Metallic nano rods loaded plasmonics resonator for improved sensing performance

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A compact and highly sensitive refractive index sensor based on square metallic nano-rods loaded Plasmonics resonator is proposed. Due to the presence of nano-rods in the resonator, the resonance is red shifted. Thus, offering a quite simple way for resonance shifting without any significant increase in the footprint. Based on this fascinating behavior, the proposed structure is tested for the sensing application. The high value of sensitivity $S = 1470\ \mathrm{nm}$ per refractive index unit is obtained, which can be further improved by incorporating Dual Resonators with Nano-Metallic Rods (DRMNR). Due to interaction between both nano-rods embedded resonators, the symmetrical nature of resonance is altered and an asymmetrical resonance profile is emerged known as Fano resonance. Two narrow peaks with line-width = 8 nm and 17 nm respectively, are observed in resonance profile. DRMNR offers a high value of sensitivity ($S = 1840\ \mathrm{nm/RIU}$) and Figure of Merit (FOM=220) which are good measures of sensing performance. Therefore, the device paves the way to be integrated as an on-chip optical sensor for detecting bio-molecule and chemical gases.

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1. Introduction

The optical signals are prone to the famous law of diffraction and thus, the signals can't be confined below the prescribed limit which hampers its viability in nano-technology [1]. Plasmonics is a new chip-scale technology, which works in synchronous with nano-technology [2-3]. It is related to the confinement of optical signals at the sub-wavelength scale. The advent of this technology has tremendous applications in bio-medical, environmental monitoring, food safety, and many more. Plasmonics deals with the interaction of Electromagnetic waves and the free electrons available at the interface of dielectric/metallic surfaces [2-3]. The related phenomenon is broadly categorized as Propagating surface plasmon (PSP) and Localized Surface Plasmons (LSP) [3-5]. The surface topology of the metallic structures defines the type of Surface plasmons excited [3-4]. In a recent surge of research, the role of Surface plasmons is inevitable in designing different optical components of sub-wavelength scale. PSP does support nano-scale confinement when special geometry of Metal-Insulator-Metal (MIM) is being used to confine the signal while this type of confinement is not apparent in IMI (Insulator-Metal-Insulator) structures [1,6]. Owing to this exciting feature, MIM waveguide is being used in designing different optical components like sensors [7,8], filters [9], gates [10] de-multiplexers [11], buffers [12], etc. It is worth noting that the resonance characteristics of the different optical devices depend on the geometrical parameters of the device and variation in the geometrical parameters tunes the resonance accordingly [12,13]. Reza et. al. also studied the effect of red shifting of resonance characteristics with increasing size of the resonator [14]. However, the increase in resonator size increases the footprint which is not at all desirable. Recently, a fascinating way of incorporating metallic nano-rods in a resonator is reported to tune the resonance characteristics of the plasmonic resonator without any change in the size of resonator [15]. The related phenomenon is being inherited from the resonance tuning in the microstrip patch [16]. The resonance characteristics can be further shaped by changing the radius of circular metallic rods [15,16]. In case, if square metallic rods are used in place of circular rods, then the resonance can be tuned based on two parameters (i.e. width and length of nano-rods).

Here, in this article, square metallic nano-rods are being used in resonator to study the effect of resonance tuning based on both parameters. Besides, the proposed device is also tested for its application in sensing. It is worth noticing that the sensing performance of the devices is also increased without an increase in footprint. The coupled effect of propagating and localized plasmons enhances the sensitivity. The structure is also modified to dual resonators with nano-metallic rods (DRNMR) for further improvement in sensitivity (i.e. S= 1840 nm/ RIU). However, the obtained value of sensitivity is not so high as compared to sensitivity reported in state of art MIM based sensors [17-24] but the Figure of Merit of the proposed sensor is quite high (FOM=220) which is a performance measure for an ideal sensor.

