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Information Industry Upgrading Sensing Technology Using Plasmonic Waveguide Directly Coupled to Rectangular Cavity

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Abstract: We analyze information industry upgrading based on sensing technology innovation of plasmonic cavity evanescently coupled to metal-dielectric-metal waveguide. The proposed optical sensor technology can detect the local variation of the refractive index inside the nanoscale cavity. We present the physical mechanism of the sensing process which promote photovoltaic industry upgrading. Numerical experiments based on the finite difference time domain method confirm our theory prediction. The resolution of refractive index of this sensor can reach 10-6 for the first order resonant mode, and the enlarged free spectral range of the system could release the influence of the background noise. Furthermore, we should increase sensing technology innovation.
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Keywords: Industry upgrading, Sensing technology innovation, Plasmonic waveguide, Rectangular cavity.

1. Introduction

With the development of economy, Sensing technology for information industry upgrading becomes more and more important. Technological innovation of a high starting point promotes information industry upgrading. Optical sensor is the necessary constituent of all optical measurement instruments, which can be aware of the variation of light beam signal in the detection environment and the intensity of the light, phase change as well as the working wavelength. Because of its potential application, optical sensor has received significant research interest this year [1]. Specially, refractive index optical sensor gain extensive study recently. Fabry–Perot interferometer is a suitable candidate for refractive index sensing due to its sensitivity on the optical path inside the interferometer [2]. Using the physical properties of Fiber Bragg grating is another way to obtain the local variation of refractive index, which can integrate the sensing function into some fiber based instrument [3, 4]. At the same time, the evanescent field of the taper fiber can be used to detect the optical change of surrounding medium [5]. Furthermore, Mach-Zehnder interferometer can be a good refractive index sensor due to its capacity of exploring coherent interference [6, 7]. As can be seen from the mentioned literatures, local change of

refractive index can introduce change in the optical phase, equivalent optical path and resonance frequency of the system. As a result, the output of the system depends on the strength of the refractive index difference. And we can map the amount of local refractive index variation from the output signal and obtain quantitative result.

With the development of information technology, a new branch of photonics which focus on microcosmic scale, people always hope to reduce the volume size of constituents while keep their functionality as they macroscopic counterpart. However, the above mentioned optical sensor is working at the macroscopic scale and cannot satisfy the needs that encounter in nanophotonics. Due to the nature of subwavelength mode profile and exchange of power between electron and photon, surface plasmon polaritons (SPPs) provide a useful platform to realize optical sensing and signal connecting between electric circuit and optical circuit. At the same time, having the advantage of overcoming the diffraction limit of light, SPPs type components can be built in the nanoscale. Therefore, variety of functional devices based on SPPs including channel add-drop filters, optical switch as well as band-reject filter have been proposed recently [8]. Actually, SPPs is one kind of surface wave which could be the best candidate to detect local change on the surface of the metal. Different types of SPPs based sensor had been proposed. However, they relied on the bulk metal films deposited on top of optical waveguide system whose typical dimensions are too large compared with integrated optical circuit. Luff et al. propose a novel nanometeric plasmonic refractive index sensor by using plasmonic cavity side coupled to metal-dielectric-metal waveguide system [9]. Given the typical size of this system and by monitoring the resonant frequency of the output, they can obtain the relationship of local refractive index inside the plasmonic cavity and the output transmission dip [10]. Therefore, quantitative refractive index variation can be obtained in the nanoscale.

In this paper, we suggest sensing technology for information industry upgrading to realize optical sensing in the nanoscale by using transmission tip rather than transmission dip. The advantage of utilizing transmission resonance for optical sensing is that we can distinguish resonant state and output signal similar to resonant state. The size of this sensing system is within 40×700 nm^2 area which is exactly hitting the diffraction limit.

The paper is organized as follows. Section 2 outlines the theoretical model. In Section 3, we present the simulation result. Section 4 concludes the paper.

