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# Fabry–Pérot-based surface plasmon resonance sensors

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A new sensing approach based on the use of an optical Fabry–Pérot (FP) cavity in conjunction with surface plasmon resonance (SPR) is proposed and theoretically investigated. The impact of the SPR on the intensity and phase response of the proposed sensor structure is evaluated using a modified FP model that takes into account the SPR effect. Compared to the conventional optical-phase-detection-based Kretschmann configuration, the proposed sensing approach requires only the measurement of the output power spectrum over a narrow wavelength span of several nanometers to evaluate the phase responses of the sensor, making it more attractive for practical high-sensitivity sensing applications. © 2012 Optical Society of America

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Surface plasmon resonance (SPR) has been used for the detection of refractive index changes right above a metal-dielectric interface [1,2]. In the last two decades, SPR-based sensors have become one of the most important label-free optical sensors for the study of biomolecular interactions and the real-time detection and identification of chemical and biological analytes. Due to their high sensitivity and selectivity, SPR sensors have now been used in a wide range of applications, including proteomics, medical diagnostics, drug designs, environmental monitoring, and food safety and security [3].

The excitation of surface plasmons in SPR sensors results in a change in one of the characteristics of the output response, which can be detected through various optical detection approaches, thus enabling the measurement of the refractive index of the sample under investigation. Several SPR sensor configurations based on different signal interrogation schemes have been reported, including detection of (1) the input optical beam angle at which resonance takes place [4], (2) the resonance wavelength [5], (3) the output optical signal intensity [6], (4) the output optical signal phase change [7], and (5) the output optical signal polarization change [8]. The first three types of signal interrogation are being used in most of today's SPR sensors, due to their simplicity, low cost, and high performance. The structures of the other types are complex, and hence they have not been widely used, although their ability to offer higher sensitivities has been demonstrated [8,9]. Recently, in order to improve the sensitivity and practicality of SPR sensors and extend their applications, many research works have been focused on devising new configurations and mechanisms while retaining the simplicity of conventional SPR sensors [10,11]. Among them, plasmonic cavities have generally been used to enhance the sensitivity of the SPR sensors [12,13].

In this Letter, we propose and investigate a new sensing approach based on the use of an optical Fabry–Pérot (FP) cavity in conjunction with SPR. Specifically, we incorporate plasmonic structure within an FP cavity and theoretically analyze the optical intensity and phase responses resulting from the SPR effect. A practical sensing scenario is analyzed to demonstrate that the combination of the FP

and SPR effects enables the measurement of the optical phase response, and hence the evaluation of the refractive index of a sample, through the measurement of the output power spectrum over a narrow wavelength span.

The proposed sensing approach is shown in Fig. 1. A metal layer of dielectric constant  $\epsilon_m$  and thickness  $d$  is coated on a prism. The refractive indexes of the prism and the sensed medium are assumed to be  $n_p$  and  $n_s$ , respectively. In order to investigate the SPR effect on the FP interference response, a  $p$ -polarized incident beam is launched normal to the prism curved entrance window, which is coated with a thin film of reflection coefficient  $r$ . The incident light then strikes the prism-metal interface at the center of the prism's curved surface at a total-internal-reflection (TIR) angle of  $\theta$ . This beam may excite surface plasmons, thus losing a portion of its energy, while the remaining energy is reflected off the dielectric-metal interface and propagated toward the other exit curved window of the prism, which is coated with the same thin film as that of the entrance window. As a result, the entrance and exit windows form an FP cavity within which SPR takes place. Note that this structure can also be realized using optical fibers or waveguides, with an SPR sensing area being sandwiched between two Bragg gratings.

The reflectance  $R$  of the prism-metal interface can be expressed as follows:

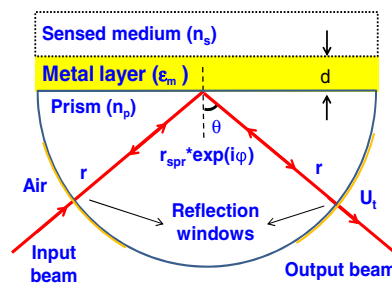


Fig. 1. (Color online) Proposed sensing approach based on the use of an optical FP cavity in conjunction with SPR. The beam entrance and exit windows are coated with a thin film of reflection coefficient  $r$ .

