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Active IR Materials for Beam Steering

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Active Infrared Materials for Beam Steering

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Abstract

The mid-infrared (mid-IR, 3 μm -12 μm) is a highly desirable spectral range for imaging and environmental sensing. We propose to develop a new class of mid-IR devices, based on plasmonic and metamaterial concepts, that are dynamically controlled by tunable semiconductor plasma resonances. It is well known that any material resonance (phonons, excitons, electron plasma) impacts dielectric properties; our primary challenge is to implement the tuning of a semiconductor plasma resonance with a voltage bias. We have demonstrated passive tuning of both plasmonic and metamaterial structures in the mid-IR using semiconductors plasmas. In the mid-IR, semiconductor carrier densities on the order of $5\text{E}17\text{cm}^{-3}$ to $2\text{E}18\text{cm}^{-3}$ are desirable for tuning effects. Gate control of carrier densities at the high end of this range is at or near the limit of what has been demonstrated in literature for transistor style devices. Combined with the fact that we are exploiting the optical properties of the device layers, rather than electrical, we are entering into interesting territory that has not been significantly explored to date.

CONTENTS

1. Background.....	9
1.1. Motivation.....	9
2. Accomplishments.....	10
2.1: Plasmonic Grating Dispersion	10
2.2: Free-carrier Tuning.....	11
2.2: Electro-optic material	14
3. Conclusions.....	16

NOMENCLATURE

1. BACKGROUND

1.1. Motivation

The field of plasmonics encompasses a large range of customizable optical structures based on charge oscillations (plasmons) at a metal/dielectric interface or in a semiconductor. We propose to develop active plasmonic structures where a voltage bias controls plasmon resonance frequencies in order to enable new functionality. Mechanical steering systems include dual axis gimbaled mirrors, de-centered lenses, and prism pairs. It is well known that achieving similar functionality in non-mechanical alternatives is desirable in terms of reduced size, weight, power requirements, and response times. We have previously demonstrated active current controlled thermal tuning of plasmonic structures, and passive tuning in the mid-infrared using free-carriers in semiconductors. The true challenge of this work is to incorporate fast active tuning, with appropriate range, in a plasmonic structure that is capable of handling potentially high optical powers required for the target applications.

2. ACCOMPLISHMENTS

2.1: Plasmonic Grating Dispersion

Surface plasmons are hybrid excitations that propagate at a metal/dielectric interface and consist of collective charge oscillations in the metal coupled to the electromagnetic (EM) wave. The surface plasmon (SP) can be quantitatively described by solving Maxwell's Equations at a metal/dielectric interface where the dielectric constant of the metal (ϵ_m) is negative and much larger (in magnitude) than the dielectric constant of the dielectric material (ϵ_d). The resulting SP dispersion relation is given by

$$k_{sp}^2 = \frac{\omega_{sp}^2}{c^2} \left(\frac{\epsilon_m \epsilon_d}{\epsilon_m + \epsilon_d} \right) \quad (1)$$

which describes the SP wavevector (k_{sp}) at such an interface for a given excitation frequency (ω_{sp}).

In order to couple light to a SP mode, momentum must be conserved. The in-plane component of the incident radiation's momentum (k_x , assuming incidence angle rotation around the y-axis only), must equal the momentum of the SP (k_{sp}). For smooth metal films, conservation of momentum prevents direct free-space coupling to such a mode for incident light at any angle (k_x always $< k_{sp}$). However, normal incidence coupling is possible for a periodically modulated, but otherwise flat, metal film. In this case, a reciprocal lattice vector associated with the periodicity of the modulated metal film results in a grating momentum of $\vec{G}_m = m(2\pi/a_o)$, where a_o is the period of the modulation. Here, SPs can be excited when both momentum and energy are conserved. Coupling of the incident EM wave to the surface plasmon mode is then allowed for certain resonant frequencies satisfying the equation:

$$\vec{k}_{sp} = \frac{\omega}{c} \left(\frac{\epsilon_m \epsilon_d}{\epsilon_m + \epsilon_d} \right)^{1/2} = \vec{k}_x \pm \vec{G}_n = \frac{\omega}{c} \sqrt{\epsilon_d} \sin \theta \pm m \frac{2\pi}{a_o} \hat{x} \quad (2)$$

where θ is the incidence angle of the radiation taken from the surface normal. The reverse of this process, SPs converting to free-space radiation at a given angle, is also possible and, in fact, vital to beam shaping and steering concepts.

