DESIGN OF ARROW-B SPR SENSORS IN AQUEOUS ENVIRONMENT WITH THE SPECTRAL SHIFT METHOD

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ABSTRACT
ARROW-B SPR sensors in aqueous environment with the spectral shift method have been investigated. Surface plasmons' propagation constant strongly depends on wavelength. When a broadband light source is launched into the waveguide, the transmitted spectrum exhibits a narrow dip whose minimum is the resonance wavelength associated with the transfer of optical energy into surface plasmons. The resonance wavelength shift with the sensed refractive index variation is studied, and the device is designed for aqueous environment application. The simulation results show that a resolution of $10^{-6}$ can be achieved, which is suitable for highly sensitive chemical sensing and biomolecular interaction analysis.

KEY WORDS
waveguide sensor, surface plasmon resonance, antiresonant reflecting optical waveguides.

1 Introduction
Surface plasmon resonance (SPR) for use in chemical and biochemical sensing has been receiving growing research efforts [1]–[15]. 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 [2]–[5], [8]. Integrated optical SPR sensors employing wavelength interrogation or spectral tuning have been reported [3], [5]–[7], [9]–[12]. 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 to provide efficient coupling with single-mode fibers. To support surface plasmon waves which are TM-polarized, polarization-insensitive ARROW-B [16] was adopted as the waveguiding structure.

In this presentation, design of ARROW-B surface plasmon resonance sensors in aqueous environment employing the spectral shift method is discussed. An Au-coated ARROW-B waveguide is designed. A buffer layer of Cr is sandwiched between ARROW-B structure and Au layer to enhance the adhesion, and a dielectric overlay is added onto the metal layer to shift the operating range into the desired environment. The spectral dependence of the ARROW-B SPR sensor is investigated and utilized for chemical sensing in aqueous environment.

2 Design of ARROW-B Waveguides
Since the first demonstration of antiresonant reflecting optical waveguides was introduced in 1986 [17], there has been increasing research interest in this type of devices. Utilizing antiresonant reflection as waveguiding mechanism instead of total internal reflection, ARROW structures are promising because of many unique features, such as polarization and wavelength selective characteristics, relaxed fabrication tolerance, effective single-mode propagation, low losses, good light confinement, and efficient connection to single-mode fibers. As a result that a conventional ARROW can only support low-loss propagation for a single TE-polarized wave and the surface plasmon wave is TM-polarized, another family of ARROW's called ARROW-B [16], which can support low-loss TM-polarized waves, has to be used. Fig. 1 shows the basic structure and the index profiles of an ARROW-B waveguide. The major difference is the refractive index of the first cladding is higher than that of the core for a conventional ARROW waveguide, while it is lower for an ARROW-B waveguide.

![Figure 1. Basic structure of an ARROW-B waveguide.](image-url)

For an ARROW-B waveguide, the thickness of the second cladding layer is governed by the transverse antires-
onant condition as [18]
\[
d_2 \simeq \frac{\lambda}{4n_2} \left[1 - \left(\frac{n_e}{n_2}\right)^2 + \left(\frac{\lambda}{2n_2 d_{ce}}\right)^2\right]^{-1/2} \cdot (2N + 1),
\]
where \(d_{ce}\) is the equivalent thickness of the core. Typically, the material of the second cladding layer is chosen as same as that of the core, hence Eq. (1) can be reduced to
\[
d_2 \simeq \frac{d_{ce}}{2} \cdot (2N + 1), \quad N = 0, 1, 2, \cdots ,
\]
and \(N\) is chosen to be zero in most cases. In order to sustain effectively single-mode and low-loss propagation, the thickness of the first cladding layer \(d_1\) has to be carefully designed. With a material system of (water/SiO\textsubscript{2}/MgF\textsubscript{2}/SiO\textsubscript{2}/Si) and corresponding refractive indices of (1.332/1.460/1.378/1.460/3.500) at the operating wavelength \(\lambda = 800\) nm, the thickness of the first cladding layer \(d_1 = 0.46\) \(\mu m\) can be found to be a suitable value for the chosen \(d_c = 4.00\) \(\mu m\) and \(d_2 = 2.00\) \(\mu m\).

3 Design of ARROW-B SPR Sensors

The basic structure of an ARROW-B SPR sensor shown in Fig. 2 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 Au \((n_m = 0.180 - 5.110i)\) thin film. The length of the sensing region is assumed to be 2 mm. To enhance the adhesion of the Au layer to the waveguide core, a buffer layer of Cr with a refractive index of 4.185 - 4.339i and a thickness of 5 nm is added between them. Moreover, a dielectric overlay added onto the Au-metal layer is used to shift the operating range to the desired aqueous environment. The material of the overlay is selected as Ta\textsubscript{2}O\textsubscript{5} with a refractive index \(n_f = 1.910\) at \(\lambda = 800\) nm [5] for its high refractive index and good environmental stability, which is important for the aqueous environment.

Because of abrupt waveguide transitions at the interface discontinuities, not only guided modes but also radiation modes will be excited. The effects of radiation modes should be considered in the ARROW-B SPR sensor. An eigenmode expansion analysis is applied to take the influence of radiation modes into account. Since back-reflections from the interface between the sensing and ARROW-B waveguide sections are very weak, multiple reflections in the waveguide structure can be neglected.

