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R. Zakaria, W. Kam, Y. S. Ong, S. F. A. Z. Yusoff, H. Ahmad & Waleed S. Mohammed

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Fabrication and simulation studies on D-shaped optical fiber sensor via surface plasmon resonance


aFaculty of Science, Photonic Research Centre, University of Malaya, Kuala Lumpur, Malaysia; bDepartment of Physics, University of Malaya, Kuala Lumpur, Malaysia; cSchool of Engineering, Center of Research in Optoelectronics, Communication and Control System (Bu-CROCSS), Bangkok University, Patum Thanee, Thailand

ABSTRACT
This paper describes simulation and experimental methods for designing a D-shaped surface plasmon resonance (SPR) fibre sensor. The sensor consists of two set-up approaches. Finite element method is used in simulation on the fibre sensor device. Two experimental methods for detecting relative intensity are used by varying the wavelength of the optical signal sources and the thickness of gold layer coated on the D-shaped fibre. In the first method, the sensor device works by detecting the relative intensity of two optical signal sources having different wavelengths. In the second set-up, the relative intensity between two D-shaped fibres coated with different thicknesses of gold is measured when a single signal source is launched at the input. The difference in intensities of the signal outputs is used to estimate the refractive index at the sensing region. A prototype SPR D-shaped fibre sensor has been fabricated and the experimental results show good agreement with simulation.

Introduction
The use of surface plasmon resonances has become popular in the fields of chemical and biosensing (1). This method can be used to measure small refractive index changes with high sensitivity while remaining unaffected by electromagnetic interference (2). Only a small amount of sample is needed to measure the refractive index at the sensing region (3, 4). Typically, SPR systems employ either angular scanning with monochromatic illumination (5) or spectral scanning with a broadband source (6). To obtain proper measurements, the angular scanning scheme requires synchronization of the angular motions of both the source and the detector. During wavelength scanning, the incident and detection angles are fixed. A new structure of sensing method has been introduced in this paper that uses modified optical fibres, such as hetero-core structure fibres (7, 8), D-shaped fibre sensors (9–13), tapered optical fibres (14, 15), half-core fibres (16) and micro-structured optical fibres (17).

In developing the device discussed, two sensing approaches that use D-shaped fibres based on surface plasmon resonance are proposed (Figure 1). Both set-ups measure intensity changes relative to a reference wavelength source (Figure 1(a)) or to the output intensity of a reference sample obtained using the same input source (Figure 1(b)). For the first proposed set-up, two input light sources are required which, one source comprised of a band of wavelengths, must experience the least variation; this is referred to as the reference wavelength and the other source is more sensitive to the environment, referred to as the operation wavelength bands. In the second configuration (Figure 1(b)), one wavelength band is used with two samples. The samples are prepared with different gold thicknesses, such that the intensity pertaining to one of these thicknesses, referred to as the reference arm, is not altered by the environment. The other gold film thickness, referred to as the signal arm, is chosen so that it responds to environmental changes with maximum sensitivity.

In the present study, numerical analysis is based on several gold thicknesses, ranging from 20 to 50 nm, coated onto D-shaped fibres. The thickness of the gold coated onto the fibres determines the positions of SPR dips and, therefore, the optimal wavelength source. Using simulation parameters, the device can be precisely tuned for its intended application. With careful choice of parameters for the operation at hand, optimized conditions can be realized for both systems.
**Methodology**

**Experimental setup**

A prototype SPR D-shaped sensor coated with a gold thickness of 30 nm has been fabricated and tested by comparing the results obtained with simulated results. A white light source and a spectrometer were used for sensor characterization, to enable investigation of the complete spectrum of the signal and to investigate resonance peaks obtained for different refractive indexes. A single-mode silica fibre is used to fabricate the D-shaped plasmonic fibre sensor. First, a fibre, the jacket of which has been removed, is epoxied onto a glass slide with a groove to ease the polishing process. The D-shaped fibre is then fabricated using a polishing machine and different sandpaper grids. First, the fibre is polished with 800-grid sandpaper until part of the cladding is removed, after which the fibre is polished with 15-micron 3M Microfinishing Lapping Film to smooth the surface of the polished region. After the D-shaped fibre is fabricated, a thin gold layer is coated on the flat side of the D-shaped fibre using an Edward Auto 306 E-beam evaporator. The fibre is first placed in a vacuum chamber at a pressure of $1.7 \times 10^{-5}$ mbar. After the pressure is stabilized in the chamber, the filament voltage is turned up to 4 kV using a current of 50 mA. After a constant deposition rate is established, the shutter is opened for 5 s. The gold layer thickness coated on the fibre is controlled by the shutter, and the thickness is measured using a Dektak surface profiler. For sample preparation, 5 concentrations of acetone solutions (0, 25, 50, 75 and 100%) are prepared by mixing acetone with distilled water. The refractive indexes of the acetone solutions are then measured at a wavelength of 632.8 nm using a Prism Coupler and an SPA-4000 loss measurement system.

