Wavelength Plasmonic Demultiplexer Based on Square-disk Resonators in MIM Waveguide

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Abstract—A plasmonic demultiplexer based on cascading square nanodisk resonators in a metal-insulator-metal (MIM) plasmonic waveguide is proposed in this paper. The basic structure of the proposed demultiplexer is a plasmonic filter which consists of two waveguides, a middle cavity and two square nanodisk resonators. According to the simulation results the transmission spectra Full Width at Half-Maximum (FWHM) in the proposed structure reaches about 10 nm. With appropriate choice of refractive index (RI) and geometrical parameters the proposed structure can be adjusted and modified. The proposed structure has low FWHM, high sensitivity and acceptable figure of merit (FoM). By putting three filters with the same dimensions together, a triple-channel demultiplexer with three different wavelengths in each of the channels is designed. The effect of cross talk in the designed demultiplexer is less than -25 dB. The proposed structure can be used in the large-scale photonic integration, ultra-compact demultiplexer devices, nanosensors, integrated plasmonic devices and the development of optical integrated circuits. These structures numerically studied using Finite-Different Time-Domain (FDTD) simulations.

Keywords—Plasmonic Filter, Metal-Insulator-Metal (MIM), wavelength demultiplexer, Waveguide, surface plasmons polaritons (SPPs).

I. Introduction

Electromagnetic waves that move and emit through the interface between dielectric and metal using an exponentially decay bilaterally are the surface plasmons polaritons (SPPs) [1, 2]. Since electrons are capable of transmitting energy and data to overcome the diffraction limit of light in the surface plasmons polaritons (SPP) wave plasmonics have received considerable attention [2, 3].

Recently, there has been remarkable progress in the fabrication, development and improvement of the plasmonic nanostructures including optical waveguides [4], lasers [5], surface enhanced Raman spectroscopy [6, 7], Splitter [8], bio/chemical sensors [9, 10], absorbers [11], reflectors [12, 13], modulators [14], Mach-Zehnder interferometers [15], Bragg reflectors [12] and logic devices [16-18]. Due to the relatively easy fabrication process, severe light limitations and the appropriate length for SPP emission, metal–insulator–metal (MIM) waveguides receive considerable attention for designing plasmonic structures [19].

The most important application of the MIM waveguides is for designing plasmonic filters. These filters have many applications such as wavelength selective waveguide [20], tooth-shaped waveguide [2], plasmonic grating [12], and filters Based on circular and square nanodisk resonators and circular and square nanoring resonators [21, 22]. MIM waveguides structures also have many other applications including, signal processing, produce desirable wavelength, and optical communication [20].

Wavelength Division Multiplexing (WDM) is one of the most important operation in the optical communication systems [20]. WDMs are consist of several filters and most important of these filters are bandpass filters. WDM-based structure have fascinating power filtering capability. It is noteworthy that, how to choose different wavelengths in each channels is very important to understand the working principle of plasmonic structures like plasmonic-based WDM.

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Plasmonic structure have been able to solve many problems because of integration and miniaturization of device. Bragg reflector is one of the plasmonic structures and have been theoretically presented in [12, 23]. The Bragg reflectors suffer from high losses and low transmission efficiency. In recent years, resonators such as nanoring and nanodisk resonators shown great potential to overcome the aforementioned limitation of the plasmonic structures.

One of the applications of nanoring and nanodisk resonators is in the design and implementation of the plasmonic multiplexers and demultiplexers. In the plasmonic multiplexers and demultiplexers wavelengths selection with the appropriate efficiency and minimum Full Width Half Maximum (FWHM) achieved by adjusting geometrical parameters and refractive index (RI) [24].

In this paper, a novel filter structure that using a 1×3 plasmonic wavelength demultiplexer based on MIM waveguide has been proposed and numerically investigated by FDTD method. The proposed design is based on the coupled nanodisk and nanoring resonators and consist of three waveguides in each channel. This structure has the ability to transfer three different wavelengths with appropriate efficiency, high quality factor and very low FWHM. The simulation results illustrate that with appropriate select of the refractive index of dielectric materials and appropriate choice of geometrical structure parameters, each channel's wavelength can selected. Our proposed demultiplexer structure is useful in application such as nanosensors and ultra-compact demultiplexer devices.

