Abstract. In this paper, an optical fiber SPR sensor based on polymer-tipped optical fiber (PTOF) coated with a gold film and a Barium Titanate (BaTiO$_3$) layer has been designed and analyzed by finite difference time-domain (FDTD) method. Three SPR dips are observed and the sensitivity is proved to be higher than the structure without BaTiO$_3$. A novel measurement method based on sum-value and difference-value of two SPR dips is proposed. Compared with conventional measurement method based on single dip, the measurement based on sum-value can significantly improve the sensitivity and the measurement based on difference-value can effectively reduce the environmental influence.

Introduction

Since R. C. Jorgenson proposed and developed a novel SPR sensor based on optical fiber for the first time in 1992[1], the optical fiber SPR sensor has gained a huge attention due to its unique features, such as flexibility, small size and capability of remote sensing [2,3].

In 2008, Bachelot R et al. presented a method of free-radical photopolymerization on the top end of single-mode fiber [4]. A micronic polymer-tip could be produced on the fiber end, which may be viewed as an extension of the fiber core. Polymer-tips with different shapes and sizes can be generated by changing exposure time, light intensity and shape (height and radius of curvature) of drop [5]. Compared with conventional optical fiber SPR sensors, the single-mode PTOF SPR sensor is simpler in fabrication, smaller in size, which has also been used in research of SPR sensors in recent years.

Barium titanate (BaTiO$_3$) is a ferroelectric crystal with perovskite structure, which has excellent electro-optical and nonlinear optical properties [6]. At present, a high crystallinity BaTiO$_3$ film with a grain size of less than 10nm can be prepared at a low temperature by a one-step sol method which allows the thin film of BaTiO$_3$ material into application [7].

In this paper, an SPR sensor based on polymer-tipped optical fiber with a gold film and a BaTiO$_3$ layer has been designed and optimized. The BaTiO$_3$ layer is proved to enhance the sensitivity of SPR sensors. Three SPR dips are observed and two of them are used for a novel measurement method based on sum-value and difference-value for the first time. The measurement based on sum-value can significantly improve the sensitivity and the measurement based on difference-value can effectively reduce the environmental influence.

The Characteristic of the Combination of BaTiO$_3$ and Polymer-tipped Optical Fiber (PTOF)

PTOF was fabricated on a single mode fiber (Corning SMF28e +) by photopolymerization method [4]. The scanning electron microscopy (SEM) of single-mode PTOF is displayed in Fig.1.
The tapered polymer-tip length can be controlled by changing the size of the drop and the tip end diameter can be controlled by changing exposure time. The longer the exposure time, the bigger the tip end diameter. The combination of PTOF and SPR shows that it can improve the performance of SPR sensors. The optimal metal layer is proved to be 50nm Au, and the optimal parameters of polymer-tip: the length of the tip is 34 $\mu$m and the width of the end of the tip is 1.5 $\mu$m [5].

As shown in Fig. 2, a certain thickness of BaTiO$_3$ crystal layer and Au layer are coated on PTOF. 200nm Au is placed on the bottom of polymer-tip to reflect light back.

Figure 2. 3D model of PTOF coated with BaTiO$_3$ layer.

Figure 3. SPR spectrum of PTOF coated with 20nm BaTiO$_3$ in different analyte.
Fig. 3 shows that three SPR dips are observed in the spectrum with 20nm BaTiO$_3$ crystal layer and the two SPR dips at short wavelength red shift with the increase of RI of analyte. But the third SPR dip near 1.2-1.4um does not displays good linear correlation with RI of analyte. In this article, the two SPR dips at short wavelength are selected for SPR sensing, which are defined as double SPR dips in this paper.

**Figure 4.** The double SPR dips with RI of analyte coated with 20nm BaTiO$_3$.

Fig. 4 depicts both two SPR dips have good linear relationship with the RI of analyte. The average sensitivity without BaTiO$_3$ is 2602nm/RIU, and the double SPR dip possesses the sensitivity of 3100nm/RIU and 4050nm/RIU respectively, which means the structure with BaTiO$_3$ layer will improve the sensitivity of sensors.

**New Measurement Method Based on Combination of Double SPR Dips**

Since the double SPR dips appear at the same time, the difference between the two resonance wavelengths will effectively decrease the influence of complex external environment, which shows that difference-value sensing can be applied in poor measurement environment. And the sensitivity will be double higher when the sum of two resonance wavelength is applied to sensing. Fig. 5 and Fig. 6 show the difference-value and the sum-value with the RI of analyte for BaTiO$_3$ layer thickness varying from 10nm to 50nm. It can be seen that the sum-value and the difference-value both behave good linearity with the increase of RI of analyte, which means the sum-value sensing and the difference-value sensing can be applied to SPR sensing to improve the performance.

**Figure 5.** The sum-value with the RI of analyte for BaTiO$_3$ layer thickness varying from 10nm to 50nm.
Figure 6. The difference-value with the RI of analyte for BaTiO$_3$ layer thickness varying from 10nm to 50nm.

Conclusions

In this paper, BaTiO$_3$ layer is proved to enhance the sensitivity of SPR sensors. Three SPR dips appears when polymer-tipped optical fiber is coated with a gold film and a Barium Titanate layer to excite SPR. A novel measurement method based on sum-value and difference-value of double SPR dips is proposed and proved to improve the performance of SPR sensors.

References

[1] R.C. Jorgenson, S.S. Yee. “A fiber-optic chemical sensor based on surface plasmon resonance”. Sensors and Actuators B-Chemical, 1993, 12(3):213-220.

[2] De Melo A A, da Silva T B, da Silva Santiago M F, et al. Theoretical Analysis of Sensitivity Enhancement by Graphene Usage in Optical Fiber Surface Plasmon Resonance Sensors[J]. IEEE Transactions on Instrumentation and Measurement, 2018.

[3] Zhao Yong. Principle and Application Technology of Optical Fiber Sensors. Beijing: Tsinghua University Press, 2007. 36-37.

[4] Bachelot R, Blaize S, Pang C, et al. “Polymer-Tipped Optical Fibers”. Fiber & Integrated Optics, 2008, 27(6):542-558.

[5] Z. Zhang, F. Chu, Z. Guo, J. Fan, G. Li and W. Cheng, "Design and Optimization of Surface Plasmon Resonance Sensor Based on Polymer-Tipped Optical Fiber," in Journal of Lightwave Technology, vol. 37, no. 11, pp. 2820-2827, June 1, 2019.

[6] Zhu Wei, Liu Yanqi, Niu Xiaojuan, Chen Zhenghao. Electrical and electro-optic properties of Ce:BaTiO$_3$ films prepared by PLD method[J]. Journal of Synthetic Crystals, 1997(Z1):153.

[7] Hao Yanan. Preparation, properties and application of nanocrystalline barium titanate-based materials [D]. Tsinghua University: School of Materials, 2016.