Sensing of liquid analytes using surface plasmon resonance at different angles of incidence

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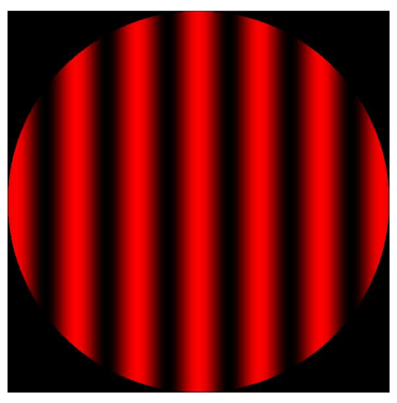

Abstract

A new method of sensing small refractive index changes of a liquid analyte using the effect of surface plasmon resonance (SPR) is presented. The method is based on detection of the phase shift induced by SPR in the Kretschmann configuration with an SPR structure comprising an SF10 glass prism, a gold coated SF10 slide with chromium adhesion layer, and an analyte (aqueous solutions of ethanol). First, the theoretical modeling of the phase shift at different angles of incidence induced by SPR is performed using the material dispersion characteristics. Second, the theoretical modeling is accompanied by an experiment utilizing a polarimetry setup [1, 2] to detect the spectral phase shift induced by SPR. In addition, the phase shift is measured at a specific wavelength as a function of the analyte parameter.

1. Theoretical results

Let us consider the SPR structure shown in Fig. **??**. It consists of three thin layers surrounded by two semi-infinite media.

- Analyte (semi-infinite, consists of ethanol and distilled water in weight ratio 0 wt%, 1.25 wt%, 2.5 wt%, 5 wt% and 10 wt%)
- Thin film of effective medium ($t_3 = 2$ nm)
- SPR layer of gold ($t_2 = 44$ nm)
- Adhesive layer of chromium ($t_1 = 2$ nm)
- Glass SF10 (semi-infinite)

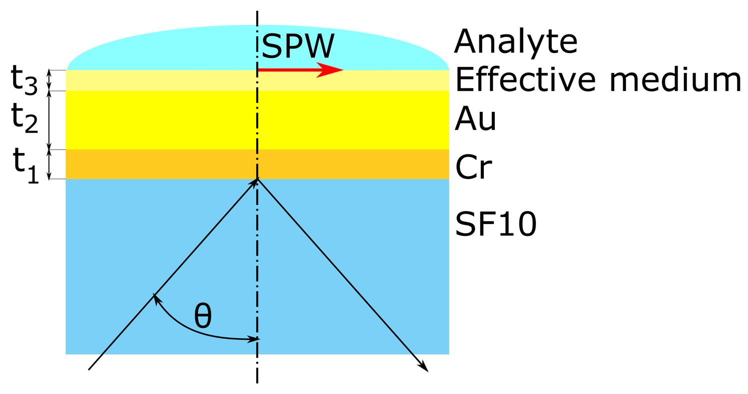

Figure 1: *The SPR structure considered for theoretical modeling.*

According to the reflection coefficients $r_{s,p} = |r_{s,p}|e^{i\phi}$, where $\phi_{s,p}(\lambda)$ is spectral phase state and indices s and p indicate polarization states, a light wave is reflected from the structure. These reflection coefficients can be expressed using dispersion characteristics. The spectral phase shift is then expressed as $\Delta_{SPR}(\lambda) = \Phi(\lambda) - \Phi_{REF}(\lambda)$, where $\Phi(\lambda) = \phi_s(\lambda) - \phi_p(\lambda)$ is the phase difference between s- and p- polarized components for analyte, when SPR occurs and $\Phi_{REF}(\lambda)$ is the reference phase difference, when SPR effect does not occur. Figure **??** shows theoretical results of the phase shifts for several angles of incidence in a range from 54° to 66°.

