Fabrication and Testing of Voltage-Tunable Plasmonic Metamaterials in Mid-Infrared

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Abstract:

The device introduced in this project has the potential to further the scope of voltage-tunable frequency-selective surfaces in the mid-infrared spectral range. Our device consists of an array of sub-wavelength plasmonic elements, resonant in the mid-infrared, fabricated on top of GaAs/$Al_{0.8}Ga_{0.2}As$ coupled-quantum-well heterostructure. The plasmonic structures were fabricated using electron beam lithography (EBL), and the devices were characterized using Fourier-transform-infrared-spectrometer-based (FTIR) reflection measurements. The fabricated plasmonic structures were resonant at 4.5 μm and intersubband absorption was measured at 6.8 μm. This resonance mismatch was too high to observe tuning.

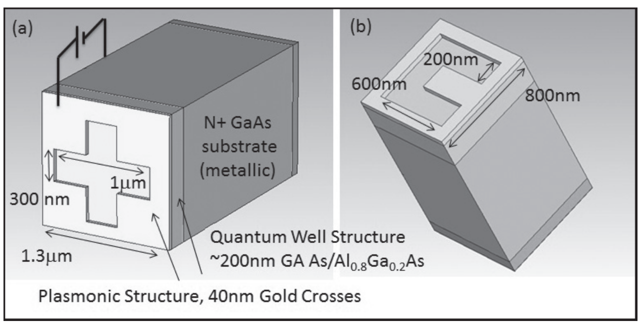

Figure 1: Device structure designed in CST Studio composed of an array of plasmonic sub-wavelength complementary (a) cross and (b) split ring resonators.

Introduction:

Metamaterials are artificial materials constructed on the sub-wavelength scale to provide electromagnetic properties such as negative refractive index that usually cannot be obtained by naturally occurring materials. Owing to the narrow fixed frequency response of plasmonic metamaterials, they may be used as frequency selective surfaces [1, 2]. Our device introduces the possibility of electrically controlling the absorption wavelength of these surfaces with a potential 10 percent of wavelength tuning range in the mid-infrared spectral range. To accomplish this, we mated the plasmonic metamaterials with quantum-well structures in which the refractive index depended strongly on applied bias voltage.

The plasmonic metamaterial consisted of an array of sub-wavelength elements patterned in a 40 nm thick gold (Au) layer. This was fabricated on the top surface of a gallium arsenide / aluminum gallium arsenide (GaAs/$Al_{0.8}Ga_{0.2}As$) coupled-quantum-well heterostructure. The simulated device structure is shown in Figure 1, and was designed in CST Microwave Studio®. The resonance wavelength of this material was determined by the geometry of the elements and the refractive index of the surrounding environment, which in this case was the quantum-well heterostructure.

The quantum-well layer absorbed in the mid-infrared through intersubband transitions in the conduction band. These had an atomic-like absorption profile with a sharp, narrow linewidth. This allowed for a large change in the refractive index through the Kramers-Kronig relation, for transverse

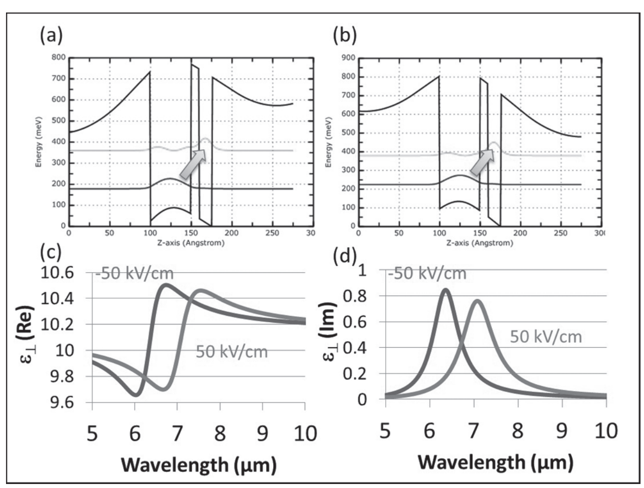

Figure 2: Intersubband transition simulation and dielectric constant of quantum wells. The device is biased at; (a) 50 kV/cm, (b) -50 kV/cm, (c) real part, and (d) imaginary part of dielectric constant at different bias voltage.

magnetic (TM) polarized electromagnetic radiation. Band structure engineering using a one dimensional Schrodinger-Poisson simulation was performed to determine the transition energies and hence the operating wavelength. This was subject to the Stark shift, so could be tuned by application of a bias voltage. This wavelength is shown in Figure 2.

