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Enhanced Figure of Merit in Fano resonance based Plasmonic Refractive Index Sensor

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***Abstract*— Surface plasmon modes possesses an intriguing feature of confining light beyond diffraction limit which makes it very attractive for sensing applications. Here, we theoretically investigated an ultra compact surface Plasmon (SP) sensor using Metal-Insulator-Metal (MIM) waveguide geometry. MIM waveguide is coupled to a pair of stub resonators and both the stub resonators are loaded with a metallic nano slit of silver. The stubs and MIM waveguide are filled with liquid/ gaseous material which is to be sensed. The Fano resonance which is very sensitive to any change in refractive index of the material, is excited in the structure by breaking marginal symmetry. The Structure is numerically simulated by Finite Difference Time Domain (FDTD) method and the result shows that resonance wavelength has a linear relation with refractive index of the material under sensing. In the optimum design of proposed sensor, the maximum sensitivity is obtained as high as S= 1060 nm/RIU with large value of Figure of merit (FOM=176.7) and an ultra narrow linewidth $\Delta\lambda = 6\,nm$. Thus, the device is well suited for designing on- chip optical sensors.**

Keywords—Surface Plasmon, Metal-Insulator–Metal (MIM), Fano resonance, Finite Difference Time Domain (FDTD), Sensitivity, Figure of merit

I. INTRODUCTION

The application of an optical refractive index sensing has gained a high degree of interest to enable on-chip integration of optical circuits [1-2]. Optical sensors based on optical waveguides [3], directional couplers [4], micro-rings [5], and Mach–Zehnder interferometers [6] have been demonstrated recently. Recently, noble metal based nano-particles have been proposed as good candidates for increasing both sensitivity and on-chip integration because nano particles are more sensitive to change in the refractive index unit [7]. Both the Localized Surface Plasmons (LSPs) and Surface Plasmon Poalitons (SPPs) based resonance are used for designing label free and highly sensitive refractive index sensor, but SPPs based sensors possesses high sensitivity [8]. Surface plasmon polaritons (SPPs) are charged density waves that propagate along the surface of the conductor because of their resonant interaction with free electrons present on the surface of conductors [2]. The development of SPP technology in metallic waveguide structures has opened new possibilities to design an ultra-compact refractometer and have the potential to guide light at deep sub-wavelength [9]. This unique feature of subwavelength confinement helps to overcome the most of the limitation imposed in designing on-chip optical sensors. Recently Zeng et. al. has proposed a nanoplasmonic ring hole interferometric sensor to measure the change in refractive index within a single sensing spot [10]. Likewise, several authors have reported highly sensitive Metamaterials and Plasmonic devices based refractive index sensors [11,12]. Barik et. al. has experimentally demonstrated the concentration of biological analytes on the surface of gold nano hole array [13]. Some authors have targeted the achievement of high sensitivity with the application of Fano resonance [14]. Fano spectral lines are quite narrower as compared to regular Lorentzian lineshape. This unique feature makes them very much attractive for sensing applications [14,15]. Singh et. al. has achieved a sensitivity level of $5.7 \times 10^4\ nm/RIU$ with Q=28 in asymmetrical spilt ring metamaterial resonator structure by exciting Fano resonance [16]. A nano Plasmonic sensor employing Fano resonance in 1D nanogratings patterned on ultra thin Ag films offers the sensing resolution of $1.46\times 10^{-6}\ RIU$ [17]. Although, sensitivity is an important parameter of sensor to detect the shift in intensity/ phase against change in refractive index unit. But FOM (Figure of merit) is also a reliable parameter to measure the performance of the device [18]. FOM accounts the influence of peak width of the sensing performance. A number of nanostructures and sensing techniques have been studied to obtain the large value of FOM [17-20]. Yanik et.al. has reported a record high figure of merit (FOM=162) by exploiting extraordinary light transmission phenomenon through high quality factor (Q=200) subradiant dark modes [21]. A large value of FOM=146 is proposed by Gao. et. al. in a novel low-background interferometric sensing [22]. Jin et. al. has recently demonstrated a novel SPP sensor based on Metal-Insulator-Metal (MIM) waveguide which is ultracompact in dimension with a few hundreds of nanometers [23]. MIM waveguide coupled resonators are very much easy to fabricate as compared to an array of nano metallic elements.

