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Plasmon-induced transparency in sensing application with semicircle cavity waveguide

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ABSTRACT

In this paper, a plasmonic nano-sensor is proposed in semicircle cavity waveguide, the transmission characteristics of the new structure are analyzed by the finite-difference time-domain method. Dual plasmon-induced transparency (PIT) phenomenon is emerged in the semicircle cavity coupled with bus waveguide, which is resulted from the destructive interference superposition of the reflected and transmitted waves from cavity resonator. High sensitivity and figure of merit (FOM) based on PIT in the resonator has been investigated in detail. The sensitivity of the proposed model is about 2000 nm/RIU and its maximum FOM is up to 85370. In addition, dual PIT peaks are found by changing the structure parameters. The simple structure with such high sensitivity and FOM provide potential implications in nano-sensing field.

1. Introduction

Electromagnetically induced transparency (EIT) is a quantum interference phenomenon that appears in atomic resonances [1–3]. Plasmon-induced transparency (PIT) as a plasmonic analogue of the EIT, which can be achieved in the plasmonic waveguide systems. PIT is a phenomenon based on the interaction between the surface plasmon and the external electromagnetic field, which means that the absorption of the optical pulse disappears due to the cancellation of the interference path, at the same time, transparency peak comes up in the position of the absorption dip. Due to its potential applications in areas of nano-sensors and slow light devices, which have aroused people's widespread attention in recent years. On account to overcome the traditional diffraction limitation [4–8] and control light at the nano-scale domain and also can realize the perfect properties and compactness. It is regarded as the most promising nanoscale optical devices. As one of the most significant optical plasmonic nano-sensors in the fields of nanoscale optical device, those nano-sensors based on metal–dielectric–metal (MDM) [9,10] plasmonic waveguide are kind of vital components in the plasmonic optical platform [10,11]. Some nano-sensors have been proposed and investigated from theories and experiments by coupling with different shape resonators, such as rectangular cavity [12] (Zheng et al. demonstrated multiple EIT-like effects in graphene metamaterials theoretically and numerically), symmetrical grooves and slot cavity [13–15], (Zhan et al. report the sensing characteristic based on plasmon induced transparency in nano cavity coupled metal–dielectric–metal waveguide, He et al. researched the aspect ratio control and sensing applications in a multimode stub). A compact plasmonic system was proposed based on a stub waveguide coupled with a nanodisk resonator [16], some papers reported that PIT can be observed in coupled optical resonator systems and plasmonic metamolecules rings [17,18]. In view of developing of nanoscale photonics, PIT is widely investigated by using the MDM waveguide recently, which are more sensitive compared to previous nano-sensors.

Based on the distinct characteristics of MDM waveguide, the PIT observed in the coupled resonator systems was theoretically indicated and experimentally proved in past researches [12–18]. Recently, there are many reports on the PIT phenomenon based on the metal plasmons also. Liu et al. proposed and demonstrated near-perfect multi-spectral PIT bands in continuous mental film structures [19], Metal structures with high optical transparency and conductivity are of great importance for practical applications [20]. Distinguished from the conventional metallic PIT devices, multiple PIT resonances in the hybrid metal–graphene PIT device are independently modulated by electrostatically changing bias voltages applied on corresponding graphene fingers [21]. Making a metal transparent has attracted increasing attention because of interesting electromagnetic properties. These properties provide a new approach to make a metal transparent. [22]. Dual-band or multiband transparent spectrum could be achieved using a core shell plasmonic crystal to support multiple plasmon resonances [23].

