A simulation of surface plasmon resonance-based tapered fiber and sensing

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Abstract. This paper presents the fabrication and simulation of tapered optical fiber. To characterize the properties of these tapered optical fiber sensors, sugar solutions ranging from 0 to 20 in weight percent were utilized. The measured reflection spectra obtained from this SPR sensor shows the observation of a dip originated from the light absorption by the generated surface plasmon wave. The dip reflectance shifts with the increase in the refractive index. A simulation of the experiment was made using OptiFDTD. The simulation and the experiment showed a similar result. The result suggests that a compact sensor based on this structure may be useful for refractive index sensors.

1. Introduction

Surface Plasmon Resonance (SPR) is an interesting optical phenomenon that has been widely applied recently for the detection and analysis of bio molecular interaction. SPR can be observed when the wave vector of the incident light parallel to the conductor surface \( k_x \) matches the surface of the plasmon (SP) wave vector \( k_{sp} \). The wave vector of the surface plasmon \( k_{sp} \) is sensitive to the change of the refractive index of the dielectric medium \( \varepsilon_s \) that is in contact with the surface of thin layer metal. The surface plasmon (SP) wave vector \( k_{sp} \) is given by

\[
K_{SP} = \frac{\omega}{c} \left( \frac{\varepsilon_m \varepsilon_s}{\varepsilon_m + \varepsilon_s} \right)^{1/2}
\]

where \( \varepsilon_m \) is the real part of the dielectric permittivity of the metal layer. When the resonance takes place, it will produce a dip in the measured reflection spectrum [1]. This wavelength and depth of the observed dip will then change when the refractive index of the dielectric medium change. In a sensor employing this SPR phenomenon, when the concentration of analyte molecules changes or the analyte molecules are bound to the sensor surface, the refractive index at the surface changes, it leads to the shift of SPR dip.

In the past few years, optical sensor based on optical fiber technology has been a subject of intensive research. In order to improve the sensitivity, an enhancement through the inclusion of SPR phenomenon has also become a critical research issue. Several theoretical and experimental studies have been carried out. Tapered fiber structure seems offer an advantage because of its ease to be integrated in the existing optical fiber system. In addition, the formed evanescent field provided by
tapered structure could be more intense, such as that it can be more effective to interact with the analyte molecules. However, the realization of this SPR sensor with tapered optical fiber structure is not easy as it is not easy to establish the resonance condition in this structure. In this paper, we report the preparation, characterization, and simulation of a SPR sensor with tapered optical fiber structure.

2. Experiment
The fabrications of tapered fiber have been demonstrated by using a wide range of techniques. In this paper, we used the flame heating technique to elongate the heated part of optical fiber, where the heated part then forms a tapered structure. This technique has proven to be one of the most versatile techniques, which can fabricate tapered fiber with good physical properties. The fabrication employed an oxy-butane torch.

Figure 1 shows the schematic diagram of fiber tapering rig used in this work. It mainly comprises of two fiber holders, an oxy-butane burner, a stepper motor, and the motor controller board. Two fiber holders were used for holding and stretching the optical fiber[2]. One was in a fixed position while the other one was mounted above a motorized linear stage that can move back and forth. The elongated part was heated by an oxy-butane burner while the linear stage was moved to pull out the fiber slowly. For controlling the movement of motorized linear stage, namely controlling the speed of the optical fiber elongation, a high precision stepper motor (S1404) with a resolution of 1.8 /step were used. The tapering routine was implemented by using a computer program. A thin Au film of a thickness about 50 nm was then deposited to the resulted tapered fiber by sputtering technique.

Figure 2 shows a photograph of the resulted SPR sensor with tapered optical fiber structure. The taper angle was found dependent on the movement speed of the linear motor stage for a particular range.

Figure 1. Fiber tapering rig.

Figure 2. The resulted SPR sensor with tapered optical fiber structure.
The experimental set-up for evaluating the performance of the optical fiber sensors fabricated in this work is shown in Fig. 3.

![Image of experimental setup](image)

**Figure 3.** The resulted SPR sensor with tapered optical fiber structure.

The sensor probe was connected to one end of a Y-branch optical fiber and, it was illuminated by light from a tungsten lamp source connected to the other end of the fiber. In order to evaluate the sensor performance, the sensor probe was dipped into a testing solution with a known refractive index. Sugar solution was used as a convenient test sample, which provided refractive index variation by changing the sugar concentration [3]. The testing solutions were then prepared by dissolving sugar in water at different weight ratios. The reflection spectra were measured by a CCD based spectrophotometer which was connected to the other end of the fiber. The experimental set-up for this measurement is shown schematically in Figure 3. The reflection spectrum of air was recorded for comparison.

