Real-time continuous-wave amplitude terahertz modulation system based on active metamaterials

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Abstract— A real-time terahertz modulation system is demonstrated using a metamaterial terahertz modulator and a continuous-wave (CW) terahertz source based on photo-mixing of two tunable distributed feedback lasers. Another photo-mixer followed by a lock-in I/Q detection of the CW spectrometer serves as a complex receiver of amplitude modulation used to determine the spectral transmitivity of the modulator. A real-time modulation dynamic range of $\sim 37dB$ was measured at 448 GHz, making it suitable for real-time imaging and communication application.

Metamaterials have been proved to be very suitable for applications in the terahertz (THz) frequency regime known as the *'THz Gap'* (0.1-10 THz) [1]. A metamaterial based active modulator at 448 GHz is implemented using a commercial GaAs process. The metamaterial is designed using the top metal layer with the geometry based on the electric split-ring resonator (ESRR) and a pHEMT device is embedded in the split gap every unit cell of the metamaterial (Fig. 1(a)) to control the resonant frequency by applying a certain gate-to-source voltage (V_{GS}), thus allowing electronic transmitivity control of THz wave [1]. The metamaterial responds to an incident THz wave with the electric field (E-field) polarized perpendicular to the split gap. The use of coherent broadband continuous-wave spectroscopy to measure real-time modulation is demonstrated, which cannot be measured using frequency-domain systems such as THz-TDS or FTIR.

The CW terahertz spectrometer generates THz frequency from 60 GHz to 1.2 THz using a pair of tuned lasers (1546 and 1550nm). The temperature controlled beat frequency is fiber-coupled to a InGaAs photo-diode with a bow-tie antenna (Fig. 1(b)). The emitted wave is collimated and then focused onto the metamaterial modulator and the detector (InGaAs photo-mixer), using a pair of off-axis parabolic mirrors. The source bias is modulated ($\pm 1.2V$ at 7.629 kHz) and the pre-amplified signal is lock-in(600 ms time-constant) detected using a proprietary FPGA module. The detected photocurrent I_{ph} depends on the amplitude of the terahertz electric field, E_{THz}, and on the phase difference $\Delta\phi$ between the terahertz wave and the laser beat signal at the detector:

$$I_{ph} \propto E_{THz} cos(\Delta\phi) = E_{THz} cos(2\pi \Delta L \nu / c) \tag{1}$$

where ν denotes the terahertz frequency, c is the speed of light and ΔL is the optical path difference at the detector. Therefore, the detected photocurrent I_{ph} oscillates with the THz frequency, and the oscillation period is set by the choice of ΔL. The frequency response of a sample is calculated by measuring the envelope of the oscillating I_{ph}. The oscillating period limits the frequency resolution, which was ≈ 0.35 GHz for our setup.

In order to demonstrate the tunability of the metamaterial, the frequency response for the range 445-460 GHz is plotted (Fig.1(c)) for the two extreme V_{GS} $(0V, \ -1.8V)$. When V_{GS} = -1.8V, the channel in the pHEMT is completely depleted, resulting in the metamaterial response with the main resonance at 448 GHz and some parasitic or coupled resonances (452, 454 GHz). When the channel is formed, $V_{GS} = 0V$, the resonances shift resulting in amplitude modulation at the resonance frequency. The difference of the envelope current ($\Delta I_{ph} = I_{ph}(0V) - I_{ph}(-1.8V)$) is plotted for the THz E-field 90-deg polarized validating the metamaterial response. Fig. 1(d) shows the real-time modulation of the THz wave (448 GHz) at a 10s period which is limited by the 600 ms integration time of the lock-in amplifier. We measured $\Delta I_{ph} \approx 7nA$ with a dynamic range of $\sim 37dB$. The metamaterial response is demonstrated my changing the polarization of the E-field by 90-deg and the response again is flat.

