Embedded HEMT/Metamaterial Composite Devices for Active Terahertz Modulation

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Most modern optical / electronic devices operate in two distinct regimes of the electromagnetic spectrum. Electronic devices operate at frequencies of a few hundred gigahertz and lower where electrons are medium for EM propagation. Optical devices operate from infrared through optical/UV frequencies where photons are the medium. In-between these two fundamental response regimes there exists a region comparatively devoid of material response, commonly referred to as the "terahertz gap" (0.1 - 10THz, l = 3mm - 30mm).
The development of artificially structured electromagnetic materials, termed metamaterials, has led to realization of electromagnetic properties in materials that cannot be obtained with natural materials. Metamaterials (MMs) are promising candidates to fill the "terahertz gap". Metamaterials typically consist of structured composites with patterned metallic subwavelength inclusions. These mesoscopic systems are built from the bottom up, at the unit cell level, to yield specific electromagnetic properties. Individual components respond resonantly to the electric, magnetic or both components of the electromagnetic field. In this way electromagnetic MMs can be designed to yield a desired response at frequencies from the microwave through to the near visible.
Although the application of metamaterial in the terahertz domain has been largely successful, the use of active devices such as MOSFETs, FETs, HEMTs, etc to tune the properties of metamaterials actively is an area of research which is still in it's infancy. Some recent breakthroughs in development of a high-speed transistor with f_T (unity current gain bandwidth) and f_{max} (maximum oscillation frequency) approaching terahertz have made this a reality. Also, in spite of the limited f_T of the commercially available short channel HEMT transistors (around 100 GHz), it is well known that such transistors can operate in **plasma wave** regimes at much higher speeds (in terahertz range for deep sub micron devices)

We demonstrate the first Galium Arsenide (GaAs) High Electron Mobility Transistor (HEMT) based metamaterial, used to modulate an electromagnetic signal of 0.55 THz at speeds up to 10MHz. The devices are constructed using a commercial GaAs technology primarily used for mobile phone technology. The metamaterial was constructed using a classical Double Electric Split Ring Resonator (DESRR) using a gold metal layer available in the technology. The Scanning Electron Microscope (SEM) photograph in Figure 1(a) shows one element of the array. The DESRR is ideal for simple polarization sensitive modulator as a result of the strong resonant response at the lowest order mode as well as providing access to gate layers which are critical to the HEMT construction. The HEMT was placed underneath the split gap with the drain and source connected to the split gap of the resonator. This allowed us to change the property of the metamaterial by applying gate bias voltage to the HEMT switch.

The sample was characterized using a THz Time-Domain Spectroscopy (TDS) system. The experimental system consists of a femtosecond pulsed laser which has pulse frequency measured of 92MHz. We use a Photoconductive Antenna (PCA) emitter and detector to transmit and receive the THz waveform and we place the MM sample at the focus between two off-axis paraboloids. For absolute transmission data referenced to open channel we placed an optical chopper right after the emitter and chopped at 377 Hz. The detecting PCA is a dipole antenna and is connected to a current Pre-Amplifier and then connected to a Lock-

In Amplifier.

The DC/static differential test is done by doing a transmitivity test with gate bias to the HEMT at 0V and then at -2V with respect to drain/source and then taking the difference between them. With 0V bias applied to the gate, the HEMT forms a high mobility 2DEG channel between the drain and source and thus disabling the metamaterial and when a -2V gate bias is applied, there is no channel formed and the metamaterial is active resulting in a difference in the narrowband region of the metamaterial resonance of 0.55 THz. This is verified experimentally as shown in Figure 1(b), a 10% relative change in the intensity is observed making it a relatively efficient narrowband THz modulator.

For dynamic measurement, the modulating signal was applied to the gate bias of the HEMT in the MM sample and the same signal served as the reference for the Lock-In Amplifier. Essentially, the MM/HEMT sample served as a chopper in the THz TDS setup. Therefore, as long as the modulator is working, the result would be interferogram of the THz picosecond pulse. As seen from Figure **2**, the interferogram from the TDS setup demonstrates modulating speed up to 10 MHz, a limitation primarily related to the board implementation and not a fundamental one. It is expected that in future realizations one could achieve switching of terahertz radiation using modulating signal closer to the f_T of technology, which is of the order of GHz.

