Terahertz Metamaterials for Modulation and Detection

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ABSTRACT

This paper reviews recent work in the area of active metamaterials where transistors and circuitry are embedded within metamaterial structures for novel functions. In one function, embedding of psuedomorphic high electron mobility transistor (pHEMT) within the metamaterial resonator allows realization of a terahertz modulator. A variation of this approach utilizes diodes to modulate the metamaterial response between a perfect absorber and a perfect detector. In another function, a transistor based power detector is embedded within each metamaterial resonator for room-temperature detection of gigahertz (GHz) radiation. The realized platform has the potential for high resolution imaging at the diffraction limit. These functions indicate range of novel devices enabled through heterogeneous integration of semiconductor devices with metamaterials.

Keywords: Metamaterial, Terahertz, Modulator, Millimeter Wave imaging, Terahertz Imaging

1. INTRODUCTION

Electromagnetic metamaterials are man-made constructs made conventionally from patterned sub-wavelength metal and dielectric geometric structures. Their electromagnetic properties are derived from the precise geometric shape and size of these constituent unit cells rather than the physical and chemical properties of the materials used to build them. Exotic functions such as negative index of refraction, cloaking, perfect lensing and perfect absorption among many others have been demonstrated using such artificial materials. Majority of metamaterial structures employed so far with few exceptions have been passive. While passive metamaterials are interesting in by itself, they are in itself not sufficient to make true impact. Many novel functions can be realized if metamaterials can be made to respond and react to physical stimuli (e.g. optical, electronic, mechanical).

Of particular interest are application of metamaterials for the terahertz spectrum, which has been devoid of a general lack of devices and components, and therefore presents a great opportunity for metamaterials to help realize practical devices such as source, modulators/demodulators and detectors. Research activities from our collaborations have focused on making hybrid metamaterials containing active circuit elements such as transistors and diodes to make active metamaterials for millimeter-wave and terahertz spectrum. In this manuscript, we showcase three specific examples from our group on integration of active semiconductor devices and circuits with metamaterials for modulation and detection. In one application, a terahertz modulator based on embedding of psuedo-morphic high electron mobility transistor (pHEMT) within a metamaterial implemented monolithically in a commercial gallium arsenide (GaAs) technology is presented(*1*). In another application, a diode-based active metamaterial is demonstrated as tunable absorber/reflector metasurface(*2*). Finally, a detector array based on metamaterial perfect absorber for pixel-level room-temperature detection of gigahertz (GHz) radiation is presented(*3*). The latter two examples utilize a hybridization of metamaterial on printed circuit board (PCB) with discrete microwave electronic components. These functions indicate range of novel devices enabled through heterogeneous integration of semiconductor devices with metamaterials.

2. HEMT/METAMATERIAL TERAHERTZ MODULATOR

Approach

The novelty of the approach relies on hybridization of metamaterials with pseudomorphic high electron mobility transistors (pHEMTs), fabricated in a commercial gallium arsenide (GaAs) process. The pHEMT is placed in the capacitive gap of the metamaterial (see figure 1). Modulating the carrier concentration in the pHEMT channel by the gate bias results modulation of THz wave transmission through the metamaterial. For gate bias -1.0 V, the HEMT channel is completely depleted and transmission shows resonance of metamaterial at 0.46 THz. When the gate bias is 0V, the conducting channel effectively shorts the metamaterial and diminishes metamaterial resonance.

