Investigation of cladding thicknesses on silver SPR based side-polished optical fiber refractive-index sensor

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A B S T R A C T

A single mode optical fiber modified using side-polishing method is applied as a sensor based on surface plasmon resonance (SPR) principles. The SPR sensor was designed using side-polished optical fiber of which the cladding was symmetrically removed and coated with different thicknesses of embedded silver film. The amount of cladding removed was based on the insertion power loss during the polishing process, where losses were recorded at 0.65 db corresponding to 20 μm thickness of remaining cladding and 1.8 dB refers to no cladding respectively. Finite Difference Time Domain (FDTD) simulation was used to investigate the effects of this configuration. The system has been constructed using different refractive indices of liquid. Silver thin layer thickness of 40 nm found to be the most desirable after it display better sensitivity in sensing mechanism. The application of 40 nm-thick Ag has been also coated on the fiber with no cladding, which shows higher sensitivity of −2166 nm/refractive index unit (RIU) and 208.333 nm/refractive index unit (RIU) using distilled water (n = 1.333) and alcohol (n = 1.345), respectively. The SPR dip transmission wavelength was recorded as ∼460 nm and ∼530 nm for both fiber conditions at active sensing area as 3 mm length operating at wavelength range of 300–1100 nm. The system has the advantages of being low-cost and applicable in bio-sensors.

Introduction

Surface plasmon resonance (SPR) has become a significant optical technique applied in various fields of study especially in sensing applications since it was firstly reported in 1983 [1]. Till now, many sensing structures for the detection of chemical and biochemical compounds using SPR technology have been developed. Theoretically, in a SPR configuration, a dielectric material coated with a thin metal film is used to generate surface plasmon waves (SPW). A transverse magnetic (TM) or plane-polarised (P-polarised) light excites oscillations of electron density at the interface between the dielectric and the negative permittivity material. These are known as surface plasmons as they are confined to the boundary of the two surfaces. At certain wavelengths of light, these plasmons will strongly resonate with the light and produce strong absorbance or attenuation of the light intensity.

SPR generated in metallic nanoparticles generally demonstrate three related conditions which are absorption, scattering and enhanced local electromagnetic field. Generally, such sensor applications involve the phenomenon of light transmission-absorption, by which the absorbance is directly related to the attenuation of light. The change in absorbance is affected by the optical characteristics of the material that the light passes through [2]. Materials sensitive to optical parameters produce significant changes to the absorbance; in the presence of specific analytes. This cause corresponding change to the guided light observed at the output of the sensor. The Lambert-Beer Law describes the absorption mechanism absorption as the transmission of light through an analyte, material, or sensitive region. Transmittance (T) represents the ratio of the light intensity before (I0) and after (I) passing through the analyte and can be expressed by T = I/I0 = 10^-αL = 10^-αC, where L is the length the sensitive area where the interaction takes place (optical path) and α is the absorption coefficient. The absorption coefficient is calculated by taking the product molar absorptivity (ε) and concentration (C) of the analyte. Sensitive materials can be incorporated onto optical fiber sensors by entrenching them with coatings or thin films [2]. There are two types of light propagation through optical fibers; a guided field within the core and an evanescent field penetrate the core to the surrounding medium. To allow the external medium to be accessible to the evanescent field for sensing purposes, the fibers must be modified by removing the cladding, bending, or tapering to enlarge the evanescent field. Claddings coated with sensitive coating materials will give significant changes from the interaction with the evanescent field. The fabrication of D-shaped optical fibers utilising wheel side-polishing method which is better in terms of safety and environmentally friendly compared to the chemical etching method [3]. In this method a rolling wheel is covered with an abrasive to grind the single mode fiber (SMF) to the required diameter. Compared to the V-groove polishing method, this fabrication process is practically more effective and convenient to alter the polished length and depth [4].

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addition, the D-shaped structure of the SMF offers several advantages over the cylindrical fiber as the polished fiber will provide a adaptable platform for photosensitive materials and particular biomaterials to be integrated in various applications, for example optimising optical fiber devices [5,6].

In SPR sensors, silver films are applied to give the sharpest resonant dip, higher resolution and lower cost than sensors with gold films [7,8]. The advantages of using side-polish were reported before, as flat surface possibly enhanced the homogeneity of metal coatings with standard of metal deposition methods [9]. Moreover, it was specifically designed to integrate with SPR technology as it is also low-cost, flexible and strongly excite SPR from evanescent field interactions [10]. Since the introduction of SPR techniques in the research of optical fiber technology, fiber-optic SPR sensors have seen significant advancements.