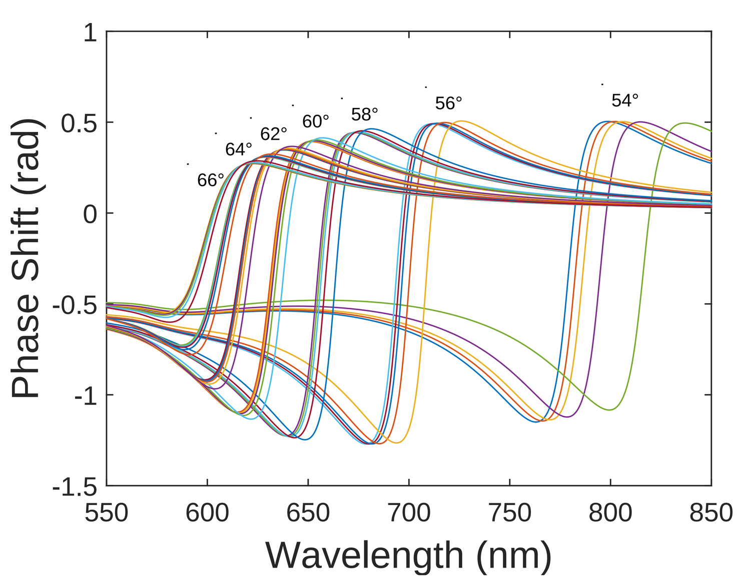

Figure 2: *Theoretical phase shifts computed for several angles of incidence and five analytes with various wt% of ethanol.*

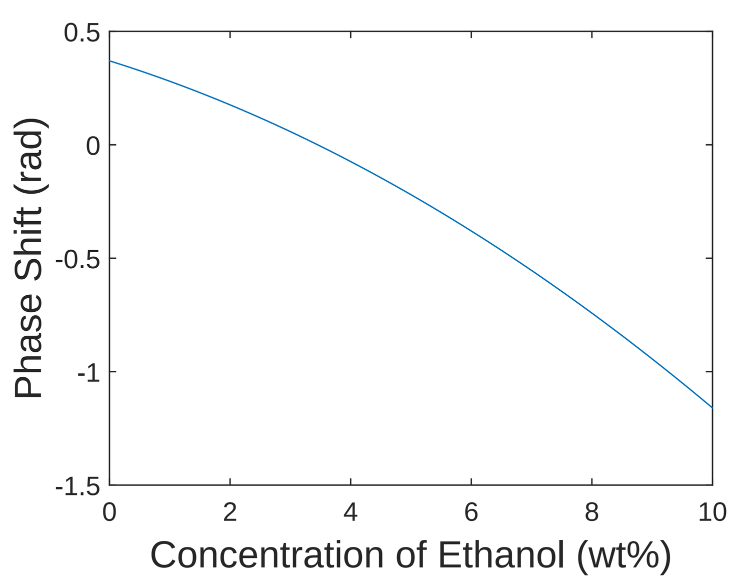

Figure 3: *Phase shift as function of concentration of ethanol in analyte (λ =700.91 nm, angle of incidence 56°).*

The most significant changes are related to angle 56°. For this and larger angles, it offers to measure the phase shifts at one specific wavelength as a function of some analyte parameter - concentration of ethanol (Fig. **??**). Sensitivity for angle of incidence 56° reaches 0.263 rad/wt%. In Fig. **??** are shown spectral derivatives of the phase shifts. For smaller angles, it is appropriate to measure positions of derivative peaks as a function of concentration of ethanol (Fig. **??**). In this case, sensitivity for angle of incidence 54° reaches 4.8 nm/wt%.

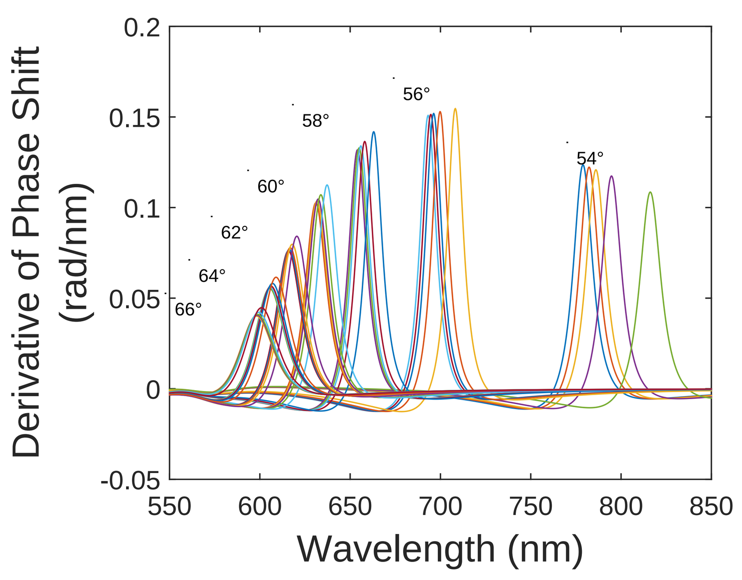

Figure 4: *Derivatives of phase shifts computed for several angles of incidence and five analytes with various wt% of ethanol.*

