High Figure of Merit for Highly Sensitive Refractive Index Sensor Based on Metal-Insulator-Metal Plasmonic Bragg Grating

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Received 2 August 2015, received in revised form 31 August 2015, accepted 3 September 2015

Abstract: **We have theoretically studied and numerically analyzed Figure of Merit (FOM) of 95.86 for highly sensitive refractive index sensor based on plasmonic Bragg grating by using the finite difference time domain method (FDTD) under a perfectly matched layer absorbing boundary condition. MIM (Metal insulator metal) waveguide geometry is used with silver as metal whose frequency dependent permittivity is characterized by Drude model. Structure is analyzed by tailoring the defect length of the waveguide. We have achieved sensitivity of 624 nm for an unity change in refractive index unit.**

Keywords: **Plasmonic Sensor, Bragg Grating, Metal Insulator Metal, Drude Model, Refractive Index, Figure-of-Merit.**

1. INTRODUCTION

Being the measurement criteria of refractive index related to structural composition in a variety of environmental and chemical application, it acts as a key parameter in optical sensors. Waveguide Bragg grating is used as sensors in which Bragg wavelength can be modulated by the surrounding environments such as the temperature, force, strain and refractive index. Most common examples related to integrated optical sensors includes direct fiber-optic reflectometry, arrow waveguides and long period gratings [1-3].In the recent years, much interest has been shown by researchers in electromagnetic excitations propagating at metallic dielectric interface commonly known as Surface Plasmon Polaritons (SPP) are basically electromagnetic modes [1] which are bound to metal-dielectric interfaces, involving charges in the metal and electromagnetic fields in both media having ability to confine and guide electromagnetic waves in nanostructures at optical frequencies [4-9].

SPP waveguides are of two types: Insulator-Metal-Insulator (IMI)-type and Metal-Insulator-Metal (MIM)-type. IMI structures suffer greatly from their poor ability of confining light into subwavelength geometries [10] and thus have longer propagation length. On the other hand, MIM-type waveguides are the most efficient means for subwavelength manipulation of light with an acceptable propagation length [10]. An MIM waveguide is essentially a layer of insulator sandwiched between two layers of metal. Due to these unique features of MIM waveguides they can be utilized to realize nanoscale photonic functionality and circuitry [11]. Several limitations are there for the FBG based refractive index sensors. Due to the material used in waveguides, maximum surrounding refractive index to be measured must be below 1.45, else no waveguide modes will be supported during optical transmission. So, the refractive index sensing range is limited. Second, the relation between the Bragg wavelength of the FBG and the surrounding refractive index is not linear (the refractive index sensitivity increases with increasing surrounding refractive index).

To overcome above limitations, we have proposed and analyzed an SPP bragg grating formed by periodically varying length of cavity in insulator layer in the MIM waveguide. Proposed MIM waveguide is compact (several tens of nanometers in width and several micrometers in length) and high sensitive refractive index sensor based on the MIM plasmonic Bragg grating in which light is trapped in band gap of waveguide by creating nano cavity in insulator part of the waveguide. By varying refractive index of cavity, sensitivity and maximum FOM is obtained at length 0.5 nm of cavity. Optical characteristics structure is analysed by using the two dimensional (2D) finite difference time domain (FDTD) method.

2. DESIGN AND NUMERICAL RESULTS

In the MIM SPP waveguide, we assume the metal to be silver whose permittivity is characterized by the Drude model

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

Where, ε_∞ is the interband-transition contribution to the permittivity, ω_p the bulk plasma frequency, and $\gamma = 2.73 \times 10^{13}$ Hz and refractive index of insulator layer is taken as 1.0. Fig.1 shows the schematic MIM waveguide Bragg grating waveguide having width as 0.4 µm and length as 9.24 µm Metallic part of waveguide is taken silver (permittivity is set according to Drude model) and filled with dielectric air (whose refractive index is varied). Metal and insulator layer combination forms MIM Bragg Grating which works as filter. photonic band gap region is found at wavelength of Input light 1550 nm and defect in length is created in dielectric part of grating and optical properties of waveguide structure is analyzed using the two dimensional (2D) finite difference time domain (FDTD) method.

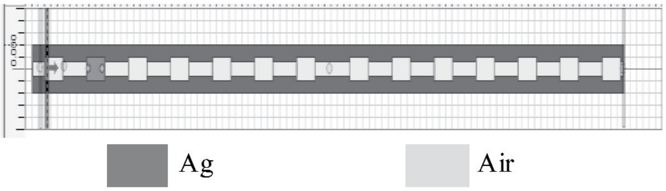

Fig 1: MIM waveguide Bragg grating with metal taken as silver (in blue colour) filled with dielectric (in green colour)

Sensitivity is defined as the ratio of change in wavelength to change in refractive index and measured in nm/RIU. Sensing in waveguide is done by detecting spectral shifts in peak positions for small changes in refractive index and half power beamwidth (HPBW) is calculated for finding Quality factor and Figure Of Merit. FOM is defined as the ratio of the wavelength sensitivity to the 3dB bandwidth of the transmission spectrum and often used to characterize the sensor performance and Quality factor is ratio of half power beamwidth (HPBW) to change in resonant wavelength.

