Electro-optic Modulator Based on a Graphene-embedded Metasurface

Electric-modulated reflectance spectra based on high-*Q* quasi-BICs in symmetry-broken metal-dielectric hybrid metasurfaces

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Abstract

Optical metasurfaces enable exceptional light manipulation [1,2], and integrating active materials with resonant structures provides a promising route toward compact, tunable photonic devices [3]. Here, we propose a reflective graphene-embedded metasurface composed of asymmetric Si gratings, a SiO_2 spacer, monolayer graphene, and an Au reflector. By breaking the in-plane symmetry of Si gratings, a quasi-bound state in the continuum (quasi-BIC) with a high quality factor (Q) is excited, producing strong near-field confinement within the Si gratings. This localized field enhances light-graphene interactions, enabling external-voltage control of the resonance for electrically reconfigurable modulators.

Methodology

The metasurface operates in reflection mode with an Au reflector eliminating transmission. Each unit cell contains two Si gratings with a designed width difference ΔW, which breaks the in-plane symmetry. Figure 1(a) presents the reflectance spectra as a function of ΔW, with insets showing the corresponding $|E|$ and E_y distributions. In a symmetric grating array (ΔW = 0), a symmetry-protected BIC exists with $Q \to \infty$, and no resonance dip appears. Introducing ΔW transforms this BIC into a quasi-BIC with a finite but high Q, enabling external excitation. A resonance dip emerges and deepens with increasing $|\Delta W|$, with stronger in-plane near-field enhancement. The corresponding Q factors are plotted in Fig. 1(b). Q_{rad} decreases as ΔW deviates from zero, while Q_{dis} remains nearly constant. Critical coupling ($Q_{rad} = Q_{dis}$) occurs at the intersection of the two curves, corresponding to the maximum resonance amplitude (minimum reflectance) in Fig. 1(a).

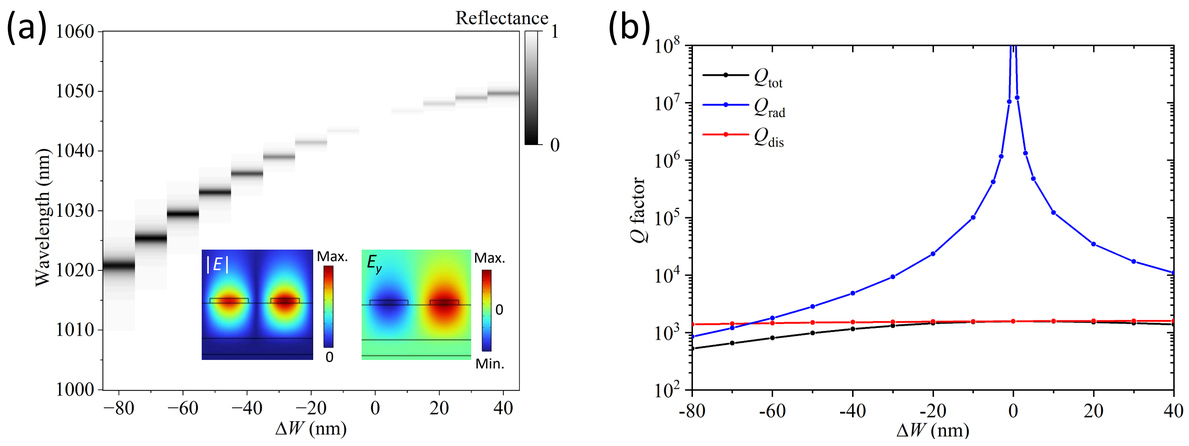


Fig. 1. (a) Reflectance spectra as a function of ΔW. The insets are the electric field norm ($|E|$) and y-component (E_y) distributions, respectively. (b) The variations of Q_{tot}, Q_{rad}, and Q_{dis} with ΔW.

Figure 2(a) shows graphene's complex surface conductivity vs E_f, and its effect on the reflectance is presented in Fig. 2(b) at E_f = 0 and 0.8 eV. As E_f increases, the dip blue-shifts and reflectance drops from about 0.7 to near-zero, yielding a modulation depth of nearly 100%. External voltage tuning of E_f thus enables dynamic control of the resonance and reflectance.

