Surface Plasmon Resonance Optical Fiber Sensor for Water Quality Diagnosis

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Abstract:
The reflective optical fiber sensor based on surface plasmon resonance (SPR) phenomena was presented in this study to detect various NaCl concentrations in water. This sensor employs wavelength interrogation. is built with a multi-mode fiber/no-core fiber (MMF-NCF) structure, with the MMF acting as both the input and output path and the NCF acting as the sensing region. NCF has a length of 1cm and an outer diameter of 125 m. For exciting SPR, the NCF's side surfaces are coated with a gold film with a thickness of 40 nm. To reflect the optical signal, the end surface of the NCF is also coated with a 60nm thick gold film. The results obtained in the experiment showed that the sensor's sensitivity is 0.24 nm/% in the range of 0 % to 25 % concentrations. Furthermore, the proposed sensor outperforms and outlasts the previously reported systems in terms of performance and mechanical strength.

Keywords : Optical Fiber, No-core Fiber, Sensor, salinity.
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1. Introduction

Water quality is determined by a variety of factors, including dissolved oxygen concentration, bacteria levels, the amount of salt in the water, and the amount of material suspended in the water, as well as the quantities of pesticides, herbicides, heavy metals, and other contaminants. These factors necessitate detection procedures that are quick, simple, sensitive, and selective.

"Electrical sensors" have recently been widely used in water quality measurement. Moreover, these sensors have some drawbacks, such as electromagnetic interference, expensive instruments, and water corrosion (Roden and Irish, 1975).

Optical fiber sensors, on the other hand, have received more attention due to their low power consumption, safe operation, long transmission distances, few electromagnetic interferences, simplicity, sensitivity, ease of use, and low cost (Di, Xin and Jian, 2018).

Because of its high sensitivity, the SPR sensor effect is a hot topic. This approach works wonderfully when paired with optical fiber technology for sensing chemical amounts and measuring refractive index or liquid concentration (Zhao, Deng and Wang, 2014).

In work done here, a reflective optical fiber sensor based on the surface plasmon resonance phenomena were was presented to detect various NaCl concentrations in a water. This sensor works in a wavelength interrogation way. The structure of the reflective sensor is multimode fiber - no core fiber (MMF-NCF) where the MMF act as both input and output path and the NCF act as sensing region. A length of NCF is 1cm and an outer diameter of 125 µm. The side surfaces of the NCF are coated with the gold film with thickness 40 nm for exciting SPR. The end surface of the NCF is also coated with the gold film with thickness 60nm for reflecting the optical signal.

2. Experimental

2.1 Preparation of NaCl Solution with Water

Distilled water DL should be used to create an impurity-free NaCl solution. NaCl solution with a 5% concentration was made by dissolving 5mg of NaCl in 100mL of DL, then stirring with a magnetic stirrer until dissolved. This technique was done three times to make NaCl solutions with concentrations of 0%, 5%, 10%, 15%, 20% and 25%. An Abbe's refractometer with a resolution of 0.001 was used to test the refractive indices of these solutions in white light. The highest concentration in the experiment is 25% due to the limitation of NaCl solubility.

2.2 Preparation Optical Fiber Sensor

The sensor was built using an MMF with a core/cladding diameter of $50/125\ \mu m$ and an NCF (made from pure silica) with a diameter of $125\ \mu m$. Using a JIC-375 mechanical optical fiber stripping machine, the polymer coating was removed from 1 cm NCF and the ends of MMFs (provided by Fujikura). The fiber end was then cut at an angle with a fiber cleaver cutter (CT-30) to make its surface flat. A Fujikura fusion splicer was used for the splicing (FSM-60S). First, an NCF was spliced with a cleanly cleaved MMF (AUTO mode). The dc plasma method, a well-known technology for generating thin metallic films (Stoian *et al.*, 2021), was used to coat the NCF sensor with a gold coating. The area is scratched with hydrofluoric acid prior to the coating process to increase the adhesion process between the gold film and the NCF sensor. After scratching, the sensor is washed several times with distilled water with great care to ensure the accuracy of the fiber diameter and to avoid cutting it when removing plankton from the NCF sensor. Before using the sensor, place it in a dry place for 24 hours. The coating time and current were varied to sputter gold films of various thicknesses. Figure 1 shows a microscopic view of the NCF sensor after 135 seconds of coating time and 6 mA of coating current. The sensor surface is equally covered with gold in the cylindrical surface image of the sensor probe. The gold film thickness is around 40 nm, which was proved to be the ideal value in (Theoretical and experimental characterization of a salinity sensor utilizing SPR probe. The end surface of the fiber was coated with a thin gold layer to allow incident light to be reflected, allowing the SPR probe to serve as a reflecting sensor

