Surface plasmon interferometer in silicon-on-insulator: novel concept for an integrated biosensor

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***Abstract*— We propose a novel configuration for a highly integrated and highly sensitive optical biosensor. The basic element of our sensor is a surface plasmon interferometer consisting of a thin layer of gold embedded in a silicon membrane. We investigate the performance of our sensor by simulation using eigenmode expansion. We calculate that refractive index changes in the order of 10^{-6} RIU (refractive index unit) are detectable for a component of length 10 μm. Moreover, we illustrate that the operation wavelength of our sensor can be tuned to a desired wavelength for a wide range of environmental refractive indices, making our device suitable for chemo- and biosensing.**

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 [5], [6], [8], 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.

In this paper, we propose a novel configuration for a biosensor in silicon-on-insulator (SOI). The basic element of our sensor is a surface plasmon interferometer consisting of a thin layer of gold embedded in the silicon membrane. The working principle of this interferometer will be outlined in detail in the next section. In the last section we investigate the sensitivity of our sensor for bulk refractive index changes and for the addition of thin dielectric films representative of protein layers.

I. THEORY

A scheme of the surface plasmon interferometer is depicted in Fig. 1. The interferometer consists of a gold layer embedded into the silicon membrane on top of a supporting silica layer. When a dielectric TM-polarized mode guided by the silicon membrane slab waveguide enters the structure and reaches the gold, two surface plasmon modes are launched, one at the upper and one at the lower interface of the gold layer. For a gold layer that is thick enough, these modes are not coupled. Therefore, their phase velocities are entirely determined by the refractive index of the upper and lower dielectric respectively. 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.

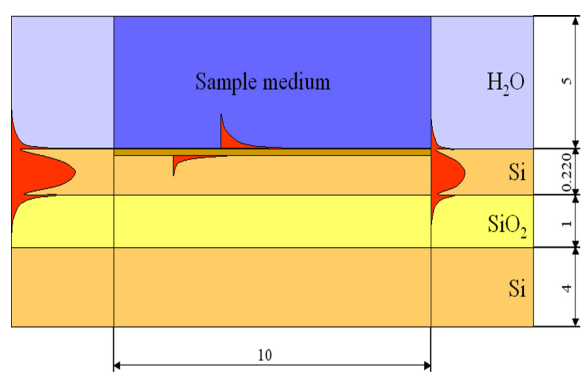

Fig. 1. Schematical setup of the proposed structure, all dimension in μm

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. When the upper and lower surface plasmon modes arrive in phase at the end of the sensing section, constructive interference leads to maximal transmission. However, for certain values of the sample refractive index, the phase difference between the two modes equals π, resulting into destructive interference and a minimum in the transmission curve.

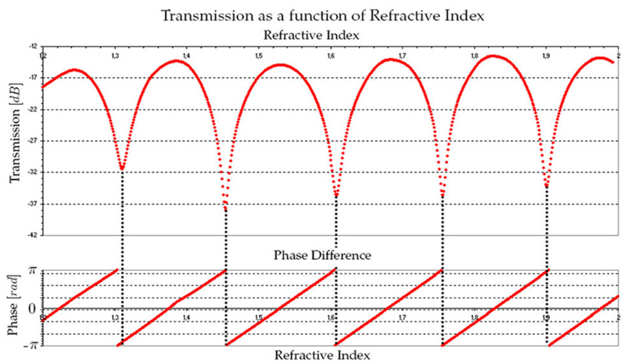

Fig. 2. Transmission of the structure depicted in Fig. 1 as a function of refractive index. The length of the structure is 10 μm

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. 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.

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.

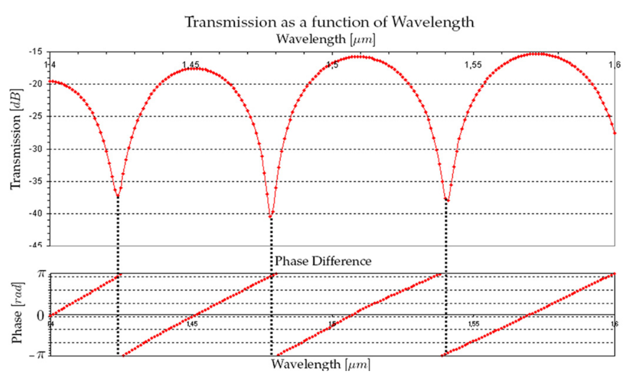

Fig. 3. Transmission of the structure as a function of the wavelength, the length of the structure is 10 μm

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.

II. Simulation Results

For our simulations, we used an in house-developed eigenmode solver CAMFR [1]. The calculation method consists of a Fourier Modal Method algorithm, which was recently improved by adding an adaptive spatial resolution at the discontinuity points of the refractive index profile [3], [4], that generates reliable estimates for an eigenmode solver. The reference data for the refractive index of gold was taken from [12].

