# Graphene-based External Optoelectronic Terahertz Modulators for High Speed Wireless Communications

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***Abstract*—the realization of terahertz external amplitude modulators with a carrier frequency of 0.8 THz is presented for application in the next generation near-field wireless communications.**

**Keywords—Terahertz, metamaterials, graphene, wireless communications.**

## I. Introduction

Development in the field of terahertz (THz) science and technology is becoming rapidly increasing to fullfil the needs for high data rates transmissions in wireless communication systems beyond 5G. The terahertz (0.1 – 10 THz) frequency band lays between the convention electronics and photonics range. From photonics point of view, external manipulation and modulation of a CW or pulsed THz laser source have a great potential for achieving robust, fast speed, small footprint, low power consumption, ease for chip-scale integration external THz modulators [1-3]. Graphene/metamaterial hybrid optoelectronic devices have demonstrated to be a viable solution for the modulation of THz radiation [4-7] thanks to its efficiency, versatility and integration with well-established fabrication technology. Here we report on a double gate graphene metamaterial array capable to provide > 20% in transmission at 0.8 THz, with a modulation speed exceeding 1GHz.

## II. Design and Fabrication

The device comprises an approximately 1.3x1.2 $mm^2$ array of metallic split ring resonators (SRRs) shunted by graphene

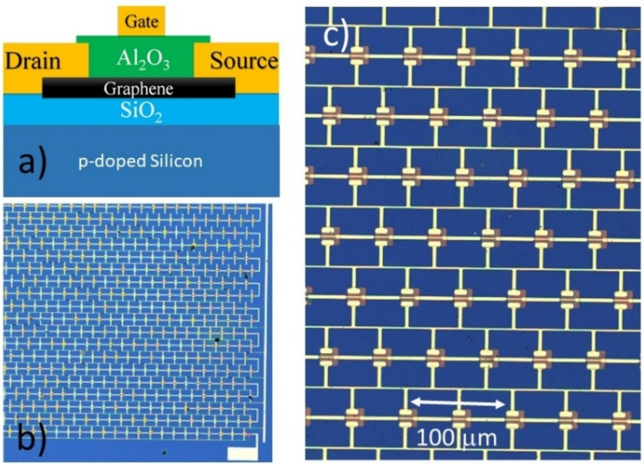


Fig. 1 Schematic of the device a) and optical microscope pictures of the metamaterial array loaded with graphene b) and c).

patches fabricated on top of a $SiO_2$/Si (300 nm/500 µm) chip. The Silicon substrate was p-doped to allow electrostatic gating via back gate. A schematic of the final device is shown in Fig 1, together with optical microscope pictures of the final device. The graphene was grown with chemical vapour deposition and then transferred over the substrate. Graphene patches were defined by using lithographic masking followed by Oxygen plasma etching. The SRRs were fabricated via optical lithography, metallic thermal evaporation (Ti/Au, 10/150 nm) and lift off. The graphene areas where encapsulated with a protective $Al_2O_3$ layer of 150 nm via atomic layer deposition, in order to reduce hysteresis, prevent

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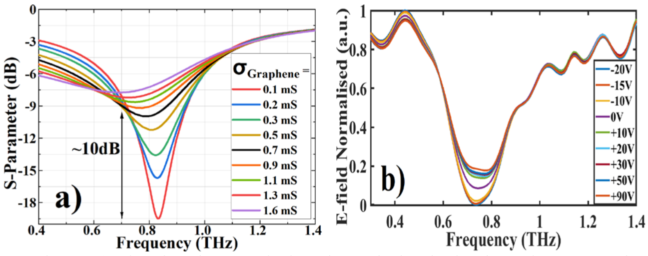

Fig. 2: a) Simulated transmission through the device by using Comsol Multiphysics commercial software modeling at different graphene conductivity values σ. b) Measured normalized transmitted amplitude at different top-gate voltages acquired by using the THz spectrometer from Menlo Systems.

graphene damage and reduce the Dirac point voltage compared to exposed graphene areas. The top dielectric layer was then selectively chemically etched to rectangular patches to isolate the resonators from the top gate metal features. These latter ones were defined by using electron beam lithography, metallic thermal evaporation (Ti/Au, 10/120 nm) and lift off and are better visible in Fig. 1 c).

