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Optical Modulation with Tunable Hybrid Metasurfaces

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Abstract

We present two compact tunable hybrid electronic-nanophotonic planar nanostructures to achieve efficient modulation of optical radiation. The reported designs are based on plasmonic and dielectric metasurfaces combined with graphene and indium tin oxide. Several new integrated nanophotonic components are envisioned based on the proposed devices, such as efficient electro-optical transmission and absorption modulators, new sensitive biosensors, and tunable photodetectors.

1. Introduction

In the next generation of information processing, devices will operate with photons rather than electrons. In these systems, information will travel with ultrafast speed, low power, and broad bandwidth. However, the optical counterparts of well-established electronic components, such as modulators and switches, remain elusive. Recent advances in nanoscale technology and in the understanding of the mechanisms of light interaction with artificial constructed ultrathin planar nanostructures, also known as metasurfaces [1], have opened a wide range of possibilities to extend the functionality and overcome the limitations of conventional bulky optical devices.

The properties of metasurfaces are usually fixed by design and arrangement of the constituent elements. Nevertheless, it is important to have robust and reliable planar nanodevices with functionalities not set in stone at the time of manufacturing. These metadevices will be characterized by optical properties that can be dynamically controlled and tuned leading to the design of integrated optical modulators and switches. Tunable functionalities must be incorporated into the current static metasurface designs to create these new efficient and compact nanophotonic components.

Fortunately, several ways are envisioned to tune and control the optical response of metasurfaces. One way is to combine them with tunable electronic materials leading to hybrid electro-optical nanophotonic configurations. An example of a tunable material is the recently discovered graphene, which is a two-dimensional (2D) conductive material with zero bandgap and linear dispersion [2]. Its properties can be dynamically altered due to an increase or decrease of its doping level [2]. They can be controlled by changing the applied voltage when an appropriate gating configuration is applied. Another interesting material with strong tunable performance that varies with the applied voltage is indium tin oxide (ITO) [3].

In this work, we present efficient electro-optical modulators operating at infrared (IR) and visible frequencies based on tunable all-dielectric and plasmonic metasurfaces combined with graphene and ITO. These hybrid nanostructures are very promising solutions towards the design of future integrated optical devices, since they have a compact, complementary metal-oxide semiconductor (CMOS) compatible geometry, especially when the metasurface is constructed by semiconductors, i.e., high index dielectrics. It is envisioned that the electronic control of electromagnetic radiation will lead to the realization of novel reconfigurable optical devices with new and improved functionalities.

2. ITO Plasmonic Metasurfaces

The proposed hybrid plasmonic silver metasurface loaded with ITO is schematically shown in Figs. 1(a) and 1(b). It is constructed by an array of silver film-coupled nanostrips with dimensions 60nm placed over an ultrathin ITO layer of 10nm. Its ultrathin compact profile can lead to low-energy consumption and compatibility with electronic nanocircuits. The nanostrips are terminated by a thick silver substrate leading to zero transmission. This device is used to obtain strong absorption or reflectance modulation at the visible frequency range, and is ideal for photodetector applications. The optical intensity in the spacer layer is greatly enhanced due to the strong localized plasmon resonance effect [4]. The amplitude of the electric field enhancement distribution at the resonance frequency is computed and shown in Fig. 1(c). The exceptionally high fields localized inside the nanogap of this metasurface configuration are expected to strongly interact with ITO and lead to tunable and modulated absorption or reflection responses.

The absorption (equal to 1-reflectance) spectrum is computed and plotted in Fig. 1(d) for two voltages applied to this configuration. The V=0V (zero doping) case corresponds to a 10-nm-thick undoped ITO layer with an original material doping level or carrier concentration density of $N_d = 8.8 \times 10^{20} cm^{-3}$ [3]. Using Poisson's equation, we have calculated that when the applied voltage is increased (V=0.6V), the ITO doping level becomes $N_d = 1 \times 10^{23} cm^{-3}$, forming a subnanometer accumulation depth layer with a thickness equal to 0.3 nm. Note that this subnanometer value is the typical thickness of the accumulation layer in conventional CMOS capacitors. The remaining ITO layer (9.7 nm thick) remains undoped. However, due to the strong electromagnetic fields confined inside the ITO layer at the nanogap [see Fig. 1(c)], the peak of the absorption resonance is substantially blueshifted at the visible frequency range, as it can be seen in Fig. 1(d).

