

Chemical Etching of Silica Optical Fibers: Effects of Core Diameter and Etching Conditions

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Abstract. This study investigates the effect of chemical etching conditions and core diameter on silica optical fibers, together with the resulting evanescent field penetration characteristics. Cladding removal was carried out using hydrofluoric acid (HF) at concentrations of 30.6% and 49%, using multimode fibers with core diameters of 105, 50, and 9 μm . The results show that the etching rate depends strongly on both HF concentration and fiber core diameter. At 49% HF, cladding removal was completed in approximately 3 minutes for the 105 μm core fiber, compared with 20 minutes for the 50 μm core fiber and 32 minutes for the 9 μm core fiber. The slower etching rate observed near the core boundary is attributed to differences in the core composition and the presence of dopants within the silica core. In addition, the evanescent field penetration depth of U-shaped fibers was evaluated mathematically at a wavelength of 1310 nm. The results show that the larger core diameter of 105 μm provides a greater penetration depth than the 50 μm core, increasing from 0.218 to 0.236 μm at a launch height of $h = 0 \mu\text{m}$. This indicates stronger interaction between the evanescent field and the surrounding medium. In contrast, the smaller core diameter results in more frequent internal reflections along the interaction region, increasing the number of interactions between the guided light and the fiber boundary. The penetration depth also increases as the refractive index of the surrounding medium approaches that of the fiber core. Overall, the results demonstrate that both etching conditions and fiber geometry play important roles in controlling evanescent field behavior and should be considered when designing fiber-based evanescent field sensors.

Keywords: Silica Optical Fiber, Chemical Etching, Evanescent Field

1 Introduction

Optical fiber sensors based on evanescent field interaction have attracted significant interest due to their high sensitivity, immunity to electromagnetic interference, and potential for miniaturization [1,2]. The sensing mechanism is based on the interaction

between the evanescent field generated at the fiber surface and the surrounding medium. In an intact optical fiber, the cladding limits the exposure of the evanescent field to the surrounding environment. Therefore, partial or complete removal of the cladding is commonly used to increase this interaction. Techniques such as tapering, polishing, and chemical etching can be used to reduce or remove the cladding and expose more of the evanescent field to the surrounding medium [3,4,5]. Chemical etching using hydrofluoric acid (HF) is widely used for silica fiber modification due to its ability to precisely reduce fiber diameter [6,7]. During etching process, the fiber diameter decreases specifically within the regions exposed to the acid. The etching rate is influenced by the HF concentration and the exposed fiber surface area. Previous studies have described the dissolution process in terms of the dissolution rate constant, exposed surface area, and HF concentration [6,8]. Therefore, controlling the HF concentration and fiber geometry is important for obtaining the desired fiber dimensions while maintaining the integrity of the silica core. In this study, the chemical etching behaviour of silica optical fibers with different core diameters was investigated using two HF concentrations. The effect of fiber diameter on the etching rate was evaluated experimentally, and the resulting fiber dimensions were used in an analytical analysis of evanescent-field penetration depth for a U-shaped fiber configuration. The results provide insight into how etching conditions and fiber geometry affect the evanescent-field characteristics of silica optical fibers.

2 Methodology

2.1 Chemical Etching of Silica Optical Fiber

The optical source was a 1310 nm laser diode. This wavelength was chosen based on the relatively low attenuation and chromatic dispersion of silica fibers in the 1310 nm region. It also lies within the near-infrared range, making it applicable to various sensing measurements. Fiber optic used in this study had a pure silica core with a refractive index of 1.4446 and a fluorine-doped silica cladding with a refractive index of 1.4271. Fibers with different core diameters were investigated: 9/125 μm single-mode fiber, alongside 50/125 μm and 105/125 μm multimode fibers. Prior to chemical exposure, the protective polymer jacket was mechanically removed to expose interaction lengths of 2 cm and 4 cm. HF concentrations of 30.6% and 49% were used to control the etching process. Higher concentrations were avoided because they cause overly rapid etching, degrade the optical surface smoothness, and pose severe safety hazards. During the etching process, the optical fiber was connected to a light source and an optical detector to continuously monitor the transmitted optical power. Simultaneously, the reduction in fiber diameter was periodically measured using an optical microscope to determine the etching rate. The relationship between HF concentration and etching time was used to achieve the desired core diameter with good reproducibility. The etching procedure was repeated several times to establish the optimum etching duration, ensuring complete removal of the silica cladding while preventing damage to the fiber core.