2. Theoretical Mode

The waveguide-cavity sensing technology system which promotes information industry upgrading is shown by Fig. 1. The structure of the device is composed of two metal-dielectric-metal waveguide and a plasmonic cavity where the material under sensing can be filled. The plasmonic cavity is evanescently coupled to two waveguide through the thin metal. The frequency dependent complex relative permittivity of silver is modeled by combining the Drude model and the two pole Lorentzian model as follow:

$$\varepsilon_{metal}(\omega) = \varepsilon_{\infty} - \frac{\omega_D^2}{\omega^2 + i\gamma_D\omega} - \sum_{m=1}^{2} \frac{\rho_{Lm}\omega_{Lm}^2 \Delta\varepsilon}{\omega^2 - \omega_{Lm}^2 + i2\gamma_{Lm}\omega} \quad (1)$$

where $\varepsilon_{\infty} = 2.3646$, $\omega_D = 8.7377$ eV, $\gamma_D = 0.07489$ eV, $\Delta\varepsilon = 1.1831$, $\rho_{L1} = 0.26663$, $\rho_{L2} = 0.7337$, $\omega_{L1} = 4.3802$ eV, $\omega_{L2} = 5.183$ eV, $\gamma_{L1} = 0.28$ eV and $\gamma_{L2} = 0.5482$ eV.

This model provides accurate description of empirical dielectric constant data for silver compared to experiment result.

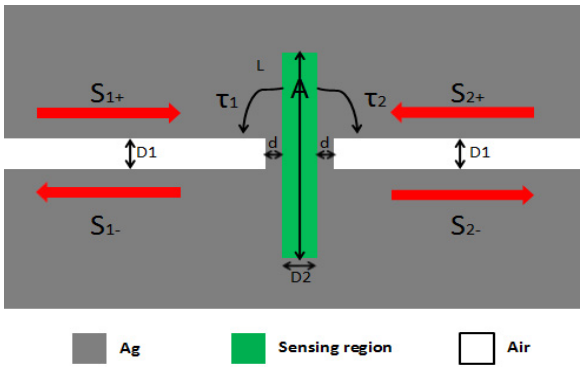


Fig. 1. Metal-dielectric-metal waveguide based plasmonic refractive index sensing.

The green shape region denotes the sensing area while gray region stands for the metal Ag and white region is the air slot. The sensing region is a plasmonic cavity evanescently coupled to the input and output waveguide which convert the dielectric change into optical signal. A stands for the complex field in the cavity S are referred to the incoming and outgoing fields in the waveguide.

Please note here that such kind of plasmonic system can be manufactured by the state of art fabrication technology such as electron beam lithography, focused-ion-beam milling and template stripping. Light signal can be coupled/decoupled by using grating. The sensing region can detect, for example, gaseous (through gas diffusion force in vacuum circumstance) or liquid (through capillarity attraction). Usually, gaseous and liquid would introduce the variation of local refractive index. And the resonant frequency of the sensing cavity would

shift according to the change of the refractive index. In order to model this structure, we consider the finite difference time domain method for dispersive medium. For an isotropic collision plasma material, we can obtain the Maxwell's equations and constitutive relation as:

$$\nabla \times E = -\mu_0 \frac{\partial H}{\partial t} \tag{2}$$

$$\nabla \times H = \varepsilon_0 \frac{\partial E}{\partial t} + J \tag{3}$$

$$\frac{\partial u_e}{\partial t} = -\frac{e}{m} E - \nu u_e \tag{4}$$

$$J = -e n_e u_e , \tag{5}$$

where H is the magnetic intensity, E is the electric field, ε_0 is the permittivity in vacuum, μ_0 is the permeability of vacuum, ν is the electron collision frequency, n_e is the electron concentration and e and m are the electric charge and corresponding mass of an electron respectively. Eq. (2) – (5) can be transformed into the frequency domain and we can obtain the relationship between J and E

$$J(\omega) = \varepsilon_0 \frac{\omega_P^2}{j\omega + \nu} E(\omega) = \sigma(\omega) E(\omega) , \tag{6}$$

where $\omega_p = \sqrt{n_e e^2 / m\varepsilon_0}$ is the plasma frequency with $\sigma(\omega) = \varepsilon_0 \dfrac{\omega_p^2}{j\omega + \nu}$. If we inversely transform the upper equation back to the time domain, here goes with the following integral:

$$J(t) = \int_0^t E(t-\tau)\sigma(\tau) \tag{7}$$

$$\sigma(\tau) = \varepsilon_0 \omega_p^2 \exp(-\nu\tau) U(\tau) , \tag{8}$$

where $U(\tau)$ is the unit step function, $t = n\Delta t$.

