A polarization-independent highly sensitive hybrid plasmonic waveguide structure

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Abstract. In this paper, we proposed a novel design of a polarization-independent hybrid plasmonic waveguide. The transverse magnetic (TM) hybrid mode is confined in the low index material sandwiched between the silicon core and top gold layer whereas the transverse electric (TE) hybrid mode is supported in a narrow air gap on both sides between the silicon core and a gold layer. For sensing applications, two vital parameters such as the sensitivity of the hybrid mode ($S_{\text{mode}}$) and evanescent field ratio ($EFR$) are studied which depends on the geometric parameters of the waveguide. The geometric parameters of the waveguide are optimized using the finite element method. The highest $S_{\text{mode}}$ and $EFR$ for both polarizations is greater than 0.91 and 0.6, respectively. This study shows that polarization-independent highly sensitive refractive index sensors or evanescent field absorption gas sensors can be realized by utilizing the proposed hybrid plasmonic waveguide design.

1. Introduction
Hybrid plasmonic waveguide (HPWG) has gathered substantial consideration as it is capable of providing both subwavelength confinement and long propagation lengths [1,2]. These waveguides are composed of a thin layer of low index material ($\text{SiO}_2$) sandwiched between the metal layer (Au or Ag) and a higher index dielectric layer (Si). Theoretical studies have shown that low index layer can hold a low loss compact mode whose propagation length robustly rely on its thickness [3]. The transverse magnetic field ($\vec{H}_t$) supported by HPWG can be written as:

$$\nabla \times (\varepsilon_{\text{ri}}^{-1} \nabla \vec{H}_t) - \nabla \times (\mu_{\text{ri}}^{-1} \nabla \vec{H}_t) - (k_0^2 \mu_{\text{ri}} - \beta^2) \vec{H}_t = 0 \quad (1)$$

Where $\nabla = \frac{\partial}{\partial x} + \frac{\partial}{\partial y}$, $\beta$ is the propagation constant and $\varepsilon_{\text{ri}}$, $\mu_{\text{ri}}$ are the relative permittivity and permeability of the medium (i) where i can be metal, low index material and high index material. The detailed solution of hybrid mode supported by HPWG is presented in our previous work [4]. The dielectric waveguide mode is generally confined in high refractive index dielectric material whereas the metal surface supports surface plasmons (SPs), which is confined near the metal surface [5]. The marriage between these two structures brings the opportunity of coupling the dielectric mode supported by a standard waveguide to the surface plasmon mode supported by the metal surface. Due to the mode coupling, the light is confined in the region between the metal and the high index medium[6]. This incredible waveguide scheme has attracted researchers worldwide who demonstrated several exceptional applications such as polarization control devices [7], compact lasers [8], electro-optic modulators [9], surface-enhanced Raman spectroscopy [10], biosensors [11-14], among others.
In this work, we proposed a novel scheme of a polarization-independent hybrid plasmonic waveguide which requires two metal-dielectric interfaces capable of supporting both TE and TM guided modes. The waveguide structure consists of a vertical hybrid plasmonic waveguide structure, besides, a thin layer of gold is deposited on both sides of the core separated by a small air gap. This arrangement of layers provides a TM mode confinement in the central part and TE mode is supported in a nano-slot on both sides of the waveguide core. The waveguide geometry is optimized at 1550 nm to obtain high mode sensitivity and evanescent field ratio. The numerical investigations showed that the obtained values are quite high which makes this waveguide an ideal candidate to be employed in evanescent field absorption gas sensors or refractive index sensing applications.

2. Waveguide geometry

The schematic of a hybrid plasmonic waveguide is shown in figure 1. The central core consists of three layers such as silicon (Si), silicon dioxide (SiO$_2$) and gold (Au) deposited on a silica substrate. The width of the waveguide core, the height of the silicon core, the height of silicon dioxide and height of the top gold layer is represented as $W_{\text{Core}}$, $H_{\text{Core}}$, $H_{\text{SiO}_2}$ and $H_{\text{top-}}$Au, respectively. This configuration facilitates the propagation of transverse magnetic (TM) hybrid mode in $H_{\text{SiO}_2}$ layer. A thin layer of gold of height ($H_{\text{rail-Au}}$) equivalent to $H_{\text{Si}}$ is deposited on both sides of the central core separated by a gap ($g$). Throughout the paper, the parameters such as $H_{\text{SiO}_2}$, $H_{\text{top-}}$Au and $g$ is fixed at 50 nm, 80 nm and 50 nm, respectively.

