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# Evanescent Field Absorption Sensor Based on Plastic Optical Fiber: Effect of Fiber Geometry

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### ABSTRACT

Optical fiber sensors based on evanescent wave absorption have attracted significant attention due to their high sensitivity and advantages over conventional sensing technologies. Despite these advantages, optimizing structural parameters and geometrical configurations to enhance sensor performance remains a significant challenge. This study aims to evaluate the influence of core diameter, exposed length, and fiber geometry on the evanescent wave absorption characteristics of unclad optical fibers. Unclad fibers were fabricated using an acetone-based etching technique and configured into U-shaped, spiral, and wave-shaped designs with varying core diameters and exposed lengths. The sensing performance was assessed by immersing the unclad regions in ethanol solutions with concentrations ranging from 10 wt% to 50 wt%. The interaction between the guided light and surrounding medium was analyzed in terms of penetration depth, evanescent wave absorption coefficient, sensitivity, and efficiency. The results indicate that fibers with larger core diameters, longer exposed lengths (6 cm), and wave-shaped configurations exhibited the highest evanescent wave coefficients and sensitivity. Increasing ethanol concentration increased the penetration depth from 253.8 nm to 315.57 nm, thereby enhancing absorption and improving overall sensor performance.

## 1. Introduction

Optical fiber technology has emerged as an essential medium for sensing and telecommunications applications. Polymer optical fibers (POFs) were subsequently introduced and began to be widely applied in medical and industrial fields [1]. The European polymer optical fiber industry further advanced POF technology by developing applications and standardization frameworks. In addition, several European research institutions contributed to the development of novel fiber materials, fiber structures, and advanced transmission techniques to support high-speed optical links. Continued progress in POF technology has been driven by the Plastic Optical Fiber Trade

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Organization (POFTO), which actively promotes the adoption of POF systems in both data and non-data communication markets [2,3].

There are two main types of optical fiber: Silica Optical Fiber (SOF) and Polymer Optical Fiber (POF). POF has gained attention for short-distance communication due to its lower signal attenuation and higher mechanical flexibility, allowing repeated bending with minimal risk of breakage, whereas SOF is more fragile [4]. POF is also easier to install in complex or confined geometries [5], though it generally supports lower data transmission capacity than SOF. Both fiber types are lightweight, immune to electromagnetic interference (EMI), and capable of multiplexing [6–8]. POF offers additional advantages, including lower cost [9], larger core diameters (0.25–1 mm), higher chemical and impact resistance, and improved light-coupling efficiency [10]. Optical fibers are widely used in diverse sensing applications, including the detection of *E. coli*, monitoring ultraviolet radiation, measuring alcohol content in beer, humidity sensing, and other environmental or chemical parameters [11–14]. Polymer optical fibers (POFs) enable multi-parameter measurements such as strain, pressure, and temperature, offering fast response and real-time monitoring [15–16]. Multimode POFs provide high strain limits, fracture resistance, bending flexibility, and compatibility with organic materials, enhancing their potential for medical applications, although their large core can reduce measurement accuracy [17]. Despite these advantages, optimizing POF-based sensors for higher accuracy and resolution remains a challenge, motivating ongoing research to expand their use in advanced sensing systems [2,18].

Unclad POFs can be used as sensors based on the principle of evanescent wave absorption. In this approach, the fiber cladding is removed and the light that is propagate inside the core will penetrate into the surrounding fluid as shown in Figure 1. Light power loss occurs as the evanescent wave interacts with ethanol or analyte, and the sensor sensitivity is determined by the evanescent wave absorption coefficient, with higher coefficients indicating greater sensitivity [19]. The performance of such fiber sensors depends on the diameter of the fiber core, the length of the unclad region, and the shape of the fiber [14]. Studies have shown that increasing the bending of the fiber sensor enhances its sensitivity by allowing greater interaction between the evanescent field and the surrounding medium. This paper investigates the optimal performance of unclad POF sensors by varying fiber geometry, unclad length, waist diameter, and bending to achieve maximum sensitivity.

