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Surface plasmons dynamic control metasurface based on bright-dark mode coupling in terahertz regime

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Abstract

Research on surface plasmons (SP) has significantly advanced various applications, including photonic signal processing, highly sensitive sensing, and on-chip integrated systems. The utilization of metasurfaces for the propagation and modulation of SP has garnered extensive attention in research. This paper presents the incorporation of graphene into a metasurface structure as a dynamic excitation source. By manipulating the Fermi energy of graphene to modify its conductivity, active control of surface plasmons is achieved, thereby offering novel possibilities for future on-chip integrated switches and data storage.

Keywords

Surface plasmons, metasurface, graphene, active control.

1. Introduction

Surface plasmons is an electromagnetic mode that propagates on the metal-dielectric surface and is formed by the interaction of free electrons and photons [1]. Due to its unique two-dimensional propagation characteristics, SP has broad application prospects, such as spectral imaging [2], focusing lens [3], and biosensing [4], etc. To realize these applications, the excitation of SP is a key step. The traditional excitation method (prism or grating coupling) has great deficiencies in the degree of freedom and flexibility of design [5-6]. By introducing the classical theory of bright-dark mode coupling in electromagnetically induced transparency (EIT), a new path is paved for the excitation of SP. Coupled resonators can obtain more peculiar SP responses, and different degrees of SP excitation can be obtained by changing the parameters of the structure [7-8]. However, most of the above work is passive, which is far from meeting the needs of new terahertz functional devices. Therefore, active tunable SP devices have attracted great attention. Graphene is a good candidate for active modulation materials. Its unique optical properties, such as patterning constraints, low ohmic loss, ultra-fast response and other unique characteristics have attracted people's research interests [9-11]. In particular, changing the conductivity of graphene by applying a static bias voltage to dynamically control the critical coupling effect of the coupled resonator has been widely used, which provides a new design idea for real-time control of SP devices [12-13].

This paper presents a design of metal slit array metasurface devices composed of bar-shape slit resonator (BSSR) and double U-shape slit resonator (DUSSR) units, based on the theory of bright-dark mode coupling. To actively control the propagating intensity of the SP beam, the graphene ribbon is integrated into the center of the DUSSR array and its Fermi energy is tuned. The results demonstrate the strong interaction between graphene ribbons and metallic resonance-based localized SP metasurfaces. These findings have broad applications in on-chip integrated switches and data storage.

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2. Design and Results

The schematic diagram of the designed unit cell structure is shown in Figs. 1(a) and (b). The metal EIT slit (EITs) composed of BSSR (as bright mode) and DUSSR (as dark mode) units are evenly distributed on the quartz substrate, and the graphene bands are integrated into the center of the DUSSR. The specific structural parameters are shown in Fig.1(a): the periodic boundary is P = 400 μm, the length and width of BSSR are l = 120 μm and g = 10 μm respectively, the length and width of DUSSR are a = 55 μm and b = 45 μm respectively, and the coupling distance between them is d = 8 μm. The open boundary conditions are set in all directions of the structure, and the terahertz wave is incident vertically from the substrate to the metasurface in an x-polarization state. The aluminum is modeled as a lossy metal with $\sigma_m = 3.56 \times 10^7$ S / m, and the quartz are modeled as lossless dielectrics with $\varepsilon_q = 3.76$. The CST Microwave Studio time domain solver based on the finite element method is used to simulate the structure.

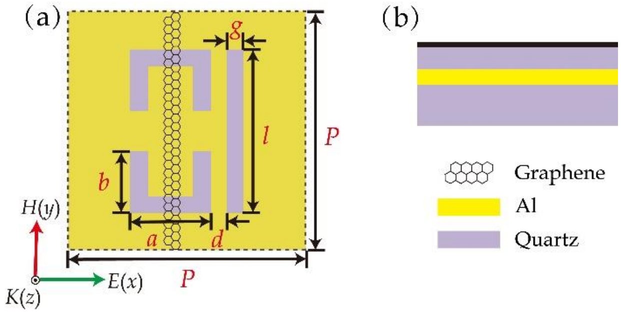

Fig. 1 Schematic of active metasurface. (a) a periodic unit cell of 8×8 EITs array, (b) side view of the metasurface.