Jorgenson and Yee in 1993 reported one of the first optical fiber sensors using the principle of SPR. In their research, they varied key characteristics of the sensing platform, such as thickness and refractive index of the metallic layer and also dimensions of the sensor’s reactive region which gives changes in the transmission spectrum [11]. Hitherto, many devices based on SPR have been reported and the phenomenon became one of the essential references in biochemical sensing [12].

Photonic crystal fibers (PCF) are specialty optical fibers where, the fiber is patterned with two-dimensional array holes throughout, leading to high birefringence and high nonlinearity [13]. PCFs offer much superior sensing performance in the criterion of stability, accuracy and high detection limit when compared to other conventional optical sensing methods [14]. D-shape PCF has become one of the interesting research as a sensor application since they come with high efficiency and compactible in size proposed for replacement of bulk SPR [15,16]. Basically, photonic crystal fiber (PCF) is introduced to overcome limitations in both sensor configuration as well as in remote sensing applications [17]. However, PCF-SPR sensors normally having significant difficulties [18] where the holes inside the PCF basically is coating by chemical vapor deposition (CVD) technique [19–21] or through pumping molten metal at high pressure [22–24]. Thus, it needs highly manufactured technique for analytes sensor applications.

In this paper, we present a single mode optical fiber (SMF) that has ~38 and ~58 μm of its cladding partially removed by side polishing method. A 40 nm-thick Ag film has been chosen to be deposited as part of the SPR sensor, using white light source (400–1000 nm) as an input. Increasing the thickness of residual cladding fundamentally reduces the interaction between the fiber mode and surface plasmon waves (SPW) and subsequently causes a reduction in the depth of the SPR dip [25]. Both experimental and numerical investigations of using SPR-based optical fiber sensors have been reported in literature. In this study, Finite Difference Time Domain (FDTD) solutions from Numerical Solution Incorporated were used to analyse the transmission wavelength of an SPR-based optical fiber. The results showed that the transmission wavelength of the SPR dip shifted towards longer wavelength when the thickness of the cladding was varied with certain thicknesses of silver. Thus, the analysis and numerical modelling of 40 nm-thick silver layer were demonstrated by varying cladding thicknesses. This method provides a full-wave solution and solves Maxwell’s curl equation in the time domain. By changing the remaining cladding thickness, a red shift of the SPR transmission dip and a refractive index sensor with optimised linearity and sensitivity was achieved. The performances of these sensors were analysed in terms of sensitivity, given by the amount of wavelength shift and signal-to-noise ratio (detection accuracy). The sensitivity evaluation of the thin film coated sensor was performed by applying various concentrations of alcohol in water.

Experimental details

Side-polished fiber (SPF) in this research was created using the wheel polishing method setup which is presented in Fig. 1(a). A 2 cm length of the buffer coating of a telecommunication grade optical fiber (Corning SMF-28) with core/cladding diameter of 9/125 ± 1.0 μm was first removed to expose the glass. The fiber with the exposed length in the centre was fastened at either end with fiber clamps. The clamp on the left side of the fiber was secured and immovable. The clamp on the right was attached to a slider. A grinding wheel was used to reduce the thickness of the fiber. The speed of the wheel rotation was controlled using a computer and the wheel was moved back and forth until the thickness of the fiber was at the required level. The grinder was covered with abrasive paper in order to obtain a smooth finish at the polished surface. The cross section and side view of the D-shaped SPF was investigated using a microscope and the observations are presented in Fig. 1(b), where ‘D’ and ‘d’ correspond to the fiber thickness and residual cladding, respectively. The section between the 3 mm-tapered transition regions was observed to be the flat effective acting region, which is where the sensing actually takes place. The transmission spectrum of the SPF was investigated using a broad-spectrum light source having a range from 400 to 1000 nm and detected using a spectrometer. A single mode glass fiber was polished using a sandpaper mounted polishing machine to produce the D-shaped optical fiber. Different sandpaper grids were used to produce a smooth finish. The prototype SPF was finally coated with silver of 40 nm-thicknesses after having showed the best response compared to other coating thicknesses when coated at the remaining side-polished cladding on top of the core. The results obtained were then compared with simulation findings (Fig. 2).