$$R = r_{\text{SPR}} * \exp(i\varphi), \quad (1)$$

where  $r_{\text{SPR}}$  is the amplitude reflectance and  $\varphi$  is the phase change induced into the beam incident onto the prism-metal interface by the SPR. Assume that the electric-field amplitude of the incident light is  $A_0$ , then after multiple reflections within the FP cavity, the successive optical beams emerging from the exit window differ in phase and amplitude, as they experience different path lengths and TIR-induced phase shifts and intensity changes. The electric fields of the first  $n$  optical beams emerging from the exit window are given by

$$\begin{aligned} U_0 &= A_0 t R t' e^{i\delta}, \\ U_1 &= A_0 t R r R r R t' e^{3i\delta} = A_0 t R^3 r^2 t' e^{3i\delta}, \\ U_2 &= U_1 r R r R e^{2i\delta} = A_0 t R^5 r^4 t' e^{5i\delta}, \\ U_3 &= U_2 r R r R e^{2i\delta} = A_0 t R^7 r^6 t' e^{7i\delta}, \\ &\downarrow \\ U_n &= A_0 t R^{2n+1} r^{2n-1} t' e^{i(2n+1)\delta}, \end{aligned} \quad (2)$$

where the coefficients  $r$  and  $t$  are the reflection and transmission of the entrance and exit windows, for light traveling from the prism medium to the air, while  $r'$  and  $t'$  are the reflection and transmission coefficients for light traveling from the air to the prism medium, and  $\delta$  is the round trip phase change caused by path length difference  $L$  within the prism medium.

The overall output electric field,  $U_t$  is the superposition of all individual electric fields,  $U_n$  with  $n = 0, 1, 2, \dots$ , therefore

$$U_t = \sum_{n=0}^{\infty} U_n. \quad (3)$$

Using Eqs. (2) and (3), the total transmitted intensity is given by

$$I = U_t U_t^* = \frac{A_0^2 r_{\text{SPR}}^2 (1 - r^2)^2}{(1 - r^2 r_{\text{SPR}}^2)^2 + 4r^2 r_{\text{SPR}}^2 \sin^2(\delta + \varphi)}, \quad (4)$$

where the relation  $tt' = 1 - r^2$  was used. From Eq. (4), it can be seen that (1) the expression of the output intensity is similar to that of FP interferometers, featuring periodic transmission peaks at optical frequencies separated by the free spectral range, (2) the SPR-induced reflectance at the prism-metal interface,  $r_{\text{SPR}}$  which depends on the coupling between the evanescent wave and the surface plasmon wave, affects the FP interference fringes, and (3) the phase change,  $\varphi$ , induced by the SPR has the similar effect of changing the FP cavity length, that is, it changes the FP peak positions.

In typical SPR sensors, the SPR curves of reflectance exhibit a minimum reflectance at the resonance angle (or frequency). This minimum reflectance,  $R_{\text{min}}$  depends on many parameters, such as the dielectric constants of the metal layer, prism, and the sensed medium; the resonance angle (or frequency); and the thickness of the metal layer. Most of the current SPR sensors are based on

the detection of reflectivity dip versus either the incidence angle or the wavelength, where  $r$  should be made low enough to ensure that  $R$  is not affected by the FP effects. For high  $r$  values, the  $I - \theta$  curve does not resemble the conventional  $R - \theta$  curve of the SPR, and hence the intensity peak measurement does not exhibit the SPR effect explicitly.

The phase shift in SPR has more impact than its amplitude counterpart and has shown better sensitivity in sensing and convenient fulfillment of SPR imaging [14]. However, most of the current SPR sensors are based on angular or wavelength interrogation, mainly because the detection of optical phase shift requires complex configurations. The proposed SPR sensing approach allows monitoring shifts in interference fringes without the need for detecting SPR-induced phase shifts, thus offering a much easier solution compared with current phase detection schemes employing complex optical heterodyne, polarimetry, and interferometry. For high detection resolution the minimum reflectance,  $R_{\text{min}}$ , is designed to be as small as possible, and this yields a shallow interference fringe when an FP cavity is used. And if  $R_{\text{min}}$  is too small, the interference fringe  $I$  will eventually degenerate into that of double-slit interference. Specifically, when  $R_{\text{min}} = 0$ , the FP fringe fails to recover the sensing information carried by the SPR. Note that in order to effectively detect the SPR-induced phase shift of the optical signal,  $R_{\text{min}}$  can be relatively large, otherwise optical amplification may be used to improve the intensity,  $I$ , of the optical signal transmitted through the FP cavity.

