PRAMANA
— journal of
physics

© Indian Academy of Sciences

Vol. 86, No. 5
May 2016
pp. 1091–1097

Tunable plasmonic filter with circular metal–insulator–metal ring resonator containing double narrow gaps

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MS received 3 April 2014; revised 11 April 2015; accepted 11 May 2015

DOI: 10.1007/s12043-015-1127-0; ***e*Publication:** 21 November 2015

Abstract. Tunable filter based on two metal–insulator–metal (MIM) waveguides coupled to each other by a ring resonator with double narrow gaps is designed and numerically investigated by finite-difference time-domain (FDTD) simulations. The propagating modes of surface plasmon polaritons (SPPs) are studied. By introducing narrow gaps in ring resonators, the transmission in different resonance modes can be effectively adjusted by changing the gap width (g), and the transmitted peak wavelength has a nonlinear relationship with g. Another structure consisting two cascading ring resonators and regular MIM waveguide have also been proposed. The mechanism based on circular ring resonators with narrow gaps may provide a novel method for designing all-optical integrated components in optical communication and computing.

Keywords. Metal–insulator–metal waveguide; surface plasmon; optical filters; ring resonator.

PACS Nos 42.79.−e; 73.20.Mf; 78.20.Bh

1. Introduction

Surface plasmon polaritons (SPPs) are surface electromagnetic waves propagating along the metal–dielectric interface and evanescently confining in the perpendicular direction of the interface [1–4]. Plasmonic waveguides transfer the electromagnetic waves coupled to surface collective oscillations of free electrons on metals that have been considered as energy and information carriers in nanophotonics. Two of the well-known multilayer plasmonic waveguides are metal–insulator–metal (MIM) and insulator–metal–insulator (IMI) structures [5,6]. Among various SPP-based waveguides, metal–insulator–metal (MIM) structures have attracted tremendous interest of researchers owing to their potential applications in subwavelength confinement of light. Many components such as splitters [7–9], couplers [10,11], multiplexers and demultiplexers [12–15], switches [16], logic gates [17], etc., have recently been studied.

Optical filters, as one of the building blocks of integrated optical circuits, have attracted considerable attention. Different types of plasmonic filters such as tooth-shaped subwavelength and add-drop topologies are introduced and analysed by numerical methods [18,19]. In addition, ring resonator filters generate opposite phase standing waves using optical cavities, to be used as a suppressor of some targeted wavelengths in the transmission spectrum [20–22]. Coupled mode theory (CMT) and numerical methods are used for the analysis of such structures. Recently, Huwang showed that a narrow gap created in the middle of the upper half of a regular MIM ring causes plasmonic fields to experience multiple reflections at the discontinuity introduced by the gap, resulting in the formation of plasmonic stop bands [23]. The central frequency and the range of stop bands are shown to be controllable by varying the width of the narrow gap.

In this paper, we do a further research on the relation between the transmitted modes and the narrow gaps of the ring resonator. A compact nanoscale all-optical plasmonic filter based on a coupled nanoring structure with double narrow gaps is proposed. We focus on the tunable filtering characteristics of this structure, and the transmission responses are studied by the FDTD method. It is found that the resonant wavelengths can be easily manipulated not only by adjusting the radius of the ring resonator but also by changing the gap distances. Our structure can decrease plasmonic filter dimensions and so may have important applications in plasmonic integrated circuits.

