Tunable and High Transmission Efficiency Metal-Insulator-Metal Power Splitter and Dual Wavelength Division Multiplexer

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Research Article

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Tunable and High Transmission Efficiency Metal-Insulator-Metal Power Splitter and Dual Wavelength Division Multiplexer

Mohammad Reza Ghasemi\textsuperscript{1,*}, Mohammad Sajjad Bayati\textsuperscript{1}, Sahereh Sahandabadi\textsuperscript{2}

Abstract—In this paper, a plasmonic power splitter and a Wavelength Division Multiplexer (WDM) based on metal-insulator-metal (MIM) surface are investigated. By using Finite Difference Time Domain (FDTD) method, the transmission spectra of the suggested devices are extracted. The simulation results demonstrate that the equal transmitted wavelengths of the two output ports can be easily tuned by changing the geometric parameters of the structure. Then, the structure geometries are modified into a WDM. Subsequently, the dependence of demultiplexing wavelengths on geometrical parameters of the structure is investigated. Besides being highly compact and efficient, having narrow-band spectra and low reflectance coefficient are the other main advantages of these devices. Therefore, the power splitter and wavelength division multiplexer presented can be of great interest in a wide range of applications from highly integrated photonic circuits to optical communication systems.

Keywords—Plasmonic, Power Splitter, Metal-Insulator-Metal, Multiplexer, Drude Model

1. INTRODUCTION

The need to develop high-performance and super compact photonic circuits is becoming indispensable with the ever-increasing demand for wideband communications. Power splitters and wavelength division multiplexers play a significant role in Photonic Integrated Circuits (PICs) and optical communication systems. Since the emergence of nanotechnology concept, miniaturization has been the key source of innovation, both in Nano-electronics and photonics. However, classic optical diffraction limit is the primary limit for downsizing photonic devices [1-4]. Surface Plasmon Polaritons (SPPs) are considered among the most proper options to overcome the diffraction limit and confine light wave in PICs and nanoscale devices. SPPs are electromagnetic waves that propagate along a metal–dielectric interface (silver-air, for instance) with an exponentially decaying field in the normal direction of both media [5].

There are various geometries for plasmonic waveguides which have the ability to carry SPPs. Among them, metal-insulator-metal (MIM) and insulator-metal-insulator (IMI) configurations are two common multilayer plasmonic structures [6]. IMI compositions can propagate waves in longer distances, but have poor light confinement. Instead, MIM structures have higher light confinement, but due to the high losses created by metal claddings, the propagation distance of these waveguides is lower. Yet, unique features of MIM-based designs have made them more desirable for Nano-photonic applications [7].

Several different Nano-guiding MIM devices based on SPPs have been investigated in recent years such as filters [8-15], power splitters [16-21], Y-shaped combiners [22], directional couplers [2,23] and
plasmonic refractive index sensors [24-28]. There have also been extensive efforts in designing WDMs based on MIM plasmonic waveguides [29-34]. Due to the fundamental role of WDMs in optical communication systems compared to other types of Nano-plasmonic devices, they have attracted more attention.

In this paper, first, a basic 1×2 power splitter with 3-dB power ratio is introduced. The goal is to design a power splitter capable of dividing and passing the input power into its output channels, but only at some specific wavelengths. As a result, the structure is extended by adding several rectangular stubs alongside the prototype structure. The modifications are made to the output spectrum so that the structure functions as a bandpass filter and power splitter, simultaneously. The dependency of the resonance wavelength of the two output channels on geometrical parameters, is also analyzed. Then, the impact of refractive index change of the dielectric material on the resonance wavelength is probed. More alterations are applied on the design and convert it into a dual WDM with an acceptable power transmittance peak. The effect of stub length on demultiplexing wavelengths of each output channel have been evaluated. Ansys Lumerical software which uses FDTD method is selected to analyze the structures and parameter variations.

The proposed configuration offers transmissions peaks at near-infrared wavelengths with nearly 88% of maximum transmission as well as negligible reflection coefficient. Further distinctive features of the proposed plasmonic WDM are being compact, adjustable regarding to output wavelengths and simple for fabrication.

2. PRINCIPLES, MODELLING AND SIMULATION METHOD

The schematic view of the simple 1×2 power splitter is shown in Figure 1(a). The width of the input port and output ports are selected to be \( w_i = 50 \text{ nm} \) and \( w_o = 20 \text{ nm} \), respectively. The value of \( w_i \) is 2.5 times wider than \( w_o \) to reduce the reflectance coefficient below 1% [35]. Moreover, the distance between two output channels is \( d = 200 \text{ nm} \).

![Figure 1](image)

**Figure 1.** (a) Schematic view of the proposed MIM structure for a basic 1×2 power splitter. (b) Transmission and reflection spectra versus wavelength for the suggested power splitter.