2.2 Analytical Modeling of Evanescent Field Penetration

To evaluate the potential performance of the etched fibers as refractometric sensors, mathematical modeling of evanescent wave propagation is commonly performed to understand the relationship between fiber geometry, bending configuration, and surrounding refractive index. The U-shaped fiber was modelled using curvature radii (R) of 1.5 and 2.5 mm. These values were selected to examine the effect of bending on the evanescent field while remaining within a practical range for silica fibers. Although a tighter bend can increase the interaction of the evanescent field with the surrounding medium, radii below 1.5 mm may increase the risk of mechanical damage or fracture in standard silica fibers [16, 17]. In contrast, increasing the bend radius reduces the associated optical sensitivity [17]. Hence, the two radii were used to represent different bending conditions while considering both sensing performance and fiber integrity. The light ray profiles entering the curve were varied across a mathematical matrix of launch heights (h) ranging from $h=0$ to $h=105 \mu\text{m}$. This variation was used only for analytical modelling, while standard full-core illumination was used in the experiments.

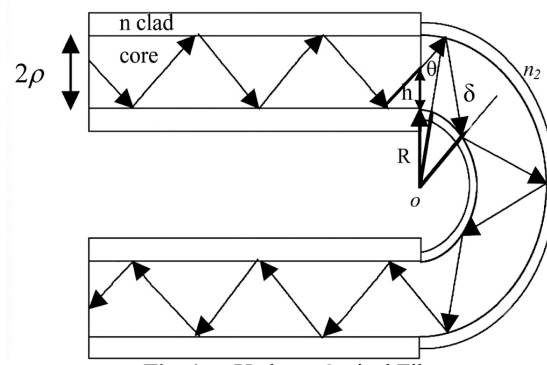


Fig. 1. U-shape Optical Fiber

The mathematical evaluation of the evanescent wave penetration depth (d_p) within the sensing region was conducted based on the Equation (1):

$$d_p = \frac{\lambda}{2\pi n_{core}(\cos^2\theta_{cs} - \cos^2\theta)^{1/2}} \quad (1)$$

where λ represents the operating wavelength simulated at the standard communication wavelengths of 850 nm, 1310 nm, and 1550 nm. Meanwhile, n_l is the core refractive index, θ is the mode propagation angle, and θ_{cs} defines the critical angle at the boundary. The penetration depth of the evanescent field was calculated based on the relationship between wavelength, refractive indices, and incident angle as described in previous optical waveguide studies [4,9]. Within a U-bend geometry, the propagation angle of internal ray angle θ changes with the fiber curvature, which can affect the evanescent field penetration and sensing performance [10,11].

3 Result and Discussion

3.1 Chemical Etching and Diameter Analysis

The etching behaviour was strongly influenced by the fiber geometry, core specifications, and acid concentration. As the silica cladding of both the 50/125 and 9/125 μm optical fibers was progressively reduced during the etching process, as shown in Fig. 2 and 3, the evanescent field became increasingly exposed to the surrounding medium, thereby enhancing the interaction between the guided optical mode and the surrounding environment [1,5]. Further reduction in cladding thickness allowed the evanescent field to extend deeper into the surrounding medium. Consequently, a greater fraction of the guided optical power interacted with the external medium, resulting in a reduction in the transmitted optical power detected at the output. Although both fibers exhibited a decrease in transmitted power as etching progressed under 49% HF, the 9/125 μm fiber showed a more pronounced power variation during the later stages of etching. This behaviour may be associated with changes in optical confinement, modal field distribution, and mode coupling as the cladding thickness was progressively reduced [6,12]. The subsequent partial recovery in transmitted power observed for the 9/125 μm fiber may reflect changes in the modal propagation conditions as the etched fiber geometry evolved.

The etching response was also affected by the material composition of the fiber [6,8]. The dissolution rate decreased considerably as the etching front approached the core–cladding interface, which can be attributed to the different chemical dissolution characteristics of the fluorine-doped silica cladding and the pure silica core [8]. The longer etching time observed for the 9 μm core fiber may be associated with its smaller core-to-cladding ratio, which requires a larger portion of the original cladding to be removed before the etching front reaches the core. In addition, the progressively reduced fiber dimensions may limit the transport of reactive fluoride species to the etched surface, potentially contributing to the lower dissolution rate during the later stages of etching.

