Design and study of microfluidic differential phase surface plasmon resonance sensor

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Abstract—In this project we design and study a differential phase surface plasmon resonance sensor combining with microfluidic technology. The differential phase Surface Plasmon Resonance (SPR) sensor is constructed by applying the Kretschman plasmon excitation structure and combing with interference spectroscopy. Through making use of simulation and experimental method, the principle of SPR sensor is theoretically and experimentally studied. In this project, we apply the SPR sensor in testing urea solution with varying weight concentration. Through the results, it can be observed that the plasma resonance absorption ranges from 640 nm to 840 nm and its detection limits can reach 0.0004 RIU. Due to its tunable plasma absorption and lower detection limits, the microfluidic differential phase surface plasmon resonance sensor illustrates a promising future in chemistry, physics and biology.

1. Introduction

SPR sensing as a novel optical sensing technology with high sensitivity, real-time response and label-free is widely used in biological and chemical fields, such as: clinical diagnosis [1], biosensor and drug analysis [2], food quality and safety assessment [3], environmental monitoring, gas detection [4], etc. Tarik et al. investigated a new coronavirus detector using SPR sensor with a detection limit of 153.85 °/RIU. Castiello et al. completed quantitative analysis of human insulin hormone based on multivariate SPR imaging, which has a detection limit of 1 nM for insulin [5]. Ashley used SPR for the detection of food allergen levels in production lines [6], and the team researched and developed an SPR sensor with α-casein-specific antibodies with a detection limit of 58 ng mL⁻¹. Also, SPR detectors can be applied for the detection of heavy metals, organic contaminants, and bacterial detection in the aqueous environment [7]. Although SPR sensors have many advantages, their poor adaptability to complex or harsh environments, low sensitivity in label-free small molecule detection and poor ability to distinguish small molecules by non-specific adsorption have limited the application of SPR sensors. Therefore, improving the sensitivity, stability, specificity and resolution of SPR sensors has become a hot research topic in this field.

In this work, we built and studied a microfluidic differential phase SPR sensing system by combining the design of a white-light co-circuit SPR sensing system with nanotechnology [8] and microfluidics [9]. By applying this system to the detection of aqueous urea solutions, it was found to have adjustable resonance absorption, wide detection range and low detection limit. Therefore, the system has very good application prospects in chemical, physical and biological fields.
2. Construction of optical system

Figure 1(a) shows a schematic diagram of the SPR sensor optical path system. The system consists of a halogen lamp light source, two linear broadband polarizers, a 300 μm thick undoped yttrium vanadate birefringent crystal, a lens, a detection prism, and a spectrometer (Fuxiang Optics PG2000) with a resolution of 0.13 nm - 0.75 nm. The light source is derived from an optical fiber and connected to a collimating lens, after which the beam passes through a linearly polarized lens at an angle of 45° to the vertical direction and then through a birefringent crystal placed horizontally on the optical axis. After passing through the birefringent crystal, the o-light and e-light undergo total reflection at the interface of the detection prism, where the o-light excites the surface plasmon effect of the gold film in the detection prism and most of the o-light is absorbed. o-light and e-light exit the prism and pass through a line polarizer at an angle of 45° to the vertical direction, their polarization directions are tuned to the same direction and collected using a spectrometer.

![Light path diagram of SPR sensor.](image)

3. Test Results and Discussions

Figure 2 shows a schematic diagram of a prismatic microfluidic chip, in which the microfluidic channel is coupled to a metal film. The flow rate of the solution in the microfluidic channel is controlled by a microfluidic pump, and the flow rate can be regulated from 1 μl/min to 1000 μl/min. The metal film is vapor deposited by a thermal evaporation deposition system on top of the BK7 glass with a thickness of 50 nm, and the BK7 glass loaded with the gold film is bonded to the prism by a matching solution with a refractive index of 1.5200. When the incident light angle is adjusted to the surface of the gold film for plasma excitation, the interference spectrum can be observed by the spectrometer. When the p-polarized beam passes through the prism at an angle greater than or equal to the critical angle, the total reflection phenomenon occurs, and the fading wave is generated at the n0 - n3 interface. When the fading wave vector and the gold film surface plasma excitation wave vector exactly match, the surface plasma resonance effect will occur, most of its energy is used to excite the SPR, a very small amount is reflected, the reflected light spectrum will be obtained through the spectrometer. As the SPR effect is very sensitive to the change of dielectric constant of the gold thin film interface, when the material on the surface of the gold film changes, its interface dielectric constant also changes leading to the change of plasmon resonance absorption, that is, its surface plasmon resonance effect excitation wave vector
changes. The change will cause the phase change of the interference spectrum, through this change can be judged by the gold thin film interface material changes.

