Simple and Improved Plasmonic Sensor Configuration Established on Mim Waveguide for Enhanced Sensing Performance

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Abstract

Herein, two simple configurations of Fano resonance-based plasmonic sensors are proposed for temperature and biosensing applications. The device optimization and sensing performance are numerically investigated via two dimensional-finite element method (2D-FEM). The former configuration is quite simple and based on the side coupled circular cavity (SCCC) whereas in the latter the circular cavity is encapsulated in the ring separated by a small gap and is known as ring encapsulated circular cavity (RECC). For temperature sensing applications, polydimethylsiloxane (PDMS) is utilized as a thermal sensing medium in the circular cavity. The numerical analysis has revealed that the temperature sensitivity (S) of SCCC and RECC configuration is ~ -0.58 nm/ $^{\circ}\text{C}$ and -0.64 nm/ $^{\circ}\text{C}$, respectively. The figure of merit (FOM) is another important parameter to analyze the sensing performance which is around 8.6 and 1955.2 for SCCC and RECC configuration, respectively. The sensing capabilities of the biosensor designs are investigated by injecting dielectric materials of different refractive indices in the circular cavity ranges between 1.33 and 1.37. The S of the SCCC and RECC sensor configuration is around 1240 nm/RIU and 1350 nm/RIU, respectively with a FOM of 18.74 RIU $^{-1}$ and 691 RIU $^{-1}$. The RECC sensor configuration is considered to be straightforward with fewer fabrication complications and offers high sensing performance.

1. Introduction

Surface plasmon polaritons (SPPs) are electromagnetic (EM) waves that propagate over the metal-insulator interface and have an exponentially diminishing field [1, 2]. They have the prospective to advance highly integrated optical circuits because of their ability to transcend the diffraction limit of light. The two foremost sorts of SPP-based waveguide systems are insulator-metal-insulator (IMI) [3] and metal-insulator-metal (MIM) waveguide architectures [4]. A MIM waveguide's mode size can be decreased to a few tens of nanometers, making it an appealing candidate for nanoscale photonic devices. On the other hand, an IMI waveguide fails to do so. Plasmonic sensors have a compact footprint and strong sensing capabilities when compared to sensors established on other platforms for example silicon photonics or optical fiber [5]. SPP waveguide formations, mainly MIM waveguides, have fascinated a lot of consideration due to their ability to overcome the diffraction limit of light, with the expectation of comprehending exceedingly integrated optical circuits due to their small footprint, ease of integration, and good balance between light localization and transmission loss [6, 7]. Sensing is a hot topic among various fascinating applications, and several plasmonic sensor concepts established on MIM waveguides for refractive index (RI) and temperature sensing have been quantitatively explored and presented in recent years [8, 9, 10, 11, 6]. Moreover, several types of other plasmonic devices established on the MIM waveguide formation have also been proposed recently, including filters [12, 13], power splitters [14, 15], and light manipulation [16], among others.

Multiprocessor system-on-chip (MPSoC) has gotten a lot of consideration in recent years due to their improved performance in applications. Thermal sensitivity, which is an important characteristic of optical devices owing to the thermo-optic phenomena, is one of the potential problems affecting MPSoC

performance [17]. As a result, monitoring processor temperature is critical for analyzing and protecting MPSoCs. Plasmonic sensors established on SPP might be a good option for this. Moreover, RI sensors offer a wide range of applications in the biochemical field and have been extensively explored in recent years for detecting solution concentration and pH value [18, 19].

