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Sensitivity Performance of Optical Waveguide Sensors with Different Shapes of Cladding Layer for Microplastics Detection

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Sensitivity Performance of Optical Waveguide Sensors with Different Shapes of Cladding Layer for Microplastics Detection

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Abstract. With microplastics pollution becoming a global concern, there comes a need for sensors to attain an optimal level of sensitivity to detect microplastics in water. This work investigated the effects of cladding layer shapes on the sensitivity performance of an optical waveguide sensor for microplastics detection in water. In this research, three different cladding shapes—C-shaped fiber, D-shaped fiber, and rectangular waveguide with circular core—were simulated by using Wave Optics Module-COMSOL Multiphysics® software. The results indicated that the C-shaped fiber exhibited significantly higher sensitivity, with a sensitivity value of 1.070×10^{-3} compared to the D-shaped fiber and rectangular waveguide with 3.845×10^{-4} and 3.842×10^{-4}, respectively. The sensitivities of the D-shaped fiber and rectangular waveguide were relatively similar and did not exhibit any significant difference. The higher sensitivity of the C-shaped fiber is attributed to its larger exposed core area to the analyte, resulting in higher interaction of the evanescent wave with the analyte. However, fabricating the C-shaped fiber is more challenging compared to the other two shapes. This research highlights the significance of cladding shapes in optical waveguide sensor sensitivities and provides design optimization insights for microplastics detection in water.

1. Introduction

Plastics have numerous uses in various industries and are commonly utilized in day-to-day life such as in packaging, food containers, and drinking bottles. Nonetheless, improper handling of discarded plastics can result in ecological degradation, particularly in water habitats like rivers, oceans, and lakes [1]. This can lead to the formation of microplastic fragments that pose a risk to aquatic animals and human health [2].

Several studies have been conducted particularly in detecting microplastics in water by adopting methods such as Raman [3], near infrared (IR) [4], and Fourier transform infrared (FTIR) spectroscopy [5]. Nevertheless, some disputed issues have risen with respect to these methods, which include their complex processing steps, low yield, and high costs, thus making them time-consuming and inefficient [6-8].

To address these limitations, a proposed solution was to simulate an optical waveguide sensor using Wave Optics Module-COMSOL Multiphysics® software. The proposed method offers prompt and in-situ detection, effectively mitigating the aforementioned issues [9]. Furthermore, three commonly known shapes of cladding waveguides were analyzed to enhance the sensor's sensitivity through further optimization. Furthermore, the study investigated the effective refractive index changes at different analyte refractive index mediums, along with the core principles of physics behind these factors.

2. Simulation Settings

The cross-sections of the novel europium-aluminum doped polymer composite optical planar waveguide sensor for the three different cladding shapes—C-shaped fiber, D-shaped fiber, and rectangular waveguide with circular core—are illustrated in **Figure 1(a)**, **Figure 1(b)**, and **Figure 1(c)**, respectively. The sensor comprises a core with diameter of 9 µm and refractive index of 1.510, surrounded by cladding with refractive index of 1.501. The operating wavelength of 617 nm was chosen because it has the lowest attenuation window of a practical waveguide [10]. The refractive index range for microplastics in water was set between 1.480 and 1.500 with an RI step increment of 0.005. In this range, 1.490 RIU represents the refractive index of low-density polyethylene (LDPE) [1].

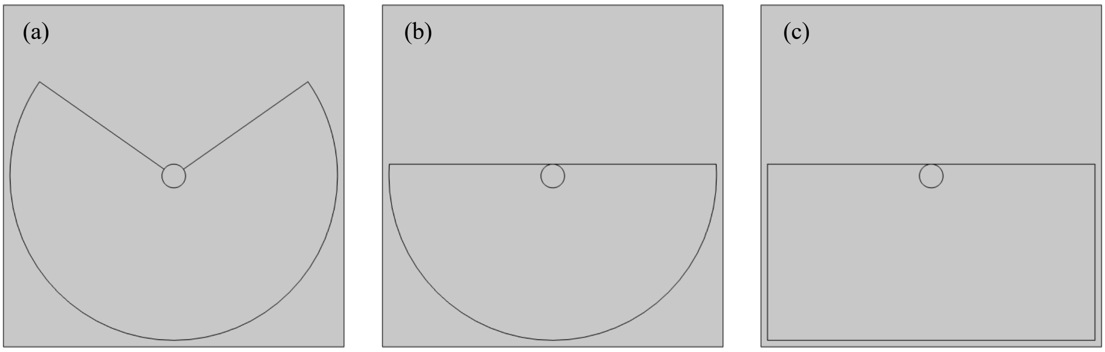

Figure 1 *Cross-sectional view of the optical waveguide sensor with three different cladding shapes:* ***(a)*** *C-shaped fiber,* ***(b)*** *D-shaped fiber and* ***(c)*** *rectangular waveguide with circular core*

3. Results and Discussion

The electric field distribution of all three waveguides with different cladding shapes can be analyzed by studying the mode field diameter (MFD) at a selective analyte refractive index (RI) of 1.490, as shown in **Figure 2**. The core-analyte border is located at the 4.5 µm position, allowing the penetration depth of the evanescent wave to be examined in the post-border region as shown in the inset of **Figure 2**. In this region, the C-shaped fiber exhibits a more significant penetration of the evanescent wave into the analyte compared to the other two cladding types. This increased penetration enables higher interaction between the evanescent wave and the analyte, resulting in higher sensitivity of the sensor.

