A surface plasmon biosensor based on sub-wavelength metal slit arrays

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Abstract. A novel surface plasmon sensor which is constructed with sub-wavelength metal slit arrays deposited on a buffer media layer is proposed. To obtain the maximum resonant transmission, the buffer layer is coated on a glass substrate and the refractive index of the buffer layer is selected close to that of the water environment. Based on rigorous coupled wave analysis, the numerical simulation shows that the resonant transmission is enhanced and the peak mediated by surface plasmon resonance is much sharper due to the buffer layer. Therefore, this surface plasmon sensor with a buffer layer provides an improved measurement precision in biosensing application.

1. Introduction
The surface plasmon resonance (SPR), excited in periodic metal nanostructures, causes an enhanced transmission of light which is accompanied by strong field localization and has great potential applications in biosensors [1-5]. The wavelength of enhanced transmission depends on the refractive index of a thin layer of solution near metal-solution interface. Thereby, the binding of biomolecules to the metal nanostructures surface causes a resonant wavelength shift due to their refractive index change. Moreover, Using the resonant wavelength shift in transmission spectrum as sensing signal results in a miniature bioanalytical instrument due to the simple optical setup, the metallic nanostructures are expected to be applied for high-throughput and chip-based detections, such as DNA microarrays and protein microarrays [6, 7].
Two types of structure of periodic nanohoes and nanoslits are used as sensing elements [8-9]. Nanoslit-based structure is demonstrated with higher sensitivity than that of nanohole-based structure and is good candidates for sensing designs. In general, sub-wavelength metal slit arrays are directly deposited on the substrate such as silicon, glass. Such structure was demonstrated with high sensitivity, but its wavelength resolution was poor due to large bandwidth of transmission resonance spectrum. To get sharp transmission resonance peak, short slit gap and large metal layer thickness are needed, however, which would result in the resonance peak attenuated due to strengthening of absorption phenomena and different resonant phase matching conditions between the refractive indices of substrate and outside water environment.

In this paper, we propose a BK7 glass/Cytop/sub-wavelength Ag slit arrays /water environment multilayer structure where Cytop is an amorphous fluoropolymer with a refractive index very close to that of water. High resonant transmission peak intensity is achieved for the Cytop buffer layer and outside water environment have the same resonant phase matching conditions.

2. Principle and design

The schematic of sub-wavelength metal slit arrays is shown as figure 1 and all the components are treated as semi-infinite along y-direction. In figure 1 (a), the metal layer is directly deposited on the substrate without the buffer layer, while in figure 1 (b), a buffer layer is deposited on the substrate first and then the metal layer is deposited on the buffer layer. The material of metal slit array is Ag and its dielectric constant is described by the Lorenze-Drude model [10]. The substrate is selected as BK7 glass whose refractive index ($n_s$) is 1.51, the material of the buffer layer is Cytop whose refractive index is 1.31, close to that of pure water (1.3335).

For sub-wavelength metal slit arrays, two types of SPR excitations are shown to be possible, where one at the upper grating-analyte interface and the other one at lower grating-substrate interface which is affected by the multiple interference or cavity-type effects. The transmission of normally incident light through sub-wavelength metal slit arrays is enhanced at the wavelengths that satisfy the SPR conditions as

$$\lambda = p \frac{\varepsilon_d \varepsilon_a}{\varepsilon_d + \varepsilon_a}$$

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Figure 1. Schematic of sub-wavelength metal slit arrays without (a) and with (b) the buffer layer.
where $\lambda$ is the resonant wavelength, $p$ is the period of array, $\varepsilon_m$ and $\varepsilon_d$ is the dielectric constant of metal and the adjacent medium, respectively. The enhanced transmission peak mediated by SPR at the upper grating-analyte interface is related to the outside surface condition and using this enhanced peak wavelength as signals, high density sensing arrays have been demonstrated.

It is well known that small bandwidth of the enhanced transmission peak will result in large measurement precision. In sub-wavelength slit arrays, the resonant bandwidth is dependent on slit width and metal layer thickness. The bandwidth of resonant peak can be narrowed with slit width decreasing and array thickness increasing, however, for the structure as shown in figure 1 (a), the resonance peak becomes attenuated due to strengthening of absorption phenomena. To improve this problem, the Cytop is chosen as buffer layer material whose refractive index is close to that of the water environment as shown in figure 1(b). From equation (1), it is known that the SPRs at upper grating-analyte interface and at lower grating-buffer interface are almost the same, therefore, they could couple with each other and more energy can be transmitted at the resonance wavelength.

3. Simulation and discussion
The rigorous coupled wave analysis (RCWA) [11] is adopted to analyze sub-wavelength metal slit arrays. In most SPR biosensors, water environment is preferred; therefore all the simulation is under the water environment condition. To achieve narrow bandwidth, the dimensions of sub-wavelength metal slit arrays are chosen as: the slit width $w=40$ nm, the Ag array thickness $d=150$ nm and the grating period $p=600$ nm, and TM incident light (with the magnetic field parallel to the slit direction) is only considered.