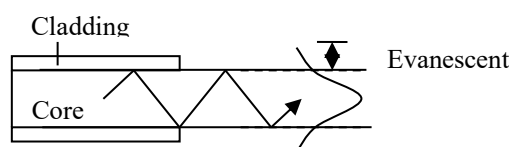


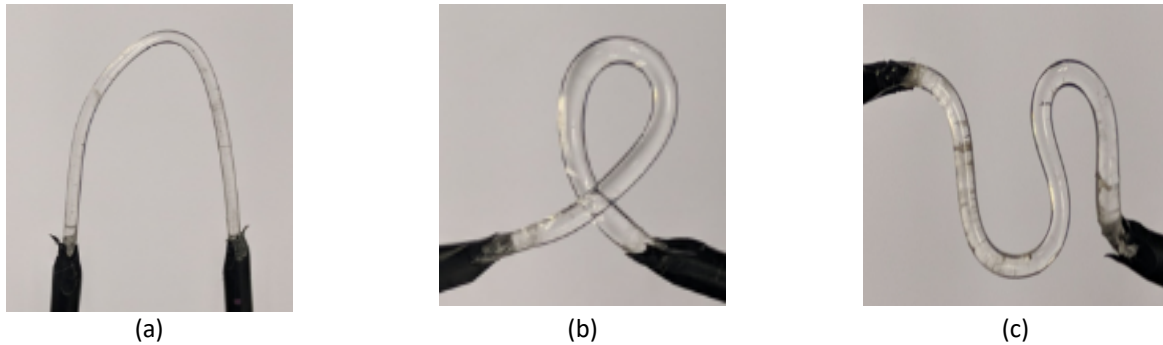
Fig. 1. Spectrometer evanescent

## 2. Methodology

The fiber was prepared by removing the fiber jacket. An unclad length of approximately 0.02 m, 0.04 m and 0.06 m was etched at the middle of the fiber while maintaining a waist diameter of 0.9 mm. The exposed fiber cladding was removed by etching using cotton buds soaked in acetone solution at room temperature. After each wiping process, the core diameter was measured using a digital Vernier caliper, and the readings were recorded. The unclad fiber was then rinsed with distilled water to stop the reaction.

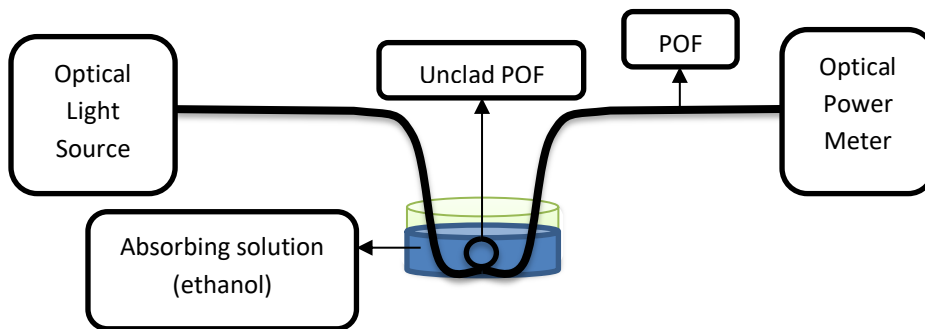
Next, the fiber waist diameter was varied to 0.5 mm, 0.7 mm, and 0.9 mm to examine the absorption coefficient of the sensor. The fiber was etched using acetone and further processed with sandpaper to achieve the desired diameters. To modify the geometry of the fiber, the unclad fiber was shaped into U-shaped, spiral-shaped, and wave-shaped configurations, as shown in Figure 2. Hot

plates were used to slightly soften the unclad polymer optical fibers (POFs), allowing them to be formed into these three shapes. Each bending and shaping process was performed carefully to avoid cracks in the POFs. The fiber diameter was fixed at 0.9 mm, and the length of the unclad region was 4 cm.



