

# Side-polished optical fiber sensor coated with a metal/oxide surface-plasmon-resonance sensing film

KUN-YI LEE<sup>a</sup>, KUEN-CHERNG LIN<sup>a\*</sup>, WOO-HU TSAI<sup>b</sup>

<sup>a</sup>Department of Electrical Engineering, China University of Science and Technology, Taipei 115, Taiwan, ROC

<sup>b</sup>Graduate Institute of Electro-Optical Engineering, Tatung University, Taipei 104, Taiwan, ROC

We propose a side-polished fiber sensor coated with a metal/oxide surface-plasmon-resonance sensing film, in which an AZO layer is added between a metal film and the side-polished surface of the fiber core to improve the device's detection performance. The metal/AZO bi-layer film is used as the active sensing member of the device. Such a device is then applied to the concentration measurement of  $CH_3COONa$  solutions. The results indicate that the additional AZO layer in the active sensing member may give rise to lower detection limits and greater sensitivity.

(Received May 15, 2014; accepted June 24, 2015)

**Keywords:** Surface plasmon resonance, Fiber sensor, Detection accuracy

## 1. Introduction

Surface plasmon resonance (SPR) phenomena in the transmission spectrum of a side-polished optical fiber coated with a metal film have been applied to develop various chemical and biological sensors [1-2]. In our previous works, a graded-index multimode fiber is used to construct such kind of fiber-optic SPR sensor [2-3]. Wherein, the optical fiber is polished along its axis so that a portion of its core and cladding is removed from their cylinder side and a proper side face of the core is exposed. The side face is then coated with a gold or silver film. Once the device is surrounded in a dielectric medium to be sensed, the combination of the metal film and the coated core will act as an SPR sensing member. The side-polished fiber sensor provides a simple sensing scheme with high sensitivity in wavelength interrogation as well as high detection limit for biomolecules [4]. Also, it has been applied to the fields of time-dependent measurements in environmental monitoring [5] and nano thin-film deposition [6].

Recently, zinc oxides (ZnO) have been used as active materials for gas sensors and biosensors due to their chemical stability [7], and Al-doped ZnO (AZO) and Ga-doped ZnO (GZO) have been suggested as indium-free electrode materials for the solar cell devices [8]. However, it is seldom reported that the ZnO composite has been applied to a side-polished SPR-based fiber sensor. In this paper, the authors demonstrate a side-polished fiber sensor which is equipped with a metal/oxide SPR sensing film, wherein an additional AZO layer is interposed between the metal film and the side face of the core so as to let us follow its effects upon the device' performance. Both detection sensitivity and accuracy of the device will be measured and analyzed in detail. Also, the SPR fiber sensor will be applied to concentration measurement of sodium acetate ( $CH_3COONa$ ) solutions, as an example

showing a good response to concentration variation.

## 2. Device structure and its fabrication

Fig. 1 schematically shows the side-polished fiber sensor proposed in the present work. The device is composed of a side-polished fiber with a gold film and an AZO layer on its polished side face. The main body of the device is a graded-index multimode fiber with a core size of  $62.5 \mu\text{m}$  and a cladding diameter of  $125 \mu\text{m}$ , commercially available from the Prime Optical Fiber Corporation, Taiwan. The fiber is side-polished along its axis so that a portion of its core and cladding is removed to obtain a flat side face including the core area. A metal/AZO bi-layered SPR sensing member is then formed on the side face.

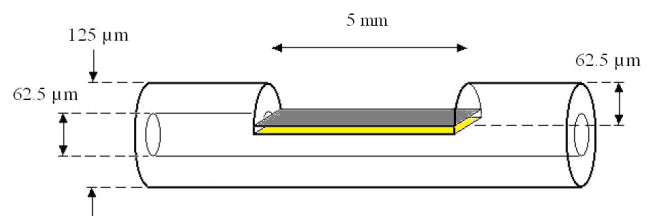


Fig. 1. The proposed side-polished fiber sensor.