The interference between a discrete state and a large continuum state causes Fano resonance, which has a sharp asymmetric line shape and a high figure of merit (FOM) in measurements [20]. Due to its advantages qualities such as asymmetric line shape, great confinement to the nanometer scale, and strong EM field augmentation, plasmonic devices established on Fano resonance are predicted to be very sensitive sensors when compared to symmetric Lorentzian characteristic line-shape [21]. It is simple to reduce the levels of transmittance spectrum from peak to trough. This transmittance spectrum's full wide at half maximum (FWHM) is rather narrow, making it easy to identify and follow, resulting in a considerable increase in sensing resolution. Due to the valuable characteristics of the Fano resonance, a group of scientists has recently utilized Fano resonance for temperature and biosensing, where the sensing performance is dependent on a sharper spectral configuration, which results in a higher FOM, allowing for higher accuracy and robust measurement [22, 23].

In this paper, we proposed two configurations of Fano resonance plasmonic sensors established on the MIM waveguide. There are no unusual geometric elements in the sensor design, such as stubs [24] or nanodots [25, 26], which might cause several resonance peaks/dips and complicate the manufacturing process. In the first configuration, the bus waveguide is side coupled to a circular cavity known as a side coupled circular cavity (SCCC), whereas, in the second configuration, the ring encapsulated circular cavity (RECC) is discussed. Both the plasmonic sensor designs are examined for temperature and biosensing applications. The spectral characteristic and sensing performance of the plasmonic sensor established on RECC configuration shows dominance over the plasmonic sensor established on SCCC configuration.

2. Sensor Designs, Optimization And Discussion

In this paper, two configurations of Fano resonance plasmonic sensors are discussed which can be employed for temperature and biosensing applications. The first configuration is quite simple where the bus waveguide is side coupled to a circular cavity with a gap g as revealed in Fig. 1a. MIM waveguide is composed of a dielectric material ($n=1.0$, air) sandwiched between metal clad on both sides. The width of the bus waveguide is denoted as W and is specified at 50 nm for both designs throughout the paper. The radius of the circular cavity is signified as R . In the second sensor design, the circular cavity is encapsulated in the ring and is connected to a bus waveguide as revealed in Fig. 1b. The width of the ring and bus waveguide is symbolized as W and is maintained at 50 nm. The gap g is maintained between the circular cavity and the ring. The spectral characteristics of both the devices are studied via the 2D finite element method (2D-FEM) by utilizing COMSOL Multiphysics software.

Metals or metal-like materials with negative real permittivity are known as plasmonic materials. Gold (Au) and silver (Ag) are the most prevalent plasmonic materials. Many other materials, on the other hand, have

metal-like optical characteristics in particular wavelength ranges. Because of its oxidation resistance and biocompatibility, Au is employed as a plasmonic material in this study. The Drude-Lorentz dispersion model defines the relative dielectric constant of Au:

$$\epsilon = \epsilon_{\infty} - \frac{\omega_p^2}{\omega^2 + j\omega\gamma}$$

1
,

Where $\epsilon_{\infty} = 9.0685$, $\omega_p = 135.44 \times 10^{14} \text{ rad/s}$, and $\gamma = 1.15 \times 10^{14} \text{ rad/s}$ [27]. The TM-polarized plane wave is coupled at the input port whereas the output is collected at the output port of the bus waveguide. A MIM waveguide's fundamental mode is an even mode with a TM-polarization. Consequently, an SPP mode is excited, which travels along with the metal-dielectric interface and couples to the designated cavity when the resonance state is fulfilled. The fundamental mode's dispersion relationship is as follows:

$$\frac{\epsilon_i p}{\epsilon_m k} = \frac{1 - e^{kW}}{1 + e^{kW}}$$

2
,

$$k = k_o \sqrt{\left(\frac{\beta_{SPP}}{k_o}\right)^2 - \epsilon_i}, p = k_o \sqrt{\left(\frac{\beta_{SPP}}{k_o}\right)^2 - \epsilon_m} \quad (3)$$

