UNIVERSITI PUTRA MALAYSIA

DESIGN AND FABRICATION OF FIBER-BASED SURFACE PLASMON RESONANCE SENSORS

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By

YUSSER A. TAQI AL-QAZWINI

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfillment of the Requirements for the Degree of Doctor of Philosophy

June 2016

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DEDICATION

I humbly and lovingly dedicate this thesis to my sister, my mother, my late father who is in heaven, and my beloved country, Iraq.

Abstract of thesis presented to the Senate of Universiti Putra Malaysia infulfillment of the requirement for the degree of Doctor of Philosophy

DESIGN AND FABRICATION OF FIBER-BASED SURFACE PLASMON RESONANCE SENSORS

By

YUSSER ALI AL-QAZWINI

June 2016

Chairman : Ahmad Shukri bin Muhammad Noor, PhD
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Surface plasmon resonance (SPR) sensors based on optical fibers, with their high level of miniaturization, high sensitivity to variations in the refractive index (RI) of the surrounding medium, and sensing capability in hazardous areas, have attracted a great attention for the past two decades as one of the most advanced real-time and label-free detection technology. The performance of these devices in terms of their sensitivity and detection accuracy is of great importance and it is strongly influenced by the design parameters such as fiber material and geometry, and the properties of the metal layer and sensing medium. This thesis presents numerical simulations to understand the impact of these parameters on the performance of a basic fiber-based SPR sensor implementing a simple waveguide layered structure. The thesis also reports the fabrication of two cost-effective fiber-based SPR sensors. The developed sensors are tested for RI sensing of aqueous media.

A simple planar layered structure is numerically simulated to provide design specifications for fiber-based SPR sensors. The numerical simulations help understand the influence of the properties of the involved layers like metal layer and residual cladding thickness, sensing length, and RI of the sensing medium on the response of SPR sensors.

An SPR sensor based on a tapered multimode fiber is fabricated and experimentally characterized for its performance. The sensor is made by tapering a standard multimode fiber using an automated tapering machine followed by coating the entire taper with gold without masking. The impact of waist-diameter, waist and transition lengths on the performance of the sensor is investigated. A simple, high-performance, yet robust sensor with a spectral width of 140-220 nm and a sensitivity of ~1600-2000 nm/RIU is realized when the waist diameter is set to 25-45 μm with a total taper length of 3-5 mm and 55-nm gold thickness.

A second configuration based on plastic optical fiber is fabricated and analyzed. This fiber brings additional advantages to SPR sensors because of its large numerical aperture, excellent flexibility, and easy manipulation. The implemented chemical etching process with concentrated Acetone preserves the fiber's circular geometry which simplifies the fabrication process and reduces the associated costs compared to side-polished ones. Same setup and sensing solutions are used while the influence of the gold thickness, fiber residual thickness, and sensing length is investigated. A low-cost, sensitive, and robust SPR sensor with an average sensitivity of 1600 nm/RIU and spectral width of 154 nm is realized when a plastic optical fiber is etched from the middle up to 964-μm with 10-mm sensing length and 55-nm gold thickness.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

REKA BENTUK DAN FABRIKASI PENDERIA PERMUKAAN RESONANS PLASMON BERASASKAN GENTIAN

Oleh

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Penderia permukaan resonans plasmon (SPR) berasaskan gentian optik, dengan tahap pengecilan saiz yang besar, kepekaan yang tinggi kepada perubahan indeks biasan (RI) dalam medium, dan keupayaan peranti di kawasan berbahaya, telah menarik perhatian tinggi sejak dua dekad yang lalu sebagai salah satu teknologi pengesanan tanpa label yang termaju. Prestasi peranti ini dari segi kepekaan dan ketepatan pengesanan adalah amat penting dan ia dipengaruhi oleh parameter-parameter reka bentuk seperti bahan gentian dan geometrinya dan sifat-sifat lapisan logam dan medium penderiaan. Tesis ini membentangkan simulasi berangka untuk memahami kesan parameter ini kepada prestasi yang berasaskan penderia gentian SPR asas menggunakan teknik pandu gelombang struktur berlapis yang mudah. Tesis ini juga melaporkan pembuatan dua penderia SPR berasaskan gentian yang kos efektif. Penderia dibangunkan dan diuji untuk penderiaan RI bagi medium cecair.

Struktur satah berlapis mudah disimulasi berangka untuk menyediakan spesifikasi reka bentuk untuk penderia SPR berasaskan gentian. Simulasi berangka ini membantu memahami pengaruh sifat-sifat lapisan terlibat seperti lapisan logam dan sisa ketebalan klad, panjang penderia, dan RI medium penderiaan pada sambutan penderia SPR.

Penderia SPR berdasarkan gentian pelbagai-mod dan diujikaji bagi menentukan ciri-ciri prestasinya. Penderia direka oleh tirus gentian mod standard di fabrikasi menggunakan mesin penirus otomatik diikuti oleh lapisan keseluruhan tirus dengan emas tanpa pelekat. Kesan diameter-pinggang, pinggang dan peralihan panjang kepada prestasi penderia itu dikaji. Penderia yang mudah, berprestasi tinggi, dan teguh dengan kepekaan ~1600-2000 nm/RIU dan lebar spektrum 140-220 nm berjaya direalisasikan apabila diameter pinggang 25-45 mikron dengan jumlah panjang tirus daripada 3-5 mm dan ketebalan emas 55-nm.

