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Analysing surface plasmon resonance phase sensor based on Mach-Zehnder interferometer technique using glycerin

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ABSTRACT

Surface Plasmon Resonance (SPR) based on Mach-Zehnder interferometer (MZI) is a very accurate tool for the detection and analysis of molecular interactions. The performance of the proposed SPR phase sensor is dependent upon multiple performance parameters that include sensitivity, repeatability, drift and the induction speed of fluid into the flow cell. The SPR Mach-Zehnder interferometer is tested for different glycerin–water concentrations to check its performance based on the different parameters. This paper highlights the enhancement of the performance of SPR phase technique based on MZI that is influenced by different parameters, measured using glycerin solutions. These four performance parameters can affect the performance of SPR based on MZI and have a particular impact on the sensor output. It also provides us information about suitable working conditions for the SPR Mach-Zehnder interferometer sensor. The experiment data shows that the sensor's sensitivity is high for small concentrations of glycerin–water mixtures. Also, any change in drift as well as in induction speed of fluid can affect the performance of SPR Mach-Zehnder interferometer. The sensitivity of SPR phase sensor is high as it can measure glycerin concentration as low as 0.05%.

1. Introduction

In the last two decades, a lot of work has been done on SPR and further developments are still under way to make it a more reliable approach for molecular interaction analysis. The SPR sensors are developed for sensing biological quantities as well as for chemical analysis [1]. There are several optical methods used for the detection of biological and chemical quantities based on the concepts of fluorescence, refractive index (n) and absorbance, but the SPR method is unique in that it is observed at the metal-glass interface [2]. The biomolecular interaction and label-free detection of biological and chemical samples are done by SPR biosensors in real-time quantitative analysis with high sensitivity [3]. The SPR phase technique is a popular bio-sensing approach used to enhance the detection limit and sensitivity of the conventional SPR setup. The detection limit and sensitivity are the main parameters that affect the performance of the SPR sensor, so with the help of SPR phase technique the performance can be improved [4]. In order to improve the detection and sensing performance of a conventional SPR sensor, interferometry techniques are utilized for SPR measurements. An Interferometer is used to measure the phase changes due to changes in the refractive index of the metal film. A sharp reflectivity dip occurs when an intensity goes to a minimum value at SPR resonance angle and phase of the reflected beam changes rapidly [5]. Compared to conventional SPR techniques, SPR phase interferometer exhibits advantages like improved spatial phase resolution and higher sensitivities. By intermixing two beams through interferometry, the sensitivity of the SPR sensor is increased in a precise way and the phase difference of the light beams is deduced from the interference fringe patterns. Consequently, the bio-molecular reaction information can be extracted accurately using the phase information obtained from the interference pattern. The SPR interferometry detection schemes offer very high phase-sensitive SPR sensors with enhanced output and the capability to measure smaller molecules [6]. The phase shift can be taken as an information parameter for sensor applications. However, the phase measurements in practice results in increased sensitivity but complicates the procedure of the process in real-time [7].

For the purpose of detecting the SPR phenomena, the interferometry technique is used to measure the n changes, surface irregularities, small displacements and study the light absorption properties [8]. The waves are intermixed using the principle of superposition and the generated combined output provides some useful information about the waves [9]. Fabry–Perot interferometer (FPI), Mach-Zehnder interferometer (MZI) and

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Michelson interferometer are the commonly used interferometers for the measurement of SPR. However, the MZI is preferred due to its simplicity and ease of implementation [10]. After the selection of the interferometer, there are multiple approaches available for the measurement of SPR changes such as phase shift, intensity, wavelength and angle interrogation, with the most prominent approach being the phase shift approach [11]. The phase is highly sensitive to small changes in n of the adjacent medium and is dependent on the parameters of the laser light reflected from the metal surface [12]. Therefore, the SPR phase technique helped us to study the nature and properties of the medium at high resolution with a lower detection limit [13]. We have experimentally tested the Mach-Zehnder interferometer-based SPR technique through ten different glycerin concentrations. The proposed setup covered a wide range from 0.05% to 20% with more glycerin concentration values compared with work done previously, with the lowest detection limit of 0.05% of glycerin concentration, an improvement over the previous limit of 0.1% [14]. Sensitivity is also optimized by incorporating some particular features.

The unique feature that optimized the performance of the proposed SPR Mach-Zehnder setup compared to previous work is the utilization of the high speed and sensitive Thorlabs DET10N-InGaAs (range: 500–1700 nm) photo-detectors that were used to measure the s- and p-polarization signals, resulting in improvement in SNR. The thickness of the gold film is fixed at 40 nm to get maximum SPR response. The flow rate of the fluid inside the flow cell is optimized to attain maximum sensitivity, while the speed of the peristaltic pump was fixed at 80 revolutions per minute (rpm). The temperature of the laser was made stable at 25 °C at constant room temperature and optimized digital filtering significantly decreased variations in phase measurements. As a result, the proposed SPR phase sensor is highly sensitive, allowing us to measure glycerin–water mixture in concentrations as low as 0.05%. In this paper, we demonstrated the performance of the proposed SPR Mach-Zehnder Interferometer based on four different parameters. These performance parameters are sensitivity, reproducibility, drift and the induction speed of the Glycerin–water solution into the flow cell. For the best results, the environment should be free of noise and mechanical vibration, and is kept under controlled temperature. The air flow rate must be maintained to avoid drift and other performance-affecting factors.

