An ARROW-B Surface Plasmon Resonance Sensor in Aqueous Environment

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Abstract

An ARROW-B (antiresonant reflecting optical waveguide, type B) surface plasmon resonance (SPR) sensor operating in aqueous environment is proposed. The characteristics and optimization of the Au-coated ARROW-B SPR sensor with a buffer layer made of Cr inserted between Au and core are discussed. The detectable changes of the refractive index down to the order of 10^{-5} can be achieved. The tolerances of the thickness and index changes of the first cladding layer, the second cladding layer, and the core layer are also discussed.

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Key Words: Waveguide sensors, surface plasmon resonance, antiresonant reflecting optical waveguides.

1 Introduction

Surface plasmon resonance for use in chemical and biochemical sensing has been receiving growing research efforts for the past two decades. Among several SPR sensor configurations, waveguide SPR sensors have many attractive features such as compact size, ruggedness, prospect of fabrication of multiple/multichannel sensors on a single chip [1], [2]. In contrast to conventional waveguides, antiresonant reflecting optical waveguides (ARROW's) utilizing antiresonant reflection as guiding mechanism instead of total internal reflection can perform low-loss single mode propagation with relatively large core size. Moreover, to support surface plasmon waves which are TM-polarized, polarization-insensitive ARROW-B [3] was adopted as the wave-guiding structure.

In this study, characteristics and design of ARROW-B SPR sensors have been investigated. A dielectric overlay added onto the metal layer can be used to shift the operating range into the desired environment. Furthermore, an adhesion buffer layer of Cr is added between ARROW-B structure and the Au layer to enhance adhesion of Au layer to the dielectric material. A design example and the optimization of Au-coated ARROW-B SPR sensors are also presented.

2 Characteristics and Design of Au-coated ARROW-B SPR Sensors

The basic structure of an ARROW-B SPR sensor shown in Fig. 1 consists of three sections. Sections F_1 and F_2 are the input and output effective single-mode ARROW-B waveguides, and S is the sensing section which supports surface plasmon waves. On top of the waveguide core is a layer of gold thin film. The length of the sensing region is assumed to be 2 mm.

When there is a variation in the refractive index of the environment (superstrate), the field profile of quasi-guided mode will change, and the output power through the sensor will be different. The relative output power through the ARROW-B SPR sensor can be expressed as:

$$p(L) = |a_0(L)/a_0(0)|^2, \tag{1}$$

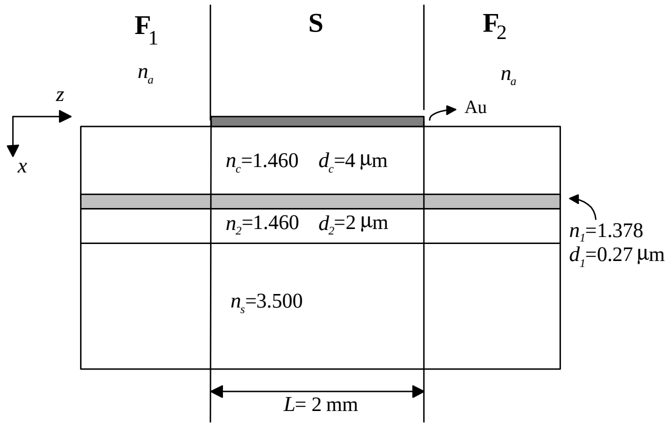

Figure 1: Basic structure of an ARROW-B SPR sensor.

where $a_0(0)$ and $a_0(L)$ are the complex amplitudes of the fundamental modes at the input and output of the sensor, respectively. Fig. 2 shows the relative output powers versus superstrate index n_a for different thickness of gold layer d_m. The minimum relative output powers corresponds to the best resonant coupling between the surface plasmon mode and the fundamental mode of the waveguide. Since the sensitivity of the sensor is proportional to the slope of the relative output power curve, the one which has a steeper slope is more suitable for sensing. By further comparison (not shown), we found that the curve for $d_m = 35$ nm has the steepest slope on both sides of the valley [4]. As a result, the thickness of the gold layer of the following ARROW-B SPR sensors was set to be 35 nm.

