Ultra-compact mid-IR modulators based on electrically tunable optical antennas

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***Abstract*—we demonstrated electrical tuning of optical-antennas over a broad wavelength range (~1100 nm, ~20% of the resonance frequency) and achieved optical modulators at the mid-infrared wavelength range with nanosecond response time.**

Keywords: optical modulator; mid-infrared; optical antennas; reconfigurable metasurface; graphene

I. INTRODUCTION

Optical antennas enable the conversion of light from free space into subwavelength volumes and vice versa, which facilitates the manipulation of light at the nanoscale[1]. Dynamic control of the properties of antennas is desirable for many applications, including biochemical sensors, reconfigurable meta-surfaces and compact optoelectronic devices. The combination of metallic structures and graphene, which has gate-voltage dependent optical properties, is emerging as a possible platform for electrically controlled plasmonic devices [2-4]. Here we demonstrate an electrically tunable coupled antenna array on graphene with a large wavelength tuning range in the mid-infrared (MIR) wavelengths range. MIR optical modulators are achieved with maximum modulation depth of more than 70% and nanosecond response times[5].

II. DEVICE DESIGN AND EXPERIMENT RESULTS

Graphene is emerging as a broadband optical material which can be dynamically tuned by electrostatic doping [4]. By combining metal and graphene in a hybrid plasmonic structure, it is possible to enhance graphene-light interaction and thus achieve in situ control of the optical response. We designed a new type of plasmonic structure comprised of closely coupled optical antennas such that field localization occurs along a significant portion of the antenna length rather than only at the ends. We found that this type of structure interacts particularly strongly with monolayer graphene, and its plasmonic modes are significantly affected by the graphene optical properties which can be dynamically controlled by electrostatic doping [5].

Figure 1 (a) shows a schematic of the tunable optical device. A graphene monolayer grown by atmospheric pressure chemical vapor deposition (CVD) was transferred onto a 30 nm thermal oxide layer on a highly p-doped silicon substrate. The plasmonic antennas and metal contacts were patterned onto the graphene sheet by electron beam lithography (EBL), electron beam evaporation (5 nm Pd and 30 nm Au) and lift-off. A detailed description of the device fabrication is provided in reference [5]. A scanning electron microscopy (SEM) picture of the fabricated structure and the zoom-in over a small region is also shown in Fig.1 (a).

The reflectance of our samples were measured using a Fourier transform infrared (FTIR) spectrometer with a MIR microscope (NA=0.4)[4]. The measured reflectance spectra of one device (L_1=L_2=480 nm, coupling gap ≈30 nm) are shown in Fig. 1 (b). The wavelength of the reflectance peak (i.e. the antenna resonance wavelength) was tuned over about 1100 nm, 80% of the FWHM of the reflectance peak. Based on the measured reflection spectra, we extracted the intensity spectra of the scattered light from the optical antennas at two gate voltages, as shown in Fig. 2 (a). The maximum modulation depth up to 70% has been achieved around 7 µm.

The time response of the modulator was characterized by measuring frequency-dependent optical modulation with a thermoelectrically-cooled mercury cadmium telluride (MCT) detector. The optical modulation depth is shown in Fig. 2 (b) as a function of modulation frequency. A 3dB cut-off frequency of 30 MHz for the optical modulation is obtained based on the measurement data, which is limited by the MCT detector response time. Based on circuit analysis, the device response time is about 5 ns, which is limited by the parasitic capacitance between the contact pads and the substrate, which can be further reduced by minimizing the contact pad size.

III. CONCLUSION

By combining metal and graphene in a hybrid plasmonic structure, we demonstrate an electrically tunable coupled antenna array with a large tuning range (1100 nm, i.e. 250 cm^{-1}, nearly 20% of the resonance frequency) of the antenna resonance wavelength at the mid-infrared (MIR) region. This makes it possible to electrically manipulate light at the nano-scale, which may lead to highly compact photonic and optoelectronic devices.

