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Band-pass plasmonic filter based on periodic cascade resonant cavities

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ABSTRACT

A band-pass plasmonic filter based on periodic cascade resonant cavities is theoretically designed and analyzed. The transmission modes of surface plasmon polariton are well studied by the finite-difference time-domain method. The structure indicates the band-pass selection capability with several types of modes in the transmission spectra. The results show that the number of the transmission modes depends on the number of the cascade cavities period. These modes exhibit a shift with varying incident intensity involving Kerr medium in cascade cavities. The structure provides flexibility in design for pass-bands filter.

1. Introduction

Surface plasmon polariton (SPP) is electromagnetic wave that propagates along the interface of metal–dielectric due to the interaction between free electrons in the metal and the electromagnetic field in the dielectric [1]. SPP as practicable energy and information carrier has promising applications in highly integrated photonic circuits because it overcomes the conventional diffraction limit and can manipulate light on the subwavelength or even nanometer scale [2,3]. Therefore, plenty of attentions have been paid to SPP devices in recent years, such as bends [4], interferometers [5], all-optical switches [6,7], splitters [8], couplers [9], modulators [10] and combiners [11]. Built on SPP, some devices based on subwavelength metallic structures with nonlinear materials have been investigated, such as metallic nano-optic lens [12], subwavelength metallic grating [13], and nonlinear SPP crystals [14]. All-optical signal processing in integrated photonic circuits and its applications in optical communications and computing require the ability to control beam with beam [14,15].

Metal–insulator–metal (MIM) waveguides have attracted much interest for scientists due to the concise structure, easy fabrication and integration in subwavelength scale. What is more, MIM waveguides exhibits the strong light confinement and considerable propagation length for SPP [16]. Optical filter constructed on MIM structure has been found important applications in many optical systems. To achieve the wavelength filtering function, various MIM structures have been used for filters [16–18]. However, the ordinary waveguide-filtering function is not evident owing to the weak resonant effect of simple F-P cavity.

In this paper, a band-pass plasmonic filter is proposed and analyzed, which consists of periodic cascade resonant cavities and waveguides. The finite difference time domain (FDTD) method is employed to simulate and study the property of the filter. In the proposed filter, the resonance characteristics of the cascade cavities and the out-coupling mode can be effectively modified by changing the number of cascade cavities period. These properties can be used to achieve the band-pass selection. Furthermore, the transmission spectrum (the resonant modes) of the filter can also be easily controlled by modulating the incident intensity after alter the insulator in these cavities with a nonlinear medium. Due to its subwavelength scale and high quality factor, this device has great potential applications in the optical communication, all-optical circuits by integrated with other devices.

2. Structures and model

Fig. 1 illustrates the schematic of the structure for filter. It is composed of inputting and outputting waveguides as well as three rectangular cavities in the middle of the MIM structure. These cavities are periodic cascaded with coupling distance $d = 10$ nm. The length and width of each cavity is $l = 190$ nm and $w = 60$ nm, respectively. A waveguide with air slit sandwiched between two

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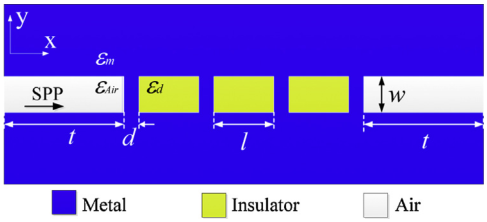

Fig. 1. Schematic of the SPP filter with triple periodic cascade cavities.

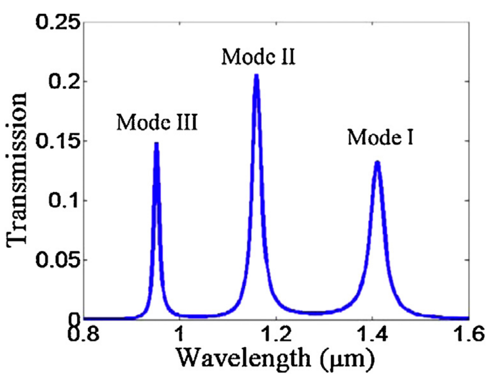

Fig. 2. The transmission of the proposed structure.

semi-infinite silver are located at each end, whose length is set as $t = 300$ nm as well as identical width with cavities. The middle part is separated to three holes filled with insulator. The dielectric constant of air slit and insulator in holes are $\varepsilon_{Air} = 1$ and $\varepsilon_d = 2.25$, respectively. The metal is chosen to be sliver, whose frequency-dependent relative permittivity ε_m is characterized by the Drude model $\varepsilon_m = \omega_p/\omega(\omega + \mathrm{i}\omega\gamma)$, with $\varepsilon_\infty = 3.7$, bulk plasma frequency $\omega_p = 9.1$ eV, and damping frequency of the oscillations $\gamma = 0.018$ eV, respectively [19].

FDTD is utilized to investigate the transmission response of this structure. In the simulations, the grid sizes along x- and y-axes are set to 5 nm. The perfect match layer is used in the x and y direction, and periodic boundary is used in the z direction. The TM polarization beam is injected along the x-axis.