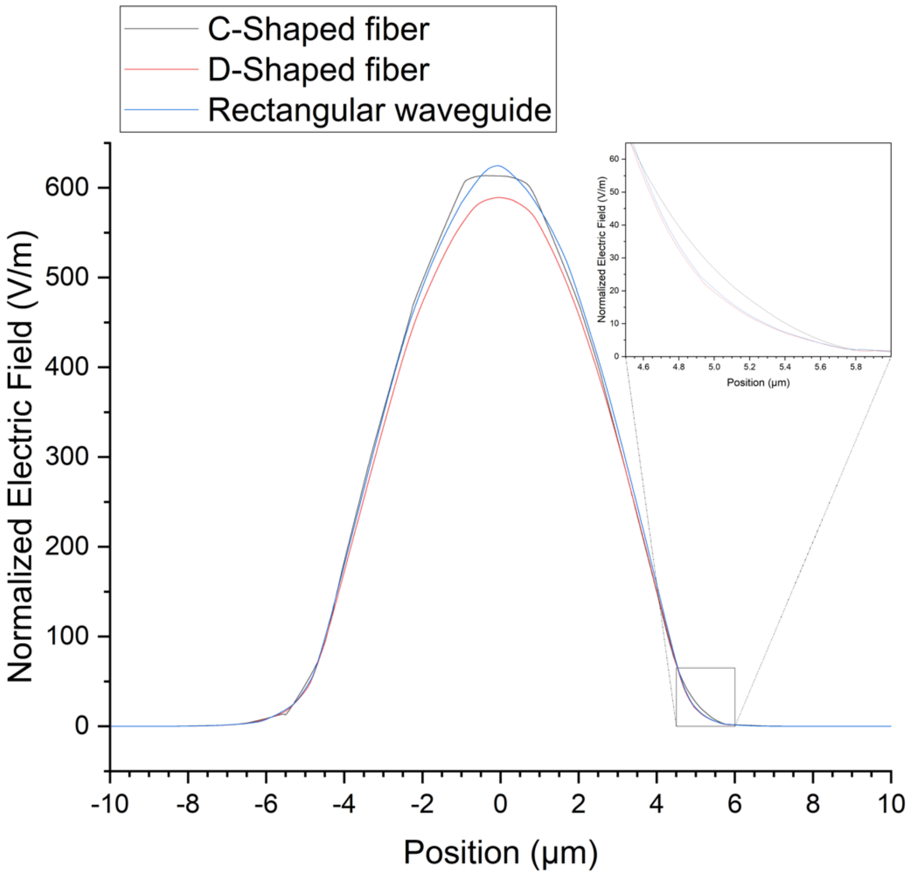

Figure 2 *MFD of the C-shaped fiber, D-shaped fiber, and rectangular waveguide at a selective analyte RI of 1.49*

Different effective mode index, n_{eff} can be achieved by varying the analyte RI. The changes in n_{eff}, referred to as Δn_{eff}, were plotted at different analyte RIs as shown in **Figure 3**. The inset graph in **Figure 3** provides a closer look at the D-shaped fiber and rectangular waveguide curves, which were separated when magnified. With an increase in the refractive index (RI) of the analyte from 1.4800 to 1.5000, the Δn_{eff} experiences a non-linear growth. This non-linear variation arises from the nonlinearity exhibited by the evanescent wave energy during its interaction with the analyte medium [10]. Nonetheless, Xiao et al. proposed a method for assessing sensitivity by examining the changes with a linear fit, thereby easily determining sensitivity based on the graph's slope [10]. As a result, the sensor recorded an estimated sensitivity for the C-shaped-fiber, D-shaped fiber, and rectangular waveguide as 1.070×10^{-3}, 3.845×10^{-4} and 3.842×10^{-4} respectively, in dimensionless unit.

The results of the study showed that the C-shaped fiber had a significantly higher sensitivity compared to the D-shaped fiber and rectangular waveguide. Conversely, no significant difference in sensitivity was observed between the D-shaped fiber and rectangular waveguide. This similarity is attributed to the indistinguishable cladding layer surrounding both the D-shaped fiber and rectangular waveguide from the core section's perspective. On the other hand, the increased sensitivity of the C-shaped fiber can be attributed to its larger exposed core area to the analyte, leading to a higher interaction of the evanescent wave with the analyte. Nonetheless, the production of the C-shaped fiber is relatively more complex compared to the other two shapes.