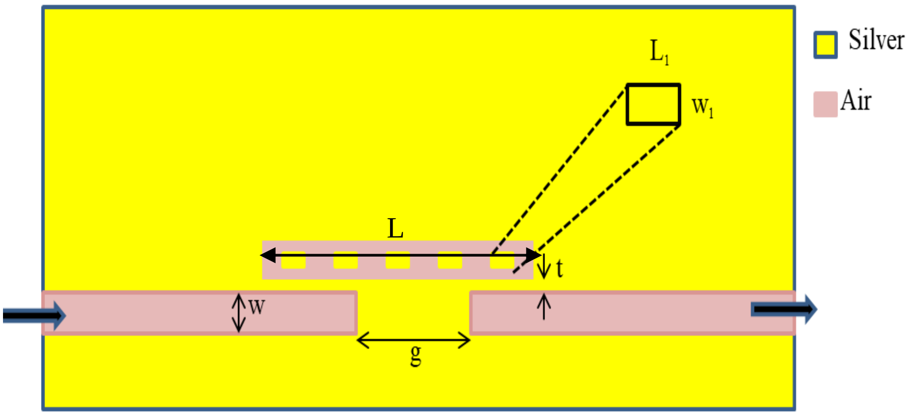


Fig. 1. Schematic of MIM waveguide side coupled resonator and the resonator is loaded with metallic nano-rods. The geometrical parameters are as follows: w is the width of resonators and MIM waveguide, g is the separation between both the bus MIM waveguide, t is the separation between resonator and MIM waveguide, L is the length of resonator, L1= length of nano-rods, w1= width of nano-rods (w=50 nm, L=410 nm, g=150 nm, t=10 nm, L1=20 nm, w1=35 nm (color online)

2. Design of MIM waveguide coupled resonators

Fig. 1 illustrates the schematic of the plasmonics resonator loaded with metallic nano rods. The rectangular resonator is side-coupled to the MIM waveguide. The metallic portion of the MIM waveguide is chosen as silver while the insulating material is air. The selection of silver as a metal is based on its better optical properties as compared to other noble metals [12-14]. The optical properties of Silver are defined using drude model [12-14]. The geometrical parameters of the proposed structure are mentioned in the Fig. 1 caption. The parameters are so selected to have resonance in the desired frequency band. The resonance wavelength can be determined as discussed in ref. [24]. The resonant wavelength depends on the phase shift of SPP induced in the round trip in resonating structure, effective refractive index of the structure and length of the resonator. The tuning of resonance can be easily attained by changing the resonator length. Thus resonant wavelength can be red shifted with increased length of resonators. However, a unique phenomenon of resonance tuning has been reported recently [15-16]. The application of nanorods in the resonator shifts the resonance condition to red wavelength. This adds an extra degree of freedom in the sub-wavelength plasmonic structure to further reduce the footprint of the devices in order to pave the way in the designing of photonic integrated circuits (PICs).

Therefore, rectangular nano-metallic rods are used in the resonating structure and the effect of resonance tuning is being studied for different sizes of rods. The focused-ion-beam milling, electron-beam lithography, or nano-imprint lithography techniques can be employed to easily create structures with features of order 20 nm [25]. Gaseous diffusion or capillary attraction methods can be used to fill the sensing region with material under test [26, 27]. The detailed discussion is presented in next section

