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Dual-band plasmon induced transparency controlled by the polarization of the incident wave

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ABSTRACT

In this paper, a hybridized plasmonic waveguide system is investigated numerically. By coupling plasmonic modes with different waveguide modes, two plasmon induced transparency (PIT) windows with high transmittance and deep modulation can be realized. Through the polarization of the incident wave, the transparency windows can be dynamically controlled.

1. Introduction

Metallic nanoparticles exhibit extraordinary optical properties due to the support of localized surface plasmon polaritons (LSPs) [1]. When LSPs are excited, local electric field around the nanoparticles could be greatly enhanced, which has been utilized in sensing [2], surface-enhanced Raman scattering [3], optical antennas [4], perfect lens [5] and nanolasers [6]. Recently, LSPs have been used to mimic the famous quantum phenomenon of electromagnetically induced transparency (EIT) [7–20]. It is also called plasmon induced transparency (PIT).

PITs are usually obtained by the interference of different plasmonic resonators. There is one superradiant mode and one or several subradiant modes. When light is projected on the material including these resonators, the coupling between them causes transparency peaks within absorbing bands in the transmittance spectrum. A rich variety of nanoparticles have been demonstrated to realize PITs [7–15]. Among them, multi-band PITs have been realized [12], and often suffers from the metal loss, resulting in low transparency peaks and weak modulation depths. Dynamic control of PIT has also been demonstrated experimentally by controlling the angle of the incident wave [13,14]. PITs obtained through coupling between plasmonic modes and waveguide modes are less affected by the metal loss and often get almost 100% transparency at the transmission peak [16–20]. In this paper, an array of plasmonic resonators is put on the waveguide system. By adjusting the parameters of the array, different plasmonic modes are coupled to different waveguide modes and dual-band PITs can be realized. By controlling the polarization of the incident wave, either one of the transmittance peaks can be suppressed dynamically. This design will be useful in biosensing, optical antennas and light emitting [21,22].

2. Structures and the simulation model

The proposed system is illustrated in Fig. 1. The silver nanoparticle array is on top of a TiO_2 waveguide slab, which is 200 nm thick and on a glass substrate. The unit cell of the array is composed of three rods, which was first proposed in Ref. [7], as shown in Fig. 1(b). The pair of parallel rods along x-axis are $L_1 = 100$ nm long and the vertical rod along y-axis is $L_2 = 115$ nm long. The space between two parallel rods is $s = 20$ nm, and the distance between the vertical rod and parallel rods is $d = 40$ nm. All these rods are 30 nm wide and 20 nm thick. The lattice constant are set to be $P_x = 575$ nm and $P_y = 400$ nm.

To investigate the resonant behavior of the structure, we employ the commercial software COMSOL Multiphysics, which is based on finite element method. The incident plane wave is normal to the array and is polarized parallel to the array. The refractive indexes of the substrate and the waveguide slab are set as 1.5 and 2.1 respectively. The permittivity of silver is taken from Ref. [23]. In our calculations, the imaginary part of the metal permittivity is set

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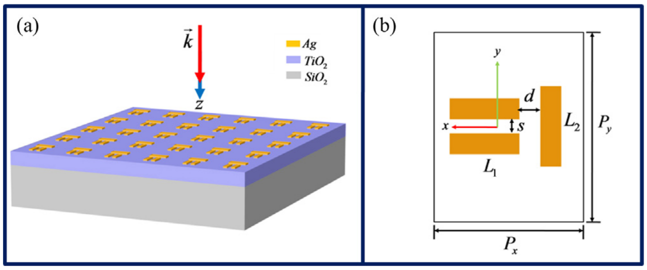

Fig. 1. Schematic of the hybrid waveguide structure (a) and its unit cell (b). The geometrical parameters: L_1 = 100 nm, L_2 = 115 nm, s = 20 nm, d = 40 nm, P_x = 575 nm, and P_y = 400 nm.

to be three times of bulk silver, to account for the grain boundary effects and imperfects in real thin films.

We take one unit cell as our simulation model. Two pairs of periodic boundary conditions are set along x- and y-axis to mimic the infinite periodic array. Perfect matched layers (PMLs) are applied on the top and bottom to absorb scattering. The substrate is treated as semi-infinite to simplify the model. Substrates used in experiments are usually 1 mm thick, which are thick enough to be regarded as semi-infinite in optical and near infrared. The incident plane wave is normal to the substrate and projected from the air side. Each calculation is composed of two steps. The electromagnetic field distribution without silver particles is calculated first and used as the excitation in the second step where we calculate the scattered field to get the transmittance T. The meshes are set to be more than six per wavelength in each dielectric media to get reliable results.

