Wavelength filtering and demultiplexing structure based on aperture-coupled plasmonic slot cavities

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Received July 7, 2011; revised August 25, 2011; accepted August 29, 2011; posted September 1, 2011 (Doc. ID 150491); published September 29, 2011

We propose a submicron plasmonic wavelength filtering/demultiplexing structure based on aperture-coupled slot cavities, which can overcome the limitation by the field skin depth of ~25 nm in a conventional evanescent-coupling approach, and thus lead to an easy-to-fabricate device structure. By introducing the stub-induced interference arm in the drop or bus waveguide, the power ratio between the different resonance modes can be effectively adjusted by changing the stub length. Also, the transmission peak can be about two times higher than that without stub structure in the bus waveguide. Our results open a way to construct nanoscale wavelength filters and demultiplexers for high-density nanoplasmonic integration circuits. © 2011 Optical Society of America

OCIS codes: 060.4230, 130.3120, 130.7408, 240.6680.

1. INTRODUCTION

Plasmonic waveguides are attracting much attention because of their ability to spatially confine light below the diffraction limit resulting from the strong localization of surface plasmon polaritons (SPPs) at metal-dielectric interfaces, thereby potentially enabling device miniaturization on a scale not accessible with conventional dielectric waveguide-based photonic circuits [1–3]. A variety of plasmonic waveguides, e.g., metallic wedges [4], V-shaped grooves [5,6], metallic stripes and nanowires [7], dielectric-loaded plasmonic waveguides [8], and metal-insulator-metal (MIM) structures [9,10], have been explored in recent years. Among them, the MIM configuration has shown the tremendous potential applications in ultra-high-density nanoplasmonic integrated circuits due to its remarkable and considerable unique advantages, such as the subwavelength mode confinement and its capability to route light through sharp bends with very high efficiency [11]. Recently, a variety of MIM waveguide-based functional structures have been numerically and/or experimentally demonstrated, including bends [11,12], splitter [12,13], Y-shaped combiner [14], couplers [15], and Mach–Zehnder interferometers [16], etc.

Wavelength selecting or demultiplexing is one of the key technologies in optical communications. Recently, plasmonic filters based on MIM waveguides have been studied widely, such as plasmonic gratings [17–19], ring and nanodisk resonators [20,21], and stub or tooth shaped waveguide filters [22–24]. All of these structure can operate as individual bandpass or bandstop filters. However, in many cases, such as WDM systems, it is necessary to separately select several specific wavelengths in different channels. In order to realize this function, many efforts are currently being devoted to develop plasmonic add/drop filters or demultiplexers, for instance, Xiao et al. and Hosseini and Massoud presented a channel drop filter by using microring resonators [25] and rectangular geometry resonators [26], respectively. Noual et al. designed a plasmonic structure with two cavities embedded in the branches of Y-bent waveguide to drop only two operating wavelengths [27]. Subsequently, Mei et al. and Wang et al. used a MIM plasmonic side-coupled Fabry–Perot [28] and nanodisk resonator [29] to realize multichannel wavelength demultiplexing capability. Recently, an ultracompact wavelength demultiplexer has been proposed by our research group by using arrayed plasmonic slot cavities [30]. All these demultiplexing structures mentioned above are working under the evanescent coupling mechanism. However, the noticeable evanescent coupling only occurs when the coupling gap between two MIM waveguides is much smaller than the field skin depth (typically around 25 nm [31] in metal), which demands rather high processing precision in the manufacture of these kinds of devices. Alternatively, the aperture structure was proposed to realize resonator excitation between the ring and straight waveguide with subdiffraction modal volumes [32], which can overcome the limitation by the field skin depth in an evanescent coupling approach and therefore provide an efficient coupling method for practical experimental processing.

In this paper, a submicron wavelength filtering and demultiplexing structure based on aperture-coupled plasmonic slot cavities is proposed and numerically analyzed using the finite-difference time-domain (FDTD) method. Both the analytic and simulation results demonstrated that not only can the specific operating wavelengths be designed by selecting proper lengths of the slot cavities, but the bandwidth of the transmission curve can be manipulated by controlling the width of the aperture. In addition, the stub-induced interference arm has been introduced in the bus waveguide and drop waveguide, respectively, to significantly increase the transmission peak and adjust the power ratio between two intrinsic resonance modes.
2. THEORETICAL ANALYSIS AND DISCUSSION OF ONE APERTURE-COUPLED SLOT CAVITY FOR WAVELENGTH FILTERING

