Using Surface Plasmon Propagation through Nanostructures for Chemical and Biological Sensing

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ABSTRACT

The propagation of surface plasmon (SP) waves through nanometer periodic structures exhibits a band gap structure in the dispersion relation of surface plasmon waves. By taking advantage of this property, we developed a new chemical and biological sensor. Compared to traditional Surface Plasmon Resonance (SPR) sensing, our sensor does not require precise control or measurement of the transverse momentum of the excitation light. Therefore, for comparable sensitivity, the Surface Plasmon Band Gap sensor will be more easily implemented in a compact format. We present here the numerical simulations and the first optical measurements that demonstrate the validity of our approach.

Keywords: surface plasmon, photonic, nanofabrication, sensor

1 CONCEPT

Surface plasmon waves or surface plasmon polariton are electromagnetic waves propagating at optical frequencies on an interface between a metal, typically gold or silver, and a dielectric. They are evanescent waves: their field intensity is concentrated in a very thin layer (few tens of nanometers) across the interface. They are characterized by a propagation constant k_{sp} given for a flat interface by :

$$k_{sp} = k_0 \sqrt{\frac{\epsilon_m \epsilon_d}{\epsilon_m + \epsilon_d}} \tag{1}$$

with ϵ_m andϵ_d the dielectric constant of the metal and the dielectric respectively, and k_0 the momentum of light in free space at the same frequency[1]. According to (Eq. 1) the SP propagation constant is strongly dependent on the variations of permittivity on the interface due, in our situation, to molecular binding on the surface. Therefore, sensing molecular surface concentrations on the interface, a proxy for bulk molecular concentration, can be done by measuring k_{sp}[2], [3]. The traditional technique used to measure k_{sp} is by photon-SP coupling, or Surface Plasmon Resonance. For coupling to occur, the momentum matching condition (Eq. 2) needs to be achieved, with k_x the transverse momentum of the excitation light, θ_i the angle of incidence of the probing beam and n the optical index of the prism.

$$k_x = nk_0 \sin\theta_i = k_{sp} \tag{2}$$

In this case, the coupling will be detected when the reflected intensity of the probing beam is greatly reduced. Since $k_{sp} > k_0$, the momentum of the excitation light needs to be increased using a grating, a prism or a waveguide. It can be seen that in this coupling technique, the transverse momentum k_x of the excitation beam is the probe used to measure k_{sp} since its precise control or measurement is necessary for accurate surface plasmon sensing.

We propose to use another method to measure k_{sp}, which does not depend on the precise knowledge of k_x. We believe that this will enable the possibility of a more robust and compact surface plasmon sensing since the control of k_x will not be as important. Our approach is based on the properties of the propagation of surface plasmon through nanostructures. When the period of the nanostructures is equal to half the SP wavelength, the propagation of surface plasmon is blocked in a manner similar to the propagation of light in a Fabry-Perot filter [4], [5]. We therefore propose to use the period of the nanostructures Λ as the probe with which we measure k_{sp} causing the SP propagation to be blocked when we have the relation:

$$k_{sp} = \frac{k_g}{2} = \frac{\pi}{\Lambda} \tag{3}$$

The sensor concept is presented in Fig 1. In order to measure whether the propagation of surface plasmon is possible or not, a light beam is sent on the device at the *momentum matching condition* in order to excite potential surface plasmon waves [6]. Contrary to what is the case in Surface Plasmon Resonance, this excitation beam does not need to be so well controlled since the final measure does not depend on the precise knowledge of k_x.

2 Numerical Simulations

In order to prove the concept of this new sensor, we did some extensive numerical calculations. We developed a code based on the Rigorous Coupled Wave Analysis [7]–[9]. This code can predict the optical behavior

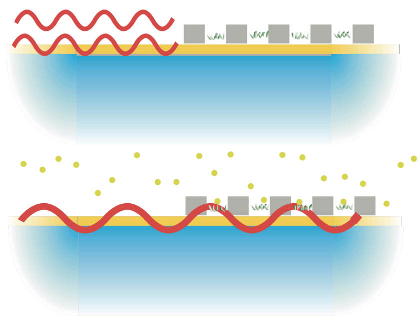

Figure 1: Surface Plasmon Band Gap sensor concept.

of a periodic optical system at different wavelengths and angles of incidence. We measured the intensity of the $0th$ order reflected beam using different wavelengths and angles of incidence. A typical result, obtained for a thin (40 nm) layer of gold on a glass prism in air is presented in figure (2). The dark region corresponds to a very low reflected intensity, which corresponds in this case to surface plasmon excitation. This data corresponds to what one would obtain for a classical surface plasmon resonance experiment. The visible different domains are due to different data sets of the optical index of gold.

