surface is shown in the inset of the figure. The electrical resonance component is minimized by aligning the polarization of light along x (the symmetry plane of the SRR structure), by using a relative large incidence angle (60 degrees), and by normalizing to the spectrum measured at near-normal incidence (10 degrees).

### Nano-fabrication

We report on our efforts to create fully left-handed meta-materials at multi-THz frequencies, our detailed optical characterizations of various structures fabricated, and our understanding to date of what the materials limitations are for making these structures smaller and smaller. Presently we are using CXRO's nano-writer to create sub-micron structures with 60 nm smallest features (Figure 4, below). We will present our



results on these and other nano-fabricated structures with resonance frequencies in the 100 THz and higher range.

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