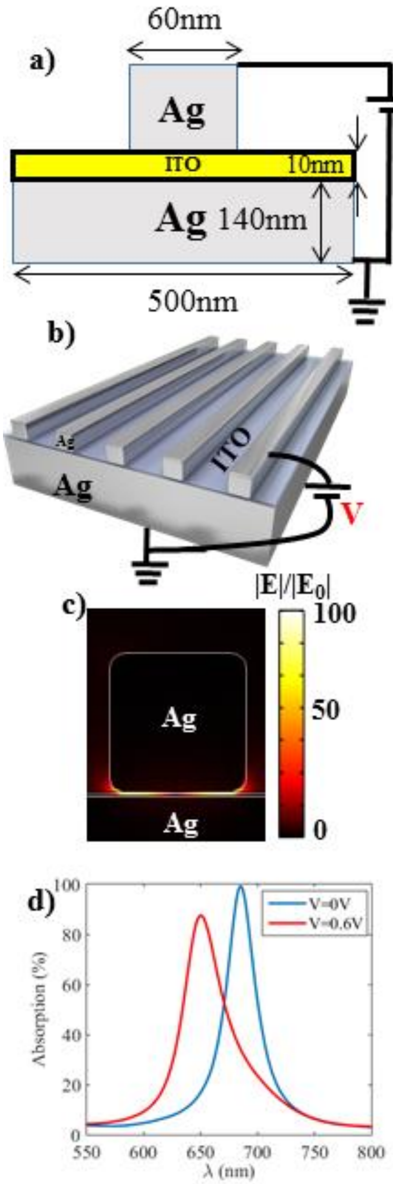

Figure 1. Plasmonic metasurface loaded with ITO for efficient absorption modulation. a-b) Geometry of the proposed modulation device. c) Field enhancement distribution at the nanogap. d) Strong absorption modulation for undoped (V=0V/blue line) and highly doped (V=0.6V/red line) ITO loaded in the nanogap.

The permittivity of ITO follows the Drude model [3]: $\varepsilon_{ITO} = \varepsilon_\infty - \frac{\omega_p^2}{\omega^2 + j\omega\gamma}$, where $\omega_p = e\sqrt{\frac{N_d}{\varepsilon_0 m^*}}$ is the varying plasma frequency depending on the carrier density concentration N_d, $\varepsilon_\infty = 3.9$ is the high frequency ITO permittivity, ω is the angular frequency, ε_0 the free space permittivity, $\gamma = 180THz$ is the electron scattering rate, $m^* = 0.35 m_0$ is the effective mass (m_0 is the electron rest mass), and e is the charge of electron. Much stronger electro-optical modulation is obtained with the proposed hybrid nanostructure compared to recent ITO/plasmonic metasurface designs [5]. The demonstrated nanodevice can act as an efficient, adaptive, and tunable planar optical photodetector.

3. Graphene Dielectric Metasurfaces

The recently discovered graphene is a 2D—one-atom-thick— conductive material with zero-bandgap and linear dispersion [2]. Interestingly, its properties can be tuned in the entire IR and optical frequency range by varying its doping level or Fermi energy with chemical, electrostatic and optical ways [2]. The real and imaginary part of graphene permittivity ε_g at near-IR and optical frequencies and at room temperature are given by [6]:

$$\varepsilon_g^{real}(E) = 1 + \frac{e^2}{8\pi E \varepsilon_0 g} \ln \frac{\left(E + 2|E_F|\right)^2 + \Gamma^2}{\left(E - 2|E_F|\right)^2 + \Gamma^2} - \frac{e^2 |E_F|}{\pi \varepsilon_0 g \left[E^2 + (1/\tau)^2\right]} \quad (1)$$

$$\varepsilon_g^{imag}(E) = \frac{e^2}{4E\varepsilon_0 g}[1 + \frac{1}{\pi}(\tan^{-1}\frac{E - 2|E_F|}{\Gamma} - \tan^{-1}\frac{E + 2|E_F|}{\Gamma})] + \frac{e^2|E_F|}{\pi\tau E \varepsilon_0 g\left[E^2 + (1/\tau)^2\right]} \quad (2)$$

