Transmission and Reflection Measurements of Mid-Infrared Left-Handed Metamaterials

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There are many things that scientists have yet to discover about left-handed materials. Left-handed materials are unique in their ability to bend light in the opposite direction of the usual forward energy flow. Since the fabrication of left-handed materials is quite a recent development, the properties of these negative index materials still need to be characterized. Using a Fourier transform infrared (FTIR) spectrometer, a mercury-cadmium-telluride (MCT) detector, a polarizer and a bi-axial rotation device (BARD) setup, we were able to analyze the amount of light transmitted and reflected by these unusual materials [1]. The BARD is a custom-made machine on which the MCT detector and the mount where we placed our sample rotated independently of one another on a common axis, as shown in Figure 1(A). We used a computer program to control the BARD and change the angle at which the sample was placed in front of the FTIR infrared source, known as the incident angle, to see how this would affect the sample's transmission. In measuring reflection, we also changed the angle at which the detector received the reflected light and observed changes in intensity as well as new features that appeared.

We measured the intensity of the light transmitted or reflected versus wavenumbers, or 1/wavelength(λ). In the collection process we took measurements of the background and obtained the ratio of the sample over background in order to eliminate artifacts primarily from water and CO_2. For transmission the background was the light source without the sample, but for reflection we used reflection off a planar mirror or a semiconductor, InGaAs. In one particular experiment, we observed the transmission measurements of a 20 μm thick sample of alternating 80 nm highly-doped InGaAs and intrinsic AlInAs layers grown on InP substrate. We rotated the sample changing the incident angle from 0 to 90 degrees. We found that at certain angles, specifically between 40 and 70 degrees, the transmission curves of this left-handed material exhibited a strong resonance in a range of 7 to 11 μm (λ), as shown in Figure 1(B). This strong feature signifies the transition to negative refraction in the material. We observed the unique characteristics found in the transmission of negative refractive index metamaterials and are currently in the process of analyzing how those metamaterials reflect mid-infrared light. The data we gathered from the transmission and reflection measurements can be used to help produce better left-handed materials that may be used in the future for various applications such as producing infrared lenses without resolution limits, gas sensing, or imaging. *This work was supported in part by MIRTHE (NSF-ERC).*

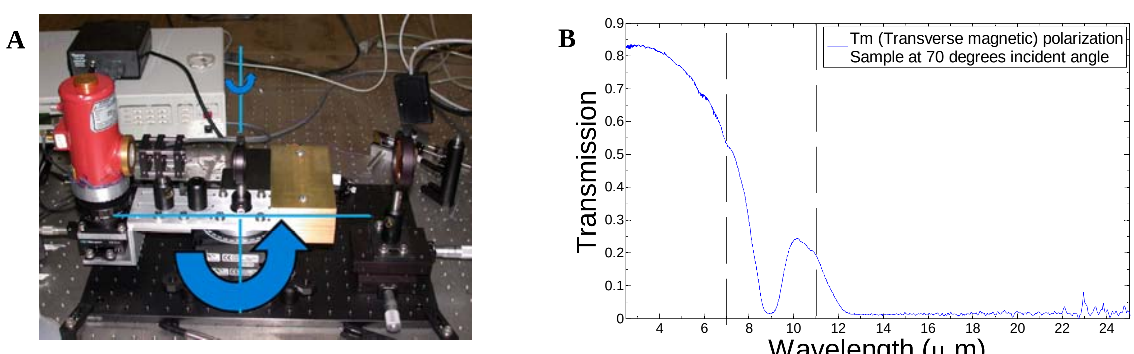

Fig. 1 **(A)** Bi-axial Rotation Device (BARD) setup, arrows indicating rotation. **(B)** Transmission of 20 μm thick sample of alternating 80 nm highly-doped InGaAs and intrinsic AlInAs layers grown on a InP substrate showing resonance found in left-handed metamaterials.

[1] Hoffman, A. J., Alekseyev, L., Howard, S.S., Franz, K. J., Wasserman, D., Podolskiy, V. A., Narimanov, E. E., Sivco, D. L., and Gmachl, C. "Negative refraction in semiconductor metamaterials", *Nature*, **Vol. 6**, 946-950, (2007)