Figure 1 shows a basic scheme of a two-dimensional plasmonic slot cavity with length $L$ side-coupled to the bus and drop waveguides via two small apertures with width $g$ and depth $t$. The materials in the gray and white areas are chosen to be silver and air ($\varepsilon_d = 1$). The widths of the bus/drop waveguides and the cavity are fixed as $w = w_1 = 100$ nm. The distance of the aperture from the cavity center is $s$, and the length of the stub structure in the drop waveguide is $d_1$. Since the widths of the MIM waveguides are much smaller than the incident wavelength, only the fundamental TM mode is excited in the structure, whose dispersion relation is governed by the following equation [31]:

$$
\varepsilon_d k_m + \varepsilon_m k_d \tanh \left( \frac{k_d}{2} w \right) = 0,
$$

with $k_d$ and $k_m$ defined as $k_d = (\beta^2 - \varepsilon_d k_0^2)^{1/2}$ and $k_m = (\beta^2 - \varepsilon_m k_0^2)^{1/2}$. $\varepsilon_d$ and $\varepsilon_m$ are, respectively, the dielectric constants of the insulator and the metal. $k_0 = 2\pi/\lambda$ is the free-space wave vector. The effective refractive index of the MIM waveguide can be represented as $n_{eff} = \beta/k_0$. The frequency-dependent complex relative permittivity of metal $\varepsilon_m(\omega)$ can be characterized by Drude mode $\varepsilon_m(\omega) = \varepsilon_\infty - \omega_p^2/\omega(\omega + i\gamma)$, where $\varepsilon_\infty$ stands for the dielectric constant at the infinite frequency, and $\gamma$ and $\omega_p$ are the electron collision frequency and bulk plasma frequency, respectively. $\omega$ is the angular frequency of incident light. The parameters for silver can be set as $\varepsilon_\infty = 3.7$, $\omega_p = 9.1$ eV, $\gamma = 0.018$ eV, which fit the experimental optical constant of silver [33] quiet well in the visible and near-IR spectral range.

To understand the realization of the wavelength filtering capability, the propagation behavior of the SPPs in the proposed structure is analyzed. When the SPPs' waves propagate along the bus waveguide, the light at the resonance wavelength can be effectively coupled into the slot cavity via the small apertures and form the standing waves herein, and then it could be partly coupled out from the cavity, as shown in Fig. 1. Defining $\Delta \phi$ to be the total phase delay of the SPPs propagating per round trip inside the slot cavity, one has $\Delta \phi = 4\pi n_{eff} L/\lambda + 2\phi_\parallel$, where $L$ is the length of the slot cavity and $\phi_\parallel$ is the phase shift of the beam reflected at one facet of the cavity. Obviously, the resonance wavelength can be obtained only when the following resonance condition is satisfied: $\Delta \phi = m \times 2\pi$, where the positive integer $m$ corresponds to the order of the resonance mode. So the resonance wavelength $\lambda_m$ can be finally expressed as follows:

$$
\lambda_m = \frac{2n_{eff} L}{(m - \phi_\parallel/\pi)},
$$

where $n_{eff}$ is the real part of the effective index in the resonant cavity and $\lambda_m$ is the vacuum wavelength of the waves. It can be seen that the resonance wavelength is linear to the effective index and the length of the cavity. It is quite obvious that only the waves that satisfy the resonance wavelengths can be formed as standing waves in the slot cavity, and then coupled into the drop waveguide to be selected.

To verify the above theoretical analysis about the wavelength filtering capability based on the aperture-coupled slot cavity, the FDTD with perfectly matched layer absorbing boundary conditions is used to calculate the transmission spectra. In the following simulations, the grid sizes in the $x$ and $z$ directions are chosen to be $\Delta x = 2$ nm, $\Delta z = 2$ nm for good convergence of the numerical calculations. The TM-polarized incoming pulse is generated at the left end of the bus waveguide, and the fast Fourier transform is used to obtain the spectral response of the proposed structure. According to the research in literature [34], the intrinsic resonance modes of the slot cavity can be alternatively suppressed by adjusting the coupling position. In this paper, one shifts the aperture over a distance $s$ (approximately equals $L/8$) away from the cavity center to make sure that both the two lowest resonance modes for $m = 1$ and $m = 2$ exist inside the slot cavity. First, the stub structure is not considered in the proposed structure, which means the stub length is fixed as $d_1 = g/2$. The other parameters of the structure are set to be $L = 600$ nm, $w = w_1 = 100$ nm, $s = 80$ nm, $g = 30$ nm, $t = 100$ nm. Figure 2(a) shows the transmission spectrum in the drop waveguide of the one aperture-coupled slot cavity structure. We can see that the wavelengths of $1.46 \mu m$ for $m = 1$ and $0.77 \mu m$ for $m = 2$ can be selected in the wavelength range of 0.6–1.8 $\mu m$ of interest. By solving Eq. (1), the effective index $n_{eff}$ of MIM waveguide at $1.46 \mu m$ and $0.77 \mu m$ with $w_1 = 100$ nm can be obtained as 1.20 and 1.22, respectively. Substituting $L = 600$ and the obtained $n_{eff}$ into Eq. (2), the resonance wavelengths can be calculated as $1.44 \mu m$ for $m = 1$ and $0.732 \mu m$ for $m = 2$ when assuming the phase shift $\phi_\parallel = 0$. We can see that the theoretical analysis agree with the simulation result fairly well. The deviation between the FDTD simulation and the calculated results from Eq. (2) could be attributed to neglecting the influence of $\phi_\parallel$.

