

Refractive Index Sensor MIM Based Waveguide Coupled with a Slotted Side Resonator

Salah E. Achi, Abdesselam Hocini*, Hocine B. Salah, and Ahlam Harhouz

Abstract—In this paper, a plasmonic sensor based on a metal-insulator-metal (MIM) waveguide with a slotted side-coupled racetrack cavity is proposed. The transmission characteristics of the cavity are analyzed theoretically, and the improvements of performance for the racetrack cavity structure compared to a single disk cavity are studied. The influence of structural parameters on the transmission spectra and sensing performances is investigated thoroughly. The achieved sensitivity for the first mode was $S = 959 \text{ nm/RIU}$ and $S = 2380 \text{ nm/RIU}$ for the second one. Its corresponding sensing resolution is $1.04 \times 10^{-5} \text{ RIU}$ for mode 1 and $4.20 \times 10^{-6} \text{ RIU}$ for mode 2, respectively, and high transmissions are achieved at the two resonant wavelengths of 898.8 nm and 1857.1 nm. The proposed plasmonic sensor is a good candidate for designing novel devices and applications, in the field of chemical and biological sensing, and also in the field of plasmonic filters, switches, etc.

1. INTRODUCTION

Due to the advances achieved in the investigations of electromagnetic properties of nanostructure materials, the interest in the field of nanoplasmonics is rapidly increasing [1–3], which has opened up many opportunities toward practical applications. The extreme confinement and enhancement of light at the nanoscale are very interesting features of metallic nanostructures [4–7]. The understanding of this confinement has led to the development of a wide range of interesting materials for various fields. Plasmonic field represents the study of the interaction between electromagnetic radiation and free electrons of a metal [1, 2]. In certain conditions these interactions are conducted to a collective excitation of conductive band electrons, a surface plasmon (SP) that is [1].

Surface plasmon polaritons (SPPs) are particularly important in the integrated optics research field [8–10]. SPPs are electromagnetic waves that propagate along the metal-air or metal-dielectric interface in plasmonic nanostructures due to their specific merit of confining and manipulating light in subwavelength scale [11–13]. They have attracted a great deal of attention and been applied to various devices and technologies based on the SPPs, such as plasmonic filters, metamaterials [14–17], optical couplers [18, 19], optical switching [20], slow-light [21, 22], and biosensors [23–26].

Among the different plasmonic structures, SPPs-based MIM waveguide [27] structures at the subwavelength scale have aroused great interest due to their good properties of light confinement [28, 29], the wide range of available frequencies, the absence of bending losses, and the ease of manufacturing. Accordingly, it is considered as an important and promising component in integrated optical circuits, and a promising candidate for integrated plasmonic biosensing devices [25, 26, 29–32]. Zhang et al. [30] proposed a plasmonic refractive index (RI) sensor based on MIM waveguide, coupled with a concentric double ring resonator (CDRR).

Received 18 June 2020, Accepted 4 September 2020, Scheduled 23 September 2020

* Corresponding author: Abdesselam Hocini (abdesselam.hocini@univ-msila.dz).

The authors are with the Laboratoire d'Analyse des Signaux et Systèmes, Department of Electronics, Faculty of Technology, University of Msila, Algeria.

Wang et al. [31] reported an RI nano-sensor composed of a MIM waveguide with a baffle and a circular split-ring resonator cavity. Ben Salah et al. [26] proposed a plasmonic refractive index (RI) sensor based on MIM waveguide coupled with double teeth and a rectangular shaped defect inside the first tooth cavity. Recently, in another study presented by Yu et al. [25], a slotted side-coupled disk resonator (SSCDR) was inserted with a metallic block based on the subwavelength MIM waveguide containing a baffle, applied to nano-filters, RI sensors, temperature sensors, and slow light devices.

In this paper, a slotted side-coupled racetrack resonator is proposed as a specific sensor to theoretically demonstrate that the cavity with a slotted racetrack resonator infiltration can be used for RI sensing, where the increase in the RI is accompanied with changes to the resonance characteristics of the cavity.

The simulation results show that the resonance wavelength is shifted with the variation of RI and the proposed cavity exhibit high RI sensitivity, with high transmission and wide measurement range.

2. STRUCTURAL AND THEORETICAL ANALYSIS

The proposed structure is shown in Figure 1, which consists of a MIM slit (waveguide) with $w = 50$ nm as a width and fixed to that value so the only excited mode is (TM) in the MIM waveguides [33], embodying a baffle with a width D . This waveguide is coupled with a Slotted-Side Coupled Racetrack Resonator (SSCRR), with R as the radius of two disks intertwined with distance X . H is the width of slot in the cavity, with a length $L1$. Y and $L2$ represent the length and width of the inserted metallic block. The values of D , R , $L1 = L2$, and H are respectively fixed to: 30 nm, 300 nm, 180 nm, and 50 nm. Gap = 10 nm is the distance between the SSCRR and the waveguide. The gray area represents the silver layer, and the white one represents the dielectric material. The frequency dependent dielectric constant of silver is calculated and expressed by Lorentz-Drude model [34]:

$$\varepsilon_m(\omega) = \varepsilon_\infty - \frac{\omega_p^2}{\omega(\omega + i\gamma)} \quad (1)$$