### 3. Simulation

The Finite Difference Time Domain (FDTD) is based on a numerical solution of the Maxwell’s equation. In the 3D lossless media, Maxwell’s equation takes the following form:

\[
H_x^{n+1/2}_{i,j,k} = H_x^{n-1/2}_{i,j,k-1/2} + \frac{\Delta t}{\mu_0} \left[ \frac{E_y^n_{i,j,k-1/2} - E_y^{n-1}_{i,j,k-1}}{\Delta z} - \frac{E_z^n_{i,j,k-1/2} - E_z^{n-1}_{i,j,k-1}}{\Delta y} \right]
\]

\[
H_y^{n+1/2}_{i,j,k} = H_y^{n-1/2}_{i-1/2,j,k} + \frac{\Delta t}{\mu_0} \left[ \frac{E_z^n_{i,j,k-1/2} - E_z^{n-1}_{i-1,j,k-1}}{\Delta z} - \frac{E_x^n_{i-1,j,k} - E_x^{n-1}_{i-1,j,k}}{\Delta x} \right]
\]

\[
H_z^{n+1/2}_{i,j,k} = H_z^{n-1/2}_{i-1/2,j,k} + \frac{\Delta t}{\mu_0} \left[ \frac{E_x^n_{i-1,j,k} - E_x^{n-1}_{i-1,j,k}}{\Delta z} - \frac{E_y^n_{i,j,k-1/2} - E_y^{n-1}_{i,j,k-1}}{\Delta y} \right]
\]

The locations of E and H components in the computational domain is shown below
Figure 4. Location of the TM field components in the computational domain[4].

The resulting finite-difference equation are solved in software.

Figure 5. Location of the TM field components in the computational domain[4].

The structure and size of sensing probe used for simulation are adjusted to the sensing probe used in the experiment. We used unicone tapered fiber with pure silica core and fluorine doped silica cladding from Ocean Optics. Numerical aperture = 0.22, fiber core thickness (large end diameter) = 600µm, small end diameter = 10µm, gold as metal with thickness = 50nm.

4. Results and discussion

Fig. 6 clearly shows the reflection spectra obtained from the fabricated SPR sensor with tapered optical fiber structure when dipped into the testing solution with different refractive indexes.
Figure 6. Overlapping reflection spectra of the tapered fiber refractive index sensors.

The comparison between the reflection spectrum measured in air (black), in water (green), in 0.15g/ml sugar solution (blue), and the reflection spectrum dipped in 0.25g/ml sugar solution (red) was shown in Figure 6. The figure shows the change of reflection spectra. The refractive index of air and water are 1.00 and 1.33, respectively, while the refractive index of sugar solution is larger than 1.33 depending on the sugar concentration. However, we also noted that the sugar solution also become darker with the increase of sugar concentration. Therefore, this leads to the increase in refractive index complex with the increase of sugar concentration.

It is noticeable that the dip wavelengths in the reflection spectra of these sensors were almost located at the same wavelength, namely at about 490 nm. With the increase of sugar concentration, we can observe the shift of the dip reflectance, although there is no significant change in the dip wavelength. Therefore, the absorbance of the dip in the reflection spectrum can be chosen as the sensitive parameter for this type of SPR sensor.

Figure 7. The fitting curve for wavelength versus refractive index curve experiment
In analyzing the data, we can find that the wavelength in which dip happened and the refractive index showed a relationship of similar linearity so we can get a fitting curve. The fitting curve is shown in figure 7. The fitting equation is as follows:

\[ \lambda = 0.44024RI + 484.35606 \]  

(3)

With RI means refractive index[5]. Sensitivity of the tapered fiber is 0.44024.

![Figure 8. Overlapping reflection spectra of the simulation.](image)

The experimental result showed small changes in profile and intensity. There might be some reasons for this. First, the tested tapered fiber sensor was not as ideal as we hoped for. Second, there might be physically adsorbed solution which also changed the properties of the tapered waveguide.

In the simulation, the shift of the reflection spectrum can be achieved by setting different media with different refractive index. Air and water were set at 13% and then sugar solution at 20% with refractive index 1.3525 and 1.3639 respectively [3]. Fig. 8 shows clearly the reflection spectra obtained from the simulation SPR sensor with tapered optical fiber structure when dipped into the testing solution with different refractive indexes. Fig. 9 shows the fitting curve.

![Figure 9. The fitting curve for wavelength versus refractive index simulation.](image)
The fitting equation is as below:

\[ \lambda = 0.13031 \text{RI} + 486.76028 \]  \hspace{1cm} (4)

where RI means refractive index. The sensitivity of the tapered fiber using simulation is 0.13031. The simulation and the experiment showed similar result.

5. Conclusion
An SPR sensor with tapered optical fiber structure has been successfully fabricated by a simple technique. The characteristics of generated SPR waves in various medium with different refractive indexes, namely air, water, and sugar solutions, were able to be measured. A dip in the measured reflection spectrum was observed where its reflectance spectrum shifts with the increase in refractive index. The simulation of the experiment was made using OptiFDTD. The simulation and the experiment showed similar result. The result suggests that a compact sensor based on this structure may be useful for refractive index sensors.

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