Konfigurasi kedua penderia berdasarkan gentian optik plastik direka bentuk dan dianalisis. Gentian ini mempunyai kelebihan tambahan kepada gentian SPR kerana apertur yang besar, fleksibiliti yang cemerlang, dan mudah untuk di manipulasikan. Proses punaran dilakukan bagi mengekalkan geometri bulat gentian ini yang memudahkan proses fabrikasi dan mengurangkan kos yang berkaitan berbanding dengan sisi-gilap. Persediaan sama dan larutan penderia bagi mengkaji pengaruh ketebalan emas, sisa ketebalan gentian, dan panjang penderia. Penderia SPR yang direalisasikan, sensitif, berkos rendah dan teguh dengan purata sensitiviti 1600 nm/RIU dan lebar spektrum 154 nm direalisasikan apabila gentian optik plastik terukir dari tengah sehingga 964-mikron dengan 10 mm panjang penderia dan tebal emas 55-nm.

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I certify that a Thesis Examination Committee has met on 20 June 2016 to conduct the final examination of Yusser A. Taqi Al-Qazwini on her thesis entitled "Design and Fabrication of Fiber-Based Surface Plasmon Resonance Sensors" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

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LIST OF ABBREVIATIONS

SPR	Surface plasmon resonance
RI	Refractive index
RIU	Refractive index unit
SMF	Single-mode fiber
MMF	Multimode fiber
POF	Plastic optical fiber
SP	Surface plasmon
SPW	Surface plasmon wave
TM	Transverse magnetic
TIR	Total internal reflection
EW	Evanescent wave
ATR	Attenuated total reflection
SNR	Signal-to-noise ratio
FWHM	Full width at half maximum
vis-NIR	Visible-near infrared
PCF	Photonic crystal fiber
LPG	Long period grating
FBG	Fiber Bragg grating
NP	Nanoparticles
LSPR	Localized surface plasmon resonance
UV-Vis	Ultraviolet-visible
MIP	Molecularly imprinted polymer
MEP	Mode expansion and propagation
FDTD	Finite-difference time-domain
PML	Perfectly matched layer
HL	Halogen
SEM	Scanning electron microscope
PMMA	poly(methyl methacrylate)
SMA	SubMiniature version A
FC	Ferrule connector

CHAPTER 1

INTRODUCTION

1.1 Overview

There is a continuing need for the development of simple and efficient methods for real-time sensing in the fields of chemistry, environmental, and biological studies, etc. To meet this ever-increasing demand, a wide-range of real-time and label-free approaches have been developed based on ellipsometry, grating couplers, interferometers, surface plasmon resonance, etc [1]. Among the aforesaid sensing technologies, surface plasmon resonance (SPR) has attracted much attention for the past two decades because of being label-free, non-destructive and highly sensitive detection method. Optical sensors based on SPR technique are very sensitive to variations in the refractive index (RI) of the sensing medium which made them highly efficient for various sensing applications.

Optical SPR sensors have evolved from the basic SPR configuration based on Kretchmann configuration which comprises basic optical components such as a glass prism, a thin metal film, and the sample layer or surrounding medium [2-4]. However, conventional prism-based SPR sensors suffer from some drawbacks such as bulky size with several mechanical and optical moving elements leading to implementation difficulties for remote sensing applications. Thus, to overcome these drawbacks, optical fibers have been deployed as an alternative to the glass prism.

The introduction of fiber-based SPR sensors as an optical sensor in the early 1990s has gained considerable attention thanks to their high level of miniaturization and sensing capability in inaccessible locations. In addition, they are immune to electromagnetic interference and can be used in hazardous areas [5-7]. Since then, fiber-based SPR sensors have been adopted in various applications and huge effort has been made to enhance their performance [8-12].

The remaining sections in this chapter address the motivation, objectives, and organization of this thesis.

1.2 Problem Statements

In fiber-based SPR sensing devices, the sensing element is typically made of a metal-coated optical fiber. The performance of SPR devices in terms of their sensitivity and detection accuracy is strongly influenced by the design parameters such as fiber material, fiber geometry, and the properties of the metal layer and sensing medium. Therefore, this thesis explores the impact of these parameters on the performance of SPR-based RI sensors starting with numerical simulations of a simple planar

waveguide structure, followed by laboratory experiments on different structures of fiber-based SPR sensors.

A typical fiber-based SPR sensor is normally made from silica fiber, either single-mode (SMF) or multi-mode (MMF) fiber. The design of SPR sensors based on SMF needs very high accuracy due to the small amount of power accommodated by the small core of single-mode fibers [13, 14]. In addition, the polarization of light has to be precisely controlled to reduce instability in the sensor output which requires the use of extra components and eventually raises the system complexity and cost [15]. One more downside of SPR sensors made with SMF is that they are very fragile complicating the sensor fabrication [16]. Multimode fibers, on the other hand, offer a much wider range of measurable refractive index despite suffering from low stability due to the intermodal coupling and modal noise. Apart from that, MMF is less fragile and the sensor system does not need a precise control of the polarization state which offers simpler and relatively lower cost option in the design of SPR sensors.