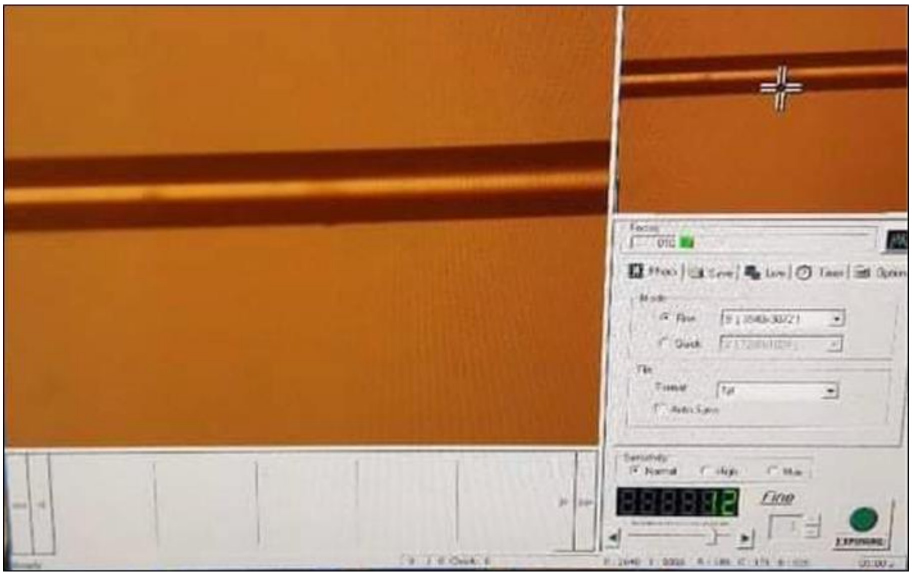

Figure 1: Optical microscope image of NOF showing the presence of the gold film upon the sensor surface.

2.2 Principle of the mechanism of sensing

When the light passes in the core of optical fiber via the total internal reflection phenomenon, an

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EW is formed in ''cladding'', with the ''electric field'' amplitude decaying exponentially from the ''core-metal interface''. The propagation constant is given for this EW at the core the metal interface is given by(Luo and Wang, 2021):

$$\beta_{ev} = \frac{2\pi}{\lambda_i} n_{co} \sin\theta \quad (1)$$

Where n_{co} is the core RI λ_i is the ''wavelength'' of the incident light, and θ is the angle of the incident light at the ''core–metal interface''. At the same time, from Maxwell equations, the propagation constant β_{SP} of surface plasmon wave propagating along the interface between the metal and surrounding medium is written as (Gupta and Kant, 2018):

$$\beta_{SP} = \frac{2\pi}{\lambda_{SP}} \sqrt{\frac{\varepsilon_m n_s^2}{\varepsilon_m + n_s^2}} \quad (2)$$

Where $\lambda_{SP}$is the ''wavelength'' of the SPP, $\varepsilon_m$is the metal material's dielectric constant and n_s is the refractive index of the sensing medium. From Eq. (2), we can see that β_{SP} at a given wavelength λ_{SP} is determined by the permittivities of the metal film and its sensing medium, i.e., ε_m and $\varepsilon_s = n_s^2$.

Surface plasmons are excited when the evanescent wave propagation constant meets the real part of the surface plasmon propagation constant at a particular wavelength called the resonance wavelength, referred to as the phase match state (Li, 2020):

$$\frac{2\pi}{\lambda_i} n_{co} \sin\theta = Re\,(\beta_{SP}) \quad (3)$$

When the refractive index of the sensing medium changes, the right-hand side of Eq. (3) changes. As a result, the resonance condition will be satisfied at some other wavelength value. The refractive index of the sensing medium can be measured by observing the shift in the resonance wavelength, which is how SPR sensors work.