Therefore, in this paper, we have explored a much simpler design based on MIM waveguide coupled stub resonators. Stub resonators are loaded with a nano metallic slit which are placed at the center of resonators. An asymmetry in the position of the nano slit is induced to excite the Fano resonance. This Fano resonance generates an ultra narrow resonance with large FOM (=176.7) and large value of sensitivity (S= 1060 nm/ RIU). Although the sensitivity is not so good, but the obtained value of FOM is quite large as compared to other sensing devices [19-24]. The large value of sensitivity and FOM achieved with the proposed device open up the avenues for designing real time on- chip optical sensors.

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II. DESIGN & THEORETICAL ANALYSIS

Fig 1(a) shows the 3 dimensional structure of proposed geometry, while Fig 1(b) and 1(c) show the cross sectional view of symmetric and asymmetric structure respectively. In fig 1(b) Metallic slit is located in the center of both the upper and lower resonators, while in fig 1(c) the position of the lower metallic slit is displaced from its center position (towards upper resonator). MIM waveguide is coupled to a pair of resonating stubs. The parameters of the proposed structure are as: h (=375 nm) is the height of lower and upper resonators. A, B represents position of input field and output

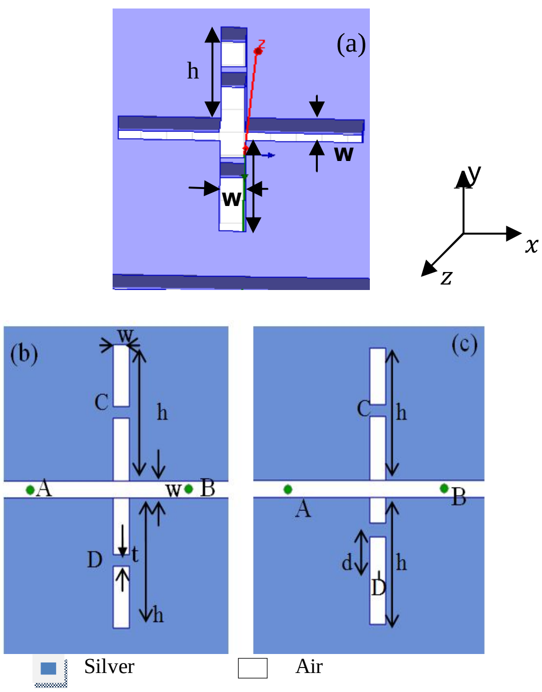

Fig 1: (a) 3 dimensional structure of proposed geometry b) cross sectional view of proposed geometry when nano slits are symmetrically positioned at the center (point C & D) of upper and lower resonators respectively c) cross sectional view of proposed geometry when lower slit is displaced from the center point D towards upper resonator by a factor of 'd'. The parameters of the structure are as follows: h= height of lower stub = height of upper stub, t is the thickness of metallic slit, w is the width of MIM waveguide and stub; 'A' & 'B' represents the observation point at input and output respectively.