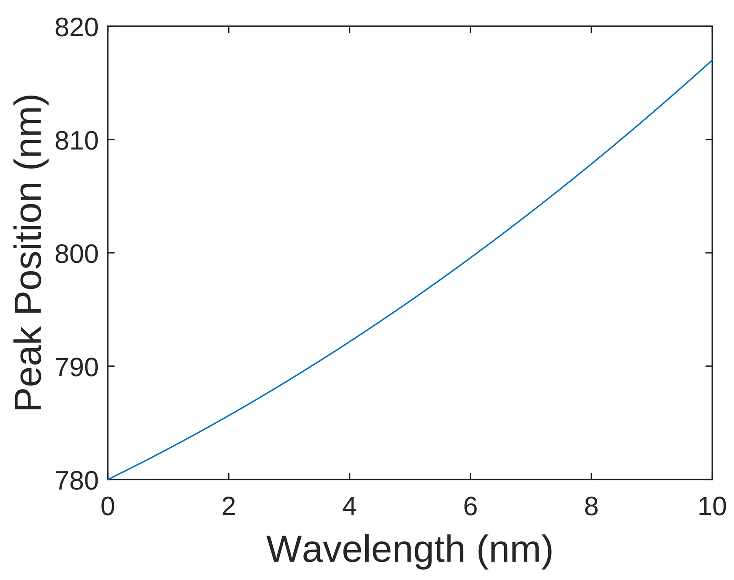

Figure 5: *Derivative of phase shift as function of concentration of ethanol (angle of incidence 54°).*

2. Experimental results

Experimental setup is shown in Fig. **??** and angle of incidence is approximately 60° since a light beam reaches a coupling prism face perpendicularly. Thickness of the golden layer is 44.8 nm and the adhesive chromium layer is of 2 nm thick (given by producer).

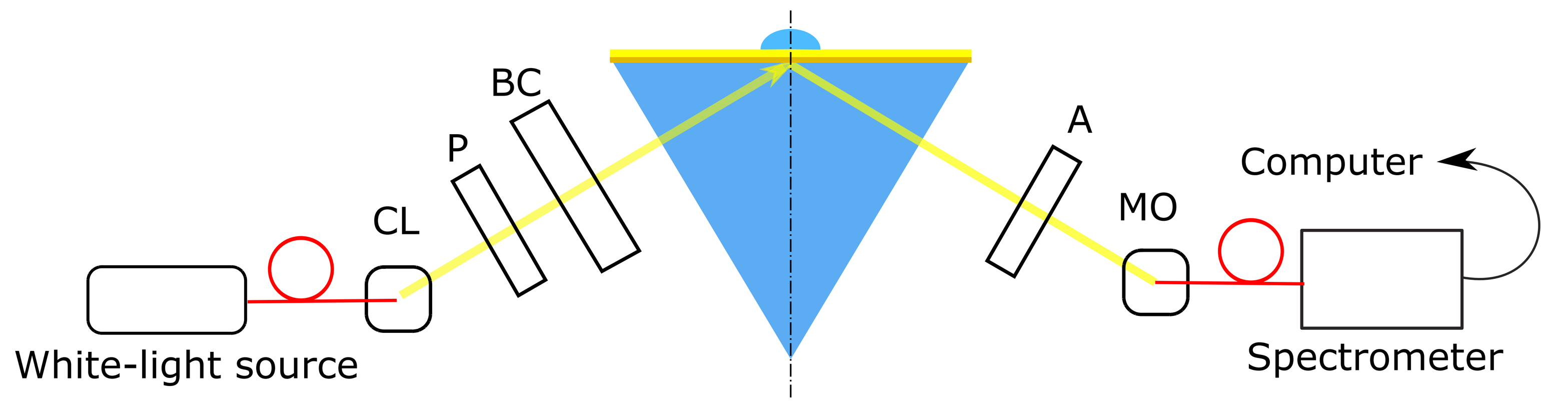

Figure 6: *Experimental setup consisting of white-light source, collimating lens (CL), polarizer (P), birefringent crystal (BC), analyzer (A) and microscope objective (MO), spectrometer and computer.*

When measuring, two channeled spectra are recorded. One spectrum for analyte, when SPR effect occurs and one reference spectrum for air, when SPR effect does not occur. Two such spectra for analyte with concentration of ethanol 10 wt% are shown in Fig. **??**. Visibility decrease is due to the SPR phenomenon. Phase shift $\Delta_{SPR}(\lambda)$ may be determined using Fourier transform analysis. In Fig. **??** is shown comparison of experimental and theoretical results. Changes in phase are the most significant for certain wavelength. These changes as a function of ethanol concentration in analyte are shown in Fig. **??**. Measurement sensitivity reaches 0.087 rad/wt%.

