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Graphene based plasmonic terahertz amplitude modulator operating above 100 MHz

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The terahertz (THz) region of the electromagnetic spectrum holds great potential in many fields of study, from spectroscopy to biomedical imaging, remote gas sensing, and high speed communication. To fully exploit this potential, fast optoelectronic devices such as amplitude and phase modulators must be developed. In this work, we present a room temperature external THz amplitude modulator based on plasmonic bow-tie antenna arrays with graphene. By applying a modulating bias to a back gate electrode, the conductivity of graphene is changed, which modifies the reflection characteristics of the incoming THz radiation. The broadband response of the device was characterized by using THz time-domain spectroscopy, and the modulation characteristics such as the modulation depth and cut-off frequency were investigated with a 2.0 THz single frequency emission quantum cascade laser. An optical modulation cut-off frequency of 105 ± 15 MHz is reported. The results agree well with a lumped element circuit model developed to describe the device. © 2016 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).

The terahertz (THz) or sub-millimeter region of the electromagnetic spectrum (0.3–10 THz) has attracted great interest in recent years in many different physical fields such as spectroscopy,1 imaging,2,3 security,4 medical diagnosis,5 and wireless communication.6 In the field of spectroscopy, external THz amplitude, phase and frequency modulators would further justify the use of THz quantum cascade lasers (QCLs). For communication, the THz region offers a broad, unutilized spectrum, with many demonstrations of high-speed communication at sub-THz and low-THz frequencies.7,8 To be a commercially viable next generation technology, efficient, high-speed, external amplitude, frequency and phase modulation of THz radiation using optoelectronic devices must be developed.

Graphene offers a superior solution to the field of THz modulation, due to its remarkable properties such as high carrier mobility9 and large achievable charge carrier densities.10 Graphene is also attractive from a processing perspective, as it is compatible with many existing semiconductor processes. Several authors have already incorporated graphene into external THz modulators11–13 but have been limited in cut-off frequency by the large areas of graphene and the architectures used. Recently, graphene was directly integrated onto a THz QCL and achieved 100% modulation depth with a modulation speed over 100 MHz.14 For use in communications, detaching the modulator and source and utilizing external modulation allow single QCL sources to be used, with the advantage that a single source is able to generate a frequency and phase stable set of independent quadrature signals for modulation.

To enhance graphene based modulators, plasmonic/metamaterial based devices are attracting a large amount of attention. These materials provide strong confinement of electromagnetic radiation at a designed frequency, which can span many orders of magnitude.15,16 Recent work in the mid-infrared using metamaterials/plasmonics with graphene has demonstrated up to 20% frequency modulation at speeds greater than 30 MHz (Ref. 17) and 30% amplitude modulation at 40 MHz.18 Further, the same group demonstrated 100% modulation depth with a theoretical modulation speed of 20GHz, using a Fabry–Pérot enhanced absorber with a graphene/metasurface tunable mirror.19

In this paper, we present a room temperature, external optoelectronic amplitude modulator, centered around 2.0 THz. The device uses graphene to actively shunt an array of bow-tie antennas, enabling modulation of incoming THz radiation generated by a 2.0 THz single frequency emission QCL. The device consists of four arrays of bow-tie antennas, with each array characterized by the length of the antenna (L), which determines the resonant frequency of the antenna array. Between the gap of each antenna is a small graphene rectangle that provides a variable shunt resistance between

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the arms. Electrically connecting the antennas to source/drain electrodes by perpendicular metallic strips results in a conductive path for the graphene to charge/discharge. By electrostatically doping the graphene, the shunt resistance is changed, and hence, the electromagnetic response of the array changes, leading to optoelectronic modulation. Optical measurements show a cut-off frequency above 100 MHz, in good agreement with a lumped circuit model developed to describe the device.

The substrate used for the device was a 525 ± 25 μm thick p-Si (Boron doped) with a resistivity of 20 ± 5 Ω·cm and 300 ± 25 nm thick thermal oxide. The large area graphene was fabricated and transferred to the substrate using a similar process as described in Refs. 20 and 21. The graphene rectangles were defined via electron beam lithography and O₂ plasma etching, while the antennas were processed via two stages of electron beam lithography and thermal evaporation. Four arrays with L = {47, 48, 49, 51} μm, corresponding to resonant frequencies \( f_{res} \) around 2.0 THz, were processed onto one chip, allowing for coarse tuning of the resonant frequency in order to account for possible differences between simulation and experiment. The fully processed device was then mounted in a Au-ceramic chip carrier with conductive Ag adhesive, allowing back gate electrical contact through the p-Si substrate. The source and drain pads for each array were Au wire bonded to different pins of the Au-ceramic chip carrier.