In Eq. (1), ε_∞ is the dielectric constant at the infinite angular frequency with a value of 3.7, ω_p the bulk plasma frequency ($\omega = 1.38 \times 10^{16}$ Hz), γ the electron collision frequency ($\gamma = 2.73 \times 10^{13}$ Hz), and ω

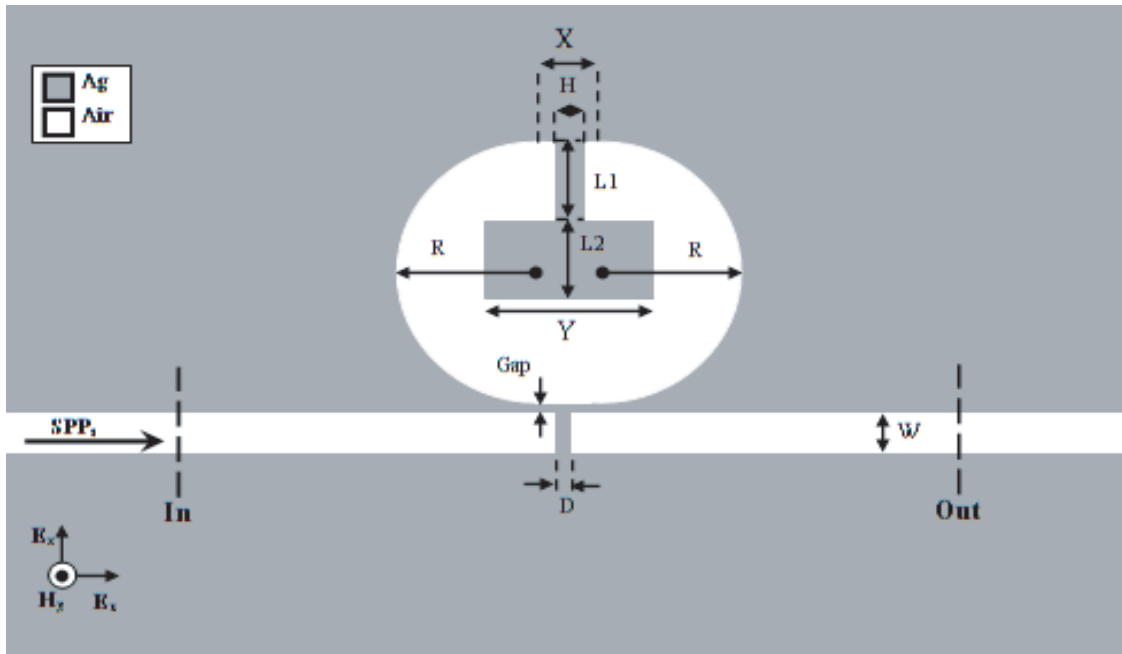


Figure 1. Schematic diagram of the proposed structure.

the angular frequency of the incident wave in vacuum [35].

To simulate the excitation process in SPP mode, the incident light must be polarized in TM mode, from where the magnetic field is parallel to y axis [36]. The resonance wavelength λ_m of the plasmonic elliptical cavity can be obtained theoretically by [37]:

$$\lambda_m = \frac{2n_{eff}S}{m - \frac{\phi_{ref}}{\pi}} \quad (2)$$

where n_{eff} is the real part of effective refractive index, S the effective length of the resonator, ϕ_{ref} the phase, and m a positive integer which signifies the resonance order in the resonator.

3. SIMULATION RESULTS AND DISCUSSION

A two-dimensional FDTD method of Rsoft tool is used to analyze the structure with perfectly matched layer (PML) absorbing boundary condition in x and z directions of the simulation domain [38]. The incident light for excitation of the SPP mode is TM-polarized. In the simulation domain, the grid sizes