After the side-polished fiber was fabricated, a silver film was applied on the polished side of the fiber using electron beam machine, Model EB43-T. Uniform thickness was achieved over the SPF with using vacuum thermal evaporation method to apply the silver film. The coating machine ran at vacuum pressure set at 10^-5 to 10^-7 Torr. Current is applied to the tungsten filament in the chamber to produce emission of electrons beams onto the target metal. Atoms of the target metal then convert into a vaporous phase and then precipitate into solid form, coating the optical fiber in the chamber. The preparation of the sample was done by mixing water to isopropyl with a ratio of 80:20. A lab grade refractometer was used to measure the refractive index of the isopropyl solution. The setup to determine the resonance peak for silver is shown in Fig. 1(a). The input to the fiber sensor is coupled to a white light source and the output is observed via a spectrometer connected to a computer with a signal processing software. After finalizing the setup, the sensing experiments were carried out by applying prepared solutions with refractive index ranging from 1.33 to 1.3450 on the optical fiber’s polished surface and recording the changes in the output spectrum.

Modelling in FDTD

Finite difference time domain (FDTD) analysis is a prevalent technique for resolving electromagnetic problems and highly advantageous for optical modelling applications. Using FDTD, broad ranges of frequency sweep can be applied at the source and observed at the output in a single simulation in time domain. This is extremely useful for SPR, where the resonant frequencies are not precisely known [26]. Two structures were designed for SPR using silver-based side-polished optical fiber through the Numerical’s optical solver (FDTD) method to detect the resonance wavelength of the surface plasmon, which can be determined by a signal dip in the transmission spectrum. A two-dimensional model was constructed to represent the SPF-based SPR sensor. The core diameter (d<sub>c</sub>) was 9 μm and cladding was removed until a cladding diameter (d<sub>cl</sub>) of 20 μm and ~0 μm remained; with cladding (0.65 dB loss) and without cladding (1.8 dB loss), respectively. According to [27], an active metal layer having a dielectric constant with absolute values is large for the real part and a small for the imaginary part value is the best candidate for SPR. This promotes light coupling into SP with low damping, which would result in increased...
sensitivity and accuracy of detection [28]. Silver became the metal of choice as it fulfilled the requirement of the largest $\varepsilon'_m$ and smallest $\varepsilon''_m$ compared to gold and copper. This characteristic will produce higher sensitivity and sharper dip in the SPR spectrum, which translate to enhanced detection accuracy [27,29,30]. The thickness of silver film was chosen to be 40 nm, whereby this thickness showed good response when coated at the side-polished fiber with remaining cladding on top of the core. This thickness was selected due to the fact that previous work on SPR sensors have confirmed this to be the best value to obtain optimum sensor performance [31,32]. A broadband source with 400–1000 nm wavelength ranges channelled light into the simulation region in the forward x-axis direction. The metal layer’s complex dielectric permittivity was modelled in the system using the Drude-Lorentz [33,34]. A two-dimensional planar waveguide constructed by three superimposed layers represented the core ($d_c$) at the bottom, the residual cladding ($d_{cl}$) in the middle and the top layer is the silver film, characterised by a dielectric function, $\varepsilon_m$ and of thickness, $d_m$. The length of the sensing region that will interact with the analyte or sample...
was represented by L. Zhang. The frequency of the light source was 562.111 THz, while the bandwidth was 374.741 THz. By limiting the wavelength from 400 nm up to 800 nm, the aim was directed on determining whether any readings below this wavelength could exhibit SPR dip for the silver film. This simulation is a way to prove that the experimental results are on the right track. The simulation results are shown in Fig. 3(a) and (b) which indicate that the SPR dip of silver with 40 nm thickness is shifting to the longer wavelength when the cladding is totally removed from side-polished fiber. SPR dip of the side-polished fiber with cladding (0.65 dB loss) forms a broad spectrum at wavelength of 450–550 nm while a sharp dip is observed at wavelength of ∼530 nm when the cladding no longer remains. There is a shifting on the SPR wavelength and it is affected by the presence of the cladding at the side-polished fiber. By comparing the experimental results, the SPR wavelength almost matches the simulation analysis, in which the intensity of transmission light without cladding is lower because the light escapes easily to the surrounding. This is supported by a previous research that reported on the effects of different cladding thicknesses by numerical simulations for 50 nm-thick silver layers. The resonance wavelength exhibits a blue shift as the residual cladding thickness increases. This observation can be attributed to the changes effective index of the SPW. Increase in the residual cladding caused tiny decrements in the real part of the SPW [35].

