Highly Sensitive Plasmonic Refractive Index Sensor with Large Figure of Merit

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Abstract: **We propose ultra compact Plasmonics based refractive Index sensor. The sensor structure includes a MIM (Metal-Insulator-Metal) waveguide, a pair of rectangular stub and a pair of taper. Two corresponding structures are simulated using Finite difference time domain (FDTD) method of opti-FDTD tool. The sensitivity of the structures is compared and it is concluded that increasing sensing area increases the sensitivity accordingly. The principle of sensing is based on estimation of refractive index by calculating shift in resonance. The stub and taper both are filled with material having unknown refractive index.**

Keywords-**Plasmonics, Metal-Insulator-Metal, Finite difference time domain method,sensitivity.**

1. INTRODUCTION

In the last few years optical sensors specifically refractive index sensors have been the topic of research due to its application in variety of sensing area viz. temperature sensing [1], pressure sensing [2], gas concentration sensing [3]. Refractive index sensor works on resonance phenomenon in which index change is estimated by calculating the shift in wavelength (deliberately induced initially). High quality factor and high sensitivity is normally demanded for efficient performance of sensors. The optical sensors are designed using different photonic crystal waveguide [4], optical fiber [5] and, optical cavities but recent development in the field of Plasmonics has revolutionized refractive index sensor with extra small footprint area. Plasmonics is the field of nano-science that deals with the propagation of electromagnetic waves along the interface of two different materials having dielectric constant of opposite sign [6]. The most intriguing effect of Plasmonics is that it allows confining of light at sub-wavelength scale. Plasmonics is broadly categorized in propagating Plasmons and localized Plasmons. Plasmons are the quantum of Plasmonics as the photons are quantum of light. Propagating Plasmons are also known as Surface Plasmon Polaritons (SPPs). SPPs are the light waves that propagate tightly along the interface of metal and dielectric. It decays exponentially away from the interface [7]. The tight confinement of signal allows sub-λ confining of signal which proves to be quite beneficial in designing optical sensors with ultra small footprint area. Multiple interface geometry of SPP known as MIM (Metal-Insulator-Metal) waveguide geometry supports true sub-λ confinement. Signal can be trapped in the area far beyond the diffraction limit. MIM waveguide can be used to design filters [8], optical demultiplexers [9], optical buffers [10], optical routers [11] etc. So, Sensing principal can also be obtained using these structures with small footprint area. Recently, Shen et. al. proposed a Plasmonic sensor with large sensitivity 1050 nm/RIU [12]. Zafar et. al. has also worked on fano resonance based Plasmonic sensor with large sensitivity and Quality factor[13]. It is reported that the sensing characteristics depends on the geometrical parameters or structures, and tailoring the parameter changes sensitivity accordingly [11,13].

In this paper we have designed and simulated an ultra compact RI sensor in which taper and rectangular waveguide or stub is used and the effect of enhanced sensitivity is studied for change in geometrical structure. The variation in temperature sensitivity is also reported. So, the proposed design opens an opportunity to be used in on-chip optical sensors.

2. DEVICE STRUCTURE AND THEORETICAL ANALYSIS

The structure shown in fig.1 is used to investigate the refractive index sensing characteristics. The MIM waveguide geometry of SPP is being used to analyze sensor. The metal used is Silver. The metal acquires somewhat dielectric nature in the Tera-hertz regime and attains dielectric character at ultra-violet frequencies [6]. So, the metal is characterized using frequency dependent dielectric constant which is given by drude model [6]. The drude model is obtained using the given relation:

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

All the constants have their specific values for specific metal [14]. The insulating material of MIM waveguide is initially set as n=1 (air) which is varied to sense the change in resonance condition. The MIM waveguide is directly coupled to rectangular stub and taper as shown in Fig 1 (a). The stub and taper is also coupled to both the side of MIM waveguide as depicted in Fig 1(b). The width of MIM waveguide and resonator is same w=50 nm. The resonators are made from the combination of rectangular and taper waveguide. 'h' is the height of rectangular stub and 'l' is the height of taper, 1(2) is used for upper and lower resonators respectively. The details of the geometrical parameter are as listed in table 1.

Table 1: Geometrical parameters for proposed structures

Fig 1(a)	Fig 1(b)
w= 50 nm	w= 50 nm
h_1 = 300nm	h_1 = 300nm
l_1 = 300nm	h_2 = 300nm
	l_1 = 300nm
	l_2 = 300nm

TM (transverse-Magnetic) field of SPPs are launched which is Gaussian modulated laser source centered at λ=1550 nm.