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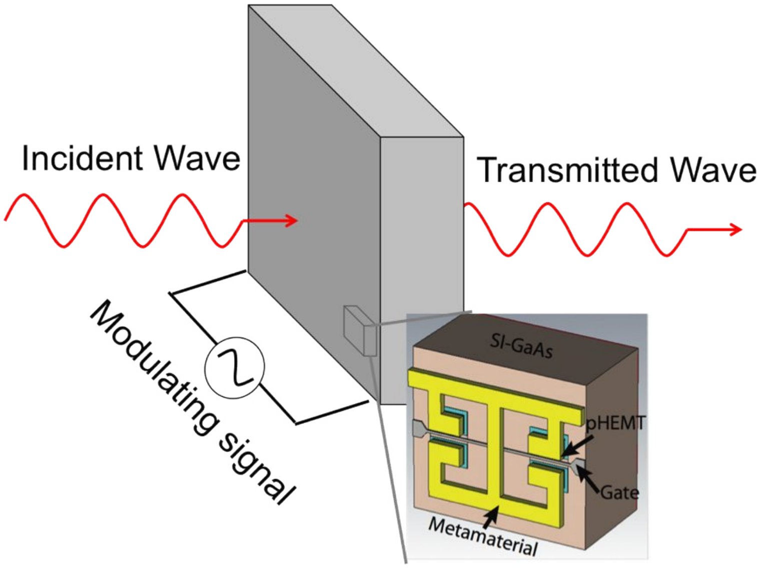

Figure 1. Configuration of terahertz metamaterial modulator(*1*). Inset shows each unit cell, consisting of electrical split ring resonator with embedded pHEMT transistor placed in the capacitive gap of the metamaterial. Turning on the transistor generates a two dimensional electron gas in the channel that shorts the capacitor (or alters the impedance in the gap), which kills (or alters) the resonance thereby enabling the terahertz radiation to transmit through.

Design

The hybrid metamaterial modulator was realized in 0.5 um GaAs HEMT technology with 3200 periodic unit cells on area of 2.7×2.6 mm^2 and metamaterial was realized with built-in metal layers in the process. The line width of the metamaterial is 4 um and the split gap is 3 um. Characterization of modulator is performed using a THz time-domain spectrometer (THz-TDS) in transmission mode. The switching of transmitted wave is achieved at resonance frequency of 0.46 THz for the gate bias between 0V to -1.1V.

Results

Applying modulating signal at gate terminal switching value over 30% and modulation frequency up to 10 MHz is demonstrated. See figure 2 which shows both the time domain of the interferogram and its FFT acquired using THz-TDS for three different modulation frequencies(*1*).

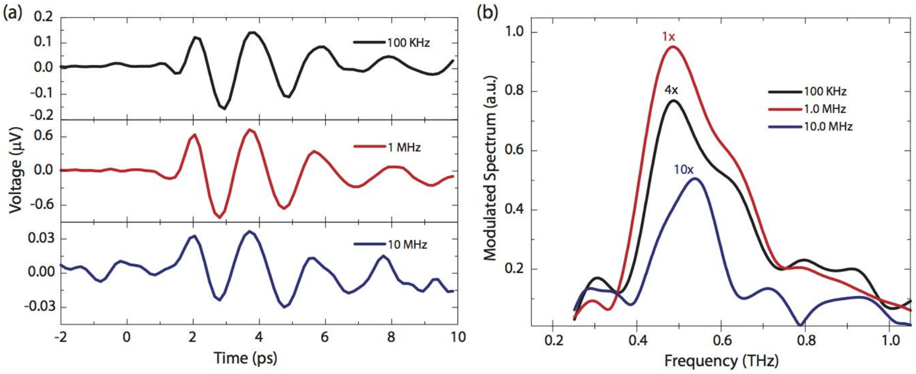

Figure 2. (a) Time domain data and (b) Spectra for modulation at frequencies of 100 Hz, 1 MHz and 10 MHz. Reprinted from [(*1*)].

