Gbps THz External Modulator based on High Electron Mobility Transistors-metamaterials

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***Abstract*—Utilizing THz wave to transmit data for communication and imaging places high demands in phase and amplitude modulation. In this paper we combined a metamaterial array with HEMT structure to form an ultrafast electronic grid-controlled THz modulator. By controlling the carrier concentration of 2DEG, a resonant mode conversion between two different dipolar resonances has been realized. In the real-time dynamic test, this THz modulator achieved 1 GHz modulation speed with 85% modulation depth and 1.26 rad phase shift. It could provide an alternate way to achieve effective and ultra-fast active devices in THz wireless communication system.**

I. Introduction

THE field of Terahertz (THz) science and technology is rapidly becoming a very noticeable area of scientific research in security checking, wireless communication, imaging and so on [1]. Recently, one of the most popular THz active device is the composite structure of metamaterials and semiconductors [2]-[4]. Different structured metamaterials play a key role in the manipulation of THz wave, and different semiconductors act as the active component in the conversion of metamaterials [5]. The high electron mobility transistors (HEMT) based on AlGaN/GaN heterostructure is one of the highest performance active materials which have high carrier concentration and mobility. With the combination of metamaterials and HEMT, an efficient and ultrafast Gbps THz external modulator (GTEM) could be realized.

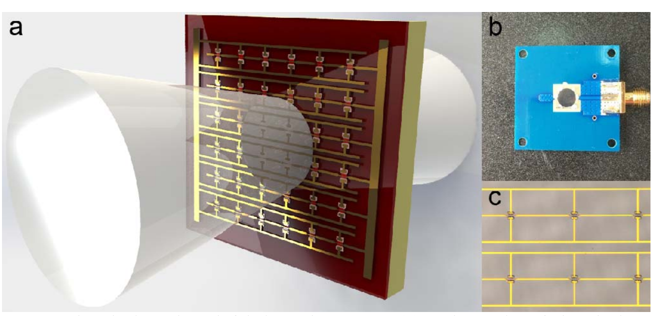

Fig. 1. The designed and fabricated GTEM. (a) Schematic of the designed GTEM; (b) Image of packaged GTEM; (c) Photomicrograph of a portion of the fabricated GTEM.

In order to overcome the obstacle of modulation speed, a collective dipolar array is carried out to reduce the parasitic parameters and simplify the fabrication process (Fig. 1). In this structure, when the source and drain are connected by 2DEG, induced THz wave will excite a dipolar resonance on the center long wire. With the 2DEG depleting, the source disconnect with drain so that there would be another dipolar resonance on the short cut wires. Based on this consideration, there will be a frequency shift which could lead to an amplitude and phase modulation at a certain frequency point.

II. Simulation

To illustrate the dynamic electrical-modulation mechanism, a finite difference time domain (FDTD) code and dispersive Drude model were used to analyze the GTEM electromagnetic properties at different carrier concentrations (equivalent to the applied gate-voltage variations in the experiments). Without an applied voltage, the source and drain were connected by the high 2DEG layer concentration in the heterostructure via the ohmic contacts. The resonance induced by the incident THz waves arose from the equivalent collective dipolar resonance in the long, central wire with fields focused at the edge of each unit cell, and the surface current on the central wire was uniform (ideal off-mode in Fig. 2). The resonant frequency for this off mode mainly depended on the distance between the up and down long wires. Applying a reverse gate-voltage increased the depletion. The 2DEG depletion in the split gap separated the source and drain, which suppressed the equivalent collective dipolar resonance on the central long wire. Instead, a new dipolar resonance was induced on the short cut wires. The surface current distribution indicates that the current oscillated on the short cut wires with the field focused on the central split gap plates (on-mode in Fig. 2).

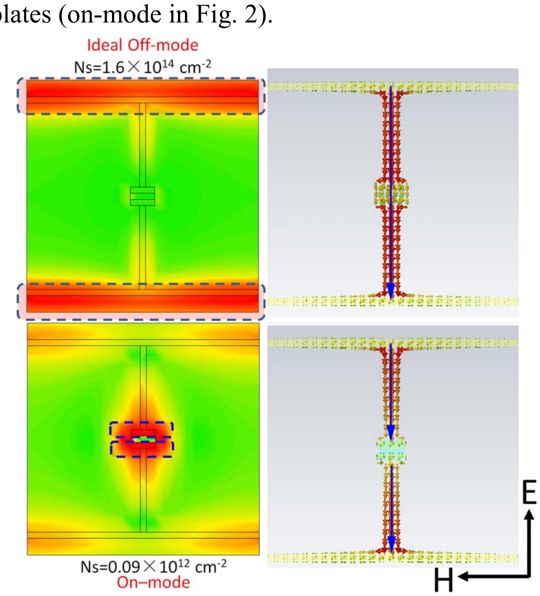

Fig. 2. The electric field and surface current distributions for the on and off modes.