In order to increase the chances of SPR to occur in an optical fiber, an evanescent field is necessary to generate surface plasmon wave at the interface of a metal layer and the surrounding medium. For that purpose, several structures of fiber-based SPR sensors have been proposed and developed such as partial removal of fiber cladding [17], side-polishing [18, 19], and tapering [20-22]. SPR sensors based on tapered optical fibers, particularly in the case of MMF, feature some advantages such as compactness, simplicity, and high sensitivity compared to those in which the cladding is removed or polished [17, 23]. There have been a large number of studies [24, 25] concerning tapered fiber-based SPR sensors but they did not provide sufficient information on the impact of the taper length considering both the taper-waist length and transition lengths. Furthermore, most of these studies involved some masking techniques to cover certain regions of the tapered fiber making the sensor fabrication more sophisticated.

Hence, this thesis experimentally demonstrates the fabrication of an SPR sensor based on a tapered MMF. The influence of design parameters including the waist diameter, taper waist-length and transition lengths on the sensor performance is thoroughly studied. The gold coating process did not involve masking which offers a simpler approach towards the sensor fabrication.

For low-cost applications, plastic optical fiber (POF) offers a good alternative compared to standard silica fibers such as SMF and MMF. SPR sensors based on POF have a number of advantages including design simplicity, low fabrication cost, and flexibility [26-28]. Most of the reported SPR sensors based on POF are made by side-polishing the polymer cladding which damages the circular symmetry of the optical fiber with consequent polarization dependent losses [29]. In these sensors, the field interaction strength is reduced by the circular asymmetry. In addition, splicing side-polished fibers is not an easy thing resulting in alignment difficulties and consequently additional losses. Besides, the process of side-polishing is mechanically complex [30, 31].

Therefore, this thesis also incorporates the fabrication of a low-cost SPR sensor based on an etched POF in which a cladding reduction approach is implemented using chemical etching with a precise control of the immersion time to control the fiber diameter while preserving the cylindrical geometry of the optical fiber. In addition, the impact of design parameters including gold thickness, amount of residual cladding, and sensing length is also investigated.

1.3 Research Objectives

The objectives of this thesis are:

- To use numerical simulation to study the basic performance characteristics of fiber-based SPR sensors using a simple planar waveguide structure.
- To fabricate an SPR sensor based on tapered MMF without the use of masking.
- To fabricate an SPR sensor based on an etched POF.
- To utilize the developed sensors for RI sensing and analyze their performance in terms of sensitivity and detection accuracy.

1.4 Outline of the Thesis

This thesis consists of six chapters organized as follows:

Chapter 1: INTRODUCTION begins with a brief background in the context of fiber-based SPR sensors. After analyzing the research motivation, objectives of this work are proposed, followed by the structure of the thesis which outlines the whole work carried out.

Chapter 2: LITERATURE REVIEW reviews the SPR theory and relevant literature on fiber-based SPR sensors. First, the chapter introduces the basics of SPR theory and its sensing principles, followed by an introduction to the prism coupling as the base of conventional SPR sensing. Next, the performance characteristics of SPR sensors are reviewed with the right choice of metals and a study of the properties of the complex propagation constant of surface plasmons. The third section provides an overview of fiber-based SPR sensors and the various available structures are reviewed. Finally, the recent advancements in the field of fiber-based SPR sensors are outlined.

Chapter 3: NUMERICAL INVESTIGATION OF A BASIC STRUCTURE OF FIBER-BASED SPR SENSOR presents a numerical investigation of the impact of main design parameters on the performance of a basic structure of fiber-based SPR sensor using a simple layered structure before going into real experimental work and more complicated structures in the subsequent chapters. The chapter serves as a starting point to understand how the performance of SPR sensors is influenced by the

properties of the involved layers including the gold layer thickness, residual cladding thickness, sensing length, and refractive index of the surrounding environment. In the second section, a brief introduction to the finite-different time-domain method is presented. The third section describes the implemented numerical model based on a simple planar waveguide structure followed by the theory related to the calculation of the normalized transmitted power. Finally, the results of the numerical simulations concerning the refractive index sensitivity and detection accuracy of the simulated SPR sensor are compared and discussed.

Chapter 4: SPR SENSOR BASED ON TAPERED MULTIMODE FIBER introduces the details of the fabrication of an SPR sensor based on tapered MMF, including the tapering process of multimode optical fibers with different tapering parameters, and coating of thin gold films on the tapered region without the use of masking. The experimental setup which comprises of simple components is described. In addition, a study of the refractive index sensitivity and detection accuracy of the fabricated SPR sensor is carried out and the results are discussed.

Chapter 5: SPR SENSOR BASED ON ETCHED PLASTIC OPTICAL FIBER reports the fabrication of an SPR sensor based on etched POF. The detailed procedure with regard to the etching technique is described, and a relationship between the fiber thickness and immersion time is presented. The details of the fabrication process, including the fiber etching and gold coating on the etched region are also introduced. Furthermore, the performance of the fabricated sensor with different design parameters is examined and the results are discussed.

Chapter 6: CONCLUSIONS AND FUTURE WORKS concludes the whole work carried out with the research findings of this thesis, summarizing the achievements made against the objectives identified in Chapter 1. This chapter also describes how the present work can be extended through future work to broaden the scope of the research.

REFERENCES

[1] G. Gauglitz, G. Proll, Strategies for label-free optical detection, in *Biosensing for the 21st Century*, ed: Springer, 2007, 395-432.

