Transmission Resonance in Mid-Infrared Left-Handed Metamaterials

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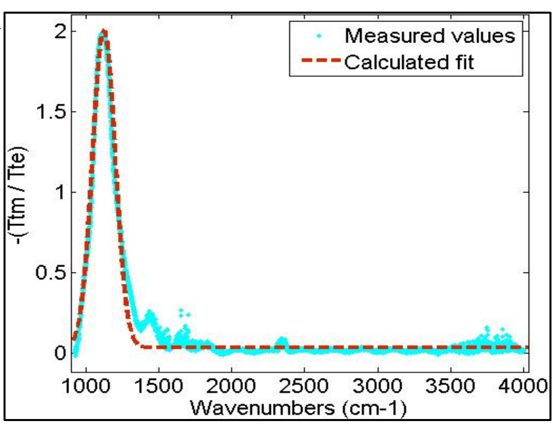
Mid-infrared left-handed metamaterials (LHMs) are strongly anisotropic materials that exhibit negative refraction for certain wavelengths of light. Molecular beam epitaxy is used to synthesize LHMs by alternating layers of highly doped InGaAs and intrinsic AlInAs on InP substrate. The ability to engineer LHMs by changing the electron density and layer thickness can allow for unique applications, such as planar birefringent lenses and subwavelength imaging [1]. However, current LHM designs are limited by negative refractive indices that are highly dependent on wavelength. Derived from the Kramers-Kronig relation, $\eta(\lambda) \propto \frac{d}{d\lambda}\alpha(\lambda)$, wherein $\eta(\lambda)$ is the refractive index as a function of wavelength and $\alpha(\lambda)$ is the absorption as a function of wavelength. Therefore, a resonance in the absorption spectrum in the 9 to 13 μm region results in large fluctuations of the refractive index. The objectives of the current study are to a) find a correlation between the width of the resonance and the incident angle and b) develop a method of quantifying the extent of resonance minimization in new LHMs.

A Fourier transform infrared spectrometer (FTIR) was used to obtain transmission measurements of the LHM. Measurements were taken of a 20μm thick sample fabricated by alternating highly doped InGaAs and intrinsic InAlAs layers on InP substrate. The ratio of transmission for transverse magnetic (TM) and transverse electric (TE) polarizations (T_{TM}/T_{TE}) was used to isolate the resonance. As pictured in Fig. 1A, a modified Gaussian distribution fit in the form $f(x) = ae^{-((x-b)/c)^2} + d$ was used to approximate the shape of the resonance curve. The baseline of the fit, d, was determined by calculating the limit of the right tail of the curve. The peak of the resonance distribution, a, was found using the maximum value of the resonance. Values for b and c were determined by MATLAB's curve fitting tool. The full width at half maximum (FWHM) for the fit was derived from the Gaussian equation: $2c\sqrt{\ln(2)}$. The FWHM was calculated for incident angles of 5° to 70° with 5° increments. The scatter plot shown in Fig. 1B depicts the trend in FWHM versus incident angle for the sample. A positive linear correlation with $r^2 = .99$ is observed, conveying that an increase in incident angle broadens and decreases refractive index fluctuation. In the near future, the absorption spectra of novel samples will be measured to test for resonance minimization. This work is supported in part by MIRTHE (NSF-ERC).

A



B

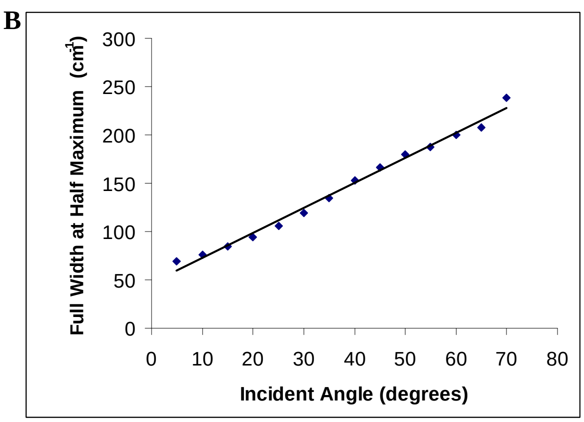


Fig. 1 **(A)** Gaussian fit, $f(x) = 1.97e^{-((x-1125)/108.1)^2} + .03$ with $r^2 = .98$, for measured values of transmission resonance in 20μm LHM sample at 50° incidence. **(B)** Linear fit, $f(x) = 2.59x + 47.12$ with $r^2 = .99$, for FWHM of transmission resonance vs. incident angle in 20μm LHM sample.

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