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Mid-Infrared Computational Spectroscopy with an Electrically-Tunable Graphene Metasurface

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Abstract: We demonstrate graphene-plasmonic metasurfaces whose mid-infrared reflection spectra are electrically-tunable. Using measurements of the power reflected by the metasurfaces at different drive voltages, the source spectrum is computationally reconstructed by the recursive least squares method.

OCIS codes: (230.4110) Modulators; (300.6340) Spectroscopy, infrared; (080.1753) Computation methods

1. Introduction

Mid-infrared (~3-12 μm) spectroscopy is important in fields that include environmental monitoring and food safety testing [1]. Miniaturized mid infrared spectrometers would be advantageous for in-field applications not requiring the very high resolution that can be achieved by traditional Fourier-transform infrared (FTIR) spectrometers. The latter are frequently bulky and expensive. Miniaturized spectrometers have been demonstrated that comprise arrays of passive (i.e. non-tunable) filters matched to detector arrays. These filters have included Fabry-Perot etalons [2], quantum dots [3], and plasmonic filters [4,5]. One of the drawbacks is that many filters (e.g. ~100) are needed for high resolution reconstruction. Replacing the passive filters with dynamically tuned filters presents an opportunity to substantially reduce the number of filters needed, thereby enabling further miniaturization. Devices with tunable resonances have been reported that combine graphene with nanoantennas [6,7], but have not been employed for spectral reconstruction. Here, we demonstrate a dynamically-tunable device that, when combined with a detector array, would permit the realization of an ultra-compact mid-infrared spectrometer. Our device consists of three electrically tunable-graphene metasurfaces, each comprising metallic nanostructures integrated with graphene and having an extent of 30 μm×30 μm. The reflectance spectrum of each metasurface can be controlled by applying a gate voltage (V_g). Our work demonstrates that even though the device contains only three metasurfaces, their electrical tunability means that this is sufficient for spectral reconstruction of a mid-infrared light source. This is done by measuring the reflection spectra and total power reflected by each metasurface at different values of V_g. The measured data is input to a recursive least square (RLS, [8]) algorithm, which estimates the incident spectrum.

2. Design and Fabrication

Figure 1a shows the schematic of our metasurface, which comprises cross shaped nanoantennas over a single layer of graphene, separated from a metallic reflector (that also functions as a back gate) by a TiO_2 spacer. The structural parameters of the device include the nanoantenna period (P), width (W), and gap (G), and the thickness (t) of the TiO_2 cavity layer. Finite difference time domain (FDTD) simulations were performed to choose these parameters to produce a reflection dip in the mid infrared regime. Simulated reflection spectra for a device with parameters P=2250 nm, G=60 nm and W=200 nm are shown in Fig 1b. In this device, there is also an Al_2O_3 layer (30 nm thick) between graphene and TiO_2, included to improve gate performance. It can be seen that the spectral position of the dip is shifted substantially as the chemical potential of the graphene was varied from 0.1 to 0.2 eV.

To fabricate the devices, a CVD graphene monolayer was transferred onto a highly doped silicon wafer pre-deposited with Au (120 nm thick), TiO_2 (800 nm thick) and Al_2O_3 (30 nm thick) layers. Three devices with P=1200, 1500 and 2250 nm were fabricated by e-beam lithography, e-beam evaporation (5 nm Ti and 25 nm Au) and lift off. Rectangles of graphene were patterned by e-beam lithography and dry etching (oxygen plasma).

3. Results and Discussion

We measured reflection spectra of the fabricated device at different V_g with an FTIR microscope system (Spotlight 200i, Perkin Elmer). To normalize the results, reflection spectra were measured from a reference sample comprising a gold film. Reflection spectra $R_{Vg}(\lambda)$ of the three devices were measured at 21 different values of V_g ranging from -10V to 12V in the steps of 1 V (Fig. 1c-e), where the wavelength of the reflectance dip (i.e. the resonance wavelength) of those devices was seen to be tuned in the range of λ=8.3 to 9.2 μm. We also determined the spectrum

$S(\lambda)$ of light reflected from each device at each V_g. This represents $S(\lambda) = g(\lambda) \times MCT_{resp}(\lambda) \times R_{Vg}(\lambda)$, where $g(\lambda)$ is power density spectrum of the light source of our FTIR system (silicon carbide globar) and $MCT_{resp}(\lambda)$ is responsivity of the mercury cadmium telluride (MCT) detector of the FTIR microscope. For each measurement, we integrated $S(\lambda)$ over λ=4.6 μm to 10 μm, which yields a column vector (69×1) that mimics what would be measured by a spectrometer consisting of a detector integrated with the filter array. This column vector was input, along with $R_{Vg}(\lambda)$, to our RLS algorithm to estimate $g(\lambda) \times MCT_{resp}(\lambda)$, i.e. the spectrum of our globar multiplied by the detector responsivity. The results were in good agreement with the globar spectrum directly measured with the FTIR microscope as seen in Fig. 1f.