3. DIODE METAMATERAIL BASED TUNABLE ABSORBER/REFLECTOR

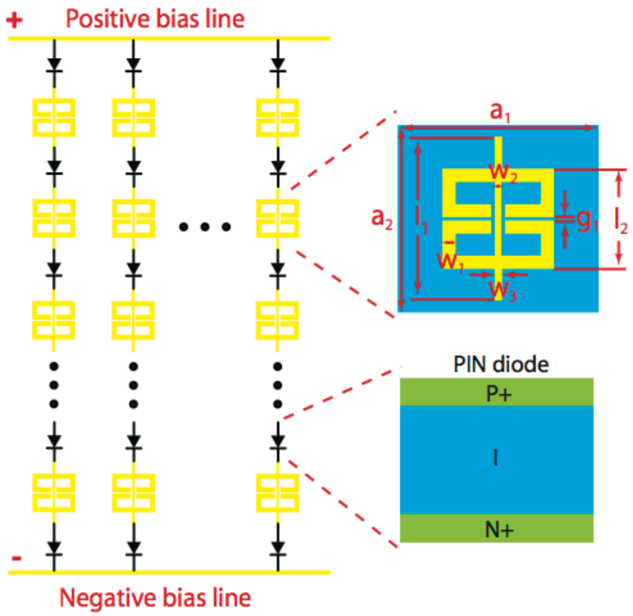

Figure 3. Schematic of diode switchable metamaterial absorber/ reflector and the dimension of one unit cell in millimeters. w1=0.6, w2=0.3, w3=0.35, l1=7.4 , l2=4.5, g1=0.13, a1=9, a2=8.4.Reprinted from [(*2*)].

Approach

Metamaterial allows realization of ultra-thin perfect absorbers over a wide range of frequencies by sizing the unit cell in the metamaterial appropriately. Switchable and tunable absorbers are quite useful in radars and antennas for beam steering and imaging applications. Our approach to tune the metamaterial performance is by embedding active semiconductor diodes in the realization of a thin switchable absorber/reflector(*2*). Diodes are placed in series between the neighboring unit cells within each column of an array(*2*). See figure 3 for conceptual realization. When the diodes are turned on, they electrically connect (short) all the unit cells in the column. This supports different electromagnetic modes in the metamaterial compared to the modes when the diodes are turned off. These modes exhibit resonances at different frequencies with two different perfect absorption profiles. Also series connection enables use of just two control lines instead of N^2 control lines for an N x N array of cells making this a highly practical solution.

Design

The proposed absorber is based on electrically coupled LC (ELC) resonators. See figure 3 for conceptual schematic. A 10x20 metamaterial array has been implemented on a 2-layer FR4 printed circuit board (PCB). The top layer is metamaterial array and the bottom layer is a conducting ground plane. The PIN diodes used in this design are Skyworks SMP1345-079LF (on resistance 1.5Ω, capacitance 0.15pF). The size of the diode is much smaller than that of the ELC resonator and is negligible compared to the wavelength of incident radiation. In order to turn on the diodes, a DC bias voltage is applied across the ”+” and ”-” lines that exceeds the sum of threshold voltage of diodes in one column. The metallic traces of the metamaterial serves function of microwave reflectors/absorbers but also to provide DC bias path for diodes.

Results

We sweep the bias voltage applied across the metamaterial array from 0V to 9V. The measurement results of voltage dependent $|S_{11}|$ is shown in figure 4. The resonant frequency for the case when diodes are biased with low voltages (diodes open) occurs at 3.5 GHz (off-resonance). The resonance shifts to higher frequency of 5.6 GHz (on-resonance) when diodes are biased with high voltages (diodes short)(*2*). There is also an unexpected resonance at 2.8 GHz in the case of low bias due to diode’s own parasitic capacitances and the trace wire inductance.