3. Results and discussion

If a homogenous dielectric slab sandwiched between two semi-infinite media with refractive indices smaller than the slab, waveguide modes exit. These modes are bounded EM states and cannot be excited by the normally incident wave. According to classical optics, the propagation index β of the optical modes satisfy the following equations:

TE:

$$t\sqrt{k_0^2\varepsilon_{WG}-\beta^2} = arctg\left(\sqrt{\frac{\beta^2-k_0^2\varepsilon_0}{k_0^2\varepsilon_{WG}-\beta^2}}\right) + arctg\left(\sqrt{\frac{\beta^2-k_0^2\varepsilon_{sub}}{k_0^2\varepsilon_{WG}-\beta^2}}\right) + n\pi \quad (1)$$

TM:

$$t\sqrt{k_0^2\varepsilon_{WG}-\beta^2} = arctg\left(\frac{\varepsilon_{WG}}{\varepsilon_0}\cdot\sqrt{\frac{\beta^2-k_0^2\varepsilon_0}{k_0^2\varepsilon_{WG}-\beta^2}}\right) + arctg\left(\frac{\varepsilon_{WG}}{\varepsilon_{sub}}\cdot\sqrt{\frac{\beta^2-k_0^2\varepsilon_{sub}}{k_0^2\varepsilon_{WG}-\beta^2}}\right) + n\pi \quad (2)$$

t = 200 nm is the thickness of the waveguide slab. $\varepsilon_0 = 1$, $\varepsilon_{WG} = 4.41$ and $\varepsilon_{sub} = 2.25$ are the permittivities of air, waveguide and substrate materials. Because of these parameters, only fundamental modes can exist in optical and near infrared, which means $n = 0$. When a 2D periodic lattice of particles is put on the slab, waveguide modes can be transformed from bound to radiative, which are called quasiguided (or leaky) modes [23–26]. Under normal incidence, the propagation index β of the optical modes can be provided by the lattice parameters.

$$\beta = \sqrt{\left(n_x\frac{2\pi}{P_x}\right)^2 + \left(n_y\frac{2\pi}{P_y}\right)^2}, \quad n_x, n_y = 0, 1, 2, \ldots \quad (3)$$

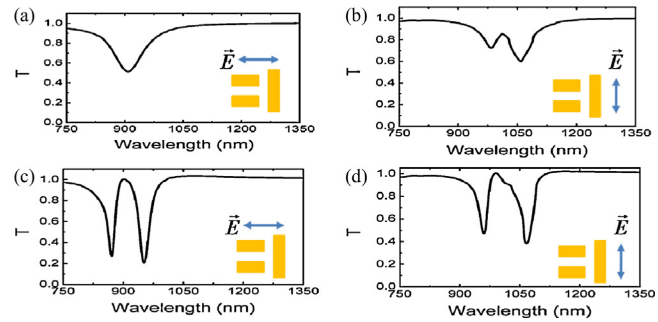

Fig. 2. Transmittance spectra for normally incident light and polarized along x axis (a and c) and y axis (b and d). (a and b) Transmittance spectra for the silver nanoparticle array mounted on TiO_2 substrate. (c and d) Transmittance spectra for the silver nanoparticle array mounted on the waveguide-substrate structure.

When the incident wave is polarized along x axis, the symmetric plasmonic mode of the parallel rods are excited at about 900 nm, as shown in Fig. 2(a). When the incident plane wave is polarized along y axis, there is a PIT at around 1000 nm caused by the individual plasmonic resonators (Fig. 2(b)). The weak modulation depth of the transmission peak is mainly due to the metal loss [8]. By solving the transcendental equations we set P_x = 575 nm so that there is a TM leaky mode at about 900 nm under x-polarized incidence and a TE leaky mode at about 1000 nm under y-polarized incidence. We set P_y = 400 to ensure all other modes will be suppressed. So we can get PIT phenomena at different wavelengths when the incident wave are orthogonal polarized, as shown in Fig. 2(c and d).

The transmission window at 900 nm is caused by the coupling of the symmetric mode of the parallel rods and the fundamental TM mode. The transmission is almost 100% at the peak and the modulation depth is almost 80%. Another transmission peak at 1000 nm is caused one superradiative mode and two subradiative modes. The longitudinal plasmonic mode of the vertical rod is the bright mode and the fundamental TE mode and the antisymmetric mode of the parallel rods serve as the dark modes. The transmission at the peak and the modulation depth are improved greatly compared with the PIT without waveguide structure (Fig. 2(b)).

We apply the model of coupled harmonic oscillators [27], to elucidate the physics involved in the coupling of plasmonic and waveguide modes. When the normally incident wave is polarized

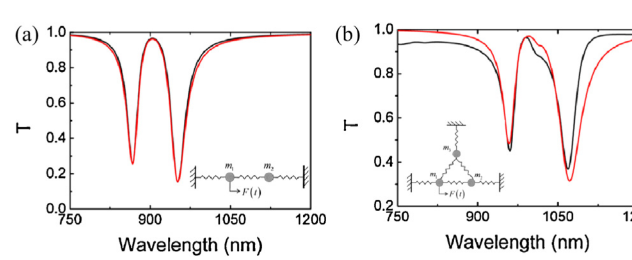

Fig. 3. Comparisons between numerical simulations (black) and classical oscillator models (red). (a) Transmittance under x polarized incident wave. (b) Transmittance under y polarized incident wave. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)