The SPR sensing member is formed by depositing an AZO layer on the polished side face and then a gold film on the AZO layer, in which the gold film is set to have a thickness of 40 nm as suggested in our previous works [2-4] and the AZO layer is set to have a thickness ranging from 50 to 150 nm. The AZO layer is grown by the RF-magnetron sputtering system with a chamber pressure of  $20 \times 10^{-2}$  Torr and a gas discharge of 10 sccm. The gold

film is deposited by the DC sputtering system with a chamber pressure of  $20 \times 10^{-2}$  Torr as well as a DC power of 5 V and 20 mA. As compared to the control-group side-polished fiber sensors with only a single layer of SPR sensing gold film, the additional AZO layer in this study is used to improve their detection performance for refractive-index variation of a testing solution.

### 3. Experimental results and discussions

Detection sensitivity and accuracy are two major parameters to examine the performance of an SPR-based sensor [1]. Considering a transmittance spectrum of a white light beam launched into an SPR-based sensor which is surrounded in a dielectric medium of refractive index  $n_s$ , a sharp dip can be observed at its resonance wavelength  $\lambda_{res}$  due to efficient energy transfer from the light beam to surface plasma. A change of refractive index of the surrounding medium from  $n_s$  to  $n_s + \delta n_s$  may induce a shift of resonance wavelength  $\lambda_{res}$  by  $\delta \lambda_{res}$ . Thus, the detection sensitivity can be defined as  $S = \delta \lambda_{res} / \delta n_s$ , which means that sensitivity of an SPR-based sensor depends on the shift of the resonance wavelength according to the refractive index change. The detection accuracy of an SPR-based sensor depends on how precisely it can detect the resonance wavelength and hence the refractive index of the surrounding medium. The narrower the dip width of the transmittance spectrum, the higher is the detection accuracy. Thus, the detection accuracy can be defined as the signal-to-noise ratio  $SNR = \delta \lambda_{res} / \delta \lambda_{1/2}$ , where  $\delta \lambda_{1/2}$  denotes the spectral width of the transmittance spectrum corresponding to a reflectance of 1/2.

In the experiments, we have fabricated SPR fiber sensors coated with a gold/AZO sensing film as shown in Fig. 1, in which the gold film is 40 nm thick and the AZO layer is 0 (as the control-group one), 50, 75, 100, 125 or 150 nm thickness. Optical characteristics of the devices are measured by using a halogen white light source (Ando AQ4303B) and an optical spectrum analyzer (Ando AQ6315A). Dip widths in the transmittance spectrums are measured first, and then their SNR values can be calculated. Fig. 2 shows the SNR values of the SPR fiber sensors according to their AZO layer thicknesses. Regarding the control-group one with only the gold film as its SPR sensing member, the SNR value is only 0.180. If an AZO layer is added to below the gold film as the SPR sensing member, the sensor's SNR value can be increased from 0.196 for the sample with a 50-nm-thickness AZO layer to a maximum of 0.317 for the sample with a 100-nm-thickness AZO layer, and then decreased to 0.234 for the sample with a 150-nm-thickness AZO layer. The result shows that detection accuracy of a side-polished SPR fiber sensor can be improved by interposing an AZO layer between the gold film and the polished side of the control-group one.

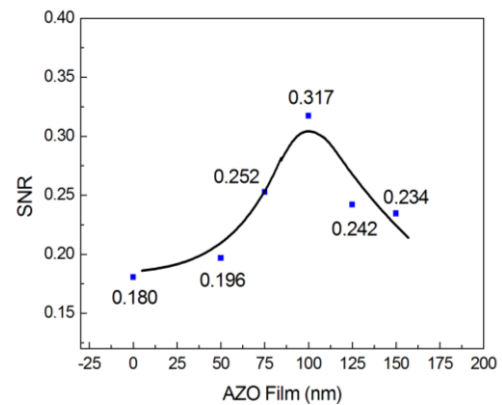
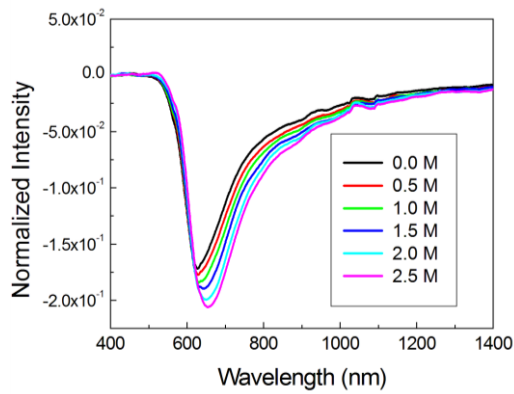