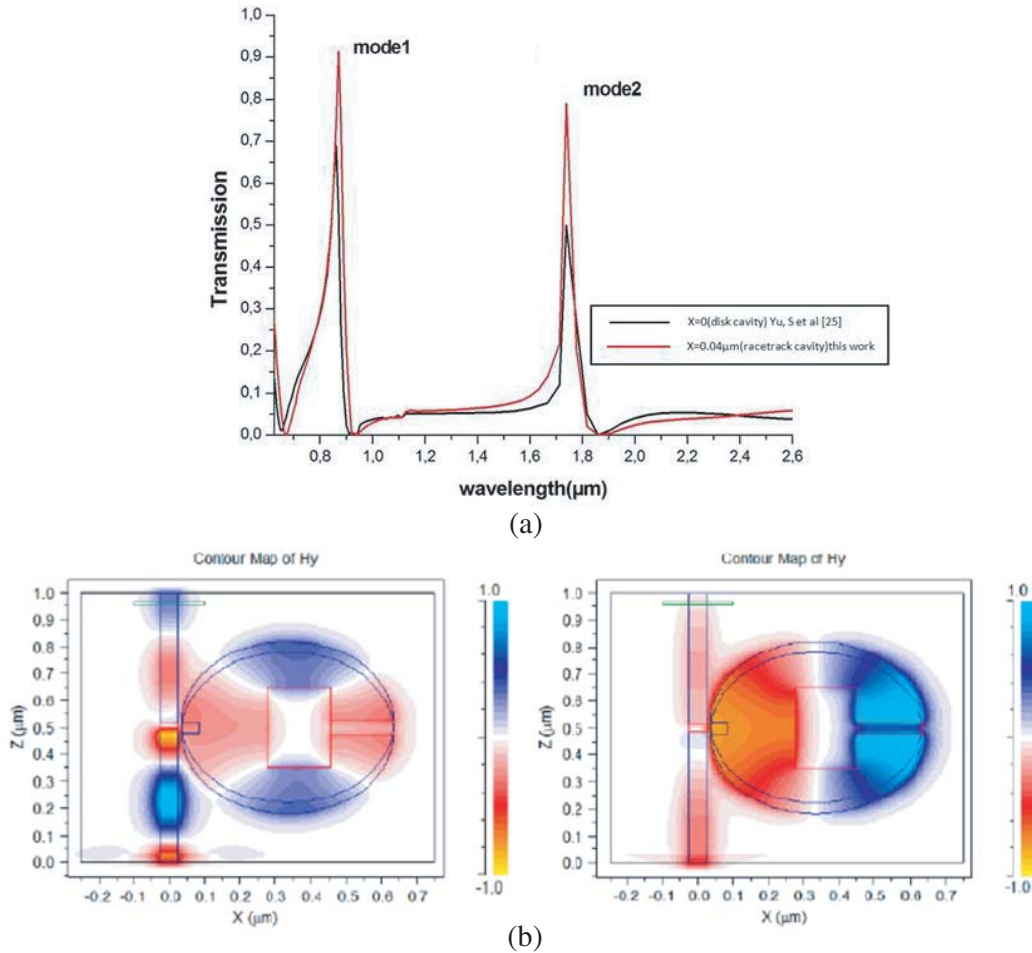


Figure 2. (a) The transmission spectra of MIM plasmonic waveguides coupled with disk and racetrack cavity with $n = 1$, $X = 40$ nm, $Y = 300$ nm. (b) Magnetic field patterns of the MIM plasmonic waveguides coupled with racetrack cavity at resonance wavelengths of $= 0.8695 \mu\text{m}$ (left), $1.7391 \mu\text{m}$ (right).

in x and z directions are chosen to be $\Delta x = \Delta z = 5 \text{ nm}$ and $\Delta t < \frac{\Delta x}{c\sqrt{2}}$ due to the Courant condition which are sufficient enough for numerical convergence.

The transmitted light was collected at the right side of the waveguide which is defined as $T = P_{\text{out}}/P_{\text{in}}$. Initially, the structural parameters are set to $X = 40 \text{ nm}$, $Y = 300 \text{ nm}$, and both the insulator in the dielectric core and the cavities have a refractive index n of 1.

As we can see in Figure 2(a), the structure with SSCDR cavity [25] exhibits a low transmission peaks (black line), compared to our design with the SSCRR (red line), at the resonance wavelengths of $\lambda_1 = 869.5 \text{ nm}$ and $\lambda_2 = 1739.1 \text{ nm}$, corresponding to the first and second resonance modes. Compared to the SSCDR structure when $X = 0$ [25], it is obvious that when $X \neq 0$ (transformation of the disk resonator to racetrack resonator), the structure has a relatively high transmittance, and it is clearly seen that there is an enhancement in the transmission of 32% for the first peak at wavelength $\lambda_1 = 869.5 \text{ nm}$, and 61% for the second peak at $\lambda_2 = 1739.1 \text{ nm}$ in our proposed racetrack resonator compared to the disk one.

Figure 2(b) depicts the field distributions $|Hy|$ of the proposed structure. It is clear that the incident light with the wavelengths of $\lambda_1 = 869.5 \text{ nm}$ and $\lambda_2 = 1739.1 \text{ nm}$ couples to the output, while the rest of the wavelengths are blocked, at these wavelengths, and the light remains confined in the structure.

To investigate the underlying physics of the Fano line shapes in the proposed structure, the structure could be divided into the following two structures: a MIM waveguide with baffle and an individual SSCRR resonator. The transmission profile of an isolated MIM waveguide with a baffle Figure 3 (Bleu line) corresponds to the broadband continuous spectrum, which has a negative slope and a low transmittance. The transmission profile of the individual SSCRR resonator (red line) has two narrow transmission dips, hence, we consider this as a narrowband discrete state.

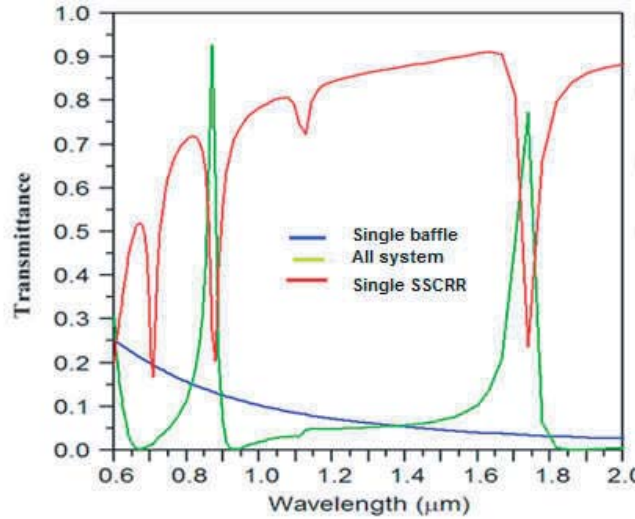


Figure 3. The FDTD simulation results. The transmission spectra of the single metal baffle, and coupled waveguide plasmonic structure, single ring resonator.