The main purpose of simulation is solving partial derivatives of the Maxwell equations using FDTD method by discretizing time and space. In simulating the proposed structure, the waveguide is excited by a plane wave source along x axis. Since width of all input and output ports are significantly smaller than the incident wavelength, only the fundamental mode TM0 exists and propagates in the structure. Grid sizes along x and y directions are chosen to be \( \Delta x = \Delta y = 2 \text{ nm} \). Furthermore, the time step is \( \Delta t = \Delta x/2c \) in which \( c \) is the velocity of light in free space. These values will provide an acceptable level of accuracy to numerical convergence. It is assumed that the structure is invariant with respect to z out of x-y plane. Because of the dispersive simulation region, Convolutional Perfectly Matched Layer (CPML) has been used as the absorbing boundary condition. Metal and insulator are assumed to be silver and air, respectively. Silver is selected because it absorbs less energy in the operating simulation frequency range compared to other metals, such as gold. The frequency-dependent dielectric constant of silver, \( \varepsilon_m \), is characterized by the Drude model as:
where $\omega$ is the angular frequency of the incident wave, $\varepsilon_{\infty} = 3.7$ is the dielectric constant at infinite frequency, $\omega_p = 1.38 \times 10^{16}$ rad.$s^{-1}$ is the plasma resonance angular frequency, and $\gamma = 2.73 \times 10^{13}$ rad.$s^{-1}$ is the plasma collision angular frequency [16]. The theoretical model fits the experimental data with a low error in operating simulation frequency spectra. The dispersion relation in an MIM waveguide with insulator width of $w$ is governed by the following equation [7]:

$$\text{tanh} \left( \frac{w \sqrt{\beta^2 - k_0^2 \varepsilon_i}}{2} \right) = \frac{-\varepsilon_i \sqrt{\beta^2 - k_0^2 \varepsilon_m(\omega)}}{\varepsilon_m(\omega) \sqrt{\beta^2 - k_0^2 \varepsilon_i}}$$

(2)

where $\varepsilon_m(\omega)$ and $\varepsilon_i$ are the dielectric constants of the silver and air, respectively. $k_0 = 2\pi/\lambda$ denotes the wave vector of light in vacuum with a wavelength of $\lambda$. Moreover, $\beta = k_0 n_{\text{eff}}$ stands for the complex propagation constant of the SPPs light wave in which $n_{\text{eff}}$ represents the effective refractive index in the MIM waveguide. The imaginary part of $n_{\text{eff}}$ refers to the propagation length of the structure and can be neglected in this stage due to being small. The propagation length is defined as the length at which the amplitude of the electromagnetic wave carried by the light wave decays to $1/e$ of its initial value. It is noted from equation (2) that the effective refractive index is relevant to the width of MIM waveguide. For a fixed wavelength of light, $\text{Re}(n_{\text{eff}})$ gradually decreases with an increase in the thickness of the insulator layer $w$. This feature is depicted in Figure 2(b). All three power monitors placed at the input and output ports are set at equal distances from the center of structure to detect incident power of $P_1$ and transmitted powers of $P_2$ and $P_3$. The transmittance and reflectance coefficients are defined as $T_2 = P_2/P_1$, $T_3 = P_3/P_1$ and $R = |S_{11}|^2$, respectively. Therefore, we can easily calculate the absorptance coefficient of $A$ using $A = 1 - T_2 - T_3 - R$. This value represents the total loss in structure.

Figure 2. (a) Schematic illustration of an MIM slit waveguide. (b) Real part of effective index of the MIM structure as a function of width of the insulator layer for different wavelengths.

After utilizing FDTD method to achieve the numerical results for the introduced power splitter, the transmittance and reflectance coefficients are calculated and demonstrated in Figure 1(b). As expected, because of the structure symmetry, the transmitted optical power is equally distributed between the two output channels such that each port’s power monitor recorded normalized transmittance of about $T_2 = T_3 = 49\%$. Additionally, the output spectrum reveals that the reflection efficiency $R$ is almost zero. More importantly, the output transmission spectrum is approximately equal for all near-infrared spectral region wavelengths; however, it is not what is being looker for in this step. In the next section, the design will be further developed to attain the main goal of having a filtered spectrum at the output channels.