II. Basic structure and simulations

The proposed basic filter structure is shown in Fig. 1(a). This structure consists of two square nanodisk resonators, two waveguides of bus and drop and a middle cavity that coupled both sides to two resonators, the length of square nanodisk resonators (L), The width of waveguides (Wt), The length of the middle cavity (L'), the coupling distance between middle cavity with the nanodisks (d2, d3) and also the waveguides with the nanodisk are (d1, d4) are 450, 50, 460, 8, and 10 nm, respectively. The separation distance between the two nanodisks is the same as the length of the cavity. Insulator material assumed air (white areas) and metal is set as silver (gray areas). The silver dielectric constant is illustrated by the famous Drude model [6, 25].

\[
\varepsilon_m(\omega) = \varepsilon_\infty - \frac{\omega_p^2}{\omega(\omega + i\gamma)}
\]  

In eq. (1), \(\omega\) is the frequency of the incident light, \(\omega_p = 1.38 \times 10^{16}\) Hz is bulk plasma frequency, \(\gamma = 2.73 \times 10^{13}\) Hz is the electron collision frequency and \(\varepsilon_\infty = 3.7\) represents the dielectric constant at the infinite frequency. In this structure, the FDTD method with 2 nm mesh precision employed.

The light source used in the proposed structure is the plane wave. Two monitors are placed at output of the right (drop) waveguide (P2) and input of the left waveguide (P1), these monitors are mounted to the resonators in order to receive and identify the incident and transmission power. \(T = \frac{P_2}{P_1}\) describes the transmission efficiency of this structure. \(P_2\) and \(P_1\) are transmission power and the total incident power which are shown are Fig. 1(a). By analyzing the diffusion behavior of SPPs in the proposed structure, we can understand the principle of wavelength filter function [15]. At first TM waves is emitted from the source to the structure, then SPPs are excited and are propagated in interface between silver and insulator longitudinally. Hence, The incident light coupled from waveguides into the square nanodisks, forms resonance mode in output of the drop waveguide because of the tunneling effect.

The SPPs are excited alone with incident TM-polarized plane waves because the incident wavelength is much bigger than the width of MIM waveguide so only TM mode is existed in the structure [26]. The dispersion relations are expressed as follows for the proposed structure, [27]:

\[
\varepsilon_d k_m + \varepsilon_m k_d \tanh\left(\frac{wk_d}{2}\right) = 0
\]  

In this structure, the FDTD method with 2 nm mesh precision employed.
Fig. 1. Schematic of proposed base filter (a) the filter 2-D schematic with \( L = 450 \) nm, \( L' = 460 \) nm, \( w = 50 \) nm, \( d1 = d4 = 10 \) nm, \( d2 = d3 = 8 \) nm, \( n_{\text{air}} = 1.0 \) and (b) the filter 3-D schematic.

In Eq. 2 \( k_m = (\beta^2 - \epsilon_m k_0^2)^{1/2} \) and \( k_d = (\beta^2 - \epsilon_d k_0^2)^{1/2} \) are propagation constants in air for metal and dielectric areas respectively, also the dielectric constants are shown with \( \epsilon_m \) and \( \epsilon_d \) for metal and dielectric. \( k_0 \) and \( n_{\text{eff}} \) are incident light wave vector and the effective refractive index. These index are defined as \( k_0 = \frac{2\pi}{\lambda} \) and \( n_{\text{eff}} = \frac{\beta}{k_0} \). Due to the fact that the transmission spectra of our structure is in the form of band-pass filter, the transmission function can be presented according to coupled mode theory as Eq. 3 expressed [20]:

\[
T(\omega) = \frac{\left(\frac{1}{\tau_\omega}\right)^2}{(\omega - \omega_0)^2 + \left(\frac{1}{\tau_i} + \frac{1}{\tau_\omega}\right)^2}
\]

where \( \tau_\omega \) is the decay rate of the field, \( \tau_i \) is the internal loss decay rate in the cavity, \( \omega_0 \) is the resonance frequency, and \( \omega \) is the incident light frequency. As Fig. 2(a) shows the resonance frequency has two transmitted peaks. In (3), it can be seen that, the resonance transmission \( \left(\frac{1}{\tau_\omega}\right)^2/(\frac{1}{\tau_i} + \frac{1}{\tau_\omega})^2 \) is close to one and for the frequencies away from the resonance frequency, the transmission function becomes zero.

