A Biosensor based on Surface Plasmon Interference

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We propose a new concept for surface plasmon sensing using a surface plasmon interferometer. The high field enhancement of surface plasmons near the metallic interface makes them ideal for use in bio- and chemical sensors where a very small change in refractive index should be detected. To our knowledge this is the first time that the SOI material system has been combined with the SPR technique for sensing purposes. The device is two orders of magnitude smaller than current integrated SPR sensors. We obtain a theoretical limit of detection of 10^{-6} *RIU for a component of length 10 μm.*

Introduction

The use of surface plasmon resonance (SPR) for biological and chemical sensing is well established. The high sensitivity of this technique to surface phenomena makes it ideal for use in real-time and label-free biosensors where very small changes in refractive index must be detected. Driven by the vision of a laboratory on a chip and its impact in numerous applications such as detection, biosensing, kinetic and binding studies and point-of-care diagnostics, extensive work has been done to miniaturize SPR biosensors. In the past decade, several integrated optical SPR sensors have been demonstrated [1, 2, 3], in which thin gold films serving as a platform for the attachment of sensing films are deposited on top of an integrated optical waveguide system. However, all integrated SPR sensors that have been investigated so far are fabricated in a material system with a low refractive index contrast, keeping typical dimensions of waveguides and optical components too large for miniaturization and consequent lab on chip applications. Working with a high refractive index material system such as silicon-on-insulator is a more straight-forward approach to meet the requirements for high-level integration and high-throughput fabrication.

Theory

The surface plasmon interferometer is schematically depicted in Fig. 1. The device consists of a gold layer embedded into the silicon membrane on top of a supporting silica layer. Upon reaching the gold-clad layer, a dielectric TM-polarized mode guided by the silicon membrane slab waveguide excites two surface plasmon modes, one at the upper and one at the lower interface of the gold layer. Due to the highly assymetric cladding layers these modes are not coupled. Therefore, their phase velocities are entirely determined by the refractive index of the upper and lower dielectric. At the end of this section, interference of the two surface plasmon modes results in a dielectric mode launched in the output waveguide. This explains the sensing functionality of the interferometer: a change in the refractive index of the medium above the gold layer results in a phase difference between the two surface plasmon modes and consequently, in a change of output intensity. For our simulations, we used an in house-developed eigenmode solver CAMFR [5]. The calculation method consists of a Fourier Modal Method algorithm, which was recently

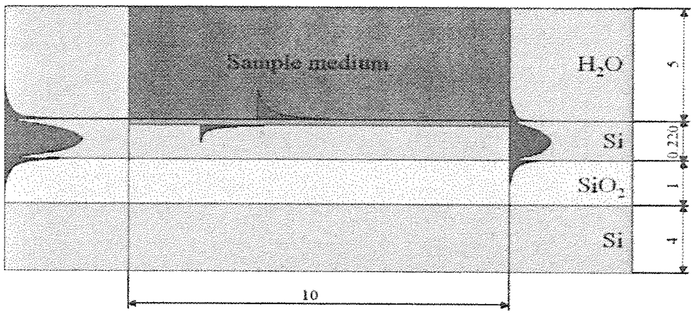

Figure 1: Schematical setup of the proposed structure, all dimension in μm

improved by adding an adaptive spatial resolution at the discontinuity points of the refractive index profile [6], that generates reliable estimates for an eigenmode solver. The reference data for the refractive index of gold was taken from [8].
Fig. 2 illustrates the interferometric nature of our device. For a sensing section of length 10 μm, the transmitted intensity of the fundamental TM mode of the silicon slab waveguide is plotted as a function of refractive index of the sample medium. For this simulation, we have chosen a wavelength of 1.55 μm, which is in the near-infrared region and suitable for biosensing applications. On the bottom of this figure, the phase difference between the two interfering waves is calculated.