[2] X. Hoa, A. Kirk, M. Tabrizian, Towards integrated and sensitive surface plasmon resonance biosensors: a review of recent progress, Biosensors and Bioelectronics, 23 (2007), 151-160.

[3] G. Gupta, J. Kondoh, Tuning and sensitivity enhancement of surface plasmon resonance sensor, Sensors and Actuators B: Chemical, 122 (2007), 381-388.

[4] M. Morjan, H. Zöchner, K. Cammann, Contributions to a reliable hydrogen sensor based on surface plasmon surface resonance spectroscopy, Surface Science, 603 (2009), 1353-1359.

[5] B. Lee, Review of the present status of optical fiber sensors, Optical Fiber Technology, 9 (2003), 57-79.

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

[7] M. Rani, STUDIES ON SURFACE PLASMON RESONANCE BASED FIBER OPTIC SENSORS, (2014),

[8] Y. Yuan, L. Ding, Z. Guo, Numerical investigation for SPR-based optical fiber sensor, Sensors and Actuators B: Chemical, 157 (2011), 240-245.

[9] R. Slavík, J. Homola, J. Čtyroký, E. Brynda, Novel spectral fiber optic sensor based on surface plasmon resonance, Sensors and Actuators B: Chemical, 74 (2001), 106-111.

[10] B. Gupta, A.K. Sharma, Sensitivity evaluation of a multi-layered surface plasmon resonance-based fiber optic sensor: a theoretical study, Sensors and Actuators B: Chemical, 107 (2005), 40-46.

[11] M. Iga, A. Seki, K. Watanabe, Gold thickness dependence of SPR-based hetero-core structured optical fiber sensor, Sensors and Actuators B: Chemical, 106 (2005), 363-368.

[12] H. Suzuki, M. Sugimoto, Y. Matsui, J. Kondoh, Effects of gold film thickness on spectrum profile and sensitivity of a multimode-optical-fiber SPR sensor, Sensors and Actuators B: Chemical, 132 (2008), 26-33.

[13] J. Homola, S.S. Yee, G. Gauglitz, Surface plasmon resonance sensors: review, Sensors and Actuators B: Chemical, 54 (1999), 3-15.

[14] J. Homola, R. Slavik, Fibre-optic sensor based on surface plasmon resonance, Electronics Letters, 32 (1996), 480-482.

[15] A. Tubb, F. Payne, R. Millington, C. Lowe, Single-mode optical fibre surface plasma wave chemical sensor, Sensors and Actuators B: Chemical, 41 (1997), 71-79.

[16] T. Anttalainen, V. Jaaskelainen, Introduction to Communication Networks: Artech House, 2014.

[17] J. Crisp, Introduction to fiber optics: Elsevier, 2005.

[18] M. Piliarik, J. Homola, Z. Manıková, J. Čtyroký, Surface plasmon resonance sensor based on a single-mode polarization-maintaining optical fiber, Sensors and Actuators B: Chemical, 90 (2003), 236-242.

[19] B. Gupta, R. Verma, Surface plasmon resonance-based fiber optic sensors: principle, probe designs, and some applications, Journal of Sensors, 2009 (2009),

[20] W.B. Lin, N. Jaffrezic-Renault, A. Gagnaire, H. Gagnaire, The effects of polarization of the incident light-modeling and analysis of a SPR multimode optical fiber sensor, Sensors and Actuators A: Physical, 84 (2000), 198-204.

[21] G. Stewart, B. Culshaw, Optical waveguide modelling and design for evanescent field chemical sensors, optical and quantum electronics, 26 (1994), S249-S259.

[22] A. Dıez, M. Andres, J. Cruz, In-line fiber-optic sensors based on the excitation of surface plasma modes in metal-coated tapered fibers, Sensors and Actuators B: Chemical, 73 (2001), 95-99.

[23] A. Díez, M.V. Andrés, J.L. Cruz, Hybrid surface plasma modes in circular metal-coated tapered fibers, JOSA A, 16 (1999), 2978-2982.

[24] W. Henry, Evanescent field devices: a comparison between tapered optical fibres and polished or D-fibres, optical and quantum electronics, 26 (1994), S261-S272.

[25] J. Villatoro, D. Monzón-Hernández, E. Mejía, Fabrication and modeling of uniform-waist single-mode tapered optical fiber sensors, Applied optics, 42 (2003), 2278-2283.

[26] S. Ju, et al., Experimental demonstration of surface plasmon resonance enhancement of the tapered optical fiber coated with Au/Ti thin film, Journal of Non-Crystalline Solids, 383 (2014), 146-152.

[27] N. Cennamo, D. Massarotti, L. Conte, L. Zeni, Low cost sensors based on SPR in a plastic optical fiber for biosensor implementation, Sensors, 11 (2011), 11752-11760.

[28] N. Cennamo, et al., Sensors based on surface plasmon resonance in a plastic optical fiber for the detection of trinitrotoluene, Sensors and Actuators B: Chemical, 188 (2013), 221-226.

[29] N. Cennamo, L. Zeni, Bio and Chemical Sensors Based on Surface Plasmon Resonance in a Plastic Optical Fiber, (2014),

[30] M. Cordaro, D.L. Rode, T. Barry, R.R. Krchnavek, Precision fabrication of D-shaped single-mode optical fibers by in situ monitoring, Lightwave Technology, Journal of, 12 (1994), 1524-1531.