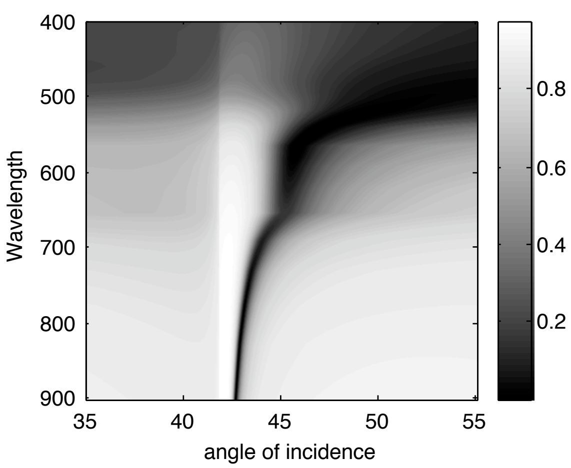

Figure 2: Numerical Simulations of the reflected intensity versus angle and wavelength on a 40 nm gold slab on a glass prism.

Once our numerical code was validated, we did the same numerical experiment when a square-shaped dielectric ($n = 1.5$) grating was laid on the gold surface. In order to observe the gap around 633 nm, we chose a grating period of 246 nm. The filling ratio was 0.5 and the height was 60 nm, which is enough to perturbate all of the surface plasmon mode whose typical penetration depth is 40 nm. We can clearly see on figure (3) the band gap structure of the surface plasmon propagation through the grating: there is an energy region where no coupling between the excitation beam and the surface plasmon waves is possible because the propagation of surface plasmon is blocked.

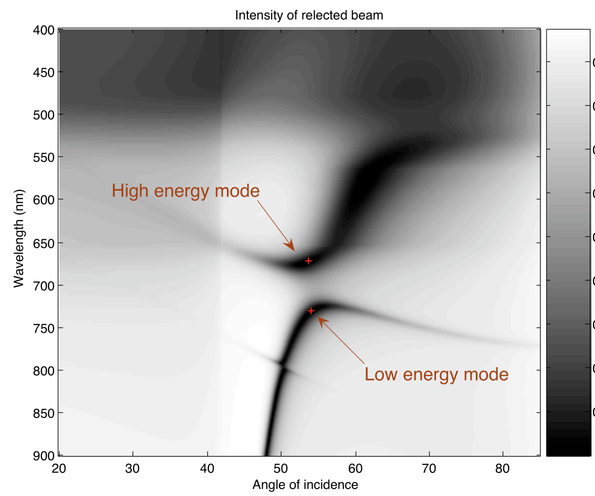

Figure 3: Numerical Simulations of the reflected intensity versus angle and wavelength on a 40 nm gold slab on a glass prism with periodic nanostructures.

In order to compare the sensor sensitivity to traditional SPR, we only had to change the value of the optical index in between the grating to simulate the binding of molecules. The sensitivity of SPR was computed in the same way by changing the optical index of the medium in contact with the bare metallic interface. Figure (4) show the results obtained when we monitor the reflected intensity for a fixed angle and wavelength, starting in the middle of the band gap for the SP band gap sensor and on the edge of the surface plasmon resonance for the SPR sensor. This corresponds to a situation where a perfect beam is used, which is difficult to achieve in a compact system. We can clearly see that the sensitivity of the band gap sensor is comparable to the sensitivity of the traditional SPR technique. This was to be expected. Indeed, the limitation of the sensitivity in the two cases is the slope of the edge of the surface plasmon dip [10], which is limited by the damping of the surface plasmon mode, in the same way than any resonance phenomenon is widened by the damping of the coupled mode.

However, if we consider an incoming beam that is not so perfect, the results are very different. To simulate this situation, we did the same numerical experiment that was described earlier with a beam that had three

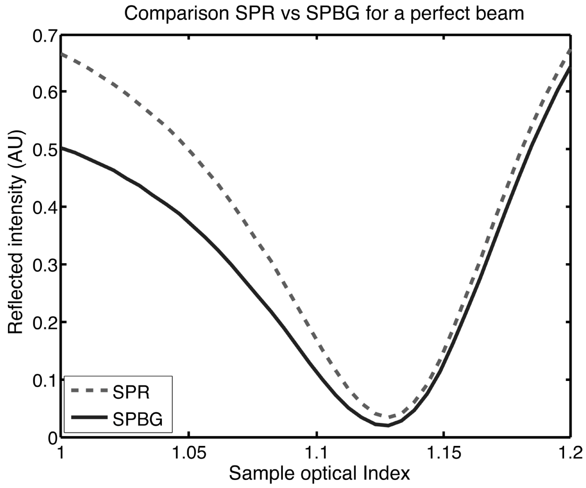

Figure 4: Comparison of the sensitivity of the Surface Plasmon Band Gap sensor (SPBG) and traditional SPR.

degrees of divergence, an arbitrary value which is likely to happen if the system is so compact that it cannot afford an excellent optical system. The results of the simulation are presented in Figure (5).