3. PROPOSED POWER SPLITTER AND SIMULATION RESULTS

It is desired to change the functionality of the power splitter in some way so that it operates as a bandpass filter in each output channel. As a matter of fact, a power splitter which filters some wavelengths, while dividing the input power is sought in this paper. To achieve this objective, some modifications must be applied on the structure. As seen in Figures 3(a) and (b), adding multiple stubs beside the power splitter...
presented in previous section, results in a filtering quality in the output spectra. To clarify the basic principle of the proposed configuration, we can use the Transmission Line Method (TLM) [36]. Each stub has its own characteristic impedance of $Z_0$ which can be calculated by using a surface integral to determine the power $P$ carried by the waveguide and a loop integral to calculate the current flow $I$ [37]. Consequently, the characteristic impedance can be easily calculated by the following equation:

$$Z_0 = \frac{P}{I^2} = \frac{\iint_{S} \vec{S} \cdot d\vec{s}}{\left(\oint_{C} \vec{f} \cdot d\vec{l}\right)^2}$$

in which $\vec{S} = \vec{E} \times \vec{H}^*$ is the Poynting vector. For an MIM waveguide with thin dielectric layer, the characteristic impedance can be approximated as follows [38]:

$$Z_0 = \frac{E_y w}{H_z W} = \frac{k_y w}{\omega \varepsilon I W}$$

where $w$ is the thickness of dielectric layer, $W$ is the unit width of the structure in the $z$-direction and $k_y$ is the wave vector of the incident wave. In fact, using TLM the metal gap between the splitter ports and additional stubs can be modeled with parasitic lumped circuit elements like inductors and capacitors [39]. Therefore, considering the aforementioned TLM method, the filtering property can be accounted for.

The new structural parameter values shown in Figure 3(a) are $L_1 = L_2 = 110 \text{ nm}$, $h_1 = 55 \text{ nm}$, $h_2 = 90 \text{ nm}$, $g_1 = 70 \text{ nm}$, $g_2 = 40 \text{ nm}$, $w_1 = 45 \text{ nm}$ and $w_2 = 30 \text{ nm}$. The values of other parameters are not changed. The transmission and reflection coefficients of the new structure are plotted in Figure 3(b). It is evident that the spectrum is resembling a bandpass filter spectrum with a resonance wavelength of about 1000 nm, 45% maximum transmission peak for each output channel, and nearly zero reflectance. In order to provide a better understanding of modified power splitter functioning, the corresponding magnetic field distributions of $|H_z|$ for two different wavelengths are shown in Figures 4(a) and (b).
Then, the impact of changing dimensions on resonance wavelength is investigated. First, the width of two rectangular stubs, $L = L_1 = L_2$, is changed. It is observed that by increasing $L$ value, the resonance wavelength tends to move to longer wavelengths, whereas transmittance peak decreases slightly which is displayed in Figure 5(a). Similarly, by changing the $g_1$ value, the resonance wavelength increases; but, unlike changing $L$ value, the transmittance peak increases in this case. Figure 5(b) shows the relation between resonance wavelength and thickness of the metal gap, $g_1$. Furthermore, in Figure 5(c) it is demonstrated that the resonance wavelength has a linear relationship to $L$ and $g_1$.

![Figure 4](image1.png)

**Figure 4.** (a) The contour profiles of magnetic intensity $|H_z|$ at (a) $\lambda = 780nm$, (b) $\lambda = 1000nm$.

![Figure 5](image2.png)

**Figure 5.** (a) Transmission spectra variations for different $L$ values. (b) Transmission spectra variations for different $g_1$ values. (c) The relationship between resonance wavelength and of $L$ and $g_1$ values. (d) Transmission spectra variations for different $g_2$ values.
Besides, the impact of altering the metal gap thickness, $g_2$, is analyzed and then plotted it in Figure 5(d), where $g_2$ is the distance between the input port and its two surrounding stubs. It is noted that by increasing $g_2$ value, the transmittance peak increases and the spectra near the resonance wavelength become wider. In fact, in order to make the curve narrower, smaller values for $g_2$ should be selected. In other words, there is a trade-off between a sharp transmission peak and maximum value of the normalized output power. Effects of changing the substrate dielectric material on the resonance wavelength, have been studied and the results are demonstrated in Figure 6. Accordingly, by choosing dielectrics with higher refractive indexes such as Silicon dioxide (SiO$_2$) instead of air, we can select longer wavelengths in the output ports of the power splitter.

In what follows, we will apply small changes on the structure to realize a dual wavelength demultiplexer with high resolution and high transmittance peak.