**Fig. 2.** Unclad fiber with a (a) U-shaped, (b) Spiral and (c) Wave shape fiber

For the experimental setup, a 650 nm optical light source and an optical power meter were connected to both ends of the coated POF, as illustrated in Figure. 3. The prepared fibers were then immersed in ethanol solutions with concentrations ranging from 10 wt% to 50 wt%. The ethanol solutions were prepared using distilled water as the diluent. The output optical power was recorded for each concentration, and the sensor sensitivity was determined based on the measured power variations.



**Fig. 3.** Experimental setup for ethanol detection

### 3. Results and Discussions

#### 3.1 Penetration Depth Evanescent Wave of the Absorbing Solution

The Penetration depth  $d_p$  is defined as a measure of how deep light or any electromagnetic radiation can penetrate into a material. It is defined as the depth at which the intensity of the radiation inside the material falls to  $1/e$  which is about 37% of its original value at (or more properly, just beneath) the light transmitted at surface explained by previous study [20]. The formula for the penetration depth is in the Eq. (1), where  $\lambda$  is the wavelength of light source,  $\theta$  is incidence angle normal at the interface,  $n_1$  is core's refractive index and  $n_2$  is cladding's refractive index.

$$d_p = \frac{\lambda}{2\pi n_1 \sqrt{\sin^2 \theta - \left(\frac{n_2}{n_1}\right)^2}} \quad (1)$$

In this experiment, ethanol solutions with concentrations ranging from 10 wt% to 50 wt% were used as the absorbing medium surrounding the core. The refractive indices of ethanol at

concentrations of 10 wt%, 20 wt%, 30 wt%, 40 wt%, and 50 wt% are 1.3395, 1.3469, 1.3535, 1.3583, and 1.3616, respectively. Variations in the refractive index due to different ethanol concentrations affect the penetration depth through changes in the refractive index contrast between the core and the surrounding alcohol solution. For instance, ethanol at 50 wt% concentration, with a refractive index of 1.3616, exhibits a penetration depth of 315.57 nm at an incident angle of 70°, whereas ethanol at 10 wt% concentration shows a lower penetration depth of 253.8 nm. Based on these results, it can be concluded that lower ethanol concentrations lead to smaller penetration depths because the refractive index difference between the core and the absorbing solution increases.

### 3.2 Effects of Unclad Length on Ethanol Detection

Figure. 4. shows the power output ratio and evanescent wave absorption coefficient of unclad POFs with lengths of 0.02 m, 0.04 m, and 0.06 m immersed in ethanol solutions. Based on the power output ratio, the unclad lengths of 0.02 m and 0.04 m exhibit the same sensitivity value of 0.002 a.u/% with slope linearities of 96.5% and 94.5%, respectively. In contrast, the 0.06 m unclad length demonstrates a higher sensitivity of 0.0029 a.u/% but a lower slope linearity of 86.5%. Meanwhile, the absorption coefficients for unclad lengths of 0.02 m, 0.04 m, and 0.06 m increase linearly with ethanol concentration from 10 wt.% to 50 wt.%. As the ethanol concentration increases, the refractive index of the solution also increases, resulting in a higher rate of optical power transmitted outside the core due to stronger evanescent wave interaction.

Shorter exposed lengths of unclad POFs result in higher data transmission and lower signal attenuation. This occurs because a shorter interaction length reduces the distance over which light propagates without cladding protection. Consequently, less light escapes, is absorbed, or scattered at the core boundary, and disruption of total internal reflection (TIR) due to insufficient incident angles is minimized. As a result, less light is refracted out of the core and lost to the surrounding environment. However, with increasing unclad length, the interaction between the evanescent wave field and the ethanol solution acting as an effective cladding becomes stronger, leading to increased attenuation [14].