$$\beta_{SPP} = n_{eff} k_o = n_{eff} \frac{2\pi}{\lambda}$$

4
,

Where W , λ , ϵ_i and ϵ_m denoted the width of the bus waveguide, an incident wavelength of light in vacuum, the relative dielectric, and metal permittivity, respectively. $n_{eff} \beta_{SPP}$ and $k_o = \frac{2\pi}{\lambda}$ are the effective index, the propagation constant of SPPs, and the wavenumber, respectively. To get realistic simulation solutions within the available computing resources, the subdomains in the proposed device are divided into a triangular mesh element with a grid size of $\lambda/45$. Prototyping a domain with open bounds, that is, a peripheral of the computational region over which an EM wave may travel without reflection is beneficial for tackling the EM wave challenges. At the outside bounds of the FEM simulation window, scattering boundary conditions (SBCs) are used to estimate an open geometry. Most of the prior plasmonic sensor research studies used 2D numerical simulations, in which one dimension is treated as

infinite [7, 15, 26]. This allows for a faster processing time and lesser loss when analyzing sensor performance, which is also the case in this study. The height of the MIM waveguide, on the other hand, has a substantial impact on the system's loss, which should be considered in practical processing [28].

3. Potential As A Temperature Sensor

MIM plasmonic waveguide devices paired with thermal sensing mediums for instance ethanol, toluene, chloroform or PDMS have recently been revealed to be effective for temperature sensing applications [25]. In this work, we have considered PDMS as a thermal sensing medium that is deposited in a circular cavity. PDMS is a siloxane-family mineral-organic polymer. Silicone is a polymeric organosilicon compound can be employed in diverse applications. The most extensively used organic polymer is PDMS, which is composed of silicone. Transparency throughout a wide wavelength range, a RI lower than fused silica, high elasto-optic and thermo-optic coefficients, biocompatibility, and minimum absorption loss are only a few of its distinguishing characteristics. It has an excellent mechanical property because of its low Young's modulus; it is soft and elastic. What's more, from the perspective of mass production, the manufacturing method must be both cost-effective and straightforward. The temperature-related fluctuation in the RI of the PDMS layer may be stated as follows [8].

$$n_{\text{PDMS}}(T) = 1.4176 - 4.5 \times 10^{-4} \cdot T,$$

5

Where T is the surrounding temperature. PDMS can be deposited in the cavity of the plasmonic sensor for temperature sensing application [29]. The RI of the material changes with the slight variation in the surrounding temperature resulting in the shift (red or blue) in the resonant wavelength. Here, both sensor configurations are analyzed to obtain the best sensing performance which contains two important factors such as sensitivity (*S*) and the figure of merit (*FOM*) [30].

$$S = \frac{\Delta \lambda}{\Delta T}$$

6

where $\Delta \lambda$ is the variation in resonance wavelength and ΔT is the variation in the surrounding temperature. *FOM* is another important measure that may be used to describe a sensor's performance. It is established on intensity variation, unlike sensitivity described in terms of spectral shift, and maybe characterized as:

$$FOM = \frac{\Delta T_r}{T_r \cdot \Delta n},$$

7

where T_r signifies the transmittance of the sensor and $\Delta T_r/\Delta n$ denotes the transmission variation caused by a RI variation at a particular wavelength. *FOM* is commonly used to evaluate and compare different plasmonic sensors from a sensing standpoint. Fano resonances are a technique for improving *FOM* by lowering the spectral width (FWHM) of a plasmonic feature [31].

3.1. Optimization of SCCC configuration

SCCC configuration is quite simple and possesses two vital variables (g and R) which need to be optimized for the finest spectral characteristics. In the first step, the gap (g) between the bus waveguide and the circular cavity is specified at 10 nm whereas R is varied between 300 nm and 350 nm. The transmission spectrum is plotted for the wavelength range of 1500 nm to 2000 nm with a step size of 0.2 nm. For that purpose, the “parametric sweep” built-in function is used. From Fig. 2a, it can be seen that resonance dip (λ_{dip}) in the shape of Fano resonance is obtained which undergoes a redshift as R increases from 300 nm to 350 nm. This analysis helps in predicting the position of λ_{dip} in the case of ± 10 nm of fabrication error that can occur during the manufacturing process.