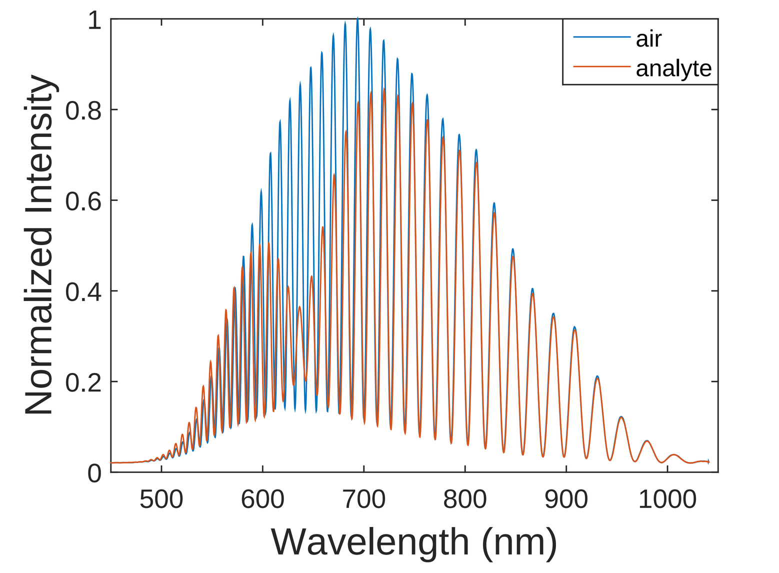

Figure 7: *Two channeled spectra and one with visibility decrease. Concentration of ethanol is 10 wt%.*

