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Triple-wavelength filter based on the nanoplasmonic metal-insulator-metal waveguides

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Abstract – In this paper, we present a proposal for compact photonic wavelength filtering and 3-dB wavelength splitting device based on nanoplasmonic metal-insulator-metal structure. The working performance of the device has been accurately simulated using the temporal coupled-mode theory. We use a numerical simulation method of eigenmode expansion propagation for the overall design process. We show that the transmission efficiency of the drop filter can be significantly enhanced by applying specifically optimization of nanostub waveguide. The proposed structure has potential applications in highly efficient ultra-compact integration circuits as well as in optical communication systems at nanoscale.

Keywords — surface plasmon polaritons (SPPs), metal-insulator-metal (MIM), Fabry-Perot nanocavity, wavelength filter, eigen mode expansion (EME) simulation.

I. INTRODUCTION

Recently, surface plasmon polaritons (SPPs) have proved the considerable potential to confine light in a nanoscale beyond the so-called diffraction limit that was unable to overcome by silicon-based photonic waveguides[1]–[3]. SPPs are regarded as a promising method for constructing highly integrated photonic circuits [4]–[6], for instance, long-range SPPs can be realized in a plasmonic hybrid silicon waveguide [7],[8]. Among SSP structures, plasmon-slot based waveguides using metal-insulator-metal (MIM) structures have been realized in both long-range propagation and sub-wavelength SSP confinement for photonic integrated circuits[9],[10]. Moreover, MIM waveguides are widely applied in designing nanoscale integrated devices because of high localization and small bending loss with a relatively easy fabrication thanks to the current advanced manufacturing technologies. These plasmonic nanostructures were applied to design variety of devices, for instance, switches [5], [11], [12], sub-wavelength imaging systems [13], biosensors [14],[15]. Furthermore, broadband MIM waveguides with low side lobes were proposed as an alternative to create Bragg gratings for coupling with optical fibers in telecommunication systems [16]. Metallic plasmonic slits used for the design of nanoscale devices with near-field applications have been demonstrated in the fact [17] because MIM waveguides can trap light with an acceptable length for SPP propagation [10]. Based on the MIM waveguide architecture, recently, several wavelength-selective devices have been proposed and investigated, e.g. plasmonic tooth-shaped filters [18],[19], and nano-disk shaped resonators [20].

In various kinds of MIM waveguides, optical resonators using nanotubes are important elements of plasmonic wavelength-multiplexing structures due to their symmetry, simplicity, and simple of fabrication [21].

Plasmonic wavelength demultiplexers allowing to filter specific wavelengths in channels play an important role in all-optical wavelength processing nanoscale circuits. Noual et al. [22] proposed a plasmonic multiplexer utilizing Y-bent MIM waveguides. However, this device needs at least 1.5 μm of the distance between the cavities making it unsuitable for a compact device. Besides, the device was only designed for adding/dropping two operating wavelengths. Another plasmonic demultiplexer based on the metallic grating in three-dimensional free space has been proposed [23] but its size seems to be unsuitable for the integration and miniaturization of devices due to the periodic array and 3D conformation. To promote the miniaturization of plasmonic devices, Hua Lu et al. [24] introduced a plasmonic triple wavelength demultiplexer, some others suggested wavelength demultiplexers based on nanocavities or coupled resonators [25]–[28]. However, investigations of such devices either suggested wavelengths not popular in WDM communication systems or the transmission efficiency is still relatively low.

In this paper, we designed a nanoplasmonic wavelength filter for three wavelength bands of 1310 nm, 1430nm and 1550 nm which is based on the channel dropping structures in MIM waveguide using isolated Fabry-Perot (FP) rectangular resonators and a double stub waveguide. The eigen-mode expansion (EME) propagation simulation method [29] based on the highly-stable modal transmission line theory [30] has demonstrated the efficient transmission and relatively low loss of the drop waveguide when introducing the double nano-stub waveguide. We demonstrated that this nanoscale plasmonic triple-wavelength filter and 3-dB wavelength splitter has efficiently performed adding/dropping/splitting functions in applications of wavelength division multiplexing devices at the telecom regime such as optical access networks and optical computing systems.

