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Analysis of Spectral-Phase Conventional and Long-Range Surface Plasmon Resonance Biosensors

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ABSTRACT

We have analyzed and compared the spectral differential phase sensing performance for conventional and long-range (LR) surface plasmon resonance (SPR) across a wide sample refractive index range (i.e. dynamic range) of 1.3330-1.3505 using Fresnel's Equations and Transfer Matrix method. We demonstrate that wide-range detection limit as high as 7.9×10^{-9} RIU (Refractive Index Unit) for conventional SPR can be achieved with a set of optimized sensing parameters and a phase measurement resolution of 2×10^{-4} rad, whereas best detection limit for LRSPR is lower. We have also investigated for the effect of sensing parameters including angle of incidence, metal film material and thickness. LRSPR is found to be quite tolerant to the choice of material and thickness of metal film. This work presents a comprehensive comparison between conventional and LR SPR for spectral-phase configuration.

Keywords: Surface plasmon resonance, spectral phase, long-range, biosensors, wide dynamic range

1. INTRODUCTION

Since in 1983 Liedberg et al demonstrated the first practical biosensors based on surface plasmon resonance (SPR) [1], the research on SPR sensing technology and application has seen dramatic progress [2]. Surface plasmon resonance is achieved when highly confined electromagnetic waves, i.e. surface plasmon waves (SPW), are excited and propagate along the dielectric/metal interface. Conventional SPR sensors are based on the Kretschmann prism coupling configuration, in which a Sample-Metal-Prism structure is used. The reflection coefficients of the p- and s- polarized components (r_p and r_s) are expressed as $r_{p,s}(\lambda) = \sqrt{R_{p,s}(\lambda)} \exp[i\phi_{p,s}(\lambda)]$ [3]. Since the efficient excitation can only be achieved under strict conditions when the tangential wave vector of the incident p-wave matches with that of the SPW, SPR is found to be extremely sensitive to the sample's dielectric constant. When varying the angle of incidence or the excitation wavelength by the resonance point, reflectivity of the sensing film, i.e. $R_{p,s}(\lambda) = |r_{p,s}(\lambda)|^2$ experiences a sharp dip, whereas the differential phase, i.e. $\phi_p - \phi_s$, also comes with a dramatic change [4]. This advantage makes SPR a highly promising technology for bio- and chemical-sensing. Traditional SPR sensors are mostly reflectivity-based, and the corresponding detection limit is around 10^{-5} to 10^{-6} in terms of refractive index unit (RIU) [5, 6]. However, in recent years interferometric methods based on phase modulation have been reported to improve detection sensitivity from SPR biosensors by at least 2 orders of magnitude [7-14]. The phase-sensitive SPR approach has not yet gained widespread market adoption since the refractive index range that phase-sensitive SPR sensors can offer best performance (i.e. dynamic range) is limited to $\sim 10^{-3}$ RIU, while the dynamic range of commercial intensity-based sensors is typically around $\sim 10^{-1}$ - 10^{-2} RIU.

Recent years, phase-sensitive schemes using white light interferometry [15] and paired plasmons [16] have been proposed to resolve the dynamic range issue. Indeed the white light phase-sensitive SPR technique we recently reported has achieved detection limit better than 2.6×10^{-7} RIU and a dynamic range of 10^{-2} RIU [17]. Through conducting differential phase measurement across a range of wavelengths, the reported white light interferometric technique has the capability of finding a region of maximum phase transition within the spectrum of the excitation source in order to cover

a wide range of sample refractive indices. Since the performance of SPR sensors is closely associated with a number of system parameters including prism material, choice of material and thickness of metal film, angle of incidence etc., simulation studies on the interplay between various parameters will lead to important insights on the expected performance limits of this new sensor design. Based on the Fresnel's Equations and Transfer Matrix technique, one can perform simple but rigorous procedures to optimize the sensor layer structure. On the other hand, the use of Long-Range Surface Plasmon Resonance (LRSPR) as sensing scheme has been reported to have produced narrower SPR characteristics over conventional SPR. Typically, a LSPR structure contains a metal layer surrounded by two dielectric layers that have similar refractive indices [18-20]. But we have yet to see any report on LRSPR sensors based on phase-sensitive scheme, nor any comparison between its spectral differential phase performance and that in conventional SPR. Our work focuses on addressing several issues: (1) optimization of conventional and long-range SPR sensor parameters for achieving best performance over a relatively wide range of refractive index values (i.e. dynamic range); (2) comparison of sensing performance including best detection limit, dynamic range, tolerance to errors in thickness and incident angle etc. between conventional and long-range spectral phase SPR sensors