[31] J.M. Kvavle, S.M. Schultz, R.H. Selfridge, Low loss elliptical core D-fiber to PANDA fiber fusion splicing, Optics express, 16 (2008), 13552-13559.

[32] R.W. Wood, On a remarkable case of uneven distribution of light in a diffraction grating spectrum, (1902).

[33] S.-S. Chang, C.-W. Shih, C.-D. Chen, W.-C. Lai, C.C. Wang, The shape transition of gold nanorods, Langmuir, 15 (1999), 701-709.

[34] C.R. Martin, "Nanomaterials--a membrane-based synthetic approach," DTIC Document1994.

[35] L. Rayleigh, III. Note on the remarkable case of diffraction spectra described by Prof. Wood, The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science, 14 (1907), 60-65.

[36] U. Fano, The theory of anomalous diffraction gratings and of quasi-stationary waves on metallic surfaces (Sommerfeld's waves), JOSA, 31 (1941), 213-222.

[37] A. Otto, Excitation of nonradiative surface plasma waves in silver by the method of frustrated total reflection, Zeitschrift für Physik, 216 (1968), 398-410.

[38] E. Kretschmann, H. Raether, Notizen: Radiative Decay of Non Radiative Surface Plasmons Excited by Light, Zeitschrift für Naturforschung A, 23 (1968), 2135-2136.

[39] R.B. Schasfoort, A.J. Tudos, Handbook of surface plasmon resonance: Royal Society of Chemistry, 2008.

[40] X. Huang, I.H. El-Sayed, W. Qian, M.A. El-Sayed, Cancer cell imaging and photothermal therapy in the near-infrared region by using gold nanorods, Journal of the American Chemical Society, 128 (2006), 2115-2120.

[41] C.L. Smith, N. Stenger, A. Kristensen, N.A. Mortensen, S.I. Bozhevolnyi, Gap and channeled plasmons in tapered grooves: a review, Nanoscale, 7 (2015), 9355-9386.

[42] A.K. Sharma, R. Jha, B. Gupta, Fiber-optic sensors based on surface plasmon resonance: a comprehensive review, Sensors Journal, IEEE, 7 (2007), 1118-1129.

[43] H. Raether, Surface plasmons on smooth surfaces: Springer, 1988.

[44] I. Pockrand, J. Swalen, J. Gordon, M. Philpott, Surface plasmon spectroscopy of organic monolayer assemblies, Surface Science, 74 (1978), 237-244.

[45] N. Harrick, K. Beckmann, Internal reflection spectroscopy, in *Characterization of Solid Surfaces*, ed: Springer, 1974, 215-245.

[46] H.R. Gwon, S.H. Lee, Spectral and angular responses of surface plasmon resonance based on the Kretschmann prism configuration, Materials transactions, 51 (2010), 1150-1155.

[47] A.K. Sharma, B. Gupta, Fibre-optic sensor based on surface plasmon resonance with Ag–Au alloy nanoparticle films, Nanotechnology, 17 (2006), 124.

[48] S.A. Zynio, A.V. Samoylov, E.R. Surovtseva, V.M. Mirsky, Y.M. Shirshov, Bimetallic layers increase sensitivity of affinity sensors based on surface plasmon resonance, Sensors, 2 (2002), 62-70.

[49] N. Cennamo, D. Massarotti, R. Galatus, L. Conte, L. Zeni, Performance comparison of two sensors based on surface plasmon resonance in a plastic optical fiber, Sensors, 13 (2013), 721-735.

[50] J. Homola, Surface plasmon resonance sensors for detection of chemical and biological species, Chemical reviews, 108 (2008), 462-493.

[51] Y. Al-Qazwini, et al., Performance evaluation of a bilayer SPR-based fiber optic RI sensor with TiO2 using FDTD solutions, Photonic Sensors, 4 (2014), 289-294.

[52] P.B. Johnson, R.-W. Christy, Optical constants of the noble metals, Physical Review B, 6 (1972), 4370.

[53] J.W. Sadowski, "Method for carrying out surface plasmon resonance measurement and sensor for use in the method," ed: Google Patents, 1994.

[54] E. Fontana, Thickness optimization of metal films for the development of surface-plasmon-based sensors for nonabsorbing media, Applied Optics, 45 (2006), 7632-7642.

[55] P. Kvasnička, J. Homola, Optical sensors based on spectroscopy of localized surface plasmons on metallic nanoparticles: Sensitivity considerations, Biointerphases, 3 (2008), FD4-FD11.

[56] A. Dhawan, Development of robust fiber optic sensors suitable for incorporation into textiles, and a mechanical analysis of electronic textile circuits: ProQuest, 2007.

[57] B.D. Gupta, S.K. Srivastava, R. Verma, Fiber Optic Sensors Based on Plasmonics: World Scientific, 2015.

[58] R.L. Earp Jr, Multiwavelength Surface Plasmon Resonance Sensor Designs for Chemical and Biochemical Detection, 1998.

[59] N.-F. Chiu, Y.-C. Tu, T.-Y. Huang, Enhanced sensitivity of anti-symmetrically structured surface plasmon resonance sensors with zinc oxide intermediate layers, Sensors, 14 (2013), 170-187.

[60] C.-T. Li, T.-J. Yen, H.-f. Chen, A generalized model of maximizing the sensitivity in intensity-interrogation surface plasmon resonance biosensors, Optics express, 17 (2009), 20771-20776.