observation point, Point C & D are the centers of upper and lower resonators respectively, the displacement factor of the lower slit from the center of the lower resonating stub is d, t (=10nm) is the thickness of metallic nano slit, the width of the MIM waveguide and stub is kept same (w=50nm) for efficient power transfer. The insulating layer on MIM waveguide and the stub is made of air medium (n=1), and it is surrounded by the metal (silver), whose frequency dependent relative permittivity is characterized by Drude model [25]:

$$\epsilon_m(\omega) = \epsilon_\infty - \frac{{\omega_p}^2}{\omega^2 + i\gamma\omega} \qquad (1)$$

where ϵ_∞ (=3.7) is the dielectric constant at infinite angular frequency, ω_p(=9.1 ev) is the bulk plasma frequency, and γ (= 0.018 ev) is the electron collision frequency and ω is the angular frequency of the incident wave in vacuum [24,25]. Silver is used here, because it offers the lowest loss among all metals at optical frequencies. The structure with width w larger than 20 nm can be easily fabricated with the technique of focused-ion-beam milling or electron-beam lithography or nano-imprint lithography [23,26]. The structure is proposed for highly sensitive refractive index sensors. Material to be sensed (liquid or gas) can be filled in waveguide and resonator by gaseous diffusion or capillary attraction [27,28]. Initially nano slit is symmetrically placed in both the upper and lower resonators (as shown in Fig 1 (b)). When the structure is excited by electromagnetic wave, normal Lorentzian resonance is excited and the reflection spectrum shows a peak at resonance. But, as the position of the lower nano slit is moved towards MIM waveguide (Fig 1(c)), an asymmetry is induced in the structure. Due to this marginal break in symmetry of structure, some special modes are allowed to propagate, which are usually considered to be forbidden in perfect structure [15, 29]. These especially excited modes are called Fano modes. The shape of Fano resonance is quite asymmetric as compared to conventional Lorentzian resonance. The broad Lorentzian mode is called bright mode, as it is highly radiative in nature, while the narrow Fano resonance is weakly coupled to radiation, so it is called dark

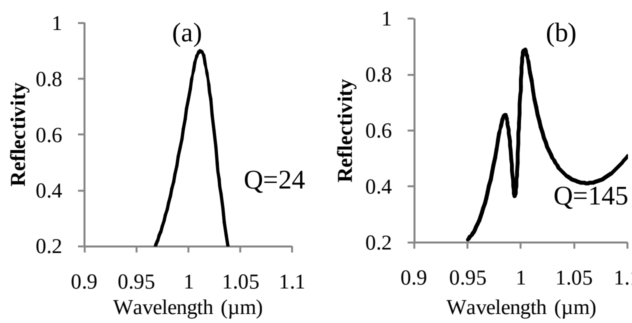

Fig 2: Reflection spectra of proposed geometry when a) nano slit is symmetrically positioned in both the upper and lower resonator b) nano slit in the lower resonator is displaced by 10 nm from the center as compared to upper slit.

mode. It is excited only when there is a break in symmetry [15,29]. An asymmetric Fano resonance is characterized by ultra high value of quality factor and it is very much sensitive to changes in geometrical parameters [15]. This unique feature of Fano resonance holds tremendous potential to be used in highly sensitive sensors. Any change in the refractive index of the material to be sensed, changes the resonance condition accordingly, which can be detected by the detector at point B (fig 1). In the next section, we have explored this structure as a sensor by changing the refractive index of material under test.

III. NUMERICAL SIMULATION, RESULTS AND DISCUSSION

A two dimensional FDTD method of optiFDTD tool is used to analyze the structure with a perfectly matched layer (PML) absorbing boundary condition in x and z direction. In the simulation domain, spatial step sizes in the x and z directions are chosen to be 2nm × 2nm and the time step is set as $c\Delta t \leq 1/\sqrt{(\Delta x)^{-2} + (\Delta z)^{-2}}$ [30]. Width of MIM waveguide and stubs is kept same for efficient power transfer. When a TM polarized plane wave is incident on the waveguide, Surface Plasmon mode propagates along the interface between the insulating layer and metal and allows the signal to be evanescently coupled to stub resonator. When the structure is