The resonant mode created with a wavelength of 1149 nm at the filter output which is shown in the Fig. 2(a). It is noteworthy that in considering the filter transmission spectrum the proposed structure offers very low FWHM (about 17 nm) Fig. 2(b) depict the field distribution for wavelengths of 1149 nm. As this figure shows energy coupling occurs from waveguides to the resonators.

In the following the effect of changes in refractive index and geometrical parameters on the transmission spectra of the proposed design is also investigated.

Fig. 2. Transmission spectra of proposed filter along with field distribution (a) The filter Transmission spectra (b) The profiles of field |Hz| for \( \lambda = 1149 \) nm.
III. Transmission properties with different parameters

Using the FDTD method, the transmission characteristics of the designed structure can be investigated. According to Fig. 3(a) with a gradual increase of the refractive index of insulator (air) medium, it is observed that the transmission spectra moves towards higher wavelengths, but by increasing the refractive index of the insulator medium, the structure faces internal losses, by its nature, the efficiency of the transmission spectra is gradually is reduced.

![Graph](a) The proposed transmission spectra curve for different refractive index

![Graph](b) The proposed filter transmission spectra curve for different square nanodisk resonators widths

![Graph](c) The proposed filter transmission spectra curve for different square nanodisk resonators widths.

Fig. 3. (a) The proposed transmission spectra curve for different refractive index (b) The proposed filter transmission spectra curve for different square nanodisk resonators widths (c) The proposed filter transmission spectra curve for different square nanodisk resonators widths.
With a little attention we find that the FWHM of the transmission spectra is slightly increases and due to the decrease of the difference between the refractive indexes of the two medium (silver and air). In other words, when the refractive index of the insulation medium increases, the refractive index of the two media become closer to each other and the light in the waveguide is less confined and as a result the FWHM increases insignificantly. As illustrated in Fig. 3(a). Fig. 4(a) also shows the wavelength change curve as a function of refractive index. In the next step, the effect of first the geometric parameter (the length of the square resonators) is also investigated. By increasing the length of the resonators similar to increasing of the refractive index of the insulator medium, the efficiency of the transmission spectra decreases and moves towards higher wavelength, while the FWHM does not change according to Fig. 3(b). The wavelength changes are shown as a function of the length of the resonators in Fig. 4(b). Finally in the last step, the second geometric parameter (the width of the resonators) is examined. Here, unlike the previous two parameters, with increasing the width of the resonators, the efficiency of the transmission spectra decreases slowly and moves towards lower wavelengths according to Fig. 3(c). The wavelength variations are shown as a function of resonators width in Fig. 4(c). Therefore, according to Fig. 3(a) and 3(b), it can be seen that the proposed structure has a high sensitivity to changing the parameters.

There are two very important parameters to check the performance of plasmonic structures. These parameters are a figure of merit (FoM) and sensitivity (S) which defined by Eq. 4 and 5, respectively [6].

\[
\text{FoM} = \frac{S}{\Delta \lambda}
\]

\[
S = \frac{\delta \lambda}{\delta n}
\]

The FOM of the sensor is the sensitivity of the sensor (S) divided by the FWHM variations (\(\Delta \lambda\)) and the sensitivity of the sensor indicates resonance wavelength displacement (\(\delta \lambda\)) divided by the changes of the refractive index (\(\delta n\)). As in the proposed structure two different refractive index \(n = 1\) and \(n = 1.05\) employed the FOM and sensitivity are calculated seperately for each of the these refractive indexes as shown in follows:

\[
S = \frac{1206_{nm} - 1149_{nm}}{1.05 - 1} = 1140 \text{ nm/RIU}
\]

\[
\text{FoM} = \frac{1140 \text{ nm/RIU}}{37_{nm} - 17_{nm}} = 57 \text{ RIU}^{-1}
\]

