Electrical tuning and switching effect in graphene-assisted polarization-insensitive terahertz metadevices

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Abstract—A tunable polarization-independent metadevice exhibiting a broadband cross-polarized transmission with amplitude as high as 40% is investigated numerically in the terahertz (THz) frequency regime. The finite-difference time domain (FDTD) method is employed to simulate the characteristics of the metal-graphene heterostructure. The spectral features of the device are dynamically modulated by varying the chemical potential of an overlaid monolayer of graphene without changing the geometrical dimensions of the resonators. The results suggest the feasibility of highly efficient, nanomaterials-based THz polarizers with vast tunability.

Keywords— metamaterial, reconfigurability, graphene, terahertz, polarizer

I. Introduction

Dynamic reconfiguration has become a vital need in modern communication systems whose aim is to integrate multiple functions to actively compensate for varying system performance in real time. In this context, the implementation of reconfigurable metamaterials (MMs) has become an intense topic of research. Several techniques of tunability have been explored and demonstrated in literature such as integrating phase-change materials [1], localized active components [2], electrically [3], optically [4] and thermally-driven materials [5,6]. The recent advances in atomic-layered two-dimensional (2D) materials such as graphene and transition metal dichalcogenides (TMDCs) have attracted increasing attention and provided new routes in achieving active metadevices [7,8]. Compared to traditional semiconductors, 2D layered materials have very high carrier mobilities and very short carrier relaxation times. For example, graphene has been integrated with metamaterials to achieve tunable electromagnetically induced transparency (EIT) and demonstrate a deep-subwavelength sensing effect in the THz frequency regime [9,10]. In this paper, a tunable hybrid metal-graphene MM exhibiting a broadband cross-polarized transmission is demonstrated numerically in the THz range. The results show that the amplitude of the cross-polarized transmission can be continuously modulated upon increasing the chemical potential of the added graphene sheet.

II. The Designed Metamaterial: Results and Dicussion

The unit cell of the investigated metadevice is schematically shown in Fig. 1(a). It is composed of a metallic cross-shape resonator (CSR) made of 100 nm-thick aluminum, deposited on the top side of a high resistivity silicon (Si) substrate. The relevant geometrical dimensions of the unit cells are: $p_x = p_y = 50$ µm, $l = 36$ µm and $w = 6$ µm. Such periodic structures do not diffract normally incident electromagnetic radiation for frequencies less than 6 THz.

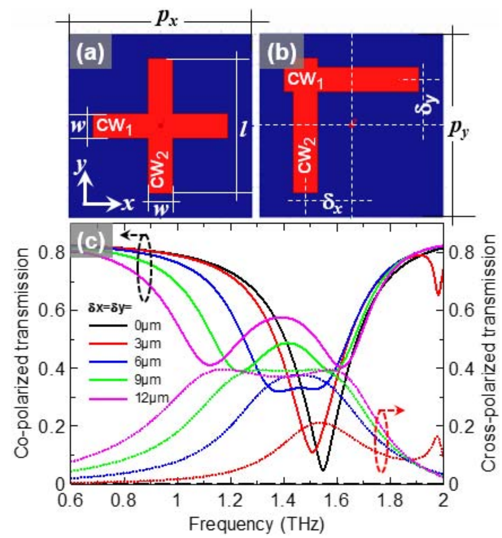

Fig. 1. (a)-(b) Unit cells of the designed symmetric and asymmetric metadevice, respectively with the relevant geometrical dimensions: $p_x = p_y = 50$µm, $l = 36$µm, and $w = 6$µm. (c) Simulated transmission spectra for different values of δ_x and δ_y, respectively.

Numerical calculations were carried out using the finite-difference time domain (FDTD) to predict the spectral response of the device. In these calculations, the elementary cell of the designed metasurface was irradiated at normal incidence, under TM polarization (i.e., E || x-axis). Due to the four-fold rotational symmetry of the CSRs structure, the device has identical response for an incident TE-polarized radiation (i.e., E || y-axis). Periodic boundary conditions were applied in the model to simulate an infinite two-dimensional periodic array. In simulations, the silicon substrate was treated as a lossless dielectric with $\varepsilon = 11.9$ and the aluminum (Al) was modeled as a lossy metal with a conductivity of 3.56×10^7 S/m.