The influence of HF concentration was also reflected in the time required to reach the target etching depth. For the 50/125 μm multimode optical fiber, the 49% HF solution reached the target depth in approximately 16 min, while the 30.6% solution required about 135 min. The faster etching observed at the higher HF concentration is associated with the greater availability of reactive fluoride species at the silica surface, which facilitates silica dissolution. The etching rate is therefore affected by the concentration of HF and the chemical reactions and mass transport at the silica–HF interface [13]. At the lower concentration, the slower dissolution of silica resulted in a considerably longer time to obtain the same etching depth.

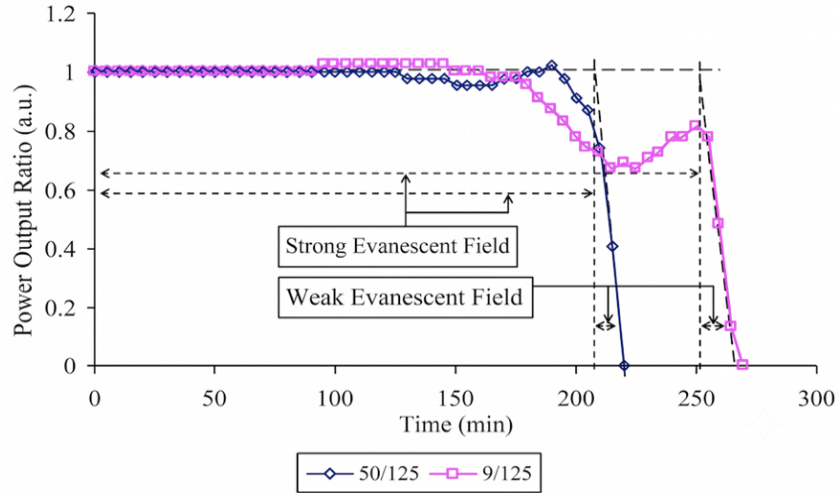


Fig. 2. Etching rate profiles for 9 μm and 50 μm core fibers at a 30.6% HF acid concentration

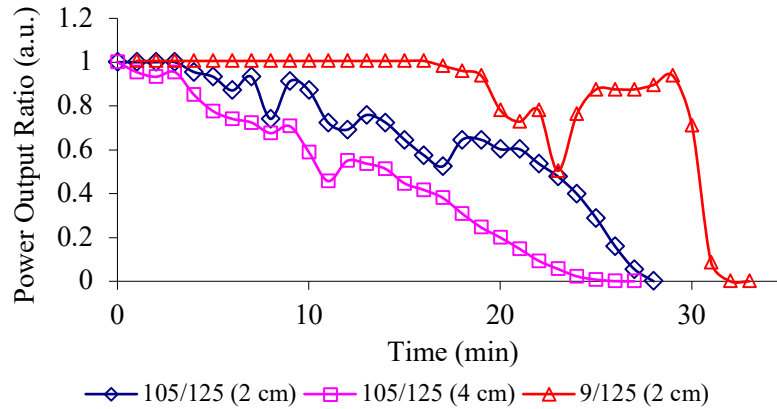


Fig. 3. Etching rate profiles for 9 μm (2 cm) and 105 μm core fibers (2 cm and 4 cm exposure lengths) at a 49% HF acid concentration.

Figure 4 presents the change in fiber diameter during etching with 49% HF. Different etching times were required for the three fiber types to reach their respective measured dimensions. The 9/125 μm fiber required approximately 32 min to reach a final diameter of 9.7 μm . In comparison, the 50/125 μm and 105/125 μm fibers reached final diameters of 51.92 μm and 105.74 μm after approximately 20 and 3 min, respectively. The differences in etching behaviour can be associated with the fiber dimensions and the conditions at the exposed silica–HF interface, which affect the dissolution of silica during the etching process. Fig. 5 presents microscopic images of the optical fibers after the etching process, showing the reduction in cladding thickness following exposure to hydrofluoric acid. The etching process

yields a uniform reduction in cladding thickness. Despite minor microscopic variations caused by localized fluid dynamics, the average final diameters across all samples were highly consistent, ensuring reliable reproducibility.