2.3 Experiment Set-up

Figure 2 depicts the experimental setup for monitoring the sensor-fabricated response. The used setup consists primarily of a laser source with an operating wavelength of 530 nm, the fabricated sensing probe, and a spectrometer. Because the entry and exit paths are the same, a Y-type2 1 optic fiber coupler is used to send and receive light. The input signal from the source is carried by one arm of the coupler, while the back-reflected light from the fiber tip is directed to the spectrometer by the other arm. The reflection signal was detected using an Ocean Optics HR 2000 spectrometer with a wavelength range of 200 nm to 1100 nm. To evaluate the SPR sensor performance, the sensing portion of the probe is completely immersed in NaCl solutions. The incident light interacts with the immobilized gold film on the sensor surface. A spectrometer connected to the other end of the coupler captures the reflected signal. As a result, the obtained signals can be displayed and monitored by a computer linked to the spectrometer. Every 10 microseconds, the signal was interrogated, and data were acquired and recorded using originlab software.

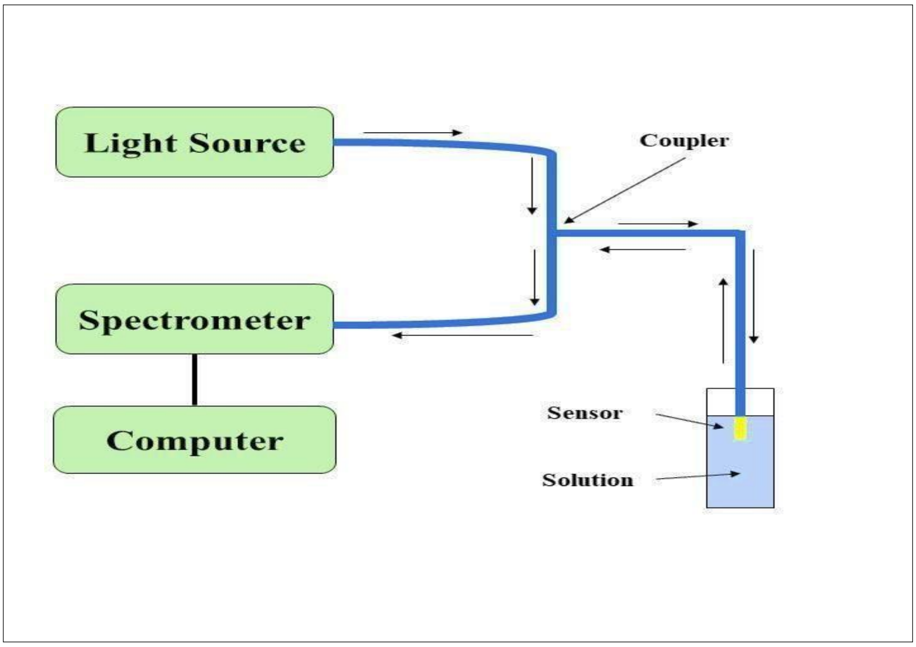

Figure 2: ''Schematic diagram of the experiment system''.

2.4 Result and Discussion

The sensing portion of the SPR sensor probe was immersed in water at first, and the reflected signal was measured. After that, it was completely immersed in NaCl solutions of varying concentrations, and the reflected signal from it was measured over a period of time after complete dissolution. The laboratory temperature should also be kept as steady as possible to ensure the correctness of the experimental results. Figure 3 depicts the reflectance spectra of the gold film-coated SPR sensor when exposed to NaCl solutions ranging in concentration from 0% (water) to 25%.