II. MODEL AND DESIGN PRINCIPLE

The conceptual diagram of the proposed three-wavelength band filter is shown in Fig. 1. The device consists of a SiO_2 bus waveguide, a symmetric double nano-stub in the vertical

Fig.1. Conceptual schematic of a nanoplasmonic three-wavelength band filter based on MIM waveguide structure. All waveguides have a width of w . The double nano-stub has a length of L for each arm. Three cavities named as Cavity1, Cavity2, Cavity3, and three output ports named as Port1, Port2, and Port3.

direction of the propagation waves and three SiO_2 rectangular nanotube waveguides in the horizontal direction that are designed to selectively couple with each wavelength band for realizing the functionality of a drop channel. The purpose of the symmetric double stub is to make the possibility of wavelength band blocking for three bands of 1310 nm, 1430 nm, and 1550 nm. Working principle of the stub waveguide based on the principle of the temporal coupled mode theory. Whereas, plasmonic rectangular nanotube waveguides play the role of nanoscale isolated Fabry-Perot cavities, also following the principle of temporal coupled-mode theory [31],[32], to selectively couple wavelength bands depending on the appropriate cavity length. In this design, we labeled three nanocavities as Cavity1, Cavity2, Cavity3. These three cavities correspond to Port1, Port2, Port3 for the dropping channels of 1310 nm, 1430 nm, and 1550 nm as seen in Fig. 1, respectively. The proposed structure based on MIM waveguides in which the insulating material in metallic slits and cavities is silica (SiO_2). Metallic layer in this device is silver, whose relative permittivity could be calculated by using the Drude model [19],[33] as follows:

$$\epsilon_m = \epsilon_\infty - \frac{\omega_p^2}{\omega(\omega + i\gamma)} \quad (1)$$

where ϵ_∞ is the dielectric constant at the infinite frequency of silver; ω_p is the bulk plasma frequency; ω and γ are the angular frequency of incident light in the vacuum and the electron oscillation damping constant, respectively. These parameters have following values $\epsilon_\infty = 3.7$, $\omega_p = 9.1 \text{ eV}$, and $\gamma = 0.018 \text{ eV}$ [34], [35]. Silver is selected in this device due to its very small imaginary part in the wavelength ranges of the telecom windows, thus, losses caused by the skin depth absorption are low enabling a long-range propagation of the SPP waves into the device. The refractive index of the fused silica glass material is described by the Sellmeier equation [36]

Fig.2. Transmission properties of the double stub waveguide solved by numerical simulation EME for different width of the stub at the wavelength of 1550 nm.

in which its value in the wavelength range of the telecom regime varies in a short-range from 1.44 to 1.46 at room temperature of 300°K [37]. In this design, we make use of silica as an insulator instead of air because its high refractive index allows the MIM waveguide to confine lightwave in a nanoscale size easier than air.

As we all know that, following the surface plasmon polariton theory, the s -polarized wave (TE-polarized wave) cannot exist in the mechanism of the SPP mode. Whereas, only the p -polarized wave (TM-polarized wave) can exist and be guided in the mechanism of the SPP mode. Therefore, in our simulation study, the light of the TM-polarized wave is lead from the input port and propagates to three desired output ports for wavelength bands of 1310 nm, 1430 nm, and 1550 nm.

Transmission characteristics of the stub nano waveguide are analyzed by applying the temporal coupled-mode theory combining the plasmon waves passing through and returning from the stub with the phase matching. In that case, the transmission expressions of the symmetric single stub (T_s) and double stub (T_d) waveguides can be expressed as [38]:

$$T_s = \frac{1}{1 + \tan^2 \left(\frac{2\pi L}{\lambda_{gp}} \right)}, \quad (2)$$

$$T_d = \frac{4}{4 + \tan^2 \left(\frac{2\pi L}{\lambda_{gp}} \right)}, \quad (3)$$

here λ_{gp} is the wavelength of the propagation plasmon in the MIM waveguide; L is the length of the single stub structure.

Optical characterizations were carried out using EME simulation with the grid sizes in a two-dimensional space as $\Delta x = \Delta z = 5 \text{ nm}$ applied for the total area of the proposed device. In this design, we choose all waveguides that have the same width, w . Fig. 2 shows the transmission curves of the single stub

Fig. 3. Transmission properties of the stub waveguide via numerical simulation EME for three wavelength bands at the width $w = 50$ nm as a function of the stub length: (a) single stub, and (b) double stub. Insets in (b) are the electromagnetic field distributions for three wavelength bands.

waveguide at the output port as the functions of the single stub length L for some values of the width w at the operation wavelength of 1550 nm. The waveguide widths for these studies are $w=25$ nm, 50 nm, 100 nm, and 200 nm. Here, we placed the stub waveguides at a distance of 1.9 μm from the input. As can be seen from Fig. 2, the wider stub width has higher efficiency. In addition, when the stub width increases the stub length for obtaining the highest resonance also increases. In order to realize the integrated circuit at the nanoscale in this design, we chose the width $w = 50$ nm.

