Modeling surface acoustic wave coupled surface plasmon resonance in layered structures

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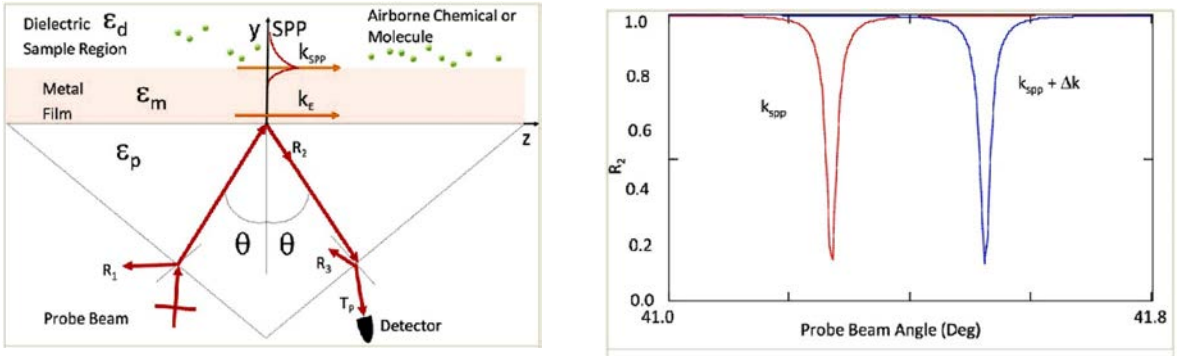
ABSTRACT

Surface plasmon resonance is widely studied and used for chemical and biological sensing. Current technology is based on angle resolved resonance detection at specific optical wavelengths. That is, changes in the reflectivity at the resonant angles are correlated to the chemical or biological substance at the surface of the sensor. In this work, we discuss the modeling and numerical techniques used to analyze a method to characterize plasmon resonances through surface acoustic wave (SAW) coupling of the incident light. The design strategies used to optimize the sensing performance of layered structures is described for several materials that are typically used as substrates and thin films.

Keywords: Plasmon resonance, biosensors, surface plasmons, surface acoustic waves

1. INTRODUCTION

Conventional SPP sensors rely on the generation of SPP waves at the interface of a metal film ε_m and a dielectric ε_d, as shown in Figure 1a. In this setup, commonly known as the Kretschmann configuration [1,2], a TM wave is incident upon the prism/metal-film interface at an angle greater than the critical angle resulting in total internal reflection. An evanescent wave is produced in the metal and couples to a SPP wave when the phase matching condition, $k_{SPP}=k_{Probe}\sin(\theta)$, is satisfied where $k_{Probe}=2\pi n_p/\lambda$ and n_p is the prism index at the probe beam free space wavelength λ. At resonance, energy is coupled into the SPP wave and the reflectivity of the prism-metal interface decreases, as shown in red in Figure 1b. When a substance is present in the sample region the dielectric can be affected causing a change in the phase matching condition for resonance. This results in a change in the incident probe beam angle needed to observe resonant absorption, shown in blue in Figure 1b, providing a means for identification of the substance. Although these sensors can be extremely sensitive, their realization requires highly accurate positioning systems, which limits its portability due to the size and complexity of the system. A detection technique that allows accurate determination of an unknown substance without requiring moving parts in the instrumentation would allow smaller, portable sensors to be developed.



(a) (b)

Figure 1. (a) Schematic diagram of the conventional plasmonic sensor configuration. (b) Plots showing how the plasmon resonance changes with the introduction of a substance at the surface of the sensor.

