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Interactions in 2D and 3D mid-infrared metamaterials

I. Brener[1,2]

[1] Sandia National Laboratories, P.O. Box 5800, Albuquerque, NM 87185
[2] Center for Integrated Nanotechnologies, P.O. Box 5800, Albuquerque, NM 87185

Abstract

We explore the issue of interactions between metamaterial resonators and different types of absorbers placed in proximity to these resonators. Very clear anticrossing behaviour and level splitting is observed when IR phonons interact with planar metamaterials. More complex dipole transitions can be designed using semiconductor bandgap engineering. We show experimentally the coupling between metamaterial resonances and intersubband transitions and discuss this mechanism for electrical tuning of metamaterials throughout the optical infrared spectral region. Finally we will discuss interactions in 3D dielectric resonator metamaterials.

1. Introduction

Planar metamaterials (or "metafilms") offer a promising platform for new types of active optical devices. Resonances in these metamaterial structures can be scaled by geometry and their spectral response is exquisitely sensitive to the local dielectric environment which can be changed using a number of tunable dielectrics [1-3]. Arrays of metamaterial resonators have already been used as amplitude and phase modulators at terahertz frequencies. [4, 5] In this paper we further explore the interaction between metamaterial resonators and various dipole resonances and discuss applications for electrical tuning of metamaterials.

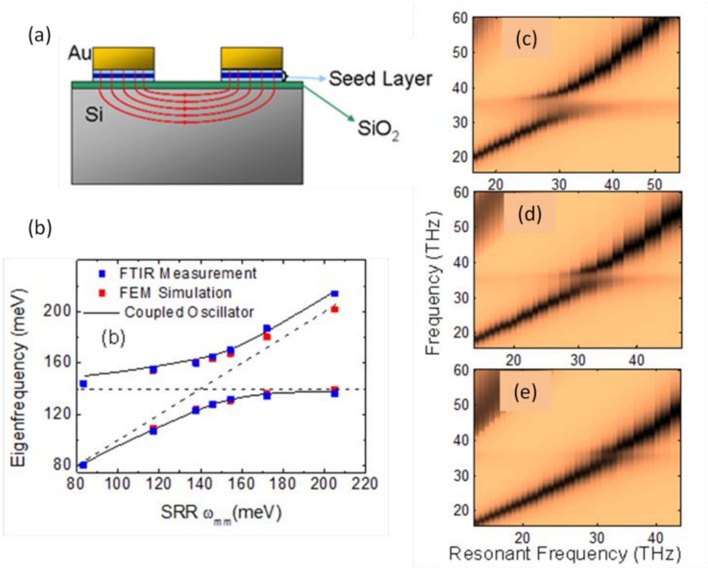

Fig. 1: (a) Schematic cross section showing thin film interface between metallic SRR elements and Si wafer including a thin SiO_2 layer. (b) the measured resonant frequencies of the coupled modes compared to the analytical model for two coupled oscillators. (c-e) Normal mode splitting simulated by FDTD as the SiO_2 layer is displaced from the SRR metamaterial elements: (c) SiO_2 in contact, (d) SiO_2 depth of 50nm, (e) SiO_2 depth=125nm.

2. Strong interaction between metamaterials and infrared phonons.

Infrared phonons in dielectrics placed in proximity with metamaterial resonators can couple strongly, leading to normal mode splitting similar to vacuum-Rabi splitting that occurs with optical emitters coupled to microcavities. The amount of coupling can be altered through the design of the metamaterial resonators, the proximity of the dielectric layer to the resonator, the dielectric film thickness, and the amount of field overlap with the dielectric layer. [6] An example is shown in Fig. 1 where split ring resonators (SRR) were fabricated on a Si substrate with a 10nm Silicon oxide film. A schematic diagram is shown in Fig. 1(a); as the SRR dimensions are scaled and the fundamental resonance is swept through the IR Si-O phonon band, a clear anticrossing is observed, indicative of strong coupling (Fig. 1(b)). The coupling strength can be further controlled by varying the depth of this dielectric layer as is shown in modeling results in Fig. 1(c).