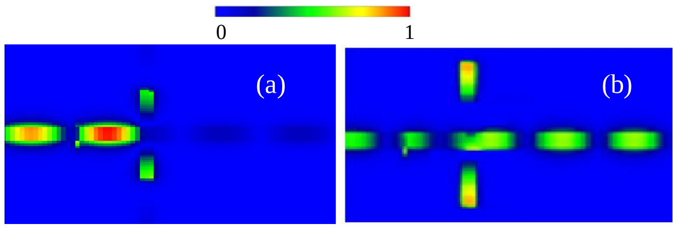

Fig 3: The magnetic field distribution of the geometry when a) nano slit is symmetrically positioned in both the upper and lower resonator b) nano slit in the lower resonator is displaced by 10 nm from the center as compared to upper slit.

symmetric as shown in fig 1(a), resonance is characterized by the minimum value of transmission at resonant wavelength, satisfying following condition [31]:

$$2k\,Re(n_{eff})L + \varphi_r = 2m\pi, \qquad m = 1,2,3, \dots .. \quad (2)$$

where $k = \frac{2\pi}{\lambda}$ is the free space wave vector, φ_r is the phase shift of a beam reflected on an insulator-metal interface at each end of the stub, m is the resonance order, L is the effective length of the stub, and $Re(n_{eff})$ is the real part of the refractive index that can be calculated from the dispersion relation of the TM mode in MIM waveguide [31]. This mode corresponds to a bright-broad mode. Fig 2(a) shows the reflection spectrum of structure (shown in fig 1) when nano slits are symmetrically aligned with respect to upper and lower stub resonator. The quality factor of the spectrum is calculated to be 24. But as the position of the lower nano-slit is displaced from the center of the lower stub (fig 1(b)), the symmetry of the structure breaks out. Fig 2(b) shows the reflection spectrum of structure when the lower nano slit is displaced from the center by an amount of 10nm. The quality factor of this Fano resonance is found to be 145, which is very much larger than conventional Lorentzian shaped resonance. Fig 3(a) & (b) describes the normalized electromagnetic field confinement H_y for symmetric structure (shown in fig 1(b)) and asymmetric structure (in fig 1(c)) respectively. It is clear that when the structure is symmetric, light gets trapped in the stub at resonance, and is escaped to be transmitted from bus waveguide. But with the marginal break in the symmetry, a new resonance window opens, which makes MIM waveguide transparent to input radiation. This transparency is shown in fig 2 (b) by ultra narrow asymmetric resonance, known as Fano Resonance. To utilize the structure as sensor, initially the refractive index of the material under sensing is assumed to have value n=1 which is linearly increased (in steps of 0.1). Fig 4(a) shows that the frequency of refelction spectra is red shifted and the dip in Fano resonance curve is observed for longer wavelength with an increase in refractive index of the material to be sensed. Two quantifying parameters are used to measure the performance of the sensor: Sensitivity and FOM (Figure of merit). Sensitivity (S) is defined as an amount of wavelength shift caused by a change in refractive index unit $\left(i.e.\, S = \frac{\Delta\lambda}{\Delta n}\right)$ [23,27], where Δn is a change in refractive index unit (RIU), and $\Delta\lambda$ is a change in wavelength. The FDTD simulation results show that for 0.1 change in the refractive index unit, wavelength shifts to approximately 106 nm. Therefore, the sensitivity of the proposed design is 1060 nm/RIU when there is a marginal break in the symmetry.