To characterize the performance of the sensor, the relative output power through the ARROW-B SPR sensor is introduced and can be expressed as:
\[
p = \frac{\int E_{x F_2}^* H_{y F_2}^* dx}{\int E_{x F_1}^* H_{y F_1}^* dx},
\]
where \(E_{x F_1}, H_{y F_1}\) and \(E_{x F_2}, H_{y F_2}\) are the transversal components of the mode fields in the input (\(F_1\)) and output (\(F_2\)) waveguide, respectively. Fig. 3 shows the relative output power of the sensor as a function of superstrate index with the thickness of Au layer \(d_m = 60\) nm and overlay \(d_f = 20, 25, 30\) nm.

![Figure 2. Schematic of an Au-coated ARROW-B SPR sensor with an adhesion layer and overlay in the sensing section S.](image)

4 Spectral Dependence of the Sensor and Optimization

The ARROW-B SPR sensors are designed for operating within a certain wavelength range from 600 to 900 nm. When there is a variation in wavelength, the field profiles of quasi-guided modes will change, and the output power through the sensor will be different. The minimum point of the relative output power curve corresponds to the best resonant coupling between the surface plasmon mode and the fundamental mode of the waveguide. Consider a light source with uniform power over the entire bandwidth. The relative spectral output power at superstrate index \(n_a = 1.332\) is shown in Fig. 4 (dash line). The wavelength of the lowest point in the dip, located at about 800 nm, is the resonant wavelength. And assume a pigtailed superluminescent diode, SLD-371, made by Superlum Ltd., Russia was used [8]. The spectral characteristics of the diode with the FWHM of 72 nm and the central wavelength at 816 nm is shown in Fig. 4 (dotted line). Fig. 4 (solid line) shows the relative spectral output power with the source. All the spectra are normalized with respect to the power of the diode at its central wavelength. Near the central wavelength, the spectral response are almost the same. However, when it’s far from the central wavelength, the effect of non-uniform power distribution of the input light source becomes significant.

The relative spectral output power of the ARROW-B SPR sensor with \(d_c = 5\) nm, \(d_m = 55\) to 65 nm, and \(d_f = 20\) to 30 nm for two values of environment index \(n_a = 1.332\) and 1.337 are calculated and shown in Figs. 5–7. The
value of the spectral shift of the relative output power for each case is almost the same. These results imply that the ARROW-B SPR sensors with $d_m = 60 \pm 5$ nm and $d_f = 25 \pm 5$ nm can provide the same good sensitivity which can be calculated as follows.

From the above relative spectral shift of the SPR response, the shift of the resonance wavelength $\Delta \lambda$ is about 12 nm, and the difference of the environment index $\Delta n_a$ is 0.005 for all of these conditions. The sensor sensitivity $S$ can be determined as

$$S = \frac{\Delta \lambda}{\Delta n_a} = \frac{12 \text{ nm}}{0.005 \text{ RIU}} = 2400 \frac{\text{nm}}{\text{RIU}},$$

(4)

where RIU is the refractive index unit. In conjunction with
Figure 6. The spectral dependence of the relative output power with $d_m = 60$ nm, $d_f = 20, 25$, and 30 nm for $n_a = 1.332$ and $1.337$, respectively.

Figure 7. The spectral dependence of the relative output power with $d_m = 65$ nm, $d_f = 20, 25$, and 30 nm for $n_a = 1.332$ and $1.337$, respectively.
a broadband source and a spectrum analyzer (a spectrograph, SD2000, Ocean Optics Inc., USA) which allows us to resolve variations in the SPR wavelength $\Delta \lambda_{\text{min}}$ of 0.0025 nm [8], the sensor is capable of detecting variations in the refractive index of environment as

$$\Delta n_{\text{min}} = \frac{\Delta \lambda_{\text{min}}}{S} = \frac{0.0025 \text{ nm}}{2400 \text{ nm/RIU}} = 1.0 \times 10^{-6} \text{ RIU},$$

where $\Delta \lambda_{\text{min}}$ is the minimum detectable variation in wavelength. If $\Delta \lambda_{\text{min}}$ is set to be 0.1 nm [5], $\Delta n_{\text{min}}$ becomes $4.0 \times 10^{-5}$. It indicates that the ARROW-B SPR sensor is quite competitive with the conventional waveguide SPR sensors, having resolution $\sim 6 \times 10^{-5}$ with the same value of $\Delta \lambda_{\text{min}}$.

5 Summary

An Au-coated ARROW-B SPR sensor with the spectral shift method has been developed. A buffer layer of Cr is added onto the metal layer so that the operating point can be adjusted to the interested range. The sensor is designed for operating in aqueous environment with a refractive index close to 1.332, and a sensitivity $\Delta \lambda/\Delta n_a$ of 2400 nm/RIU can be achieved. With the minimum detectable wavelength variation of 0.0025 nm, the minimum detectable change in environment refractive index is $1.0 \times 10^{-6} \text{ RIU}$.

References