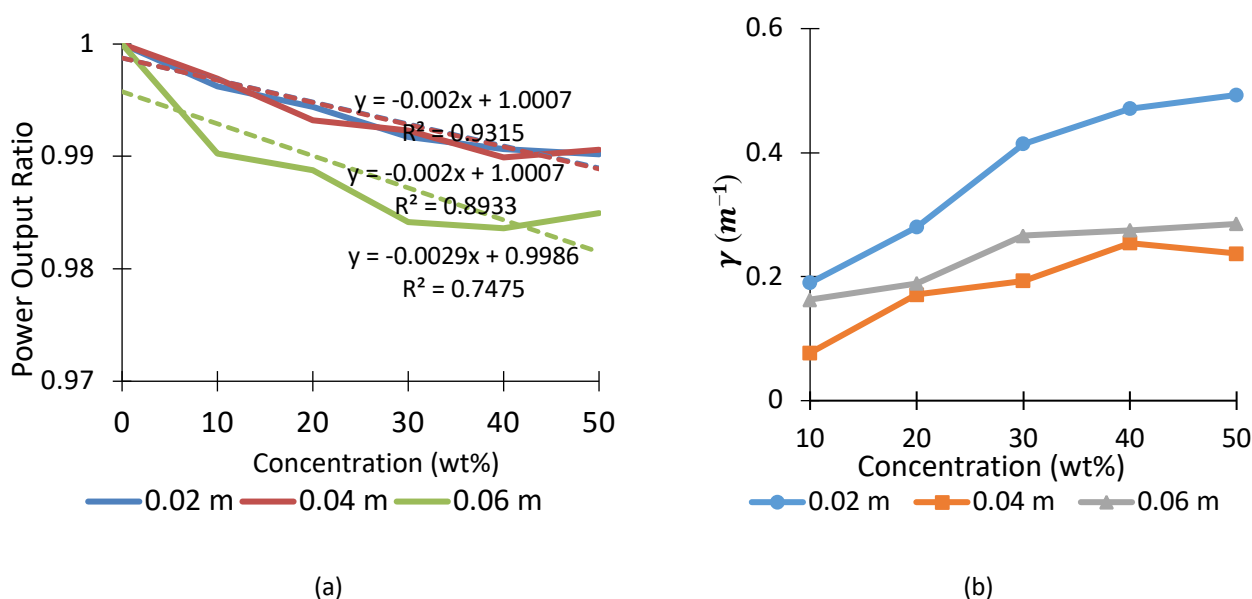


Fig. 4. Effect of fiber's length on (a) power output ration and (b) absorption coefficient

### 3.3 Effects of Core's Diameter on Ethanol Detection

Figure 5(a) presents the sensitivity of POFs with waist diameters of 0.5 mm and 0.7 mm at an unclad length of 0.04 m. The 0.5 mm waist diameter exhibits a sensitivity of 0.0053 a.u./% with a slope linearity of 87.8%, whereas the 0.7 mm waist diameter shows a higher sensitivity of 0.0082 a.u./% but with a significantly lower slope linearity of 28%. Therefore, although the 0.7 mm waist diameter provides higher sensitivity, the 0.5 mm waist diameter demonstrates superior linearity in terms of power output variation with ethanol concentration. Figure 5(b) illustrates that the absorption coefficient increases with ethanol concentration for both 0.5 mm and 0.7 mm waist diameters of the unclad fiber. At 50 wt.% ethanol concentration, the absorption coefficient reaches 41.5 m<sup>-1</sup> for the 0.7 mm waist diameter, compared to 35.28 m<sup>-1</sup> for the 0.5 mm waist diameter. This indicates that a higher absorption coefficient for 0.7 mm corresponds to improved sensor performance in terms of sensitivity.

The experimental results demonstrate that optical fibers with larger core diameters exhibit higher sensitivity compared to those with smaller diameters. Nevertheless, the observed variation in sensitivity is not highly significant, as the difference between the fiber diameters is relatively small. The interaction between the evanescent wave field and the surrounding medium is governed by both the penetration depth and the number of light reflections per unit length,  $N$ . As the core diameter increases, the penetration depth of the evanescent field correspondingly increases, enhancing the interaction with the surrounding medium [21]. However, this increase in core diameter also leads to a reduction in the number of internal light reflections per unit length, which partially offsets the sensitivity enhancement.