The two Fano resonances were excited by the MIM waveguide with a baffle mode interacting with the symmetric two modes of the SSCRR resonator.

The interference of the continuous spectrum (resonator) and the discrete spectrum (baffle which is the new resonator) results in an asymmetric Fano-like line (green line).

Figure 4(a) depicts the transmission spectra of the proposed structure, by increasing the refractive index from 1 to 1.08 in steps of 0.02. The increase in the refractive index led to a red-shift of resonance wavelengths of the transmitted spectra, with a larger shift in mode 2 than mode 1. Figures 4(b) and (c), show the linear relationships between the refractive index and the wavelength of modes 1 and 2.

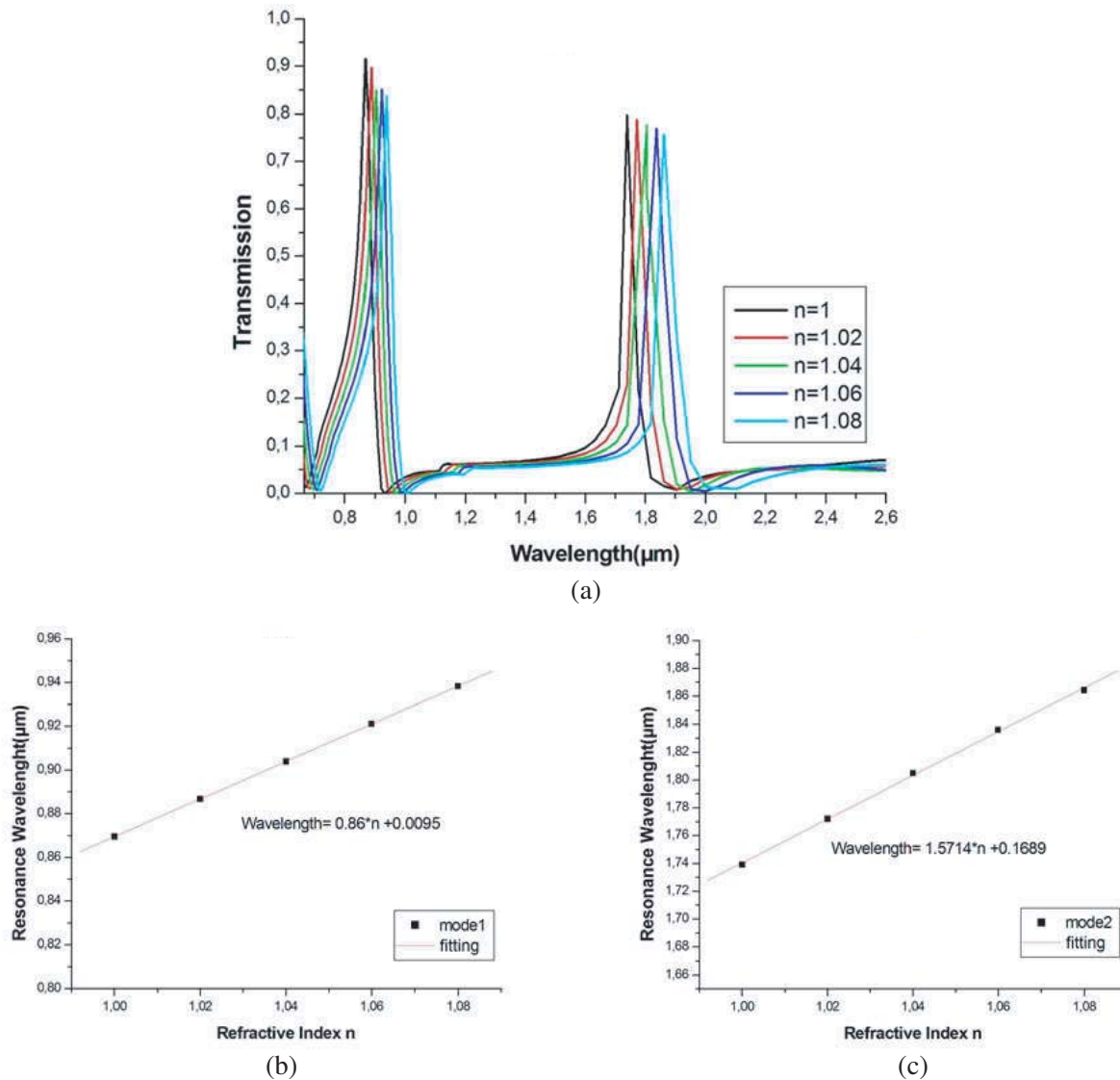


Figure 4. (a) The transmission spectrum of MIM sensor for different refractive index n . (b) The resonance wavelength versus the refractive index n of the material under sensing for mode 1. (c) The resonance wavelength versus the refractive index n of the material under sensing for mode 2.

For designing and analyzing the SPR based sensors, the sensitivity is a very important aspect, which can be calculated as $S = \Delta\lambda/\Delta n$ (nanometer per refractive index (nm/RIU)) [39], where $\Delta\lambda$ denotes the shifting rate of resonant peak wavelength of transmittance, and Δn represents the changing rate in the refraction index in the plasmonic sensor structure.

