Proposal for metal–insulator–metal plasmonic power splitter and demultiplexer suitable for implementation in optical switches

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Abstract
The authors propose a nanoplasmonic structure based on metal–insulator–metal (MIM) waveguides which consists of a 3 db power splitter and a side-coupled nanocavity placed between its two output ports. The proposed structure is analysed by the resonant theory and dispersion relation. Transmission spectra of the presented device are also extracted using the finite difference time domain method. Numerical simulations demonstrate that the structure operates as a band-stop filter in each output channel. Moreover, the resonance wavelengths can be tuned by adjusting the geometrical parameters of the nanocavity. Meanwhile, the authors developed the cavity and added an extra stub to it to append a new stopband to the output spectrum. Each resonance wavelength can be easily manipulated by changing the widths of the nanocavity and the added stub. In the end, by choosing two different lengths for the side-coupled cavities, the authors convert the power splitter into a wavelength division multiplexer. These introduced MIM, the authors proposed here, may have various meaningful applications in nanoscale high-density photonic circuits such as optical switches, logic plasmonic circuits and slow-light devices.

1 | INTRODUCTION

Plasmonic structures are the basic elements for designing optical devices which can propagate light waves along the surface of a metal–dielectric interface. Electromagnetic waves enclosed in the metal–dielectric interfaces are known as surface plasmon polaritons (SPPs). The salient feature of such waves is their exponentially decaying field in the normal direction of the metal–dielectric interface. By manipulation of light wave at subwavelength scales, SPPs can significantly overcome the classical light diffraction limit [1]. Moreover, because of the low curvature losses, which are not achievable with conventional waveguides, recently, SPPs attracted more attention from researchers. Hence, SPPs are regarded as the best candidate to design miniaturised photonic integrated circuits (PICs) [2, 3].

In recent years, various plasmonic SPP-guiding structures have been emerged including nanowires [4], nanogrooves [5], metal wedges [6] and so on. Among the structures, those made of metal–insulator–metal (MIM) waveguides, considered to have remarkable because of giving more light confinement and simplicity in implementation [7]. A MIM structure is composed of two metallic claddings and a dielectric core which commonly are chosen to be silver and air, respectively. Today, MIM waveguides have been widely applied in numerous compact all-optical devices such as filters [8–11], directional couplers [12], switches [13], plasmonic sensors [14,15], power splitters and demultiplexers [16–20]. Power splitters, with equal power ratio, play an indispensable part in designing multi-way PICs. Also, wavelength division multiplexer (WDM) structures are very practical due to their ability to split the input signal into multiple wavelength spectrums.

Here, in Section 2, we will start with clarifying the principles of the MIM structures and models, and then in the following, we will design a $1 \times 2$ power splitter that can equally distribute the input power into its output ports. The function of the designed structure can be attributed to the resonant theory and dispersion relation which will be stimulated by the finite difference time domain (FDTD) method. We aim to have a band-stop filtered spectrum in each output port of the power splitter. To this end, we add an H-shaped nanocavity at centre of the power splitter between the two output ports. After running the simulation, resonance wavelength will be 1310 nm which can be easily manipulated by changing length of the nanocavity. Then, in Section 3, we will make minor changes to...
the nanocavity, which cause another stopband to be created in the output spectrum. Effects of changing the dimensions of the cavity on the dual-stopband spectrum, also will be discussed. Finally, in Section 4, by selecting two different lengths for the nanocavities, we will develop a WDM that has the ability to select two different resonance wavelengths. The introduced WDM functions like a switch; this means that for a specified wavelength, all of the input power will pass through Port 2 and for another wavelength, the entire power will be directed to Port 3. In this case, the resonance wavelengths can be tuned by changing the geometrical parameters of the structure and also the refractive index of the dielectric material. Furthermore, we compare the performance of our proposed devices with other similar reported structures. Finally, our conclusions will be drawn in Section 5.