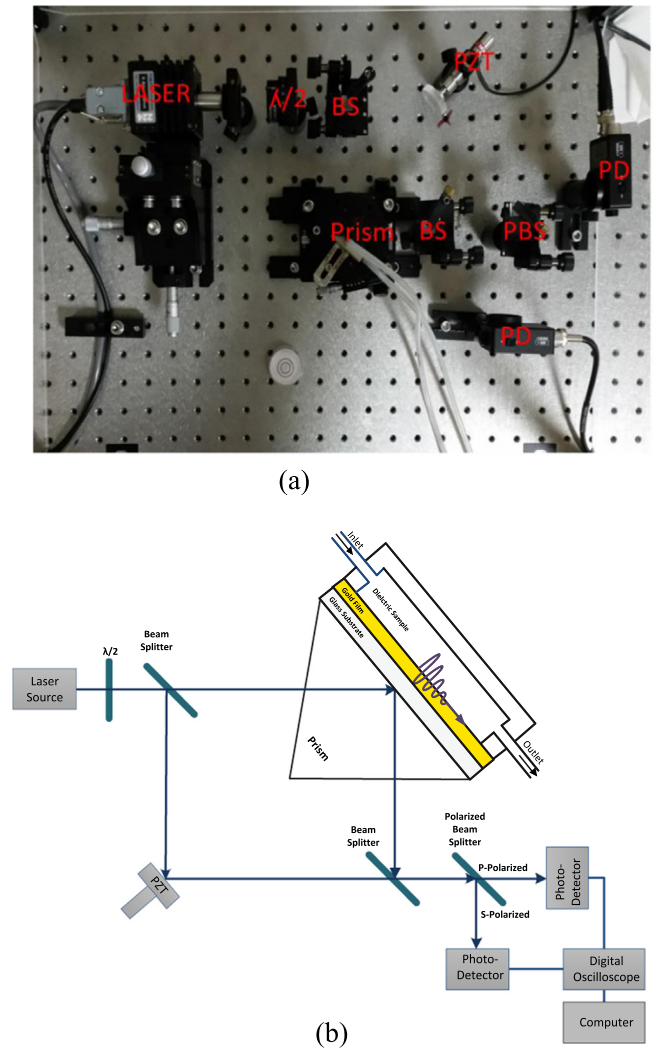

Fig. 1. The Phase SPR sensor which is based on Mach-Zehnder interferometer. (a) The experimental setup where BS is the beamsplitter, PBS is the polarization beamsplitter, PD is the photodetector, PZT is the piezo actuator and λ/2 is the Half-wave plate. (b) The schematic diagram of the experimental setup.

2. Experimental setup

The performance of the proposed sensor was examined using glycerin–water solutions with deionized (DI) water taken as reference. The Phase SPR sensor based on Mach-Zehnder interferometer is used to measure sensitivity, repeatability, drift, and induction of solution into the flow cell. All these parameters were observed in terms of their effect on phase shift. In this experiment, the Kretschmann configuration is adopted to perform the SPR as shown in Fig. 1. The prism coupled waveguide consists of four layers; the topmost being the glycerin–water solution, followed by gold (Au) thin film, glass substrate and prism, respectively. A single mode Litrax LX-VCS-850-T101 vertical-cavity surface emitting laser (VCSEL) operating at a wavelength of 850 nm was used as the optical source with 1 mW output power. In this configuration, the thickness of the glass substrate, Au thin film and glycerin–water solution are $d_1 = 0.14$ mm, $d_2 = 40$ nm and $d_3 = 6$ mm, respectively. In the proposed Mach-Zehnder interferometer setup, the laser source was used to produce a collimated light beam and the required polarisation state was achieved by employing the half wave plate. The beam splitter was then used to split the light beam into its component parts: a probe and a reference beam. The probe beam entered the prism coupled waveguide that was based on the Kretschmann configuration and went through the phase changes due to p-polarization. A reference mirror mounted on piezoelectric transducer (PZT) was utilized to modulate the reference beam at a frequency of 20 Hz. The reference and probe beam were recombined to generate an inference pattern of 10 fringes. A polarized beam splitter was used to separate the p- and s-polarizations. Eventually, both the signals were detected using the sensitive and high speed Thorlabs (DET10N InGaAs) photo-detector. The phase information is then extracted using an oscilloscope and a computer system.

3. Results and discussions

3.1. Differential phase response

In this experiment, nine glycerin–water concentrations ranging from 0.05% to 20% together with deionized (DI) water as reference were examined to check the performance of the SPR Phase sensor. For the proposed Mach-Zehnder interferometer, the SPR differential phase stepped up with respect to time as the glycerin concentration was changed in a fixed amount as shown in Fig. 2. The phase response was different for each level, depending upon the