Modeling and analysis of the RI sensitivity of plasmonic sensor based on MIM waveguide-coupled structure

I Zeggar1, A Hocini2 and H Ben salah1,3
1 LIST Laboratory, University of M’Hamed Bougara Boumerdes, Avenue of Independence, 35000 Boumerdes, Algeria
2 Laboratoire d’Analyse des Signaux et Systèmes, Department of Electronics, University of M’Sila BP.166, Route Ichebilia, M’Sila, 28000, Algeria
2 Université Yahia Fares de Médéa, Medea, 26000, Algeria
E-mail: i.zeggar@univ-boumerdes.dz

Abstract. In this paper, a plasmonic sensor is proposed based on a metal-insulator-metal waveguide coupled with a double-triangle resonator. The sensing structure is numerically and theoretically investigated using the two-dimensional finite difference time domain (FDTD) method. The results show the presence of a linear relationship between the materials refractive indices and the sensor’s wavelength resonances. The proposed structure revealed a high sensitivity value, reaching the maximum value for mode 1 \( S_{\text{mode1}} = 1374 \) nm/RIU, and for mode 2 \( S_{\text{mode2}} = 2365 \) nm/RIU. The proposed sensor can be classified as a high-performance nano-sensor that can be used to identify different materials.

1. Introduction
The electron charges on a metal boundary can perform coherent fluctuations, which are called surface plasma oscillations. Their existence has been demonstrated in electron energy loss experiments. Surface plasmon polaritons (SPPs) are electromagnetic excitations that propagate along a metal-dielectric surface with an exponentially decaying field in both neighboring media. In fact, the coupling of the electromagnetic fields to oscillations of the conductor’s electron plasma induces the aforementioned electromagnetic surface waves [1, 2, 3]. SPPs have attracted a great deal of attention because of their sub-wavelength confinement below the light diffraction limit and the enhancement of light-matter interactions [4, 5, 6].

The metal-insulator-metal (MIM) waveguide structure is considered one of the most popular structures for SPP waveguide. It has two metal-dielectric interfaces close to each other and can guide SPPs to propagate along the interfaces [7]. The MIM structure has attracted increased attention due to their deep-sub-wavelength confinement of light and thus has find wide applications in deep-sub-wavelength optical devices [8]. They offer a promising platform for the realization of chip-scale photonic functionality and devices. Recently, some wavelength-selective structures based on MIM waveguides have been proposed and demonstrated, such as resonators-coupled plasmonic waveguide systems. As key factors in the systems, plasmonic resonators would be one of the crucial elements of plasmonic wavelength-selective structures because of the simplicity and ease of fabrication [9]. Just a few devices among all those manufactured based on a MIM structure are couplers [10], demultiplexers [11], filters...
[12], sensors [13]. There are numerous applications for surface plasmon resonance sensors, especially in biomedicine [14] and biology [15], because of their high sensitivity and fast response.

Currently, the plasmonic sensors are characterized low sensitivity, which remains a challenge for researchers. However, for geometrically compact devices, one way to overcome this challenge is by extending the interaction length, which can be achieved by introducing hybrid cavities to facilitate the re-circulation of the optical and plasmonic resonance waves [16].

In this study, we propose a high-sensitivity sensing structure composed of an MIM waveguide and a double triangle resonator. We obtain the reflection characteristics of the structure by using the two-dimensional (2D) finite-difference time-domain (FDTD) method implemented in the R-STOP software. This structure can be employed for different useful sensors with proper designs based on the refractive index variation.

2. Model and theoretical analysis of the structure

The schematic of the plasmonic sensor structure is shown in figure 1. The structure consists of a waveguide and a double triangle resonator. The gray area is silver, which is the metal used in the device, the white area is the dielectric, which is air; the side length of the first triangle is denoted by the symbol $a$, and the side length of the second triangle is $b$. Table 1 lists the physical parameters of the structure according to figure 1.

The sub-wavelength waveguide supports transverse magnetic (TM) mode because only the fundamental mode is capable to propagate through the plasmonic waveguide, which does not support the transverse electric (TE) mode. The TM mode dispersion relation is expressed as [17, 18]:

$$\varepsilon_m \sqrt{n_{eff}^2 - \varepsilon_d \tanh \left( \frac{w \pi \sqrt{\varepsilon_{eff}^2 - \varepsilon_d}}{\lambda} \right)} + \varepsilon_d \sqrt{n_{eff}^2 - \varepsilon_m} = 0. \quad (1)$$

Here $\lambda$ is the incident light wavelength, $w$ is the waveguide width, $\varepsilon_d$ is the permittivity of the dielectric and $\varepsilon_m$ is the permittivity of the metal, $n_{eff}$ is the effective refractive index of the MIM waveguide, which can be described as follows:

$$n_{eff} = \sqrt{\varepsilon_d \left( 1 + \frac{\lambda}{\pi \omega_{wg} \sqrt{\varepsilon_m \varepsilon_d}} \right) \left( 1 + \frac{\varepsilon_d}{\varepsilon_m} \right)^{1/2}}. \quad (2)$$

The chosen metal is silver due to its low ohmic loss; its frequency-dependent permittivity can be described by the Lorentz–Drude relation [13, 19]

$$\varepsilon_m(\omega) = 1 - \frac{\omega_p^2}{\omega(\omega - \imath \Gamma_0)} + \sum_{n=1}^{\infty} \frac{f_n \omega_n^2}{\omega_n^2 - \omega^2 + \imath \omega \Gamma_n}, \quad (3)$$

where $\omega$ is the angular frequency of incident light, $\omega_p$ is the plasmonic frequency, $\Gamma_0$ is the damping constant, $f_n$ is the dominant frequency, $\omega_n$ is the resonance frequency and $\Gamma_n$ is the damping frequency. The dispersion relation in the structure is determined by the equation:

$$\varepsilon_d k_m + \varepsilon_m k_d \tanh \left( \frac{\varepsilon_d}{2} \omega \right) = 0 \quad (4)$$

$$k_m = \sqrt{\beta^2 - \varepsilon_m k_0^2} \text{ and } k_d = \sqrt{\beta^2 - \varepsilon_d k_0^2}, \quad (5)$$

where $\beta$ denotes the constant of propagation for SPPs and $k_0 = 2\pi/\lambda_0$ is the wave vector of the light with $\lambda_0$ being the free-space wavelength [20].
3. Results and discussion