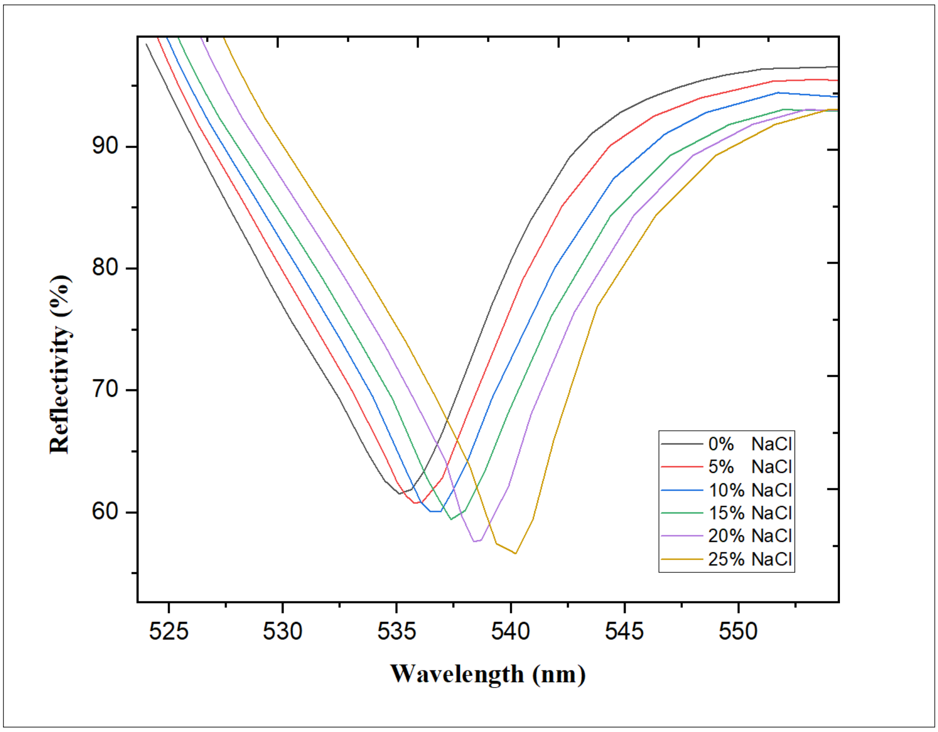

Figure 3: SPR reflection range of various concentrations of NaCl solution.

As illustrated in Fig. 3, there is a clear redshift in SPR wavelength as the concentration of the NaCl solution increases. As the concentration of NaCl in the solution increases, so does the dielectric constant of the solution. As a result, the solution will be more polarized, and the accumulated charge in the resonance zone will be attenuated (Zhou *et al.*, 2018). When the electric charge of gold is reduced, the restoring electric force is reduced. Furthermore, decreasing the restoring force decreases the resonance frequency, resulting in a red-shifted resonance wavelength (Zhou *et al.*, 2018).

The shift in resonance wavelength for all "concentrations" was determined by taking the resonance wavelength corresponding to zero concentration of solution as the reference for the probe. Figures 4 illustrates the fluctuation of a "shift in resonance wavelength" with "NaCl solution" concentrations.

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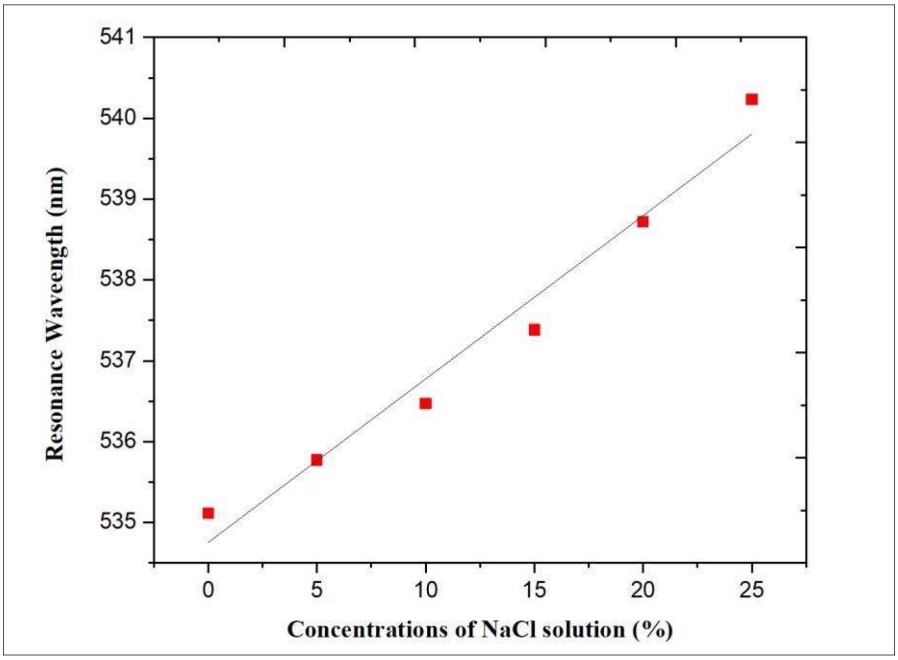

Figure 4: Resonance wavelength shift vs concentration of NaCl solution

Figure 4 clearly shows the relationship between the resonance wavelength and the volume concentration of NaCl solution, and it agrees well with the quadratic fitting.

Figure 3.10 also demonstrates that "the shift in resonance wavelength increases with increasing solution concentration" (Zhao, Deng and Wang, 2014) and that the relationship between resonance wavelength and solution volume concentration is linear.