A. Optimalization

Because the device is based on interference, the resonance of the system can be tuned to a multitude of required wavelength ranges, or refractive index ranges. The main parameters governing the response of this device are the length of the sensing region, the thickness of the Si waveguide in the sensing region, and the thickness of the Au layer.

The length of the sensing region influences the phase of both propagating surface plasmon modes, and thus determines the position of the resonance. To achieve maximal interference the losses along the upper and lower 'branch' of the interferometric section should be approximately equal. Since the internal plasmon mode propagates in a high-index material system, the loss of this mode is much higher than the loss of the external plasmon mode. This loss-difference can be compensated by choosing the appropriate thickness of the Si waveguide in the sensing region, thus modifying the coupling of the incoming waveguide mode to the internal/external surface plasmon mode. A third and last parameter is the thickness of the Au layer. By modifying this thickness we can tune the phases and losses of the surface plasmon modes.

By varying these three parameters we have optimized the sensor depicted in Fig. 1 so that the transmission would be minimal for a refractive index of the sample medium of 1.33, and a wavelength of 1.55 μm. In the optimized design the thickness of the silicon membrane is equal to 101 nm, and the length of the device is equal to 6.055 μm. Simulation results for this device are shown in Fig. 4.

B. Sensitivity of the Device

If we work at a fixed wavelength and vary the refractive index of the sample medium, we can calculate that sensor 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. This value is comparable with that of other integrated surface plasmon sensors [8], the dimensions however are two orders of magnitude smaller. This means that the smallest amount of a certain molecule that can be detected will also be two orders of magnitude smaller than current integrated surface plasmon sensors.

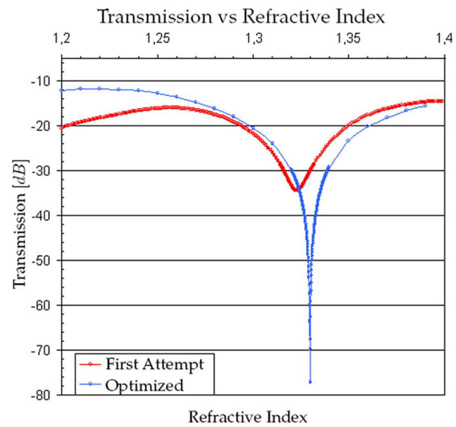

Fig. 4. Simulation results for the optimized structure

In the broadband operation mode, the sensitivity can be determined by two numbers. The first number is the shift of the resonance wavelength as a function of the refractive index of the sample medium ($\Delta\lambda/RIU$). A second sensitivity measure is the shift of the resonance wavelength as a function of the thickness of an adsorbed layer at the Au-sample medium interface. These numbers can be derived from Figs. 5 and 6.

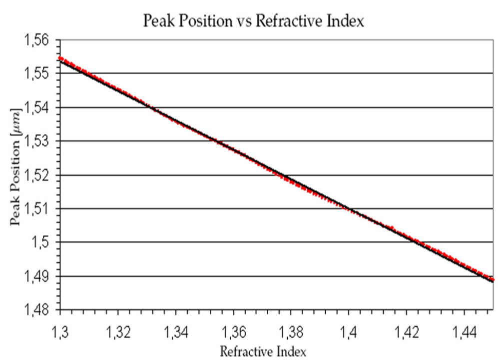

Fig. 5. Shift of the resonance wavelength as a function of the refractive index of the sample medium

From Fig. 5 we can see that the shift of the resonance wavelength as a function of the refractive index of the sample medium is equal to 463.5 nm per refractive index unit.

To determine the influence of the layer thickness on the shift of the resonance wavelength, we have determined the resonance wavelength for adsorbed layer thicknesses varying from $1\ nm$ to $1.5\ \mu m$. The refractive index of this adsorbed layer is equal to 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 $6\ pm/nm$.

III. 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.

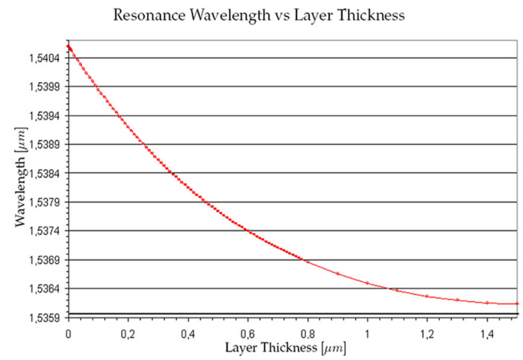

Fig. 6. Shift of the resonance wavelength as a function of the thickness of the adsorbed layer

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.

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