2. THEORY AND SIMULATION METHODS

Since previous literature has shown that the measurement of differential phase using an interferometer is practically feasible and the phase fluctuation is typically 2×10^{-4} rad or 0.01° in most experimental cases of phase-detecting SPR sensors [7, 9-12, 15, 17], we shall use 2×10^{-4} rad as the phase resolution baseline of our simulation for the purpose of making realistic relative assessment on the performance of the proposed scheme, so that this value should be readily achievable in most cases. Additionally, as the findings are based on beam propagation analysis using standard Fresnel's Equations, the conclusions should be sufficiently reliable to represent practical situations in general. In the present simulation investigation, the key to performance assessment under different conditions lies in the calculation of differential phase using an appropriate numerical analysis model. Here we use a Transfer Matrix method [3] to cover both single-layered structure in conventional SPR and multi-layered case in long-range SPR, i.e. sample-metal-teflon-BK7 structure.

Fig. 1 shows the transmission and reflection of electromagnetic wave in isotropic multi-layered system. A_k and B_k ($k=1,2,\dots,n$, n is the number of layers, i.e. $n=4$) are two electromagnetic waves propagating in transmission and in reflection respectively. Using transfer matrix M_{ij} to represent amplitudes in adjacent layers and propagation matrix P_{ij} to represent two interfaces of a particular layer, the n -layer system can be solved by

$$\begin{bmatrix} A_1 \\ B_1 \end{bmatrix} = M_{12} P_2 M_{23} P_3 \cdots M_{n-1,n} P_n \begin{bmatrix} A_n' \\ B_n' \end{bmatrix} \quad (1)$$

where transfer matrix M_{ij} and propagation matrix P_{ij} are given by

$$M_{ij} = \frac{1}{t_{ij}} \begin{bmatrix} 1 & r_{ij} \\ r_{ij} & 1 \end{bmatrix} \quad \text{and} \quad P_j = \begin{bmatrix} e^{-ik_y d_j} & 0 \\ 0 & e^{ik_y d_j} \end{bmatrix} \quad (2)$$

where t_{ij} and r_{ij} are p-polarized Fresnel coefficients of transmission and reflection, respectively. These two terms are

$$\text{given by } t_{ij} = \frac{2\varepsilon_i k_{yj}}{\varepsilon_i k_{yj} + \varepsilon_j k_{yi}} \quad \text{and} \quad r_{ij} = \frac{k_{yi}/\varepsilon_i - k_{yj}/\varepsilon_j}{k_{yi}/\varepsilon_i + k_{yj}/\varepsilon_j}$$

Figure 1. Schematic diagram of electromagnetic wave propagating in multi-layered system.

Given the fact that in the n -th layer only downward-propagating EM wave is present, i.e. $B_n'=0$, the p-polarized reflection coefficient $r_p=B_1/A_1$ can readily be calculated using Eq. (1). By the definition of r_p , the differential phase can be extracted (there is no phase change in s-polarized wave).

In our simulation, we use the first three terms of Sellmeier Equation to obtain the refractive index of glass prism [21], i.e.

$$n^2(\lambda)=1+\sum_{i=1}^3 \frac{B_i \lambda^2}{(\lambda^2-C_i)}, \text{ where } B_i, C_i \text{ are constants obtained from Ref. [22]. Dielectric constants of metals are taken}$$

from Ref. [23]. In our simulation investigation, the refractive index range is fixed at 1.3330-1.3505, which corresponds to that of 0 - 10% NaCl in water at room temperature [24] and should be sufficient to cover most bio-sensing situations. Since the LRSPR occurs with metal film surrounded by dielectric materials with symmetrical refractive indices (sample-metal-teflon), we set the refractive index of Teflon at the middle point of the sample refractive index dynamic range, i.e. 1.3418. This refractive index can be achieved since the refractive index of PTFE is 1.350 ± 0.033 and varies from different production processes [25].