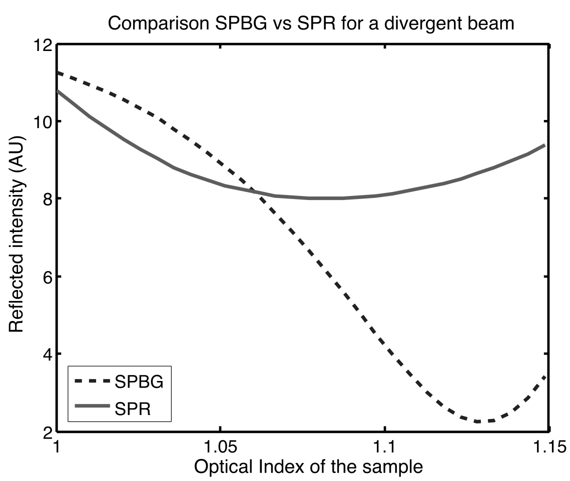

Figure 5: Comparison of the sensitivity of the Surface Plasmon Band Gap sensor (SPBG) and traditional SPR for a beam with three degrees of divergence.

We can clearly see that in this case, the surface plasmon band gap sensor is much more sensitive because it does not rely on the knowledge or control of k_x, the transverse momentum of the excitation beam. When k_x cannot be well controlled, the surface plasmon band gap sensor outperform the traditional SPR sensor.

3 Experimental results

Our experimental setup is very simple and was inspired by Yoon's work [11]. It also narrowly corresponds to what is simulated in the numerical experiments. A cylindrical cone of white light was shot through a cylindrical prism on a glass chip optically connected to the prism. A thin (40 nm) layer of gold was evaporated on top of the glass chip and a dielectric grating was made using holographic lithography, nanoimprinting or nanostamping. The reflected beam was dispersed with a prism and the intensity was measured using a CCD camera. Figure (6) is the schematic of the experiment.

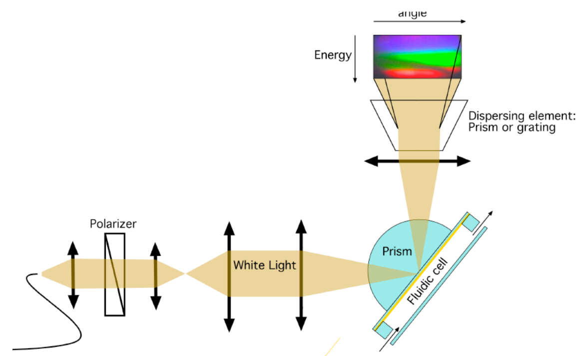

Figure 6: Schematic of the experimental setup

The image on the camera corresponds to the intensity of the reflected beam versus the wavelength and the angle of incidence. Figure (7a) represents the results for a bare interface, which corresponds to a classical SPR experiment. We can clearly see a black line that corresponds to the surface plasmon resonance. Figure (7 b) shows the results when a grating is laid on top of the surface. This time we can clearly see the surface plasmon band gap which corresponds to the discontinuity of the line of low reflected intensity. Future efforts will introduce some changes in the optical index over the surface and observe the behavior of the surface plasmon band gap.

Conclusion

By taking advantage of the properties of the propagation of surface plasmon through nanostructures, we invented a new sensor whose performance, contrary to SPR sensors, does not depend on the control or knowledge of the transverse momentum of the excitation beam to do the measurment. We presented here a numerical proof of concept and some preliminary experimental results that demonstrates its feasibility.

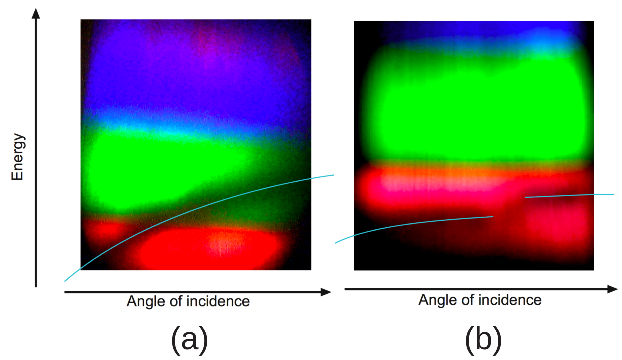

Figure 7: Experimental results. Surface plasmon excitation on a flat surface (a), with nanostrucutres (b). The dark area corresponds to the surface plasmon excitation.

This material is based upon work supported by the National Science Foundation under Grant No. CCF-0120778.

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