3. Interaction with infrared intersubband transitions using bandgap engineered heterostructures.

Another tuning mechanism that we are currently exploring is the interaction of metamaterial resonances with intersubband transitions (IST) in semiconductor heterostructures. The major advantage of ISTs is the wide scalability in wavelength response that can be obtained through QW structural parameters such as the doping level, energy spacing between subbands and the use of different material systems. An example is shown in Fig. 3: arrays of SRRs and control square loops were fabricated on top of a semiconductor heterostructure consisting of two coupled QWs as the basic unit cell. The quantum well structure was grown by molecular beam epitaxy (MBE) and consists of 30 repetitions of a unit cell comprised of a coupled quantum well (QW) structure 15/5.75/1.13/2.5/15 nm thick layers of ($Al_{0.5}Ga_{0.5}As/GaAs$), followed by a Si δ -doped layer. The electron density within each coupled QW structure is about $2x10^{11}cm^{-2}$. The selection rules for this type of engineered transition are such that the optical field needs to have TM components, namely, inside the plane of the QWs. Even upon normal incidence in a TE geometry, a significant fraction of TM light is provided through the fringing fields of the SRRs. We scale the SRR geometry and sweep it through the IST transition designed at λ~10μm. Significant interaction can be observed for the polarization parallel to the gap (Figs. 3(c-e)), as evidenced by the broadening of the resonance in comparison with the same SRR arrays fabricated on a control undoped GaAs wafer. These effects can now be coupled with electrical tuning of the subband levels in order to electrically tune metamaterial resonances and this will be discussed in the talk.

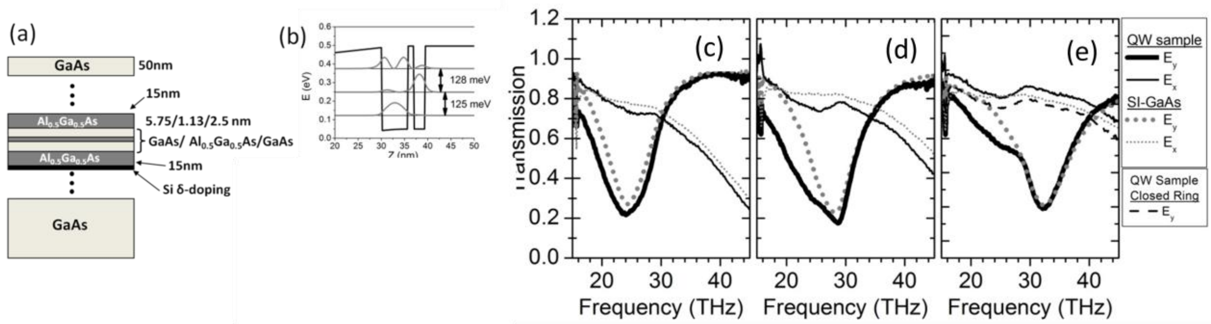

Fig. 3: (a) - The layer sequence of the QW sample. (b) An energy band diagram of two asymmetric coupled QWs. The subbands and their corresponding wavefunctions (modulus) are shown as well. (c-e) Transmission spectra for three different SRR arrays, which were scaled (length, linewidth, gap size and periodicity) to resonate at different frequencies. The legend indicates the polarization of the incident light for each transmission line and the substrate beneath the SRRs.

4. Interactions in 3D Dielectric Resonator Metamaterials.

An alternative path to low loss and 3D metamaterials is to use high permittivity dielectric inclusions (i.e., spheres or cubes) in a low permittivity matrix [7-9]. Recently, we have developed IR metamaterials based on etched cubes of Tellurium fabricated on an IR transparent substrate. [10, 11] We will discuss issues of coupling in these 3D metamaterials, such as resonator proximity and coupling to metallic inclusions.

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