The set-up for characterizing the sensor is shown in Figure 2, in which one end of the fibre is coupled to a white light source via an objective lens and the output is connected to a spectrometer. A polarizer is placed at the coupling input to attain the TM and TE polarizations. An objective lens is used to collect the output signal of the fibre, which is split in two, with one half projected towards the camera to enable observation of the output image and the other half coupled to a spectrometer with wavelengths ranging from 300 to 1000 nm. After alignment is complete, five prepared solutions, with refractive indexes ranging from 1.3312 to 1.35733, are placed on top of the optical fibre's polished surface. The signal spectrum obtained is analysed using Matlab. Afterwards, the solutions are removed, and the whole process is repeated for the next sample solution.

**Numerical study**

A single-mode D-shaped fibre has been modelled, and the structure is shown in Figure 3. The propagation constant
of light in the D-shaped fibre has been investigated using finite element method numerical simulation, in which 6 refractive index values, ranging from 1.000 to 1.3573, and four gold layer thicknesses, ranging from 20 to 50 nm, are swept to obtain the propagation constant over a range of visible wavelengths. The refractive index of the fibre core is set in a range of 1.47139–1.46213 throughout the simulation while for the cladding, the values of refractive index is varied in a range of 1.46579–1.45677. Meanwhile, refractive index of gold layer is varied in a range of 0.13100–1.3831, depends on the variation in wavelength, ranging from 0.5 to 0.7 μm (18).

Results and discussion

Based on a transfer matrix method in which the propagation constant value is simulated using Comsol, the transmittance of the SPR D-shaped fibre at visible wavelengths is calculated. Figure 4 shows the simulation results obtained from the SPR spectrum of refractive indexes when the D-shaped fibre is coated with different gold thicknesses. One noteworthy observation is the peak widening at a wavelength between 570 and 600 nm, approximately. This peak widening may be due to the higher SPR mode that appears around this wavelength region because the surrounding refractive index now serves as the cladding of the fibre. Regardless, this peak widening does not substantially alter the method’s sensitivity because the mode is weak. In fact, this broadening of the SPR spectra is beneficial for both proposed set-ups, as it results in an appreciable difference in intensities as the associated refractive indexes change.

The wavelength sensitivity of each gold thickness has been evaluated based on the red shift of the SPR dip when the refractive index increases. Figure 5 shows a graph of resonance wavelength (λ<sub>res</sub>) vs. refractive index (n). As summarized in Table 1, the sensitivity of the method is calculated based on the following relationship: \( S_n = \frac{\delta \lambda_{res}}{\delta n} \). It seems that the degree to which the resonance wavelength shifts depends on the gold thickness; in this regard, the sensitivity varied from 490 to 2732 nm/RIU when the gold layer thickness varied from 20 to 50 nm. Moreover, it can be observed that a resonance peak with the same refractive index (1.331 to 1.357) shifted to a 30–60 nm higher wavelength range. Hence, for amplitude mode operation, a longer input wavelength source, which can be adjusted

Figure 4. Transmittance spectra of the SPR sensor as a function of wavelength for different gold thicknesses and refractive indexes.
40-nm coating when the operating wavelength is 664 nm; meanwhile, the 20-nm coating demonstrates a more linear response to changes in refractive index. These characteristics enable the coating thickness to be optimized for specific applications, depending on the range of refractive indexes and the wavelength sources.

**Approach A – experimental results**

Based on the simulation results above, a D-shaped SPR fibre sensor has been fabricated and experiments have been performed using aqueous solutions containing five different acetone solutions. The refractive index measurements are shown in Table 3. A white light source is used to obtain the full spectral range of the resonance peak. A 30-nm gold layer thickness was chosen to enable detection of a wide range of refractive indexes and to compare the range of resonance wavelengths obtained with the simulated data. Figure 7 demonstrates the resonance peak shifts pertaining to the different refractive indexes encountered in both experimental and simulated results.

Both resonance wavelength ranges appear at approximately 545–565 nm, demonstrating good agreement with simulation results. A red shift occurs in the SPR peak as the refractive index of the medium increases, in agreement with simulated data. The slight deviation observed with regard to the resonance dip value may have resulted from light scattering at the tapered region and scattering due to the varied surface roughness obtained by polishing the fibre with sandpaper (19). Moreover, for simulation

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**Table 1.** Summary of sensitivities corresponding to wavelength interrogation for different gold thicknesses.

<table>
<thead>
<tr>
<th>Gold thickness (nm)</th>
<th>Wavelength interrogation sensitivity (nm/RIU)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>469.8</td>
</tr>
<tr>
<td>30</td>
<td>1668.4</td>
</tr>
<tr>
<td>40</td>
<td>2732.3</td>
</tr>
<tr>
<td>50</td>
<td>1408.3</td>
</tr>
</tbody>
</table>

**Table 2.** Reference and signal wavelengths chosen for the first intensity interrogation set-up.

<table>
<thead>
<tr>
<th>Gold thickness (nm)</th>
<th>Reference wavelength (nm)</th>
<th>Signal wavelength (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>500</td>
<td>527</td>
</tr>
<tr>
<td>30</td>
<td>480</td>
<td>590</td>
</tr>
<tr>
<td>40</td>
<td>500</td>
<td>664</td>
</tr>
<tr>
<td>50</td>
<td>511</td>
<td>677</td>
</tr>
</tbody>
</table>

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**Figure 5.** Wavelength corresponding to the SPR dip as a function of refractive index for four gold thicknesses.