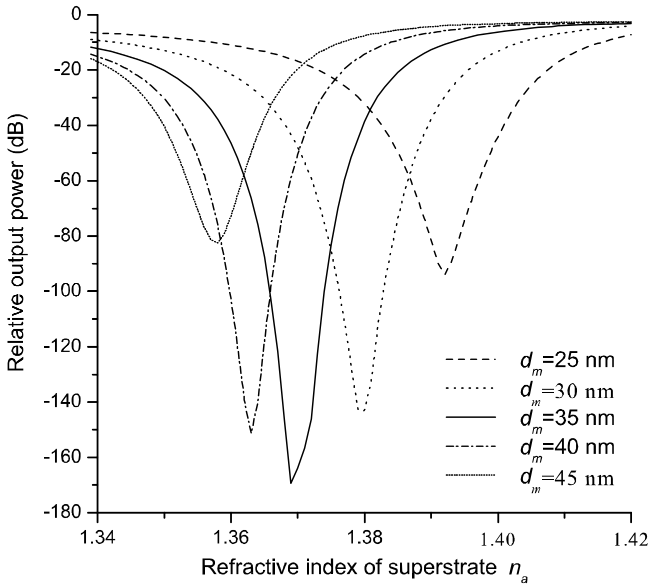

Figure 2: Dependence of the relative output power on the superstrate index.

3 Au-coated ARROW-B SPR Sensors with a Cr Buffer layer

The structure of an ARROW-B SPR sensor with a buffer layer shown in Fig. 3. On top of the waveguide core is an additional buffer layer between gold and core in the sensing section S. The length of the sensing region is still assumed to be 2 mm. After adding an ultra-thin Cr layer, the real parts of the effective refractive indices are nearly the same.

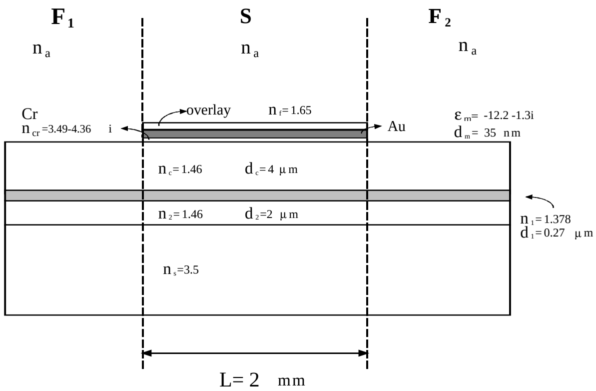

Figure 3: Structure of an ARROW-B SPR sensor with an adhesion layer.

4 Overlay Tuning and Optimization

Although the ARROW-B SPR sensor presented in the previous section is highly sensitive to superstrate index changes, the operating range is somewhat away from the desired aqueous environment. In order to shift the location of the minimum relative output power, a dielectric overlay was added on the top of the Au-coated ARROW-B SPR sensor as shown in Fig. 3.

To optimize the Au-coated ARROW-B SPR sensor in aqueous environment, the sensing resolution or minimum detectable change in the superstrate index n_a defined as (2) could be used as a measure [5]:

$$|\delta n_{min}| = \left| \frac{M \; p(L)}{\frac{\partial p(L)}{\partial n}} \right|_{n=n_a} , \qquad (2)$$

where $p(L)$ is the relative output power defined as (1), and M is the measurement precision of $p(L)$ as a percentage (typically, 1% [2]). A smaller $| \delta n_{min} |$ value stands for a better resolution. To transform δn_{min} into $(\delta n_{min})^{-1}$ is convenient for observation.

Table 1: The values of $(\delta n_{min})^{-1}$ at $n_a = 1.332$ of Cr thicknesses ranging from 1 to 4 nm combined with overlay thicknesses ranging from $11 - 16$ nm.