In Fig.3, transmission spectra characteristics are illustrated as a function of the stub length L in the range from 0 to 0.4 μm for three wavelengths of 1310 nm (blue), 1430 nm (red), and 1550 nm (green) for the single stub (a) and the double stub (b) at the width $w = 50$ nm. Both sides of the double stub waveguide have the same length $L = 160$ nm. The resonant peaks for these three wavelengths are 140 nm, 160 nm, and 170 nm for both cases of single stub and double stub, respectively. Moreover, the maximum transmissions occur at a length of about 330 nm with a loss of 1.5 dB. However, the full width at half maximum

(FWHM) of the resonant dips of the double stub is larger than that of the single stub for each corresponding wavelength. Furthermore, the depth of the resonant peaks corresponding to the minimum transmissions in the case of the double stub is significantly larger than that of the single stub. Simulation results are in good agreement with analytic characteristics depicted by Eq. (2) and Eq. (3). Insets in Fig. 3 (b) illustrate the distribution of electromagnetic fields by mean of eigen mode propagation method for three wavelength bands. It is seen that the double stub plays the role of a three bands holder, which helps enhance the efficiency of the dropping wavelengths in nano-cavities.

In this section, we will design the dropping channels by using nanotubes, which operate like FP cavities for selectively coupling at proper wavelength bands. First, we assume that the TM-polarized wave is injected into the device from the input bus waveguide with the incident power as P_i . We denote O_1 , O_2 , and O_3 for the drop ports with outgoing powers as P_{O_1} , P_{O_2} , and P_{O_3} , respectively. Transmission characteristics of the drop

channels can be defined as $T_{d_1} = \frac{P_{O_1}}{P_i}$, $T_{d_2} = \frac{P_{O_2}}{P_i}$, and $T_{d_3} = \frac{P_{O_3}}{P_i}$.

For the plasmonic structure in our proposed MIM waveguides, the temporal evolution of amplitudes of incoming and outgoing waves are described by the interference between incident and reflected waves. These waves depend on the quality factors of the three nanotube cavities determined by the innate loss of propagating light over cavities. The accumulative phase between two reference planes satisfying the phase-matching condition is expressed by the following equation:

$$\varphi = d\beta_{\text{spp}} = dn_{\text{eff}}k_0 \quad (4)$$

where n_{eff} stands for the effective refractive index of the SPP mode propagating into the bus waveguide which depends on the wavelength λ and the width w of the bus waveguide; k_0 is the wave number of incident light in the vacuum; and β_{spp} represents the propagation constant of the SPP mode in the MIM waveguide. Eq (4) presents the phase-matching condition of the dispersion relation in the plasmonic waveguide which is governed by [19]:

$$\varepsilon_m \sqrt{n_{\text{eff}}^2 - \varepsilon_d} \tanh\left(\frac{w_i k_0 \sqrt{n_{\text{eff}}^2 - \varepsilon_d}}{2}\right) + \varepsilon_d \sqrt{n_{\text{eff}}^2 - \varepsilon_m} = 0 \quad (5)$$

here ε_m and ε_d are the dielectric constants of the silver cladding and silica insulating layers. Three maximum transmissions of the dropping ports are expressed in the final forms owing to the mutual effects between cavities as follows [24]:

$$T_{d_1, \text{max}} = \left| \frac{[1+r_1]^2 / (2Q_{d1}Q_1)}{[1/Q_1 + 1/(2Q_{d1}) + (1+r_1)/(2Q_{d1})]^2} \right| \quad (6)$$

$$T_{d_2, \text{max}} = \left| \frac{[1+r_2]^2 / (2Q_{d2}Q_2)}{[1/Q_2 + 1/(2Q_{d2}) + (1+r_2)/(2Q_{d2})]^2} \right| \quad (7)$$

Fig. 4. EME simulation of the power transmission spectrum at the output Port2. The transmission is normalized to the input power. Inset: electromagnetic field in the nanoscale size of 50 nm× 210 nm in the output Port2.