Simulation range of incident light wavelength is chosen to match with a practical range of sample refractive indices. Also, the sampling resolution is carefully optimized to prevent errors due to aliasing. For each wavelength in the spectral range under investigation, our program will calculate the differential phase for a range of sample refractive index values. We choose the best detection limit value among all wavelengths for each refractive index data point in order to produce a plot showing the variation of detection limit with respect to RIU value. The phase detection limit is defined as the ratio between phase fluctuation (i.e. 2×10^{-4} rad) and the slope of the differential phase plot.

3. RESULTS AND DISCUSSION

3.1 Optimization of Conventional Spectral-Phase SPR sensors

In Fig. 2(a), we show the spectral-phase change characteristics versus refractive index from a typical 51nm gold/BK7 prism configuration for a wavelength range of 680-711nm with the angle fixed at 70.9° . Each plot contains a narrow and distinctive region in which a small variation of RIU value will result in very large phase swing. This effectively means that one can always find a suitable spectral peak within the RIU range of interest (i.e. 1.3330-1.3505) for achieving high detection sensitivity. It should be mentioned that the slope of differential phase goes from positive to negative as we change the wavelength across the SPR dip. Indeed, this configuration provides a detection limit better than $10^{-7.19}$ RIU (6.46×10^{-8} RIU) throughout the whole refractive index range of 1.3330-1.3505 (blue line of Fig. 2(b)), which is similar to experimental data (2.6×10^{-7} RIU) reported in the literature [17]. Fig. 2(b) also shows the variation of detection limit upon changing the angle of incidence. For our wavelength range, varying the angle of incidence only leads to a shift in the refractive index sensing region, while there are marginal changes in the shape of the plots and the absolute value of the detection limit.

Past research has shown that there exists an optimal thickness under certain conditions for both reflectivity dip and differential phase change [26]. Through varying the film thickness, one can optimize the wide detection range region for the sensor, i.e. Fig. 2(c), using specific conditions for each thickness. Fig. 2(c) indicates that sensitivity improves when metal film thickness increases from 45nm, and reaches its best at 51nm. After this peak, detection performance drops rapidly. This means sensing performance degrades less rapidly if the film is thinner than the optimal value. Further investigation shows this trend is generally true for different metal materials.

Figure 2. (a) Differential phase curves for different wavelengths. (b) System detection limit versus refractive index for different incident angles. (c) Effect of varying gold film thickness. Figure legends show gold film thickness, angle of incidence and wavelength range of each data point, respectively.

We have also investigated the effect of metal film uncertainty. Due to run-to-run film deposition variation, thickness uncertainty ($\pm 2\text{nm}$) can lead to degradation of SPR sensing performance while the angle of incidence remains fixed (Fig. 3(a)). Since in real situations the angle of incidence is often set to match the nominal thickness, it is important to analyze how tolerant the sensor is towards thickness deviation. For each of the cases, detection limit drops to around $10^{-6.80}$ with 1nm deviation and $10^{-6.60}$ with 2nm deviation. This indicates that best performance only occurs within a narrow range of thicknesses for a given incident angle. On the other hand, it is interesting to note from Fig. 2(b) and Fig. 3(a) that the spectral-phase SPR approach may offer the flexibility of maintaining high detection sensitivity over the RIU range of interest by adjusting the incident angle slightly even when the final sensor film thickness is not exactly identical to the optimum value, e.g. between 49 – 51 nm in the present case. Another issue is concerned with variation of material constants caused by deposition process and experimental environment. In a deposition process, the vacuum base pressure, deposition rate and substrate temperature are well under control. To use thickness uniformity, i.e. thickness variations within the sensing area or run-to-run thickness reproducibility, as a main parameter to represent process-related variations in the metal film should be a sensible approach.