In Fig. 1, a slot/grating structure is shown that exhibits prism like dispersive behavior. The structure consists of a 3 micron pitch grating etched into GaAs and then coated with gold. A focused ion beam was then used to mill out a slot in the grating structure to enable slot coupling to surface plasmons. In Fig. 1 (b), a tunable laser was focused onto the slot, and angular dependent measurements were performed on the transmitted beam (through the GaAs). As shown, the beam is reformed on the other side of the slot with an output angle that varied as a function of wavelength.

Fig. 1: Slot coupled grating structure. In (a) a grating device is shown where a focused ion beam was used to carve a slot in the structure to allow coupling to surface plasmons. (b) The transmission through the slot as measured with light focused on the slot on the air/metal side and collection on the GaAs/metal side.

2.2: Free-carrier Tuning

To move beyond the passive dispersion regime shown in Sec. 2.1, it is necessary to implement a tunable dielectric underneath the grating structure. The impact of free-carriers, introduced by doping, on the dielectric function of a semiconductor is shown in Fig. 2 for GaAs. As shown, the additional electrons in the material reduce the dielectric constant for a given wavelength. The basic concept here is to leverage electrical gating or some other mechanisms (such as pn junction depletion) in order to dynamically control the carrier density in the material.

Attempts were made to implement Schottky gates directly on doped GaAs epilayers. In this case, two-dimensional hole arrays were fabricated on top of the doped layers and contacts were annealed into the material in order to achieve a transistor style geometry. In Fig. 3, the grating geometry have a pitch of 3 microns is shown. The transmission through the device is shown in Fig. 3 (b). Here, slight tuning of the resonant transmission was observed. As carriers are depleted from the doped layer, the response is red-shifted, as it should. At a voltage bias beyond -8 V, there is enough leakage in the device to begin heating the underlying structure. It turns out that heating GaAs has the same general effect as depletion, a redshift of the

Fig. 2: Effect of free carriers on dielectric function. The case for GaAs with no damping is illustrated. Clearly, free-carriers have a greater impact at longer wavelengths.

response. One can tell the difference in the overall decrease in transmission amplitude. If the redshift were solely due to free-carrier depletion, we would expect the overall losses to improve. In the case of heating, the underlying substrate material is also heated which increases the bulk free-carrier density resulting in higher transmission losses. It is important to note such effects as it heating can easily be mistaken for modification of the free-carrier density with the electrical bias.

Fig. 3: Tunable transmission through metal hole arrays. In (a) an image of the hole array is shown. The device layers are shown inset to the transmission in (b).

To explore tunable concepts, it is not necessary to restrict experimental geometries to plasmonic concepts. Another class of structures, namely split-ring metamaterial resonators, can also exhibit unique functionality when fabricated on tunable substrates. For initial investigations, these structures exhibit more tightly confined electric fields and permit the use of thinner doped layers in order to achieve dielectric shifts that impact the optical response.

In Fig. 4, we show the transmission through split-ring structures fabricated on InSb doped epi-layers of varying doping density. As shown in Fig. 3 (b), the transmission is shifted dramatically as doping is varied from $2 \times 10^{17} \text{ cm}^{-3}$ to $2 \times 10^{18} \text{ cm}^{-3}$. The key feature to note is that even at the higher doping concentrations the overall quality factor of the resonance is not adversely impacted. A much harder task is to implement electrical control over similar levels of carriers.

Fig. 4: Split ring resonators on doped InSb. Arrays of total area 5 mm x 5 mm were fabricated on InSb having various dopings. The dimensions of the resonators are shown in (a). The transmission through the structures is shown in (b). The reference material is nominally undoped.

To alleviate the effect of leakage currents and parasitic heating effects on free-carrier tuning, we began working with the gate dielectric hafnia (HfO_2). The underlying concept here is that by using a thin gate dielectric material, we can achieve gating while reducing the overall leakage currents inherent to Schottky devices.