3. Results and discussions

The structure is numerically investigated using Finite difference Time domain (FDTD) method using optiFDTD tool with the following simulation parameters: Mesh size $\Delta z = \Delta x = 5$ nm is the step size in spatial domain; Δt is the time step and is selected as per Courant condition: $c\Delta t < \frac{1}{\sqrt{(\Delta x)^2+(\Delta y)^2}}$ [13], the boundary condition is Advanced Perfectly Matched (APM) layer, 2-dimensional simulation environment is being selected in order to maintain simplicity and fast computation. The incidence of TM polarized plane wave in the waveguide leads to excitation of SP mode along the interface between the insulating layer and metal. In the absence of metallic nano-rods, the proposed device acts as a simple plasmonic band-stop filter and the resonance tuning is obtained by tailoring the size of the resonator (as discussed in equation 1). Fig. 2 (solid line) shows the transmission spectrum of the signal being trapped in the resonator while fig. 2 (Dash line) depicts the behavior of the proposed resonator coupled to rectangular nano-rods. The red-shifting of resonance is being observed in the presence of nano-rods. The underlying physics behind this tuning can be easily understood using the field distribution of the structure as shown in Fig. 3. Fundamental mode is excited in the resonator (absence of nano-rods) as the width of resonator and MIM waveguide is the same($w = 50\ nm$). The field is illustrated at λ = 1510 nm. In the presence of nano-rods, the transmittance and field is nearly zero at λ = 1510 nm as the resonance is shifted to higher wavelength (λ = 1550 nm). The incoming signal is confined in the resonator. The rectangular nano-rods provide an extra degree of freedom to tune the resonance characteristics. The resonance characteristics can be controlled by varying width and length of resonator. Fig. 4 shows the effect of variation in width and length on the resonance characteristics. The maximum width of the metallic rod is maintained to l_1=0.32 nm as the linear red shifting is maintained up to this value. Further increment in l_1 of the metallic rod enhances the near field interaction between the rods and resonance profile is not such symmetric. Due to this near field interaction between two nano-rods higher order modes are excited.

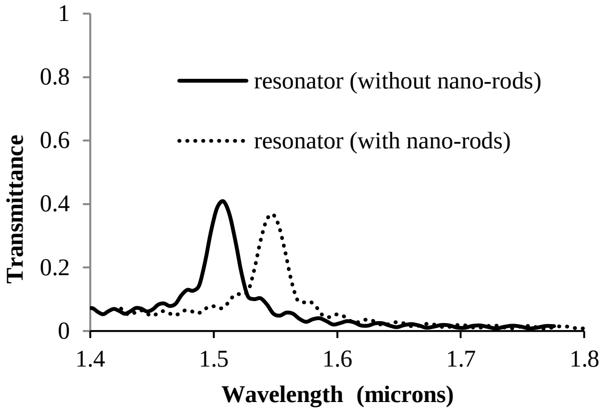


Fig. 2. Resonance characteristics of proposed device with/without nano-rods

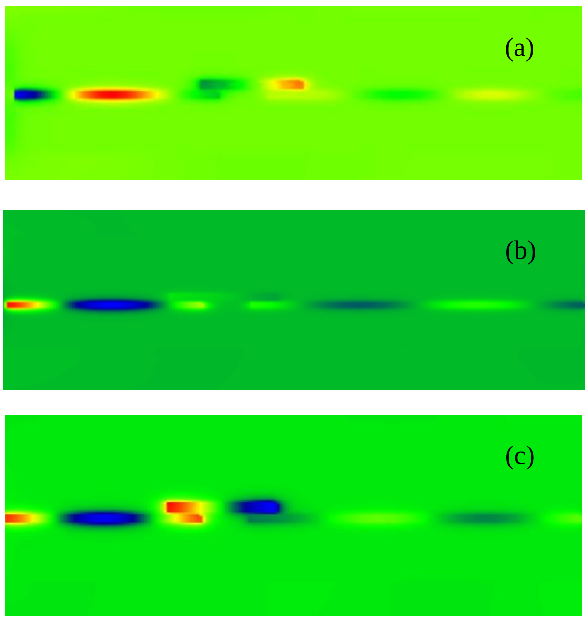
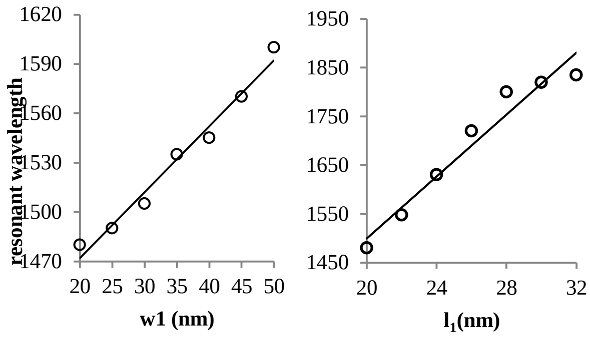