Based on the theoretical analysis above, the operating wavelength of the proposed structure can be effectively modulated by altering the length of the slot cavity and the effective index of SPPs in the cavity, which is determined by its width. Figure 2(b) reveals that the transmission wavelengths of each resonance mode have a nearly linear relationship with the length of the slot cavity (but with different slope factors) and exhibits red shift while increasing the value of $L$. This result is in conformity with the solution of Eq. (2). Therefore, the desired wavelength can be achievable by properly selecting the specific parameters of the structure, such as the length or width of the slot cavity.

Figure 2(c) shows the transmission spectra of the proposed structure with different aperture widths. One can see that the
resonance wavelength blue shifts with an increase of the aperture width, which can be attributed to the influence of the aperture on the effective index $n_{\text{eff}}$ of the cavity in the coupling segment. Moreover, the bandwidths of curves become a bit narrower with decreased $g$, because a narrow aperture width would result in small coupling strength which will enhance the cavity effect due to the small amount of energy coupled out of the slot cavity. Besides, one can find that a narrow aperture will also decrease the transmittance of the peak wavelength in the drop waveguide. For clarification, Fig. 2(d) shows the FWHM and peak wavelength of the transmission spectra vary with the aperture width. Accordingly, the bandwidth of the proposed filtering structure can be modified by controlling the aperture width.

As shown in Fig. 2(a), two resonance peaks appear in the transmission curve of the proposed structure, which correspond to the mode 1 ($m = 1$) and mode 2 ($m = 2$), respectively. In this paper, the stub structure has been designed in the drop waveguide to modify the transmission characteristic of the proposed filter. As illustrated in Fig. 1, the fields $H$ coupled to the drop waveguide will be divided into two parts $H_1$ and $H_2$ propagating in opposite directions, and then they will interfere with each other when $H_1$ reflects back from the end of the stub structure. Therefore, the stub structure works as an interference arm in this case. Figure 3(a) reveals the transmittance of the peak wavelength corresponding to two resonance modes as a function of the stub length. It is seen that the transmission characteristic can be modified by changing the stub length. Particularly, as seen in Fig. 3(b), only the first (second) resonance mode can be transmitted in the drop waveguide when the stub length is chosen as 140 nm (290 nm), which correspond to points A and B in Fig. 3(a). It is because when the following formula is satisfied: $k_{\text{app}} \times 2d_1 = \pi$ ($d_1 = \lambda_{\text{app}}/4$), the fields $H_1$ of the corresponding resonance mode would interfere with the other part destructively in the drop waveguide, resulting from the phase difference of $\pi$ between $H_1$ and $H_2$. Therefore, the power ratio between modes 1 and 2 can be controlled by adjusting the value of $d_1$.

Next, the stub structure used at the end of the bus waveguide is also considered in the proposed structure, as shown in the illustration of Fig. 4(a). First, when the stub waveguides is stopped at the end of the aperture structure, which means $d_2 = g/2$, the transmission spectra in the drop waveguides are depicted in Fig. 4(a). Compared with the result of Fig. 2(a), we can find that the maximum transmittance has increased up to 80%, which is nearly two times higher than the result obtained in Fig. 2(a). It is because the bus waveguide end can reflect the transmitted power, and thus more power is coupled into the slot cavity via the aperture structure. Based on the interference arm analysis above, we can also deduce that when the stub length approximately equals to $\lambda_{\text{app}}/4$, the corresponding resonance mode would be completely removed in the drop waveguide, and only one resonance peak appears in the transmission spectra, as shown in Fig. 4(b). Therefore, the stub structure can be used to increase the transmission peak of both/resonance wavelength(s) by selecting proper stub length in the proposed filtering structure.
3. DISCUSSION OF MULTIPLE APERTURE-COUPLED SLOT CAVITIES FOR WAVELENGTH DEMULTIPLEXING