![Figure 1. Schematic of a polarization-independent hybrid plasmonic waveguide structure.](image)

The E-field distribution, effective refractive index ($n_{\text{eff}}$) and mode sensitivity ($S_{\text{mode}}$) analysis of the proposed waveguide design are carried out via a 2D finite element method (FEM)-based model in COMSOL Multiphysics 5.1. The EM-wave frequency domain (emw) has been chosen as the physics interface and the modal analysis was added to the study. Whereas, the evanescent field ratio (EFR) is investigated with the help of the 3D model in the above-mentioned module. In COMSOL simulations, the waveguide geometry is divided into triangular mesh elements with a "very fine" mesh grid size for the whole design. The computational power of the system is one of the limiting factors which ensure how swiftly simulations can be carried out. For wave propagation systems, it is always desired to model a domain with open boundaries of the computational domain as it allows the EM wave to pass without any reflection. The open geometry is estimated by assigning a scattering boundary conditions (SBC) at the outer edges of the simulation window.

The real part of $n_{\text{eff}}$ of TE and TM hybrid mode is dependent on the geometric parameters of the waveguide which is calculated by varying $H_{\text{Core}}$ and $W_{\text{Core}}$ and maintaining the remaining parameters such as $H_{\text{SiO}_2}$, $H_{\text{top-Au}}$ and $g$ to 50 nm, 80 nm and 50 nm, respectively. The evaluation of $n_{\text{eff}}$ is very important when designing the optical system because it governs the propagation constant of the optical field. It is even critical in high-speed communications where dispersion can be a limiting factor. The real part of $n_{\text{eff}}$ of TE and TM hybrid mode is calculated by varying $H_{\text{Core}}$ and $W_{\text{Core}}$ in the range of 100 nm-350 nm. From 2 (a,b), it can be seen that the real part of $n_{\text{eff}}$ of both hybrid modes increases with the growing size of the waveguide core. Because at very large core dimensions, there is a gradual transformation of hybrid mode into the dielectric mode. Therefore, geometric parameters should be optimized which ensures the confinement of mode in low index region ($g$) instead of high index Si.
core. The geometric parameters ($H_{\text{Core}}$ and $W_{\text{Core}}$) ≥ 350 nm results in a dielectric mode which is confined in $Si$ core as shown in figure 2 c.

![Figure 2](image)

Figure 2. The real part of $n_{\text{eff}}$, a) TE-polarized hybrid mode, b) TM-polarized hybrid mode, c) E-field distribution of dielectric mode at $H_{\text{Core}}$=450 nm and $W_{\text{Core}}$=450 nm.

The imaginary part of $n_{\text{eff}}$ ($Im(n_{\text{eff}})$) strongly depends on the waveguide geometry which reduces significantly as $H_{\text{Core}}$ and $W_{\text{Core}}$ increases. The reduction in $Im(n_{\text{eff}})$ signifies that the system has low loss which can be useful in the realization of the waveguides with longer propagation length. The loss associated with TE hybrid mode is significantly smaller than the TM hybrid mode as shown in figure 3. This is because TM hybrid mode is confined in low index $SiO_2$ (n=1.44) layer whereas TE hybrid mode is concentrated in two air slot (n=1.0).

![Figure 3](image)

Figure 3. The imaginary part of the effective refractive index, a) TE-polarized hybrid mode, b) TM-polarized hybrid mode.