The simulated co- and cross-polarized transmission spectra are plotted in Fig. 1(c) for different values of δ_x and δ_y, respectively. In the symmetric case, (i.e., $\delta_x = \delta_y = 0$ µm), the co-polarized transmission coefficient exhibits a standard dipole resonance localized at around 1.55 THz (black solid line). Upon increasing simultaneously δ_x and δ_y [i.e., by breaking the

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symmetry of the structure, see Fig. 1(b)], one can observe the emergence of a cross-polarized transmission component with a a gradual increase in its amplitude and bandwidth. Indeed, in the extreme asymmetric case, the cross-polarization transmission coefficients (i.e., $t_{yx} = t_{xy}$) reach an amplitude as large as 40% with a full width at half maximum (FWHM) bandwidth of about 880 GHz.

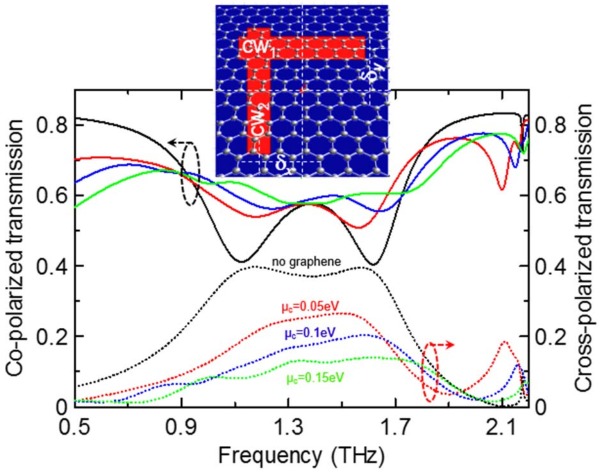

Fig. 2. Evolution of the spectral features of the hybrid graphene-metal metadevice for different values of the chemical potential μ_c.

To demonstrate the dynamic tunability of the spectral features of the asymmetric metadevice, we integrate monolayer graphene into the unit cell, as illustrated in the inset of Fig. 2, and investigate the effect of the chemical potential μ_c on the transmission properties. The graphene sheet is characterized by its surface conductivity σ, which is the sum of the intraband term σ_{intra} and the interband term σ_{inter}. The intraband term can be expressed as [11] :

$$\sigma_{intra}(\omega) = -j\frac{e^2 k_B T}{h^2(\omega - j2\Gamma)}\left(\frac{\mu_c}{k_B T} + 2ln\left(e^{\left(-\frac{\mu_c}{k_B T}\right)} + 1\right)\right) \quad (1)$$

where e is the charge of the electron, k_B is the Boltzmann constant, T is the temperature in K, h = $h/2\pi$ is the reduced Planck's constant, $\Gamma = 1/\tau$ is the carrier scattering rate with τ being the carrier relaxation time and μ_c is the Fermi energy in graphene. The interband term of the graphene conductivity can be expressed for $k_B T \ll |\mu_c|, h\omega$ as :

$$\sigma_{intra}(\omega) = -j\frac{e^2}{4\pi h} ln\left(\frac{2|\mu_c| + (\omega - j2\Gamma)h}{2|\mu_c| - (\omega - j2\Gamma)h}\right) \quad (2)$$

Therefore, the surface conductivity σ of the graphene sheet can be written as :

$$\sigma(\omega) = -j\frac{e^2 k_B T}{h^2(\omega - j2\Gamma)}\left(\frac{\mu_c}{k_B T} + 2ln\left(e^{\left(-\frac{\mu_c}{k_B T}\right)} + 1\right)\right) - j\frac{e^2}{4\pi h} ln\left(\frac{2|\mu_c| + (\omega - j2\Gamma)h}{2|\mu_c| - (\omega - j2\Gamma)h}\right) \quad (3)$$

As the chemical potential of the graphene increases from 0.05 eV to 0.15 eV, the amplitude of the cross-polarized transmission gradually decreases from 40% to about 15% and similar modulation effect is observed on the co-polarized transmission coefficient [see Fig. 2].

III. Conclusion

In conclusion, we have demonstrated numerically an active control and modulation effect in a graphene-based metadevice exhibiting a broadband cross-polarized transmission in the THz frequency regime. Our results could pave the way towards the development of compact tunable and highly efficient polarization control metadevices.

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