[61] Z. Zalevsky, I. Abdulhalim, Integrated nanophotonic devices: Elsevier, 2014.

[62] W.L. Barnes, A. Dereux, T.W. Ebbesen, Surface plasmon subwavelength optics, Nature, 424 (2003), 824-830.

[63] S. Kumar, G. Sharma, V. Singh, Sensitivity of tapered optical fiber surface plasmon resonance sensors, Optical Fiber Technology, 20 (2014), 333-335.

[64] S. Shukla, N.K. Sharma, V. Sajal, Sensitivity enhancement of a surface plasmon resonance based fiber optic sensor using ZnO thin film: a theoretical study, Sensors and Actuators B: Chemical, 206 (2015), 463-470.

[65] J. Luo, J. Yao, Y. Lu, W. Ma, X. Zhuang, A silver nanoparticle-modified evanescent field optical fiber sensor for methylene blue detection, Sensors, 13 (2013), 3986-3997.

[66] K. Balaa, M. Kanso, S. Cuenot, T. Minea, G. Louarn, Experimental realization and numerical simulation of wavelength-modulated fibre optic sensor based on surface plasmon resonance, Sensors and Actuators B: Chemical, 126 (2007), 198-203.

[67] R. Verma, B. Gupta, Theoretical modelling of a bi-dimensional U-shaped surface plasmon resonance based fibre optic sensor for sensitivity enhancement, Journal of Physics D: Applied Physics, 41 (2008), 095106.

[68] A. Socorro, I. Del Villar, J. Corres, F. Arregui, I. Matias, Spectral width reduction in lossy mode resonance-based sensors by means of tapered optical fibre structures, Sensors and Actuators B: Chemical, 200 (2014), 53-60.

[69] A.A. Rifat, et al., Photonic Crystal Fiber-Based Surface Plasmon Resonance Sensor with Selective Analyte Channels and Graphene-Silver Deposited Core, Sensors, 15 (2015), 11499-11510.

[70] M.-H. Chiu, S.-F. Wang, R.-S. Chang, D-type fiber biosensor based on surface-plasmon resonance technology and heterodyne interferometry, Optics letters, 30 (2005), 233-235.

[71] T. Allsop, et al., Generation of infrared surface plasmon resonances with high refractive index sensitivity utilizing tilted fiber Bragg gratings, Applied Optics, 46 (2007), 5456-5460.

[72] C. Ribaut, et al., Small biomolecule immunosensing with plasmonic optical fiber grating sensor, Biosensors and Bioelectronics, 77 (2016), 315-322.

[73] A.K. Sharma, B. Gupta, Comparison of performance parameters of conventional and nano-plasmonic fiber optic sensors, Plasmonics, 2 (2007), 51-54.

[74] P. Hlubina, M. Kadulova, D. Ciprian, J. Sobota, Reflection-based fibre-optic refractive index sensor using surface plasmon resonance, Journal of the European Optical Society-Rapid publications, 9 (2014),

[75] H.-Y. Lin, W.-H. Tsai, Y.-C. Tsao, B.-C. Sheu, Side-polished multimode fiber biosensor based on surface plasmon resonance with halogen light, Applied Optics, 46 (2007), 800-806.

[76] N.D. Herrera, et al., Improved performance of SPR sensors by a chemical etching of tapered optical fibers, Optics and Lasers in Engineering, 49 (2011), 1065-1068.

[77] L. Coelho, et al., Sensing structure based on surface plasmon resonance in chemically etched single mode optical fibres, Plasmonics, 10 (2015), 319-327.

[78] J. Moura, et al., Evaporation of volatile compounds in suspended-core fibers, Optics letters, 39 (2014), 3868-3871.

[79] H.-F. Hu, Z.-Q. Deng, Y. Zhao, J. Li, Q. Wang, Sensing Properties of Long Period Fiber Grating Coated by Silver Film, Photonics Technology Letters, IEEE, 27 (2015), 46-49.

[80] L.-Y. Shao, Y. Shevchenko, J. Albert, Intrinsic temperature sensitivity of tilted fiber Bragg grating based surface plasmon resonance sensors, Optics express, 18 (2010), 11464-11471.

[81] J. Cao, E.K. Galbraith, T. Sun, K.T. Grattan, Cross-comparison of surface plasmon resonance-based optical fiber sensors with different coating structures, Sensors Journal, IEEE, 12 (2012), 2355-2361.

[82] R.C. Jorgenson, S.S. Yee, Control of the dynamic range and sensitivity of a surface plasmon resonance based fiber optic sensor, Sensors and Actuators A: Physical, 43 (1994), 44-48.

[83] V. Sai, T. Kundu, S. Mukherji, Novel U-bent fiber optic probe for localized surface plasmon resonance based biosensor, Biosensors and Bioelectronics, 24 (2009), 2804-2809.

[84] R. Kashyap, G. Nemova, Surface plasmon resonance-based fiber and planar waveguide sensors, Journal of Sensors, 2009 (2009),

[85] M.-H. Chiu, C.-H. Shih, Searching for optimal sensitivity of single-mode D-type optical fiber sensor in the phase measurement, Sensors and Actuators B: Chemical, 131 (2008), 596-601.

[86] M.-H. Chiu, C.-H. Shih, M.-H. Chi, Optimum sensitivity of single-mode D-type optical fiber sensor in the intensity measurement, Sensors and Actuators B: Chemical, 123 (2007), 1120-1124.