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In this work, an optical plasmonic nano-sensor is proposed in semicircle cavity waveguide based on plasmon-induced transparency by using the method of finite difference time domain (FDTD) in the two-dimensional space, and plasmon-induced transparency phenomenon can be emerged in the simple semicircle cavity resonator system (SCR). Furthermore, high sensitivity sensing and high sensitivity and figure of merit (FOM) have achieved by changing the radius (r) of the semicircle, the distance (d) between semicircle and bus waveguide and the refractive index (n) of the dielectric. What makes us interested is that dual PIT peaks are found. Moreover, the sensing function of the Plasmon-induced transparency at different r, d and n are illustrated. The proposed SCR structure can be arrived as a favorable plasmonic nano-sensor with a sensitivity of about 2000 nm/RIU and figure of merit (FOM) larger than 85 370.

2. Structure and simulation

The proposed structure of the 2D schematic is graphically shown in Fig. 1(a), where the blue and white areas represent metal and dielectric, respectively. It consists of a bus waveguide coupled with a semicircle cavity resonator (SCR) [24]. The semicircle cavity is asymmetrical in the x direction and symmetrical in the y direction [14]. The width of bus waveguide and the radius of the semicircle are settled as h and r, respectively. In addition, d represents the distance between the semicircle cavity and the bus waveguide. At the points P_{in} and P_{out} of the bus waveguide lays two power monitors to detect the incident power and the transmitted power, respectively. $T = P_{out}/P_{in}$ is used to calculate the transmittance and the transmission characteristics are investigated numerically and theoretically by the method of FDTD. FDTD method is applied to simulate the light performance in the 2 dimensional waveguide, the perfectly matched layers (PML) acted as the boundary conditions. Time step is setting as $dx/2c$, where c is the velocity of the light in vacuum and mesh steps are setting as $dx = dy = 5$ nm. The intensity of the light has the shape of the Gaussian distribution [12]. On the metal–dielectric interface when an incident Gaussian source injects along x-axis in the waveguide [13], the surface plasmon polaritons (SPPs) can be activated with the transverse-magnetic mode and restricted in the waveguide. Partial SPPs spread along the x-axis and get pass the waveguide and the other part of the SPPs reflect backwards and forwards in the cavity resonator. Based on the Coupled Mode Theory (CMT), we define the Φ to be the phase delay per round-trip in the semicircle cavity resonator, then the equation will be fixed in $\Phi = \frac{4\pi n_{eff} l_{eff}}{\lambda_m} + \Phi_0$ [14,25], where Φ_0 is the phase shift of a beam reflected on the circumference above and diameter facets of the resonator, l_{eff} is the effective length of SPPs in cavity, λ_m is the resonance wavelength of the cavity resonator. Resonance conditions meet the equation $\Phi = M \cdot 2\pi$, and M is expressed positive integer and corresponds to the order of the resonance mode. The resonance wavelength is indicated by

$$\lambda_m = 2n_{eff} l_{eff}/(M - \Phi_0) \tag{1}$$

n_{eff} is effective refractive index which can be get by the dispersion equation [26]:

$$\varepsilon_m \sqrt{n_{eff}^2 - \varepsilon_a} tanh\left(\frac{h\pi\sqrt{n_{eff}^2 - \varepsilon_a}}{\lambda}\right) + \varepsilon_a \sqrt{n_{eff}^2 - \varepsilon_a} = 0. \tag{2}$$

Where ε_m indicates the dielectric constant of metal, $\varepsilon_a = 1$ represents as air permittivity constant. In terms of the equation, the effective refractive index n_{eff} with the length of waveguide for wavelength ranging from 500 nm to 2000 nm are set as $h = 100$ nm.

