Optical filter based on metal-insulator-metal plasmonic coupled cavities

A Lounis¹, A Hocini¹ and H Ben salah¹,²

¹Laboratoire d’Analyse des Signaux et Systèmes, Department of Electronics, University of M’Sila BP.166, Route Ichelibia, M’Sila, 28000, Algeria
²Université Yahia Fares de Médéa, Medea, 26000, Algeria

E-mail: ahmed.lounis@univ-msila.dz

Abstract. In this study, an optical filter based on a plasmonic metal-insulator-metal (MIM) coupled waveguide resonator is simulated and investigated. Using the proposed structure leads to realizing a filter function between targeted wavelengths by manipulating the appropriate geometrical parameters of the resonators. Two-dimensional FDTD-based simulation is implemented to analyze the filter properties. The filter proposed proves to be a potential candidate for highly integrated optical circuit applications.

1. Introduction
Nanotechnology has seen an exponential growth over the past two decades [1], where the field of plasmonic gained increasing interest due to the recent advances in the investigations of the electromagnetic (EM) properties of nanostructured materials. The metallic nanostructures have very distinctive features, such as confinement of the incident radiation [2]. Surface plasmon polaritons (SPPs) are electromagnetic waves that travel along a metal–dielectric or metal–air interface [3]. This involves many research fields, such as materials science, nanotechnology, electromagnetism [4]. The unique optical properties caused by surface plasmons has attracted extensive attention in view of development of tunable optical filters, surface enhanced Raman scattering, photo catalysis, photolithography, biosensors and terahertz plasma waves [4]. MIM structures have been in the center of attention of numerous researches involving their analysis due to the fact that MIM structures have a strong electric field confinement and long propagation ranges [5]. Several SPP-based MIM structures have been proposed for numerous applications, such as in optical filters [6], couplers [7], splitters [8], demultiplexers [9], and sensors [10, 11]. For visible and near-infrared light, the plasmonic materials are metals, such as silver, that exhibit low losses at telecom wavelengths [12, 13].

In this work, we present a double-sided waveguide-based filter that consists of a rectangular cavity. The transmission spectrum can be tuned by changing the geometric parameters of the proposed structure, which makes it a potential candidate for applications in highly integrated optical circuits.

2. Theoretical and structural analysis
The proposed structure is shown in figure 1, which presents an MIM-based slit (waveguide) with a fixed width \( w = 50 \text{ nm} \), with (TM₀) being the only excited mode in this waveguide [14]. The waveguide is coupled with a rectangularly-shaped ring resonator cavity with a width \( X_1 \), a length \( Y_1 \) and a thickness \( a \); \( g \) is the coupling space between the waveguide and the resonator’s cavity. The gray area represents
the silver layer, and the white one, the dielectric material. The frequency-dependent dielectric constant of silver is calculated by Lorentz–Drude model [15]:

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

(1)

Where \( \varepsilon_\infty \) is the dielectric constant at the infinite angular frequency with value 3.7, \( \omega_p \) is the bulk plasma frequency \( (\omega_p = 1.38 \times 10^{16} \text{ Hz}) \), \( \gamma \) is the electron collision frequency \( (\gamma = 2.73 \times 10^{13} \text{ Hz}) \) and \( \omega \) is the angular frequency of the incident wave in vacuum [16].

![Figure 1. Schematic diagram of the proposed MIM-based plasmonic structure.](image)

Simulating the structure in an SPP mode means that the incident light must be polarized in the \( (\text{TM}_0) \) mode, hence, the magnetic field is parallel to the \( y \) axis [17]. The resonance wavelength \( \lambda_m \) of the rectangular plasmonic cavity can be calculated as follows [18]:

\[
\lambda_m = \frac{2n_{\text{eff}}S}{m - \varphi_{\text{ref}}} \pi
\]

(2)

Where \( n_{\text{eff}} \) is the real part of the effective refractive index, \( S \) is the effective length of the resonator, \( \varphi_{\text{ref}} \) is the phase, and \( m \) is a positive integer denoting the resonance order in the resonator.