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2. SURFACE ACOUSTIC WAVE SURFACE PLASMON COUPLED SENSORS

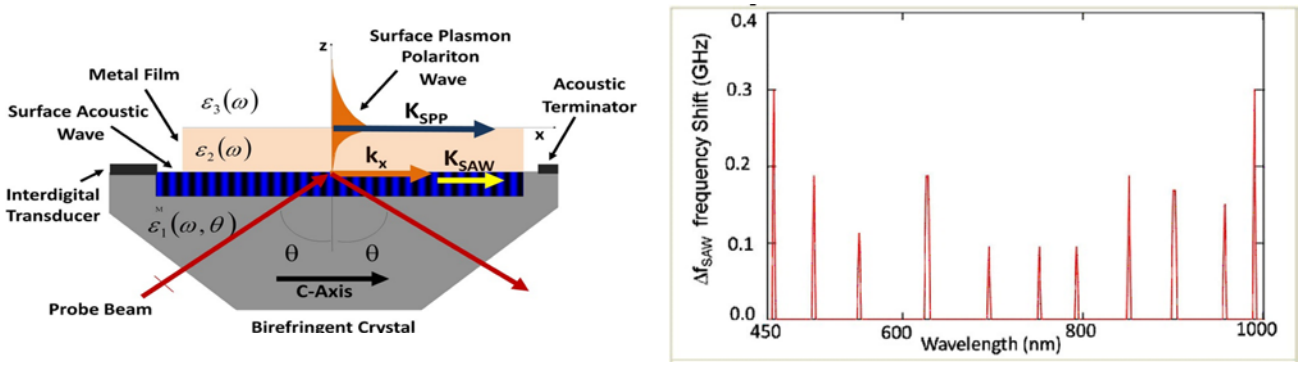
Consider the modified Kretschmann configuration shown in Figure 2a [3-5]. In this system, an InterDigital Transducer (IDT) is fabricated on the surface of a $LiNbO_3$ prism. A probe beam of wavelength λ_p is directed to the prism-metal interface at an angle θ, such that an evanescent wave with wave vector k_E propagates parallel to the z-axis of the crystal.

A description of how this system can be used as a sensor for chemical and molecular spectroscopy is given below.

To observe a SPP/SAW spectra:

- A probe beam, that can be tuned to any one of N discrete wavelengths $\lambda_1, \lambda_2, \ldots \lambda_N$, is directed onto the prism/metal-film interface.
- The angle θ is chosen such that the evanescent wave vectors are less than that needed to phase match the SPP wave vector
  $k_x < k_{SPP}$, prohibiting resonance.
- An InterDigital Transducer (IDT) is used to launch a SAW of wave vector K_{SAW} parallel to the evanescent wave vector. The frequency f_n of the SAW is chosen so that phase matching occurs, $K_{SAW} + k_x = k_{SPP}$, resulting in resonant absorption.
- The set of frequencies $f_n(\lambda_n)$ that corresponds to resonant absorption for the probe beam wavelengths λ_v can be used as the baseline response of the system.
- A single chemical or molecular species placed in the sample region causes a shift in the SPP resonant wave vectors k_{SPP} at each probe beam wavelength λ_n as shown in Figure 2b.

Therefore, there is a shift in the SAW frequencies $\delta f_n(\lambda_n)$ needed for phase matching at each probe beam wavelength. Identification of a substance by the change in its set of frequency resonances $\delta f_n(\lambda_n)$ for a given substance, termed SPP spectral lines, is similar in principle to identifying substances by their Fraunhofer or Raman lines. Therefore, the SPP lines of a substance will provide unique signatures that could allow real time spectroscopy of chemical, molecular, and biosensing.



(a) (b)

Figure 2. (a) Schematic diagram of the configuration used to couple a probe beam k_x into the surface plasmon resonance k_{SPP} using surface acoustic waves K_{SAW}. (b) Plots showing how the shift in the SAW frequency needed for resonance at the probe beam wavelength can be used as a signature to specify a specific substance.

To investigate the feasibility of this spectroscopic technique, this model uses $LiNbO_3$ for the acoustic wave prism, a 20 nm silver film, and an IDT deposited on the surface as in Figure 2a. The spectral range of the probe beam is 450 – 1000 nm and the z-axis of the crystal is parallel to the evanescent wave vector

$$k_x(\omega,\theta) = \frac{\omega}{c}\sqrt{\epsilon_1(\omega,\theta)}\ \ sin(\theta) \tag{1}$$

and the surface plasmon wave vector

$$k_{spp}(\omega) = \frac{\omega}{c}\sqrt{\frac{\epsilon_2(\omega)\,\epsilon_3(\omega)}{\epsilon_2(\omega)+\epsilon_3(\omega)}} \tag{2}$$

where $\epsilon_1(\omega,\theta)$ is the dielectric function for $LiNbO_3$, $\epsilon_2(\omega)$ is the metal film dielectric function, $\epsilon_3(\omega)$ is the sample region dielectric function, ω is the probe beam angular frequency, θ is the incident angle, and c is the vacuum speed of light. The IDT can be used to launch a surface acoustic wave, as shown in Figure 2a, with a wave vector K_{SAW} that satisfies the Bragg condition