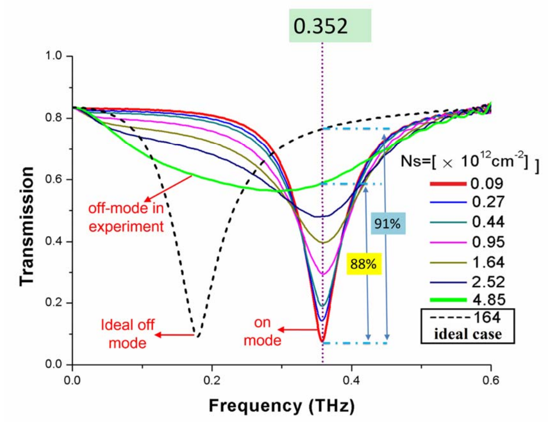

Fig. 3. Transmission spectra for different carrier concentrations.

The simulated THz wave transmission spectra (Fig. 3) indicate such dipolar resonance mode conversions caused a large resonant frequency blueshift. A blueshift from 0.18 THz (ideal off-mode) to 0.352 THz (on-mode) with a 91% modulation depth was obtained, as shown by the black dashed and red solid lines in Figure 3b. A carrier concentration of 4.85×10^{12} cm^{-2} with a mode conversion between off- and on-modes could yield an 88% simulated modulation depth at 0.352 THz (corresponding to the green and red solid lines in Fig. 3). Most importantly, the GTEM resonant mode conversion exhibited a reduced parasitic capacitance and inductance relative to the equivalent LC-circuit resonance for conventional SRR structures, which ensures a high modulation speed.

III. Results

THz static and dynamic test are carried out to characterize the performance of GTEM. From the THz-TDS experimental results, 85% amplitude modulation and 68 degree phase modulation are shown in Fig. 4(a) and (b) with the voltages varying from 0 V to 7 V.

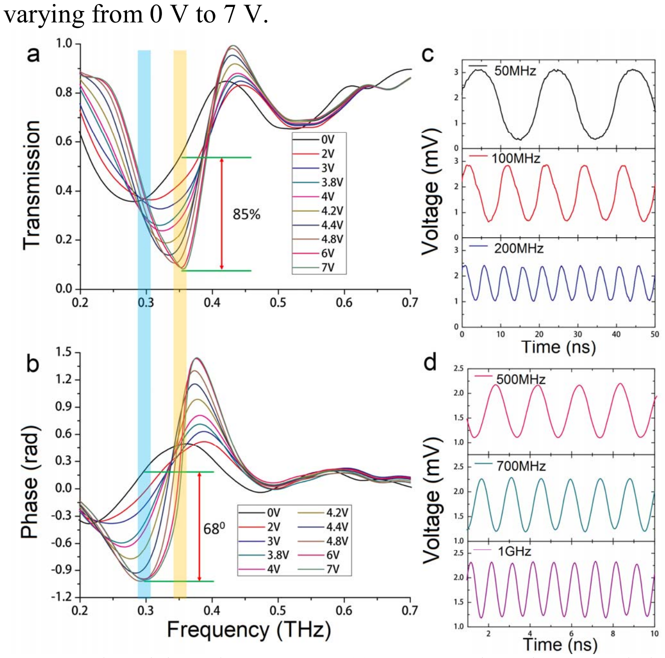

Fig. 4. Static and dynamic test GTEM. (a) Frequency-dependent transmission tested by THz-TDS at different voltages; (b) Frequency-dependent phase shift characterized by THz-TDS at different voltages; (c) and (d) Different modulation speeds detected by receiver in dynamic THz experiment.

To further test the real-time modulation speed of our device, we set up a 340 GHz continuous wave (CW) test system. Different frequency sinusoidal signals are loaded on the GTEM. A THz receiver records the modulated waveforms at some typical frequency as is shown in Fig. 4(c) and (d). It can be found that up to 1 GHz all the detected signals remain as standard sinusoidal waveforms rather than triangular waveforms that are caused by response time. Therefore, this modulator may be capable of loading up to 1 Gbps data on the carrier wave.

IV. Conclusion

In conclusion, combining an equivalent collective dipolar array with an AlGaN/GaN heterostructure yielded a Gbps THz modulator based on dipolar resonance conversion. The superior 2DEG performance in the heterostructure and high dipolar resonant intensity allowed this modulator to achieve a 1-GHz modulation speed and 85% modulation depth. More importantly, this device could be adapted to various THz sources, including Watt-level CW sources, which demonstrates the enormous potential for long-distance, high-speed wireless free-space-modulation THz communication systems.

References

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