The gap (g) between the bus waveguide and the resonator cavity plays an important role in obtaining an optimum coupling power. Therefore, an optimized value of g is required to avoid under coupling of the resonant wavelength. In this analysis, R is specified at 325 nm and g is varied between 10 nm and 30 nm with a step size of 5 nm. From Fig. 2b, it can be noticed that the coupling power at the resonance wavelength increases as g decreases from 30 nm to 10 nm which appears in the form of a strong dip in the transmission spectrum. Fig. 2 (a, b) provides the guideline for the selection of optimized geometric variables resulting in the finest spectral characteristics. Furthermore, it can be used for analyzing the sensing performance of the device.

The norm. H-field mapping in the SCCC configuration at off-resonance and on-resonance state is revealed in Fig. 3a and Fig. 3b, respectively. The optimized geometric variables ($g=10$ nm, $R=325$ nm) obtained from figure 2 has been utilized in this plot.

To analyze the sensing capabilities of the plasmonic sensor, the temperature of the surrounding medium is varied between 20 °C and 80 °C. We have selected the reference temperature at 20 °C considering the standard laboratory temperature. The optimized geometric variables such as g and R are maintained at 10 nm and 325 nm, respectively. From Fig. 4a, it can be seen that λ_{dip} executes a blueshift as the surrounding temperature increases from 20 °C to 80 °C. The blueshift in wavelength is related to the decrease in the RI of the PDMS layer as the temperature increases. The RI of the PDMS layer dependence on the surrounding temperature is revealed in Table 1. The variation in the resonance wavelength ($\Delta\lambda$) concerning the surrounding temperature is plotted in Fig. 4b. It can be seen that there is a linear increase in λ_{dip} offering an $S = -0.58$ nm/°C.

Table 1
RI of PDMS layer dependence on the surrounding temperature.

Temperature (°C)	20	30	40	50	60	70	80
n_{PDMS}	1.4086	1.4041	1.3996	1.3951	1.3906	1.3861	1.3816

3.2. Optimization of RECC configuration

RECC configuration contains a circular cavity filled with PDMS enclosed in the ring. The radius of the circular cavity is signified as R . The cavity is separated from a ring with a minor gap (g) and the bus waveguide connects the ring on one side whereas the output is obtained from the other side of the ring. In the first step, the gap (g) between the ring and the circular cavity is specified at 15 nm whereas R is varied between 300 nm and 350 nm with a step size of 5 nm. The transmission spectrum is plotted for the wavelength range of 1500 nm to 2100 nm with a step size of 0.2 nm. For that purpose, the “parametric sweep” built-in function is used. From Fig. 5a, it can be seen that resonance dip (λ_{dip}) in the shape of Fano resonance is obtained which accomplishes a redshift as R surges from 300 nm to 350 nm. The gap (g) between the ring and the circular resonator cavity plays an important role in obtaining an optimum coupling power. Therefore, an optimized value of g is required to avoid under coupling of the resonant wavelength. In this analysis, R is specified at 325 nm and g is varied between 15 nm and 35 nm with a step size of 5 nm. From Fig. 5b, it can be noticed that the coupling power at the resonance wavelength increases as g decreases from 35 nm to 15 nm which appears in the form of a strong dip in the transmission spectrum.

The norm. H-field mapping in the RECC configuration at off-resonance and on-resonance states is displayed in Fig. 6a and Fig. 6b, respectively. The improved geometric variables ($g=15$ nm, $R=325$ nm) obtained from Fig. 5 has been used in this plot.