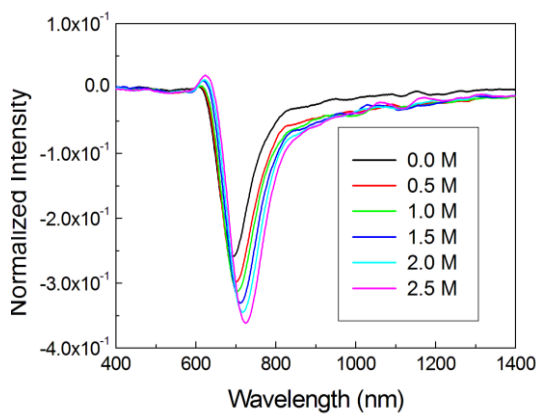
Fig. 2. The SNR values of the SPR fiber sensors with their AZO layer thickness of 0, 50, 75, 100, 125, and 150 nm, respectively.

To look the device response to refractive-index variation of the surrounding medium to be detected, the proposed SPR fiber sensor with a 40-nm-thickness Gold film over a 100-nm-thickness AZO layer as its SPR sensing member was used to measure  $CH_3COONa$  solutions of different concentrations. The results will be compared to the control-group one without the AZO layer. Figs. 3(a) and 3(b) respectively show the transmittance spectra of the proposed device and the control-group one in the measurements of  $CH_3COONa$  solutions with different concentrations. The SPR dips are close to each other in the spectra. The SPR dip widths of the proposed device are much less than those of the control-group one without the AZO layer. This suggests that an AZO layer between the gold film and the polished side face of the control-group fiber sensor may improve the device's detection accuracy. The SPR dip wavelength of the proposed device shifts from 694.5 nm for the 0-M  $CH_3COONa$  solution to 724.3 nm for the 2.5-M  $CH_3COONa$  solution, while the SPR dip wavelength of the control-group one shifts from 628.5 nm for the 0-M  $CH_3COONa$  solution to 667.2 nm for the 2.5-M  $CH_3COONa$  solution.

The relationships of the SPR dip wavelength to the  $CH_3COONa$  solution concentration are summarized in Figs. 4(a) and 4(b) for the proposed device and the control-group one, respectively. It can be observed that a linearly proportional relationship between the SPR dip wavelength and the  $CH_3COONa$  solution concentration. The slope of the linear fitting lines represents the device's sensitivity to the concentration of the  $CH_3COONa$  solution. The sensitivity of the proposed device versus the  $CH_3COONa$  solution concentration is 12.1 nm/M, lower than that (15.3 nm/M) of the control-group device. This implies that the added AZO layer may induce a little sensitivity loss to the SPR fiber sensor in the measurement of  $CH_3COONa$  solution concentration.



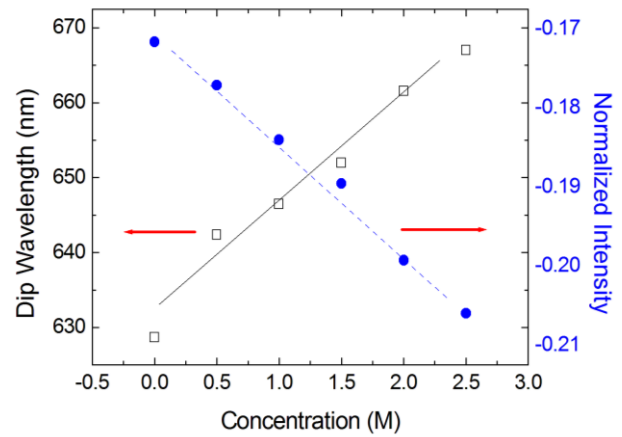
(a)