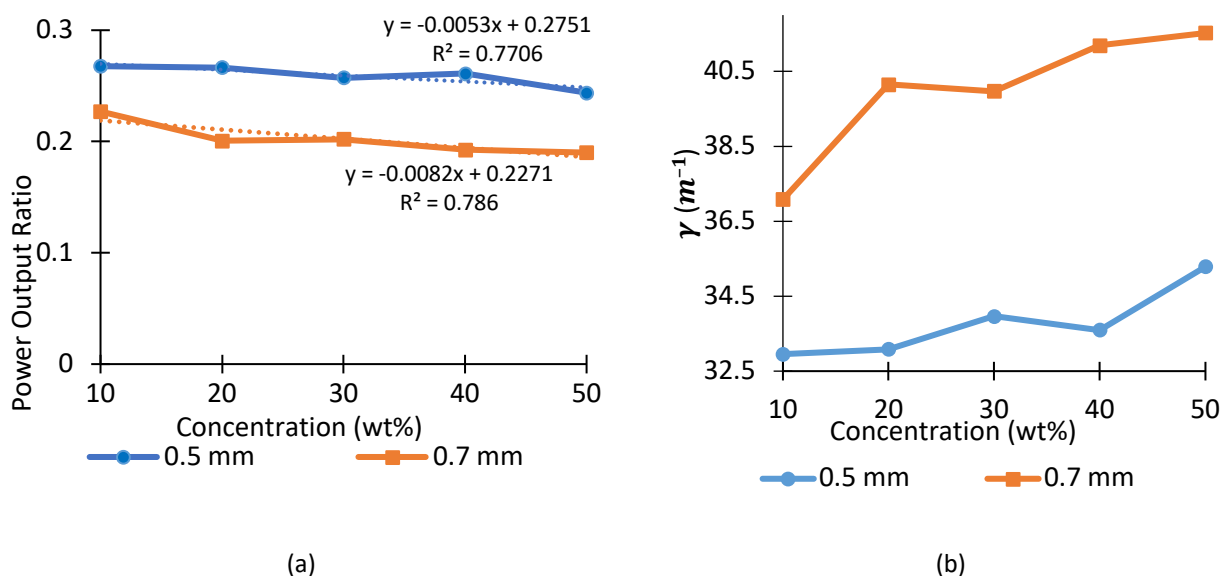


Fig. 5. Effect of core's diameter on (a) power output ration and (b) absorption coefficient

### 3.4 Effects of Fibers Geometry on Ethanol Detection

Figure 6 (a) shows the power output ratio of unclad fibers with U-shape, spiral, and wave geometries under varying ethanol concentrations. The U-shaped fiber exhibits a sensitivity of 0.0167 a.u./% with a linearity of 72.3%, whereas the spiral and wave-shaped fibers show sensitivities of 0.0175 a.u./% and 0.0478 a.u./%, with slope linearities of 94.3% and 94.47%, respectively. These results indicate that the wave-shaped fiber achieves the highest sensitivity among the three

geometries. The evanescent wave absorption coefficient further confirms this trend by referring to Figure 6 (b). At 40 wt.% ethanol concentration, the wave-shaped fiber exhibits the highest absorption coefficient of  $63.3 \text{ m}^{-1}$ , compared to  $28.8 \text{ m}^{-1}$  for the spiral shape and  $1.316 \text{ m}^{-1}$  for the U-shape. The spiral shape, which contains moderate curvature, and the U-shape, which has minimal bending, demonstrate lower absorption coefficients. This behavior can be attributed to the effect of bending on light propagation: increased curvature in the fiber core enhances the penetration of the evanescent field into the surrounding medium, thereby increasing signal attenuation and sensor sensitivity. For the wave-shaped fiber, the extensive curvature introduces significant macro-bending losses, which contributes to its higher sensitivity.