3. RESULT AND DISCUSSIONS

Plasmonic Sensor is designed with input wavelength 1550 nm and transverse magnetic field is launched at the input port. Sensitivity is measured by varying refractive index of dielectric by 0.1(from 1 to 1.5) shown in Fig.2. Detection is made by monitoring shift in resonant wavelength according to variation in refractive index. Keeping defective length of dielectric constant at 0.5 nm, various readings are obtained by varying refractive index. For an index change of 0.1, a large wavelength shift of ($\Delta\lambda$ = 62.39 nm) was estimated. Half power beam width (taken as 6.50905 nm).

Out of various readings shown in table 1 strongest spectral resonant peak is chosen for taking out sensitivity and FOM. According to definition, sensitivity of MIM plasmonic waveguide is experimentally calculated and found to be 624 nm. Further value of FOM and quality factor is calculated and found to be 95.86 and 296 (when length of defect is taken as 0.543 µm). Larger defective length results in improvement of light confinement hence it enhances FOM. FOM is measure as ratio of sensitivity and FWHM.(SENSITIVITY/ FWHM).Sensitivity is measured approx 624 nm and FWHM is 6.509. So FOM is calculated to be 95.8665.

In Fig. 2 various plots are shown in different colours, for each change in index resonant wavelength shift.

Table (4.3): Optimal Location and Capacitor Sizes using four candidate buses for 34-Bus Radial Distribution System

Refractive Index (n) (RIU)	Resonant Wavelength (λ_0) (nm)	Half power Beamwidth ($\Delta\lambda$) (nm)
1	1492.51	5.24572
1.1	1538.46	5.34361
1.2	1593.91	5.55407
1.3	1655.22	6.12264
1.4	1717.61	6.50905
1.5	1778.93	7.18653

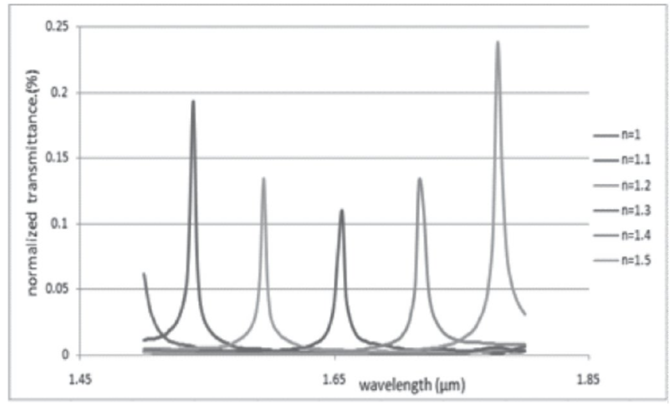

Fig. 2. Shows the variation of wavelength shift with change in refractive index

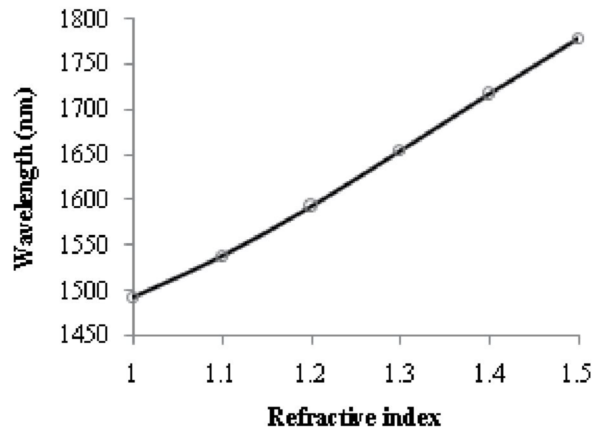

Fig 3: Variation of resonance condition against changing refractive index

Light is trapped in cavity and the shift is seen in resonant wavelength. With changing refractive index unit, spectral resonance wavelength changes accordingly. Fig 3 shows that refractive index of device displays linear relation with resonance wavelength.

4. CONCLUSION

To summarise, we have proposed and numerically analysed surface Plasmon MIM waveguide Bragg Grating by varying length of insulator cavity while creating defect in waveguide. And by introducing a nano- cavity in the uniform MIM plasmonic Bragg grating structure, a high refractive index sensitivity of 624nm/RIU and large FOM of about 95.86 around the resonance wavelength of 1550nm was obtained. Comparing with other plasmonic sensors which are of same configuration, FOM of this proposed device is too high. In previous researches, refractive index sensitivities found are 983nm/RIU, 1286nm/RIU and 1488nm/RIU, respectively but the corresponding FOMs are about 18.9, 22.2 and 19.8, respectively. FOM of the refractive sensor can be increased by tracking the transmission peak of the MIM Bragg grating with a nano-cavity. The proposed MIM plasmonic Bragg grating refractive index sensor has the merits of compact size (nanometric), high sensitive, linear response, large sensing range and relative high FOM, which makes it very promising for integrated chemical and biological sensing applications. Other applications are nanophotonics, in filters for WDM application and also form the basis for future photonic integrated circuits.

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