In order to test the detection performance of differential phase spectral interferometric sensing measurement system with co-optical path structure, different concentrations of aqueous urea solutions were tested. Distilled water was prepared before the experiments and proportioned to low concentration urea aqueous solutions with mass fractions of 0%, 0.3%, and 0.6%, and high concentration urea aqueous solutions of 1%, 3%, 6%, 9%, 12%, 15%, 18%, 21%, 24%, 27%, 30%, 33%, and 36%, respectively. For the experimental tests, the light source was first allowed to run for 30 min to stabilize its output. After that, when the signal spectrum of the optical path to be measured is stable, 0%, 0.3% and 0.6% low concentration urea aqueous solutions are injected into the microfluidic channel at a rate of 10 μl/min for 500 seconds continuously by a microfluidic syringe pump for measurement and data acquisition, respectively. The spectrometer sampling integration time was 1 s, and the average value was collected five times. Similarly, 1%, 3%, 6%, 9%, 12%, 15%, 18%, 21%, 24%, 27%, 30%, 33%, 36% high concentration urea aqueous solutions were measured and data were collected. It is worth noting that the microfluidic channel is cleaned with deionized water after each sample enters the microfluidic channel at a flow rate of 10 μl/min for 10 min.

To test the performance of the designed SPR detection system, we combined water (RI = 1.3330) with mass fractions of 1% (RI = 1.3345), 3% (RI = 1.3373), 6% (RI = 1.3420), 9% (RI = 1.3466), 12% (RI = 1.3512) 15% (RI = 1.3558), 18% (RI = 1.3604), 21% (RI = 1.3651), 24% (RI = 1.3700), 27% (RI = 1.3743), 30% (RI = 1.3789), 33% (RI = 1.3836), and 36% (RI = 1.3882) of the highly concentrated urea aqueous solution flowed sequentially through the detector through the microfluidic channel and obtained the results shown in Figure3 (a-n ). From Fig. 3 (a-n), it can be observed that the resonance absorption interference peak position changes when different mass fractions of aqueous urea solutions flow through the detector. It is noteworthy that the resonance absorption wavelengths were recorded using estimated readings after the interferometric spectrogram of the aqueous urea solution with a mass fraction of 24%, since the position of the resonance absorption peak is close to the wavelength position where the spectrogram does not interfere. Figure 4 demonstrates the relationship between the mass fraction of aqueous urea solution and its plasma resonance. From Figure 6, it can be learned that as the mass fraction of urea aqueous solution increases, the position of its resonance absorption peak wavelength shifts red and the resonance wavelength becomes larger. This is due to the fact that as the concentration of urea at the interface of the gold film gradually becomes larger refractive index, the interface dielectric constant becomes larger, which is consistent with the simulation results. The sensor
performance is two orders of magnitude higher than the detection accuracy of the SPR sensing spectrometer with high detection resolution based on angular modulation by Xinlei Zhou et al [10]. The sensor performance is two orders of magnitude higher than the detection accuracy of the D-type fiber SPR infrared sensor based on wavelength modulation by Chao Liu et al [11].

Fig. 3 (a-n) Interference spectrum of water, 1%, 3%, 6%-36% urea aqueous solution

Fig. 4 The relationship between the refractive index of water and the concentration of 1%, 3%, 6%-36% urea aqueous solution and its interference light resonance absorption peak position
4. Conclusion

Based on the results and discussions presented above, the conclusions are obtained as below:

(1) It is shown that a microfluidic SPR sensing system based on the combination of a white-light common path interference system and a prismatic SPR excitation principle is investigated. The system adopts the Kretschmann-Raether type of SPR excitation structure, and the prismatic SPR sensing system with five layers of media is designed and built based on the Maxwell equation system and the Fresnel multi-layer media refraction theory.

(2) The failure forms of the system to the detection of urea in aqueous solution, and it was found that the plasmon resonance absorption of the system can range from 640 nm to 840 nm, and the detection accuracy of the system can reach 0.0004 RIU when the refractive index of the measurement medium ranges from 1.3330 RIU to 1.3338 RIU. Composite slabs involve local buckling of the thin-wall steel beams, overall torsion of the steel beams and through cracks on top surface and lower surface of concrete panel.

(3) It is concluded that the excellent performance of this device, it has a great potential to be used in the fields of biosensors, environmental testing, food safety, drug screening, etc.

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