The sensing capabilities of the plasmonic sensor established on RECC configuration is analyzed by varying the temperature of the surrounding medium between 20 °C and 80 °C. The optimized geometric variables such as g and R are maintained at 15 nm and 325 nm, respectively. From Fig. 7a, it can be seen that λ_{dip} undergoes a blueshift as the surrounding temperature increases from 20 °C to 80 °C. The blueshift in wavelength is related to the decrease in the RI of the PDMS layer as the temperature increases. The variation in the resonance wavelength ($\Delta\lambda$) concerning the surrounding temperature is plotted in Fig. 7b. It can be seen that there is a linear increase in λ_{dip} offering an $S = -0.64$ nm/°C which is higher than the one offered by the plasmonic sensor established on SCCC configuration. Moreover, the FOM of the RECC configuration is extremely high ~ 1955.2 RIU⁻¹ which is due to the deep and narrow FWHM of the Fano resonance. Table 2 provides a general comparison of the sensing performance of the proposed sensors models with the previously available sensor designs.

Table 2
Proposed temperature sensor performance comparison with literature.

Sensor design	$S(\text{nm}/^{\circ}\text{C})$	FOM (RIU^{-1})	Sensing material	Design complexity	Ref.
Dual symmetric coupled hexagonal cavities	-0.45	-	Not defined	low	[32]
Asymmetric ellipse resonators	-3.64	-	Ethanol	high	[33]
Defective oval resonator	-0.44/-0.94/-1.282/-2.46	2.27×10^4	Ethanol	high	[23]
Connected concentric double rings resonator	-1.48	56.6	Ethanol	high	[34]
Semi-square ring	-4	269	PDMS	low	[35]
Double resonator cavities	-0.36	-	Ethanol	low	[36]
Modified Bragg grating	-0.47	-	PDMS	low	[29]
SCCC	-0.58	8.6	PDMS	low	This work
RECC	-0.64	1955.2	PDMS	low	This work

4. Potential As A Biosensor

Unlike conventional biosensors established on the silicon-on-insulator platform [37], Fano resonance-based biosensors are highly sensitive and compact. The schematic of the proposed biosensor designs is revealed in Fig. 8 (a, b). Instead of depositing a PDMS (for temperature sensing application), the circular cavity is filled with the material under sensing (MUS) for biosensing application. All the remaining geometric variables of the sensors are the same as used in the previous section. To fill the cavity with MUS, a nano-filling approach established on capillary attraction can be used [38]. Both the sensor design configurations are analyzed for the RI range of 1.33-1.37 with a step size of 0.005 which corresponds to the biological range.

The transmission spectrum of SCCC and RECC is revealed in Fig. 9a and 9b, respectively. The optimized geometric variables are utilized in both cases where maximum extinction ratio (ER) is obtained calculated by means of the subsequent expression:

$$ER(\text{dB}) = 10 \times \log \left(\frac{P_{out}}{P_{in}} \right),$$

Where P_{out} and P_{in} are the power collected at the output and power inserted at the input of the bus waveguide, respectively. The ER of SCCC and RECC configuration at $n=1.33$ is -3.21 dB and -13.87 dB, respectively. It can be seen that λ_{dip} undergoes a redshift as the surrounding RI increases from 1.33 to 1.37. The H-field distribution in the SCCC and RECC at the on-resonance and off-resonance state is revealed in the inset of Fig. 9a and 9b, respectively. It is well noted that the resonance wavelength of the RECC configuration has quite a narrow FWHM compared to the SCCC configuration. The variation in resonance wavelength concerning the surrounding RI for both the sensor configurations shows a linear trend as plotted in Fig. 9c. The S and FOM of the SCCC configuration are 1240 nm/RIU and 18.74 RIU⁻¹, respectively. Where the RECC configuration shows dominance in both S and FOM which is around 1350 nm/RIU and 691 RIU⁻¹, respectively. Table 3 listed the sensing performance of previously proposed biosensor designs which suggest that the RECC configuration-based biosensor shows dominance in terms of S and FOM .

Table 3
Proposed biosensor performance comparison with literature.