Cr (nm) \ overlay (nm)	11	12	13	14	15	16
1		10593	12589	6481	-5629	-15570
2		11399	14358	-3488	-17008	-13372
3	10234	12213	11623	-27031	-14264	
4	10669	12498	-3504	-14956	-12317	

Table 4-1 lists the values of $(\delta n_{min})^{-1}$ at $n_a = 1.332$ for each combination of Cr-thickness and overlay-thickness. When $d_{cr} = 3$ nm and $d_f = 14$ nm, the value of $| (\delta n_{min})^{-1} |$ which equals to 27031 is the largest among all. As a result, $d_{cr} = 3$ nm and $d_f = 14$ nm is best condition for the ARROW-B SPR sensor having the resolution of $\delta n_{min} = -3.7 \times 10^{-5}$.

5 Influence of Device Parameter Variation on the Performance of the SPR Sensor

To study the tolerance of the sensor, the resolution δn_{min} is examined with respect to the thickness and refractive index of the first cladding layer (d_1 and n_1), the second cladding layer (d_2 and n_2), and the core (d_c and n_c), respectively. The range of the thickness change is chosen as 10% of the designed value

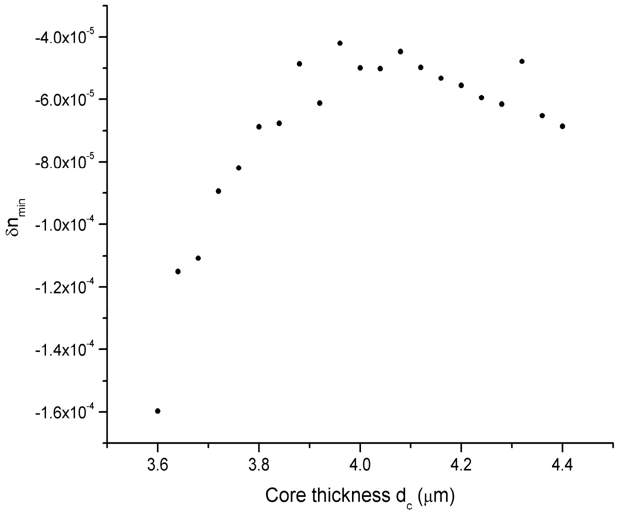

Figure 4: The dependence of δn_{min} on the core thickness d_c.

at optimal condition. The ranges of each layer are

$$\begin{array}{lcl} 0.270 - 0.270 \times 10\% < d_1 < 0.270 + 0.270 \times 10\% & \longrightarrow & 0.243 < d_1 < 0.297\ (\mu\text{m}), \\ 2.000 - 2.000 \times 10\% < d_2 < 2.000 + 2.000 \times 10\% & \longrightarrow & 1.800 < d_2 < 2.200\ (\mu\text{m}), \\ 4.000 - 4.000 \times 10\% < d_c < 4.000 + 4.000 \times 10\% & \longrightarrow & 3.600 < d_c < 4.400\ (\mu\text{m}). \end{array}$$

In the first interval, δn_{min} changes very little, and the worst value is about -4.6×10^{-5}, the resolution is still very good and the tolerance of our sensor to the first cladding thickness is good. In the second interval, it has a worst value of about -5.7×10^{-5}, the tolerance to the second cladding thickness is also good. As for the case of the core thickness change shown in 4, when the core thickness is less than 3.7 μm, the resolution is out of the order of 10^{-5}. Although the thickness of and the core affects the resolution more seriously than those of the first cladding layer and the second cladding layer do, this won't be a big problem because the I.C. technology at present is so good that the thicknesses can be controlled very precisely.

Next consider the changes of δn_{min} with respect to the index variation of the three layers. The variation of the refractive index in each case is set as a value of ±0.01. The tolerance of the device to the first cladding index is very good because $|\ \delta n_{min}\ |$ is less than 5.0×10^{-5} during the whole interval. If the second cladding index is larger than 1.463, the resolution will be out of the order of 10^{-5}.As shown in Fig. 5(a), it can be seen that the resolution is strongly influenced by the refractive index of the core. Assume that the material of the core is very pure and the variation of the refractive index is caused by the temperature change. The refractive index change per Celsius (dn/dT) of the core (SiO_2) is $11.9 \times 10^{-6}/°$C, and n_c is equal to 1.46 at 25°C [6]. If the temperature of the aqueous environment ranges from 0°C (freezing point) to 100°C (boiling point), the range of refractive index of SiO_2 will be 1.45971 to 1.46087. Fig. 5(b) is a plot of δn_{min} versus n_c of the above range. When δn_{min} falls beyond the order of 10^{-5}, n_c is about 1.46071 which corresponds to 86°C. If the operating temperature is lower than 86°C, the resolution will be better than 10×10^{-5}.