$$k_{spp}(\omega,\theta,K_{SAW}) = k_x(\omega,\theta) \pm K_{SAW} \tag{3}$$

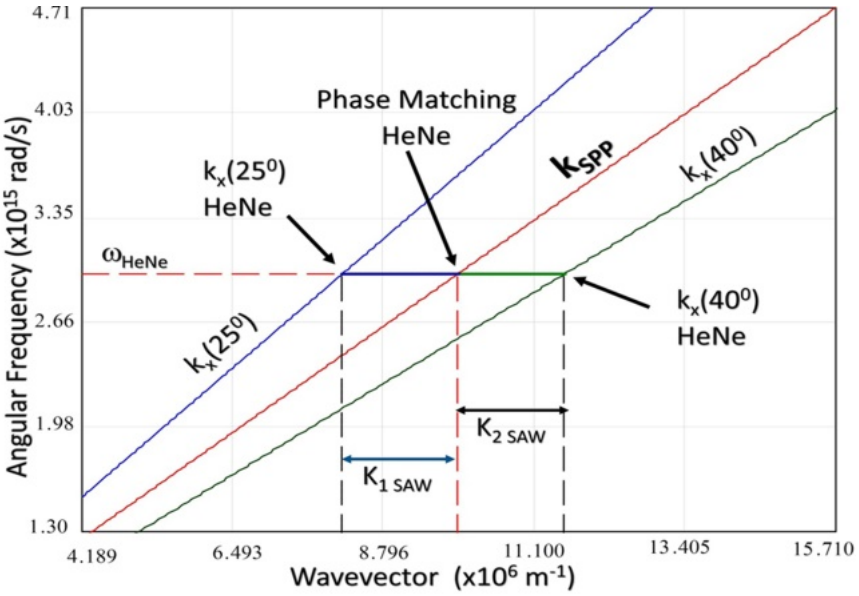


Figure 3. Dispersion curves for the surface plasmon Polariton for Ag films on $LiNbO_3$ as shown in figure 2a.

It can be seen from Figure 3 that a HeNe probe beam requires the addition of the SAW wave vector for 40° incident angles and subtraction of the SAW wave vector for 25° angles. To model the reflectivity the phase matching condition Eq. 3 becomes

$$k_{spp}(\omega,\theta,f_{SAW}) = \frac{\omega}{c}\sqrt{\epsilon_1(\omega,\theta)}\sin(\theta) + \frac{2\pi f_{SAW}}{v_s} \tag{4}$$

where f_{SAW} and v_s are the frequency and speed of the surface acoustic wave in $LiNbO_3$ in the z direction. The reflectivity of this system is given by

$$R_{123}(\omega,\theta,f_{SAW}) = r^*_{123}(\omega,\theta,f_{SAW})\; r_{123}(\omega,\theta,f_{SAW}) \tag{6}$$

where

$$r_{123}(\omega,\theta,f_{SAW}) = \frac{r_{12}(\omega,\theta,f_{SAW}) + r_{23}(\omega,\theta,f_{SAW})\; e^{2i\delta}}{1 + r_{12}(\omega,\theta,f_{SAW})\; r_{23}(\omega,\theta,f_{SAW})\; e^{2i\delta}}\;, \tag{7}$$

$$\delta = \frac{\omega}{c}\sqrt{\epsilon_2(\omega)}\; d \tag{8}$$

, $$r_{12}(\omega,\theta,f_{SAW}) = \frac{\frac{k_{1Z}(\omega,\theta,f_{SAW})}{\epsilon_1(\omega,\theta)} - \frac{k_{2Z}(\omega,\theta,f_{SAW})}{\epsilon_2(\omega)}}{\frac{k_{1Z}(\omega,\theta,f_{SAW})}{\epsilon_1(\omega,\theta)} + \frac{k_{2Z}(\omega,\theta,f_{SAW})}{\epsilon_2(\omega)}} \tag{9}$$