Keeping other parameters unchanged and increasing the refraction index from $n = 1$ to $n = 1.08$, the sensitivity for the first mode is around 860 nm/RIU and for the second mode is around 1571.4 nm/RIU. Subsequently, we will calculate and optimize the transmission and sensitivity of the SSCRR by adjusting the geometrical parameters of the racetrack cavity made by air, the intertwined distance X , and the length of the inserted metallic block Y .

At first, in order to study the effect of the difference X between the radii of two disks on the transmission characteristics, X is gradually increased from $X = 0$ to $X = 65$ nm ($X = 0, 20, 40, 60$, and 65 nm), and other parameters are fixed at $Y = 300$ nm and $n = 1$. Figure 6(a) shows the transmission spectra of the two modes for different values of X , where it can be noted that as the distance X

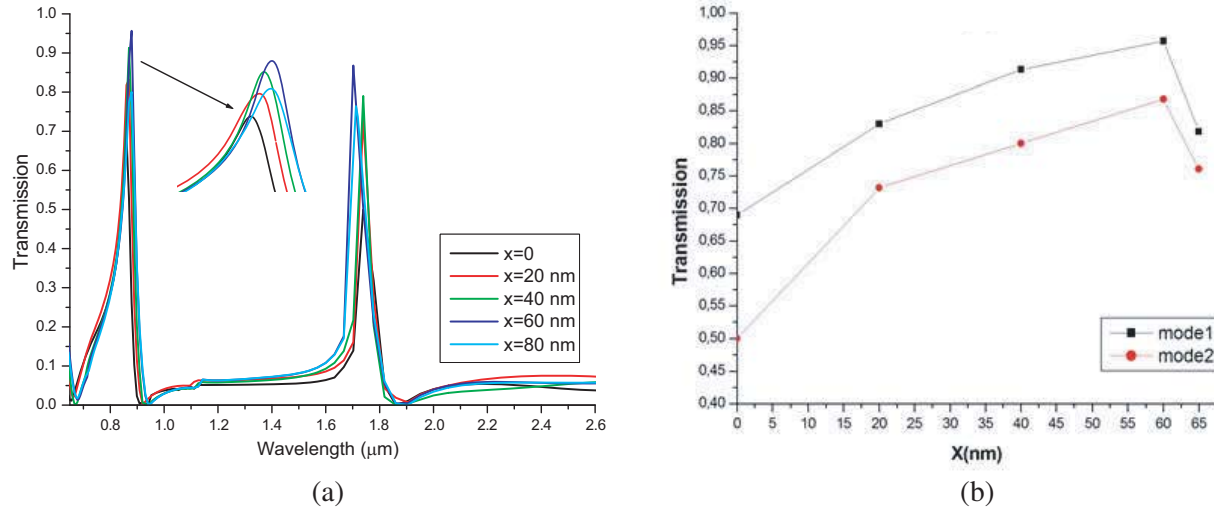


Figure 5. (a) Transmission spectra of MIM sensor for X varying from 0 to 65 nm. (b) The transmission versus the distance $X = 0, 20, 40, 60$ and 65 nm and $Y = 30$ nm of the two modes.

increases, the resonance wavelength exhibits a slight blue-shift, with an increase followed by a decrease in the transmission. From Figure 5(b), it is seen that when the distance X is increased and within the interval of 0–60 nm, the transmission level is enhanced, conversely to the case outside this interval, where the transmission level is decreased.

Racetrack resonator possesses characteristics of both rectangle and disk cavity. A rectangle resonator can support Fabry-Perot modes FPMs, and a disk resonator can have whispering-gallery modes WGMs [40]. Therefore, such a racetrack resonator possesses a hybrid characteristic of both rectangle and disk resonators via changing parameter X of the ellipse, and the resonant wavelengths of FPMs and WGMs can be independently tuned and close to each other.

The best transmission values of 0.95 and 0.86 were observed for mode 1 and mode 2, respectively, at $X = 60$ nm.

Secondly, in order to study the influence of the length of the inserted metallic block Y , on the position of the resonance wavelength, Y is gradually increased from $Y = 280$ nm to $Y = 360$ nm with an interval of 20 nm, and the other parameters are fixed at $X = 60$ nm and $n = 1$. Figure 5(a) illustrates the transmission spectra of MIM structure for different values of Y .

It is noted that the resonance wavelength increases with the increment in the value of Y (see Figure 6(a)), meaning that the change in Y causes a shift in resonance wavelength, and the shift for mode 2 is larger than that in mode 1. Figure 6(b) shows an approximately linear relationship in the resonance wavelengths of the two modes as a function of Y .

Third, we also study how the length of the inserted metallic block Y affects the sensitivity of the MIM sensor. The refractive index n is gradually increased from $n = 1$ to $n = 1.08$ nm in steps of 0.02 for different lengths of the inserted metallic block Y ($Y = 280$ nm to $Y = 360$). Figure 7(a) shows the linear relationship between the resonance wavelength and the refractive index for different values of Y for both mode 1 and mode 2.

Figure 7(b) depicts the sensitivity as a function of the length of the inserted metallic block Y . It is noted that an enhancement of the sensor's sensitivity is achieved by increasing the value of Y in the range of 280–340 nm. For mode 1, the sensitivity was 959 nm/RIU whereas in the case of mode 2, the sensitivity was 2380 nm/RIU.