Overall, the results indicate that increasing the bending of the unclad fiber enhances the interaction of the evanescent field with the surrounding medium, improving sensor performance. However, the maximum sensitivity is limited by the bending radius at which significant light scattering begins to occur. Furthermore, as the refractive index of the surrounding medium ( $n_2$ ) increases, the fiber's numerical aperture (NA) decreases, leading to greater light scattering and a corresponding effect on sensitivity [21].

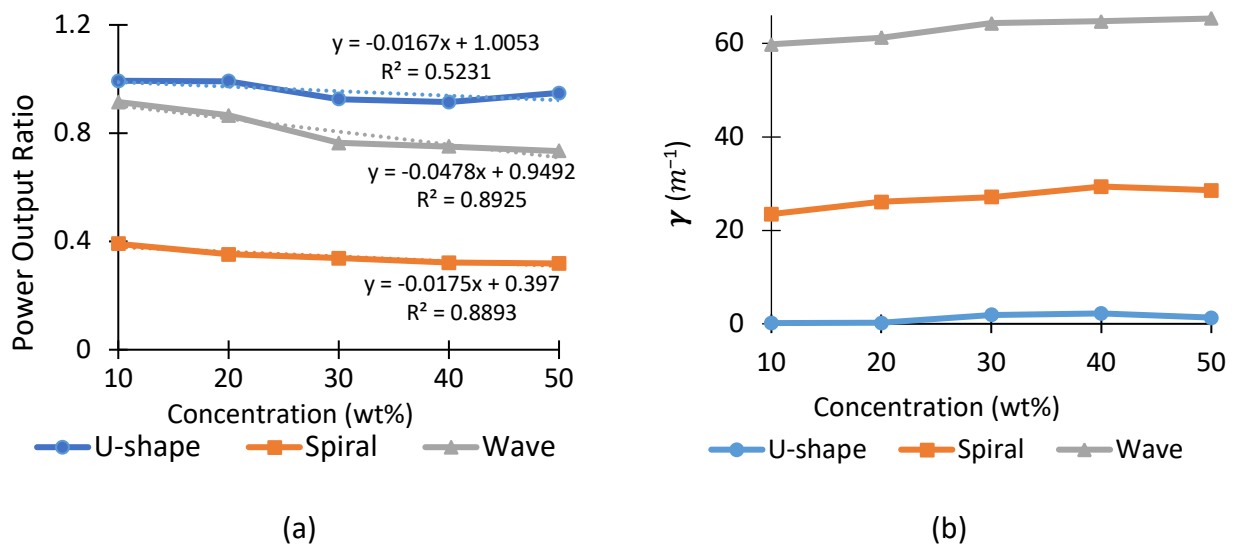


Fig. 6. Effect of fiber's shape on (a) power output ratio and (b) absorption coefficient

#### 4. Conclusions

In this study, the performance of unclad polymer optical fiber (POF) sensors was investigated under varying ethanol concentrations, with a focus on fiber length, waist diameter, bending radius, and geometry. The results demonstrate that sensor sensitivity is strongly influenced by the interaction between the evanescent field and the surrounding medium.

Shorter unclad lengths provide higher data transmission and lower signal attenuation, while longer lengths enhance evanescent wave interaction, increasing sensitivity. Larger waist diameters also improve sensitivity due to greater penetration depth, although at the cost of reduced linearity. Reducing the bending radius or introducing curved geometries, such as spiral and wave shapes, further increases evanescent field penetration and sensor sensitivity, with the wave-shaped fiber exhibiting the highest sensitivity and absorption coefficient among the tested configurations. However, excessive bending introduces scattering losses that limit maximum achievable sensitivity.

Overall, the study confirms that careful optimization of fiber geometry, length, diameter, and bending can significantly enhance the sensitivity of unclad POF-based sensors. These findings provide

valuable design guidelines for developing highly sensitive optical fiber sensors for chemical and biochemical detection applications.

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