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Exploring a novel approach to manipulating plasmon-induced transparency

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ABSTRACT

Plasmon-induced transparency (PIT) effect is an important optical phenomenon in plasmonic structures. In this paper, we design a plasmonic structure to realize the manipulation of PIT simply by varying the angle of the ellipse. It consists of a single hexagonal resonator inserting a rotatable ellipse coupled with the metal–insulator–metal (MIM) waveguide. According to the temporal coupled-mode theory, it is found that the PIT effect results from the destructive interference of two modes. The finite-difference time domain (FDTD) simulations reveal that by rotating the angle of the ellipse the transmission of transparency peak can range from 0.9% to 83% as the full width at half maximum (FWHM) of transparency window varies from 0 nm to 68.6 nm. In addition, the influences of other structural parameters such as the side length of the hexagon, radii of the ellipse, the refractive index of the resonator and so on, are also studied by simulations. Since the PIT effect can be regulated in a single resonator without changing other structural parameters, the proposed plasmonic structure has a great significance on highly nano-integrated optical circuits.

1. Introduction

Surface plasmon polaritons (SPPs) are a special kind of electromagnetic wave that perform highly characteristic of localization [1–4]. They trap on the metal–insulator interface which have the capabilities to overcome the classical diffraction limit and manipulate light in the sub-wavelength domain [5,6]. Therefore, SPPs have potential applications in the design of precision photonic devices. Predecessors mainly research varieties of functional devices based on SPPs, such as filters [7–9], sensors [10–12], demultiplexers [13,14] and so on. Most of them are implemented owing to the PIT effect. PIT is a special optical phenomenon based on SPPs [15–17]. It not only possesses the advantages of low power consumption, ultrafast response time and extremely narrow linewidth, but also is able to break the limits of harsh conditions such as low-temperature environments and stable gas lasers [18–21]. Therefore, researchers pay more attention to the study of PIT effect. Many types of structures are proposed. For instance, a structure based on the stub waveguide coupled with a nanodisk resonator [22], a phase-coupled PIT scheme based on dual resonators [23], and a device based on PIT which is composed of a MIM waveguide side coupled with slot resonators [24]. These structure also achieve better results, but they deserve further investigation. The majority of structures require more than one resonator to achieve the PIT effect, which extends the size of materials and is not conducive to improve the integration further. Most importantly, for the regulation of PIT, the traditional approach is to change geometric dimensions which seems impractical and inconvenient. Because once the device is manufactured, geometric dimensions of the structure are difficult to be changed unless re-make it. Thus it is urgent to propose a new kind of device which can solve these problems simultaneously.

In order to achieve PIT effect simply, to our acknowledgment, we design a novel plasmonic structure that PIT can be implemented and manipulated in a single resonator. It is composed of a hexagonal resonator inserting a rotatable ellipse with a metal–insulator–metal (MIM) waveguide. The coupled mode theory and finite-difference time-domain (FDTD) method are introduced to investigate the PIT phenomenon theoretically and numerically. The results show that through rotating the angle of ellipse, not only can PIT effect be realized in a single resonator but also the values of transparency peak and transparency window can be tuned by a large margin. In order to obtain more suitable structural parameters, we also study the effects of geometric dimensions of the structure and the refractive index of the resonator on the transmission characteristics. This structure could be used to design a

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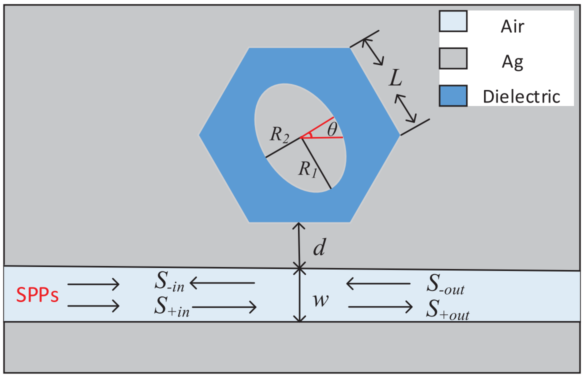

Fig. 1. Schematic diagram of the hexagonal resonator inserting a rotatable ellipse coupled with the MIM waveguide.

variety of functional devices, such as sensors, filters, optical switching, slow-light devices and so on. It will play significant roles in highly nano-integrated optical circuits.