Figure 1(a) shows a scanning electron microscope image of a device with L = 51 μm along with a schematic shown in Fig. 1(b). The bow-tie antennas have a flare angle of 5° and a gap between the two arms of 2 μm. The graphene rectangles between the arms have an area of 8 × 4 μm². The pitch between adjacent antennas in the x and y directions are 1.55·L and 0.33·L, respectively. In total, 15 columns and 41 rows of antennas covering a total area of 1 × 1.2 mm² were defined. The two metallic antenna arms are nominally 60 nm of Pd and 60 nm of Ti, both capped with a 15 nm layer of Au. For the purpose of modulation, this bimetallic design does not significantly affect performance but opens upon the possibility of detection.

To simulate the spectral response of the device, we employed the commercial software COMSOL Multiphysics® v 5.1. A single unit cell was modelled with periodic boundary conditions. The optical properties of the materials were defined via the complex permittivity \( \varepsilon_r \) with the SiO₂ layer defined as \( \varepsilon_r = 3.9 \) and the graphene, Pd, Ti, and p-Si described by the Drude model. A plane wave with an electric field polarization along the antenna length is excited by a port boundary condition which is also used to monitor the reflected power. Figure 2(a) shows the spectral reflectivity for the L = 51 μm device at different graphene sheet conductivities (\( \sigma_G^\delta \)). A clear modulation of the reflected light is observed with the maximum modulation depth seen at the resonant frequency \( f_{res} \approx 2 \) THz. Figure 2(b) shows that the resonance is tunable by acting on the antenna length L, with an approximate \( f_{res} \propto 1/L \) relationship as expected. As expected, when the incident THz radiation is polarized perpendicular to the antenna’s major axis, no resonant features are observed, only a Drude like response at low frequencies. Also, due to the small area of graphene on this device, there is no appreciable modulation away from resonance as \( \sigma_G^\delta \) is changed. Figure 2(c) presents the simulated reflectivity spectrum for the L = 51 μm array along with the measured reflectivity spectrum from a commercial THz time-domain spectroscopy (THz-TDS) system (Imaga 2000 from Teraview,
UK), a broadband THz source. The sample was biased at its Dirac point (lowest conductivity). The resonance agrees well with graphene sheet conductivity between 0.1 and 0.5 mS, which is consistent with graphene grown under the same conditions and processed in a similar procedure as in Refs. 27 and 28. Figure 2(d) shows electric field mode profiles for the antenna gap which decrease in intensity as \( \sigma_p \) increases.

The sheet resistance of the graphene on the device cannot be accurately measured. Large contact resistances,\(^{29}\) non-parallel conductivity, and geometry dependent current paths caused by the taping of the antennas distort the measurement non-linearly. However, simulations show that modulation is achievable for physically attainable values of graphene sheet conductivity (see Figure S1 in the supplementary material\(^{31}\)).

To simulate the speed characteristics of the device, a lumped element circuit model as shown in Fig. 3(a) was developed. The equivalent circuit is driven by an AC voltage source with a 50 \( \Omega \) output impedance. The device is modelled as many parallel elements/impedances, where \( C_p \) is the capacitance of the source/drain pads which were calculated to be 40 pF each. \( R_p \) is the back gate resistance to each of these pads and was calculated to be 94 \( \Omega \) by using numerical methods to account for fringing fields. The remaining parallel elements are 615 unit cell impedances \( Z_{UNIT} \). Figure 3(b) shows the \( Z_{UNIT} \) sub circuit, consisting of several different elements. \( R_{Si} \) is the unit cell resistance through the p-Si substrate, which by using Pouillet’s law was calculated to be 71.5 k\( \Omega \). \( C_A \) and \( C_G \) represent a single antenna arm and graphene capacitances, respectively. Both were simulated using COMSOL Multiphysics v 5.1, to account for fringing fields and yielded values of 5 fF and 3 fF, respectively. \( R_g \) represents an average graphene resistance for each of the antenna halves and was estimated based on geometry and a value of graphene sheet resistivity of 1 k\( \Omega \) (measured from large area graphene of a similar device), giving \( R_g = 2 \) k\( \Omega \). \( R_{PD} \) and \( R_{TT} \) have values of 12.6 \( \Omega \) and 50.4 \( \Omega \), respectively, and represent the resistances of the connecting lines between adjacent antennas. Due to the symmetry of the device, a single cell in the middle of a column of antennas (N = 41) is taken as \( Z_{UNIT} \). To solve the full circuit characteristics, the SPICE simulator was employed to solve the AC voltages and currents of the circuit shown in Fig. 3(a). The optical cut-off frequency \( (f_0) \) was taken as the \(-3 \) dB value of the voltage transferred across the graphene capacitors from the total circuit, and this is related to the electrical cut-off frequency \( (f_{3dB}) \) by \( f_0 = \sqrt{3} f_{3dB} \). This ensures the optical cut-off frequency is related to the voltage and not the power transferred across the graphene.\(^{28}\) Figure 3(c) shows the numerical solution for the voltage transfer function across the graphene capacitors giving a \( f_0 \) frequency of 115 MHz. This lumped element model is a simplification of the physics involved but does provide an adequate approximation of \( f_0 \) for this class of device.\(^{17,27,28}\) More importantly, such models are useful for determining limiting factors of \( f_0 \), which through careful study was found to be the large capacitance of the source/drain pads.