![Figure 2](image1.png)  
**Figure 2.** The transmission spectrum of sub-wavelength metal slit arrays with and without the Cytop buffer layer.

![Figure 3](image2.png)  
**Figure 3.** The dependence of the enhanced peak intensity on the buffer layer thickness.

The calculated transmission spectrum of sub-wavelength metal slit arrays with and without the Cytop buffer layer is shown in figure 2. The enhanced transmission peaks for the two cases are both at 800 nm, which are induced by the SPR at the upper grating-analyte interface. The intensity of the enhanced transmission peak when without the buffer layer is too small, just about 1.67 to identify. However, with 500 nm thick buffer layer, the intensity of the enhanced transmission is almost three times larger than that without the buffer layer and the bandwidth of peak is as narrow as 5 nm.
The SPR mode localized on the lower grating-buffer interface is influenced by the substrate, if the buffer layer thickness is less than the SPR field penetration depth. In this case, the buffer layer and the substrate can be considered as an equivalent semi-infinite medium with an effective dielectric constant 
\[ \varepsilon_{\text{eff}} = \varepsilon_{\text{buf}}^{-1} \left[ 1 - \exp(-h/g) \right] + \varepsilon_{\text{sub}}^{-1} \exp(-h/g) \]
under lowest order approximation [12], \( \varepsilon_{\text{buf}} \) and \( \varepsilon_{\text{sub}} \) are the dielectric constants of the buffer layer and the substrate, respectively, \( g \) is the penetration depth of the SPR field localized on the lower grating-buffer interface and \( h \) is the thickness of the buffer layer. The effective refractive index \( n_{\text{eff}} \) of the equivalent semi-infinite medium can be calculated from the effective dielectric constant of \( \varepsilon_{\text{eff}} \). So the effective refractive index \( n_{\text{eff}} \) depends on the buffer layer thickness and is in the range of the buffer refractive index \( n_{\text{buf}} \) (1.31) to the substrate refractive index \( n_{\text{sub}} \) (1.51). When the effective refractive index \( n_{\text{eff}} \) is equal to the water environment refractive index, the resonant peak obtains the maximum transmission.

To get the optimal thickness range of the buffer layer, various values of the buffer layer thickness are used in the calculation. Figure 3 shows the dependence of the enhanced peak intensity on the buffer layer thickness. It can be clearly seen that there is a maximum transmission value about 0.487 at depth of 500 nm, when the depth is less than 500 nm, the transmission increase with depth; when the depth is more than 500 nm, it is in verse. Moreover, when the thickness is in the range of 370-670 nm, the transmission is beyond 0.45, which is considered as the optimal thickness range of the buffer layer due to high resonant transmission.

![Figure 4](image_url)

**Figure 4.** Transmission spectrum against the refractive index of the water environment
(a) Without the buffer layer. (b) With the buffer layer.

Figure 4 shows the transmission spectrum in water and different methanol/water mixtures under the conditions without and with the buffer layer. The refractive indexes of pure water and different methanol concentrations of 10\%, 20\%, 30\%, 40\%, 50\% are 1.3335, 1.3355, 1.3380, 1.3400, 1.3415 and 1.3320, respectively. The buffer layer thickness is 500 nm. It is noted that both the enhanced resonant peaks in figure 4 (a) and (b) move toward long wavelength with increasing refractive index of the outside medium, which is predicated by the equation (1). The resonant peaks in figure 4 (b) have better spectral resolution than that in figure 4 (a) due to higher resonant peak intensity and narrower bandwidth.
Figure 5 shows the dependence of the resonant peak wavelengths on the refractive index of the outside medium and the corresponding linear fitting curves. The slope of the fitting curves shows the sensitivity to bulk refractive index change of the outside medium. When the structure without the buffer layer, the sensitivity to bulk refractive index is as high as 600 nm/RUI while 535 nm/RUI for the structure with the buffer layer. So the sensitivity is affected by the buffer layer. Meanwhile, the bandwidth of resonant transmission peak is narrowed and become sharper, greater accuracy on the measurement of the resonant wavelength provides better refractive index resolution.

4. Conclusion
In summary, the transmission spectrum of sub-wavelength metal slit arrays in the water environment is investigated based on the rigorous coupled wave analysis. The numerical simulations show that the resonant transmission can be enhanced by inducing the Cytop buffer layer. Choosing the optimum buffer layer thickness, the resonant transmission peak intensity becomes largest and the sensitivity of sub-wavelength metal slit arrays remains high although which is affected by the buffer layer. Therefore adopting the buffer layer of the optimum thickness and the periodic array of narrow slit and thick metal layer, the SPR peak with narrow bandwidth and high transmission peak intensity would be achieved, which guarantees accurate determination of peak location.

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