![Fig. 4.](image)

(a) Transmission wavelength changes relative to refractive index (b) Transmission wavelength changes with respect to different Length for square nanodisk resonators (c) Transmission wavelength changes with respect to different widths for square nanodisk resonators.
Table 1. The FWHM and efficiency values of the proposed structure with respect to the change in the material of the metal medium

| Material  | Efficiency | FWHM |
|-----------|------------|------|
| Silver (Ag) | 75%        | 17 nm |
| Gold (Au)  | 22%        | 35 nm |
| Copper (Cu) | 16%        | 39 nm |

According to Fig. 4(a), when the refractive index of the structure is 1, the wavelength of the transmission spectra is 1149 nm and when in the refractive index is 1.05, the wavelength of the transmission spectra is 1206 nm. According to Eq. 4, the sensitivity of the proposed structure can be easily calculated. But, in order to calculate the FoM of the structure, we used the calculated sensitivity at the refractive index of 1.05 and 1, which are equal to 37 and 17 nm, respectively.

In the next step the type of metal of the proposed structure is changed. Thus, by using gold (Au) and copper (Cu) instead of silver (Ag), the transmission efficiency of the structure is reduced due to the increase of the internal losses of the structure, as illustrated in Fig. 5.

### IV. Design and simulation of wavelength demultiplexer

By using several filters together, a wavelength demultiplexer can be designed. According to Fig. 6, the proposed demultiplexer structure consists of three band pass filters, each of which has two waveguides, a middle cavity, and two square nanodisk resonators. These three filters are connected to each other by a vertical cavity, and an input waveguide is connected horizontally to this vertically connected cavity, which is responsible for transmit energy from the source to other parts of the structure. In the proposed multiplexer structure the geometric parameters are $L_1 = 1200$ nm, $L_A = 455$ nm, $L_B = 450$ nm and $L_C = 445$ nm (the length and width of square nanodisk resonators), $L = L' = L'' = 450$ nm (the length of middle cavities), $L_2 = L_3 = L_4 = 260$ nm (the length of filter input waveguides). According to the simulation results of proposed demultiplexer, the transmission spectra for each of the channels 1 to 3 are 1130, 1149 and 1168 nm, respectively, with a FWHM of 10, 18 and 11 nm as shown in Fig. 7(a).
Fig. 7. (a) Transmission spectra with triple-channel output. The profiles of field $|\text{Hz}|$ for proposed structure in different wavelengths (b) at $\lambda_1 = 1130$ nm, (c) at $\lambda_2 = 1149$ and (d) at $\lambda_3 = 1168$ nm.

Fig. 7(b) shows the field distribution profiles for these three different wavelengths, as the 1149 wavelength has a higher transmission efficiency than the 1168 wavelength, means that the second channel has a stronger coupling of energy between the waveguides and the two square resonators than the other two channels. The simulation results show that the crosstalk effect of each channel on the other is less than -25 dB.

V. Conclusion

In this paper, a novel plasmonic demultiplexer based on square nanodisk resonators in an MIM waveguide is proposed. This structure consists of two waveguides at the input and output with a central cavity and two square resonators. The proposed structure can be adjusted by selecting the refractive index and appropriate geometric parameters such as length and width to achieve the desired transmission spectra at the output of the structure. According to the simulation results, the FWHM of the filter reaches 10 nm. Using three proposed plasmonic based filters, a triple-channel plasmonic demultiplexer is also designed and simulated. The proposed WDM structure has three output channels with three different wavelengths in each of the channels. The effect of cross talk is less than -25 dB. The proposed structure can be used in the ultra-compact demultiplexer devices, large-scale photonic integration, integrated plasmonic devices, nanosensors and the development of optical integrated circuits. The proposed structure is analyzed numerically by utilizing FDTD method.

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