2 THEORETICAL ANALYSIS OF MIM STRUCTURES, DESIGN A POWER SPLITTER AND SIMULATION

Figure 1a illustrates the schematic of the designed 1 × 2 MIM power splitter with an H-shaped nanocavity placed between its two output ports. We have selected the material of the insulator layer (shaded white) to be air with a dielectric constant of εd = 1 which makes the implementation process easier. The metallic layer (shaded grey) has chosen to be silver because it absorbs less energy compared to other metals such as gold. The frequency-dependent dielectric constant of silver εm is characterised by the Drude model, which can be expressed as Equation (1):

\[ ε_m(ω) = ε_∞ - \frac{ω_p^2}{ω^2 + jωγ} \]  

where ω is the angular frequency of the incident wave, ε∞ = 5.7 is the dielectric constant at infinite frequency, \( ω_p = 1.38 \times 10^{16}\text{rad.s}^{-1} \) is the plasma resonance angular frequency, and γ = 2.73 \( \times 10^{13}\text{rad.s}^{-1} \) is the plasma collision angular frequency [17]. This is a theoretical model and fits the experimental data with a negligible error margin. For a simple MIM structure consists of only one slit insulator layer with the width of w sandwiched between two semi-infinite metal slabs, we can calculate the electromagnetic field components inside the insulator layer by solving the Maxwell field equations analytically. We know that if w ≪ λ only a single propagation mode, TM0, can exist in this MIM waveguide. Hence, we get the dispersion relation as follows [21]:

\[ \tanh \left( \frac{ω √(β^2 - k_0^2 ε_i)}{2} \right) = -\frac{ε_i √(β^2 - k_0^2 ε_m(ω))}{ε_m(ω) √(β^2 - k_0^2 ε_i)} \]  

where \( k_0 = 2π/λ \) denotes the wave vector of light in vacuum with a wavelength of λ. Also, \( β = k_0 n_{eff} \) stands for the complex propagation constant of the SPPs light wave in which \( n_{eff} \) represents the effective refractive index in the MIM waveguide. But in most MIM waveguides, including the case shown in Figure 1(a), we are dealing with a complex structure which Maxwell field equations could not be solved simply. Therefore, we utilise FDTD to solve partial derivatives of the Maxwell field equations by discretising time and space. We set dimensions of our proposed power splitter to be d = 250 nm, \( w_1 = 50 \text{ nm, } w_2 = w_3 = 20 \text{ nm, } g = 10 \text{ nm, } L_1 = 90 \text{ nm, } L_2 = 30 \text{ nm, } b_1 = 30 \text{ nm and } b_2 = 190 \text{ nm. } \) Note that the H-shaped filter is symmetric by y-axis. The input waveguide port is excited by a plane wave source propagating along x-axis. The grid sizes in x and y directions are chosen to be \( Δx = Δy = 2\text{nm}. \) Also, the time step is set as \( Δt = Δx/2c \) in which c is the velocity of light in free space. The grid sizes and time step are assigned in such a way that provide an acceptable level of accuracy to numerical convergence. As well as, the structure has invariance with respect to z out of x–y plane. To prevent reflections of outgoing waves and also due to the dispersive simulation region, the absorbing boundary conditions is chosen to be convolutional perfectly matched layer. Power monitors located at the input and output ports are set at an equal distance from centre of the structure to detect
incident power of \( P_1 \) and transmitted powers of \( P_2 \) and \( P_3 \). Using the fast Fourier transforms of the electromagnetic fields obtained from the power monitors, we can calculate transmittance and reflectance coefficients as \( T_2 = P_2 / P_1, T_3 = P_3 / P_1, R = |S_{11}|^2 \) and also the corresponding spectral response. After running the FDTD simulation under the conditions mentioned above, the transmission properties extracted and demonstrated in Figure 1(b). The output spectrum is resembling a band-stop filter spectrum with a resonance wavelength of 1310 nm. The only difference between the proposed structure with a filter is that the input power distributed equally between the two output ports because of the symmetry of the structure. Hence, the output power monitors of \( P_2 \) and \( P_3 \) recorded approximately 45% transmittance at all of the wavelengths in simulation range except the resonance wavelength, 1310 nm. This phenomenon can be explained by the resonant theory. We have placed a filter on the way of the light wave. This causes that in a specific wavelength, the resonance condition satisfied and part of the signal coupled and entered into the H-shaped nanocavity. In the nanocavity filter, the forward and backward components of the coupled signal interfered with together and completely reflected back into the input waveguide. The resonant theory is expressed as Equation (3):

\[
\lambda_m = \frac{2n_{\text{eff}}L_1}{m - \frac{\Delta \Phi}{2\pi}}
\]

(3)

in which \( \Phi_r \) is the phase shift of the beam reflected at the left and right sides of the nanocavity, and \( n_{\text{eff}} \) is the effective refractive index of SPPs in the cavity. Also, positive integer \( m \) stands for the \( m \)-th order resonant mode of the nanocavity [22], which we only consider the first resonance mode in this section.