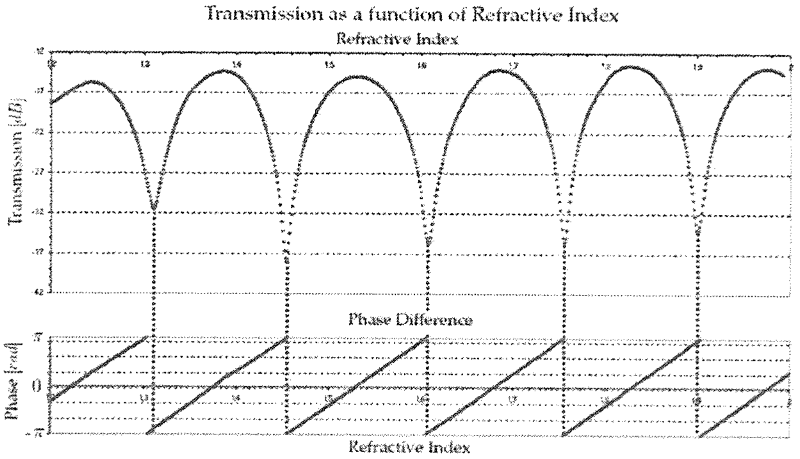

Figure 2: Transmission of the structure depicted in Fig. 1 as a function of refractive index. The length of the structure is 10 μm

Although the theory as outlined above has been presented here for a fixed wavelength and variable refractive index of the sample medium, there is a second, and perhaps more useful, method of using this device. As outlined above, the first method is to use a monochromatic input mode and monitor the output power as a function of the refractive index of the sample. This approach is known as the 'intensity measurement mode'. The second mode of operation uses a broadband input mode and as a function of the refractive index of the sample medium we monitor the position of the spectral minima in the transmission curve. This is the 'wavelength interrogation mode'.
In Fig. 3 we have simulated the response of the structure shown in Fig. 1 to a broadband incoming waveguide mode. The refractive index of the sample medium is fixed at a value of 1.33. This behavior can also be explained by comparing the phase difference between

the internal and the external plasmonmodes as can be seen in the bottom of Fig. 3.

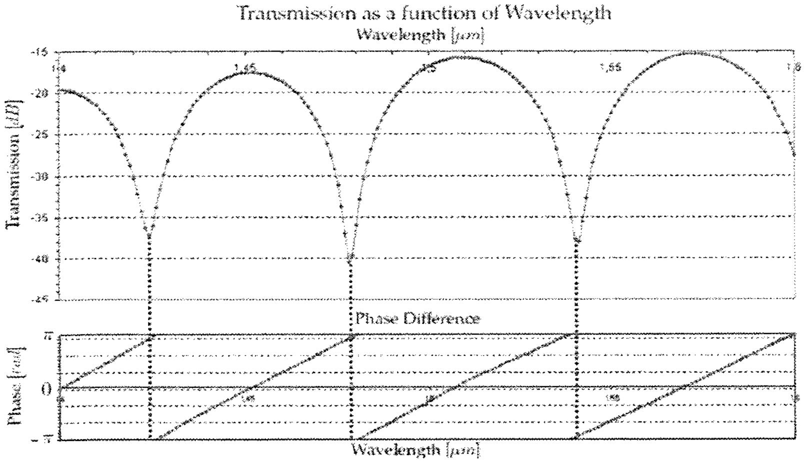

Figure 3: Transmission of the structure as a function of the wavelength, the length of the structure is 10 μm

In both modes of operation a sensor length of approximately 10 μm should suffice, which is two orders of magnitude smaller than current integrated surface plasmon sensors.

Sensitivity of the Device

If we take the intensity measurement approach to detect refractive index changes we can calculate that the sensitivity for this device reaches values of 10000 dB/RIU (refractive index unit). In conjunction with an optoelectronic system which can measure changes in the optical power of 0.01 dB, variations in the refractive index as small as 10^{-6} can be measured. Integrated surface plasmon resonance sensors in low-index contrast material systems typically boast values of 2000 dB/RIU, this corresponds to a detection limit of 5×10^{-6} RIU [3].
Taking the wavelength interrogation approach, sensitivity is defined as the shift of the wavelength for which transmission is minimal as a function of the refractive index of the sample medium ($\Delta\lambda/RIU$). From Fig. 4 one can see that the shift of the wavelength for which transmission is minimal as a function of the refractive index of the sample medium is equal to 463.5 nm per refractive index unit. According to [7] a prism based sensors has a shift of 13800 nm per refractive index unit at 850 nm, an a grating based device has a value of 630 nm per refractive index unit.
In order to demonstrate that our proposed device can detect very thin dielectric layers representative of thin protein layers, we have determined the shift of the wavelength for which the transmission is minimal as a function of the thickness of an adsorbed layer at the Au-sample medium interface. In Fig. 5 the adsorbed layer thicknesses varyies from 1 to 400 nm and has a refractive index of 1.34. By inspection of the slope of the curve we can estimate the dependence of the peak position on the layer thickness to be approximately equal to 6 pm/nm. This demonstrates that our device can be used to measure layer thicknesses of absorbed protein layers.