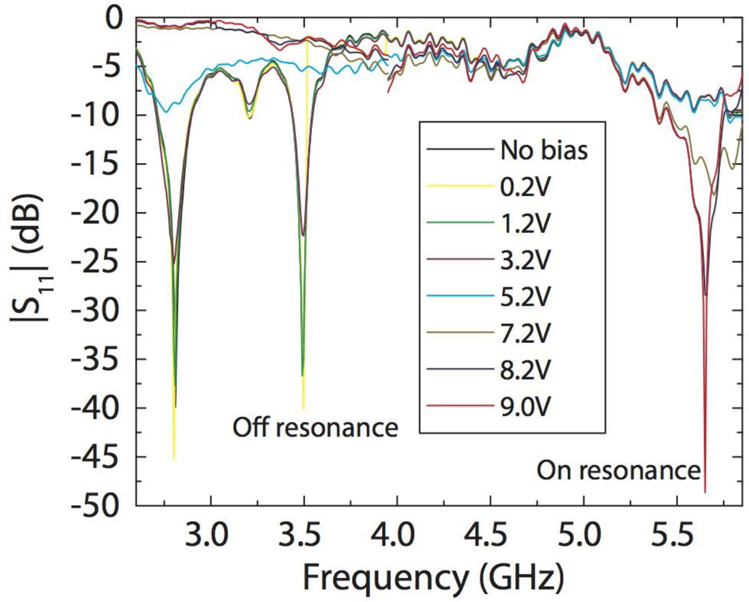

Figure 4. The measured $|S_{11}|$ of metamaterial reflector. The black curve shows the measured $|S_{11}|$ when there is no bias voltage applied across the metamaterial reflector array. The red curve shows the measured $|S_{11}|$ of metamaterial reflector when a 9.6 V DC voltage is applied across the positive and negative bias lines. Reprinted from [(*2*)].

4. METAMATERIAL BASED DETECTOR ARRAY

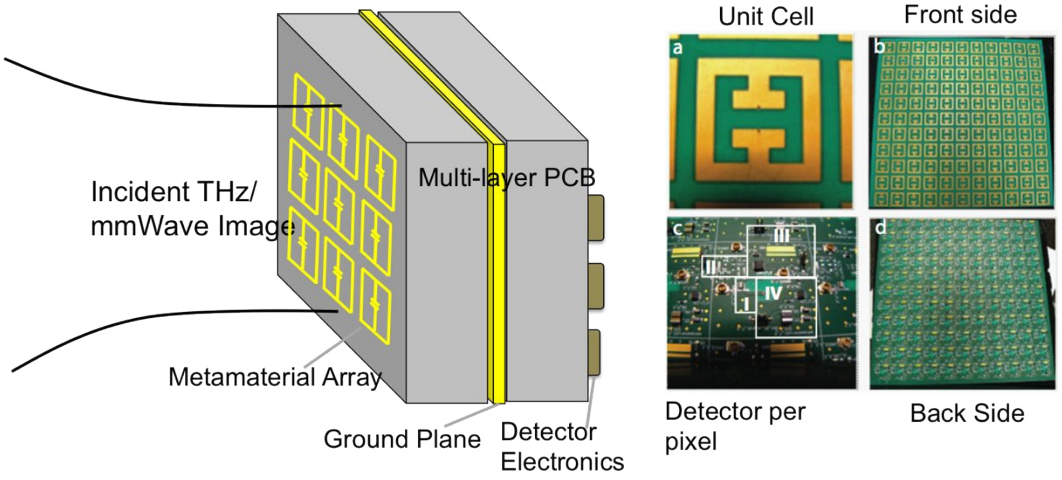

Figure 5. (left) Shows the conceptual diagram for metamaterial inspired detector array. (Right) Shows atual design. Each unit cell is an electrically split ring resonator (ESRR) connected to a impedance matched power detector on the other side of the ground plane using vias for connection. Detector electronics consist of (i) balun (ii)impedance matching circuitry (iii) low noise amplifier and (iv) power detector [(*3*)].

Approach

One key design feature afforded by metamaterials is the ability to engineer materials with a specified electric $\varepsilon(\omega)$ and magnetic $\mu(\omega)$ response such that its impedance, $Z(\omega) = \mu(\omega)/\varepsilon(\omega)$ is matched to free space. This “perfect match” condition has the potential to absorb all incident radiation at resonance. We utilize this perfect absorber condition of metamaterial to harvest the incident electromagnetic energy at resonance for detection and imaging(*3*).