3. Simulation results and discussion

In this paper, the R-Soft simulator is used based on the FDTD method [19]. The perfectly matched layers (PML) condition is imposed and applied to the structure to simulate its transmission characteristics, namely, the outgoing waves are absorbed by the sides of the structure. The grid size in \( x \) and \( z \) directions is chosen as \( \Delta x = \Delta z = 5 \text{ nm} \) [5], with an input type based on a continuous TM polarized Gaussian wave.

When a cavity-waveguide coupling occurs, the electromagnetic wave is collected on the right side of the waveguide, where the ratio \( T = P_{\text{out}}/P_{\text{in}} \) is defined.

First, we set the structural parameters to be \( X_1 = 200 \text{ nm}, Z_1 = 400 \text{ nm}, a = 50 \text{ nm} \) and \( g = 10 \text{ nm} \), with the insulator in the dielectric core and the cavities having a refractive index \( n \) of 1.

As shown in figure 2 (a), the structure with the rectangular ring cavity exhibits two resonance modes, the first mode 1 at a resonance wavelength of 885.7 nm, and mode 2, at 1664.7 nm, both of them being off-resonance modes.
Figure 2. (a) Transmission spectra of an MIM plasmonic structure with $n = 1$, $X_1 = 200$ nm, $Z_1 = 400$ nm, $a = 50$ nm and $g = 10$ nm. (b) Magnetic-field patterns of the MIM plasmonic structure at the resonance wavelength 1664.7 nm (right) and at the wavelength 1100 nm (left).

Figure 2 (b) shows the field distribution of $|H_y|$ in the proposed structure, where one can clearly notice the coupling of the incident light in the resonance wavelengths $\lambda_1 = 1100$ nm (on-resonance) and $\lambda_2 = 1664.7$ nm (off-resonance) of the rectangular ring cavity. At these wavelengths the light remains confined in the cavity.

Figure 3. (a) Transmission spectra of the MIM filter for different distances $a$. (b) Resonance wavelength as a function of the distance $a$.

Firstly, in order to study the effect of the thickness $a$ on the transmission characteristics, $a$ is varied, while the other parameters are fixed as follows: $X_1 = 200$ nm, $Z_1 = 400$ nm, $g = 10$ nm and $n = 1$. Figure 3 (a) depicts the transmission spectra of the MIM filter for different values of the thickness $a$: $a = 50$ nm (dark), $a = 37.5$ nm (red) and $a = 25$ nm (green); as is clearly seen, a decrease in the thickness $a$ leads
to a red-shift of the resonance wavelengths of the transmitted spectra; the case of \( a = 25 \) nm is chosen as the optimal thickness for the proposed optical filter. Figure 3 (b) shows the relationships between the thickness and the wavelength of mode 1 and 2.

![Figure 3](image3.png)

**Figure 3.** Transmission spectrum of the structure versus the wavelength with different coupling distances \( g \) for \( n = 1, \ X_1 = 200 \) nm, \( Z_l = 125 \) nm and \( a = 25 \) nm

Secondly, in order to study the influence of the coupling distance \( g \) between the waveguide and the resonant cavity on the transmission spectra of the filter proposed, \( g \) is gradually increased from \( g = 10 \) nm to \( g = 18 \) nm with an interval of 4 nm, while the other parameters are fixed as: \( X_1 = 200 \) nm, \( Z_l = 125 \) nm, \( a = 25 \) nm and \( n = 1 \). Figure 4 illustrates the transmission spectra of MIM structure for different values of \( g \); one should note that the transmission spectra contain narrower bands for both modes when the coupling distance is decreasing, so that the optimal coupling distance chosen was \( g = 10 \) nm.

![Figure 4](image4.png)

**Figure 4.** Transmission spectrum of the structure versus the wavelength with different coupling distances \( g \) for \( n = 1, X_1 = 200 \) nm, \( Z_l = 125 \) nm and \( a = 25 \) nm

We also propose another design consisting of a double rectangular-ring resonator, as shown in figure 5 (a). The resonant cavity is formed of two identical ring rectangles, the first vertical and the other horizontal, intersected at a distance \( D \) between the intersection of the two rectangles and the left outer side of the horizontal ring rectangle.