[87] T.L. Lowder, et al., Polarization analysis of surface-relief D-fiber Bragg gratings, Applied Optics, 46 (2007), 2387-2393.

[88] A. Leung, P.M. Shankar, R. Mutharasan, A review of fiber-optic biosensors, Sensors and Actuators B: Chemical, 125 (2007), 688-703.

[89] Y. Yuan, L. Wang, L. Ding, C. Wu, Theory, experiment, and application of optical fiber etching, Applied Optics, 51 (2012), 5845-5849.

[90] B. Grunwald, G. Holst, Fibre optic refractive index microsensor based on white-light SPR excitation, Sensors and Actuators A: Physical, 113 (2004), 174-180.

[91] Y.-C. Kim, W. Peng, S. Banerji, K.S. Booksh, Tapered fiber optic surface plasmon resonance sensor for analyses of vapor and liquid phases, Optics letters, 30 (2005), 2218-2220.

[92] T.A. Birks, J.C. Knight, P.S.J. Russell, Endlessly single-mode photonic crystal fiber, Optics letters, 22 (1997), 961-963.

[93] X. Yu, et al., A selectively coated photonic crystal fiber based surface plasmon resonance sensor, Journal of Optics, 12 (2010), 015005.

[94] A. Hassani, M. Skorobogatiy, Design of the microstructured optical fiber-based surface plasmon resonance sensors with enhanced microfluidics, Optics express, 14 (2006), 11616-11621.

[95] A. Hassani, M. Skorobogatiy, Design criteria for microstructured-optical-fiber-based surface-plasmon-resonance sensors, JOSA B, 24 (2007), 1423-1429.

[96] X. Yu, et al., A selectively coated photonic crystal fiber based surface plasmon resonance sensor, Journal of Optics, 12 (2009), 015005.

[97] P. Bing, J. Yao, Y. Lu, Z. Li, A surface-plasmon-resonance sensor based on photonic-crystal-fiber with large size microfluidic channels, Opt Appl, 42 (2012), 493-501.

[98] Y.Y. Shevchenko, J. Albert, Plasmon resonances in gold-coated tilted fiber Bragg gratings, Optics letters, 32 (2007), 211-213.

[99] Y.-J. He, Y.-L. Lo, J.-F. Huang, Optical-fiber surface-plasmon-resonance sensor employing long-period fiber gratings in multiplexing, JOSA B, 23 (2006), 801-811.

[100] B. Lee, S. Roh, J. Park, Current status of micro-and nano-structured optical fiber sensors, Optical Fiber Technology, 15 (2009), 209-221.

[101] G. Nemova, R. Kashyap, Fiber-Bragg-grating-assisted surface plasmon-polariton sensor, Optics letters, 31 (2006), 2118-2120.

[102] B. Špačková, et al., Novel concept of multi-channel fiber optic surface plasmon resonance sensor, Sensors and Actuators B: Chemical, 139 (2009), 199-203.

[103] A. Iadicicco, S. Campopiano, A. Cutolo, M. Giordano, A. Cusano, Refractive index sensor based on microstructured fiber Bragg grating, Photonics Technology Letters, IEEE, 17 (2005), 1250-1252.

[104] E. Udd, W. Schulz, J. Seim, J. Corones, H. Laylor, "Fiber optic sensors for infrastructure applications," 1998.

[105] Ü. Özgür, et al., A comprehensive review of ZnO materials and devices, Journal of applied physics, 98 (2005), 041301.

[106] A.B. Djurišić, Y.H. Leung, Optical properties of ZnO nanostructures, small, 2 (2006), 944-961.

[107] K. Ozga, et al., Second order optical effects in Au nanoparticle-deposited ZnO nanocrystallite films, Nanotechnology, 19 (2008), 185709.

[108] R. Tabassum, B.D. Gupta, Performance Analysis of Bimetallic Layer With Zinc Oxide for SPR-Based Fiber Optic Sensor, Journal of Lightwave Technology, 33 (2015), 4565-4571.

[109] B. Sepúlveda, P.C. Angelomé, L.M. Lechuga, L.M. Liz-Marzán, LSPR-based nanobiosensors, Nano Today, 4 (2009), 244-251.

[110] Z. Zhao, Y. Duan, A low cost fiber-optic humidity sensor based on silica sol–gel film, Sensors and Actuators B: Chemical, 160 (2011), 1340-1345.

[111] M. Rani, N.K. Sharma, V. Sajal, Localized surface plasmon resonance based fiber optic sensor with nanoparticles, Optics Communications, 292 (2013), 92-100.

[112] M. Tu, T. Sun, K. Grattan, LSPR optical fibre sensors based on hollow gold nanostructures, Sensors and Actuators B: Chemical, 191 (2014), 37-44.

[113] H. Tu, T. Sun, K.T. Grattan, SPR-based optical fiber sensors using gold–silver alloy particles as the active sensing material, Sensors Journal, IEEE, 13 (2013), 2192-2199.

[114] B. Sciacca, T.M. Monro, Dip biosensor based on localized surface plasmon resonance at the tip of an optical fiber, Langmuir, 30 (2014), 946-954.

[115] J.G. Ortega-Mendoza, et al., Optical fiber sensor based on localized surface plasmon resonance using silver nanoparticles photodeposited on the optical fiber end, Sensors, 14 (2014), 18701-18710.

