Optics Communications 414 (2018) 16–21

Contents lists available at ScienceDirect

Optics Communications

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

Multiple plasmonically induced transparency for chip-scale bandpass filters in metallic nanowaveguides

Hua Lu *, Zengqi Yue, Jianlin Zhao

MOE Key Laboratory of Material Physics and Chemistry under Extraordinary Conditions, and Shaanxi Key Laboratory of Optical Information Technology, School of Science, Northwestern Polytechnical University, Xi'an 710072, China

ARTICLE INFO

Keywords:
Surface plasmon polaritons
Waveguides
Filters

ABSTRACT

We propose and investigate a new kind of bandpass filters based on the plasmonically induced transparency (PIT) effect in a special metal–insulator–metal (MIM) waveguide system. The finite element method (FEM) simulations illustrate that the obvious PIT response can be generated in the metallic nanostructure with the stub and coupled cavities. The lineshape and position of the PIT peak are particularly dependent on the lengths of the stub and coupled cavities, the waveguide width, as well as the coupling distance between the stub and coupled cavities. The numerical simulations are in accordance with the results obtained by the temporal coupled-mode theory. The multi-peak PIT effect can be achieved by integrating multiple coupled cavities into the plasmonic waveguide. This PIT response contributes to the flexible realization of chip-scale multi-channel bandpass filters, which could find crucial applications in highly integrated optical circuits for signal processing.

1. Introduction

With the development of integrated circuits, the processing speed of electronic devices is approaching the limitation of physics and technology. Compared with the electron, the photon as an information carrier has more significant advantages with higher transmission speed and lower loss. However, it is particularly difficult for the traditional optical devices to reach nanoscale level due to the constraint of the diffraction limit of light. Reducing the size of optical devices is crucial for the realization and development of integrated optical circuits. Surface plasmon polaritons (SPPs) are electromagnetic waves coupled with the electron oscillation on the metal surface and propagating along the metal–dielectric interface with an exponentially decaying field on both sides [1]. As a promising way to achieve integrated optical circuits, SPPs can break the diffraction limit of light and realize the light manipulation at the nanoscale [2–5]. A great variety of devices based on SPPs have been numerically investigated and experimentally demonstrated, such as plasmonic filters [6], logic gates [7], multiplexers [8,9], detectors [10], switches [11,12], modulators [13,14], amplifiers [15], Bragg reflectors [16,17], couplers [18,19] etc. Because of the strong confinement of light [20], the metal–insulator–metal (MIM) waveguides attract broad attentions for the design of integrated plasmonic devices, especially plasmonic filtering elements [6,16,21–26]. Han and Park proposed the Bragg reflector filters based on the MIM plasmonic waveguides [16,17]. Subsequently, the simple cavity-coupled MIM structures were proposed for the realization of filtering function at the nanoscale [21–26]. The plasmonic filters as the wavelength-selective elements exhibit significant applications in highly integrated plasmonic circuits for signal processing and optical communications [6]. As a crucial filtering component, the multi-channel bandpass filters attract particular attention in the MIM waveguides. The complicated Fibonacci-sequence gratings and cascading filtering units in the MIM waveguide were proposed to realize the high-channel-count bandpass plasmonic filters [27,28]. Even so, it is particularly necessary to make the multi-channel plasmonic filtering architecture more simple for broader applications.

In this paper, we propose a new kind of multi-channel bandpass plasmonic filters by means of the multi-peak PTI effect in the simple MIM waveguide systems consisting of a bus waveguide, a stub cavity, and coupled cavities. The numerical simulations demonstrate that the obvious PIT effect can be generated when the coupled cavity is effectively coupled with the stub cavity in the MIM plasmonic waveguides, which are in good agreement with the theoretical analysis results. It is found that the operating wavelength and spectral lineshape of the PIT peak can be flexibly controlled by adjusting the geometrical parameters of the waveguides, such as the lengths of the stub and coupled cavities as well as the coupling distance between the stub and coupled cavities.