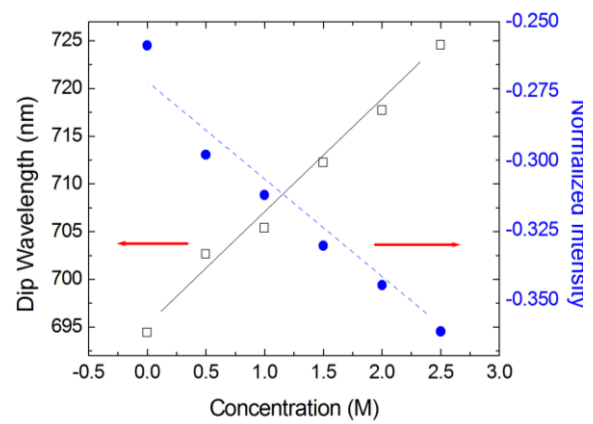
(b)

Fig. 3. Transmittance spectra of (a) the proposed device and (b) the control-group one in the measurements of  $CH_3COONa$  solutions with different concentrations.

Moreover, the normalized intensity at the SPR dip wavelength of the proposed device decreases from -0.258 for the 0-M  $CH_3COONa$  solution to -0.362 for the 2.5-M  $CH_3COONa$  solution, while the normalized intensity at the SPR dip wavelength of the control-group one decreases from -0.172 for the 0-M  $CH_3COONa$  solution to -0.206 for the 2.5-M  $CH_3COONa$  solution. Figs. 4(a) and 4(b) also shows the relationship of the normalized intensity at the SPR dip wavelength to the  $CH_3COONa$  solution concentration for the cases of the proposed SPR fiber sensor and the control-group one, respectively. The normalized intensity at the SPR dip wavelength of the proposed device is more affected by the solution concentration than that of the control-group one. This drops a hint that a little loss of detection stability is induced by the addition of the AZO layer, balanced off by the increased detection accuracy of the device.



(a)



(b)

Fig. 4. Relationship of the normalized intensity at the SPR dip wavelength to the  $CH_3COONa$  solution concentration for (a) the proposed device and (b) the control-group one.

#### 4. Conclusions

We have demonstrated a side-polished fiber sensor with a SPR sensing member composed of a gold film and an AZO layer. The device is based on a graded-index multimode fiber, and the AZO layer is interposed between the gold film and the side-polished surface of the fiber core. The gold/AZO bi-layer film is used as the active sensing member of the device to improve its performance. According to the experimental results, the sensing member with a 100 nm thick AZO layer below a 40 nm thick gold film can provide a most improvement of detection accuracy. Such a device was then applied to the concentration measurement of  $CH_3COONa$  solutions. The results indicate that the added AZO layer in the SPR sensing member may induce a little loss of detection sensitivity and stability in the measurements of solution concentration. These findings would further provide side-polished SPR-based fiber sensors with potential applications in the chemical and biological sensing fields.

**References**

- [1] B. D. Gupta, R. K. Verma, *J. Sensors*, 979761 (2009).
- [2] Y. C. Lin, Y. C. Tsao, W. H. Tsai, T. S. Hung, K. S. Chen, S. C. Liao, *Sens. Actuators B: Chem.*, **133**, 370 (2008).
- [3] Y. C. Tsao, Y. C. Lin, W. H. Tsai, M. S. Wu, *Sens. Actuators A: Phys.*, **166**, 9 (2011).
- [4] Y. C. Lin, W. H. Tsai, Y. C. Tsao, J. K. Tai, *IEEE Photo. Tech. Lett.*, **20**, 1287 (2008).
- [5] H. Y. Lin, Y. C. Tsao, W. H. Tsai, Y. W. Yang, T. R. Yan, B. C. Sheu, *Sens. Actuators A: Phys.*, **138**, 299 (2007).
- [6] Y. C. Tsao, W. H. Tsai, W. C. Shih, M. S. Wu, *Sensors*, **13**, 9513 (2013).
- [7] Z. L. Wang, *Appl. Phys. A*, **88**, 7 (2007).
- [8] H. K. Park, J. W. Kang, S. I. Na, D. Y. Kim, H. K. Kim, *Solar Energy Materials & Solar Cells*, **93**, 1994 (2009).

---

\*Corresponding author: kclin@cc.cust.edu.tw