2. Structures and model

Figure 1 shows the schematic diagram of the plasmonic filter, which is composed of inputting and outgoing MIM waveguides as well as a ring resonator with double narrow gaps in the middle of the structure. The dielectric in the metal slit is air with

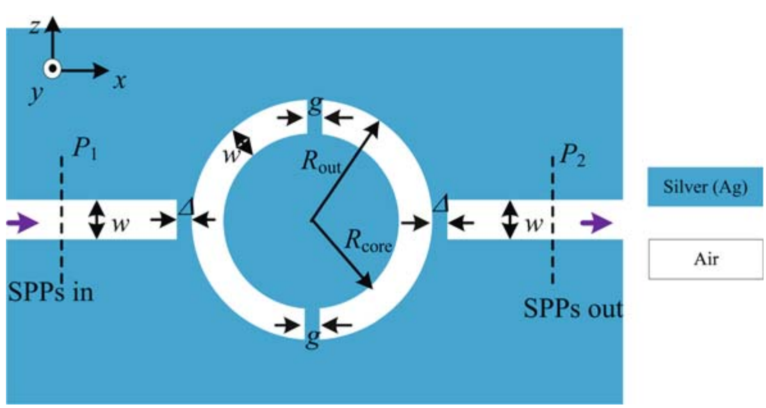

Figure 1. Schematic diagram of the MIM plasmonic filter with a circular ring resonator. w, R_{core} and R_{out} are the width of the MIM waveguide, the radius of the core and the outer radius of the ring resonator, respectively. Δ is the coupling length between the waveguide and the resonator, g is the width of the narrow gap.

Table 1. Values of Lorentz–Drude parameters for Ag [24].

Parameters	Values
ε_∞	3.7187
ω_p (rad/s)	1.396×10^{16}
ω_0 (rad/s)	6.496×10^{15}
τ_0 (s^{-1})	3.29×10^{-14}
τ_b (s^{-1})	1.697×10^{-16}
f_1	0.4242

refractive index $n = 1$. The frequency-dependent dielectric constant of silver is expressed by Lorentz–Drude model [24]:

$$\varepsilon(\omega) = \varepsilon_\infty - \frac{\omega_p^2}{\omega^2 + i\omega/\tau_0} - \frac{f_1\omega_p^2}{\omega^2 - \omega_0^2 + i\omega/\tau_b}, \tag{1}$$

where ω_p is the plasmon frequency of the metal, τ_0 is the relaxation time, ω is the frequency of interest, i denotes the complex number ($i = \sqrt{-1}$), and ε_∞ is the contribution from interband transitions at infinite frequency (that is, the static contribution). The new Lorentz term includes the Lorentz oscillator damping time τ_b, the Lorentz resonance width ω_0 and a weighting factor f_1. The values of different parameters for silver are given in table 1.

FDTD method is used to study transmission properties of this structure, with the perfectly matched layer (PML) absorbing boundary conditions in x and z directions of the simulation domain. The incident light for excitation of the SPP mode is TM-polarized (the magnetic field is parallel to y-axis). In the following numerical simulations and analysis, the grid sizes in the x and z directions are chosen to be $\Delta x = \Delta z = 2$ nm and $\Delta t = \Delta x/2c$ which are sufficient enough for numerical convergence. Two power monitors are set at points P_1 and P_2 to detect the input power A_1 (without the circular ring resonator) and the transmitted power A_2 (with the circular ring resonator). Hence the power transmittance is $T = A_2/A_1$ [25]. The auxiliary differential equation (ADE) method is used to model dispersive materials in FDTD which utilizes time-domain auxiliary differential equations linking polarization and the electric flux density.

3. Simulation results and discussions

First of all, we plot the transmission spectrum and the field distributions of the propagation of SPPs in regular MIM ring resonator in figure 2a. The parameters of the structure are set to be $\Delta = 10$ nm, $w = 50$ nm, $R_{out} = 200$ nm and $R_{core} = 150$ nm. This is a typical plasmonic band-pass filter consisting of two MIM waveguides coupled together by a circular ring resonator. Figures 2b, 2c and 2d depict the contour profiles of the field $|H_y|^2$ for three different wavelengths. Wang *et al* [18] studied the influences of radius of the ring and coupling gaps on the wavelengths of the transmission peaks. In this investigation, in order to have fundamental mode, w is considered to be 50 nm to achieve a definitive subwavelength structure.

