Voltage-Tunable Plasmonic Metamaterials Based on Stark Tunable Intersubband Polaritons

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Abstract:

This paper explores ways of producing voltage-tunable plasmonic metamaterials. By combining plasmonic metamaterials with intersubband transitions in $In_{0.53}Ga_{0.47}As/Al_{0.48}In_{0.52}As$ coupled quantum well heterostructures, we fabricated and tested devices with optical response sensitive to applied bias voltage. The metamaterials consisted of an array of sub-wavelength plasmonic elements resonant in the mid-infrared. The plasmonic structures were fabricated using electron-beam lithography. The devices were characterized using Fourier transform infrared spectrometer (FTIR)-based reflection measurement. Resonance matching between intersubband transition and plasmonic resonances was confirmed by observing polaritonic splitting of absorption peaks in reflection spectrum. Experimentally, applying 5.5 volts of DC bias achieved 71 nm of wavelength tuning at 7 μm wavelength.

Introduction:

Plasmonic metamaterials are artificial materials constructed on the sub-wavelength scale to provide electromagnetic properties that cannot be obtained by naturally occurring materials. Our goal was to produce voltage-tunable plasmonic metamaterials by combining plasmonic metamaterials with artificial semiconductors designed for electro-optic effect. The tunability was based on the integration of intersubband transitions, which occurred from excitation of an electron between quantized energy levels within a multi-quantum-well (MQW) [1], and plasmonic absorption from surface plasmon polaritons (SPP's), which occurred when infrared waves struck a metal and caused electron oscillations [2]. Intersubband transitions were designed to have diagonal transitions in real space in which sharp absorption allowed for changes in permittivity in the direction normal to the surface based on the Kramers-Kronig relation for transverse-magnetic (TM) polarization; see Figure 1(c). Bias voltage tunes the position of intersubband absorption lines; see Figure 1(a), (b). With proper planar configuration, we could apply bias through the MQW layer and utilize ε_z for tuning. The bias voltage led to significant tuning of absorption peak position in the plasmonic absorption spectrum.

Our device confirmed the potential for spectral tuning in the mid-infrared range with bias voltages, known as the Stark Shift. We modeled a unit cell of our structure with Computer Simulation Technology (CST) Microwave Studio; see Figure 2(a). The structure consisted of a MQW layer positioned between bottom and top metal layers. The plasmonic resonance wavelength was based on the geometry of the elements and dimensions of the resonator. Band structure engineering determined the transition energies and operating wavelengths. Since the refractive index of the surrounding environment of the plasmonic metamaterial changed, there was a resultant shift in the resonance frequency; see Figure 2(b). The resonance frequency of the plasmonic metamaterial and multi-quantum-well structure must coincidently align to achieve maximal tuning of the plasmonic resonance.

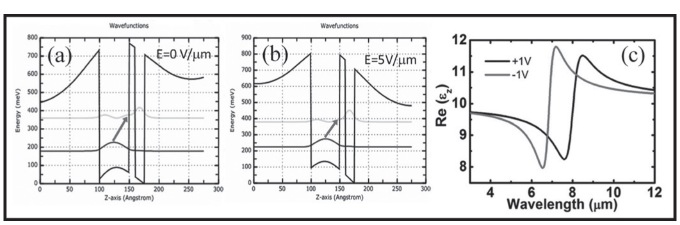

Figure 1: Intersubband transition simulation when the device is biased at (a) 0V and (b) 1V. (c) Calculated real part of dielectric constant at different bias voltage.

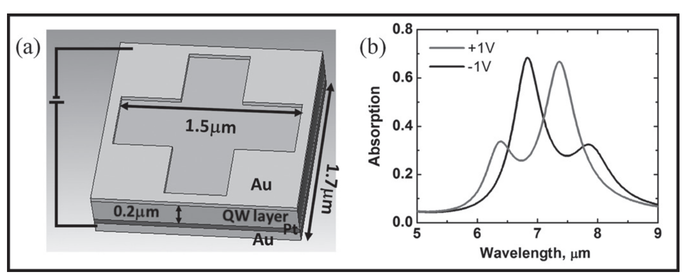

Figure 2: (a) Device structure designed in CST Microwave Studio composed of complementary cross resonators. (b) Simulated plasmonic absorption tuning at different bias voltages.

