Optics Communications 396 (2017) 199–205

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Plasmonic induced transparency in a coupled system composed of metal-insulate-metal stub and trapezoid cavity resonator

Pengfei Zheng, Huimin Yang, Linsen Jiao, Meiyong Fan, Binfeng Yun*, Yiping Cui*

Advanced Photonics Center, Southeast University, Nanjing, China, 210096

ARTICLE INFO

Keywords:
Surface plasmon polaritons
Plasmonic induced transparency
Trapezoid cavity
Slow-light

ABSTRACT

A plasmonic induced transparency system constructed by a metal-insulate-metal stub coupled with a trapezoid cavity resonator was proposed. The results show that the spectra of different narrow modes in the trapezoid resonator can overlap with the broad stub mode and induce the plasmonic induced transparency effect. However, some of them cannot produce a plasmonic induced transparency effect because there is hardly any near field overlap between the trapezoid cavity mode and the stub mode, which was proved by the mode field distributions in the coupled resonator system. The “disappeared” plasmonic induced transparency can be reproduced by changing the relative position between the stub and trapezoid resonator. Also the coupling strength can be modulated by this method to manipulate the plasmonic induced transparency and slow light effect.

1. Introduction

Surface plasmon polaritons (SPPs) are the electromagnetic waves coupled with free-electrons in metal and trapped on the interface between metal and dielectric materials. The SPP waveguide based on metal-insulator-metal (MIM) structure has attracted much attention because electromagnetic waves can be restricted in subwavelength scale that makes MIM plasmonic structure possible for integrated photonic devices.

Electromagnetically induced transparency (EIT) is a quantum effect occurred in an atomic system, where a quantum destructive interference between two different excitation pathways leads to a transparency window with strong dispersion and a significant slow light effect near the transparency peak. Also it has been proved to have promising applications in nonlinear optical processing, ultrafast switching and optical data storage for its noble property of slow light effect. An EIT-like effect, also known as coupled resonance induced transparency (CRIT) that occurs in some coupled micro-cavities has been analyzed theoretically and observed experimentally in normal silicon based photonics systems [1–3]. Besides, the EIT-like effect can also be found in plasmonic systems based on the MIM structures. Until now, a lot of works have been done to analyze the EIT-like phenomenon based on coupled plasmonic resonators which are also known as plasmonic induced transparency (PIT). Lu et al. theoretically investigated the PIT effect in a plasmonic system composed of multiple cascaded micro-disk resonators which were aperture-side-coupled to MIM bus waveguides [4]. Based on the disk resonator, a serious of PIT systems have been investigated [5,6]. Moreover, there are also some articles refer to PIT systems based on ring resonators [7] and F-P resonators [8–10]. Some studies have focused on rectangular resonators which can provide unique properties by their novel designs [11–13]. On the basis of these designs, some new structures were proposed to implement more functionality by modulating the offset positions of resonators [14] or rotating the angles of the ring resonators [15]. Recently, Song et al. proposed a trapezoid resonator which shows novel transmission properties and mode distributions [16]. In Song's paper, they discussed the dependence of transmission spectra and resonance wavelengths on the parameters of the trapezoid resonator.

It is well known that the near field coupling of two MIM plasmonic resonators can induce the PIT phenomenon. Here, a PIT system based on an MIM stub resonator coupled with a trapezoid resonator was proposed to realize the PIT and slow light effect. To analyze this system conveniently, the modes of trapezoid resonator were defined and their variation trends depended on the lower bottom length of trapezoid were analyzed. Then the PIT effects induced by different modes of trapezoid resonator coupled with stub were analyzed and some abnormal phenomena were found. Some of the mode-coupling systems cannot generate a PIT effect, although the wavelengths of trapezoid mode and the stub are well overlapped. By investigating the mode distributions of those PIT systems, we found the mode overlap between those trapezoid modes and stub modes is too weak that causes a very weak coupling strength between the two resonators and leads to the

* Corresponding authors.
E-mail addresses: ybf@seu.edu.cn (B. Yun), cyp@seu.edu.cn (Y. Cui).

http://dx.doi.org/10.1016/j.optcom.2017.03.067
Received 9 January 2017; Received in revised form 21 February 2017; Accepted 27 March 2017

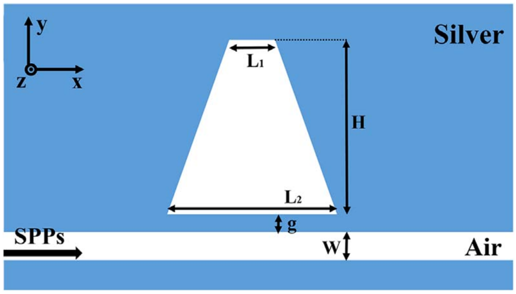

Fig. 1. Schematic of trapezoid resonator coupled with MIM bus waveguide directly.

absence of the PIT effect. Further investigation shows that the relative position between the two resonators affects the overlap of their mode fields, which can determine the coupling strength and the slow light effect based on the proposed PIT system. By altering the relative position, the PIT and slow light effect can be modulated and optimized to achieve the largest group index.

All the results in this article were simulated by the finite-difference time-domain (FDTD) method with grid size of 1 nm×1 nm. Our work offers a new perspective through the PIT based slow light device and we expect that our work would do some help to the design of other PIT systems and make the slow light system more efficiently. The plasmonic devices can be fabricated by a sequence of lithography and etch processes. A silver film will be evaporated onto a substrate which can be SOI wafer or glass. Then, the designed profile structure will be etched by electron beam lithography and etch process. Fiber to chip couplers should be fabricated by lithography step and dry etching at the two ports of the plasmonic device [17,18].