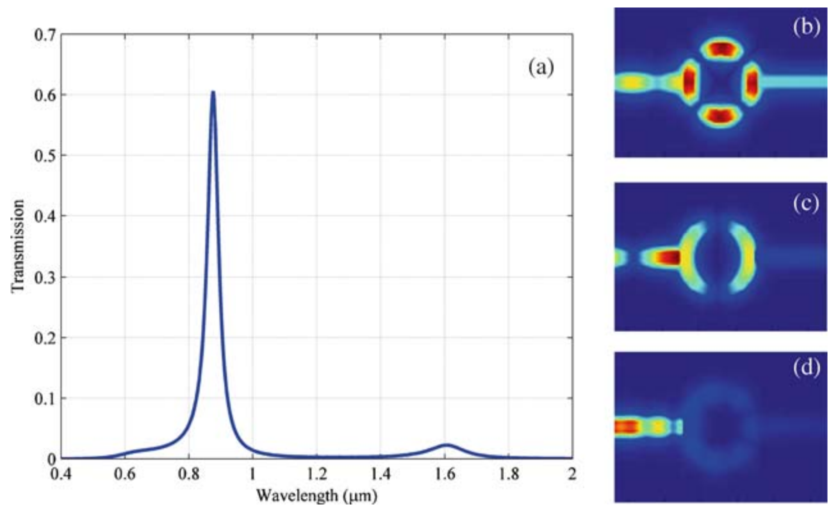

Figure 2. (**a**) The transmission spectrum of the regular ring resonator. The contour profiles of the field $|H_y|^2$ of the nanoscale resonator at different wavelengths: (**b**) $\lambda = 0.867$ μm, (**c**) $\lambda = 1.606$ μm and (**d**) $\lambda = 0.502$ μm.

We introduce double gaps with the width $g = 20$ nm in the middle of the circular MIM ring which is connected to the input and output feed lines (see figure 1) with coupling length Δ. When a narrow gap g is introduced into the MIM ring resonator, it must be noted that the wavelengths of the transmission peaks do not satisfy the simple relation $\lambda_m = 2(2\pi r - g)/m$, where m is the mode number in the ring. It can be understood that the transmittance dips found in the FDTD results are caused by multiple reflections at the edges of the gap. The incident SPPs at the dip frequencies from the input waveguide are divided into the upper and the lower part of the ring and experience multiple reflections with destructive interference occurring at the output port. Figure 3a shows the transmission spectrum and figures 3b–3d depict the contour profiles of fields $|H_y|^2$ with different wavelengths. When standing waves form in the ring at resonance, most part of the SPPs can propagate through the ring and transmit from the waveguide.

Figure 4 shows the transmission spectra of the SPPs for the ring with different gap widths. It is quite obvious that only the waves that satisfy the resonance conditions can be constructed as standing waves in the ring resonator, and then coupled into the corresponding drop waveguide. As can be seen from figure 4, the number of transmission peaks decreased as g increased. We also consider the relationship between the gap width of the resonator and the transmitted peak wavelength; we find that the transmitted peak wavelength has a nonlinear relationship with g. Different modes can be separated from each other, but intervals between them are not large enough. These results will provide theoretical basis for designing band-pass filters at the given wavelength. When g is larger than 40 nm, single wavelength filtering effect can be achieved. As the loss of the metal is inevitable, the transmittance cannot reach 1.0.