Experimental Procedure:

We fabricated a 400 μm by 400 μm array of complementary cross-shaped resonators on a 200 nm-thick MQW layer. The MQW structure was grown by molecular beam epitaxy (MBE) on an n-doped InP substrate. After wafer bonding, polishing, and wet etching, electron beam lithography (EBL) was used to fabricate the plasmonic structures. The minimum feature was 214 nm, and the maximum was 1.544 μm. Titanium and gold were deposited onto the sample's surface, and lift-off was performed.

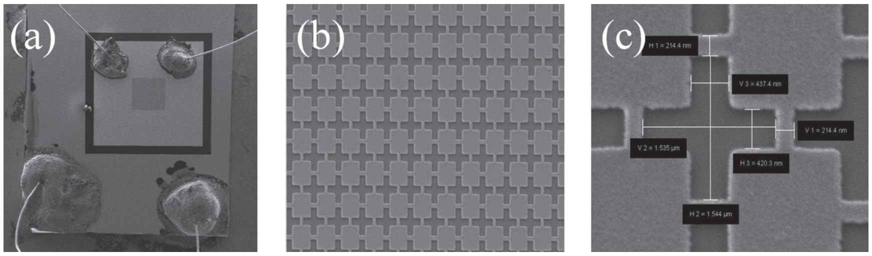

Figure 3: SEM images of (a) a finished device with bonded wires, (b) array of crosses, and (c) one period of cross.

Figure 2 (a-c) show scanning electron microscope (SEM) images of the cross-shaped pattern and finalized device.

A mesa-structure was necessary to prevent current spreading away from the plasmonic metamaterial. The samples were cleaved and mounted to a copper carrier block. Using a manual tool, we created multiple wire connections to bottom and top metal contacts for current flow. We performed several tests 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 during e-beam writing.

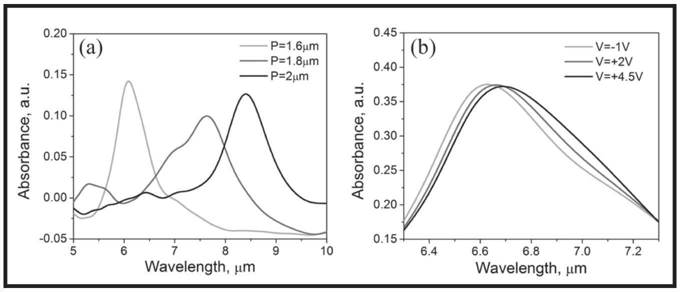

Figure 4: (a) Experimental absorption spectrum of devices with different periods of cross resonator. (b) Experimental absorption spectrum tuning by applied bias voltages.

The FTIR characterized the finished device with spectral measurements. A broadband mid-infrared light from a globar lamp inside the FTIR was focused onto the plasmonic array via objective lens, and the reflected signal was measured through a beam splitter and ZnSe lens with a liquid nitrogen cooled mercury cadmium telluride (MCT) photo-detector.

Results and Conclusions:

Resonance matching between intersubband transitions in the MQW and plasmonic resonances was confirmed by observing polaritonic splitting of absorption peaks, which occurs when two new energy states are effectively constructed as shown in Figure 4(a). The evident trend proved that as the period of the unit cell increased, the resonance wavelength increased. We were able to see that the polaritonic splitting of the absorption occurred with a period around 1.8 μm. We applied tuning to the structure with matched resonance of period 1.75 μm. We achieved 71 nm of wavelength tuning at 7 μm wavelength with 5.5 volts of DC bias. We observed plasmonic absorption tuning through a quantum-confined Stark Shift by applying bias through the MQW; as the voltage increased, the absorption peak spectrum shifted to longer wavelengths as shown in Figure 4(b).

Future Work:

Adjusting the structure to have a plasmonic absorption line closer to the intersubband absorption line of the MQW may broaden the tuning range. Technologies including spectrometry, photo-detectors, and quantum cascade lasers immensely benefit from such insights.

Acknowledgements:

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References:

[1] Delacourt, Dominique, et al. "Mid-Infrared Phase Modulation via Stark Effect on Intersubband Transitions in GaAs/GaAlAs Quantum Wells." IEEE Journal of Quantum Electronics, 29, 8, 1-4 (1993).

[2] Liu, X., et al. "Infrared Spatial Frequency Selective Metamaterial with Near-Unit Absorbance." Phys. Rev. Lett. 104, 20, 2313-2318 (2010).