where $g = 1nm$ is the assumed thickness of graphene, in agreement to previous relevant studies which included graphene simulations [6]. The parameter Γ leads to the interband transition broadening at near-IR and optical wavelengths and is equal to $\Gamma = 110meV$ [6]. The free carrier scattering rate $1/\tau$ is assumed to be equal to zero because interband transitions dominate at near-IR and optical frequencies over the much weaker intraband transitions [6]. Note that graphene is modeled as anisotropic medium due to its one-atom thickness. The in-plane permittivities are given by Eqs. (1), (2) $\left(\varepsilon_x = \varepsilon_y = \varepsilon_g\right)$ and the out-of-plane permittivity is equal to free space $\left(\varepsilon_z = 1\right)$. This is different from modeling bulk isotropic media, like the ITO metasurface presented in the previous section.

However, the interaction of graphene with light is relatively poor due to the vast mismatch between its subnanometer thickness and the wavelength of light, a problem that is particularly acute at infrared and optical wavelengths. This problem can be solved with the currently proposed hybrid graphene/dielectric metasurface design with unit cell geometry presented in Fig. 2 that can achieve strong tunable modulated transmission at near-IR frequencies [7].

The all-dielectric hybrid metasurface presented in Fig. 2 is composed of periodically arranged pairs of asymmetric silicon (Si) nanobars with graphene placed on top of this configuration. The silicon nanorods have dimensions: w=600nm, t=150nm, h_1=100nm, h_2=150nm, d=175nm, and g=50nm. The unit cell has equal vertical and horizontal periodicities of w_s=700nm and the thickness of the silica (SiO_2) substrate is t_s=675nm. These all-dielectric silicon-based metasurfaces are powerful platforms to enhance light-matter interactions at nanoscale regions. Their low-loss nature, CMOS processing compatibility, and increased damage threshold promise to outperform the functionalities of the recently established plasmonic metallic metasurfaces, which exhibit high ohmic losses and broader scattering or transmission responses. The low-loss properties of all-dielectric metasurfaces can lead to very high quality factor (Q-factor) Fano resonances and electromagnetically induced transparency (EIT) effects [8]. In addition, these configurations can also sustain very strong and localized electric fields in subwavelength regions.

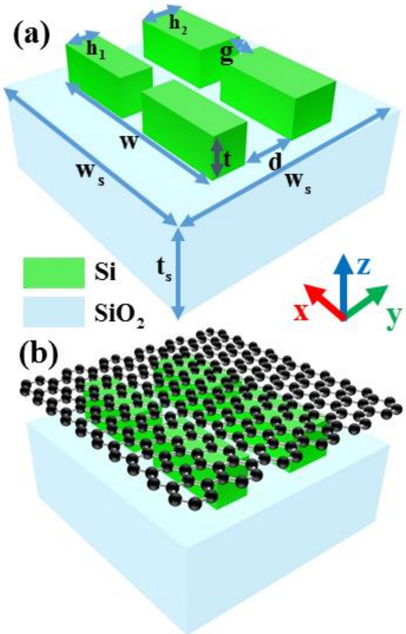

Figure 2. Unit cell geometry of the hybrid graphene/dielectric metasurface a) without and b) with graphene on top.

This particular dielectric metasurface can sustain trapped magnetic resonances with a sharp Fano-type transmission or reflection spectrum signatures [9]. The strong in-plane electric field distribution at the resonance (λ=952nm) is computed and shown in the inset of Fig. 3(a). One-atom-thick graphene based on chemical vapor deposition (CVD) can be transferred and placed over this dielectric metasurface using standard transfer techniques [10]. Very strong transmission modulation is obtained at near-IR wavelengths, around 952nm, very close to visible frequencies, when the doping level [or Fermi energy (E_F)] of graphene is increased, as it is demonstrated in Fig. 3(a). The enhanced in-plane fields (E_x component) along the all-dielectric metasurface strongly interact with graphene. This leads to strong coupling between the incoming electromagnetic radiation and graphene.