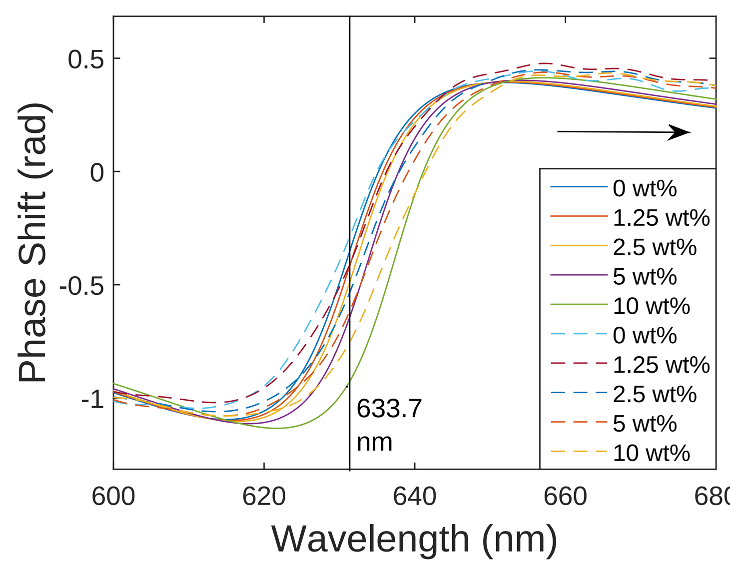

Figure 8: *Phase shifts - comparison of theory and experiment.*

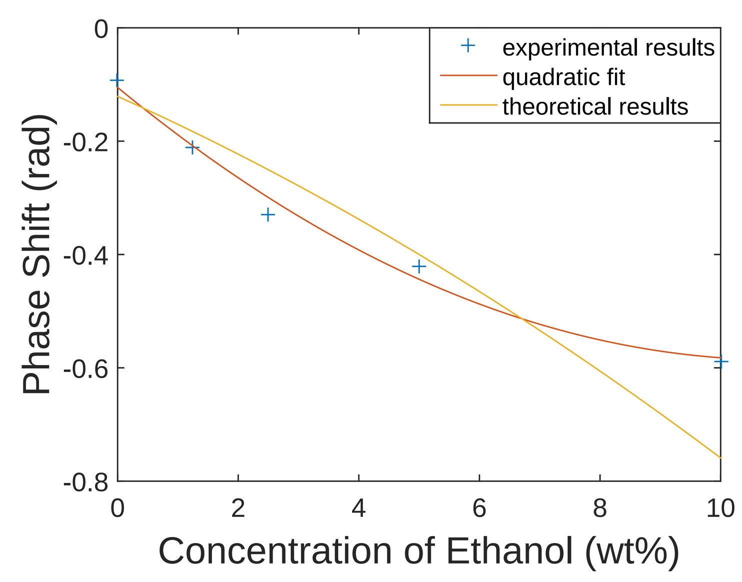

Figure 9: *Phase shift as function of concentration of ethanol in analyte.*

In Fig. **??** is shown comparison of theoretical and experimental results of the phase shift derivatives. Figure **??** shows positions of peaks as a function of concentration of ethanol. Measurement sensitivity reaches 1 nm/wt%.

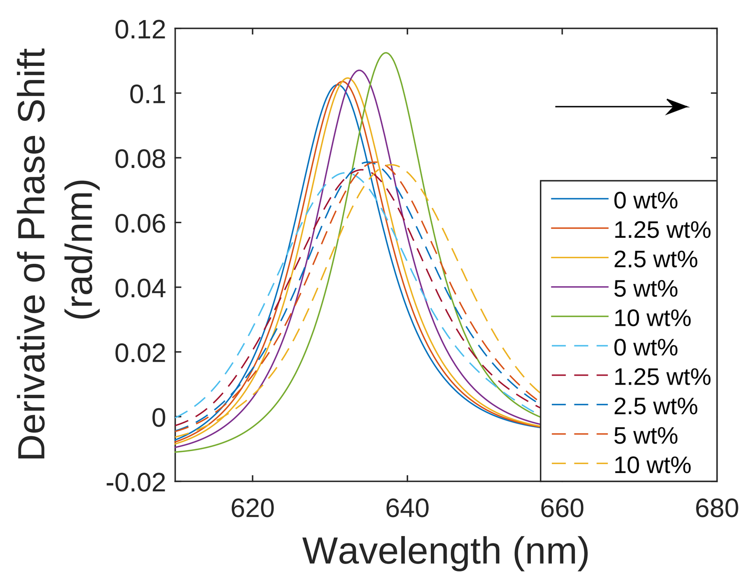

Figure 10: *Derivatives of phase shifts - comparison of theory and experiment.*

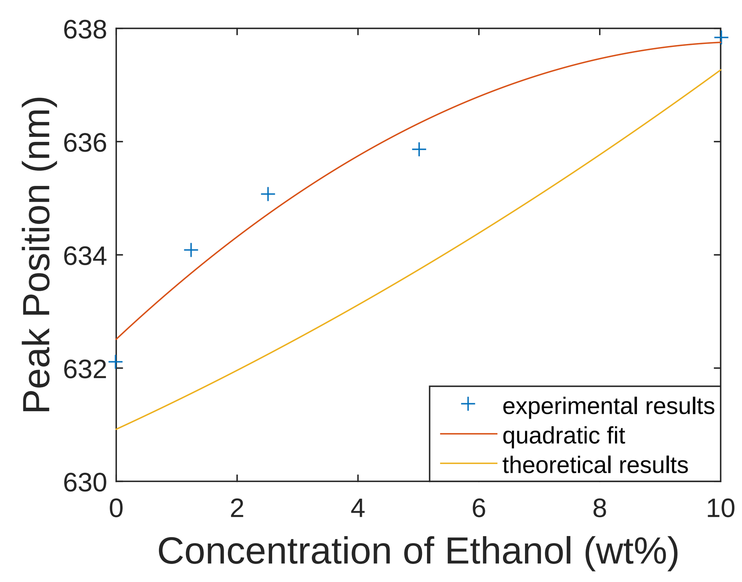

Figure 11: *Peak position as function of concentration of ethanol in analyte.*

3. Conclusions

- A spectral interferometric technique to detect the phase shift induced by SPR in the Kretschmann configuration was used in sensing small refractive index changes in a liquid analyte. Results are important in developing new sensors and sensing techniques.

Acknowledgments

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References

[1] P. Hlubina *et al*, *Opt. Commun.* **354**, 240–245 (2015).
[2] P. Hlubina, D. Ciprian, *Plasmonics* **12**, 1071–1078 (2017).