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Plasmon-induced transparency based on aperture-coupled cascade resonators without gap

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ABSTRACT

We numerically and theoretically investigate a metal-insulator-metal (MIM) system based on aperture-coupled cascade resonators without gap to achieve plasmon-induced transparency (PIT). Such structure not only can be fabricated easily, but also possesses low intrinsic loss. Consequently, a high transmitted PIT peak more than 90% can be achieved, and this device also has good performance on sensing and slow light. Finally, multi-channel PIT and slow light can be achieved via cascade multiple resonators. This work provides a valuable approach to realize on-chip PIT in practical experiments.

Electromagnetically-induced transparency (EIT) is a quantum phenomenon owing to the interference between two different excitation pathways in a three-level atomic system [1], and the strong dispersion within the transparent window can promise for the application on slow light [2] and enhancing nonlinear optical effect [3]. However, the experimental conditions of EIT are harsh such as stable pumping and low temperature [1], which restrict its extensive application. Recently, plasmon-induced transparency (PIT) has been widely studied. As an EIT analogue in a plasmonic system, PIT comes from the interference between plasmonic bright mode and dark mode [4] and can be realized on metamaterials [4] and plasmonic high-compact circuits [5], which make possible nanoscale applications for filter [6,7], sensor [8,9] and slow light [10,11].

Although suffering from the metal intrinsic loss (ohmic loss), the metal-insulator-metal (MIM) waveguide, one of the basic plasmonic structure, has been widely applied to on-chip all-optical circuits, because MIM can constrain the surface plasmon polaritons (SPPs) well and possesses easy fabrication. In a MIM system, generally, PIT can be realized based on a bus waveguide side-coupled with resonators, and many different works has been reported numerically based on such scheme [12–21]. However, there are few related experimental results, because the gap (the metal area between two resonators or waveguide and resonator) is only a dozen nanometers in most works [12–21], which requires high processing precision. Besides, most proposed works [12–21] are based on 2D simulation for simplicity, the third dimension of which is regard as infinite [22]. However, it has been reported that the thickness (in the third dimension) should be no less than 1 μm to get the same results as 2D scheme [23–25]. In that case, the gap will become a thin metal wall, which is easy to collapse in practice, consequently almost impossible to be formed. Furthermore, the gap will lead to more system ohmic loss, making the performance of a plasmonic device worse.

Here, we numerically propose a MIM waveguide structure aperture-coupled with cascade resonators to produce PIT, and corresponding phenomenon can be theoretically analyzed by coupled mode theory (CMT). Such structure has no gap, therefore possesses low loss and easy fabrication, and the peak transmission of PIT can reach more than 90%. Besides, the performance of this device on

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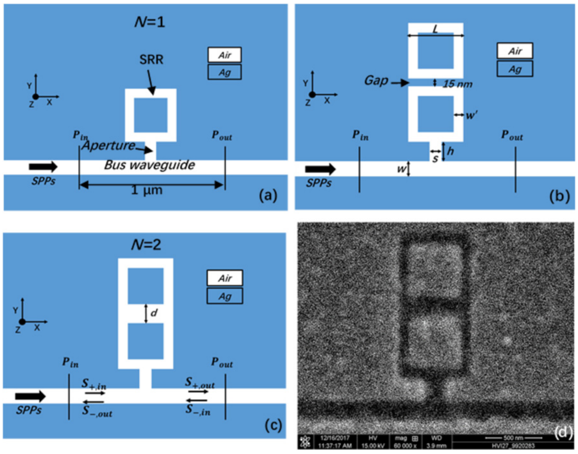

Fig. 1. (a) The bus waveguide is aperture-coupled with single SRR. The distance between two monitors is 1 μm. (b) The second SRR is coupled at the upper side of the first SRR with gap. The structural geometric parameters: $w = 100$ nm, $s = 80$ nm, $h = 130$ nm, $w' = 50$ nm, $L = 375$ nm. (c) The second SRR is coupled at the upper side of the first SRR without gap. $d = 100$ nm. (d) The image of the structure fabricated by FIB. The bright region is silver and the dark region is the substrate silicon. The thickness of silver is 100 nm.

sensing and slow light is comparable with previous similar works [12–15]. Finally, multi-channel PIT can be achieved based on cascade multiple resonators with no gap. This work provides a scheme to achieve PIT and multi-channel PIT with a simple framework, which can promote the practical realization of PIT in integrated all-optical circuits.