![Figure 5](image5.png)

**Figure 5.** (a) Schematic of the proposed MIM-based plasmonic structure. (b) Transmission spectra of an MIM plasmonic waveguide coupled with single rectangular-ring and intersected double rectangular-ring resonators with \( n = 1, X_1 = 200 \) nm, \( Z_l = 400 \) nm, \( a = 25 \) nm, \( g = 10 \) nm and \( D = 200 \) nm.

Figure 5 (b) shows the transmission spectra for the two structures: a single and double rectangular-ring resonator with \( n = 1, X_1 = 200 \) nm, \( Z_l = 400 \) nm, \( a = 25 \) nm, \( g = 10 \) nm and \( D = 200 \) nm. The transmission spectrum of the first structure (in black) contains three (3) resonance modes, while in the case of the intersected double rectangular-ring resonators structure a fourth mode appears, in addition to the fact that there is a red-shift for the first three modes compared to the first structure.
4. Conclusion
A filter with a single rectangular ring is theoretically proposed and optimized. The influence is studied of the geometric parameters on the resonance modes and their wavelengths. This structure is found to be sensitive to variations in the refractive index, which allows it to be used as an IR sensor. Another optical filter with a double rectangular ring resonator is proposed and found to possess new resonance modes. These, at their corresponding wavelengths, can be used as an off-resonance mode (the light remains confined inside the cavity), while the other wavelengths can be used as an on-resonance mode (the light passes through the waveguide).

References
[1] Strobbia P, Languirand E R and Cullum B M 2015 Optical Engineering 54 100902
[2] Rafiee E, Negahdari R and Emami F 2019 Photonics Nanostruct. Fundam. Appl. 33 21–8
[3] Zeng S, Baillargeat D, Ho H P and Yong K T 2014 Chemical Society Reviews 43 3426–52
[4] Qi Y, Zhou P, Zhang T, Zhang X, Wang Y, Liu C, Bai Y and Wang X 2019 Results in Physics 14 102506
[5] Ben salah H, Hocini A, Temmar M N and Khedrouche D 2019 Chin. J. Phys. 61 86–97
[6] Zou F, Zou, X, Pan W, Luo B and Yan L 2017 Plasmonics 12 1589–94
[7] Veronis G and Fan S 2007 Opt. Express 15 1211–1221
[8] Lu Z, Yang R, Wahsheh R A and Abushagur M A G 2010 Integrated Optics: Devices, Materials, and Technologies XIV 7604 760419
[9] Onbasli M C and Okyay A K 2010 Plasmonics: Metallic Nanostructures and Their Optical Properties VIII (United States :International Society for Optics and Photonics) pp 77573R
[10] Hocini A, Bensalah H, Khedrouche D and Melouki N 2020 Opt. Quant. Electron. 52 1–10
[11] Achi S E, Hocini A, Salah H B and Harhouz A 2020 Progress In Electromagnetics Research M 147–156
[12] West P R, Ishii S, Naik G V, Emani N K, Shalaev V M and Boltasseva A 2010 Laser & Photonics Reviews 4 795–808
[13] McPeak K M, Jayanti S V, Kress S J, Meyer S, Iotti S, Rossinelli A and Norris D J 2015 ACS Photonics 2 326–33
[14] Gai H, Wang J and Tian Q 2007 Applied optics 46 2229–33
[15] Johnson P B and Christy R W 1972 Physical review B 6 4370
[16] Zhang X, Shao M and Zeng X 2016 Sensors 16 1730
[17] Wei P K, Huang Y C, Chiang C C, Tseng F G and Fann W 2005 Optics Express 13 10784–94
[18] Zhang Q, Huang X G, Lin X S, Tao J and Jin X P 2009 Optics Express 17 7549–55
[19] Rsoft Design Group, FullWAVE, Inc. 200 Executive Blvd. Ossining, NY 10562