With the wavelength detection resolution of $\Delta\lambda = 0.01$ nm, which is a high-resolution, optical spectrum analyzer can process it, the sensing resolution of the refractive index sensor, defined as $R = (dn/d\lambda)\Delta\lambda$ [41], will be 1.04×10^{-5} RIU for mode 1 and 4.20×10^{-6} RIU for mode 2, respectively corresponding to the value $Y = 340$ nm, in comparison to sensitivity of 840 nm/RIU for mode 1 and 1776.5 nm/RIU for mode 2 where the value of Y was 280 nm.

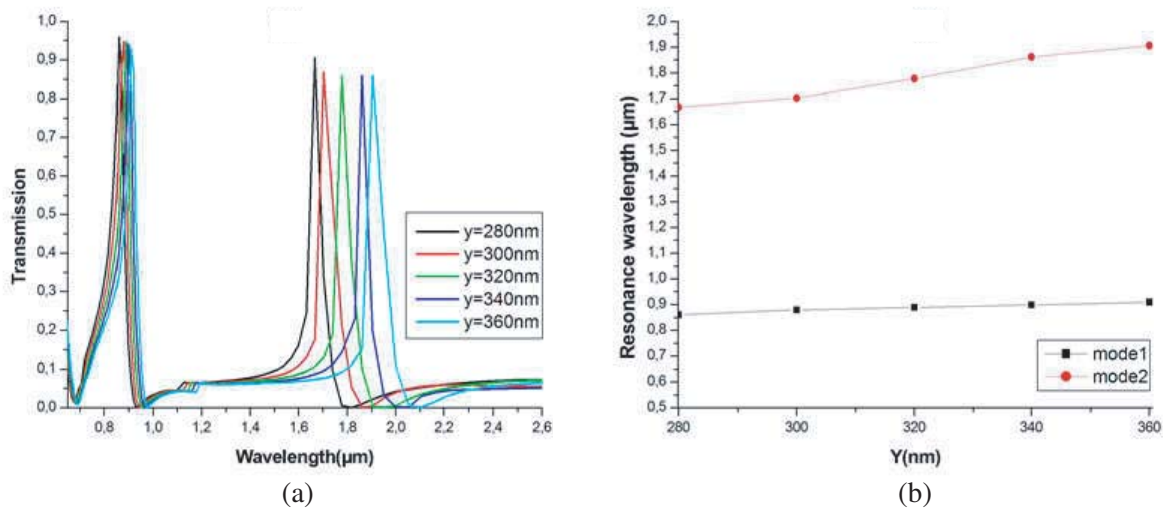


Figure 6. (a) Transmission spectra of MIM sensor for different lengths of the inserted metallic block Y . (b) Resonance wavelength as a function of the length of the inserted metallic block Y .

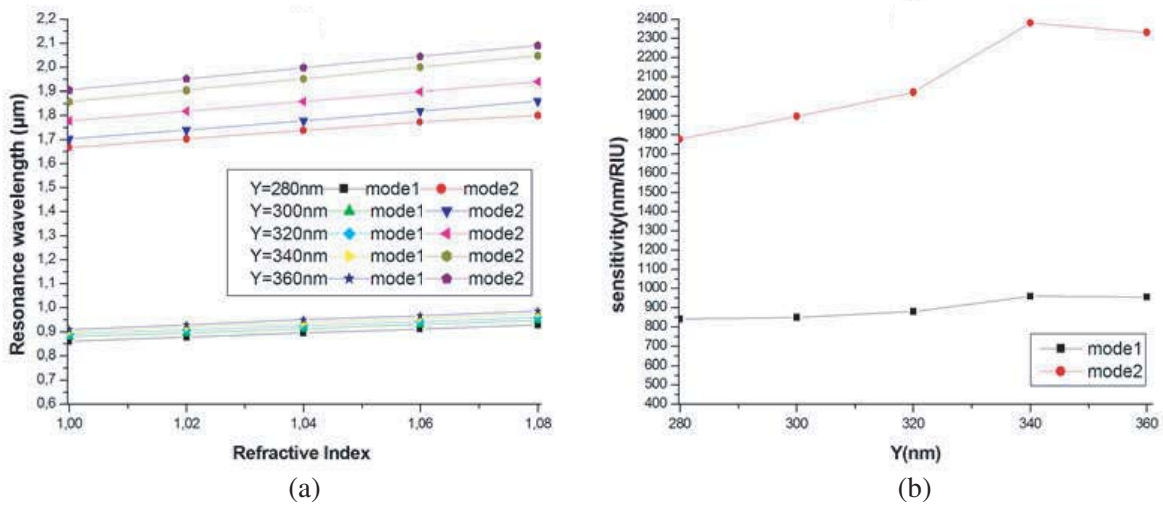


Figure 7. (a) The resonance wavelengths versus the refractive index for different Y . (b) Sensitivities of MIM sensors as a function of Y .

Table 1. Sensitivity comparison of different sensor structures.

Reference	Sensitivity (nm/RIU)	Year
[42]	1540 for mode 1 and 1010 for mode 2	2018
[30]	1060	2018
[31]	1114.3	2019
[26]	2602.5	2019
[25]	1700 for mode 2 and 900 for mode 1	2020
Our results	2380 for mode 2 and 959 for mode 1	2020

Table 1 compares the sensitivity (S) of our proposed structure to other MIM based plasmonic sensors in the literature.