Sellmeier equations are applied when the cladding of the sample is totally removed. The fiber core is considered the first layer. The RI of fused silica \( n_1 \) changes with wavelength, indicated by Sellmeier dispersion relation given as [36]; where \( \lambda \) = wavelength of incident light in micrometres (μm) with Sellmeier coefficients \( A_1 = 0.6961663, A_2 = 0.4079426, A_3 = 0.8974794, B_1 = 0.0684043 \mu m, B_2 = 0.1162414 \mu m, \) and \( B_3 = 9.896161 \mu m \).

The Ag metal layer is surrounded with sensing medium, the dielectric constant \( \varepsilon_m \) can be determined from Drude model as

\[
\varepsilon_m(\lambda) = \varepsilon_{\infty} + \frac{i\omega_{ph}^2}{\omega^2 - \omega_p^2} - \frac{i\omega_c^2}{\omega^2 - \omega_c^2}
\]

Fig. 2. (a) A numerical model comprises a three-layer system representing an SPR-based optical fiber sensing element (a) 2D structures of FDTD simulation (b) 3D structure of 0.65 dB loss (with cladding) (c) 3D structure of 1.8 dB loss (without cladding).

Fig. 3. (a) Transmittance spectra of the SPR as a function of wavelength (a) Resonant wavelength of Ag 40 nm at 0.65 dB loss (with cladding). (b) Resonant wavelength of Ag for 40 nm thickness at 1.8 dB loss (without cladding).

\[
\frac{2\pi}{\lambda} \sin \theta = \text{Re}(k_p)
\]

where \( k_p = \sqrt{\mu_m \varepsilon_m - \varepsilon^\infty} \) is the surface plasmon propagation constant, \( c \) is speed of light in vacuum and \( \omega \) is frequency of incident light. In Eq. (3), the left hand side of the equation represents the propagation constant of the light incident at an angle \( \theta \) and the other side shows the real part of
the propagation constant of the surface plasmon. The shift of the resonant wavelength is used to determine the difference in the refractive index of the measurand.

Results

Solving Maxwell equation for semi-infinite mediums metal and dielectric with an interface comprising of the two, yields the TM-polarisation and electric field’s exponential decay. The equation to determine the surface plasmon wave’s propagation constant (ksp) along the interface between the metal and dielectric is given by

\[ k_{sp} = \frac{\omega}{c} \sqrt{\frac{\varepsilon_m \varepsilon_s}{\varepsilon_m + \varepsilon_s}} \]  

(4)

From (4), it can be observed that there is a strong correlation between the propagation constant of the surface plasmon wave and the dielectric constants of the metal-dielectric interface. Light that has the identical polarization condition as the surface plasmons can in turn energise the surface plasmons. Eq. (5) represents the propagation constant (ks) of the light signal with wavelength, \( \omega \) propagating through the dielectric medium.

\[ k_s = \frac{\omega}{c} \sqrt{\varepsilon_s} \]  

(5)

Since \( \varepsilon_m \) is negative for metals and \( \varepsilon_s \) is positive for dielectric at a specific frequency, this will cause the propagation constant of surface plasmon (ksp) to be larger than the propagation constant of the light wave in a dielectric medium (ks). In order to generate surface plasmons, these two wave vectors should be equal. It is not possible to excite surface plasmons using merely direct light at the metal-dielectric interface.

Table 1 showing refractive index within different percentage of alcohol in water respectively.

| % of Alcohol in Water | Refractive index at 30 °C |
|-----------------------|--------------------------|
| 0                     | 1.333                    |
| 20                    | 1.3450                   |

The sensitivity \( S_n \) of the SPR sensor can be calculated from the shift in resonant wavelength, \( \lambda_{res} \) versus the change in refractive index, \( n_s \)

\[ S_n = \frac{\Delta \lambda_{res}}{\Delta n_s} \text{ (nm/RIU)} \]  

(6)

A side-polished fiber (SPF) with its claddings removed is a way to access the evanescent field of the guide mode to be coupled with the SPR characteristics, which involves depositing uniform metal film to

![Fig. 4. The mode distribution in the core of SPF (a) Mode distribution at 0.65 dB loss (with cladding) (b) Mode distribution at 1.80 dB loss (without cladding).](image)
Fig. 5. Transmittance spectra of the SPR sensor as a function of wavelength for 40 nm and 50 nm Ag at different refractive index. (a) Inset graph of resonance wavelength shows the dip spectra at 474 nm for 40 nm Ag (b) Graph shows resonance wavelength of 40 nm Ag, DI and 20% of alcohol with inset graph enlarge dip spectra at 474.5 nm and 477 nm (c) Graph shows resonance wavelength of 50 nm Ag, DI and 20% of alcohol within range at 0.65 dB loss (d) Graph of resonance shift wavelength of Ag, DI and 20% of alcohol within range 450–650 nm at 1.8 dB loss with inset graph enlarge the dip spectra at 520 nm, 524 nm and 550 nm.