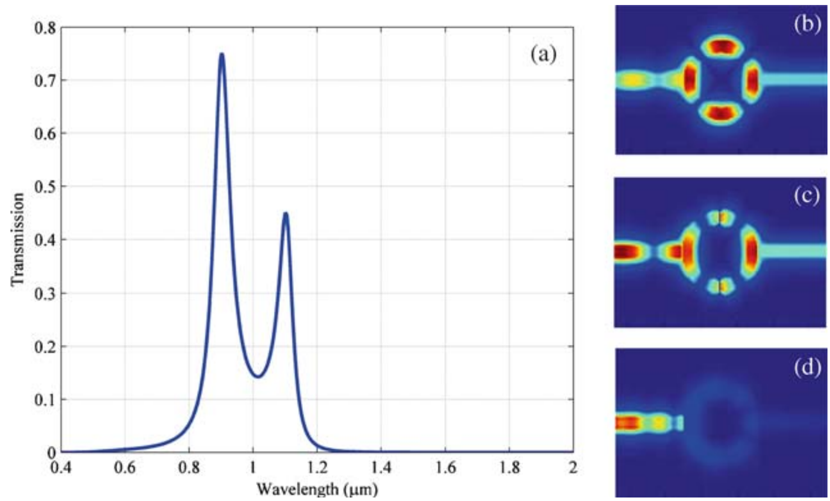

Figure 3. (**a**) The transmission spectrum of the MIM ring resonator with dual narrow gaps. The contour profiles of the field $|H_y|^2$ of the nanoscale resonator at different wavelengths: (**b**) $\lambda = 0.898$ μm, (**c**) $\lambda = 1.095$ μm and (**d**) $\lambda = 0.502$ μm.

Multiple ring resonators are widely used in optical filtering. Here we used two cascading ring resonators to investigate the design consideration about the optical filter. The proposed structure is depicted in figure 5. Two circular ring resonators with narrow gaps

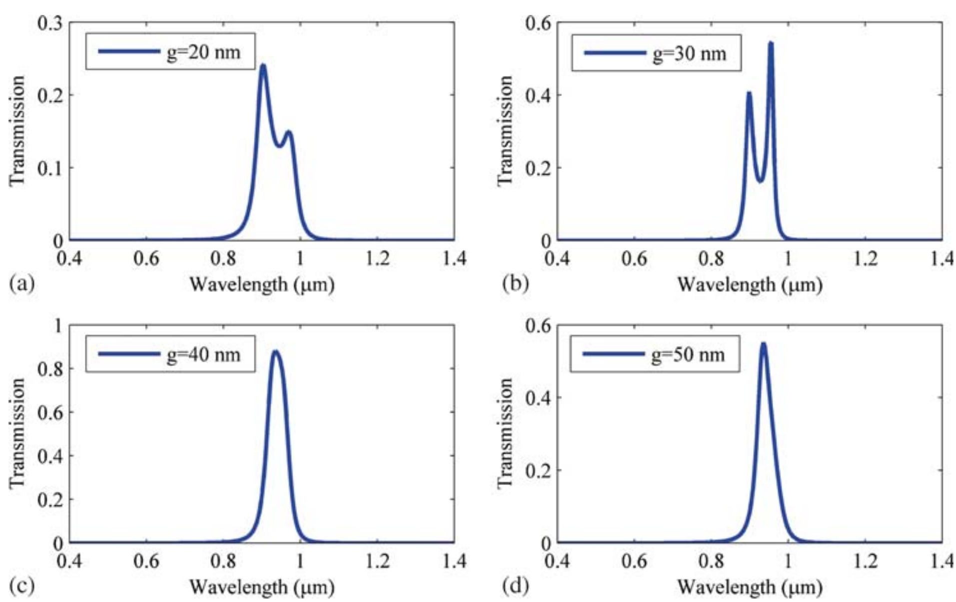

Figure 4. The transmission spectrum of the MIM ring resonators containing double narrow gaps with different widths.