4. DUAL WDM

For the last part of this paper, the proposed power splitter will be transformed into a dual WDM. This requires minor changes to be performed on the structure. It can be seen in Figure 7(a) that we have four rectangular stubs at the top and bottom of the WDM which two of them are bigger than the other two. This sole change is enough to have different wavelengths at each channel. The lengths of the stubs are set to $L_1 = L_2 = 150 \text{ nm}$ and $L_3 = L_4 = 70 \text{ nm}$, respectively; as well as, $g_1 = 110 \text{ nm}$. Other parameters are the same as the previous section. Figure 7(b) depicts the transmission and reflection profile of the current WDM. Owing to the obtained results, it can be stated that there is a high resolution and high transmission efficiency WDM which its two output wavelengths have a separation of about 360 nm. The selected wavelengths of port 2 and 3 are $\lambda_{\text{port 2}} = 1272 \text{ nm}$ and $\lambda_{\text{port 3}} = 912 \text{ nm}$ with transmission efficiencies about 76.44% and 88.03%, respectively.
For the suggested low cross-talk WDM, the normalized magnetic field distribution profiles of $|H_z|$ in the demultiplexing wavelengths of the two output channels are demonstrated in Figures 8(a) and (b). In addition to this, Figures 9(a) and (b) show the variation of demultiplexing wavelengths versus changing the value of $g_1$. It is worth mentioning that we can easily tune the demultiplexing wavelengths of the WDM by changing the value of $g_1$. Increasing $g_1$ results in increasing the demultiplexing wavelengths of the two output channels. By contrast, decreasing the value of $g_1$ shifts the demultiplexing wavelengths towards shorter wavelengths.

Figure 8. The contour profiles of magnetic intensity $|H_z|$ of the device at (a) $\lambda_{\text{port 2}} = 1272\,\text{nm}$, (b) $\lambda_{\text{port 3}} = 912\,\text{nm}$.

As a result, the introduced WDM provides significant improvement in transmission efficiency compared to earlier works which is listed in Table 1. The table includes method of the simulation (Method), the model used to describe the frequency-dependent dielectric constant of silver (Model), the total size of the structure (Size), resonance wavelengths ($\lambda$) and maximum transmittance at resonance wavelengths ($T_{\text{max}}$). The data reported in this table imply that the proposed compact WDM is suitable for a wide range of practical light splitting applications.

Figure 9. Transmission spectra of both output channels by changing $g_1$. (a) Transmittance of channel 2, (b) Transmittance of channel 3.
5. CONCLUSION

In summary, a tunable and simple plasmonic waveguide structure is proposed and investigated, numerically. The suggested structure consists of a 1×2 power splitter with a built-in bandpass filter. The power splitter is of an ultra-compact size and has low insertion loss. Our simulated results demonstrate that the additional rectangular stubs, have a favorable influence of filtering some wavelengths. Moreover, the FDTD simulation shows that by increasing the lengths of the added stubs and also the thickness of the metal gap, we can shift the wavelength of through output power to longer wavelengths. Additionally, the suggested high-performance power splitter is designed in such a way that can be easily converted into a WDM just by applying a slight change in its dimensions and breaking the symmetry of the structure. Considering these features, the proposed device which can operate as both power splitter and wavelength division multiplexer, may find extensive applications in optical communication systems. It is also a potential candidate for nanoscale integrated photonic circuits.

REFERENCES


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Table 1. Comparison of the proposed plasmonic WDM and previously published papers.

<table>
<thead>
<tr>
<th>References</th>
<th>Method</th>
<th>Model</th>
<th>Size (nm²)</th>
<th>λ (nm)</th>
<th>$T_{max}$ (%)</th>
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<td>[17]</td>
<td>FDTD</td>
<td>Drude</td>
<td>810×810</td>
<td>910, 1470</td>
<td>42, 55</td>
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<td>[32]</td>
<td>FDTD</td>
<td>Drude-Lorentz</td>
<td>1100×500</td>
<td>917, 1096</td>
<td>79, 81</td>
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<td>[33]</td>
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<td>Drude</td>
<td>800×400</td>
<td>1310, 1550</td>
<td>63, 61</td>
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<tr>
<td>[40]</td>
<td>FDTD</td>
<td>Drude-Lorentz</td>
<td>750×380</td>
<td>1043, 1310</td>
<td>52, 48</td>
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<tr>
<td>[41]</td>
<td>FDTD</td>
<td>Drude</td>
<td>1000×900</td>
<td>712, 820, 928</td>
<td>70, 68, 65</td>
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<tr>
<td>[42]</td>
<td>FEM</td>
<td>Johnson &amp; Christy</td>
<td>1000×1000</td>
<td>1210, 1500</td>
<td>74, 70</td>
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<tr>
<td>[43]</td>
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<td>Drude</td>
<td>1040×1040</td>
<td>1328, 1392</td>
<td>60, 72</td>
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<tr>
<td>[44]</td>
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<td>[45]</td>
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<td>This work</td>
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<td>Drude</td>
<td>650×290</td>
<td>912, 1272</td>
<td>88, 76</td>
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</table>


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Conflict of Interest Statement
We the undermentioned authors of the manuscript entitled “Tunable and High Transmission Efficiency Metal-Insulator-Metal Power Splitter and Dual Wavelength Division Multiplexer” submitted to the Journal of Computational Electronics for publication hereby attest and affirm that this work is original and has not been published elsewhere, nor is it currently under consideration for publication elsewhere.

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Data Availability Statement
The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.