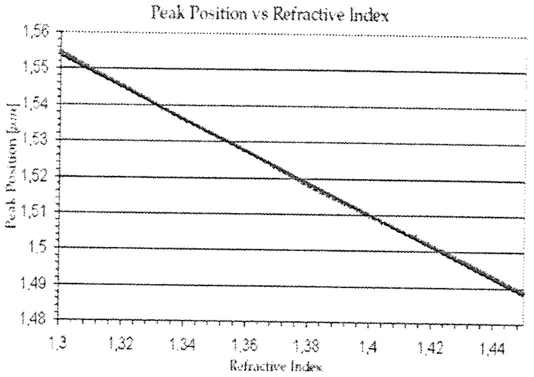

Figure 4: Shift of the resonance wavelength as a function of the refractive index of the sample medium

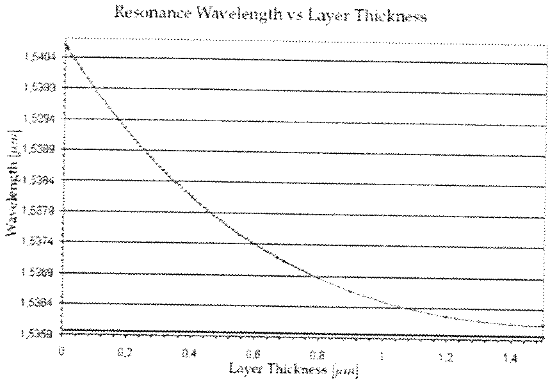

Figure 5: Shift of the resonance wavelength as a function of the thickness of the adsorbed layer

Conclusions

We have presented in this paper a novel concept for a biological sensor using surface plasmon waves. The new device was described from a theoretical point of view, and simulation results show its potential for sensing applications.
Due to its different working principle as compared to other devices, this device has a number of interesting benefits. Firstly, the device is two orders of magnitude smaller than conventional surface plasmon waveguide sensors, due to the integration into a high-index contrast material system. Secondly the device is highly tunable, due to the fact that it is based on interference rather than loss. This makes it an excellent candidate for a vast number of applications. Thirdly, the sensitivity of this device is comparable with that of state-of-the art biological sensors.
The authors believe this novel concept to be an important step toward a fully integrated surface plasmon lab-on-chip solution.

References

[1] Čtyrocký J. *et al*, "Theory and Modelling of Optical Waveguide Sensors Utilising Surface Plasmon Resonance", *Sensors and Actuators B*,**54**, pp. 66 - 73 1999.

[2] Harris Rd, Wilkinson JS, "Waveguide Surface Plasmon Resonance Sensors", *Sensors and Actuators B*,**29**, pp. 261 - 267 (1995)

[3] Homola J, Čtyrocký J, Skalský M, Hradilová J and Kolářová P, "A Surface Plasmon Resonance Based Integrated Optical Sensor", *Sensors and Actuators B*,**38-39**, pp. 286 - 290 (1997)

[4] Debackere P, Scheerlinck S, Bienstman P and Baets R, "Surface plasmon interferometer in silicon-on-insulator: novel concept for an integrated biosensor", *Optics Express*, **14**, pp.7063-7072 (2006)

[5] Bienstman P and Baets R, Optical Modelling of Photonic Crystals and VCSELs using Eigenmode Expansion and Perfectly Matched Layers", *Opt. Quantum Electron* **33**(4–5), pp. 327-341 (2001)

[6] Debackere P, Bienstman P, Baets R, "Improved ASR Convergence for the Simulation of Surface Plasmon Waveguide Modes", *to appear in special issue of Optical and Quantum Electronics on Optical Waveguide Theory and Numerical Modeling*, (2006)

[7] Homola J, Sinclair S and Gauglitz G, "Surface Plasmon Resonance Sensors: Review", *Sens. Actuators B*, **54**, pp. 3-15 (1999)

[8] Handbook of Optical Constants of Solids ,*edited by E. Palik*, Academic Press New York, (1985)

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November 30 | December 1 | 2006

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ISBN: 90-6144-989-8

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