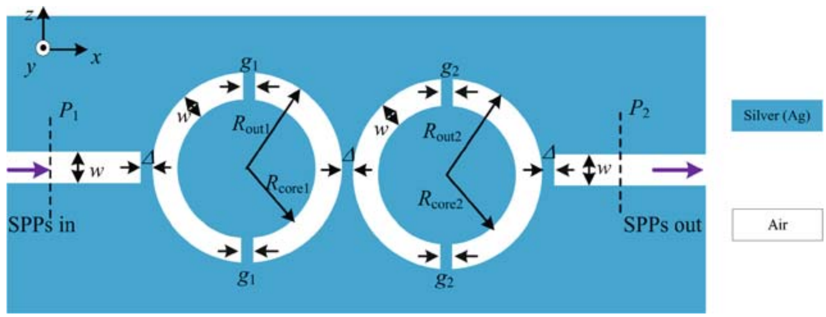

Figure 5. Schematic of a plasmonic MIM filter using two circular ring resonators with narrow gaps.

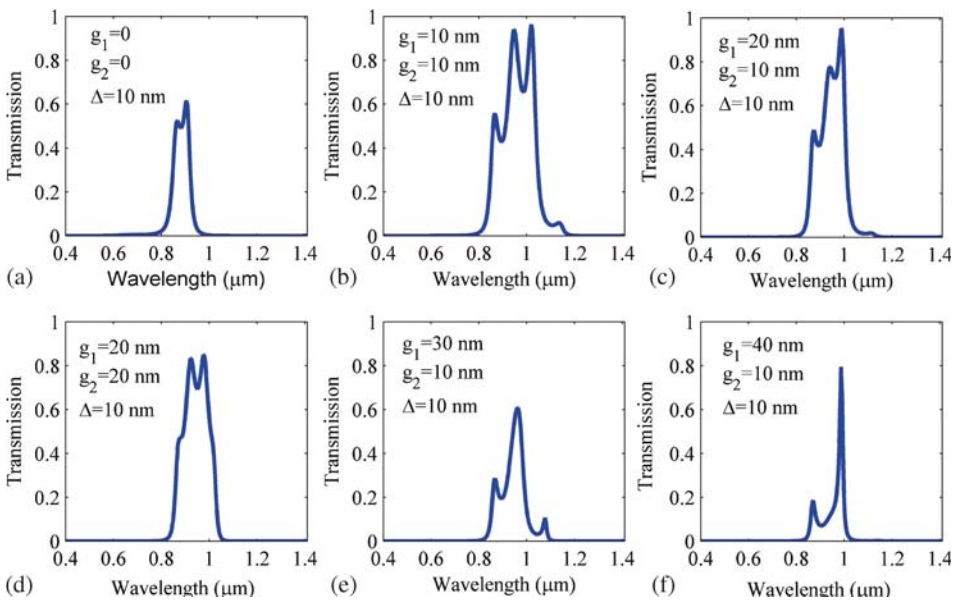

Figure 6. The transmission spectrum of the plasmonic filter containing two ring resonators with narrow gaps.

could be configured with two bus waveguides. The transmission spectra of the SPPs for the ring with different parameters are shown in figure 6. Based on the theoretical analysis above, the operating wavelength of the proposed structure can be effectively modulated by altering the effective index of SPPs in the cavity, which is determined by g.

4. Conclusions

In this paper, we have numerically investigated one type of compact plasmonic filter based on coupled ring resonator structures with narrow gaps. The structure is made up of MIM waveguide coupled laterally to a circular ring resonator, which has been designed to modify the transmission characteristic of the proposed filter. The optical response has been studied by FDTD method. The dependence of the transmission wavelength of the channel on geometrical parameters of the structure is discussed. The simulation results show that the narrow gaps created in the regular MIM ring causes plasmonic fields to experience multiple reflections at the discontinuity introduced by the gap. The fabrication of our structure is simple and it can decrease plasmonic filter dimensions, based on which we shall find potential applications in highly integrated optical circuits.

Acknowledgements

This work is partially supported by the National Natural Science Foundation of China (Grant Nos 61203211, 11304157) and the Natural Science Foundation of the Jiangsu Higher Education Institutions of China (Grant No. 13KJB140006). The authors would especially like to thank Dr Xu Yi from Guangzhou University and Dr Wei Su for their useful discussions.

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