Sensor design	S (nm/RIU)	FOM (RIU ⁻¹)	Reference
Stub resonators loaded with metallic slits	1060 ↓	176.7 ↓	[39]
Circular ring	800 ↓	37 ↓	[40]
Concentric rings	1060 ↓	203.8 ↓	[41]
Square convex ring resonator	1120 ↓	2.68x10 ⁵ ↑	[4]
Q-resonator	2260 ↑	211.42 ↓	[10]
Semi ring resonator	1260.5 ↓	41.67 ↓	[42]
Elliptical resonator	550 ↓	282.5 ↓	[43]
Concentric double ring resonator	2260 ↑	56.5 ↓	[34]
Symmetric MIM waveguide formation	1268 ↓	280 ↓	[44]
SCCC configuration	1240	18.74	This work
RECC configuration	1350	691	This work

5. Conclusion

In this paper, two straightforward configurations of Fano resonance-based plasmonic sensors are numerically investigated via 2D-FEM. In the first configuration, the circular cavity is side coupled to a bus waveguide and is known as a side coupled circular cavity (SCCC). Whereas in the second configuration, the circular cavity is encapsulated in the ring with a small gap between them. The straight waveguide is connected to the ring providing input and output port. This configuration is expressed as ring encapsulated circular cavity (RECC). The geometric variables of both sensor designs are optimized for

best sensing performance. The sensor designs are employed for two important applications such as temperature and biosensing. For temperature sensing applications, a thermal sensing material, PDMS can be deposited in a circular cavity. The thermal sensitivity of $-0.58 \text{ nm}/^{\circ}\text{C}$ and $-0.64 \text{ nm}/^{\circ}\text{C}$ is obtained for the plasmonic sensor established on SCCC and RECC configuration, respectively. Moreover, the RI sensitivity of $1240 \text{ nm}/\text{RIU}$ and $1350 \text{ nm}/\text{RIU}$ is obtained for the plasmonic sensor established on SCCC and RECC configuration, respectively. Due to the strong coupling of EM waves in the cavity, the RECC configuration offers a Fano resonance with high extinction ratio resulting in a higher *FOM* than the one offered by SCCC. The numerical study shows the dominance of plasmonic sensors established on RECC configuration on the side coupled-cavity design.

Declarations

Author's contribution. We declare the equal contribution from all the authors.

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Data Availability. The data that support the findings of this study are available from the corresponding author upon reasonable request.

Ethics Approval. There is no ethical approval required. "Not applicable."

Consent to Participate. Informed consent was obtained from all individual participants included in the study. Not applicable.

Consent for Publication. Authors are responsible for the correctness of the statements provided in the manuscript.

Conflict of Interest. The authors declare no competing interests.

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Figures

Figure 1

Schematic representation of plasmonic temperature sensor established on MIM waveguide, a) SCCC, b) RECC.

Figure 2

Geometric optimization of a SCCC, a) Transmission spectrum versus R , b) Transmission spectrum versus g .

Normalized H-field distribution

Figure 3

Norm. H-field mapping in the SCCC configuration at, a) off-resonance state ($\lambda=1731.2$ nm), b) on-resonance state ($\lambda=1775.6$ nm).

Figure 4

Spectral characteristics of a plasmonic sensor, a) transmission spectrum versus different surrounding temperature, b) variation in resonance wavelength plot versus different surrounding temperature.

Figure 5

Geometric optimization of a RECC, a) Transmission spectrum versus R , b) Transmission spectrum versus g .

Figure 6

Norm. H-field mapping in the RECC configuration at, a) off-resonance state, b) on-resonance state.

Figure 7

Spectral characteristics of RECC sensor configuration, a) transmission spectrum versus different surrounding temperature, b) variation in resonance wavelength plot versus different surrounding temperature.

Figure 8

Schematic representation of Fano resonance biosensor established on MIM waveguide, a) SCCC, b) RECC.

Figure 9

Analysis of biosensing performance, a) Transmission spectrum of SCCC configuration, b) Transmission spectrum of RECC configuration, c) $\Delta\lambda$ versus n .