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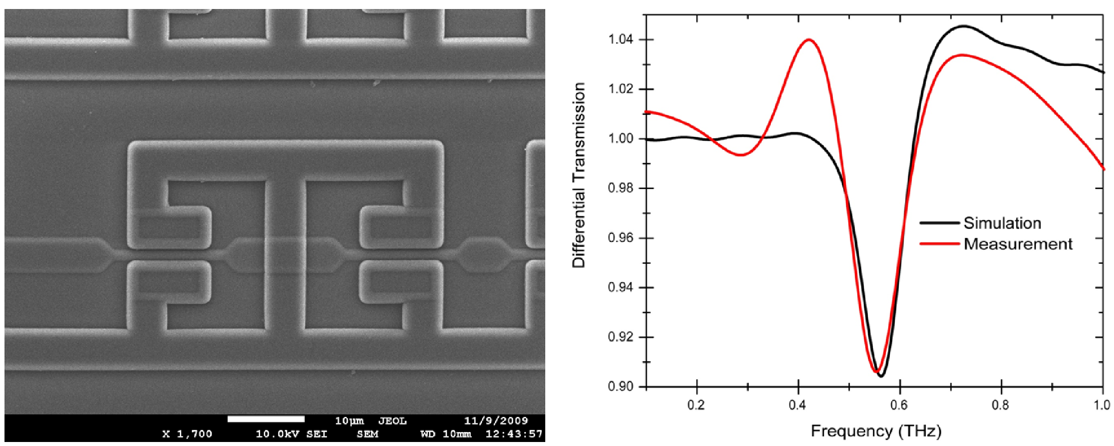

(a) (b)

Figure 1: (a) SEM picture of a single element of the HEMT/MM sample (b) Measurement vs Simulation result of static differential transmission test of the sample. The differential measurement done with gate bias of -2V and 0V with respect to drain.source.

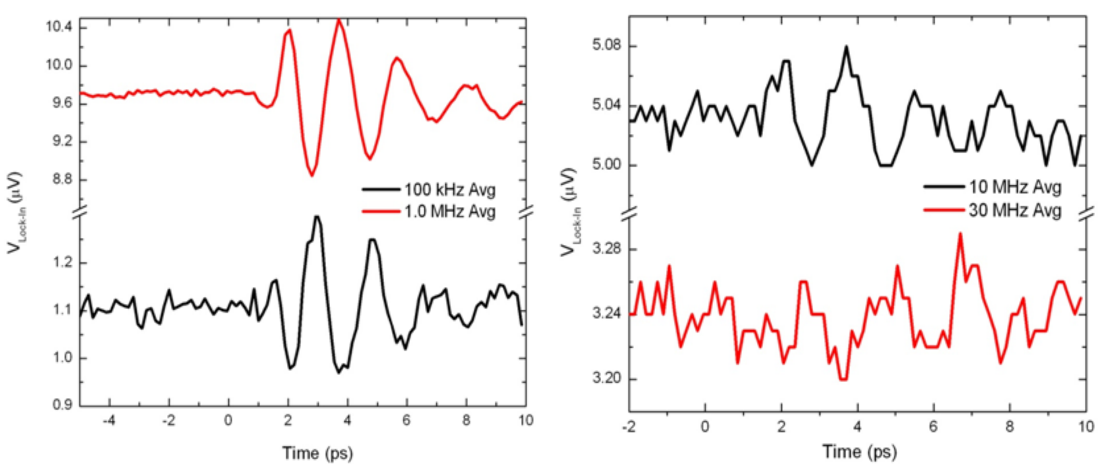

Figure 2 : : Interferogram result from the TDS setup demonstrating modulation at 100 KHz, 1 MHz , 10 MHz and 30 MHz.