Fig. 6. Relationship between refractive index and resonant wavelength (a) Resonant wavelength in Ag SPR sensor is shifted to the longer wavelength with 2.5 nm difference changes in RI (b) With modification of loss, the resonant shift is increase to 26 nm with changes in RI.
excite the SPR \[39,40\]. Under phase matching condition, the transmission spectrum distributes over a particular wavelength range, leaks off the evanescent field, and couples to the SPW of the Ag coating. The degeneration of the Ag film affects only the resonance wavelength but not the sensitivity of the sensor. The degeneration of the Ag film affects only the resonance wavelength but not the sensitivity of the sensor. The larger evanescent field gives better results in sensing \[41–45\] for the light-matter interaction. Evanescent waves are decayed electric fields that form at the interface between the fiber-optic probe and ambient environment (Fig. 6).

Whenever light is transmitting or propagating along the fiber optic, the light is continuously reflecting off within the core and cladding interface of the fiber without a loss of power transmission which this concept known as total internal reflection (TIR). Light will extend into the cladding or medium that surround with the core when it reflects at angles close to the critical angle. This light that propagates at a decaying intensity as it extends further from the interface is called evanescent wave. The limitation of this phenomenon is it only extends for a short distance from interface and the power is drop exponentially with distance \[46\]. The evanescent field will propagate at the metal layer when the cladding is removed. The loss increases if the fiber is coat with metal as the refractive index for metal is higher than the core. So, the light will leak out of the cladding resulting in higher loss. The influence of the structural changes in the optical fibers structure, such as the thin metal film, causes changes to the propagation constant (effective index). This in caused changes to the propagation performance of electric or magnetic field of the optical wave. Due to the metal’s negative dielectric constant, the proposed fiber possesses a lower effective index, higher absorption loss in the transmission region (short wavelengths), flatter slope in the transition region and higher reflection in the attenuation region (long wavelengths) than those of a non-coated device \[47\]. By allowing the evanescent field interact with the metal with no cladding attached, it makes the combination more sensitive compared with cladding remain. This phenomenon generates surface plasmon resonance behavior since it is involving incident light to interact with free electrons of the metal.

Crystallite size and morphology effects of silver nanoparticles have been explored in previous reports \[4,48,49\] pertaining to the thickness of coating layers and thermal annealing temperature in different applications. Liu et al. reported on LSPR peaks exhibiting red shifts with the increase in sample solutions \[50\]. The integration of silver nanoparticles (AgNPs) into optical fiber sensor applications was also documented by Liu et al. whereby sensitivity was recorded as 120 nm/RIU with limitation of AgNPs aggregating fractionally. AgNPs were also investigated in the studies of optical fiber tips as sensors such that reported by J. Gabriel Ortega-Mendoza et al \[51\]. As this work mainly focused on metallic coatings embedded onto D-shaped optical fibers, the changes in the transmission spectrum were investigated by varying the key parameters such as film thickness, film refractive index and refractive index of liquid sensor; SPR-based resonance optical sensors have the potential of becoming an essential reference for biochemical sensing in the future.

Table 2 summarises the performance of the silver-coated SPR sensor with (0.65 dB) and without cladding (1.8 dB) layer remaining on the SPFs. It can be observed that SPFs without cladding could enhance the sensitivity of Ag SPR sensors, consequently increasing SNR, which leads to better power signal received. As the Ag film is brought closer, thus modifying the evanescent fields and changing the parameters of guided light.

Conclusions

This work sets to prove that the SPR dip can shift to longer wavelength by manipulating cladding thickness on side-polished fibers. FDTD simulation has been used to verify the results from the experimental findings whereby the results are unequivocally in good agreement. Some features of SPR sensors based on side-polished single mode optical fibers are good stability, low in-cost, outstanding plasmonic properties, having higher refractive index sensitivity and strong bio-molecular immobilisation ability. The silver-coated SPR sensor with no cladding remaining has been found to be more sensitive compared with that of cladding being left on top of the core; sensitivity is measured as 2166.667 nm/RIU when tested with 20% of alcohol in comparison to 208.333 nm/RIU for that of cladding remained.

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![Table 2](image-url)
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