The structure is presented in the form of 2D as shown in Fig. 1(a–c), N represents the number of square ring resonators (SRRs), and the detailed structural geometric parameters are given in the caption. Fig. 1(d) shows that bus waveguide, aperture and square ring resonator (SRR) can be etched on the silver (Ag) layer by focused ion beam (FIB), which can prove the easy fabrication of such structure. The permittivity of Ag can be described by Drude model [26]:

$$\varepsilon_{\mathrm{m}} = \varepsilon_{\infty} - \frac{\omega_p^2}{\omega(\omega + i\gamma)} \tag{1}$$

where ε_{∞} is the dielectric permittivity of the infinite frequency, ω_p refers to the bulk frequency for plasma, γ is the damping frequency for electron oscillation, and ω gives the incident light angular frequency. The corresponding parameters of Ag are $\varepsilon_{\infty} = 3.7$, $\omega_p = 1.38 \times 10^{16}$ Hz, and $\gamma = 2.73 \times 10^{13}$ Hz. In MIM waveguide, only transverse-magnetic (TM) mode can exist [27]. Compared with incident wavelength, the width of the waveguide is much smaller, so there is only fundamental TM mode. The dispersion relation of this fundamental mode is described as follows [27]:

$$\frac{\varepsilon_i p}{\varepsilon_m k} = \frac{1 - e^{kw}}{1 + e^{kw}} \tag{2}$$

$$k = k_0\sqrt{\left(\frac{\beta_{spp}}{k_0}\right)^2 - \varepsilon_i}\,,\ p = k_0\sqrt{\left(\frac{\beta_{spp}}{k_0}\right)^2 - \varepsilon_m} \tag{3}$$

$$\beta_{spp} = n_{eff}k_0 = n_{eff}\frac{2\pi}{\lambda} \tag{4}$$

here w refer to the width of the waveguide, λ is incident light wavelength in vacuum, ε_i and ε_m are the dielectric and metal permittivity, β_{spp} is propagation constant of SPPs, n_{eff} refers to the effective refractive index of MIM waveguide, and $k_0 = 2\pi/\lambda$ is the wave number. The 2D Finite-Difference Time-Domain (FDTD) solution with the highest mesh accuracy is applied to simulate this system with the boundary condition of perfectly matched layers (PML) to maintain convergence. To detect the incident and transmitted power, two monitors are put symmetrically at P_{in} and P_{out} as shown in Fig. 1(a–c). The light source is in the same position with P_{in}. The transmission spectrum of power is calculated by. $T = P_{out}/P_{in}$.

The simulated transmission spectrum of three structures in Fig. 1(a–c) is depicted in Fig. 2(a). When only single aperture-coupled SRR exists, the spectrum shows that there is a resonant wavelength at 820 nm, and corresponding field distribution of $\boldsymbol{H}_z$ is given in the inset of Fig. 2(a). The resonance condition of such mode can be described as follows [28]:

$$m\lambda = 4L_{eff}\,\mathrm{Re}(n'_{eff}),\ m = 1,2\ldots \tag{5}$$

where n'_{eff} refers to the effective refractive index of resonators, which can be solved by Eqs. (2)–(4)). Here n'_{eff} is 1.31. L_{eff} is the effective side length of SRR, generally refers to the average of the inner and outer side length. m refers to mode number which is an integer. If the second SRR is coupled at the upper side of the first SRR with the gap distance 15 nm, the transmission spectrum will possess a PIT profile as shown in Fig. 2(a). Here, the mode in the aperture-coupled SRR is directly excited, acting as the bright mode.