For many years, gold has been the preferred material for SPR sensors in light of its chemical stability, despite that silver may offer as much as one order of magnitude improvement in sensitivity limit [8]. We have investigated the dielectric constants of the metals that are known to be SPR active, i.e. gold, silver, copper, aluminum and platinum. Dielectric constants of these metal materials are shown in Fig. 3(b) using data from Ref. [23]. In terms of wavelength dependence, the dielectric constants of gold, silver and copper show similar characteristics. On the other hand, aluminum and platinum exhibit quite different behaviors. In particular, the imaginary part of aluminum and platinum are much larger than those of other materials, thus resulting in rapid optical attenuation inside the medium. The sensor film hence has to be very thin ($\sim 10\text{nm}$) in order to excite surface plasmons efficiently. At this thickness, we see neither a sharp reflectivity dip nor any sharp differential phase change. On the other hand, it is interesting to note that there are very few reports on the SPR sensing performance of copper, despite that copper exhibits similar characteristics as gold and silver. We therefore focus our study on the performance comparison between copper and traditional sensing film metals. Thickness-dependent performance for gold, silver and copper is shown in Fig. 3(c). Our result indicates that the refractive index sensing performance of copper (46nm, 655–705 nm, 2.88×10^{-8} RIU) is slightly better than silver (48nm, 655–758 nm, 2.95×10^{-8} RIU), and is significantly better than gold (51nm, 680–711 nm, 6.46×10^{-8} RIU). Although copper is

chemically less inert than silver or gold, its much lower cost may offer a significant advantage, particularly for high volume production of SPR sensor devices.

Figure 3. (a) Effect of errors in controlling the gold film thickness on spectral-phase conventional SPR. (b) Dielectric constants of different metals with real and imaginary parts demonstrated respectively. (c) Spectral-phase conventional SPR detection limit versus film thickness for gold-, silver- and copper-films.

3.2 Optimization of Long-Range Spectral-Phase SPR Sensors

The spectral-phase SPR sensing performance of a typical long-range scheme is demonstrated in Fig. 4, with a set of optimized system parameters (BK7 Prism/1200nm Teflon/27nm Gold/Sample structure, 63.67° angle of incidence and 600-1100nm wavelength range). Fig. 4(a) shows the simulated reflectivity curves, which corresponds with previous literatures. We only show the results for five wavelengths in order to clearly indicate the trend of the curve shifting. Fig. 4(b) shows the best detection limit across the dynamic range gained from the spectral differential phase, whereas Fig. 4(c) shows a set of differential phase curves under different wavelengths. In the sample refractive index region of interest (1.3330-1.3505), the system offers a sensing detection limit better than $10^{-6.68}$ RIU (2.09×10^{-7} RIU). This detection limit is not as good as that in optimized gold-film spectral-phase conventional SPR indicated above. We note that the reflectivity curve experiences a smaller and flatter dip when sample refractive index is larger than the resonant point. At the same time spectral-phase detection limit curve also experience a small dip. We can thus make use of this small dip to extend the system dynamic range. Additionally, the wavelength range for spectral-phase LRSPR (600-1100nm) we use is much larger than that for spectral-phase conventional SPR. This is due to the fact that the excitation of LRSP corresponds only to a symmetrical structure surrounding the metal film, so the detection limit dip always occurs when the dielectric constants of sample and Teflon are the same. And we find that the proper wavelength range is quite fixed for different system parameters. When the wavelength is smaller than 600nm, we see very small differential phase. When wavelength exceeds 1100nm, the curves do not demonstrate much dispersion any more. Under such circumstance, continuously increasing wavelength does not lead to increase in dynamic range.

Figure 4. Performance of spectral-LRSPR. (a) Reflectivity curves for different wavelengths (600nm, 700nm, 800nm, 900nm, 1000nm). (b) Spectral-phase detection limit versus refractive index. (c) Differential phase curves for different wavelengths.

We have again investigated the effect of metal-film thickness and metal-film material on the spectral-phase performance. Fig. 5(a) shows optimized wide-range detection limit versus metal-film thickness using different metal materials, i.e. gold, silver and copper. Best detection limits for gold, silver and copper are respectively 1.91×10^{-7} RIU (26nm gold film with 63.63° angle of incidence), 2.04×10^{-7} RIU (26nm silver film with 63.605° angle of incidence), and 2.29×10^{-7} RIU (27nm copper film with 63.59° angle of incidence). Simulation results show that spectral-phase LRSPR sensing performance is not sensitive to metal material or metal film thickness. With 25-32 nm gold-, 25-32 nm silver-, or 27-29 nm copper-films, the optimized detection limits are always in the range from $10^{-6.60}$ RIU to $10^{-6.70}$ RIU. This characteristic readily offers two advantages. First, the system is quite tolerant to metal film thickness variation caused by deposition process (thickness error issue will be discussed later). Second, the use of alloy or multi-layered structures with these metals will not result in much deviation of the spectral-phase resolution curves. This means multi-layered structure using these metals will not change the detection limit performance much, e.g. a thin coating gold film which serves to prevent the oxidation of silver or copper layer. Another finding is that some other metals, e.g. aluminum, can also generate reasonable spectral-phase LRSPR curves, whereas they cannot be used for conventional SPR sensing. Simulation result for aluminum is demonstrated in Fig. 5(b). Although results show that aluminum cannot be directly used for the current configuration since its best-performance region cannot cover for our region of interest in the wavelength range of 600-1100nm, it still gives similar best detection limit point and can be used if reduced dynamic range is acceptable.

