Tunable Graphene-based Metamaterial Terahertz Modulators

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Abstract: We demonstrate metamaterial-based electro-absorption THz modulators employing frequency-selective-surfaces (FSS) and graphene. By placing the graphene layer at an optimal distance from the FSS, the sensitivity of THz transmittance can be greatly enhanced.

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1. Introduction

Graphene has been shown to be a promising platform for manipulating terahertz (THz) waves [1]. However, limited by the typical quality of state-of-the-art large-area single-layer graphene, the degree of reconfigurability in these devices is not yet strong enough for practical applications. In this work, we experimentally verify our recent proposal [2] that, by placing graphene layers at an optimal distance from a metamaterial frequency-selective-surface (FSS), the interaction between graphene and THz photons can be substantially enhanced, thus resulting in an improved electro-absorption modulation for THz waves.

2. Design and fabrication

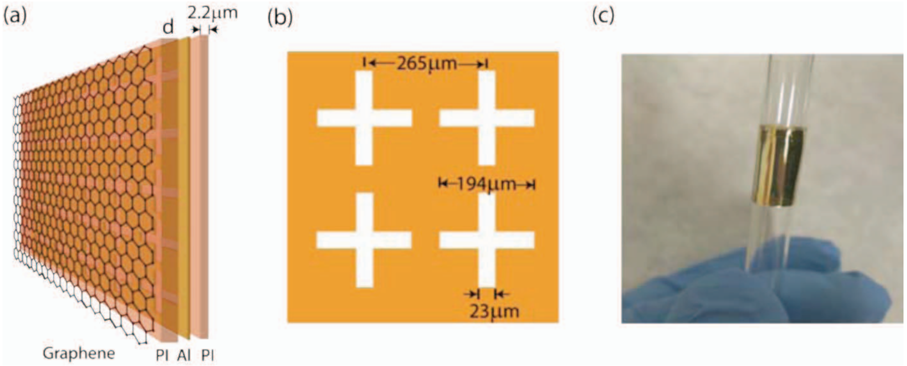

Fig. 1 (a) Illustration of the device structure. (b) Dimensions of the cross slots. (c) Optical image of the fabricated metamaterial-based graphene THz electro-absorption modulator structure.

The devices are fabricated on a polyimide (PI) substrate as schematically shown in Fig. 1 (a), consisting of graphene separated from the metallic FSS by a polyimide spacer with a variable thickness. The liquid PI-2610 is spin-coated onto a Si wafer followed by a thermal curing process to form a PI substrate. The metallic FSS pattern is then defined via a standard photolithography process. Graphene layers, grown by chemical vapor deposition on a copper foil, are transferred onto the devices; multi-layer graphene stacks are realized by multiple transfer processes. Control of the PI thickness is achieved by multiple coatings and curing steps. The freestanding device on the PI substrate, as shown in Fig .1 (c), is finally peeled off from the Si substrate.

3. Transmittance measurements and discussion

The THz transmittance is measured using an EMCORE PB7200 THz frequency domain spectrometer, and experiments are correlated with HFSS simulations. To characterize the conductivity of the graphene [1], we first measured the transmittance of a monolayer graphene film alone on a 2.2 um PI substrate, as shown in Fig. 2 (solid curve). Assuming a conductivity of 0.3mS, the simulated transmission (dashed curve), fairly matches with the experimental result. It is worth noting that all the graphene layers used in this work are transferred from the same

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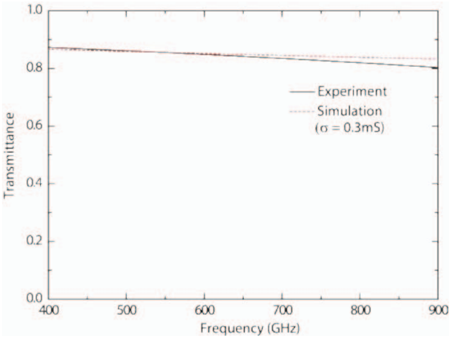

Fig. 2 Transmittance of the monolayer graphene on polyimide substrate.

piece of copper under the same growth and process conditions, which roughly guarantees similar quality in terms of doping level and mobility.

The THz transmittance on devices with one, two, and three layers of graphene are shown in Fig .3 (a). Note that the total conductivity in each device can be assumed to be the sum of the conductivities of the individual graphene layers [3]. Corresponding simulations by assuming graphene conductivities of σ = 0.3 mS (1 layer), 0.6 mS (2 layers) and 0.9 mS (3 layers) are shown in Fig. 3 (b), in good agreement with experimental results. It can be seen that, for a fixed distance *d*=4.5 μm, the THz transmittance decreased from 22% to 6% when the graphene conductivity varies from 0.3 to 0.9 mS, showing an excellent modulation depth of 73%. The large THz beam attenuation is a result of strong light-matter interactions [2]. To explore the dependence of transmittance on graphene placement, we fabricated devices with a fixed graphene conductivity of 0.4 mS and several different PI spacer thicknesses. We find, shown in Fig. 3(c), that as *d* increases from 4.5 μm to 16.5 μm, the peak transmittance intensity increases from 20% to 40%, which results from a decreasing electromagnetic coupling between the graphene and the FSS. Both the σ- and *d*-dependent transmittances are summarized in Fig. 3(c); experimental and simulation results match closely. Figure 3(c) also shows transmittance versus conductivity for a graphene film without FSS; the comparison shows that modulation depth is dramatically enhanced after placing the graphene in conjunction with a FSS. Having a large modulation depth for typical graphene conductivity swings is of importance for THz applications such as communications and imaging [2].

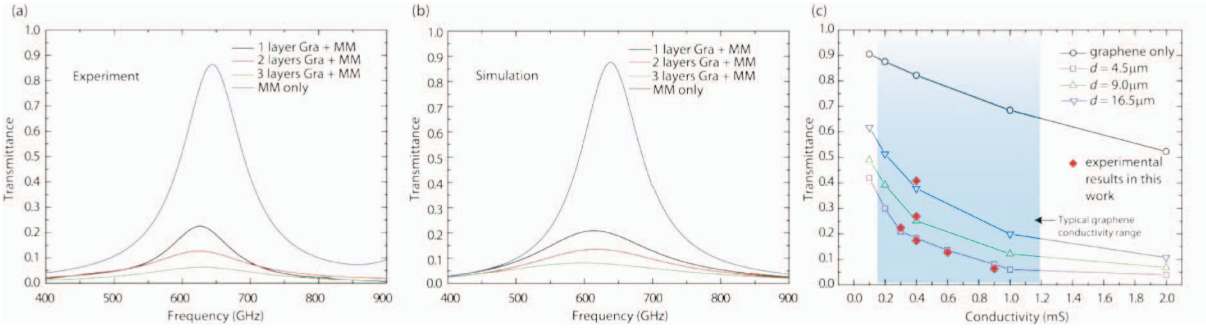

Fig. 3 (a) and (b) Experimental and simulated transmittances for the graphene/metamaterial(MM) structures and the metamaterial alone. (c) Simulated peak transmittance vs. graphene conductivity for all the analyzed structures.

4. Conclusion

Our experiments and simulations reveal that the sensitivity of THz transmittance to graphene conductivity can be controlled by varying the separation between the graphene layer and the FSS. The low transmittance at small separations is the result of both stronger graphene/THz wave interaction and enhanced reflection. Based on this principle, by employing self-gated graphene pairs thus dynamically controlling the graphene conductivity, one can substantially enhance the THz modulation with respect to that of stand-alone graphene pairs. This device concept can be extended to other material systems besides graphene by optimizing the device geometry.

5. References

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