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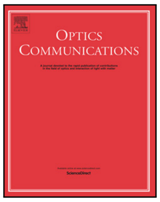

Pump-tuned plasmon-induced transparency for sensing and switching applications

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ABSTRACT

A novel implementation for plasmon-induced transparency (PIT) is investigated theoretically and numerically. The structure is composed of a bus waveguide coupled to a nanodisk and two internally tangent disks (TITD). It is shown that the PIT peak can be tuned from 782 to 815 nm using an external pump laser with an intensity of up to 24.39 MW/cm^2 (power $\cong$ 2 mW). The wavelength, transmission and width of the PIT peak can be adjusted by changing the nanodisk-TITD gap and the radius of the internal disk. The proposed structure can be well employed as a nanosensor, with a refractive index sensitivity and figure of merit equal to 690 nm RIU^{-1} and 49.28 RIU^{-1} respectively. In addition, the operation of a plasmonic switch based on the proposed structure is investigated. The switch demonstrates a good modulation depth (up to 20 dB), increasing almost monotonically with an increase of the pump intensity in the range of 0–28 MW/cm^2.

0. Introduction

Electromagnetically induced transparency (EIT) effect is defined as the emergence of a transparency window inside the original absorption band of an atomic system [1–3]. Due to the sharp resonance and high dispersion near the appeared transparency window, this phenomenon has found many applications in the nonlinear optics, optical data storage and slow light propagation [4,5]. However, the practical applications of EIT did not emerged in chip-scale owing to the demanding cumbersome experimental conditions (low temperatures, stable gas lasers, etc.) [4]. Therefore, researchers focused on different systems for realizing EIT-like effect with easier experimental conditions. Several approaches were proposed, such as metamaterial-induced transparency [6,7], and coupled resonators in photonic crystals (PCs) [8–10]. However, large dimensions of the proposed PC structures prevented miniaturization of the proposed devices.

Meanwhile, the surface plasmon polaritons (SPP) were introduced as one of the most promising way for realization of highly integrated optical circuits [4]. Mathematical calculations indicated that SPP waves can be used to manipulate the light in nanoscale domain and hence overcome the classical diffraction limit. Until now, several plasmonic devices based on SPPs have been proposed and fabricated, such as filters [11–15], splitters [16,17], wavelength demultiplexers [18], and switches [19–23].

There are also great efforts for realizing the EIT-like effect using SPPs, i.e. plasmon induced transparency (PIT). The PIT phenomenon has been observed in different systems such as nano-particles coupled to waveguides [4], graphene layers [24] and cavities coupled with metal–dielectric–metal (MIM) waveguides [25–29]. However, putting nanoparticles near the waveguide surface is difficult in fabrication process. In addition, there are challenges for graphene-based SP components in integrated circuit devices. One of the best candidates for implementation of PIT effect is using MIM waveguides, due to simplicity in fabrication process, implementation possibility in integrated circuits and strong confinement of light [30]. However, the MIM-based structures have low transmission and/or have broad transparency window at the PIT peak wavelength.

Motivated by the above studies, in this paper, a novel tunable plasmonic structure for PIT implementation is proposed. The structure consists of a MIM bus waveguide directly coupled to a nanocavity and two internally tangent disks. The wavelength of the PIT can be controlled by adjusting the intensity of an external transverse optical pump. Compared to the above mentioned structures, our structure has two main advantages, one of which is the existence of a very narrowband PIT window in the transmission spectrum, which allows designing nanosensors with a good sensitivity and high figure of merit (FOM). Another is controllability of the PIT through an external optical pump, without changing the geometry of the structure. To the best of our

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knowledge, most of the proposed plasmonic structures tune the wavelength of the PIT by changing the shape of the structure. For instance, an inverse T-shape plasmonic structure consisting a MIM waveguide coupled to two perpendicular rectangular cavities is proposed by Boxun Li et al. in 2016 [31]. They show that the wavelength of the PIT peak emerged in the transmission spectra could be tuned by changing the position of one of the cavities. Despite simple geometry, high sensitivity and suitable transmission at the PIT peak, the need for changing the position of the cavity makes PIT-tuning impossible once the structure is fabricated.