For the numerical analysis and simulation of the transmission characteristics of the proposed structures, the 2D-FDTD method is applied with perfectly matched layers (PML) as the boundary condition for all sides of the computational window to absorb outgoing waves [21, 22]. The spatial mesh steps in x and z directions are set at $\Delta x = \Delta z = 5$ nm and the time step, at $0.95/c\sqrt{\Delta x^2 + \Delta z^2}$ due to the Courant condition; $c$ is the speed of light in free space. The input type is a continuous slab mode modulated wave of a TM polarized field. Fast Fourier transforms of the input and output fields measured at two power monitors are used to obtain the transmission spectra of the normalized power $T = P_{\text{out}}/P_{\text{in}}$. Both the incident power $P_{\text{in}}$ and the transmitted power $P_{\text{out}}$ are observed at positions A and B. The sensitivity is an important factor in sensor design which is defined as [23]: $S = \Delta \lambda/\Delta n$, where $\Delta \lambda$ and $\Delta n$ are the resonant wavelength variation and the rate of change of the refraction index in the plasmonic sensor structure, respectively.

Figure 2 presents the spectral transmission of the proposed structure for the values given in Table 1. In the case $n = 1$, the result shows two resonances. Using the magnetic-field patterns of the MIM plasmonic structure, the wavelength for the two modes is checked and no resonance is found at the wavelength of 1.60 $\mu$m. Figure 2 shows the structure as resonating at the wavelengths 2.0489 $\mu$m and 1.1098 $\mu$m.

| Parameter                  | Symbol | Quantity |
|----------------------------|--------|----------|
| Waveguide width            | $w$    | 50 nm    |
| Coupling distance          | $g$    | 10 nm    |
| Side length of the first triangle | $a$ | 400 nm |
| Side length of the second triangle | $b$ | 300 nm |

Figure 2. The transmission spectrum of an MIM sensor with $n = 1$, $a = 400$ nm, $b = 300$ nm, $g = 10$ nm; the resonance wavelengths are 2.0489 $\mu$m, 1.1098 $\mu$m.
Figure 3. (a) The transmission spectra of an MIM sensor for different refractive indexes $n, g = 10 \text{ nm}$, $a = 400 \text{ nm}$ and $b = 300 \text{ nm}$. (b) The resonance wavelength versus the refractive index $n$ of the material under sensing.

In figure 3 (a), the value of the refractive index is varied from 1 to 1.08 with a step of 0.02. When the refractive index is increased, the resonance wavelength shifts for both the first and second modes. Figure 3 (b) presents the linear relationship between the wavelength resonance and the refractive index for both the cases of mode 1 and mode 2; the sensitivity of the sensor $S_{\text{mode1}}$ and $S_{\text{mode2}}$ are 1035 nm/RIU and 1951 nm/RIU, for mode 1 and mode 2, respectively.

The side length of triangle $b$ is varied from 290 nm to 320 nm at a 10-nm step. Figure 4 (a) shows that as the length of side $b$ increases, so does the resonance wavelength, with the shift being larger for mode 2. Further, figure 4 (b) shows that the linear relationship between the resonance wavelength and the refractive index is preserved despite the increase in the length of $b$. The increase in the length $b$ from 290 nm to 320 nm leads to an improvement in the sensitivity of this sensor. Thus, at length $b = 290 \text{ nm}$, the sensitivity $S_{\text{mode1}} = 980 \text{ nm/RIU}$ and the sensitivity $S_{\text{mode2}} = 1768 \text{ nm/RIU}$; while at length $b = 320 \text{ nm}$, the sensitivities for modes 1 and 2 are $S_{\text{mode1}} = 1374 \text{ nm/RIU}$ and $S_{\text{mode2}} = 2365 \text{ nm/RIU}$, respectively. Thus, a linear relationship exists between the length $b$ and the sensor’s sensitivity, as shown in figure 4 (c).
Figure 4. Sensing properties as functions of $b$: (a) transmission spectra of index 1 for $b$ varying from 290 nm to 320 nm; (b) resonance wavelengths versus the refractive index for different $b$; (c) sensitivities of the plasmonic sensors for $b$ varying from 125 nm to 145 nm.

Table 2 compares the sensitivity ($S$) of different MIM plasmonic sensors reported in literatures.

| Reference | Sensitivity (nm/RIU) | Year |
|-----------|----------------------|------|
| [24]      | 820                  | 2014 |
| [25]      | 1125                 | 2017 |
| [26]      | 1100                 | 2016 |
| [27]      | 2000                 | 2019 |
| **This work** | **1374 for mode 1, 2365 for mode 2** | 2020 |

4. Conclusion
In this work, a novel plasmonic RI sensor with an MIM waveguide coupled to a double-triangle resonator is proposed. The sensor is examined numerically and theoretically using the FDTD method and a good linear relationship between the resonance wavelength and the refractive index is obtained. After optimizing the structural parameters, the results show that the proposed sensor has a high sensitivity value, the maximum sensitivity being 1374 nm/RIU and 2365 nm/RIU for mode 1 and mode 2, respectively. With its simple structure, this sensor promises to be a good choice for applications in integrated optics.

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