---

[*] Corresponding author.
E-mail address: hualu@nwpu.edu.cn (H. Lu).

https://doi.org/10.1016/j.optcom.2017.12.083
Received 28 September 2017; Received in revised form 19 November 2017; Accepted 29 December 2017

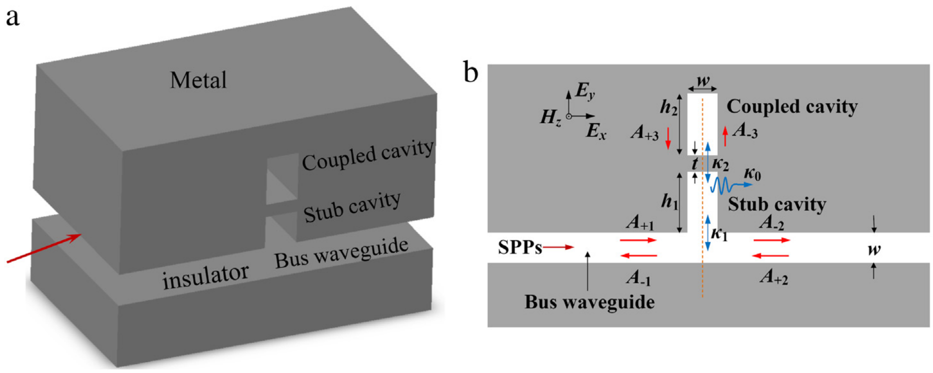

Fig. 1. (a) Schematic diagram of the MIM plasmonic waveguide structure consisting of a bus waveguide, a stub cavity, and a coupled cavity. (b) Cross-section profile of the MIM waveguide. Here, h_1 and h_2 are the lengths of stub cavity and coupled cavity, respectively. t represents the coupling distance between the stub cavity and coupled cavity. w is the waveguide width. A_{+1} and A_{-1} (A_{+2} and A_{-2}) stand for the amplitudes of the incoming and outgoing waves on the left (right) side of the stub cavity in the bus waveguide, respectively. A_{+3} and A_{-3} are the amplitudes of coupled waves along different directions in the coupled cavity, respectively. κ_1 and κ_2 are the decay rates of light power in the stub cavity resulting from the light escape to the bus waveguide and coupled cavity, respectively.

Based on the PIT response, the simple MIM waveguide structures with multiple coupled cavities facilitate the realization of chip-scale multi-channel bandpass plasmonic filters.

2. Structure and theoretical model

Fig. 1 shows the MIM plasmonic structure which consists of a bus waveguide, a stub cavity, and a coupled cavity. The dielectric in the waveguide is set as air ($\varepsilon_i = 1$), and the metal is assumed as silver. For the silver, the frequency-dependent complex permittivity can be described by the Drude model: $\varepsilon_m = \varepsilon_\infty - \omega_p^2/[\omega(j\gamma + \omega)]$. Here, $\varepsilon_\infty = 3.7$ represents the dielectric constant at infinite frequency, $\omega_p = 9.1$ eV stands for the bulk plasma frequency, and $\gamma = 0.018$ eV is the electron collision frequency [17]. In the configuration, h_1 and h_2 are the lengths of stub cavity and coupled cavity, respectively. t stands for the coupling distance between the stub cavity and coupled cavity. w is the width of the waveguide. When the transverse magnetic wave is coupled into the bus waveguide, the highly confined SPP mode will be formed on the metal–dielectric interfaces and propagate along dielectric layer between the metal claddings. If a stub cavity is introduced in the MIM waveguide, the coupling of SPP wave will induce the plasmonic resonance in the stub cavity at the resonance wavelengths [29]. When a coupled cavity is closed to the stub cavity, the resonant mode in the stub cavity will couple into the coupled cavity because of the tunneling effect [30,31]. In the plasmonic waveguide systems, the temporal coupled-mode theory (TCMT) is an effective method to theoretically analyze the SPP propagation features [31,32]. To simplify the theoretical model, the coupling and propagation losses in the waveguide can be neglected [32]. As shown in Fig. 1, A_{+1} and A_{-1} (A_{+2} and A_{-2}) represent the amplitudes of incoming and outgoing waves on the left (right) side of the stub cavity, respectively. A_{+3} and A_{-3} are the amplitudes of incoming and outgoing waves in the coupled cavity, respectively. Here, we consider that the incident light is only injected into the waveguide from the left port (i.e., $A_{+2} = 0$). Therefore, the field amplitude of plasmonic resonance mode in the stub cavity can be described as