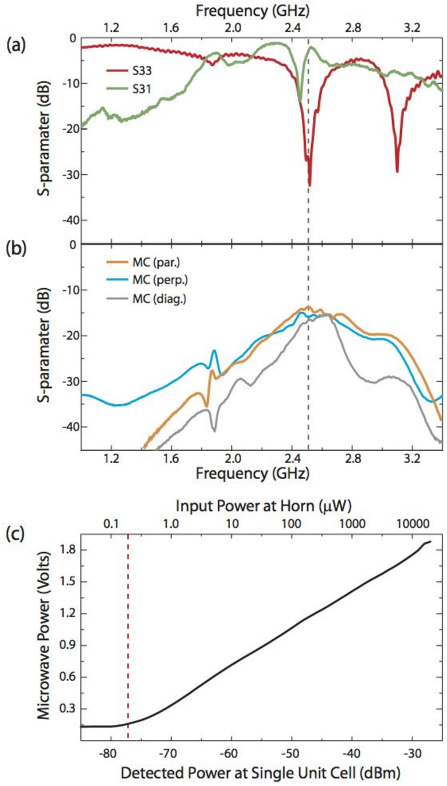

Figure 6. (left) Experimental measurements in anechoic chamber for the center pixel on the metamaterial array(*3*). (a) S-parameter data shows the reflection coefficient (S33 red curve) and the transmission (S31 green curve) with the dashed grey line at 2.5 GHz the frequency for sensitivity and off-angle measurements. (b) Mutual coupling (MC) between neighboring metamaterial pixels located parallel (gold curve), perpendicular (blue curve), and diagonal (grey curve) with respect to the electric field polarization. (c) Sensitivity characterization with the output of microwave power detector of single pixel as function of incident power, and is sensitive as indicated by dashed red line down to -77 dBm at 2.5 GHz.

Design

The design consists of an array of 11 x 11 electrical split ring resonator (ELC) metamaterial unit cells printed on the front side of a microwave circuit board, and the receiver system for each unit cell on the back side of four layer printed circuit board (PCB) as shown in figure 5. The readout circuitry for each ELC resonator consists of a balun, impedance matching circuit, Low Noise Amplifier (LNA) and a microwave power detector. The second layer is made of a ground plane and third layer is a power routing plane.

Results

Free space measurements of the center pixel were performed within an anechoic chamber with all neighboring unit cells having 50 Ω terminations. The metamaterial array was placed 1.75 m away from the horn antenna to be in the far field of the horn's radiating field. In figure 6(a), the green S_{31} curve shows a peak about 2.5 GHz overlapping with the minimum observed in S_{33} as expected. The gold curve in figure 6(b) displays the measured mutual coupling (MC) between neighboring unit cells parallel, perpendicular and diagonal to the electric field direction. Values of MC are significantly low, especially considering the proximity of nearest neighbors at lattice spacing of $\lambda/4.4$ (27.3 mm) and with edge separation of $\lambda/40$ (3.0 mm). This is a significant result since it indicates that one can pack metamaterial resonator antennas in close geometry without interference between them. Results also show excellent sensitivity of -77dBm(*3*).

5. CONCLUSION

This manuscript reviewed the research activities that demonstrated the viability of incorporating metamaterials into mature semiconductor technologies and established a new path toward achieving electrically tunable THz devices. Functions ranging from terahertz modulation, to tunable absorbers and imaging platforms were discussed. We believe the future research activities in the metamaterials area will focus on hybridization of metamaterials with mainstream semiconductor technology such as CMOS or GaAs.

REFERENCES

[1] D. Shrekenhamer *et al.*, High speed terahertz modulation from metamaterials with embedded high electron mobility transistors. *Opt Express* **19**, 9968 (2011).

[2] W. Xu, S. Sonkusale, Microwave diode switchable metamaterial reflector/absorber. *Appl Phys Lett* **103**, 031902 (2013).

[3] D. Shrekenhamer *et al.*, Experimental Realization of a Metamaterial Detector Focal Plane Array. *Physical Review Letters* **109**, 177401 (2012).