In summary, we have demonstrated dynamic control of mid-infrared light by tuning the resonance of a graphene integrated metasurface and used the same to demonstrate spectral reconstruction of a globar source.

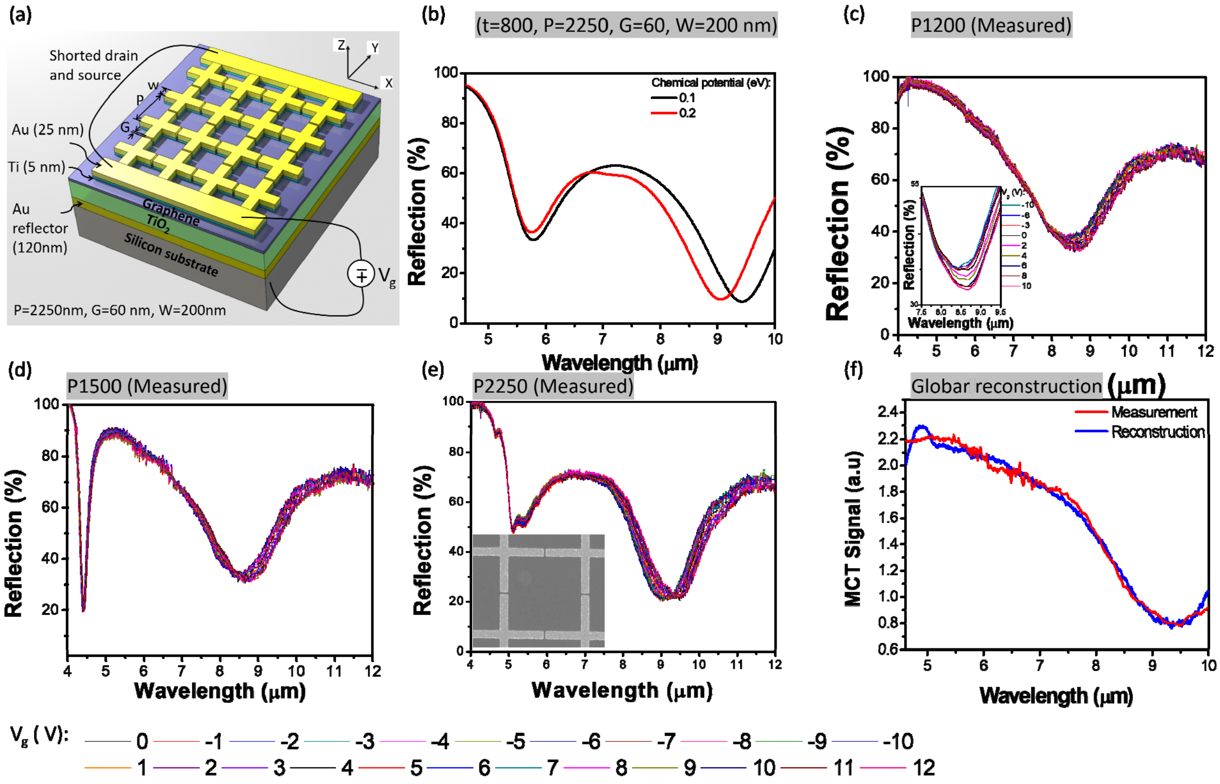

Fig. 1. (a) Schematic of metasurface device with back gate. (b) Simulated reflection spectra of device for different graphene chemical potentials Measured reflection spectra for fabricated devices with *P*= (c) 1200 nm; Inset: Magnified image of reflection spectra (d) 1500 nm and (e) 2250 nm at different V_g; Inset: SEM image of the fabricated antennas (f) Reconstruction of MCT signal of globar source (i.e. $g(\lambda) \times MCT_{resp}(\lambda)$) over a wavelength range of 4.6 µm to 10 µm, with 1917 data points.

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