$$\frac{da}{dt} = (-j\omega_0 - \kappa_0 - \kappa_1 - \kappa_2)a + e^{j\theta_1}\sqrt{\kappa_1}A_{+1} + e^{j\theta_2}\sqrt{2\kappa_2}A_{+3}, \tag{1}$$

where, ω_0 is the resonance frequency of the stub cavity. κ_0 is the decay rate of the light power, which is derived from the intrinsic loss of the stub cavity. κ_1 and κ_2 are the decay rates of the power in the stub cavity, which result from the light escape into the bus waveguide and coupled cavity, respectively. θ_1 (θ_2) is the phase of coupling coefficient between the stub cavity and bus waveguide (coupled cavity). The incoming and outgoing waves in the bus waveguide and coupled cavity satisfy the relations

$$A_{-2} = A_{+1} - e^{-j\theta_1}a\sqrt{\kappa_1}, \tag{2}$$

$$A_{-3} = -A_{+3} + e^{-j\theta_2}\sqrt{2\kappa_2}a. \tag{3}$$

In Eq. (3), the SPP waves in the coupled cavity satisfy the relation: $A_{+3} = \delta e^{j\varphi}A_{-3}$. Here, φ and δ represent the phase change and amplitude attenuation of the incoming and outgoing waves in the coupled cavity, respectively. The transmission of the SPP wave propagating in the bus waveguide can be expressed as

$$T(\omega) = \left| \frac{j(\omega_0 - \omega) + \kappa_0 + \frac{\kappa_2(1-\delta e^{j\varphi})}{1+\delta e^{j\varphi}}}{j(\omega_0 - \omega) + \kappa_0 + \kappa_1 + \frac{\kappa_2(1-\delta e^{j\varphi})}{1+\delta e^{j\varphi}}} \right|^2. \tag{4}$$

From the above equation, we can see that the transmission $T(\omega)$ is dependent on the phase term φ, which can be described as

$$\varphi = \frac{2\omega \mathrm{Re}(n_{eff})h_2}{c} + \theta, \tag{5}$$

where, c is the speed of light in vacuum, θ represents the additional phase shift of metallic planes in the coupled cavity, and n_{eff} stands for the effective refractive index of SPP wave in the MIM waveguide, which can be achieved by solving the SPP dispersion equation [33,34]

$$\varepsilon_m\sqrt{n_{eff}^2 - \varepsilon_i}\,\tanh\left(\frac{\pi w\sqrt{n_{eff}^2 - \varepsilon_i}}{\lambda}\right) = -\varepsilon_i\sqrt{n_{eff}^2 - \varepsilon_m}, \tag{6}$$

where, λ is the wavelength of incident light. The calculated value of n_{eff} is about 1.4 in the wavelength of interest [31]. By combining the above equations, the transmission spectrum of SPP wave in the MIM plasmonic systems can be theoretically calculated and analyzed.

3. Simulation results and analysis

We numerically investigate the transmission properties of SPP wave in the MIM waveguides by using the finite-element method (FEM). In detail, we use the finite-element software COMSOL Multiphysics to obtain the simulation results. In the simulations, the port boundary is set at the left and right sides of the computational space, and the scattering boundary condition is set at the top and bottom sides. The minimum mesh size is set as 5 nm. In Fig. 2(a), we can see that the transmission spectrum possesses a broad dip at the wavelength of 1006 nm in the MIM plasmonic system without the coupled cavity. When a coupled cavity is close to the stub cavity in the plasmonic waveguide,