Fig. 5. EME simulation of normalized transmissions as a function of the wavelength for three output ports with (P1, P2, P3) and without (P'1, P'2, P'3) contribution of the double stub.

$$T_{d_3, \max} = \left| \frac{[1 + r_3]^2 / (2Q_{d3}Q_3)}{[1/Q_3 + 1/(2Q_{d3}) + (1 + r_3)/(2Q_{d3})]^2} \right| \quad (8)$$

where Q_1 , Q_2 , and Q_3 are the quality factors of Cavity1, Cavity2, and Cavity3, respectively; Q_{d1} , Q_{d2} , and Q_{d3} are decayed quality factors due to reducing of power into the dropping waveguides; $r_1 = 1/[1 + 2Q_{d1}/Q_1]$, $r_2 = 1/[1 + 2Q_{d2}/Q_2]$, and $r_3 = 1/[1 + 2Q_{d3}/Q_3]$ are the reduced quality factors from the bus waveguides due to the Ohmic absorption of the propagation waves.

Fig. 4 shows the normalized transmission amplitude of the magnetic field $|H_y|$ (TM-polarized SPP mode) that was simulated by utilizing the 2D-EME simulation method at the output Port2 in the absence of the Cavity1 and Cavity3 as well as the double stub waveguides. The inset shows the electromagnetic field distribution of the TM mode ($\lambda=1430$ nm) in the nanoscale size of 50 nm× 210 nm at the output Port2.

In order to separate three wavelengths bands into the desired output ports, we need to design Cavity1, Cavity2, and Cavity3

properly so that Cavity1 is highly resonant with the wavelength of 1310 nm but is not resonant with the other wavelengths, and vice versa. In the same way, the Cavity2 and Cavity 3 are designed for the resonant wavelengths of 1430 nm and 1550 nm, respectively. Note that no analytical solution exists to describe the resonant effects of propagation waves in plasmonic waveguides. Thus, this paper will apply numerical simulation methods for investigation. Although both EME and FDTD (finite-difference time-domain) simulations are rigorous solutions for simulating plasmonic circuits that have been efficiently proved in many of the previous related works [35], [39]–[43], the FDTD method is time consuming on simulating and characterizing the circuit when compared to the EME method. To that end, in this paper, we utilize the EME method to simulate and optimize for design processes, nonetheless the obtained results are accurate.

In the simulation, we set the initial baffle thickness between rectangular cavities and the corresponding dropping waveguides as $t_1 = t_2 = t_3 = t = 10$ nm, the gap between cavities and the bus waveguide is also initially set the same value of $g = 0$ nm. We design selectively to realize highly efficient transmissions at the nanocavities via numerical simulation. The process is carried out by searching for the highest transmission efficiency at an accumulative phase condition of Cavity1 $\phi_1 = (2m + 1)\pi / 2$ for the wavelength of 1310 nm by changing both the distance D_1 and the length L_1 of Cavity1. Here D_1 denotes the distance from Cavity1 to the input port which was initially set as 455 nm. m is an integer that we expect to be a minimum value, capably. Similar steps are also carefully performed in cases of Cavity2 and Cavity3. Finally, we found that the lengths of Cavity1, 2, and 3 are 400 nm, 640 nm, and 575 nm, respectively. The reference distances D_1 , D_2 , D_3 from the corresponding cavities numbers to the input port are found out as 455 nm, 1305 nm, and 860 nm for obtaining the highest transmission efficiencies.

Fig. 5 presents the transmission efficiencies of the proposed drop filter at three desired output ports for three desired wavelength bands of 1310 nm, 1430 nm, and 1550 nm by using numerical simulation in two cases, with and without the contribution of the double stub waveguide. Here, the normalized powers (to the input power) for the Port1, Port2, and Port3 are denoted as P1, P2, and P3 with the contribution of the double stub waveguide, and without this contribution as P'1, P'2, and P'3, respectively. Simulated results show that the transmission efficiencies of the SPP modes at the desired output ports are significantly enhanced for all three wavelength bands when introducing the double stub waveguides. Based on the working principle of the filter device, we can design a 3-dB three-wavelength band splitter by mirroring the output ports over the straight bus waveguide. The detailed characterization of these devices will be presented in the next section.