Fig. 3. Magnetic field intensity of proposed structure a) in the absence of nano-rods at λ = 1510 nm b) in the presence of nano-rods at λ = 1510 nm c) in the presence of nano-rods at λ = 1550 nm (color online)



a) b)

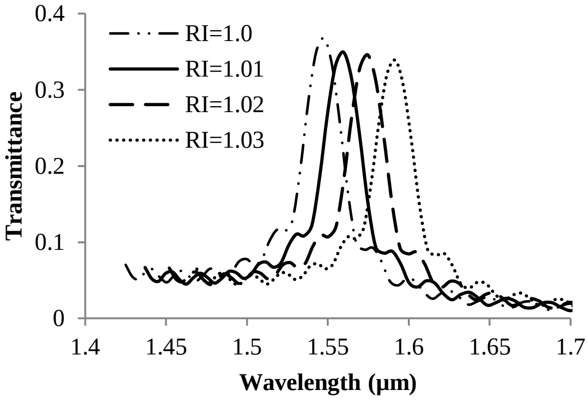
Fig. 4. Variation of Resonant wavelength as a function of a) width of nano-rods while keeping L1=20 nm and b) length of resonator while keeping w1=25 nm

The performance of the device can be measured by Quality Factor which is defined as $Q = \frac{\Delta\lambda}{\lambda_0}$ [24]. It measures the selectivity of the device, where $\Delta\lambda$ is Full width at Half Maxima (FWHM) or line-width and λ_0 is the resonant wavelength. $\Delta\lambda = 30$ nm, $\lambda_0 = 1540$ nm is obtained for given structure. The quality factor is $Q \approx 51$. The line-width of the resonance profile decreases with changing size of metallic nano-rods but this is not quite significant. The device offers good value of quality factor without any significant increase in footprint which makes it viable in designing on-chip optical devices and also in the field of bio-medical and chemical industries for point of care units. As it is well known that the sensing performance of the plasmonic devices depends on light-matter interaction [2, 3]. The light-matter interaction is the function of length of resonators. Therefore the demand for improvement in sensitivity leads to increased footprint. But, the proposed structure may be used for improvement in sensitivity without any rise in footprint which is discussed in the next section.

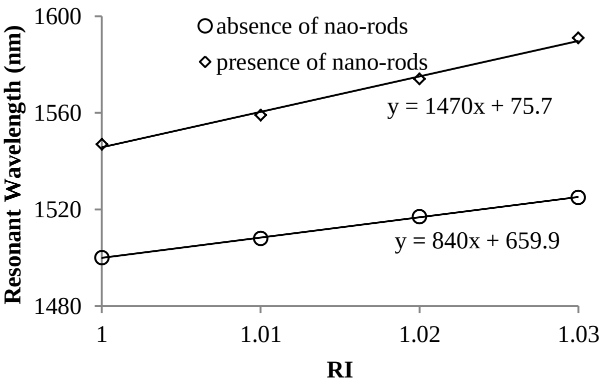
4. Application as sensor

The proposed structure is tested for its sensing performance. The resonator is initially filled with material whose refractive index is known. Any change in the refractive index leads to a shift in resonance condition. The change in the resonance condition is calibrated in terms of change in refractive index and thus, the principle can be utilized in detection of any unknown material. Fig. 5 shows the transmission spectrum when the refractive index is being increased from RI=1 to 1.03. The resonance is red shifted for increasing value of refractive index. The MIM waveguide coupled resonator is aided with the surface plasmonics phenomenon and the reflected spectrum depends on the surrounding conditions of the Metal-Insulator interface. When the refractive index of the surrounding medium is increased, the resonance is red shifted. Sensitivity is the performance measuring parameter for the sensor. It is defined as the change in the resonance condition for change in the refractive index unit