**Figure 6.** Difference in transmittance intensities between two selected wavelength sources as a function of refractive index.

**Table 3.** Refractive indexes of distilled water and acetone solutions of different concentrations.

<table>
<thead>
<tr>
<th>Acetone solution (%)</th>
<th>Refractive index (n)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 (only distilled water)</td>
<td>1.3312</td>
</tr>
<tr>
<td>25</td>
<td>1.3377</td>
</tr>
<tr>
<td>50</td>
<td>1.3443</td>
</tr>
<tr>
<td>75</td>
<td>1.3508</td>
</tr>
<tr>
<td>100</td>
<td>1.3573</td>
</tr>
</tbody>
</table>

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40-nm coating when the operating wavelength is 664 nm; meanwhile, the 20-nm coating demonstrates a more linear response to changes in refractive index. These characteristics enable the coating thickness to be optimized for specific applications, depending on the range of refractive indexes and the wavelength sources.

**Approach A**

The first proposed scheme (Figure 1(a)) consists of the fibre sensor, two input light sources of different wavelengths and a spectrometer or power meter and intensity changes are extracted from spectra data. Few wavelengths are selected for the reference light source, and the operating wavelength is adjustable based on the region where the SPR peak is located or the spectral region exhibiting largest variations in amplitude with refractive index. Based on the reference and operating wavelengths chosen (see Table 2), a graph of the transmittance difference between the two input sources vs. refractive index is derived (Figure 6). As demonstrated in Figure 6, the transmittance difference curve obtained varies with gold thickness, such that highest sensitivity is obtained for the sensor with a
purposes, the D-shaped fibre is assumed to be polished until the side of the core is reached, the ideal polishing scenario. Under experimental conditions, however, the roughness of the polisher may cause the polishing depth to be uneven.

For the intensity interrogation approach, the chosen source wavelength is around the peak of the dip in the spectrum, which is 577 nm, and the reference wavelength is 533 nm (Figure 9). In this case and similar to the results trend depicted in Figure 8, the difference in wavelength source transmittance shows an almost linear increase with refractive index. Lower transmittance differences are due to the weak coupling efficiency of the experimental set-up. Moreover, under experimental conditions, the liquid substance dropped on the sensing part is only 4 mm in diameter. The sensitivity increases as the length of the sensing region immersed in the liquid is increased.

**Approach B**

In the second proposed set-up (Figure 1(b)), two sensors having different gold thicknesses are connected to the same wavelength source. To simulate the results obtained with this sensing approach, the selected input source wavelength is that which shows the largest variations in transmittance intensities between water and air pertaining to different gold thicknesses (Figure 10). To simplify the simulation, the same source wavelength, 638 nm, was used for the other refractive index sample. The relationship between transmittance intensity differences and gold film thicknesses ranging from 20 to 50 nm is depicted in Figure 11, in which the slope of the graph varies with refractive index from 1.3312 to 1.3573. These data enable estimation of the intensity differences between two fibre sensors coated with different gold thicknesses.

If it is assumed that the reference sample is coated with a 20-nm-thick gold layer for all refractive index measurements and that the gold thicknesses employed
Both proposed experimental set-ups demonstrate advantages compared to the common SPR sensing system that utilizes a broadband light source. The output signals demonstrate higher sensitivity due to higher changes in signal intensities.

**Conclusion**

Two SPR sensing approaches are proposed and theoretically investigated. The first case employs one fibre sensor with two light sources with different wavelength. Because simulation results show red shifts when refractive indexes increase, a suitable wavelength parameter should be determined based on the thickness of the gold layer to ensure optimal sensing performance. A prototype D-shaped fibre sensor has been fabricated and coated with a 30-nm-thick gold layer to compare experimental with simulated results. The experimental results obtained show...
a similar trend of red shifting with lower transmittance intensities, which is presumably due to surface roughness and coupling loss. In the second approach, a 638-nm wavelength source has been chosen, for which the graph of transmittance difference vs. gold thickness is shown. Using simulated data, the thickness of the gold coating can be tuned for different refractive index ranges to enhance measurement performance because SPR peaks shift to the right as the gold layer thickness increases. To simplify and ensure accurate measurements, it is important that we utilize proven methodology to determine the gold thicknesses on commercial unclad fibre sensors that are best used for measurements requiring specific operating wavelengths. Both sensing systems discussed herein provide stable, direct and high-resolution outputs with lower noise due to environmental conditions or source intensity variations. With appropriate choices of operating wavelengths and gold thicknesses, the sensitivity of the sensor can be optimized.

**Disclosure statement**

No potential conflict of interest was reported by the authors.

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**References**