III. DEVICE PERFORMANCE AND CHARACTERIZATION

First, we use numerical simulations to evaluate the functions of the three-wavelength band filter and the three-wavelength band 3-dB splitter as well as characterize the optical

Fig. 6. Magnetic field amplitude distribution $|H_y|$ of plasmonic modes is simulated for three wavelength bands of 1310 nm (a), 1430 nm (b), and 1550 nm (c) for the proposed plasmonic wavelength filter; while (d), (e), (f) exhibit the confinement of light at Cavity1, 2, 3 for wavelengths of 1200 nm, 1650 nm and 1800 nm, respectively. The axis units are in μm .

Fig. 7. Magnetic field amplitude distribution $|H_y|$ of plasmonic modes is simulated for three wavelength bands of 1310 nm (a), 1430 nm (b), 1550 nm (c) and structure diagram (d) for the proposed plasmonic 3-dB wavelength splitter. The axis units are in μm .

performances of the proposed device by mean of EME method. Fig. 6 (a), (b), (c) and Fig. 7 (a), (b), (c) show magnetic field distributions, $|H_y|$, of plasmonic modes at the individual wavelength bands for the wavelength filter and the wavelength splitter, respectively. The 2D-plots of the field distribution for

the modes at three wavelength-bands clearly demonstrate functions of filter and 3dB-splitter of the proposed device with high efficiencies with negligible crosstalk between optical fields at each output ports. In addition, 2D-plots corresponding to Fig. 6 (d), (e), (f) also exhibit the confinement of light at Cavity1, 2, 3 for wavelengths of 1200 nm, 1650 nm and 1800 nm, respectively.

Because the three-wavelength 3-dB power splitter is designed by using a symmetrical structure to the design of three-wavelength filtering device, we only consider the characteristics of the proposed device in the role of the wavelength filter. We investigate the performance of this device in the wavelength domain by scanning wavelength from 1200 nm to 1700 nm via EME simulation. Fig. 8 illustrates the transmission properties of three output ports as functions wavelength. As can be seen, the power transmissions at three output ports obtain the highest resonant peaks at the wavelength bands of 1310 nm, 1430 nm, and 1550 nm with the corresponding powers of -5.37 dB, -6.19 dB, and -5.68 dB, respectively. Besides, a 3-dB bandwidth ($\Delta\lambda_{FWHM}$) of three bands obtained from the simulation exhibits the widths of 90 nm, 80 nm, and 100 nm as presented by the blue, red, and green double arrows in Fig. 8, respectively. However, for assuring the difference level between the desired power and undesired powers, or in term of crosstalk, is not smaller than 10 dB, the bandwidths for the output ports Port1, Port2, and Port3 in this case are as much as 90 nm, 40 nm, 100 nm. The bandwidths of these calculated transmission spectra are relatively broad, and therefore, the proposed filter is suitable for application in broadband access optical networks. In order to make narrower bandwidth and increase the wavelength resolution for the wavelength selective filter in the application of wavelength division multiplexing (WDM) technique, we can modify the resonant properties of the isolated FP resonator to Fano-line shape resonator by adjusting the thickness, position of the silver baffles and the distance, and the length of FP resonators [44],[45].

To fabricate the MIM waveguide at the nanoscale size, high-resolution lithography techniques such as focused ion-beam (FIB) lithography, which based on heavier particles, can be used for patterning across a surface in order to create very small structures instead of using ultraviolet or X-ray photolithography techniques. Although the FIB technique has high accuracy, it still exists a finite tolerance because these heavier particles have more momentum for etching the patterns. Therefore, it is important to investigate the effect of geometrical fabrication tolerance regarding the width of cavities and the main bus waveguide for the performance of the proposed wavelength filter. Fig. 9 illustrates the variation of power transmissions at three output ports corresponding to the wavelength bands of 1310 nm (a), 1430 nm (b), 1550 nm (c), and total absorption and total reflection of the wavelength filter (d). With a tolerance of $\Delta w = \pm 2$ nm, the power transmissions are not smaller than 7 dB, the crosstalk powers are below -15 dB, the absorptions are not exceeded 1 dB and reflections are lower than -10 dB.

Fig. 8. Wavelength response for three desired output ports of the proposed plasmonic wavelength filter.

Fig. 9. Optical transmission characteristics as functions of width tolerance at three output ports: (a) Port1 at 1310 nm, (b) Port2 at 1430 nm, (c) Port3 at 1550 nm, and (d) total absorption and total reflection at three wavelength bands for three output ports.