In conclusion, a real-time terahertz modulation system at 448 GHz is demonstrated using a metamaterial terahertz modulator and a continuous-wave terahertz source. A real-time modulation dynamic range of $\sim 37dB$ was measured at room temperature. The results demonstrate a low-cost and compact THz modulation system, very advantageous to commercialize THz applications, such as high-speed THz communication and single-pixel THz imaging systems. In recent years, similar THz modulation systems have been based on optically controlled silicon [2], electrically controlled graphene [3] and thermally controlled MEMS [4]. Their high cost, large size and use of esoteric devices makes them unsuitable for volume production.

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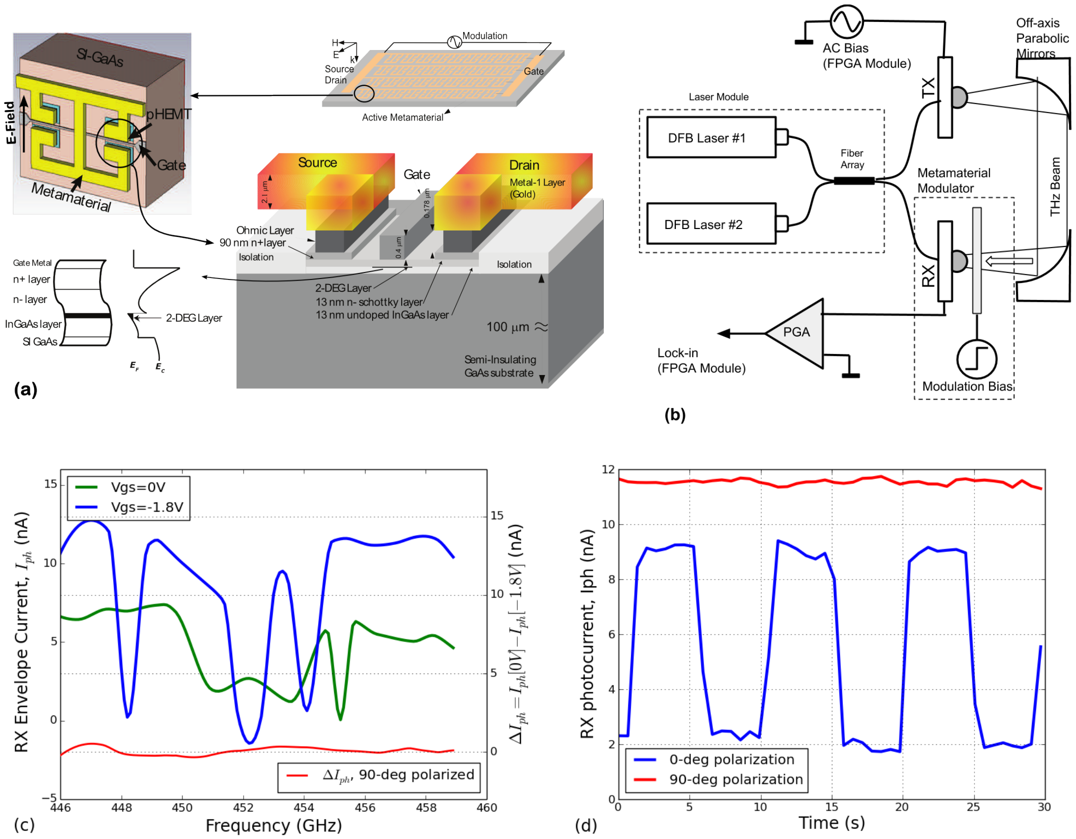

Figure 1: (a)Design and structure detail of the HEMT based metamaterial modulator. (b) CW THz modulation system setup. (c) Frequency response of the modulator for $V_{GS} = 0V$(green) and $V_{GS} = -1.8V$(blue). Differential photocurrent ΔI_{ph} response (red) for 90-deg polarized E-field (d) Real-time modulation response with orthogonal polarizations.