2. Resonance modes in trapezoid resonator

The structure of trapezoid resonance system is shown in Fig. 1, where L_1, L_2, H and g are the upper bottom length, the lower bottom length, the height of the trapezoid cavity and the gap between the trapezoid cavity and the bus waveguide, respectively. The width of bus waveguide, noted as w, is fixed as 50 nm.

The basic theory to analyze this system is coupled mode theory (CMT), with which we can get the transmission property theoretically [4,5]. In this system, the permittivity of silver is given by the Drude model: $\varepsilon(\omega)=\varepsilon_\infty-\omega_p^2/(\omega^2+i\omega\gamma)$, where ε_∞ is the relative permittivity at infinite frequency with the value of 3.7, ω_p is the plasma frequency which is set as 1.38×10^{16} Hz, γ is the damping frequency of the oscillations and the value is 2.73×10^{13}Hz, and ω is the angular frequency of the incident light [19].

The transmission spectrum and resonance modes at different wavelengths were investigated with the parameters set as: L_1=50 nm, L_2=250 nm, H=300 nm and g=20 nm. Fig. 2(a) shows the transmission spectrum, in which three resonant modes can be observed. As only TM modes are supported by the MIM plasmonic waveguides, the modes are defined as TM_{mn}, where m and n denote the number of horizontal and vertical zero points in the mode fields of trapezoid resonator, respectively. The similar definitions were proposed in Ref. [12].

The influences of lower bottom lengths (L_2) on the transmission spectra and relevant modes were investigated. Fig. 3(a) shows the transmission spectra of the trapezoid resonator versus different lower bottom length L_2. With the increasing of L_2, the variation trends of the resonance wavelengths of different modes are complex. The resonance wavelength of TM_{01} mode decreases firstly and then increases, while the resonance wavelength of TM_{10} increases almost linearly. As TM_{10} mode resonates in horizontal direction like a standing wave, whose resonance wavelength depends on horizontal length of the resonator, namely, the lower bottom length of trapezoid cavity. And TM_{01} mode resonates in vertical direction, so the resonance wavelength depends mainly on the height of the trapezoid cavity. As H is fixed as 300 nm, the resonance wavelength of TM_{01} mode is varying around the same value and is influenced by the changing of L_2. For TM_{01} mode, the trapezoid resonator can be treat as an F-P resonator, whose resonance wavelength is given by: $m\lambda_{res}=2N_{eff}H$, where m is an integer, λ_{res} is the resonance wavelength, N_{eff} is the effective index of the cavity. N_{eff} is determined by the width of the MIM structure, namely, the lower bottom length L_2 of the trapezoid cavity as discussed in ref. [20]. With the increasing of L_2, the effective index diminished, which leads to the blue shift of resonance wavelength. Furthermore, the degeneracy of TM_{10} mode and TM_{12} mode were found when L_2 =150 nm, and when L_2 =350 nm, the TM_{01} mode and TM_{10} mode are degenerated. The resonance wavelengths of different modes versus the lower bottom length of trapezoid were extracted and plotted in Fig. 3(b). The resonance wavelength of TM_{12} decreases firstly and then increases with the increasing of L_2, while the wavelength of TM_{30} increase steadily.

3. PIT induced by TM_{01} mode

The results aforementioned indicate that many modes can resonate in the trapezoid resonator and their resonance wavelengths can be changed by altering the geometric parameters such as the lower bottom length. As known, when the resonance modes of two resonators overlap with each other, a PIT effect can be induced due to the interference of these two modes.

Stub resonator is a kind of classical MIM filer. Here, a PIT system consist of the stub resonator and the trapezoid resonator was proposed and shown in Fig. 4. By the near field coupling between them, a PIT effect can be achieved. The width and height of the stub are set as W_s=50 nm and H_s=120 nm, respectively. And the resonance wavelength of the stub is around 820 nm which is near the resonance wavelength of TM_{01} mode of the trapezoid.

The PIT effect induced by two coupled resonance cavities can be analyzed theoretically by the CMT, in which the transmission is derived as [5]:

$$T=\left|\frac{j(\omega-\omega_s)+\gamma+\frac{\gamma}{j(\omega-\omega_T)}}{(\omega-\omega_s)+\gamma+\beta+\frac{\gamma}{j(\omega-\omega_T)}}\right|^2 \quad (1)$$

Here, ω_s and ω_T stand for the resonance frequency of stub resonator and trapezoid resonator, respectively. β is the coupling coefficient of the waveguide and stub resonator, γ is the coupling coefficient of the stub resonator and trapezoid micro-cavity, j stands for the imaginary unit. The transmission spectrum of the PIT system with the lower bottom length of trapezoid L_2=260 nm is shown in Fig. 5(a). The PIT peak appears at the resonance wavelength of 772.24 nm, which is near the resonance wavelength of trapezoid resonator, with the transmission of 0.53. Fig. 5(b) is the normalized distribution of z component of magnetic field (H_z) at the PIT wavelength, while Fig. 5(c) and Fig. 5(d) are the H_z distributions of the left dip (760.93 nm) and the right dip (860.98 nm), respectively. The mode field in the stub and bus waveguide have opposite phases, which leads to the destructive interference at the wavelengths of these two dips.

It is noted that the spectra in Fig. 5 (a) are similar to the spectra generated by Fano resonance that gives rise to asymmetric spectra. There is no essential difference between the spectra of our PIT system and the spectra induced by Fano resonance. The PIT effect in this paper is obtained by the interaction of the stub mode and the trapezoid mode. As the Q-factor of stub is small, its spectrum is much broader than the trapezoid resonator whose Q-factor is larger. So they can also be treat as “broad bright mode” and “narrow dark mode”, respectively. The generation mechanism of PIT effect is the same as Fano resonance [21,22]. And the transparent peaks essentially come from the destructive inference of two optical paths in the plasmonic systems.