Finally, we study the effect of insulating materials on the characteristics of the proposed wavelength-selective filter. To do that we will investigate the performance of the device with the refractive index change, Δn , of different materials in comparison to that of the crystalline silica used in the previous section using the Sellmeier model [36]. Fig. 10 presents the power transmissions at output ports Port1, Port2, Port3, and output port Port0 of the main bus waveguide corresponding to wavelength bands of 1310 nm (a), 1430 nm (b), and 1550 nm (c). Fig. 10 (d) presents the total absorption and power transmission of individual wavelength bands. One can see a strong dependence of the optical characteristics at the output ports with the index difference of insulator materials. However, no clear behavior trend was observed rather the fluctuation. Both power transmission and absorption are the highest for silica material, about -5 dB to -6dB for power transmission and 1 dB for absorption.

Fig. 10. Optical transmission characteristics as functions of index difference of insulating material at four output ports: (a) at 1310 nm, (b) at 1430 nm, (c) at 1550 nm, and (d) total absorption and total power at three wavelength bands for three output port. $\Delta n = 0$ is corresponding to silica.

IV. CONCLUSION

In conclusion, a triple-wavelength filter using MIM waveguides with thin baffles and a double nanostubs was introduced as isolated FP resonators and wavelength band selector. Based on the strong coupling effect of various isolated FP resonators and enhancement of nanostub waveguide, a compact and highly efficient broadband wavelength filter and a broadband 3-dB wavelength splitter were demonstrated numerically via EME simulation. The proposed structure exhibits high transmission, low absorption, relative large tolerances, and relative broadband for applications in optical access networks at the telecom windows. In addition, the narrower bandwidth and the high wavelength resolution can be obtained via Fano-line shape resonance mechanism, which may provide a novel method for designing nanoscale and high resolution wavelength components in optical communications and computing, especially in wavelength division multiplexing and switching systems.

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DECLARATIONS

The authors declare no conflicts of interest.

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Figures

Figure 1

Conceptual schematic of a nanoplasmonic three-wavelength band filter based on MIM waveguide structure. All waveguides have a width of w . The double nano-stub has a length of L for each arm. Three cavities named as Cavity1, Cavity2, Cavity3, and three output ports named as Port1, Port2, and Port3.

Figure 2
Transmission properties of the double stub waveguide solved by numerical simulation EME for different width of the stub at the wavelength of 1550 nm.

Figure 3

Transmission properties of the stub waveguide via numerical simulation EME for three wavelength bands at the width $w = 50$ nm as a function of the stub length: (a) single stub, and (b) double stub. Insets in (b) are the electromagnetic field distributions for three wavelength bands.

Figure 4

EME simulation of the power transmission spectrum at the output Port2. The transmission is normalized to the input power. Inset: electromagnetic field in the nanoscale size of 50 nm $\times$ 210 nm in the output Port2.

Figure 5

EME simulation of normalized transmissions as a function of the wavelength for three output ports with (P1, P2, P3) and without (P'1, P'2, P'3) contribution of the double stub.

Figure 6

Magnetic field amplitude distribution $|H_y|$ of plasmonic modes is simulated for three wavelength bands of 1310 nm (a), 1430 nm (b), and 1550 nm (c) for the proposed plasmonic wavelength filter; while (d), (e), (f) exhibit the confinement of light at Cavity1, 2, 3 for wavelengths of 1200 nm, 1650 nm and 1800 nm, respectively. The axis units are in μm .

Figure 7

Magnetic field amplitude distribution $|H_y|$ of plasmonic modes is simulated for three wavelength bands of 1310 nm (a), 1430 nm (b), 1550 nm (c) and structure diagram (d) for the proposed plasmonic 3-dB wavelength splitter. The axis units are in μm .

Figure 8

Wavelength response for three desired output ports of the proposed plasmonic wavelength filter.

Figure 9

Optical transmission characteristics as functions of width tolerance at three output ports: (a) Port1 at 1310 nm, (b) Port2 at 1430 nm, (c) Port3 at 1550 nm, and (d) total absorption and total reflection at three wavelength bands for three output ports.

Figure 10

Optical transmission characteristics as functions of index difference of insulating material at four output ports: (a) at 1310 nm, (b) at 1430 nm, (c) at 1550 nm, and (d) total absorption and total power at three wavelength bands for three output port. $\Delta n = 0$ is corresponding to silica.