The sensor's sensitivity is defined as "the change in resonance wavelength per unit change in sample concentration or refractive index." The "slope of curves" in Figure 4 was used to calculate the sensing probe's sensitivity to NaCl solution.

Table 1 compares the performance of the proposed sensor to that of comparable other devices reported in the literature. According to the findings, the sensor described in this paper outperforms previously reported systems in terms of performance and mechanical strength, and it has a high sensitivity. Also, as long as the solution RI is less than the RI of coreless optical fiber, this sensor can measure other types of liquid, giving the sensing probe a wider measurement range.

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Table 1 Comparison with former researches.

Optical Fiber Type	Sensing Principle	Structure	Sensitive Material	Salinity Sensitivity nm/%	Mechanical Strength	Ref
SMF	Fabry-Perot interferometer	Transmissive	/	0.048	Good	(Nguyen, Vasiliev and Alameh, 2011)
MMF	SPR	Transmissive	Ag film	0.120	Poor	(Hu, Zhao and Song, 2016)
SMF	Mach-Zehnder interferometer	Transmissive	Fluorinated polyimide	0.064	Poor	(Wang *et al.*, 2019)
SMF	SPR	Transmissive	Au	0.125	Poor	(Velázquez-González *et al.*, 2017)
NOF	SPR	Reflective	Au	0.24	Good	This work

2.5 Conclusion

The current work fabricates and characterizes a reflective optical fiber SPR sensor for salinity detection. First and foremost, the results show that the proposed sensor's resonance wavelength red shifts with NaCl concentration in solutions, and the sensor has a linear response in the range 0–25 percent of NaCl solution concentration. Because gold prevents sensor oxidation, the probe's life is extended. Furthermore, the sensor is not limited to a single NaCl solution and can be used when a mixture of several solutions is present. The sensor coated for NaCl solution has a sensitivity of 0.24 nm per percent.

Declaration of Competing Interest

The authors declare that there are no conflicts of interest.

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6. Reference

Di, H., Xin, Y. and Jian, J. (2018) 'Review of optical fiber sensors for deformation measurement', Optik, 168, pp. 703–713.

Gupta, B.D. and Kant, R. (2018) 'Recent advances in surface plasmon resonance based fiber optic chemical and biosensors utilizing bulk and nanostructures', Optics & Laser Technology, 101, pp. 144–161.

Hu, T., Zhao, Y. and Song, A. (2016) 'Fiber optic SPR sensor for refractive index and temperature measurement based on MMF-FBG-MMF structure', Sensors and Actuators B: Chemical, 237, pp. 521–525.

Li, J. (2020) 'A review: Development of novel fiber-optic platforms for bulk and surface refractive index sensing applications', Sensors and Actuators Reports, 2(1), p. 100018. doi:10.1016/j.snr.2020.100018.

Luo, M. and Wang, Q. (2021) 'A reflective optical fiber SPR sensor with surface modified hemoglobin for dissolved oxygen detection', Alexandria Engineering Journal, 60(4), pp. 4115–4120.

Nguyen, L.V., Vasiliev, M. and Alameh, K. (2011) 'Three-wave fiber Fabry–Pérot interferometer for simultaneous measurement of temperature and water salinity of seawater', IEEE Photonics Technology Letters, 23(7), pp. 450–452.

Roden, G.I. and Irish, J.D. (1975) 'Electronic digitization and sensor response effects on salinity computation from CTD field measurements', Journal of Physical Oceanography, 5(1), pp. 195–199.

Stoian, M. et al. (2021) 'Techniques of Preparation of Thin Films: Catalytic Combustion', Catalysts, 11(12), p. 1530.

Velázquez-González, J.S. et al. (2017) 'Simultaneous measurement of refractive index and temperature using a SPR-based fiber optic sensor', Sensors and Actuators B: Chemical, 242, pp. 912–920.

Wang, S. et al. (2019) 'Hybrid structure Mach-Zehnder interferometer based on silica and fluorinated polyimide microfibers for temperature or salinity sensing in seawater', Measurement, 135, pp. 527–536.

Zhao, Y., Deng, Z. and Wang, Q. (2014) 'Fiber optic SPR sensor for liquid concentration measurement', Sensors and Actuators B: Chemical, 192, pp. 229–233.

Zhou, X. et al. (2018) 'Graphene enhanced optical fiber SPR sensor for liquid concentration measurement', Optical Fiber Technology, 43, pp. 62–66.

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