Accordingly, each vector component of J and E can be represented as:

$$J_i(n\Delta t) = \int_0^{n\Delta t} E_i(n\Delta t - \tau)\sigma(\tau) d\tau \qquad i = x, y, z \tag{9}$$

With the assumption of piecewise linear functional dependence of electric field on Δt, each vector component of electric field in the upper equation can be outlined as:

$$E_i(n\Delta t - \tau) = E_i^{n-m} + \frac{E_i^{n-m-1} - E_i^{n-m}}{\Delta t}(\tau - m\Delta t) \tag{10}$$

Combined Eq. (8) - (10), we can obtain each component of J at n time step and next time step:

$$J_i^n = \sum_{m=0}^{n=1} [E_i^{n-m}\sigma^m + (E_i^{n-m-1} - E_i^{n-m})\xi^m] \tag{11}$$

$$J_i^{n+1} = \sum_{m=0}^{n} [E_i^{n+1-m}\sigma^m + (E_i^{n-m} - E_i^{n+1-m})\xi^m] \tag{12}$$

$$\sigma^m = \int_{m\Delta t}^{(m+1)\Delta t} \sigma(\tau) d\tau = \frac{\varepsilon_0 \omega_p^2}{\nu} [1 - \exp(-\nu\Delta t)] \exp(-m\nu\Delta t) \tag{13}$$

$$\xi^m = \frac{\varepsilon_0 \omega_p^2}{\nu^2 \Delta t} [1 - (1 + \nu\Delta t)\exp(-\nu\Delta t)] \exp(-m\nu\Delta t) \tag{14}$$

From Eq. (11) and (12) we obtain:

$$J_i^{n+1} + J_i^n = (\sigma^0 - \xi^0) E_i^{n+1} + \xi^0 E_i^n + \sum_{m=0}^{n=1} [E_i^{n-m}(\sigma^m + \sigma^{m+1}) + (E_i^{n-m-1} - E_i^{n-m})(\xi^m + \xi^{m+1})] \tag{15}$$

With central difference formulation, Eq. (3) is written as:

$$(\nabla \times H)_y^{n+1/2} = \varepsilon_0 \frac{E_y^{n+1} - E_y^n}{\Delta t} + \frac{J_y^{n+1} + J_y^n}{2} \tag{16}$$

Combined Eq. (15) and (16), we can get the time evolution equation for electric field:

$$E_y^{n+1} = \frac{1}{1 + \frac{\Delta t}{2\varepsilon}(\sigma^0 - \xi^0)} [(1 - \frac{\Delta t}{2\varepsilon_0}\xi^0) E_y^n + \frac{\Delta t}{\varepsilon_0}(\nabla \times H)_y^{n+1/2} - \frac{\Delta t}{2\varepsilon_0}\psi_y^n]$$

$$\psi_i^n = (\sigma^0 + \sigma^1 - \xi^0 - \xi^1) E_i^n + (\xi^0 + \xi^1) E_i^{n-1} + \exp(-\nu\Delta t)\psi_i^{n-1} \tag{17}$$

And the equations for x and z components can be obtained by the same way. Given the dielectric distribution of the medium, we have all the necessary information for numerical experiment. Directly solving the Maxwell's equations can give us intuitional idea of how the sensing system response to the input optical signal although it is a time consuming process. Here we also provide a phenomenological time coupled mode based model to describe the response of the system with more efficiency. Let's suppose the field in the cavity (sensing region) is proportional to variable A where $|A|^2$ is the electromagnetic energy stored in the cavity and neglect the metal loss. The fields in the waveguide are the sum of incoming and outgoing waveguide modes which are defined by $S_{l\pm}(l = 1, 2)$. S_{l+} is the amplitude of the waveguide mode going forwards the cavity and S_{l-} stands for the mode going away from the cavity as indicated in Fig. 1.

Because of the conservation of energy and the time reversal symmetry of the system, we can obtain the temporal coupled mode equations for the sensing system in Fig. 1.'

$$\frac{da}{dt} = -j\omega_0 A - \sum_{l=1}^{2} A/\tau_l + \sum_{l=1}^{2}\sqrt{\frac{2}{\tau_l}}S_{l+}$$
$$S_{l-} = -S_{l+} + \sqrt{\frac{2}{\tau_l}}A \quad (18)$$

With the harmonic assumption, we can derive a stationary equation set describing the response of the system:

$$-j\omega A = -j\omega_0 A - \frac{A}{\tau_1} - \frac{A}{\tau_2} + \sqrt{\frac{2}{\tau_1}}S_{1+}$$
$$S_{1-} = -S_{1+} + \sqrt{\frac{2}{\tau_1}}A \quad (19)$$
$$S_{2-} = \sqrt{\frac{2}{\tau_2}}A$$

