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Single Mode Optical Fiber based Refractive Index Sensor using Etched Cladding

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Abstract: The use of optical fiber for sensor applications is a topic of current interest. We report the fabrication of etched single mode optical fiber based refractive index sensor. Experiments are performed to determine the etch rate of fiber in buffered hydrofluoric acid, which can be high or low depending upon the temperature at which etching is carried out. Controlled wet etching of fiber cladding is performed using these measurements and etched fiber region is tested for refractive index sensing application. We report significant optical power change in fiber sensor at 1550 nm wavelength, in the presence of IPA solution and also the sugar solution with varying concentration.

Keywords: Optical fiber, refractive index sensor, etched fiber sensor

INTRODUCTION

The optical fibers are extensively used in present day high bandwidth telecommunication networks. Technological progress in fiber optics and optoelectronics has also led to the development of novel photonic sensors, which are easy to deploy, provide information in real time, and in some cases even better than their electronic counterparts. Fiber optic sensors are broadly categorized into intensity, evanescent, spectral and interference based sensors.

The multimode tapered fiber based refractive index sensor has been reported earlier [1]. Fiber Bragg grating (FBG) based refractive index sensors are reported in single mode fiber, where wet etching is used to remove the cladding [2]. All fiber high-resolution refractive index sensor relies on a partial and localized etching of the cladding layer along a standard micro-structured fiber Bragg grating [3]. Ambient refractive index (ARI) sensing characteristics of metal-coated side-polished optical fiber gratings based on the excitation of the pure surface Plasmon polarization is investigated for possible bio/chemical application [4]. In another approach, creating a mismatch in core alignments between single and multimode fiber is reported to give refractive index resolution of about $7 \times 10^{-5}$ [5]. Refractive-index sensor based on dual fiber-Bragg gratings interposed multimode-fiber taper has been experimentally demonstrated [6]. Highly sensitive fiber optic refractive index sensor based on edge written long-period fiber grating (LPFG) [7] and miniature fiber-optic refractive-index sensor based on Fabry-Perot interferometer [8] are also discussed.

We report fabrication of intrinsic single mode fiber based refractive index sensor using wet etching of fiber cladding. The sensor fabrication requires precise control over the fiber etching process by means of continuous monitoring of fiber transmission loss during etching. We adopted an alternative approach of first calibrating the fiber etching process in terms of time and temperature of etching, which can then be controlled to obtain desired diameter of the fiber after etching. Many single mode fibers have been etched with high process yield, and used for refractive index sensing experiments.

CONTROLLED ETCHING OF SINGLE MODE OPTICAL FIBER

The fiber has a core of higher refractive index compared to that of surrounding cladding region, thus confining the light in core. The fiber core ($D_{CO}$) and cladding ($D_{CL}$) diameters typically measure 8.4 μm and 125μm respectively. Etching cladding to a reasonably thin layer, just sufficient to confine and guide most of light in the core, and also allowing a part of it to leak into medium surrounding the cladding, is utilized for making fiber sensor.

The experimental arrangement for etching SM fiber consists of a hot plate, base plate for placing fiber and hydrofluoric acid (HF) dispensing mechanism, as shown in fig.1. The fiber jacket is removed from central portion (~1 cm) and cladding is brought in contact with 40% buffered HF. The hotplate temperature controller is set to a value between 30°C and 70°C and fibers are etched for varying time duration.

![Fig. 1: Setup for wet etching of optical fiber](image-url)
The fiber diameter in etched portion is measured under the Olympus optical microscope and plotted as a function of etching time for various etch temperatures, as shown in fig.2. All the measured diameters ($D_e$) at a constant hotplate temperature ($T$) follow a linear variation in etching time ($t$), described by eq. 1.

$$D_e(T) = \alpha(T) \cdot t + \beta(T)$$

[1]

Here $\alpha(T)$ and $\beta(T)$ are the etch rate ($\mu$m/min) and fiber diameter at $t = 0$ (intercept on y axis) respectively, for given temperature.