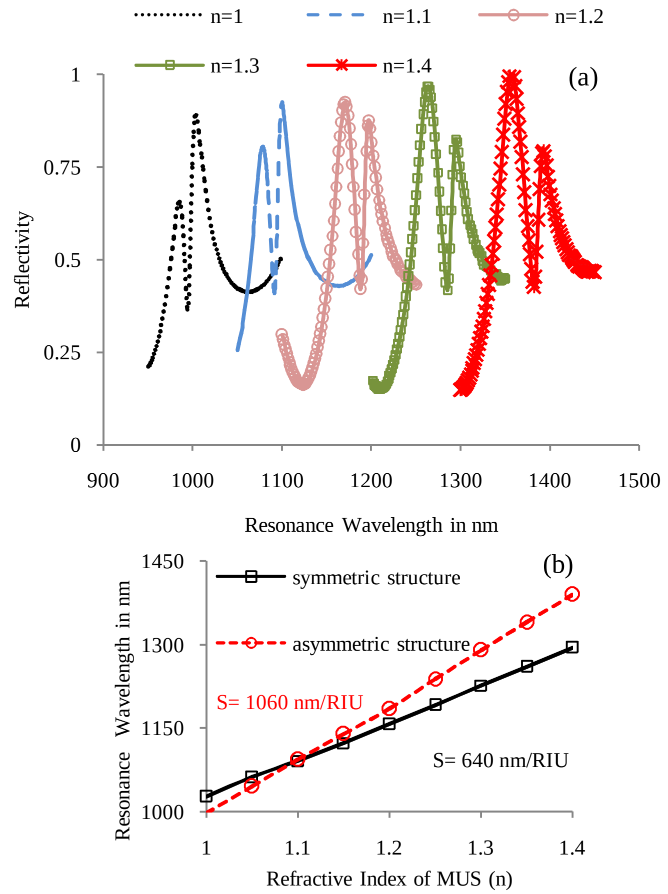

Fig 4 (a) Reflection spectrum for changing refractive index of material under sensing (MUS). b) Resonance wavelength as a function of refractive index of MUS for symmetric (black solid curve) and asymmetric (red dash curve) structure.

While the sensitivity of symmetric device (shown in fig 1 (b) is quite low (S=640nm/RIU) as compared with this asymmetric design. The difference between the sensitivity of both the device is described in fig 4 (b). Another important parameter which is used to quantify the performance of the sensor is Figure of merit (FOM). FOM is defined as the ratio of wavelength sensitivity to the 3 dB bandwidth of reflection spectrum and it is used to characterize performance of sensor [18,19]. Figure of merit (FOM) can be calculated as [18, 22]

$$FOM = \frac{S}{\Delta\lambda} \qquad (3)$$

Table 1: Comparison of FOM and quality factor reported in various Plasmonic sensor

Reference	Q	FOM
[10]	---	146
[19]	---	108
[20]	227	---
[21]	---	146
[22]	200	164
[24]	---	52.1
[34]	11.6	2.3

For the sensitivity of 1060 RIU/nm, FOM is found to be 176.7, for 6 nm of 3 dB FWHM (Full width at half maximum) bandwidth. Therefore, the proposed sensors not only provides large value of sensitivity (S=1060 nm/RIU), but also offers an ultra large value of FOM (= 176.7) with an ultra narrow linewidth $\Delta\lambda = 6$ nm. The obtained value of FOM is quite large as compared to value of FOM reported in other sensing devices [20-24]. Table 1 compares the FOM and quality factor for different sensors previously reported. The large value of sensitivity and FOM achieved with the proposed device open up the avenues for designing real time on- chip optical sensors.

IV. Conclusion

An ultra compact SPP sensor based on Metal-Insulator-Metal (MIM) waveguide is proposed. MIM waveguide is coupled to asymmetrical nano slit loaded stub resonators. Any change in refractive index of the material to be sensed leads to linear change in resonance condition. Due to a marginal break in the symmetry of the structure, special modes, known as Fano modes are excited. Fano resonance is characterized by ultra high value of quality factor and large FWHM. This unique feature of Fano resonance holds tremendous potential to be used in highly sensitive refractive index sensors. Any change in refractive index of the material to be sensed leads to variation in resonance condition. The result shows that resonance wavelength has a linear relation with refractive index of material under sensing. In the optimum design of proposed sensor, the maximum sensitivity is obtained as high as S= 1060 nm/RIU with large value of Figure of merit (FOM=176.7) and an ultra narrow linewidth $\Delta\lambda = 6$ nm. Therefore, proposed sensor with an ultra large value of sensitivity of refractive index can be used as a highly sensitive on chip optical sensor.

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