After describing the structure, the behavior of the proposed structure is investigated theoretically by use of temporal coupled-mode theory (CMT). Then, the relationship between the transmission characteristics and the geometric parameters of the structure and also the optical pump intensity is studied. Lastly, two potential applications of the proposed structure is discussed: A plasmonic refractive index nanosensor based on PIT and a nanoscale plasmonic switch (by embedding a nonlinear polymer rod in the tangent disks).

1. Description of the structure

Figs. 1(a) and (b) show the schematic geometry of the proposed structure in 2D and 3D respectively. The device consists of a MIM bus waveguide directly coupled to a nanocavity and two internally tangent disks (TITD). TITD is composed of a nonlinear polymer rod (yellow rod) with radius r_p and refractive index n_p internally tangent to a nanodisk of radius R and refractive index n (green area). The refractive index of the polymer rod can be altered by the external pump laser (marked with red cylinder in the Fig. 1(b)) according to $n_p = n_0 + n_2 I$, where n_0 is the linear refractive index equal to 1.3, n_2 is the nonlinear refractive index coefficient (related to the third-order nonlinear susceptibility $\chi^{(3)}$ via $\frac{3Z_0\chi^{(3)}}{4n_0^2}$ where Z is the impedance of free space), and I is the pump light intensity. The value of the $\chi^{(3)}$ of the polymer is set to be 10^{-6} esu ($n_2 = 2.87 \times 10^{-8}$ cm^2/W) [32]. The location of the polymer rod is chosen by physical insight and performing several simulations, which are omitted in the present paper to avoid prolongation.

The width of the bus waveguide is set to $d = 50$ nm, which is fixed in the whole work. The radius of the nanocavity is r and the gap between it and TITD is called g. The white color area indicate air with unity refractive index and the background (gray color) is assumed to be silver whose the dielectric constant is described by the Drude model and is plotted in Fig. 1(c) [33]:

$$\varepsilon_m = \varepsilon_\infty - \frac{\omega_P^2}{\omega^2 + ib\omega} \tag{1}$$

where $\varepsilon_\infty = 3.7$ is the dielectric constant at infinite angular frequency, $b = 2.73 \times 10^{13}$ rad/s (0.018 eV) is the electron collision frequency, $\omega_p = 1.38 \times 10^{16}$ rad/s (9.1 eV) is the bulk plasma frequency and ω is the angular frequency of the incident light. Two-dimensional numerical method based on Finite-Difference Time-Domain (FDTD) with Perfectly Matched Layer (PML) boundary conditions was used to simulate the structure [34]. The grid sizes of the x, z directions and temporal steps in the simulation were set to $\Delta x = \Delta z = 5$ nm and $\Delta t = \frac{\Delta x}{2c}$ respectively (c is the velocity of light in the vacuum), which are sufficient for the numerical convergence.

2. Theoretical model and PIT generation

First, to gain a physical insight, a theoretical study based on CMT is employed. To simplify the theoretical calculations, we assume $n = 1$, and $I = 0$. The decay rates due to the internal loss of the TITD and the cavity are taken equal to $1/\tau_0$. The coupling losses between cavity and the bus waveguide and between the cavity and TITD, and the propagation loss in the bus waveguide are not considered. $1/\tau_1$ and $1/\tau_2$ are decay rates of the cavity mode amplitude into the bus waveguide and TITD resonator, respectively. The temporal evolution of the normalized mode amplitude "a" of the cavity could be described as [35]:

$$\frac{da}{at} = \left(-i\omega_r - 1/\tau_0 - 1/\tau_1 - 1/\tau_2\right) a + e^{-i\theta_1}\sqrt{1/\tau_1}C_{+11} + e^{-i\theta_2}\sqrt{1/\tau_2}C_{+21}. \tag{2}$$

Due to energy conservation, the relation between the incoming and outgoing waves in the bus waveguide and TITD could be written as follows:

$$C_{+21} + C_{-21} = e^{i\theta_2}\sqrt{2/\tau_2}a\ ,\ \ C_{+21} = e^{i\varphi}C_{-21}\ \ ,\ C_{+11} - C_{-12} = e^{i\theta_1}\sqrt{1/\tau_1}a \tag{3}$$

where C_{+s} and C_{-s} represent the amplitudes of the incoming and outgoing waves in the bus waveguide and TITD (see Fig. 1(a)), θ_1 and θ_2 are the phase of the coupling coefficients and ω_r is the resonance frequency of the nanocavity. In addition, φ is the phase shift term of the SPP mode during a round trip in the TITD resonator.