[116] M. Consales, et al., Lab-on-fiber technology: toward multifunctional optical nanoprobes, ACS nano, 6 (2012), 3163-3170.

[117] S.K. Srivastava, V. Arora, S. Sapra, B.D. Gupta, Localized surface plasmon resonance-based fiber optic U-shaped biosensor for the detection of blood glucose, Plasmonics, 7 (2012), 261-268.

[118] R. Bharadwaj, S. Mukherji, Gold nanoparticle coated U-bend fibre optic probe for localized surface plasmon resonance based detection of explosive vapours, Sensors and Actuators B: Chemical, 192 (2014), 804-811.

[119] J. Chen, et al., Optimization and Application of Reflective LSPR Optical Fiber Biosensors Based on Silver Nanoparticles, Sensors, 15 (2015), 12205-12217.

[120] Y. Al-Qazwini, A. Noor, M.H. Yaacob, S. Harun, M. Mahdi, Fabrication and Characterization of a Refractive Index Sensor Based on SPR in an Etched Plastic Optical Fiber, Procedia Engineering, 120 (2015), 969-974.

[121] N. Cennamo, D. Massarotti, L. Conte, L. Zeni, Sensors Based on SPR in Plastic Optical Fiber: Numerical Analysis and Experimental Results, in *Sensors*, ed: Springer, 2014, 391-395.

[122] N. Cennamo, G. D'Agostino, M. Pesavento, L. Zeni, High selectivity and sensitivity sensor based on MIP and SPR in tapered plastic optical fibers for the detection of L-nicotine, Sensors and Actuators B: Chemical, 191 (2014), 529-536.

[123] A.K. Sharma, B. Gupta, Absorption-based fiber optic surface plasmon resonance sensor: a theoretical evaluation, Sensors and Actuators B: Chemical, 100 (2004), 423-431.

[124] Y.S. Dwivedi, A.K. Sharma, B. Gupta, Influence of design parameters on the performance of a surface plasmon sensor based fiber optic sensor, Plasmonics, 3 (2008), 79-86.

[125] J. Homola, On the sensitivity of surface plasmon resonance sensors with spectral interrogation, Sensors and Actuators B: Chemical, 41 (1997), 207-211.

[126] R. Slavík, J. Homola, J. Čtyroký, Single-mode optical fiber surface plasmon resonance sensor, Sensors and Actuators B: Chemical, 54 (1999), 74-79.

[127] R.K. Verma, A.K. Mishra, Highest achievable detection range for SPR based sensors using gallium phosphide (GaP) as a substrate: a theoretical study, Photonic Sensors, (2015), 1-6.

[128] J.S. Kimmel, D.A. Christensen, Finite-difference time-domain modeling and experimental characterization of planar waveguide fluorescence sensors, in *Chemical, Biochemical, and Environmental Fiber Sensors III*, 1992, 136-146.

[129] D. Christensen, D. Fowers, Modeling SPR sensors with the finite-difference time-domain method, Biosensors and Bioelectronics, 11 (1996), 677-684.

[130] K.S. Yee, Numerical solution of initial boundary value problems involving Maxwell's equations in isotropic media, IEEE Trans Antennas Propag, 14 (1966), 302-307.

[131] C. Ronot-Trioli, A. Trouillet, C. Veillas, H. Gagnaire, Monochromatic excitation of surface plasmon resonance in an optical-fibre refractive-index sensor, Sensors and Actuators A: Physical, 54 (1996), 589-593.

[132] A. Taflove, S.C. Hagness, "Computational Electrodynamics, The Finite-Difference Time-Domain Method. Boston, Artech House," ed: Inc, 2000.

[133] K.S. Kunz, R.J. Luebbers, The finite difference time domain method for electromagnetics: CRC press, 1993.

[134] K. Han, C.-H. Chang, Numerical modeling of sub-wavelength anti-reflective structures for solar module applications, Nanomaterials, 4 (2014), 87-128.

[135] A.Z. Elsherbeni, V. Demir, The Finite-difference Time-domain Method for Electromagnetics with MATLAB® Simulations: SciTech Pub., 2009.

[136] L. Solutions, "Inc. Home Page. Lumerical FDTD solutions v. 7.5. 2," ed.

[137] M. Kanso, S. Cuenot, G. Louarn, Roughness effect on the SPR measurements for an optical fibre configuration: experimental and numerical approaches, Journal of Optics A: Pure and Applied Optics, 9 (2007), 586.

[138] K.M. Byun, S.J. Yoon, D. Kim, Performance analysis of extinction-based localized surface plasmon resonance biosensors in the presence of surface roughness, in *SPIE BiOS: Biomedical Optics*, 2009, 71920Z-71920Z-71927.

[139] A. Kolomenski, A. Kolomenskii, J. Noel, S. Peng, H. Schuessler, Propagation length of surface plasmons in a metal film with roughness, Applied Optics, 48 (2009), 5683-5691.

[140] Y. Zhao, Z.-q. Deng, Q. Wang, Fiber optic SPR sensor for liquid concentration measurement, Sensors and Actuators B: Chemical, 192 (2014), 229-233.

[141] Y. Al-Qazwini, A. Noor, P. Arasu, A. Sadrolhosseini, Investigation of the performance of an SPR-based optical fiber sensor using finite-difference time domain, Current Applied Physics, 13 (2013), 1354-1358.