To realize the origin of this equation, \( \Delta \Phi \) will be defined as the total phase delay of SPPs per round-trip inside the H-shaped nanocavity, which is expressed as follows:

\[
\Delta \Phi = \frac{4\pi n_{\text{eff}}L_1}{\lambda} + \Phi_r
\]

(4)

A stable standing wave will be formed in the nanocavity only when \( \Delta \Phi = 2m\pi \). This is referred to as the resonant condition. Hence, Equation (4) will be simplified to the same, which was in Equation (3).

The analytical results are gained from Equation (3) and demonstrated in Figure 2(b). To extract the resonance wavelengths, first, the effective refractive index should be calculated from dispersion relation for a dielectric layer of width \( b_1 = L_2 = 30 \) nm (width of the H-shaped nanocavity). In the following, the phase shift \( \Phi_r \) can be calculated numerically by submitting \( \lambda = 1310\) nm into Equation (3) [22]. It is important to note that because of symmetry of the power splitter, the total length of the H-shaped nanocavity for each output port is equal to:

\[
L_{\text{total}} = 2 \times \left( \frac{b_3}{2} + \frac{b_1}{2} \right) + L_1 = 220 + L_1
\]

(5)

In other words, each output port has a nanocavity with length of \( L_{\text{total}} \) and width of \( b_1 = L_2 = 30 \) nm. This property has shown in the inset of Figure 2(b). So, \( L_{\text{total}} \) which is only a function of \( L_1 \), should be replaced in Equation (3). Hence, the value of phase shift will be obtained as \( \Phi_r \approx 1.58 \). The calculated analytical results for different \( L_1 \) lengths are given in Table 1. This table contains length of the H-shaped nanocavity \( L_1 \), total coupling length \( L_{\text{total}} \), effective refractive index \( n_{\text{eff}} \), resonance wavelength obtained from FDTD simulation \( \lambda_{\text{simulation}} \) and results gained from Equation (3) \( \lambda_{\text{analytical}} \). The difference between resonance wavelength values in columns 4 and 5 of Table 1 is because of the dependence of \( \Phi_r \) to working wavelength which is not considered here (\( \Phi_r \) assumed to be a fixed value).
Similar to the analytical method, the FDTD simulation demonstrated that the resonance wavelength is proportional to the cavity length \( L_1 \) and the resonance wavelength shifts to longer wavelengths with an increase of the \( L_1 \) value. This relationship is demonstrated in Figure 2(a) and (b).

### 3 | GAINING SPECTRUM OF A DUAL-STOPBAND FILTER INDUCED BY MANIPULATING THE NANOCAVITY

In the continuation of the previous section, we develop the structure by dividing the H-shaped filter into two separate pieces and adding extra stubs in middle of them. This manipulation has a favourable influence on the output spectrum and causes the power splitter operates similar to a dual-stopband filter. Based on the theoretical analysis in Section 2, a portion of the input light wave escape and will be coupled in the nanocavities and causing resonances to be formed in the transmission spectra. By carefully adjusting the geometrical parameters of the new structure, we can tune the transmitted-dip wavelengths and also the difference between them. The schematic of the new structure has shown in Figure 3(a) with dimensions of \( d = 340 \) nm, \( w_1 = 50 \) nm, \( w_2 = w_3 = 20 \) nm, \( g_1 = 45 \) nm, \( g_2 = 40 \) nm, \( L_1 = L_2 = 60 \) nm, \( L_3 = L_4 = 80 \) nm, \( b_1 = 60 \) nm, \( b_2 = 130 \) nm, \( a = 80 \) nm and \( b = 20 \) nm. According to the schematic view, it is clear that the dimensions of two nanocavities are same and each one is symmetric to \( y \)-axis. As seen in Figure 3(b), the two resonance wavelengths which appeared in output spectra are about 850 and 1310 nm, respectively. The reflectance coefficients in resonance wavelengths are about 75% which means that many parts of the light wave are reflected back into the input port, and the remained amount of it has been absorbed and dissipated in the nanocavity structures. Hence, we consider absorbance coefficient of \( A = 1 - T_2 - T_3 - R \) which is also plotted in Figure 3(b). In this section as well, because of symmetry of the power splitter, the output spectrums of port 2 and port 3 are similar.

