Graphene-based Metasurfaces for Multimode Tunable Terahertz Modulators

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Abstract: We present a hybrid graphene metasurface and its modulation by electrostatically tuning the conductivity of the graphene. Through modification of unit cell symmetry, multiple Fano-like resonances arise for additional modes over a 300 GHz range.

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1. Introduction

Recently, electro-optic modulators featuring graphene have shown great promise as ultrafast optical interconnects with transfer rates up to 20 GBit/s [1]. The increase in demand for higher speed communications applications have many predicting that TBit/s speeds will be available within the next 10 years, and due to operation at terahertz (THz) frequencies, new formats are predicted, such as a 5G cellular network. However, most THz photonic devices such as sources, detectors and modulators are still in the design and development stages. Graphene metastructures have several advantages over traditional metallic structures including high carrier mobility, material flexibility, and resonance frequency tunability [2]. A diverse set of graphene metamaterials structures such as split-ring resonators (SRRs) have been theoretically proposed with amplitude modulation up to 80% and frequency tunability up to 400 GHz [3]. Therefore, the aim of this work is to realize the high amplitude modulation and broad frequency modulation by fabricating novel hybrid graphene devices with asymmetric SRR metasurfaces to generate multiple Fano resonances.

2. Methods

Numerical calculations were carried out using the commercial finite difference time domain (FDTD) software package CST Microwave Studio. In these calculations, the elementary cell of the designed metamaterial was irradiated by a normally incident plane wave with the electric field parallel to the x-axis and the magnetic field parallel to the y-axis. Periodic boundary conditions were applied in the numerical model in order to mimic the functioning of a 2D infinite structure. In the simulation, the silicon was treated as a lossless dielectric with $\varepsilon_{Si} = 11.9$ and the copper was modeled as a lossy metal with a conductivity of 5.8×10^7 S/m.

Metasurfaces were fabricated on SiO_2/Si (285 nm/500 μm) wafers using a standard electron beam lithography technique. First, a typical RCA procedure was used to clean the substrates. A monolayer graphene was transferred from CVD grown samples on copper (Graphenea). The copper was etched with a ferric chloride solution. Then, the PMMA/graphene film was rinsed with DI water several times. The floated sheet was moved to a bath of 3:1 H_2O:HCl for 15 minutes to remove ionic contaminations and again rinsed with DI water. Finally, the suspended PMMA/graphene stack was transferred to the substrate. After drying the sample, it was placed in an acetone bath to remove the PMMA for four hours. The patterns were drawn using ultra-high resolution electron beam lithography (Raith-150). Metallization was performed with thermal evaporation to deposit 200 nm of Cu as the metasurface metal and Cr/Au (10 nm/120 nm) pads were deposited as device contacts. The active surface of the fabricated devices is 2.5 x 2.5 mm^2 and measurements to monitor the ability to modulate THz waves were made using a high resolution terahertz time-domain spectrometer (HASSP-THz) in the transmission configuration.

3. Summary of Results and Discussion

For the symmetric unit cell (Fig. 1 (a)), as the conductivity of the graphene layer is varied by adjusting the gate voltage, the amplitude of the transmission is modulated up to 40% and there is a noticeable frequency shift to higher frequency

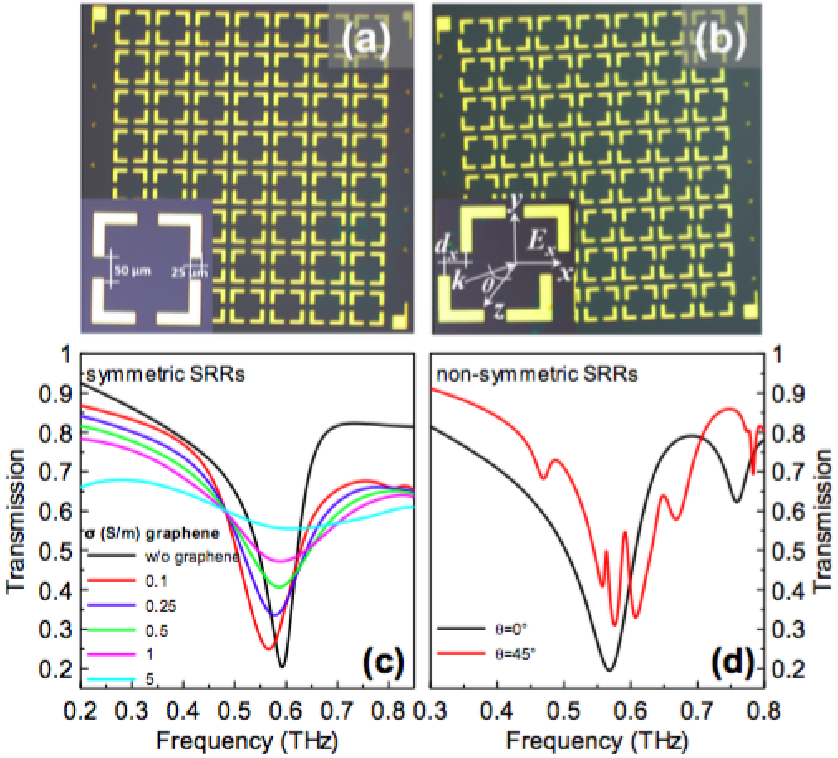

Fig. 1. Images of the (a) symmetric and (b) assymetric metasurfaces on a graphene/Si substrate. Representative data highlighting the tunability of the symmetric unit cell in (c) and the multimode operation of the assymetric unit cell in (d).

(up to 50 GHz), shown in Fig. 1 (c). This is a direct result of the localized surface plasmon being electrostatically tuned to interact with the characteristic inductive capacitance resonance frequency of the metasurface. If the brackets of the 4 gap resonator are offset by 40 μm, we create an asymmetric unit cell as seen in Fig. 1 (b). At an oblique incidence, such as the case of TM polarization with optimum incident angle = 45°, the asymmetry results in Fano-like resonances at 7 additional operating frequencies with an overall frequency coverage on the order of 300 GHz (Fig. 1 (d)). THz metasurfaces with Fano resonances have been shown to increase the Q-factor ($Q = \frac{\nu_0}{\Delta\nu}$, where ν_0 is the center frequency and $\Delta\nu$ is the linewidth) and sensing capabilities [4, 5]. Furthermore, if we then couple this new asymmetric metasurface with an atomic-layered material like graphene, we can take advantage of the electrostastic modulation of the amplitude. An additional application for this multimode tunable device is biosensing due to the enhanced Q factor and multiple operating modes with narrow linewidths.

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