,

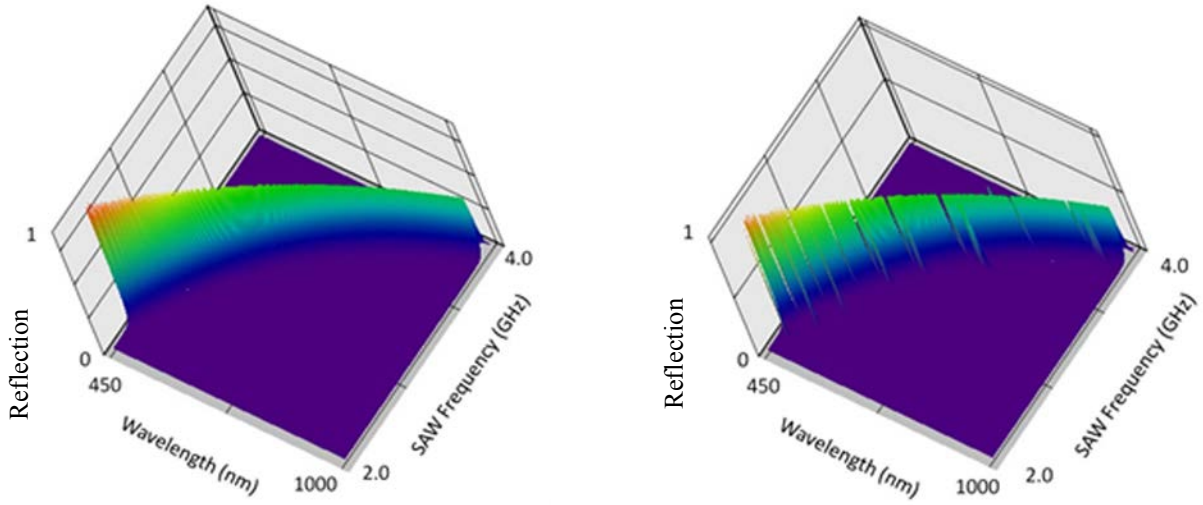
$$r_{23}(\omega,\theta,f_{SAW}) = \frac{\frac{k_{2Z}(\omega,\theta,f_{SAW})}{\epsilon_2(\omega)} - \frac{k_{3Z}(\omega,\theta,f_{SAW})}{\epsilon_3(\omega)}}{\frac{k_{2Z}(\omega,\theta,f_{SAW})}{\epsilon_2(\omega)} + \frac{k_{3Z}(\omega,\theta,f_{SAW})}{\epsilon_3(\omega)}} \quad (10)$$

$$k_{1Z}(\omega,\theta,f_{SAW}) = \sqrt{\frac{\omega^2}{c^2}\,\epsilon_1(\omega,\theta) - \left[\frac{\omega}{c}\sqrt{\epsilon_1(\omega,\theta)}\sin(\theta) + \frac{2\pi f_{SAW}}{v_s}\right]^2}\ , \quad (11)$$

$$k_{2Z}(\omega,\theta,f_{SAW}) = \sqrt{\frac{\omega^2}{c^2}\,\epsilon_2(\omega) - \left[\frac{\omega}{c}\sqrt{\epsilon_1(\omega,\theta)}\sin(\theta) + \frac{2\pi f_{SAW}}{v_s}\right]^2}, \quad (12)$$

$$k_{3Z}(\omega,\theta,f_{SAW}) = \sqrt{\frac{\omega^2}{c^2}\,\epsilon_3(\omega) - \left[\frac{\omega}{c}\sqrt{\epsilon_1(\omega,\theta)}\sin(\theta) + \frac{2\pi f_{SAW}}{v_s}\right]^2}. \quad (13)$$

and d is the Ag film thickness. Using Eqs 1-13, a numerical simulation of the transmission of the prism was accomplished that calculates the efficiency as a function of the acoustic wave frequency needed to observe SPP resonance for a particular probe beam wavelength with no material in the sample chamber. Figure 4a is a plot of the spectral response of the system. If a substance is introduced into the sample region, it will induce changes in the SPP resonant frequencies at different wavelengths as shown in Figure 4b. The gaps in the spectral response that are representative of a specific material are similar in appearance to Fraunhofer lines in the solar spectrum.



(a) (b)

Figure 4. Simulation of the transmission of the sensor showing the transmission with the sample region empty, shown in (a), and with the sample region containing a hypothetical material, shown in (b).

3. CONCLUSION

We have modeled the coupling of surface acoustic waves and surface plasmon resonance. Our results show that by creating a data set of probe beam wavelength and the surface acoustic wave frequency at plasmon resonance that a spectra can be obtained that can be used to identify specific substances.

4. ACKNOWLEDGEMENTS

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