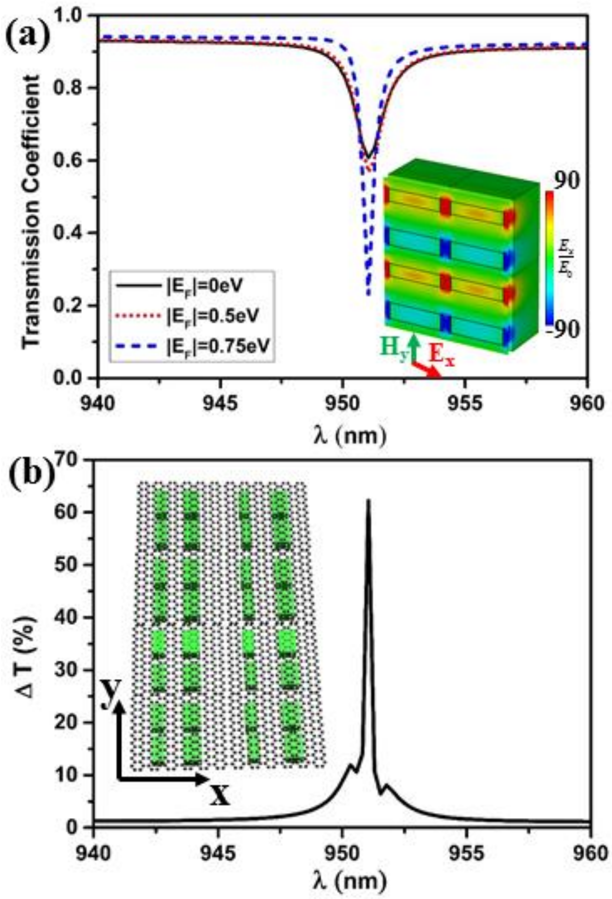

Figure 3. Hybrid graphene dielectric metasurfaces. a) Strong transmission modulation for different doping levels of graphene. Inset: Field enhancement distribution at the resonance. b) Higher than 60% transmission modulation between undoped and heavily doped graphene is obtained in a narrow frequency region.

The transmission amplitude modulation of the proposed structure is presented in a more quantitative way by calculating the difference in transmission between heavily doped ($E_F=0.75eV$) and undoped ($E_F=0eV$) graphene. The absolute value of the transmission difference, $\Delta T=|T(E_F=0.75eV)-T(E_F=0eV)|$, is plotted in Fig. 3(b) as a function of the impinging radiation wavelength. Interestingly, the transmission difference, ΔT (optical modulation), can reach values higher than 60% at the Fano resonance transmission dip (λ=952nm). Note that moderate modulation is also obtained within a narrow wavelength range around the resonance transmission dip. A pair of transparent electrodes placed between either the silica substrate or the silicon nanorods and the graphene can be used to increase or decrease its doping level. The required voltage values for this configuration will be in the range of 2-5V and these low values are not expected to lead to dielectric breakdown [7]. The obtained modulation values are much larger compared to similar designs based on hybrid plasmonic metasurfaces [6] because the in-plane field components (E_x) of the incident wave can be strongly coupled to the deposited graphene only with the proposed all-dielectric metasurface, as it can be seen by the field distribution depicted in the inset of Fig. 3(a). In addition, the modulation speed of this design can reach ultrafast values on the order of tenths of GHz [7, 11]. The proposed hybrid dielectric metasurface design can also be used to boost different properties of other 2D materials, such as fluorescence coming from MoS_2 [12].

4. Conclusions

To conclude, we have presented tunable absorption and transmission responses from hybrid ITO and graphene plasmonic and dielectric metasurfaces. The carrier density concentration of ITO can be varied with the applied voltage [3]. In addition, the doping level of graphene can be altered with electrochemical gating based on ionic liquid electrodes that was used before to gate other relevant hybrid graphene/plasmonic structures [6] or other transparent electrode configurations. The presented hybrid metasurface configurations are envisioned to advance the design of efficient hybrid electronic-nanophotonic configurations that are expected to be fundamental building blocks of the new optical communications and information technology systems. Several novel integrated nanophotonic components are envisioned based on the proposed devices, such as new biosensors, photodetectors, and efficient electro-optical modulators and switches.

5. Acknowledgements

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