To achieve active control of the SP, the conductivity of graphene is adjusted by changing the Fermi energy. For graphene ribbons, the electromagnetic properties are considered by the surface conductivity σg through the Kubo model intra-band (σ_{intra}) and inter-band (σ_{inter}) transitions [11-13]:

$$\sigma_g = \sigma_{\text{intra}} + \sigma_{\text{inter}}, \tag{1}$$

$$\sigma_{\text{intra}} = i\frac{e^2 k_B T}{\pi\hbar^2(\omega + i\tau^{-1})}\left[\frac{E_F}{k_B T} + 2\ln(\exp(-\frac{E_F}{k_B T}) + 1)\right], \tag{2}$$

$$\sigma_{\text{inter}} = i\frac{e^2}{4\pi\hbar}\ln\left[\frac{2|E_F| - \hbar(\omega + i\tau^{-1})}{2|E_F| + \hbar(\omega + i\tau^{-1})}\right]. \tag{3}$$

where, $\hbar$ is the Planck constant, e is the electron charge, T is the temperature, k_B is the Boltzman constant, τ is the electron-phonon relaxation time, E_F is the Fermi energy, respectively. Under the incidence of weak terahertz field, τ = 50 fs remains basically unchanged.

Fig. 2 illustrates the simulated distribution of the SP field at 0.73THz and the normalized transmission spectrum for different E_F (0.2, 0.6, and 0.12 eV). In Fig. 2(c), it can be observed that as the E_F of graphene increases, the SP field at the top (P_1) disappears, while the suppressed SP field on the left (P_2) gradually emerges, resulting in an overall horizontally propagating SP field. The transmission spectra in Figs. 2(a) and (c) show that the resonance valley at P_2 gradually transitions into a resonance peak, while the resonance peak at P_1 diminishes as the Fermi energy increases.

To analyze the modulation phenomenon mentioned above, we first provide a brief description of the EIT microstructure without graphene ribbons illustrated in Fig. 3(b). The metal rod serves as a localized surface plasmon resonator, where the electric field along its length is connected to localized surface plasmon oscillations. The E_x and H_z field distributions of the bar-shape resonator (BSR) are depicted on the left side of Figs. 3(c) and (d), respectively. Based on the Lorentz theorem, the surface current of the double U-shaped resonator (DUSR) circulates counterclockwise when coupled with the H_z field. Similarly, the surface current of DUSR also circulates counterclockwise when coupled with the E_x field. Under the joint action of electromagnetic coupling, the surface current circulates in the same phase, resulting in in-phase interference of the DUSR resonance. This in turn leads to a strong interference effect with the BSR, as depicted on the right side of Figs. 3(c) and (d). Applying the Babinet principle [14], we can infer a similar coupling mechanism between BSSR and DUSSR, where the coupling fields are the electric field E_z and the magnetic field H_x.

Next, we designed EITs as shown in Fig. 3(a) and then simulated the E_z and H_x field distributions of EITs and BSSR. From Fig. 3(e), we can see that SP is excited symmetrically by BSSR, but the phase is opposite, and there is no SP on the top of BSSR. It can be seen from Fig. 3(f) that the H_x field is mainly excited at the end of the BSSR. When the DUSSR is placed on the left side of the BSSR, we can find that the SP strength on the DUSSR side is strongly suppressed, and the E_z and H_x fields work together on the DUSSR leads to its strong excitation, see Figs. 3(g) and (h). Such an EIT-like coupling mechanism of SP excitation provides the basis for its active control. So, integrating graphene into the center of DUSSR and increasing its E_F leads to an increase in conductivity. This increase in conductivity causes a resonance loss in DUSSR similar to the EIT coupling effect [12], resulting in a weakening of the resonance intensity of DUSSR itself. As a result, the suppression on the left side of the BSSR is reduced, leading to the disappearance of the SP fields at the top and bottom of the structure, while the suppressed SP field appears on the left side of the BSSR.