To characterize the optical modulation characteristics of the device, an optical setup as shown schematically in Fig. 4 was used. THz radiation generated from a 2.0 THz single frequency emission QCL was collimated using a 90° off-axis parabolic mirror (OAPM) with an effective focal length (EFL) of 7.5 cm. A Si beam splitter at 45° was placed in the collimated beam path and another 90° OAPM (EFL = 2.54 cm) focused the light through a 1 mm pinhole onto the sample. The peak power of THz radiation incident on the device was estimated to be 81 \( \mu \)W. The reflected light was re-collimated and semi-reflected by the beam splitter onto a large area Golay cell via a final 90° OAPM (EFL = 15 cm). The laser was operated in continuous pulse mode with a 20 kHz repetition rate and 30% duty cycle, which due to the Golay cell’s slow response time (~25 ms), appeared as a constant power source. The array with

FIG. 3. Lumped element circuit model of the device. (a) Total device circuit. (b) Circuit for a unit cell, \( Z_{UNIT} \). (c) Transfer function across the graphene capacitor, for the total device circuit. \( H_d \) is the transfer function across the device, and \( H_p \) is the transfer function across the graphene capacitors. \( H_{TOTAL} = H_d \times H_p \).

FIG. 4. Optical setup. 1, Single frequency emission 2.0 THz QCL at 4 K. 2, 90° OAPM, EFL = 7.5 cm. 3, Si beam splitter. 4, 90° OAPM, EFL = 2.54 cm. 5, \( \varnothing = 1 \) mm pin hole. 6, Device. 7, 90° OAPM, EFL = 15 cm. 8, Golay Cell detector. 9, Back-gate bias circuit.
L = 51 μm was chosen as this size of antennas has its resonance peak centered around 2.0 THz. The sample had both source and drain electrodes grounded. The gate voltage \( V_G(t) \) was taken as the output from a voltage summing circuit that added a 10 V peak-to-peak square wave with a frequency \( f_{MOD} \), \( V_{AC}(f_{MOD}, t) \) to a constant DC value \( V_{DC} \), such that

\[
V_G(f_{MOD}, t) = V_{DC} + V_{AC}(f_{MOD}, t).
\]

By setting \( f_{MOD} \) as 22 Hz, the amplitude of modulation could be measured directly by the Golay cell and lock-in amplifier with the same reference frequency. This method of characterization was chosen because of the superior signal to noise ratio obtained and increased tolerance for thermal and mechanical drift of the optical system. Figure 5 shows the optical modulation depth for THz radiation polarized parallel to the antenna’s major axis and the absolute value of DC differential resistance. The inset shows modulation when the polarization of the THz radiation is perpendicular to the antenna’s major axis.

In conclusion, we have presented a fast room temperature external optical modulator working at THz frequencies. By reducing the parasitic capacitance from the source/drain pads and optimizing the geometry of the device \( f_0 \) frequencies above 10 GHz should be achievable. Several methods to improve the modulation depth of this non-optimized device are possible: Optimized graphene processing and chemical passivation, using top gate dielectrics, would lead to much higher modulation depths, due to a simultaneous reduction of the Dirac point voltage and decrease in homogeneous and

\[
H(f) = \frac{1}{\sqrt{1 + \left(\frac{f}{f_{3dB}}\right)^2}}.
\]

\( f_0 \) was found to be 105 ± 15 MHz, in very good agreement with the circuit model developed.

FIG. 5. Optical modulation depth measurement as a function of DC voltage offset \( V_{DC} \). The crosses (×) show the modulated power of THz radiation for a 10 V peak-to-peak square wave at 22 Hz, and the squares (□) show the absolute value of DC differential resistance. The inset shows modulation when the polarization of the THz radiation is perpendicular to the antenna’s major axis.

FIG. 6. Normalized optical modulation speed measurement. The blue curve corresponds to the fitting of the data using Equation (2). Each point was acquired with a 500 ms integration time and 3.5 s dwell time.
inhomogeneous broadening of the conductivity/doping. The antenna geometry can be altered to obtain a higher overlap between the optical mode and graphene. Furthermore, the antenna density on the device can be increased further with an overall reduced device size. With such optimizations, it is estimated that modulation depths >25% are feasible, without reducing the device’s speed.

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28See supplementary material at http://dx.doi.org/10.1063/1.4947596 for an additional simulation of reflectivity at resonance (Figure S1) and measured graphene resistance (Figure S2).