6 Conclusion

An Au-coated ARROW-B SPR sensor operating in aqueous environment has been investigated. An ARROW-B SPR sensor with an adhesion buffer layer of Cr is more stable. This new layer is so thin that the characteristics of SPW hardly change. Even when $d_{cr} = 3$ nm and $d_f = 14$ nm, the resolution is somewhat improved with the value of $|\ \delta n_{min}\ |= 3.70 \times 10^{-5}$ compared with the previous value of

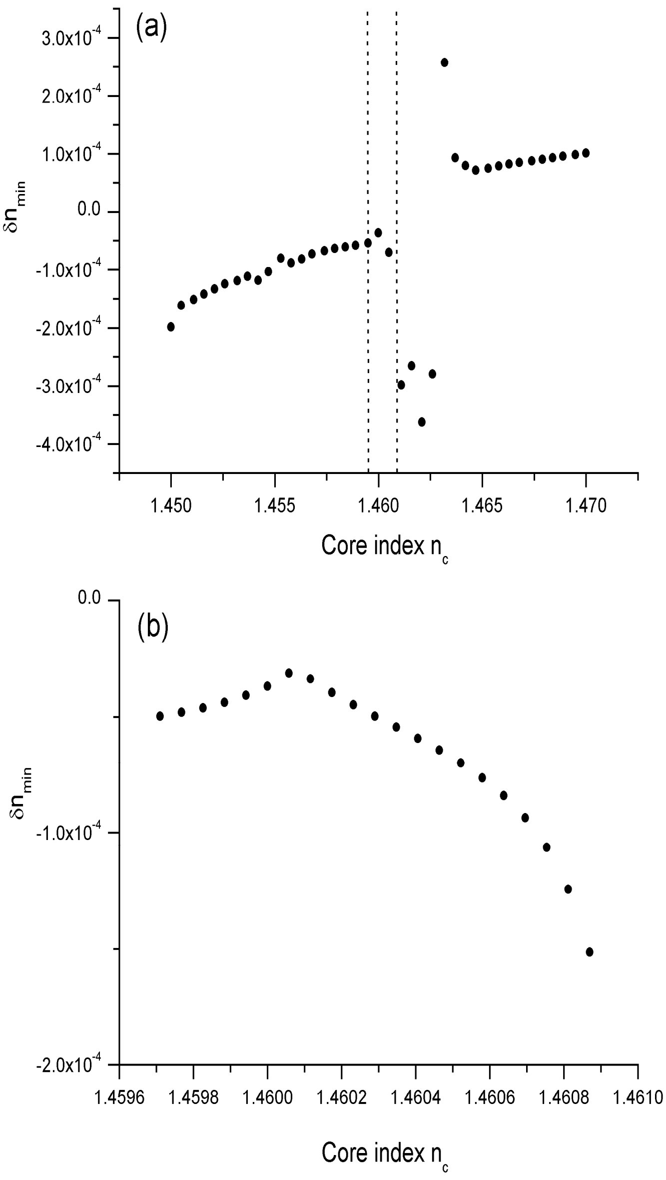

Figure 5: The dependence of δn_{min} on the core index n_c (a) from 1.450 to 1.470 (b) from 1.45971 to 1.46087 (the range between the dotted lines in (a)).

5.56×10^{-5}[4]. The ARROW-B SPR sensor is still competitive to conventional waveguide sensors having resolution $\sim\ 6 \times 10^{-5}$ [7].

The tolerances to the first and second cladding thicknesses and to the first cladding index are good whereas those to the core thickness and to the second cladding index are acceptable as long as the core thickness is not lower than 3.7μm or the second cladding index is not larger than 1.463. As for the core index change which affects the resolution most seriously among all, the resolution will still be better than 10×10^{-5} if the core index is lower than 1.46071. When the operating temperature is less than 86°C in the aqueous environment with the resolution better than 10×10^{-5}.

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