

Resolving the Optical Modulation Mechanism of Graphene-hybridized Plasmonic Metamaterials

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Abstract:

Optical modulation characteristics of graphene-hybridized plasmonic metamaterials is investigated. It is revealed that resonance peak transmission can be effectively tuned by the applied gate voltage, suggesting an electro-absorption modulation (EAM) mechanism.

I. INTRODUCTION

Optical modulators with broad operating wavelength range or large modulation depth are desirable in a range of data-communications and signal processing applications [1]. Recently, hybridizing graphene with plasmonic metamaterials is becoming a viable route to build highly integrated optical modulators, operating across the infrared and Terahertz range [2, 3]. This is enabled by the ultra-broadband and doping-dependent absorption of graphene, intrinsic plasmon resonance in graphene as well as the engineering freedom to customize the resonance wavelengths of plasmonic nanostructures [4-6]. Despite the remarkable progress, the underlying physical mechanisms governing the interaction between graphene and plasmonic metamaterials remains scarcely explored, especially for the near-infrared. Recently, Papisimakis et al. fabricated a graphene covered metal plasmonic structure that supported "trapped mode" resonance and observed pronounced red-shift of the "trapped mode" resonance peaks in the contrast spectra [7]. While the exact physical mechanism leading to the red shift of the resonance wavelength is still debated [8], whether such a spectral shift can be subsequently controlled via an applied gate voltage to enable novel electro-optical modulators remains an open question. To the best of our knowledge, no experimental or numerical investigations have been carried out to explicitly clarify the optical modulation mechanism of such a hybrid device.

In this work, we have experimentally investigated the spectral shift of a graphene-hybridized plasmonic device (periodically structured nano-aperture arrays) in the near-infrared and then numerically investigated its spectral response to an externally applied gate voltage, where a thin dielectric layer ~ 5 nm functions is considered. In particular, we focus on how resonance wavelengths and peak transmission are affected by the applied gate voltage. Our results reveal that such a device works in a regime where the resonance peak transmission (or absorption), rather than the resonance wavelengths, is effectively tunable with the applied gate voltage, corresponding to an electro-absorption mechanism.

II. RESULTS AND DISCUSSION

In our experiment, periodically structured nano-aperture arrays were etched by focused ion beam milling through an 80 nm thick gold film evaporated on a 100 μm thick quartz substrate. The sample with a diameter of $D=0.5$ μm and a period of $P=1.0$ μm was fabricated. Graphene is grown by chemical vapor deposition method and then transferred on top of the metamaterial using the standard PMMA assisted transfer procedures. Fig. 1(a) shows the SEM image of the plasmonic structure with clear and continuous coverage of graphene. The spectral response of the metamaterial before and after graphene deposition was measured experimentally in a micro-photospectrometer (CRAIG). Fig. 1(b) illustrates the transmission spectra. Red-shift of the resonance features is observed as reported in ref [7]. Fig. 1c illustrates the device structure we investigated numerically, to reveal the gate dependence of the optical response of the hybrid structure. 5 nm thick SiO_2 overlayer is considered as the gate dielectric. A graphene sheet is placed on top of the thin dielectric layer. A voltage applied to the device can be used to tune the Fermi level of the graphene. The plasmonic waveguide has a period of 0.6 μm and the diameter of the hole is chosen to be 0.3 μm with two distinct plasmonic resonance peaks in the near-infrared range.

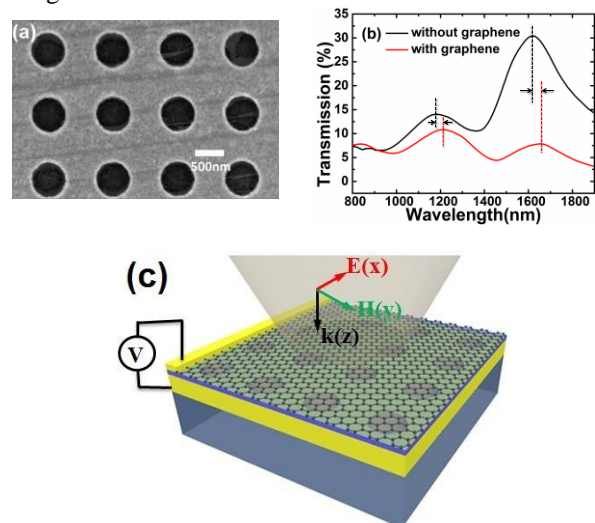


Fig. 1(a) SEM image of a plasmonic nano-aperture arrays covered with graphene. (b) Measured transmission spectra with and without graphene hybridization (dashed lines indicates red shifts of resonance wavelengths). (c) Schematic illustration of gate controlled graphene-hybridized plasmonic metamaterial.