2. Structure model and theoretical analysis

Fig. 1 shows a two-dimensional schematic diagram of the proposed plasmonic structure which consists of a MIM waveguide and a hexagonal resonator inserting a rotatable ellipse. The dimensional parameters of the structure L, R_1 and R_2 are the side length of the hexagonal resonator, the two different radii of the ellipse respectively. θ is the angle between the positive direction of the X-axis and the short axis of ellipse. d denotes the coupling distance between the boundaries of the hexagonal cavity and the MIM waveguide, w is the width of the MIM waveguide. In the structure, the medium of waveguides is set to be air. The refractive index of dielectric embedded in the resonator is n. Besides, the background metal is supposed to be silver whose frequency-dependent relative permittivity can be characterized by the Drude model [25]:

$$\varepsilon_m(\omega) = \varepsilon_\infty - \omega_p^2/[\omega(\omega + i\gamma)] \tag{1}$$

where $\varepsilon_\infty = 3.7$, $\omega_p = 9.1$ eV and $\gamma = 0.018$ eV respectively represent the dielectric constant of the infinite frequency, the bulk plasma frequency and the electron collision frequency. ω represents the angular frequency of the incident wave. Then, in this model, SPPs waves are generated from the fundamental TM mode whose dispersion relation in the MIM waveguide can be obtained by the following equations:

$$(\varepsilon_m k_d) tanh(\frac{wk_d}{2}) + \varepsilon_d k_m = 0 \tag{2}$$

$$k_d = \sqrt{\beta^2 - \varepsilon_d k_0^2} \tag{3a}$$

$$k_m = \sqrt{\beta^2 - \varepsilon_m k_0^2} \tag{3b}$$

where ε_d, ε_m, k_d, k_m are the permittivities and propagation constants of the dielectric and metal, individually. $k_0 = 2\pi/\lambda$ means the wave vector in vacuum and $\beta = k_0 n_{eff}$ stands for the wave vector in the waveguide. When SPPs are coupled to the hexagonal resonator, it needs to satisfy the following resonance condition:

$$\frac{L_{eff}}{\lambda_n} Re(N_{eff}) + \phi = 2\pi m \tag{4}$$

$\lambda_n = 2\pi c/\omega_n$ is the resonant wavelength of TM_{2a} and TM_{2b}, c is the speed of light propagating in the vacuum. $Re(N_{eff})$ presents the effective index of the resonator for SPPs, which is dependent on the refractive index n. L_{eff} is the effective resonant length. m is a positive integer, corresponding to the number of antinodes of the standing wave in the resonator, and ϕ represents the total phase shift at the corners of the hexagonal resonator. According to Eq. (4), it is apparent that the resonance wavelength is related to the L_{eff} and $Re(N_{eff})$.

The SPPs propagating from the input port to the output port couple into the resonator. The transmission characteristics of the structure can be investigated according to the temporal coupled-mode theory. There are two kinds of modes in this system. They are TM_{2a} and TM_{2b} respectively. The PIT effect is resulted from the destructive interference between two modes in the single resonator. Similar physical principles are found in [26]. The temporal evolution of normalized mode amplitude a_n $(n = 1, 2)$ can be described as:

$$\frac{da_n}{dt} = (-j\omega_n - k_{i,n} - k_{c,n})a_n + e^{j\phi_n}\sqrt{k_{c,n}}(S^n_{+in} + S^n_{-in}) \tag{5}$$