At room temperature the etch rate for fiber is relatively slow, typically 1.69 $\mu$m/min, which rapidly increases to 6.62 $\mu$m/min at 65°C. The fiber etching rate is determined by the slope of measured linear plots. The etch rate variation as a function of temperature is shown in fig.3.

The measured fiber etch rate $\alpha(T)$ is found to follow exponential dependence on temperature described by

$$\alpha(T) = 0.865 e^{T/32.26}$$

[2]

Eq. 1 and 2 provide us a tool to perform wet etching of optical fiber by controlling the time and temperature of etching (kept less than 70°C) for a pre-estimated etch diameter. Alternatively, transmitted optical power through fiber can be continuously monitored during etching to obtain the desired etched diameter.

### ETCHED SINGLE MODE FIBER AS SENSOR

The etched fiber is stretched and fixed on a glass slide using Epotek epoxy OG 146 put on two sides of the fiber. The etched portion in the middle is left exposed to air, and used in refractive index sensing, as shown in fig. 4.

We tested many sensors using sugar and Isopropyl alcohol (IPA) solution. It is observed that a thin cladding (<3 $\mu$m) facilitate interaction between guided light and the outer medium, thus resulting in a strong optical response to refractive index changes in the medium.

Preparing sugar solution is easy and also cost effective. We dissolved 20 gm sugar in 15 ml DI water and measured the net weight of solution. The sugar content in the solution divided by total weight of solution is taken as the sugar concentration. More water is added to dilute the solution and reduce sugar concentration. A 9.8$\mu$m etched diameter fiber sensor is used for sugar concentration detection. The refractive index measurement setup is shown in fig.5. Effect of sugar concentration on transmitted optical power through the etched fiber sensor is shown in fig. 6.
The transmitted optical power through fiber sensor is observed to follow a linear fall, as the sugar concentration increases from 10% to 43%, followed by rather slow fall but still showing linear behaviour. This observation is attributed to light leaking out of the fiber due to increase in sugar concentration. No such optical power variation is observed in unetched fiber.

In another experiment, sugar solution is replaced by solution containing mixture of Isopropyl alcohol (IPA) and de-ionized water. The refractive index of this solution varies between that of pure IPA \( n_{IPA} = 1.377, 13.029 \text{ moles/litre} \) and water \( n_{w} = 1.333 \), and determined by [9]

\[
 n_{ns} = [K.n_{IPA}^2 + (1-K).n_{w}^2]^{1/2} \tag{3}
\]

Where \( K \) is the mole ratio of IPA in the solution. Fiber sensors with five different etched diameters 10.5μm, 13.8μm, 19.5μm, 26.5μm, and 37.5μm are tested using IPA solution. The optical power variation as a function of refractive index change is shown in fig. 7.

All the fiber sensors show linear power variation in refractive index, described by equation

\[
 \Delta P(D_e) = \gamma(D_e) \cdot n + \delta(D_e) \tag{4}
\]

Where \( \Delta P \) is the change in optical power, \( \gamma(D_e) \) and \( \delta(D_e) \) are refractive index sensitivity (slope of line) and \( \gamma \) intercept respectively, and \( D_e \) is the etched diameter in μm. It is important to note that smaller the etched diameter, higher is \( \gamma \) and higher the diameter, smaller is the \( \gamma \). Very high refractive index sensitivity is therefore possible for smaller but optimally etched fiber, as shown in fig. 8. The 10.5μm diameter is highly sensitive to refractive index variation, nearly 300 μW/unit index change compared to <10 μW/unit index change for 37.5μm fiber.

\[
 S = 1296.e^{-0.13D_e} \tag{5}
\]

\[
 \text{CONCLUSION}
\]

Experiments on controlled wet etching of single mode fiber have been performed. The temperature of buffered HF and etching time are used to control the fiber etch rate. The process after calibration is found to be extremely simple for fabrication of etched fiber based sensors, used subsequently for refractive index sensing application. Optical power variation in sensor output is demonstrated in the presence of sugar solution with varying concentration. Refractive index sensing between 1.333 and 1.378 using optimally etched single mode optical fiber is also demonstrated.

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 \text{REFERENCES}
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