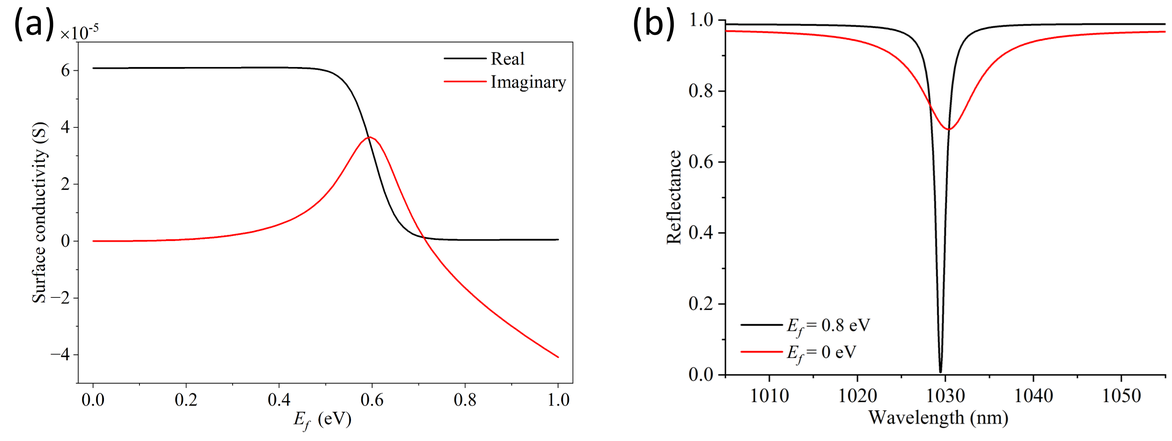


Fig. 2. (a) The real part and imaginary part of graphene surface conductivity versus Fermi energy at the wavelength of 1030 nm. (b) The reflectance spectra obtained under normal plane-wave incidence at graphene's E_f of 0 eV and 0.8 eV, respectively.

Results

Based on the quasi-BIC mechanism, the proposed metasurface can function as a wavelength-tunable modulator, as shown in Fig. 3. For TE-polarized incidence in the x-z plane, increasing the incident angle ϑ induces a red shift of the resonance [Fig. 3(a)]. For TM-polarized incidence in the y-z plane, the resonance exhibits a blue shift with increasing ϑ [Fig. 3(b)]. The modulation amplitude, defined as the reflectance difference between the Fermi level of 0 eV and 0.8 eV, remains stable in both configurations. These results demonstrate that the metasurface enables angle-tunable resonance wavelength switching with stable modulation amplitude, offering a compact platform for reconfigurable photonic devices.

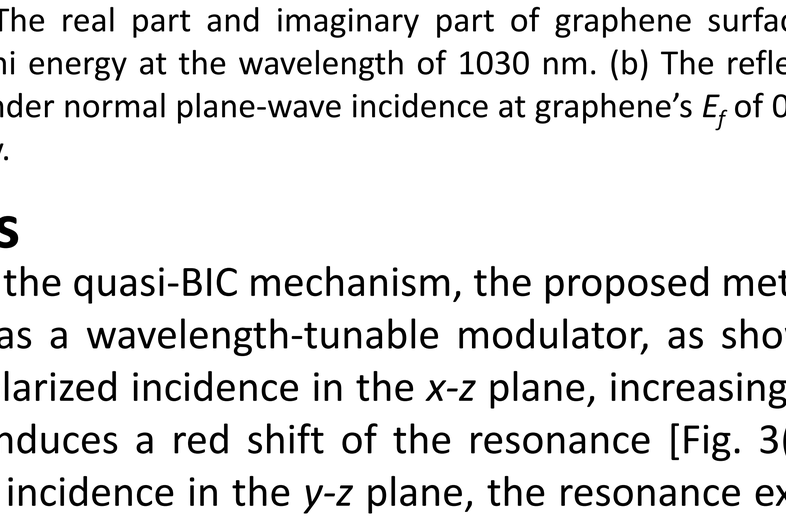


Fig. 3. (a) Schematic of TE-polarized oblique incidence in the x-z plane (top) and modulation amplitude at different incident angles ϑ (bottom). (b) Schematic of TM-polarized oblique incidence in the y-z plane (top) and modulation amplitude at different ϑ (bottom).

References

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