As mentioned before, our new introduced power splitter is designed such a way that we can easily tune the resonance

| \( L_1 \) (nm) | \( L_{\text{total}} \) (nm) | \( n_{\text{eff}} \) | \( \lambda_{\text{simulation}} \) (nm) | \( \lambda_{\text{analytical}} \) (nm) |
|---------------|-----------------|-----------|-----------------|-----------------|
| 50            | 270             | 1.5886    | 1133            | 1146.08         |
| 70            | 290             | 1.5852    | 1220            | 1228.32         |
| 90            | 310             | 1.5824    | 1310            | 1310.71         |
| 110           | 330             | 1.5801    | 1402            | 1393.25         |
| 130           | 350             | 1.5783    | 1492            | 1475.98         |

**Abbreviation:** FDTD, finite difference time domain.

**FIGURE 3** The modified power splitter: (a) schematic of the modified power splitter and (b) transmittance, reflectance and absorptance coefficients of the new structure

**FIGURE 4** Tunability of the modified power splitter: (a) transmission spectrum and resonance wavelengths changes for different values of \( L_3 = L_4 \) and (b) evolution of the first resonance wavelength versus changing length \( a \)
wavelengths by changing the lengths of \( L_3 = L_4 \). Increasing these lengths results in increasing the two resonance wavelengths together. On the contrary, decreasing them, shifts the resonance wavelengths towards shorter wavelengths. This property has shown in Figure 4(a). Furthermore, it can be seen from Figure 4(b) that we have control over the value of the shorter resonance wavelength by changing the \( a \) length. In other words, we can change the first resonance wavelength, without manipulating the other one. These two mentioned features will give us the capability to assign two arbitrary stopband resonance wavelengths without any limitation.

4 | STRUCTURE OF WAVELENGTH DIVISION MULTIPLEXER APPLICABLE IN OPTICAL SWITCHES, RESULTS AND DISCUSSIONS

Based on simulations and the resonant theory mentioned in Section 2, it is experimentally and analytically verified that we can change the length of the filter in order to set the resonance wavelength. This is the main idea to develop a power splitter with two different resonance wavelengths. Therefore, we introduce a structure similar to previous sections, but in this case the structure is not symmetric. The new proposed power splitter is schematically illustrated in Figure 5(a). The structural parameters are set as \( d = 360 \) nm, \( w_1 = 50 \) nm, \( w_2 = w_3 = 20 \) nm, \( g_1 = 45 \) nm, \( g_2 = 60 \) nm, \( g_3 = g_4 = 20 \) nm, \( L_1 = 300 \) nm, \( L_2 = 210 \) nm and \( b_1 = b_2 = 60 \) nm. As seen in Figure 5(b), simulation results demonstrate that the power splitter operates like a wavelength division multiplexer and has
two different resonance wavelengths of \( \lambda_{\text{port}_2} = 1550\text{nm} \) and \( \lambda_{\text{port}_3} = 1310\text{nm} \). We have assigned the value of \( L_1 \) and \( L_2 \) using Equation (3) to obtain these resonance wavelengths which are the most common near-infrared wavelengths in optical communications especially in fibres and laser equipment. However, we can easily shift the two resonance wavelengths together just by changing the distance between output ports \( d \). As shown in Figure 6(a) and (b), the resonance wavelengths monotonically increase with the increase of \( d \).