4. CONCLUSION

A slotted side-coupled racetrack cavity for RI variation measurement was theoretically proposed and optimized. When the transmission sensitive characteristics of the structure are incorporated with the resonance characteristics of the cavity, the variation of RI could be theoretically obtained by monitoring the output resonance wavelength of the cavity. After optimizing the structural parameters of the proposed design, the proposed slotted side-coupled racetrack cavity sensor exhibited a high sensitivity of 959 nm/RIU and 2380 nm/RIU for mode 1 and mode 2. It was also demonstrated that the optimized cavity could be used in a large scale of RI measurements, making it a possible candidate for gas sensing applications.

ACKNOWLEDGMENT

This work was supported by the Algerian Ministry of Higher Education and Scientific Research and La Direction Générale de la Recherche Scientifique et du Développement Technologique (DGRSDT) via funding through the PRFU Project No. A25N01UN28012 0180001.

REFERENCES

1. Maier, S. A., *Plasmonics: Fundamentals and Applications*, Springer, Bath, UK, 2007.
2. Strobbia, P., E. R. Languirand, and B. M. Cullum, "Advances in plasmonic nanostructures for sensing: A review," *Optical Engineering*, Vol. 54, No. 10, 100902, 2015.
3. Aberasturi, D. J., A. B. Serrano-Montes, and L. M. Liz-Marzán, "Modern applications of plasmonic nanoparticles: From energy to health," *Advanced Optical Materials*, Vol. 3, No. 5, 602–617, May 2015.
4. Zarrabi, F. B. and M. N. Moghadasi, "Investigated the Fano resonance in the nano ring arrangement," *Optik*, Vol. 138, 80–86, 2017.
5. Giannini, V., A. I. Fernandez-Dominguez, S. C. Heck, and S. A. Maier, "Plasmonic nanoantennas: Fundamentals and their use in controlling the radiative properties of nano emitters," *Chem. Rev.*, Vol. 111, 3888–3912, 2011.
6. Pandesh, S., M. Maleki, and F. B. Zarrabi, "The sub-wavelength plasmonic nano-antenna based on cross structure," *Optik*, Vol. 127, 3770–3774, 2016.
7. Zarrabi, F. B., M. Naser-Moghadasi, S. Heydari, M. Maleki, and A. S. Arezomand, "Crossslot nano-antenna with graphene coat for bio-sensing application," *Optics Commun.*, Vol. 371, 34–39, 2016.
8. Barnes, W. L., A. Dereux, and T. W. Ebbesen, "Surface plasmon subwavelength optics," *Nature*, Vol. 424, 824–30, 2003.
9. Tang, B. J., J. C. Wang, X. S. Xia, X. Y. Liang, C. Song, and S. N. Qu, "Plasmonic induced transparency and unidirectional control based on the waveguide structure with quadrant ring resonators," *Appl. Phys. Express*, Vol. 8, No. 3, 032202, 2015.
10. Bana, X., X. Pang, X. Li, B. Hu, Y. Guo, and H. Zheng, "A nonlinear plasmonic waveguide based all-optical bidirectional switching," *Opt. Commun.*, Vol. 406, 124–127, 2017.
11. Gramotnev, D. and S. Bozhevolnyi, "Plasmonics beyond the diffraction limit," *Nat. Photonics*, Vol. 4, No. 83, 2010.
12. Zayats, A., I. Smolyaninov, and A. Maradudin, "Nano-optics of surface plasmon polaritons," *Physics Reports*, Vol. 408, Nos. 3–4, 131–314, 2005.
13. Barnes, W., W. Murray, J. Dintinger, E. Devaux, and T. Ebbesen, "Surface plasmon polaritons and their role in the enhanced transmission of light through periodic arrays of subwavelength holes in a metal film," *Physic Review Letters*, Vol. 92, 107401, 2004.