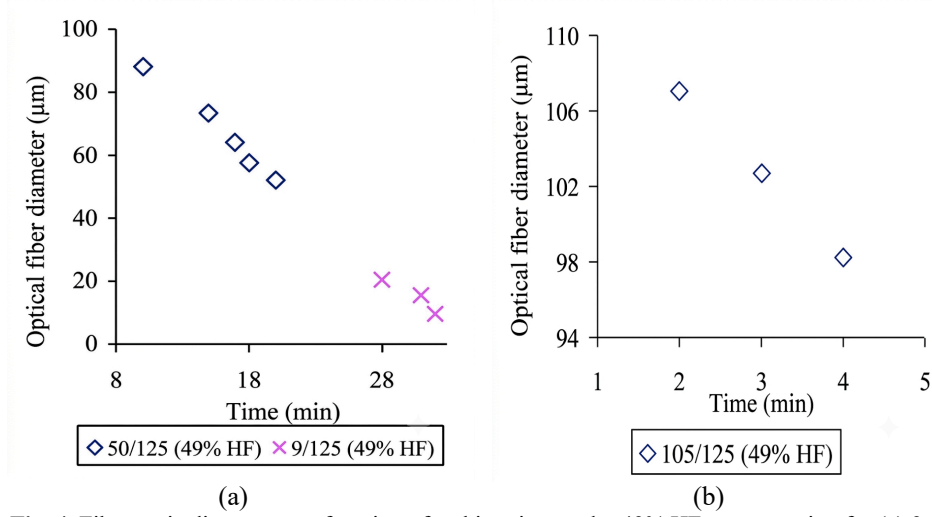


Fig. 4. Fiber optic diameter as a function of etching time under 49% HF concentration for (a) 9 μm and 50 μm , and (b) 105 μm cores.

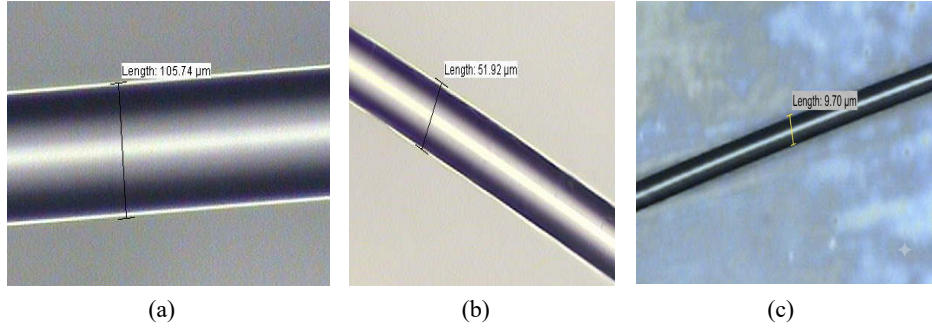


Fig. 5. Microscopic micrographs of the chemically etched optical fibers for (a) 105 μm (x5 magnification), (b) 50 μm (x10 magnification), and (c) 9 μm (x20 magnification)

3.2 Evanescent Field Modeling and Penetration Depth

While the experiments in Section 3.1 measured a drop in optical power, the mathematical models in this section calculate the penetration depth to explain the physical reason behind that power loss. The input ray profiles entering the U-bent structures were systematically varied across discrete launch h ranging from 0 to 105 μm , assum-

ing a fixed bend radius of 1.5 mm. Numerical calculations of the evanescent wave penetration depth were executed across varying core dimensions under diverse surrounding refractive index environments. Assuming an air surrounding medium, it shows that the penetration depth increases from $0.1532 \mu\text{m}$ to $0.2795 \mu\text{m}$ at $h = 0 \mu\text{m}$ as the wavelength increases from 850 nm to 1550 nm (Fig. 6(a)). The $105/125 \mu\text{m}$ fiber exhibits a greater penetration depth of $0.236 \mu\text{m}$ than the $50/125 \mu\text{m}$ fiber, which has a penetration depth of $0.218 \mu\text{m}$, as shown in Fig. 6(b). As a result, fibers with a larger core diameter provide a greater evanescent field penetration depth, indicating a larger interaction region with the surrounding medium. Since the propagation characteristics of guided modes depend strongly on fiber geometry and core dimensions, the number of internal reflections varies with the core radius and numerical aperture [9,14].