The transmission of this system is determined by the transmission:

$$T(\omega) = \frac{|S_{2-}|^2}{|S_{1+}|^2} = \frac{\frac{4}{\tau^2}}{(\omega-\omega_0)^2 + \frac{4}{\tau^2}}, \quad \tau_1 = \tau_2 = \tau \quad (20)$$

Here the evanescent couplings from the cavity are symmetry as the system outlined in Fig. 1 which has mirror symmetry respecting to the long axes of the cavity. As can be seen from Eq. (20), the system would have a unit transmission when the input frequency of the light signal is the same as the eigen-frequency of the cavity if the system is lossless. Although real metal process Ohm heating thus power loss, the physical properties is still the same which can be fully described by the upper time coupled mode model. Therefore, the physical picture behind this sensing structure is that local change of the refractive index would change the eigen-frequency of the plasmonic cavity (ω_0) accordingly. And the shift of the eigen-frequency would introduce different transmission tip in the output spectrum which can provide the information of the amount of refractive index variation.

3. Simulation Result

Let's consider the effective index of the plasmonic waveguide under investigation first. The equation describing the dispersion relation of the fundamental transverse magnetic wave (here we consider two-dimension case with electric field lying in the plane is:

$$k_l\omega = 2\arctan\left(\frac{\varepsilon_d\alpha}{\varepsilon_M k_l}\right)$$
$$k_l^2 = k_0^2\varepsilon_d - \beta^2 \quad (21)$$
$$\alpha^2 = (\beta^2 - k_0^2\varepsilon_M),$$

where $\varepsilon_d = n^2$ is the dielectric constant of the dielectric layer, ε_M is determined by Eq. (1) and $k_0 = 2\pi/\lambda$ is the k-vector of free space. Fig. 2 shows the effective index of the plasmonic waveguide defined by $n_{eff} = \beta/k_0$ with the dielectric layer is air and with 50 nm width. As can be seen from the figure, the real part of the effective index is dispersive among the interesting wavelength and the imaginary part of the effective index follow similar trend as the real one.

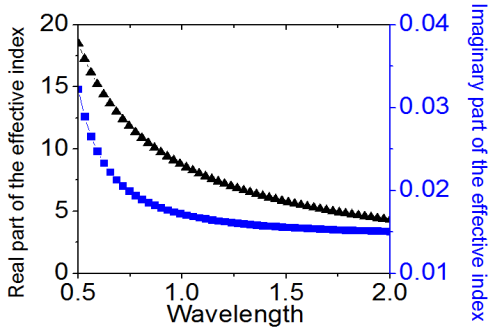


Fig. 2. Real and imaginary part of the effective index of the metal-dielectric-metal waveguide.

Here the data is calculated by using Ag as the metal and air as the dielectric material. D1 is set to be 50 nm.

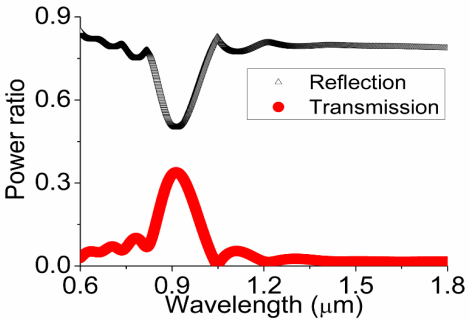
It should be pointed out that the resonant transmission is different with directly coupled cavity and side coupled cavity. The resonant condition is

$$\Delta\phi = \frac{4\pi\,\mathrm{Re}(n_{eff})L}{\lambda_0} + 2\varphi_{ref} = m\cdot 2\pi \qquad (m = 2,4,6-)' \quad (22)$$

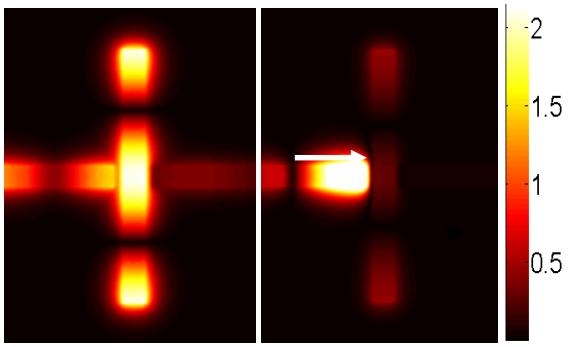
where $\Delta\phi$ is the round trip phase shift, φ_{ref} is the phase shift when reflected at the metal dielectric interface, L is the length of the plasmonic cavity, λ_0 is the corresponding wavelength in vacuum. As can be seen in this equation, suck kind of resonance only contains resonant mode with even mode node. This is because the vertical cross of the cavity and the waveguides.