ω_n is the angular frequency of TM_{2a} and TM_{2b}. $k_{i,n} = \omega_n/2Q_{i,n}$ and $k_{c,n} = \omega_n/2Q_{c,n}$ are decay rates of the field due to internal loss in the cavity and coupled loss from the MIM waveguide to the resonator. $Q_{i,n}$ and $Q_{c,n}$ are the intrinsic and coupling quality factors. ϕ_n stands for the phase of the coupling coefficient of TM_{2a} and TM_{2b}. $S^n_{\pm in}$ is the amplitude of the inputting wave of two modes in the MIM waveguide. The amplitudes of outgoing waves $S^n_{\pm out}$ can be written as:

$$S^n_{-out} = S^n_{-in} - e^{-j\phi_n}\sqrt{k_{c,n}}a_n \tag{6a}$$

$$S^n_{+out} = S^n_{+in} - e^{-j\phi_n}\sqrt{k_{c,n}}a_n \tag{6b}$$

As shown in Fig. 1, $\pm$ represent two propagating directions of waveguide modes. According to the above equations, transmission and reflection coefficients of a single mode can be obtained as follow:

$$t_n = \frac{j(\omega_n - \omega) + k_{i,n}}{j(\omega_n - \omega) + k_{i,n} + k_{c,n}} \tag{7a}$$

$$r_n = -\frac{k_{c,n}}{j(\omega_n - \omega) + k_{i,n} + k_{c,n}} \tag{7b}$$

Consequently, inputting and outgoing waves of the nth mode in multi-mode-coupled waveguide systems satisfy the following transfer equation:

$$\begin{bmatrix} S^n_{-in} \\ S^n_{+out} \end{bmatrix} = \begin{bmatrix} -\frac{r_n}{t_n} & \frac{1}{t_n} \\ 1 + \frac{r_n}{t_n} & \frac{r_n}{t_n} \end{bmatrix} \begin{bmatrix} S^n_{+in} \\ S^n_{-out} \end{bmatrix} \tag{8}$$

The propagation waves should satisfy the relationship in the steady state: $S^1_{-in} = S^2_{-out}e^{j\varphi}$, $S^2_{+in} = S^1_{+out}e^{j\varphi}$. φ represents the phase difference of two modes. Thus, the transmission characteristic in the entire system can be described as:

$$\begin{bmatrix} S_{-in} \\ S_{+out} \end{bmatrix} = \begin{bmatrix} -\frac{r_1}{t_1} & \frac{1}{t_1} \\ 1 + \frac{r_1}{t_1} & \frac{r_1}{t_1} \end{bmatrix} \begin{bmatrix} 0 & e^{j\varphi} \\ e^{-j\varphi} & 0 \end{bmatrix} \begin{bmatrix} -\frac{r_2}{t_2} & \frac{1}{t_2} \\ 1 + \frac{r_2}{t_2} & \frac{r_2}{t_2} \end{bmatrix} \begin{bmatrix} S_{+in} \\ S_{-out} \end{bmatrix} \tag{9}$$

where $S_{\pm in}$ and $S_{\pm out}$ represent the amplitudes of the inputting and outgoing waves in the entire system. When the SPPs are launched only from the left port of the waveguide that means $S_{-in} = 0$, the output transmission efficiency can be derived as:

$$T = \left|\frac{S_{+out}}{S_{+in}}\right|^2 = \left|\frac{t_1 t_2}{1 - r_1 r_2 e^{j2\varphi}}\right|^2 \tag{10}$$

When $\varphi = 0, \pi, 2\pi, 3\pi \ldots$, the maximum value of transmission can be obtained.

$$T_{max} = \left|\frac{t_1 t_2}{1 - r_1 r_2}\right|^2 \tag{11}$$

According to the above equations, we know that T is related to t_n and r_n, in addition, t_n and r_n are related to ω_n. Therefore, we can change ω_n by tuning structural parameters such as θ to achieve the regulation of T.