3. Simulation results and discussion

Fig. 2 shows the calculated transmission spectrum of the structure consists of triple periodic cascade cavities. Three transmission peaks are observed, whose positions are $\lambda_1 = 1412$ nm (marked Mode I), $\lambda_2 = 1160$ nm (marked Mode II), and $\lambda_3 = 952$ nm (marked Mode III), respectively. The quality factor is also investigated which is defined as $Q = \lambda/\Delta\lambda$ [20], where λ is the resonance wavelength of the cascade cavities and $\Delta\lambda$ is the full width at half maximum (FWHM) of transmission spectrum. Q-factors of mode I, II and III are 34, 52 and 75, respectively. It means that Mode III has a lowest rate of energy loss relative to the stored energy of the resonator, but Mode I opposite.

In order to theoretical analysis, a simple model is extracted from Fig. 1, as shown in Fig. 3. In general, since the widths of the waveguides are much smaller than the incident wavelength, only a single propagation mode TM_0 can exist in a simple MIM waveguide [21], whose complex propagation constant can be calculated from the following dispersion equation [21,22]:

$$\tanh\left(\frac{w\sqrt{\beta^2 - k_0^2\varepsilon_i}}{2}\right) = \frac{-\varepsilon_i\sqrt{\beta^2 - k_0^2\varepsilon_m}}{\varepsilon_m\sqrt{\beta^2 - k_0^2\varepsilon_i}} \tag{1}$$

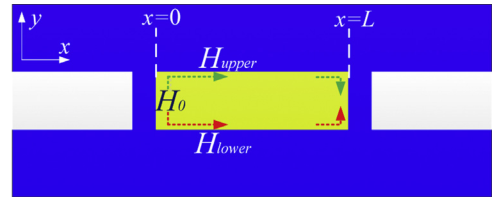

Fig. 3. Schematic of SPP described by the magnetic field propagating oppositely at interfaces.

where $k_0 = 2\pi/\lambda_0$ is the wave vector of light in vacuum, ε_i is the relative dielectric constant of the insulator in MIM structure. For Fig. 3, stable standing waves can be exited within the cavity only when the following resonance condition is satisfied:

$$\Delta\phi = \beta_n \cdot 2L + \phi_r = 2n\pi \tag{2}$$

where $\phi_r = \phi_L + \phi_R$, ϕ_L and ϕ_R is phase shift of a SPP reflected on the left and right facets of the cavity, respectively. β_n is the propagation constant of SPP corresponding to the nth order resonance mode in the cavity. Thus, the resonant wavelengths can be obtained as follows [23]:

$$\lambda_n = \frac{2n_{eff}L}{n - \phi_r/\pi} \tag{3}$$

where $n_{eff} = \beta_n/k_0$ is the effective refractive index of the cavity. Given this structure, the magnetic field in H cavity inside the cavity is divided into two nearly identical portions H_{upper} and H_{lower} propagating oppositely at interfaces as depicted in Fig. 3. Considering the x-axis symmetry of this cavity, the relation between them is $H_{upper} = H_{lower} = H_{cavity}/2 = H_0$. H_0 represents the magnetic field at the initial facet of cavity ($x = 0$). A loss coefficient of the cavity is assumed as η, which represents the dissipation of the SPP propagating per round-trip in the cavity, including the absorbing loss by the metal and the loss caused by the power coupled out of the cavity. Since the superposition principle is also satisfied for the cavity model, the magnetic field H inside the cavity with an arbitrary position can be described as follows:

$$H_n(x, t) = \frac{2H_0}{\eta}[\exp(\mathrm{i}\beta_n x) + \exp(\mathrm{i}\beta_n \cdot 2L - \mathrm{i}\beta_n x)] \cdot \exp(-\mathrm{i}\omega t) \tag{4}$$

In this configuration, we only consider the first resonance mode of the cavity (Fig. 2). According to the above resonance condition as described in Eq. (2), the equation $\beta_n \cdot 2L \approx 2n\pi$ should be satisfied with ignoring a very small parameter ϕ_r [23]. Therefore, for the resonance of the first order ($n = 1$), we can obtain the magnetic field H inside the cavity as follows:

$$\begin{aligned} H_1(x, t) &= \frac{2H_0}{\eta}[exp(i\beta_1 x) + exp(-i\beta_1 x)] \cdot exp(-i\omega_1 t) \\ &= \frac{2H_0}{\eta}\cos(\beta_1 x) \cdot exp(-i\omega_1 t) \end{aligned} \tag{5}$$

Three first order resonance modes (Mode I, Mode II, Mode III) observed from simulation in Fig. 2 should be described by Eq. (5) as well as resonance condition (Eq. (2)) satisfied.

Actually, the configuration with metal–dielectric multi-layer can be equivalent into another dielectric medium [24]. Thus, this structure with triple periodic cascade cavities can be regard as three combinations of adjacent grouped cavities superposed, as shown in Fig. 4. Concretely, Mode III, Mode II and Mode I can be treated as the cavity with three cavities grouped (Fig. 4), the superposition of first two cavities and last two cavities (Fig. 4), and the superposition of three different independent cavities (Fig. 4), respectively. Fig. 4 gives the simulated z-component magnetic field (H_z) with wavelength of incident light $\lambda = 952$ nm (Mode III), $\lambda = 1160$ nm (Mode