The blue area is plasmonic silver, whose complex relative permittivity is denoted by the Drude Model [27]

$$\varepsilon_m(\omega) = \varepsilon_\infty - \omega_\rho/(\omega^2 + i\omega\gamma_\rho). \tag{3}$$

The $\varepsilon_\infty = 3.7$ at the infinite angle frequency, ε_m represents the angle frequency of incident wave, ω_ρ is the bulk plasma frequency which equal to 1.38×10^{16} rad/s, and the damping rate $\gamma_\rho = 2.73 \times 10^{13}$ rad/s which represents the absorption loss. l_{eff} of the SPPs in the semicircle cavity can be achieved by the length formula, which is represents as

$$l_{eff} = 1/2 \times 2\pi \times r/2 = \pi r/2. \tag{4}$$

3. Results and discussions

The semicircle cavity has the small size and simple structure, transmission spectra characteristics of the proposed plasmonic waveguide structure is further investigated with different structural parameters. The transmission spectra with $r = 250$ nm and $d = 20$ nm is shown in Fig. 1(b), when the radius rises up to 300 nm and d remain unchanged. Apparently, there are two resonance peaks at the wavelength of 446 nm and 591 nm in Fig. 1(c), respectively. In the whole paper, h is set as 100 nm, furthermore various transmission characteristics are proved with different radius (r), different distance (d), and various refractive indices (n) according to the dual PIT windows [24]. Fig. 2(a) and (b) shows the transmission spectra from the same constructive parameters ($d = 20$ nm, $h = 100$ nm), yet with $r = 250$ nm, 300 nm, 400 nm, 500 nm, 600 nm, 700 nm, 800 nm and 900 nm. It is found that dual transparent peak windows increase in strength and become more conspicuous as r increases from 250 nm to 900 nm. For the lossless metal case, the transmission spectra for $r = 900$ is also shown in Fig. 2(c). It can be seen that the transparent bandwidth keeps unchanged and we achieve uniform peak transmission in the transparent windows. In addition, the magnetic field distributions of the SCM system at dip1, peak1, dip2, dip3, peak2, dip4 from Fig. 2(c) and corresponding wavelength to 1578 nm, 1520 nm, 1462 nm, 1160 nm, 1153 nm and 1139 nm, are plotted in Fig. 2(e)–(j), respectively. Most of the power is limited to the cavity in dip1, dip2, dip3 and dip4. Besides, the power is transported out when wavelength at 1520 nm in the peak1 and transmit a portion of light at the peak2. Fig. 2(d) shows the wavelength shift of dip1/peak1/dip2 against the different r with a step of 100 nm. With the increasing of the r, dip1/peak1/dip2 is monotonically increasing and shift to longer wavelength. Above all, the PIT windows come up redshift with increasing the radius of the semicircle. Based on the equation $\lambda_m = 2n_{eff} l_{eff}/(M - \Phi_0)$, the reason of the redshift phenomenon is that with the increasing of the r and $l_{eff} = \pi r/2$. Therefore, this work may put the valid foundation on the future study in realization of nanoscale optical devices and this paper mainly discusses the applications in nano-sensor.

4. Sensing applications based on PIT

Fig. 3(a) shows the transmission spectra with different d at $r = 900$ nm. It is clear that the transparent bandwidth of the first PIT window almost keep the same construction, the second PIT window becomes higher then decreases as d increases from 20 nm to 24 nm, the transmission spectra reach the maximum value at $d = 21$ nm.

When resonance conditions meet the equation $\Phi = M \cdot 2\pi$, M is expressed positive integer and corresponds to the order of the resonance mode. The resonance wavelength is indicated by $\lambda_m = 2n_{eff} l_{eff}/(M - \Phi_0)$. Fig. 2(a) and (b) show the transmission spectra shift with the increase of radius (r) at the two PIT peaks, respectively. Especially when $r = 300$ in the structure, a very clear dual PIT can be seen. The first PIT window is situated two dips wavelength at 1463 nm and 1578 nm, where the transparent peak at 1520 nm and another one is located between two dips at 1139 nm and 1160 nm at the peak of 1153 nm. It is found that transparency windows are split by the second-order mode as increasing the radius of the semicircle cavity gradually [28]. The two transparency windows all display redshift in Fig. 2(d). As the refractive index increases, the resonance wavelength grows linearly when $r = 800$ nm and $r = 900$ nm from Fig. 4(c) and (d). When the