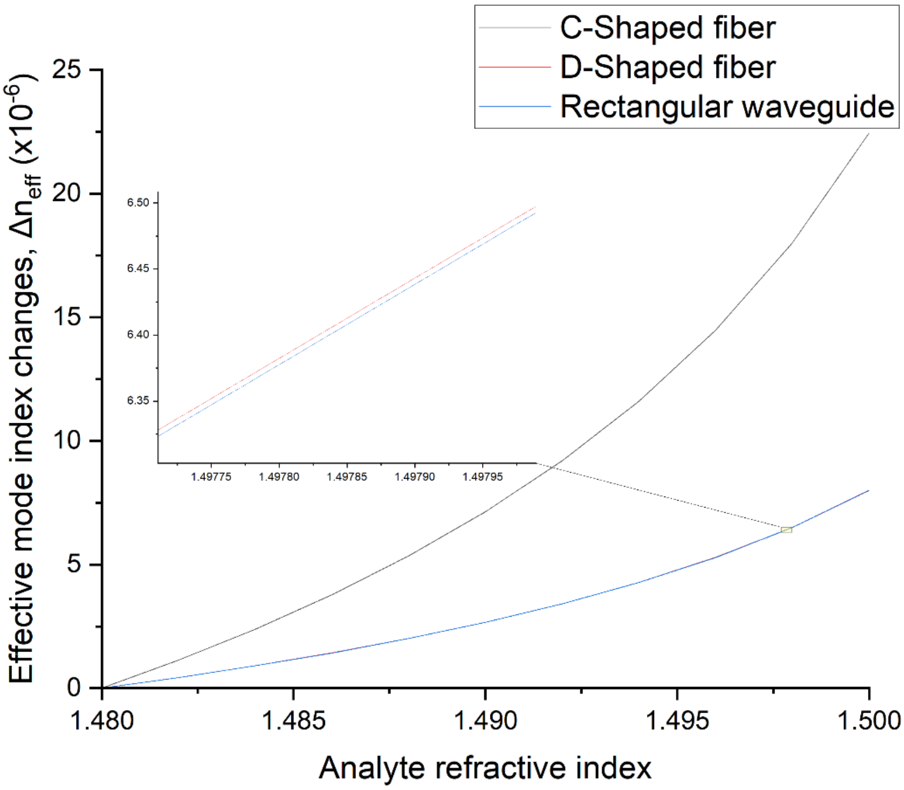

Figure 3 *Effective mode index changes Δn_{eff} versus analyte refractive index for all three cladding shapes: C-shaped fiber, D-shaped fiber, and rectangular waveguide. The inset graph provides a closer look at the D-shaped fiber and rectangular waveguide curves, which were separated when magnified.*

4. Conclusion

The study demonstrated the simulation of an optical waveguide sensor with different cladding shapes for detecting microplastics in water. The sensor was simulated for a range of analyte refractive indices from 1.480 to 1.500, relative to the microplastic refractive index. The C-shaped fiber exhibited the highest sensitivity of 1.070×10^{-3}, while the D-shaped fiber and rectangular waveguide had sensitivities of 3.845×10^{-4} and 3.842×10^{-4}, respectively, in dimensionless units. This higher sensitivity of the C-shaped fiber is attributed to its larger exposed core area to the analyte, which enhances the interaction of the evanescent wave with the analyte. Overall, the simulated optical waveguide sensor designs provide valuable insights into increasing the potential of optical waveguide sensors for microplastics detection in water.

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References

1. Asamoah, B.O., et al., A prototype of a portable optical sensor for the detection of transparent and translucent microplastics in freshwater. Chemosphere, 2019. **231**: p. 161-167.
2. Yadav, H., S. Sethulekshmi, and A. Shriwastav, Estimation of microplastic exposure via the composite sampling of drinking water, respirable air, and cooked food from Mumbai, India. Environmental Research, 2022. **214**.
3. Fu, D., et al., Quantitative Chemical Imaging with Multiplex Stimulated Raman Scattering Microscopy. Journal of the American Chemical Society, 2012. **134**(8): p. 3623-3626.
4. Liu, J.B., Y.C. Du, and Y.H. Zhao, Soil Microplastics Spectrum Based on Visible near-Infrared Spectroscopy. Bangladesh Journal of Botany, 2022. **51**(4): p. 971-977.
5. Michel, A.P.M., et al., Comparison of Laboratory Analytical Techniques for the Rapid Identification of Marine Plastics. Oceans 2019 - Marseille, 2019.
6. Ainali, N.M., et al., Do poly(lactic acid) microplastics instigate a threat? A perception for their dynamic towards environmental pollution and toxicity. Science of the Total Environment, 2022. **832**.
7. Mohammed, F., et al., Analytical methods to detect adulteration of argan oil: A critical review. Microchemical Journal, 2021. **168**.
8. Mogha, N.K. and D. Shin, Nanoplastic detection with surface enhanced Raman spectroscopy: Present and future. Trac-Trends in Analytical Chemistry, 2023. **158**.
9. Razali, N.M. and N.N.H. Saris. Simulation of Optical Planar Waveguide Sensor for Microplastics Detection in Water. in Proceedings of the International Conference on Numerical Simulation of Optoelectronic Devices, NUSOD. 2022.
10. Saris, N.N.H., et al., Waveguide length and pump power effects on the amplification of europium aluminum doped polymer. Optik, 2021. **239**.