Finite difference time domain numerical experiment confirms the prediction, as is shown by Fig. 3. For the cavity with L=600 nm and D1=50 nm, the system has a resonant transmission at 920 nm within the wavelength region from 600 nm to 1800 nm. The corresponding magnetic field

distributions are plot in Fig. 3 (b) and (c). It can be seen from the figures that highly excited plasmonic cavity is the signature of the resonant transmission. Non-resonant blocking happens at other wavelength. The position of the transmission tip provides the information of the refractive index inside the cavity. Fig. 4(a) shows the response of the system for different refractive index of the cavity. As can be seen from the figure, the resonant frequency is red shifted with the increasing of the refractive index. The relationship between the refractive index and the wavelength of peak transmission is quasi-linear as is shown in Fig. 4 (b). Compared to the system proposed, the shift of the second peak wavelength as the function of the refractive index is equal to 1000 nm per refractive index unit ($dn/d\lambda=0.001$). If the sensing resolution of refractive index is defined as $\Delta\lambda dn/d\lambda$ and the wavelength resolution of the optical spectrum analyzer is $\Delta\lambda=0.01$, we have the resolution about 1×10^{-5} of the first order resonance which is more than twice sensitive than the one proposed in Ref. The way how the plasmonic cavity coupled to the waveguide is attributed to the enhancement of sensitivity. At the same time, using the transmission resonance together with large free spectrum range facilitate the precision of the sensing process. For example, it can be immune from the background noise while the one using transmission dip could be affected by the noise.



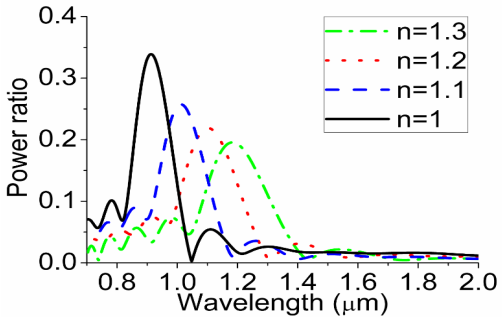
(a)



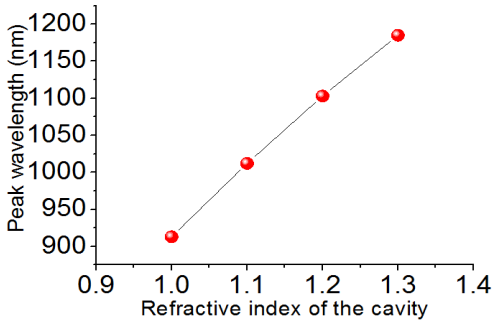
(b) (c)

Fig. 3. Transmission and reflection spectrum calculate by Finite difference time domain numerical experiment.

Black triangles stand for reflection while solid circles represent transmission. Here the data is calculated by using Ag as the metal and air as the dielectric material. D1 is set to be 50 nm, L=600 nm and all the dielectric materials are air. The steady magnetic field distribution when the wavelengths of incident light are 920 nm shown in (b)] and 1200 nm [shown in (c)] respectively, which are also indicated by the arrows in (a).



(a)



(b)

Fig. 4. (a) Response of the system for different refractive index inside the cavity. (b) Relationship between the peak wavelength and the refractive index of the cavity.

4. Conclusions

In conclusion, with the development of sensing technology innovation, new sensing technology promotes information industry upgrading. a plasmonic sensor which is more suitable for optical sensing is proposed theoretical and demonstrated numerically. Being the basic building block of this refractive index sensing, the vertical coupled plasmonic cavity provides with twice free spectral range compared to conventional metal dielectric metal waveguide based sensor. The resolution of this refractive sensor at the first order resonant frequency is about 10^{-6}. We expect also the sensor can find its application in biological industry, communication technology as well as other industry which needs

refractive index sensor with subwavelength dimension.

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