Since the input light is injected into the bus waveguide from the left port, C_{+22} will be equal to zero. Hence, by combining Eqs: (2)–(3) and defining the transmission coefficients (ξ_t) as the ratio of C_{-12} to C_{+11}, the transmission of the structure ($T = \left|\xi_t\right|^2$) will be equal to:

$$T = \left|\xi_t\right|^2 = \frac{\left(1/\tau_0\right)^2 + \left(\left(\omega - \omega_r\right) + 1/\tau_2 \tan\left(\varphi/2\right)\right)^2}{\left(1/\tau_0 + 1/\tau_1\right)^2 + \left(\left(\omega - \omega_r\right) + 1/\tau_2 \tan\left(\varphi/2\right)\right)^2}. \tag{4}$$

According to this equation, for $\omega = \omega_r$ (with neglecting the internal loss, i.e. $\frac{1}{\tau_0} = 0$), the transmission becomes:

$$T_{\max} = \frac{1/\tau_2^2 \tan^2\left(\varphi/2\right)}{1/\tau_1^2 + 1/\tau_2^2 \tan^2\left(\varphi/2\right)}. \tag{5}$$

Obviously, the maximum transmission is obtained when $\varphi = (2m+1)\pi$ with $m = 0, 1, 2\ldots$, corresponding to a standing wave in the TITD resonator at $\omega = \omega_r$. Therefore, a peak appears in the transmission spectrum of the device at $\omega = \omega_r$ for $\varphi = (2m+1)\pi$. This is explained simply as follows: for the structure without TITD, there is a destructive interference or a π radians phase difference between the incident light and the escaped light from the cavity to the bus waveguide at $\omega = \omega_r$ (corresponding to zero transmission in the output spectrum for the case of $1/\tau_2 \rightarrow 0$). However, by adding TITD, another π radians is experienced by light due to increased optical path traveled by light, and therefore the total phase difference becomes equal to 2π, corresponding to constructive interference between incident light and the escaped light from cavity and TITD to the bus waveguide. Hence, zero transmission in the previous spectrum tends to maximum transmission, which means the emergence of a PIT in the transmission spectrum.

Fig. 2(a) shows the transmission spectrum with and without TITD resonator. As we see, a narrow PIT peak with a 70% transmission and a FWHM equal to 14 nm emerges at 782 nm between two dips at 760 and 825 nm (black curve) which is in agreement with the above theory. It is noted that 782 nm corresponds to the resonant wavelength of the single nanocavity (blue curve). The quality factor (Q) of the emerged PIT peak is 55.85 which is bigger than the previous report [28].

In order to have an insight into the physical mechanism behind the observed PIT, the magnetic field distribution at the PIT wavelength with and without the TITD are depicted in the inner parts of Fig. 2(a).

One can see that when the TITD is present, destructive interference between the incident light and the escaped light from cavity becomes constructive. The resonant wavelength of the standing wave could be obtained approximately by: $\frac{\omega}{c} Re\left(n_{eff}\right) \times L_{eff} + \psi = (2m+1)\pi$, where m (=0, 1, …) is a positive integer value corresponding to the order of the resonant mode, ψ is the phase shift due to reflection from the TITD boundary, L_{eff} is the effective length of the SPP propagation in the TITD, and $Re(n_{\mathrm{eff}})$ is the real part of the refractive index of the SPP wave in the TITD resonator which could be obtained by SPP dispersion relation below [36] (see Fig. 2(b)):

$$\tanh\left(\frac{2\pi}{\lambda}\cdot\frac{d}{2}\sqrt{n_{eff}^2 - 1}\right) + \frac{\sqrt{n_{eff}^2 - \varepsilon_m}}{\varepsilon_m \cdot \sqrt{n_{eff}^2 - 1}} = 0 \tag{6}$$