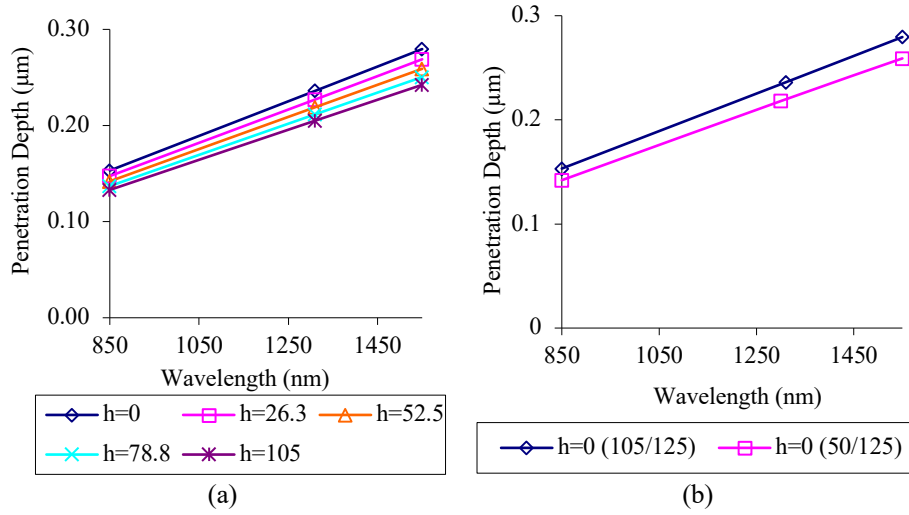


Fig. 6. Penetration depth for (a) $105 \mu\text{m}$ fiber with varying h value, (b) $105 \mu\text{m}$ and $50 \mu\text{m}$ core diameter fiber configurations

The penetration depth is strongly influenced by the optical parameters of the ambient environment, particularly the surrounding refractive index [1,15]. As the surrounding refractive index increases, the penetration depth value expands as shown in Fig. 7. This increase allows the evanescent field to extend further into the surrounding medium, resulting in greater interaction between the optical field and environment. Consequently, more optical power is coupled into the surrounding medium, leading to a decrease in the measured output power of the sensor. These calculated penetration depths ranged from $0.406 \mu\text{m}$ to $1.02 \mu\text{m}$ under standard launch conditions. These values are comparable with those reported for U-bent multimode optical fiber sensors [16, 17]. The present results are therefore consistent with the expected behaviour of the evanescent field. The analysis also shows that fiber curvature and core diameter

affect the penetration of the evanescent field into the surrounding medium, which can contribute to improved refractometric sensitivity [14,18].

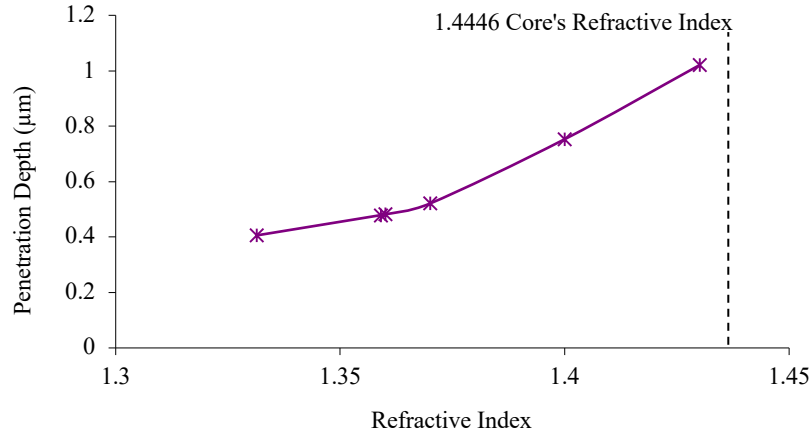


Fig. 7. Evanescent wave penetration depth at the outer curvature curve under varying-surrounding refractive indices

4 Conclusion

This study investigated the effects of chemical etching conditions and fiber geometry on the evanescent-field behaviour of multimode silica optical fibers for refractometric sensing. The etching results showed that the removal of the silica cladding by hydrofluoric acid (HF) depends on both HF concentration and fiber core diameter. A 49% HF concentration provided faster cladding removal, with the 105 μm core fiber being fully exposed within 3 min. The analytical and geometric modelling further showed that the U-bent configuration increased the interaction of the evanescent field with the surrounding medium compared with a straight fiber configuration. In addition, the modelling results showed that an increase in the surrounding refractive index reduces the total internal reflection condition, resulting in greater evanescent-field interaction and attenuation of the transmitted optical power. Overall, the findings provide useful guidance for selecting fiber geometry and etching conditions in the development of evanescent-field optical fiber sensors.

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