## III. Amplitude Modulation: Simulations and Experimental Measurements

The metamaterial active device has been modeled by the RF module of COMSOL Multiphysics software to simulate the electromagnetic response of a single metamaterial unit-cell, which under appropriate Floquet periodic lateral boundary conditions is representative of the real array composed of hundreds of resonators. The optical conductivity of the graphene layer is varied in this simulation over a range of conductivity consistent with previous experiments, by using a Drude model as described in [4-7]. The transmitted electric field has been measured by plotting the $S_{21}$ parameter which shows a 10 dB difference in the transmitted E-field amplitude between graphene conductivities of 0.1 to 0.7 mS as shown in Fig 2 a). Simulations show a larger modulation depth as we plot the transmission curves over a broader graphene conductivity range than the one that can be accessible experimentally. While we are confident that the conductivity range for our devices lies in this interval, we cannot precisely determine it in advance as graphene is very sensitive to many fabrication steps. In the simulations, we model graphene conductivity directly by using a Drude model. Experimentally, we modulate in reality the graphene conductivity via electrostatic gating, hence the measured values are expressed as a function of different gate voltages. A terahertz time-domain spectroscopic system from Menlosystems, model TeraK15 was used for the characterization of the device at different values of the graphene conductivity. The graphene conductivity, and hence the optical response of the device, was modulated via electrostatic gating by using top and back gates, showing consistent results. Figure 2 b) shows the modulation recorded

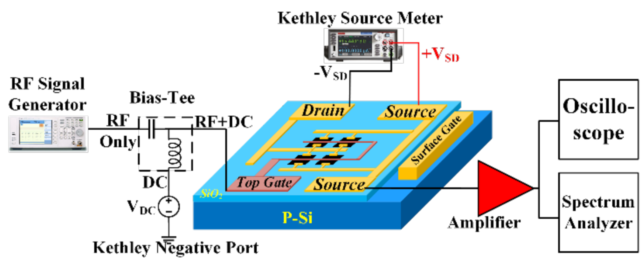

Fig 3. Setup used for the electrical characterization of the reconfiguration speed of the device

for top gate voltages applied through the Silicon substrate whilst grounding graphene via the drain and source pads, with voltages ranging between -20 V (Dirac point) and +90 V. The position of the resonant feature is around 0.75 THz, in a very good agreement with the simulated one. The modulation depth achievable is larger than 20% in good agreement with previous results achieved for electrostatic gating. Lower frequency components < 1 THz might have an optical spot size larger than the array area. This factor, together with an imperfect alignment might contribute to reduce the measured modulation depth. A leakage towards gate of a few μA might limit as well the achievable modulation depth.

## IV. Reconfiguration Speed Measurements

The device was then mounted on a high speed board for electrical characterization in a configuration shown in Fig 3. A RF signal from an Agilent RF generator model N9310A, which varied between 100's MHz to a few GHz was added to

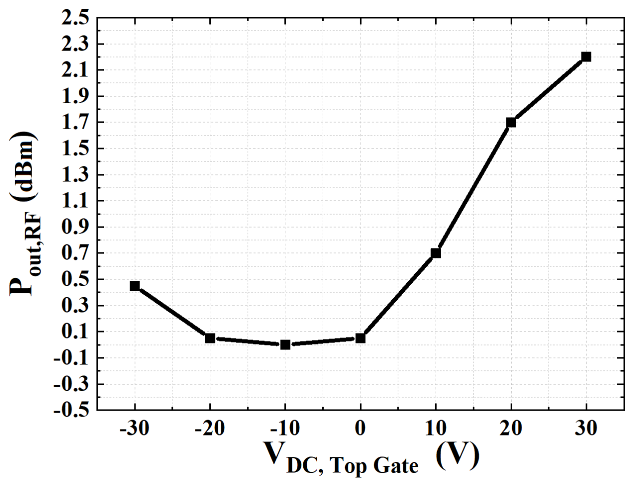

Fig. 4. AC output voltage measured for a top gate input of 20dBm and different $V_{DC}$ voltages applied. The AC frequency was 750 MHz.

a DC voltage by using a bias tee and fed to the top gate. The DC voltage is needed in order to set the working point along the Dirac curve. A constant current < 1 μA was applied between source and drain with a Keithley source-measure unit model 2450, and the voltage across the terminal was amplified and sent to a scope and to a spectrum analyser from Rohde& Schwarz (model FS300). Leakage current between top-gate and drain was in the order of 1-10 nA following no trend with the $V_{gate}$. Figure 4 shows a typical measurement acquired for the AC output $P_{out,\ RF}$ (scaled to the lowest output level) achieved at 750 MHz and with a $P_{in,\ RF}$ of 20dBm, for different $V_{DC}$ applied to the bias tee. As expected, the minimum AC signal takes place around Dirac point around 10-15 V where the top gate modulation is less effective, in good agreement with Fig. 2 b). Similar measurements were recorded up to a few GHz also in different arrays yielding a good reproducibility.

## V. Conclusion

In conclusion, we reported on a graphene/metamaterial array based on a double gate architecture operating around 0.8 THz with a modulation depth > 20% and reconfiguration speed of a few GHz. The device was modelled with finite element method software and characterized optically with a fs pulse THz spectrometer yielding a very good agreement with the simulation. This represents an important progress towards high speed next generation of THz wireless communication.

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