The E-field distribution of TE hybrid mode and TM hybrid mode at 1550 nm in HPWG is shown in figure 4 where the $W_{\text{Core}}$ and $H_{\text{Core}}$ are fixed at 100 nm, 250 nm and 350 nm. For $W_{\text{Core}}$ and $H_{\text{Core}}$ ≤ 250 nm, there is a perfect hybrid mode confined in the nano-slot (Air in case of TE hybrid mode and low index material in case of TM hybrid mode). For $W_{\text{Core}}$ and $H_{\text{Core}}$ ≥ 350 nm, the waveguide ($Si$ core) can support TE and TM dielectric modes which makes the hybrid mode less sensitive.
3. Mode sensitivity analysis

For sensing applications, mode sensitivity ($S_{mode}$) is an essential parameter which should be taken into consideration while designing optical waveguides. We evaluated $S_{mode}$ versus the geometric parameters of the waveguide. $S_{mode}$ is calculated with the help of the following expression[15]:

$$S_{mode} = \frac{n_{eff2} - n_{eff1}}{n_2 - n_3},$$

where $n_{eff2}$ is the effective refractive index at the refractive index of the analyte ($n_2$) and $n_{eff1}$ is the effective refractive index at the refractive index of air ($n_3$). In this analysis, $n_2=1.35$ is used to calculate the sensitivity of TE and TM hybrid modes as shown in figure 5 (a,b). For TE hybrid mode, $H_{Core}$ plays an important role in enhancing the $S_{mode}$ but $H_{Core}$ > 150 nm makes the mode highly vulnerable which decreases $S_{mode}$ drastically when $W_{core}$ > 250 nm. $S_{mode}$ for TM hybrid mode shows the same behaviour with increasing core dimensions which is more vulnerable as $H_{Core}$ increases. For instance, at $H_{Core}$ and $W_{Core}$=150 nm, the $S_{mode}$ of 0.87 and 0.764 is obtained for TE hybrid mode and TM hybrid mode, respectively.

4. Evanescent field ratio (EFR) analysis

The sensitivity of the optical waveguide is directly proportional to the large light confinement in the upper cladding. The evanescent field ratio (EFR) is the core parameter for the realization of sensors
based on the interaction with the evanescent field. The sensors with high EFR can have strong interaction with the ambient medium, which in turn improves the sensitivity of the sensor. EFR is expressed as the ratio of intensity integration of upper cladding to the overall intensity integration in the WG and is calculated by using the following expression:

$$EFR = \frac{\iint_{\text{upper cladding}} |E(x,y,z)|^2 dxdydz}{\iint_{\text{total}} |E(x,y,z)|^2 dxdydz}$$

The intensity integration of the upper cladding of the waveguide is the sum of energy in the nano-slot and energy above the waveguide. The EFR of TE and TM hybrid mode is calculated by varying \(H_{\text{Core}}\) and \(W_{\text{Core}}\) and keeping the other parameters such as \(H_{\text{SiO2}}, H_{\text{Si}/\text{Au}}\) and \(g\) fixed at 50 nm, 80 nm and 50 nm, respectively. The EFR calculations are quite in agreement with the calculations of \(S_{\text{mode}}\). For instance, the EFR of TE hybrid mode and TM hybrid mode is ~0.6 and 0.54, respectively at \(H_{\text{Core}}\) and \(W_{\text{Core}}= 150\) nm as shown in figure 6.

![Figure 6. EFR of a) TE hybrid mode, b) TM hybrid mode.](image_url)

**5. Conclusion**

We proposed a novel design of a hybrid plasmonic waveguide which is capable of supporting both transverse electric (TE) and transverse magnetic (TM) hybrid modes at 1550 nm. This waveguide structure can be utilized in integrated sensors where strong light-matter interaction is required. For sensing applications, the waveguide geometry should be optimized taking into account the mode sensitivity (\(S_{\text{mode}}\)) and evanescent field ratio (EFR) of the hybrid mode. For TE hybrid mode, the highest \(S_{\text{mode}}\) and EFR of 0.98 and 0.68 is obtained by optimizing the geometric parameters of the waveguide, respectively. Almost the same modal characteristics are obtained for TM hybrid mode where \(S_{\text{mode}}\) is 0.92 and EFR is 0.6. This study shows that polarization-independent highly sensitive refractive index sensors or evanescent field absorption gas sensors can be realized by utilizing the proposed hybrid plasmonic waveguide design.

**Acknowledgement**

This work was financially supported by the Ministry of Science and Higher Education within the State assignment FSRC "Crystallography and Photonics" RAS (No. 007-GZ/Ch3363/26) and RFBR (No. 18-58-14001).
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