Since the refractive index of the surrounding environment of the plasmonic metamaterial was altered, there was a resultant shift in the resonance frequency. The resonance frequencies of plasmonic metamaterial and quantum-well structure should be coincident in order to achieve maximal tuning of the plasmonic resonance.

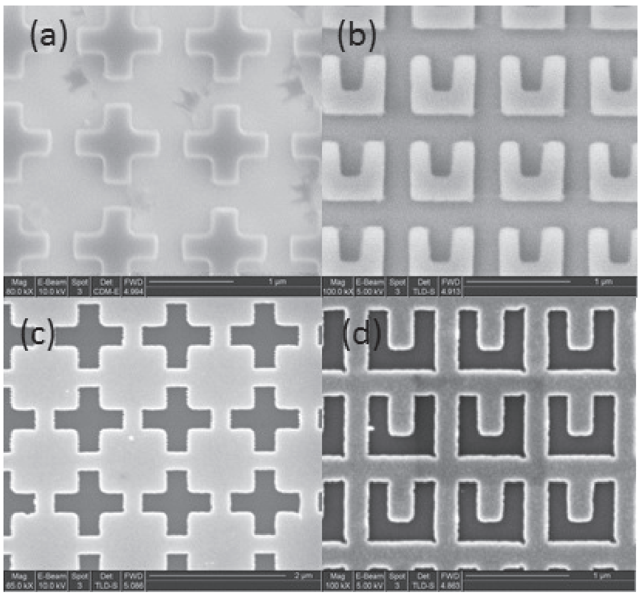

Figure 3: SEM images of; (a) cross, (b) split ring pattern covered by photoresist, and (c) cross, (d) split ring pattern after gold evaporation.

Experiment Procedure:

We fabricated two devices with different plasmonic patterns: complementary crosses and split rings. The quantum well structure was grown by molecular beam epitaxy (MBE) on the *n*-doped gallium arsenide (GaAs) substrate. EBL was used to fabricate the plasmonic structures. These had minimum feature sizes on the order of a few hundred nanometers. Several tests were performed to obtain a close approximation to the designed structure, including adjusting the dose factor of the electron beam and changing the dimension of the pattern file. 40 nm of Au was evaporated onto the samples' surface, and a lift-off performed. Figure 3 shows scanning electron microscopy (SEM) images of the array of cross and split ring patterns both in photoresist and after metallization. Mesa structures were fabricated to prevent current spreading and instead, confine the current through the plasmonic metamaterial. Using a solution of 1:4:45 ratio of phosphoric acid:hydrogen peroxide:water (H_3PO_4:H_2O_2:H_2O), the surrounding area was etched down by ~ 500 nm. The samples were then thinned down to 200 μm and mounted with indium solder to a copper carrier block. Multiple wire bonds to the array were made, to accommodate a potentially large current.

The finished device was characterized by FTIR, and spectral measurements were taken. A broad band mid-infrared source (globar) was focused onto the plasmonic array and the reflected signal measured with a liquid helium cooled mercury cadmium telluride (MCT) detector.

Results and Conclusions:

The resonance frequencies of the cross and split ring resonators were 4.5 μm and 3.1 μm respectively, while the resonant frequency of quantum well structure was 6.8 μm, as shown in Figure 4. Voltage biasing of the underlying semiconductor layer was attempted, but no tuning was observed. This was due to the large resonance mismatch between the fabricated plasmonic structures and the quantum wells.

Future Work:

The frequency-selective-surface device presented relies on matching the resonance wavelength of the plasmonic metamaterial with the absorption wavelength of the semiconductor layer. We expect future structures in which the plasmon and quantum well resonances are matched should allow for widely tunable plasmonic devices.

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References:

[1] X. Liu, T. Starr, A. F. Starr, and W. J. Padilla, Phys. Rev. Lett. 104, 207403 (2010).

[2] X. Liu, T Taylor, T. Starr, A. F. Starr, N. M. Jokerst, and W. J. Padilla, Phys. Rev. Lett. 107, 045901 (2011).

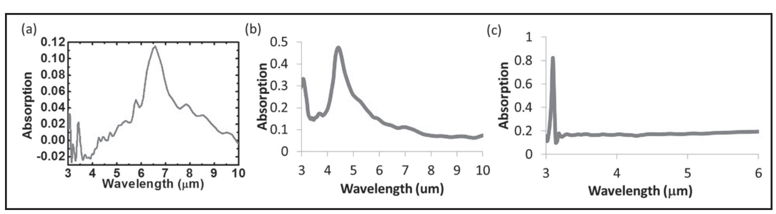

Figure 4: Experimental data of absorption intensity versus wavelength; (a) quantum wells, (b) cross resonator, and (c) split ring resonator.