To numerically demonstrate the concept of the FP-based SPR sensor, a silver thin film of plasmon wavelength  $\lambda_p = 1.2915 \times 10^{-7}$  m, and the collision wavelength  $\lambda_c = 5.4377 \times 10^{-5}$  m, were chosen. The other sensor parameters used were  $\theta = 66.5^\circ$ ,  $d = 50$  nm,  $n_p = 1.46$ ,  $L = 0.001$  m, and  $r = 0.9$ . Figures 2(a) and 2(b) show the reflectance spectrum,  $r_{\text{SPR}}$  the phase shift,  $\varphi$ , and the transmitted intensity,  $I$ , for different  $n_s$ . It is shown in Fig. 2 that the SPR excitation results in absorption dips in wavelength around  $1.53 \mu\text{m}$  for  $n_s = 1.3302$  and  $1.54 \mu\text{m}$  for  $n_s = 1.3303$ . It is also shown that at these wavelength dips the phase shift  $\varphi$  changes dramatically because SPR is dominant but can easily be detected by monitoring the corresponding fringe shift [inset of Fig. 2(c)]. As shown in the inset of Fig. 2(c), over the wavelength range where the phase shift is dramatic, the fringe shift is around  $0.2$  nm for a refractive index change of  $0.0001$ . Therefore, by using an optical spectrum analyzer of resolution  $0.01$  nm, the resolution of the proposed sensor can be as high as  $\Delta n_{\text{min}} = 5 \times 10^{-6}$  refractive index unit (RIU). Note that the interference fringes have similar intensity dips as those of  $r_{\text{SPR}}$ , which are caused by the SPR. A large intensity dip of SPR reflectance results in a deep interference fringe, making the measurement of peak shift feasible and more accurate; however, the trade-off is a small penalty in sensitivity. Note that in the wavelength range where SPR is insignificant, the phase shift is mainly caused by TIR, leading to a negligible fringe shift.

It is important to note from Eq. (4) that the SPR-induced phase shift  $\varphi$  can be compensated by adjusting the FP-induced phase shift  $\delta$  to keep the transmitted output,  $I$ , constant. A mature method to control the

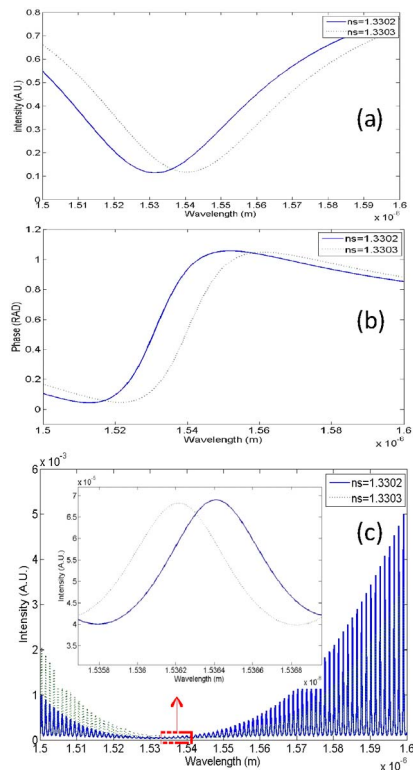


Fig. 2. (Color online) (a) SPR reflection  $r_{\text{SPR}}$ , (b) phase shift  $\phi$ , and (c) transmitted intensity  $I$  versus wavelength for the SPR-based optical FP sensor, for  $n_s = 1.3302$  and  $1.3303$ .

FP-induced phase is to use a voltage-driven piezoelectric transducer. In this case, the sensing system can be further simplified by using a fixed-wavelength laser in conjunction with a phase modulator.

It can also be seen from Eq. (4) that the sensitivity of phase detection through the measurement of FP peak shifts also depends on the cavity length  $L$ . A long cavity length leads to low phase detection sensitivity. It is important to mention here that waveguide-based SPR sensors have the inherent capability of achieving a short-length cavity, making them more advantageous and flexible than their prism-based counterparts whenever phase-shift detection is the main method used for refractive index measurements. FP-based SPR optical sensing offers an effective, accurate, reliable, simple, and convenient approach for detecting optical phase shifts, compared to current techniques such as Mach-Zehnder interference. More importantly, compared with conventional wavelength-interrogation SPR sensors that require a super wideband light source and a spectrometer (which is the main reason limiting their implementation using

infrared light waves), our approach requires only a narrowband light source with a wavelength span of several nanometers for measuring the phase-induced SPR, making the proposed sensing scheme practical and cost effective.

In conclusion, an FP-based SPR optical sensing approach has been proposed and investigated. Theoretical analyses have shown that the phase change induced by SPR effect can be monitored through the use of an FP cavity. Therefore, this simple approach enables high-resolution sensing through the use of narrow-waveband wavelength interrogation (or monitoring the output intensity of a fixed-wavelength laser signal) for measuring SPR-induced optical phase shift. The combination of SPR and FP effects has potential applications in biological and chemical sensing.

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