Figure 5. (a) Wide-range detection limits versus film thickness for gold-, silver- and copper-LRSPR configurations. (b) Spectral-phase detection limit versus refractive index for aluminum LRSPR.

Here we further investigate about how the performance insensitivity to metal-layer thickness of LRSPR would affect the application of spectral-phase LRSPR sensors. From the study of conventional SPR we know that if the angle of incidence is set at the ideal value for the nominal thickness, system detection sensitivity will drop by around 1.6 times/nm, and the wide-range detection limit degrades to around $10^{-6.60}$ RIU with ± 2 nm thickness variation. Fig. 6 demonstrated the simulation result for fixed-angle detection limit when metal film faces variations. When the thickness is smaller than the nominal value, we see similar performance degradation as conventional spectral-phase SPR. However on the right side of the nominal value, sensitivity drops by less than 25% with +2 nm thickness variation. This characteristic mainly results from two reasons: (1) the nominal angles of incidence for different thicknesses do not deviate much; (2) the detection resolution curves experience a minor dip on the right side of the ideal resonant point. This indicates that if the gold film thickness is in a range of 26-28 nm, which is readily achievable using standard deposition equipment, we can directly fix our angle of incidence at 63.63° and the sensing detection limit will remain at the level of $10^{-6.60}$ RIU (2.51×10^{-7} RIU). This offers a convenient approach to achieve fast but highly sensitive bio- and chemical-sensing with good tolerance to variation in metal films.

Figure 6. Effect of gold film thickness variations on spectral-phase LRSPR.

4. CONCLUSIONS

We have investigated the spectral-phase sensing performance in a sample refractive index dynamic range of 1.3330-1.3505 for both conventional SPR and long-range SPR configurations using Fresnel's equations and the Transfer Matrix method. This is the first time that spectral-phase LRSPR performance is analyzed and the comparison between conventional and long-range spectral-phase SPR is presented. For conventional spectral-phase SPR, we indicate that copper as a sensing film can offer a detection limit of 2.88×10^{-8} RIU across the sample refractive index range of interest. The optimized parameters are 46 nm copper film, 70.5° angle of incidence and 655-705 nm wavelength range. The best detection limits for silver and gold are respectively 2.95×10^{-8} RIU (48 nm film thickness, 68.3° angle of incidence and 655-758 nm wavelength range) and 6.46×10^{-8} RIU (51 nm film thickness, 70.9° angle of incidence and 680-711 nm wavelength range).

wavelength range). Best spectral-phase sensing performance for LRSPR is found to be 1.91×10^{-7} RIU with BK7 prism/26nm gold film/1200nm Teflon structure, 63.63° angle of incidence and 600-1100nm wavelength range). For silver and copper, the best detection limits are respectively 2.04×10^{-7} RIU (film thickness, angle of incidence and wavelength range equal to 26nm, 63.605° and 600-1100 nm) and 2.29×10^{-7} RIU (27nm, 63.59° and 600-1100 nm). Spectral-phase LRSPR does not give as high sensitivity as conventional SPR configuration, and it need much larger wavelength range since the differential phase curve does not shift much against change in wavelength. If we use narrower dynamic range, LRSPR may offer much better sensitivity and other metals such as aluminum can also be used as sensing layer. On the other hand, the best detection limit of LRSPR is found to be insensitive to the choice of metal film material and its thickness. We have analyzed the effect of errors in controlling metal film thicknesses for both conventional and long-range SPR. Our results show that with angle of incidence fixed at the ideal value for the nominal thickness, LRSPR is much more tolerant to thickness error than conventional SPR.

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