The optical switching characteristics of the hybrid system is simulated using FDTD method. The graphene sheet is modeled as an anisotropic layer with a thickness of $t=0.5$ nm ($\epsilon_x=\epsilon_y=2.5+j\sigma_g/(\epsilon_0\omega t)$, $\epsilon_z=2.5$) [2]. The effect of the external gate voltage is manifested in the Fermi level of the graphene sheet, i. e. $E_f \propto (V_g)^{1/2}$ [2]. We have focused on the Fermi level range of ~ 500 -700 meV to cover the optical transitions of interests for the investigated structure. When Fermi level is < 500 meV, the optical conductivity for both resonances remains constant and is not tunable with the external voltage. Fig. 2 shows the resonance peak response (for the bottom metal-dielectric interface resonance) as a function of applied gate voltage. Unlike the modulator based on guided-mode resonance in graphene [2], no pronounced spectral shift (< 5 nm) of the resonance wavelengths is detected. We attribute this observation to the fact that optical conductivity mainly modulates the in-plane optical response of graphene, while the resonance of the hybrid system is largely dependent on the out-of-plane dielectric configurations. Therefore the results are compatible with our numerical model where a fixed out-of-plane dielectric constant is assumed for graphene ($\epsilon_z=2.5$). However, under strong nonlinear light excitation, i.e. using ultra-short laser pulses, the system is likely to exhibit more pronounced variation of resonance wavelengths as a result of nonlinear Kerr effect [9]. We observe a gradual change of $\Delta T=T_{\text{doped}}-T_{\text{undoped}}$ with Fermi level for the bottom interface resonance. The contrast of optical switching for this resonance defined by $\Delta T / T_{\text{undoped graphene}}$ is estimated to be around 21%. Such a figure of merit is not ideal for direct modulation of CW signals for data-communications, but could be useful for acting as a modulation element inside a laser cavity such as a Q-switch or saturable absorbers.

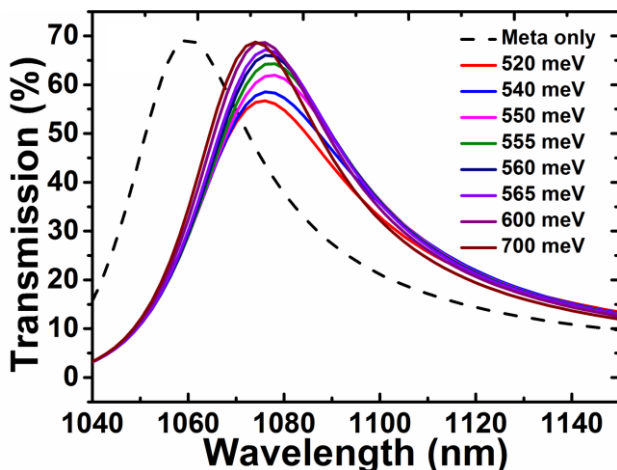


Fig. 2 Spectral response of the graphene hybridized plasmonic metamaterial under different applied voltages (or graphene Fermi levels).

III. CONCLUSIONS

Optical modulation characteristics of graphene-hybridized plasmonic metamaterials is investigated in the near-infrared range. Our results demonstrate that although hybridization with graphene results in a red shift of the

experimental resonance peaks of the plasmonic metamaterials, subsequent tuning of the Fermi level of graphene through a gate voltage is likely to only lead to change of the resonance peak transmission, not the resonance peak positions, as revealed by our numerical simulation. The long wavelength resonance, occurring at the bottom metal-dielectric interface, is found to exhibit a modulation depth of $\sim 21\%$. Our work provides important design guidelines for realizing novel electro-optical modulators based on graphene-hybridized active plasmonic structures.

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