(RIU) i.e. $S = \frac{\Delta\lambda}{\Delta n}$ [7,8]. The sensitivity for the proposed waveguide geometry (in the absence of nano- rods) is obtained as 840 nm/RIU while the sensitivity (in the presence of nano- rod) is 1470 nm/RIU. Fig. 5(b) shows the comparative analysis of sensor (in the presence/ absence of nano rods). The slope of the curve defines the sensitivity. The sensor-1 (resonator with nano rods) is more sensitive to change in RI as compared to sensor-2 (resonator without nano rods).



a)



b)

Fig. 5. a) Transmission spectrum for variation in RI from 1.0 to 1.03 b) Resonant wavelength for variation in RI in the presence and absence of nano-rods

The high value of sensitivity obtained in the presence of nano-rods is attributed to the fact that two phenomena (Propagating Surface Plasmons (PSP) and Localised Surface Plasmons (LSP)) are acting simultaneously and both effects are quite sensitive to change in surrounding environment. However, the resonance of PSP and LSP does not coincide but localized plasmons shows so pronounced dependency on any change in surrounding that it affects the resonance characteristics of PSP too. While, in the absence of nano-rods, only PSP is active to affect the resonance characteristics due to change in surrounding condition. Therefore, high value of sensitivity is obtained with the proposed waveguide geometry (resonator coupled with metallic nano rods) without increase in footprint.

Besides sensitivity, FOM (Figure of Merit) is one more important parameter to analyze the performance of a sensor. It is defined as $FOM = \frac{S}{\Delta\lambda}$ [7]. FOM is related to the quality factor of the device. FWHM is 27 nm for resonant wavelength (λ=1540 nm) and FOM is measured approximately 54.5. The sensitivity of the device can be further improved by incorporating Dual Resonators with Metallic Nano-rods (DRMNR) as shown in Fig. 6.

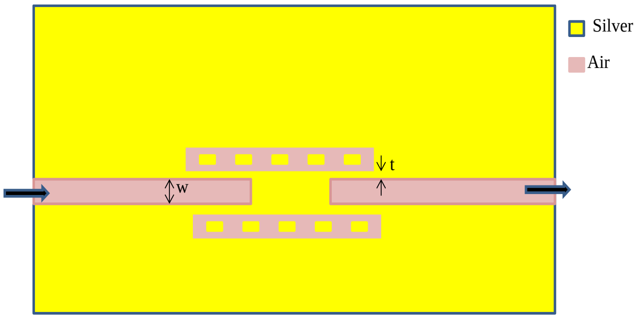
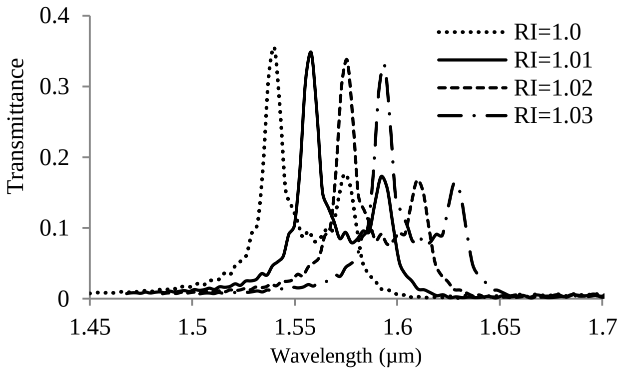
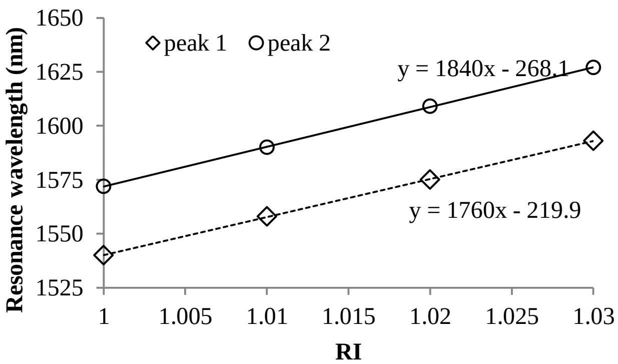