To move forward with this gating concept, two other GaAs samples were explored. A Schottky sample comprised of 10 nm of AlGaAs grown on 0.5 micron thick n-GaAs ($7 \times 10^{17} \text{ cm}^{-3}$). The hafnia sample is 10 nm of hafnia (annealed 400 C/60 seconds) on 0.5 micron thick n-GaAs ($7 \times 10^{17} \text{ cm}^{-3}$). Essentially, the Hafnia takes the place of the AlGaAs barrier. The basic geometry of the devices is shown in Fig. 5.

Fig. 5: Interconnected metamaterial resonators for gated devices. An individual resonator and dimensions is shown in (a). A larger portion of the 5 mm x 5 mm device is shown in (b).

The IV characteristics of the two devices is shown in Fig. 6 for many test sections of the devices on the same die. Clearly, the hafnia layer provided better leakage current characteristics compared to the AlGaAs insulator. As an aside, it should be noted that many variations of hafnia deposition were attempted included electron beam, atomic layer deposition, and sputtering. In all cases, as-grown hafnia exhibited unreliable characteristics including leakage and hysteretic capacitance-voltage characteristics. The annealing process on sputtered films using 400 C/60 seconds was critical to obtaining low leakage devices with reliable gating behavior.

Fig. 6: IV characteristics of doped GaAs epilayers with an AlGaAs (a) and hafnia (b) gate barriers.

While significant progress was made in understanding hafnia deposition and controlling gate leakage, it turns out that the device dimensions in the hafnia metamaterial structures did not turn out as designed. In future work, we simply need to spend some more time with dose testing prior to the electron beam lithography that is used for writing of these relatively difficult structures.

2.2: Electro-optic material

Another approach to obtaining a tunable dielectric response is to utilize electro-optic materials. Within this effort we explored a commercial material known as ‘optoceramic’ (available from Boston Applied Technologies). This material has relatively high transmission in the 2-5 micron wavelength regime. Beyond simply directly tuning the dielectric environment surrounding plasmonic or metamaterial structures, this material has other application in more basic interferometric arrangements that can provide unique functionality.

The basic properties of this material are highlighted in Fig. 7 where a 400 micron thick slab of the material is characterized. In Fig. 7 (a) the transmission through the material (uncoated) is displayed showing excellent transmission for wavelengths shorter than 5 microns. Devices were fabricated from this material consisting of 2.5 micron pitch metal

Fig. 7: Optoceramic properties. The transmission through an ‘as-purchased’ piece of material is shown in (a). The phase delay vs. applied voltage is shown in (b).

hole arrays on either side of the material. By applying a voltage bias across the top and bottom surfaces, the phase delay can be modified. By using a tandem interferometer setup, we measured the phase delay for various applied voltages. The results are shown in Fig. 7 (b) where it can be seen that roughly 180 degrees of phase delay can be obtained at 5 microns wavelength with 400 V applied between the top and bottom metallic structures. Transmission measurements through this dual metal hole array sample are shown in Fig. 8. In Fig. 8 (a), on the low energy side of the resonant transmission peak, one can see a ripple effect due to fabry-perot resonances in the relatively thick sample. In Fig. 8 (b), the main peak is highlighted to show the shift in the resonance as a function of applied voltage. The dielectric shift of the Optoceramic material is clear up to 400 V before it begins to decay at 450 V. When we attempted to drive the sample harder it cracked presumably due to strain in the material at high biases.

Fig. 8: Optoceramic performance. A piece of Optoceramic material was patterned on both sides with a 2.5 micron pitch metal hole array (Ti/Au). Voltage was applied between the front and back surfaces in order to tune the electro-optic material. The full fundamental bandpass of the structure is shown in (a) with a zoomed view in (b).

3. CONCLUSIONS

Under this project we had the opportunity to investigate dielectric tuning mechanisms in the 3-12 micron wavelength range and assess their compatibility with plasmonic and metamaterial concepts. We did demonstrate a small level of tuning which shows there may be some promise in free-carrier or electro-optic based approaches. Clearly, the material problems at hand in order to achieve significant tuning (1 percent or more) will require further investigation.

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