As an application of the wavelength-selecting properties, the above aperture-coupled slot cavity can be exploited to construct a submicron plasmonic wavelength demultiplexer. Figure 5(a) shows a typical $1 \times 4$ demultiplexer structure, consisting of a MIM bus waveguide side-coupled with four slot cavities via the aperture structure. The four cavities have different lengths of $L_1 = 410$ nm, $L_2 = 460$ nm, $L_3 = 530$ nm, and $L_4 = 600$ nm for four wavelengths demultiplexing capability. The distances of the apertures away from the corresponding cavity center are chosen as $s_i = L_i/8 (i = 1, 2, 3, 4)$, where $i$ stands for the channel number. All the other parameters are set as follows: $w = w_t = 100$ nm, $g = 30$ nm, $t = 100$ nm, $D = 615$ nm. Figure 5(b) shows the transmission spectra at the output of four channels. We can find that this multiple aperture-coupled slot cavities based structure demonstrates the wavelength demultiplexing function; the transmission bands of 1061, 1178, 1338, and 1493 nm are selected in channels 1–4, and the maximum transmittance of the four bands is 76%, which is rather high because the bus waveguide is stopped (stub length $d_2 = 0$) at the end of the last aperture structure. Cross talk is defined as the ratio between the power of undesired and desired bands at the outputs. As an example, we can calculate the cross talk for the first channel band (1061 nm). From the figure, one can see that the cross talk between channels 1 and 2 is around $-27.1$ dB for the 1061 nm branch; the cross talk between channels 1 and 3 is around $-28.6$ dB for the 1061 nm branch; and the cross talk between channels 1 and 4 is around $-21.6$ dB for the 1061 nm branch.

Figures 5(c) and 5(d) show the propagations of field $H_y$ and the demultiplexing effect for two monochromatic waves with different wavelengths of 1061 and 1493 nm launched into the $1 \times 4$ wavelength demultiplexing structure. From it, one can see that the wave with the wavelength of 1061 nm is just passing through the slot cavity of channel 1, while the one with the wavelength of 1493 nm is just transmitting from the cavity of channel 4. This phenomenon reaches good agreement with the transmission spectra shown in Fig. 5(b).

Finally, we make a simple comparison of our proposed structure with those considered in [20, 21, 25–30, 34]. All the filtering or demultiplexing structures proposed in these literatures work under the evanescent coupling approach. In this case, the noticeable filtering characteristics could be achievable only when the coupling gap (usually less than 20 nm) in the coupling region is much smaller than the field skin depth ($\sim 25$ nm) in metal, which would significantly increase fabrication difficulty with demand of high processing precision in the manufacture of the device. While, our proposed structure works under the aperture-coupling mechanism rather than the evanescent coupling method, which overcomes the limitation of minimum dimension in the fabrication processing caused by the field skin depth, therefore could be fabricated more easily. In common with the work in [34], the wavelength tenability can be realized by changing the geometrical parameters of the slot cavity. However, the bandwidth of this proposed structure can be modified by controlling the aperture.
width, rather than the coupling distance in [34]. In addition, the stub-induced interference arm has been introduced in this proposed structure to selectively increase the transmission peak of both/specific resonance wavelength(s) (about two times higher) and adjust the power ratio between the two intrinsic resonance modes, which are unachievable in [34].

4. CONCLUSION

In conclusion, an easy-to-fabricate aperture-coupled slot cavities structure is proposed and analyzed by the two-dimensional FDTD method. Narrowband wavelength filtering and demultiplexing capabilities have been realized and demonstrated. Both the theory and simulation results show the characteristics of the transmission band, including the peak wavelength and bandwidth, in each drop waveguide can be modified by adjusting the length of the cavity and the width of the aperture. In addition, the stub-induced interference arm has been introduced in the bus waveguide and drop waveguide, respectively, to significantly increase the transmission peak (about two times higher) and adjust the power ratio between two intrinsic resonance modes. The result above implies that the wavelength demultiplexing structure can find favorable applications in all-optical integrated architectures for optical computing and communication, especially in WDM systems in nanoscale.

ACKNOWLEDGMENTS

This work is partial supported by the Key Program of the National Natural Science Foundation of China (NSFC) (grant 61036011).

REFERENCES