Fig. 6. Dual resonator coupled metallic Nano-rods (DRMNR) with the same geometrical parameters as mentioned in Fig. 1 (color online)



a)



b)

Fig. 7. (a) Resonance characteristics of the DRMNR for variation in RI (refractive index) from 1.0 to 1.03, b) Resonant wavelength for both peaks of resonance

Due to the interaction between the dual resonators, the surface plasmons polaritons excited at both the interface interact and interfere in such a manner that the symmetrical resonance profile is changed and the asymmetrical profile emerges as depicted in Fig. 7. This asymmetrical resonance profile is called Fano resonance. Two resonance peaks appear in the resonance profile. Both the peaks show different sensing behavior. The sensing performance (sensitivity) of both peaks is compared in Fig. 7(b). The refractive index sensitivities of Fano profile peak 1 and peak 2 is 1760 nm/RIU and 1840 nm/RIU respectively. FWHM of peak1 and peak 2 is 8 nm and 17.5 nm respectively. The FOM for peaks 1 and 2 of this Fano profile is also computed and listed in Table 1. This Table also shows the comparative analysis of state of art sensors and proposed work. Although the sensitivity of the proposed sensor is not as good as compared to state of art sensors, but the FOM and Q is quite high which claims its viability in designing on-chip optical sensors. The proposed design is based on the sensing the shift in the resonance condition for change in the refractive index of material under test (MUT). However the RI of MUT is varied in the steps of 0.01 units (i.e. from 1.0 to 1.01, 1.02, and so on) to detect the change or shift in resonance condition, the same concept can be extended to detect the change in the RI of any unknown material or any other physical quantity. For e.g. the concentration of hemoglobin in human blood is refractive index dependent and the proposed sensor can be efficiently utilized to check the human health to detect anemic condition [7]. However, obtaining precise and accurate measurements of refractive index is a difficult operation that necessitates accurate calibration of the sensing device. The response of the sensor can be correlated with the refractive index of the target medium using calibration techniques. Monitoring the plasmonic response in relation to solution concentration and temperature can be used to calibrate the device [32].

Table 1. Comparative analysis of Sensitivity, Q and FOM of proposed and state of art sensors

References	S	Q	FOM
[17]	3400	42.28	36
[18]	2320	-	-
[19]	1160	73	62
[20]	1295	-	159.6
[21]	1500	-	75
[22]	700	-	21.9
[23]	907	-	-
[28]	725.1		91.78
[29]	948.67		-
[30]	718.6		156.217
[31]	-		108.36
Proposed work	1840	192.5	220

5. Conclusion

A new design of plasmonic MIM waveguide coupled resonator is proposed and investigated numerically for sensing application. The resonator is loaded with rectangular metallic nano-rods and therefore offers extra degrees of freedom to control the resonance tuning without any change in footprint. The sensitivity obtained is S=1470 nm/RIU, which is quite high as compared with sensitivity (S=840 nm/RIU) achieved in the absence of nano-rods. The enhancement in sensitivity is attributed to the fact that in the presence of metallic nano-rods loaded resonator, both propagating and localized plasmons are working in parallel and thus the dependence of resonance condition is more pronounced on changing refractive index of the resonator. The sensitivity is further improved by incorporating Dual Resonators with Metallic Nano-rods (DRMNR) and high value of sensitivity (S=1840 nm/RIU), FOM=220 and Q=192.5 is attained. The high value of Sensitivity, FOM and Quality factor indicate that the proposed structure can be used to develop on-chip optical sensors.

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