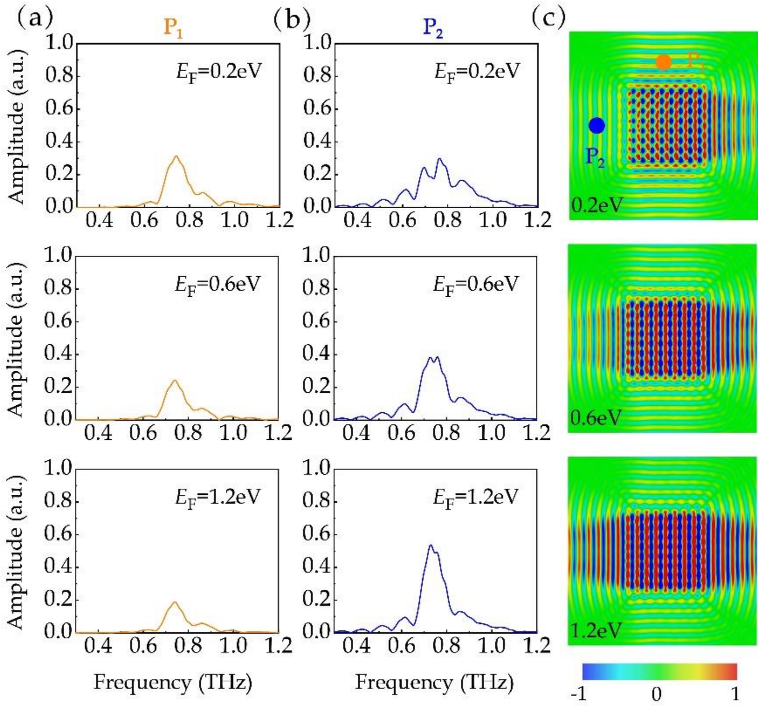

Fig. 2 The normalized transmission spectrum and SP field distribution are analyzed as a function of the E_F. (a) and (b) show the extracted normalized transmission spectra at the top and left sides, respectively, at a distance of 3 nm from the center. (c) The SP field distribution at 0.73 THz.

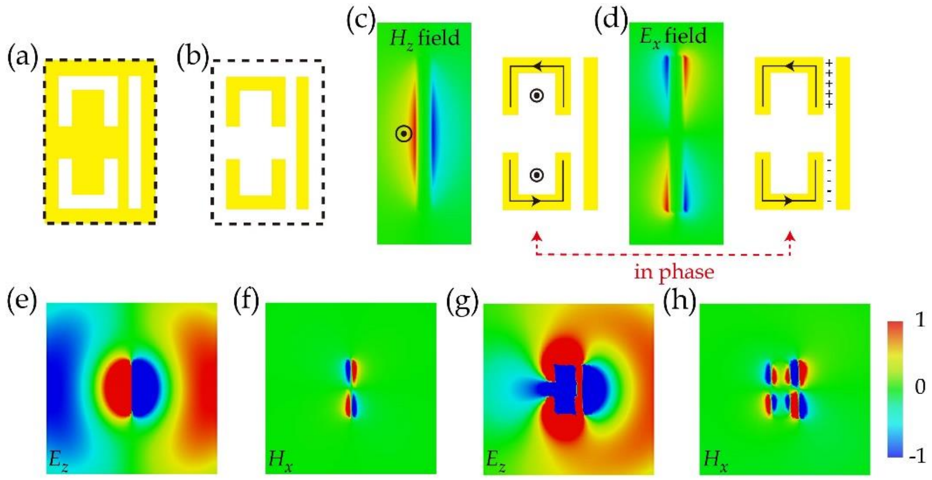

Fig. 3 Resonance coupling analysis based on Babinet principle. (a) the EITs structure scheme, (b) the metal EIT structure for the proposed EITs, the H_z and E_x field distributions of the simulated BSR on the left side of (c) and (d), while the surface current circulating directions in the DUSR at a same moment are shown on the right, which are indicated by the corresponding black arrows, (e-h) the E_z and H_x field distributions of the simulated BSSR and EITs, respectively.

3. Conclusion

In this study, we introduce a theoretical proposal for an active surface plasmon (SP) metasurface by leveraging the interaction between bright and dark modes. Taking inspiration from the coupling mechanism observed in electromagnetically induced transparency (EIT), we incorporate graphene into an integrated array of EITs metasurface and manipulate its Fermi energy to actively control the intensity of the excited SP. This approach opens up new possibilities for manipulating and transporting light in upcoming integrated optical chips.

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