When \( d \) is increasing, the total coupling length for each resonance cavity increases as well. Hence, regarding to Equation (3), the resonance wavelength shifts to longer wavelengths. From the schematic demonstrated in Figure 5(a), it needs to be clarified that when we extend the distance of \( d \), the values of \( g_2 \), \( g_3 \) and \( g_4 \) remain unchanged. Subsequently, for a better prospect of the device operation, the corresponding magnetic field distributions of \( |H_z| \) has shown in Figure 7(a) and (b). In resonance wavelength of \( \lambda_{\text{port}_2} \), all of the input signal will approximately go to port 3 and conversely, in \( \lambda_{\text{port}_3} \) the entire input power will pass through port 2. Eventually, in other wavelengths, the input power splits almost equally between output ports. This characteristic allows us to employ this WDM in optical switching circuits.

Now, we demonstrate in Figure 8(a) and (b) that by changing the refractive index of the dielectric material \( n \), we can modify the resonance wavelengths of the output ports. It can be seen that by increasing the value of \( n \), the resonance wavelengths shift to longer wavelengths. The reason for this is that increasing \( n \) causes an increase in \( n_{\text{eff}} \). So, according to Equation (3), the resonance wavelength grows up. The main advantage of this tuning over the previous one (changing the value of \( d \)) is that we can easily select longer resonance wavelengths up to about 1900 nm without disrupting the overall performance of the switch.

At the end, a concise comparison between the performance of the proposed WDM with similar structures is performed and presented in Table 2. In Table 2, used materials for each of the MIM layers (Materials), method of the simulation (Method), model used to simulate the dispersive metallic layer (Model), dimension of the structure (2D or 3D) resonance wavelengths (\( \lambda \)) and maximum transmittance at resonance wavelengths (\( T_{\text{max}} \)) are compared. As seen in Table 2, in comparison to other 1×2 WDMs and switches with resonance wavelengths equal to our study, our proposed WDM has the highest transmittance peak.

5 | CONCLUSION

Here, we have studied a compound MIM structure consisted of a plasmonic power splitter and side-coupled nanocavity filter using the FDTD method. The proposed structure

![Figure 8](image-url) Illustration of the transmittance spectrum versus variation of the dielectric material refractive index for (a) Port 2 and (b) Port 3

| References | Materials | Method | Model | Dimension of the structure \( \lambda (\text{nm}) \) | \( T_{\text{max}} \) (%)
|------------|-----------|--------|-------|---------------------------------|---------|
| [1]        | Silver and air | FDTD   | Drude | 2D | 750 and 1500 | 92 and 55 |
| [18]       | Silver and air | FDTD   | Drude | 3D | 1310 and 1550 | 63 and 61 |
| [23]       | Silver and \( \text{Al}_2\text{O}_3 \) | FDTD   | Johnson and Christy | 2D | 1280, 1310 and 1340 | 55, 51 and 44 |
| [24]       | Silver and air | FEM    | Johnson and Christy | 2D | 788 and 820 | 74 and 79 |
| [25]       | Silver and air | FDTD   | Drude-Lorentz | 2D | 1353.5, 1450.5 and 1553.5 | 51, 48 and 50 |
| [26]       | Silver and a Kerr nonlinear material | FDTD | Johnson and Christy | 2D | 1310 and 1550 | 61 and 65 |
| Our work   | Silver and air | FDTD   | Drude | 2D | 1310 and 1550 | 78 and 81 |

Abbreviation: FDTD, finite difference time domain.
revealed that the resonance wavelength has a linear relationship with the length of the filter and analytically verified the results with Equation (3) (the resonant theory). In the following, we developed the structure by adding another stub into the nanocavity which caused us to convert the transmission spectrum into a dual-stopband filter spectrum. Moreover, we have tuned each stopband transmitted-dip wavelength by changing the geometrical parameters of the nanocavity. Eventually, by assigning two different lengths for the nanocavities, we obtained two resonance wavelengths for output channels and transformed the structure from a power splitter into a WDM with the ability to switch the input signal between the output ports. We also investigated the effects of changing the dimensions of the structure and the used dielectric material on the switching wavelengths. These structures clearly have good performances as power splitters, wavelength selection devices and nanoscale photonic switches and undoubtedly can play a significant role in PICs and optical communication systems.

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