14. Chen, Z., H. Li, B. Li, Z. He, H. Xu, M. Zheng, and M. Zhao, "Tunable ultra-wide band-stop filter based on single-stub plasmonic-waveguide system," *Applied Physics Express*, Vol. 9, No. 10, 102002, 2016.
15. Zhan, G., R. Liang, H. Liang, J. Luo, and R. Zhao, "Asymmetric band-pass plasmonic nanodisk filter with mode inhibition and spectrally splitting capabilities," *Optics Express*, Vol. 22, No. 8, 9912–9919, 2014.
16. Yang, C., W. Shen, J. Zhou, X. Fang, D. Zhao, X. Zhang, C. Ji, B. Fang, Y. Zhang, X. Liu, and L. Gu, *Adv. Opt. Mater.*, Vol. 4, 1981, 2016.
17. Shi, L., J. He, C. Tan, Y. Liu, J. Hud, X. Wu, M. Chen, X. Zhang, and S. Zhan, "Plasmonic filter with highly selective wavelength in a fixed dimension based on the loaded rectangular ring cavity," *Optics Communications*, Vol. 439, 125–128, 2019.
18. Sun, W., Q. He, S. Sun, and L. Zhou, "High-efficiency surface plasmon meta-couplers: Concept and microwave-regime realizations," *Light: Science & Applications*, Vol. 5, e16003, 2016.
19. Huang, Y., C. Min, and G. Veronis, "Compact slit-based couplers for metal-dielectric-metal plasmonic waveguides," *Optics Express*, Vol. 20, No. 20, 22233–22244, 2012.
20. Hoessbacher, C., Y. Fedoryshyn, A. Emboras, A. Melikyan, M. Kohl, D. Hillerkuss, C. Hafner, and J. Leuthold, "The plasmonic memristor: A latching optical switch," *Optica*, Vol. 1, No. 4, 198–202, 2014.
21. Raza, S. and S. Bozhevolnyi, "Slow-light plasmonic metamaterial based on dressed-state analog of electromagnetically induced transparency," *Optics Letter*, Vol. 40, No. 18, 4253–4256, 2015.
22. Huang, Y., C. Min, P. Dastmalchi, and G. Veronis, "Slow-light enhanced subwavelength plasmonic waveguide refractive index sensors," *Optics Express*, Vol. 23, No. 11, 23, 14922–14936, 2015.
23. Gao, Y., S. Zhan, Q. Liu, and Y. Liu, "Controllable plasmonic sensing based on Fano resonance in a cavity coupled defective MDM waveguide," *Journal of Physics D: Applied Physics*, Vol. 49, 265109, 2016.
24. Im, H., H. Shao, Y. Park, V. Peterson, C. Castro, R. Weissleder, and H. Lee, "Label-free detection and molecular profiling of exosomes with a nano-plasmonic sensor," *Nat. Biotechnol.*, Vol. 32, No. 5, 490, 2014.
25. Yu, S., S. Wang, T. Zhao, and J. Yu, "Tunable plasmonic system based on a slotted side-coupled disk resonator and its multiple applications on chip-scale devices," *Optik — International Journal for Light and Electron Optics*, Vol. 212, 164748, 2020.
26. Ben Salah, H., A. Hocini, M. N. Temmar, and D. Khedrouche, "Design of mid infrared high sensitive metal-insulator-metal plasmonic sensor," *Chinese Journal of Physics*, Vol. 61, 86–97, 2019.
27. Zhang, Q., X. Huang, X. Lin, J. Tao, and X. Jin, "A subwavelength coupler-type MIM optical filter," *Optics Express*, Vol. 17, No. 16, 7549, 2009.
28. Wen, K., L. Yan, W. Pan, B. Luo, Z. Guo, Y. Guo, and X. Luo, "Electromagnetically induced transparency-like transmission in a compact side-coupled t-shaped resonator," *Journal of Lightwave Technology*, Vol. 32, No. 9, 1071–1707, 2014.
29. Yu, S., T. Zhao, J. Yu, and D. Pan, "Tuning multiple fano resonances for on-chip sensors in a plasmonic system," *Sensors*, Vol. 19, No. 7, 2019.
30. Zhang, Z., J. Yang, X. He, J. Zhang, J. Huang, D. Chen, and Y. Han, "Plasmonic refractive index sensor with high figure of merit based on concentric-rings resonator," *Sensors*, Vol. 18, 116, 2018.
31. Wang, M., M. Zhang, Y. Wang, R. Zhao, and S. Yan, "Fano resonance in an asymmetric MIM Waveguide structure and its application in a refractive index nanosensor," *Sensors*, Vol. 19, 791, 2019.
32. Hocini, A., H. Ben Salah, D. Khedrouche, and N. Melouk, "A high-sensitive sensor and band-stop filter based on intersected double ring resonators in metal-insulator-metal structure," *Opt. Quant. Electron.*, Vol. 52, 336, 2020.
33. Gai, H. F., J. Wang, and Q. Tian, "Modified debye model parameters of metals applicable for broadband calculations," *Appl. Opt.*, Vol. 46, No. 12, 2229–2233, 2007.
34. Johnson, P. B., "Optical constants of the noble metals," *Phys. Rev. B*, Vol. 6, 4370–4379, 1972.

35. Zhang, X., M. Shao, and X. Zeng, "High quality plasmonic sensors based on fano resonance created through cascading double asymmetric cavities," *Sensors*, Vol. 16, 1730, 2016.
36. Wei, P. K., Y. C. Huang, C. C. chieng, F. G. Tseng, and W. Fann, "Off angle illumination induced surface plasmon coupling in subwavelength metallic slits," *Opt. Express*, Vol. 13, No. 26, 10784–10794, 2005.
37. Zhang, Q., X. G. Huang, X. S. Lin, J. Tao, and X. P. Jin, "A subwave length coupler-type MIM optical filter," *Opt. Express*, Vol. 17, No. 9, 7549–7555, 2009.
38. Rsoft Design Group, FullWAVE, Inc., 200 Executive Blvd., Ossining, NY 10562.
39. Wu T., Y. Liu, Z. Yu, Y. Peng, C. Shu, and H. He, "The sensing characteristics of plasmonic waveguide with a single defect," *Optics Communications*, Vol. 323, 44–48, 2014.
40. Zhang, Z. et al., "A plasmonic ellipse resonator possessing hybrid modes for ultracompact chipscale application," *Phys. Scr.*, Vol. 94, 125511, 2019.
41. Dolatabady, A., et al., "A nanoscale refractive index sensor in two dimensional plasmonic waveguide with nanodisk resonator," *Optics Communications*, Vol. 300, 265–268, 2013.
42. Ghorbani, S., M. A. Dashti, and M. Jabbari, "Plasmonic nano-sensor based on metal dielectric-metal waveguide with the octagonal cavity ring," *Laser Physics*, Vol. 28, 066208, 2018.