ACKNOWLEDGMENT

We gratefully acknowledge discussions with R. Blanchard, P. Genevet, D. Wolf, Y. Zhang and C. Wang. Device fabrication was performed at the Center for

978-1-4799-2767-8/50 $31.00 © 5250 IEEE
DOI 10.1109/SUM.2014.37

Nanoscale Systems, which is a member of the National Nanotechnology Infrastructure Network supported by the National Science Foundation (NSF). This research is supported in part by the Air Force Office of Scientific Research under grant number FA9550-12-1-0289 and by IARPA under grant N66001-13-1-2007 vice N66001-13-1-3005. M. L. and R. S. gratefully acknowledge the financial support by NSF via the collaborative research grant EECS-1028519.

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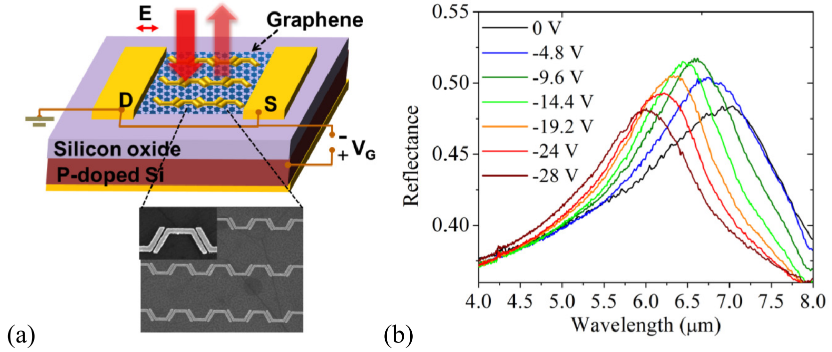
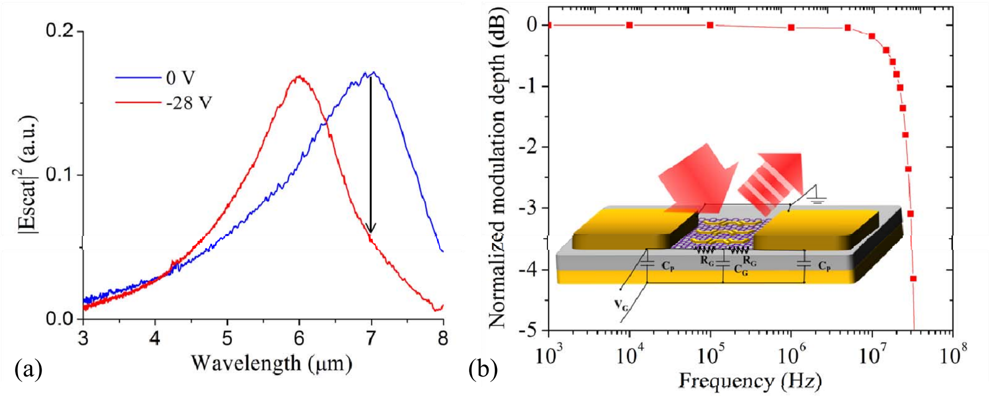


(a) (b)

Figure 1. (a) Schematic of the tunable plasmonic device with a back gate and scanning electron microscope (SEM) image of the plasmonic structure and a zoomed-in portion. (b) Measured reflection spectra from a device (antenna length L_1=480 nm, L_2=480 nm, bending angle 60 degree, gap size 30 nm, lateral period 2 μm) for different gate voltages (V_G-V_{CNP}, V_{CNP} is the gate voltage when the concentrations of electrons and holes in the graphene sheet are equal). All spectra are normalized to the reflection spectra from a 300 nm Au film evaporated on the same substrate.



(a) (b)

Figure 2. (a) Scattered light intensity spectra from the antennas extracted based on the measurement results in Fig. 1(b) for two gate voltages. (b) Frequency response of the normalized modulation depth of optical modulation and gate voltage modulation with respect to that at DC limit. The inset shows the schematic of the frequency response measurement and the high frequency circuit model of the sample.