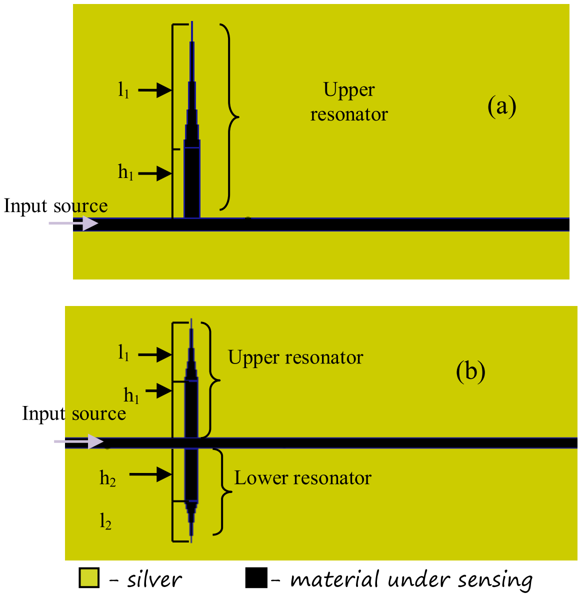

Fig.1. Structure schematics (a) a linear waveguide with single stub and taper w is the width of linear waveguide and h1, l1 are the height of rectangular stub and taper (b)a linear waveguide two stub and taper. w is the width of linear waveguide, h1,h2 are height of upper and lower rectangular stub and l1,l2 are height of upper and lower taper respectively.

3. SIMULATION RESULT

The 2D-FDTD (Finite Difference in Time domain) method of opti-FDTD tool is being used for analysis of structure numerically. The structure is tested for sensing characteristics under the specific resonance. The refractive index of unknown material is measured by detecting change in resonance condition. The resonance condition specifically depends on structural and material properties. When the optical property of material i.e. refractive index is varied, resonance shifts accordingly. The resonance is depicted by dip in the transmission spectrum as shown in Fig.2. It explains the effect of shift in resonance for 0.1 unit in RI. The refractive index sensitivity is calculated by the ratio of change in resonance condition and change in refractive index as depicted by formula given below [13]:-

$$S = \Delta\lambda/\Delta n \qquad (2)$$

The refractive index of taper and stub is incremented in 0.1 RI units. This is the step size for RI and the shift in resonance is measured. Figure.2 shows the effect of red shifting of resonance with increasing RI of resonators.

The sensitivity is measured equal to 1240 nm/RIU for structure (as shown in fig 1(a)), while it increases to 1440 nm/RIU (for structure 1(b)). The effect of increased sensitivity is depicted in Fig 3.

The increased sensitivity is inclined to the structure coupled to MIM waveguide with lower and upper resonators due to the fact that sensing area is increased.

The performance of sensor is also quantified by Figure of Merit (FOM) [10]. FOM is the ratio of sensitivity to half point bandwidth. Table:2 compares both the sensor for sensing performance.

Table 2: Comparative analysis of structures for Sensitivity and FOM.

Structure	Sensitivity	FOM
I	1240 nm/RIU	15.5
II	1440 nm/RIU	88

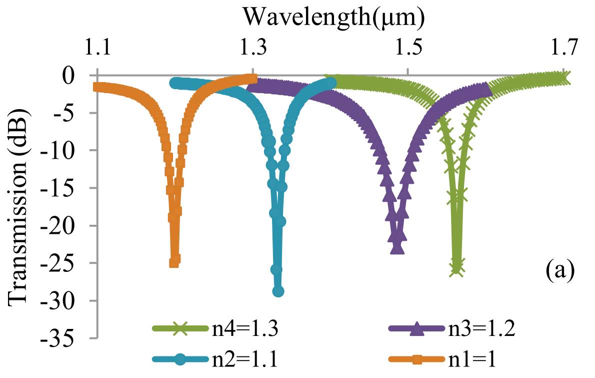

Fig. 2: The transmission spectrum of fig:1(a) structure for different refractive index for normalized value.

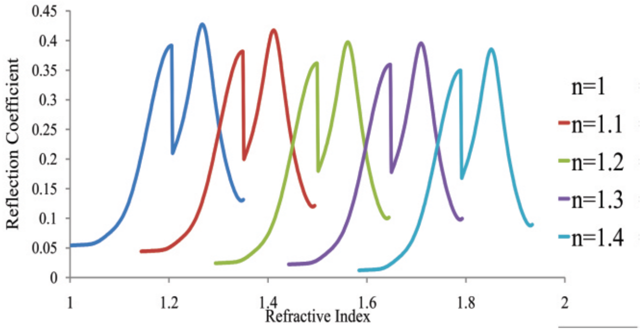

Fig. 3: Transmission spectrum of fig:1(b) proposed structures for changing different refractive index of material under sensing

The device is well suited for sensing different gas concentration, temperature variation and RI variation. The device offers small sensing area. So, it is viable for future on-chip sensing applications.

4. CONCLUSION

A new refractive index sensor is proposed which is based on combination of rectangular and taper resonator. Two different designs of proposed geometry are proposed and their performances are compared for sensitivity and FOM. The large FOM=19.2 is obtained for large Sensitivity.

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