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Adiabatic tapered optical fiber fabrication in two step etching

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ABSTRACT

A two-step etching method using HF acid and Buffered HF is proposed to fabricate adiabatic biconical optical fiber tapers. Due to the fact that the etching rate in second step is almost 3 times slower than the previous droplet etching method, terminating the fabrication process is controllable enough to achieve a desirable fiber diameter. By monitoring transmitted spectrum, final diameter and adiabaticity of tapers are deduced. Tapers with losses about 0.3 dB in air and 4.2 dB in water are produced. The biconical fiber taper fabricated using this method is used to excite whispering gallery modes (WGMs) on a microsphere surface in an aquatic environment. So that they are suitable to be used in applications like WGM biosensors.

1. Introduction

Adiabatic biconical optical fiber tapers (ABFTs) allow extraction of optical power from the fiber, while maintaining fiber–optic compatibility. Adiabatic taper profile of ABFTs converts an initial fundamental fiber mode to a fundamental taper mode and vice versa when propagating through the tapered region results in minimum power coupling between core and cladding modes. In addition, their smooth fiber surface minimizes the scattering losses [1]. Due to strong evanescent field of ABFTs, they are convenient means for coupling light into the microresonators such as microsphere and exciting the whispering gallery modes (WGMs). The ABFT/microresonator photonic devices have been widely suggested and demonstrated for sensing of physical [2–5], chemical [6–8], and biological [9–12] properties of the environment situated near or at the microresonator surface.

There are two main methods for fabricating biconical tapers from single mode fibers namely the heat-pulling techniques and etching method. The heat-pulling is a relatively fast method and tapers fabricated by this technique have ultralow-loss transmissions. All of heat-pulling techniques require motorized translation stages for pulling fibers and a heat source like CO_2 lasers [13–15], microceramic heaters [16,17], or flames [18–20]. An alternative approach for fabricating a biconical taper is HF acid etching. This method is simple and can be performed in any fiber laboratory. However, the etching method have attracted less attention because the tapers fabricated by etching method have had high loss [21]. Recently, a droplet etchant method is proposed which is based on surface tension driven flow of HF acid microdroplets [22]. ABFTs produced by the acid droplet etching method, have exhibited losses comparable to heat-pulled tapers. Moreover, etched ABFTs have much shorter tapered region in comparison to heat-pulling tapered. Shorter ABFTs are more suitable for the purpose of miniaturization.

In spite of advantages of previous acid droplet etching method such as simplicity and smooth transition region formation using outflow of HF acid, we have found out that this method is hardly controllable to achieve micron and submicron tapered waist diameter. Furthermore, the waist diameter of taper has nonlinear dependence on etching time, so there is not a clear relation for termination time of the fabrication process. Hence, here we propose a two-step etching process using HF acid in first step and Buffered HF in second step to improve the control over terminating the fabrication process. In addition, we show that by monitoring the transmission spectrum the final properties of the taper can be deduced even when the diameter cannot be measured by microscopy system.

2. Material and methods

As a prerequisite for the etching process, we mechanically strip a standard SMF-28 fiber and clean it with isopropyl alcohol. Then the fiber is fixed tightly on an HF-resistant U shaped Plexiglas piece (fiber holder) as shown in Fig. 1. A plastic Petri dish is used as an acid container. The hydrophobic property of Petri dish forms a droplet of HF acid on its surface. The Petri dish also is transparent

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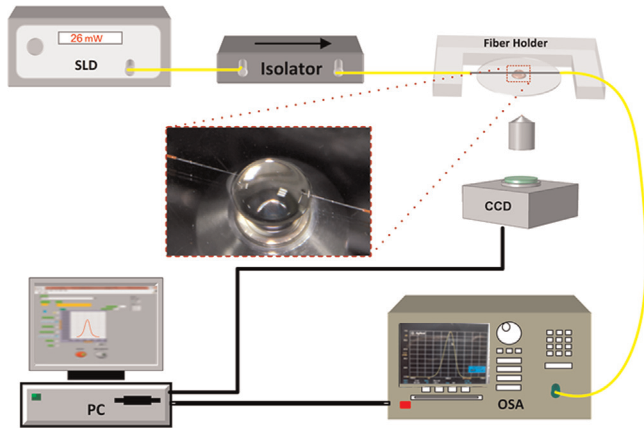

Fig. 1. The etch setup; a schematic view of the apparatus.

so the fiber waist could be measured from the bottom through a microscope. To perform the etching, the bared fiber is placed at a certain height above the container by a translation stage.

The lower etching rate results in achieving more precise waist diameter which can be done practically by using lower concentrations of HF acid. However, performing the entire etching process with a diluted HF acid solution takes too much time because the cladding material etches at a substantially slower rate than the core material. Therefore, it is advantageous to slow down just the etching rate of the core. From this point of view, the etching process is done in two steps. In the first step, a 200 µl droplet of 48% HF (by weight) is injected on the container. When the clad material of the fiber is removed, the HF droplet is extracted and the fiber is washed with DI water. In the second step, thinner taper waist diameter is achieved by injecting a 200 µl Buffered HF (BHF) droplet. BHF solution is a mixture of HF and NH_4F. The concentrations of H^+, F^-, HF^{2-}, and H_2F_2 in solution which determine the etching rate can be adjusted by changing the weight ratios of NH_4F/HF. In addition, using BHF instead of diluted HF would result in fabricating a desirable smooth silica surface [23]. BHF with volumetric ratio of 10:1 is used in our experiment (40 wt% NH_4F/48% HF). In order to terminate the etching, the BHF is extracted using a pipette and the remaining etchant on the fiber is removed by rinsing it in DI water immediately after etching.

During the experiment, the etching progress and taper quality is monitored through the fiber power loss and the fiber diameter measurements which are measured by an optical spectrum analyzer and a microscopy system, respectively (Fig. 1). The microscopy system consists of a 40 × objective lens and a 3 megapixel CCD camera which provides a 0.14 µm resolution. However due to diffraction of light, our measurement is accompanied by some errors, especially when the waist diameter is around 1 µm or less. Therefore final waist diameter of tapers are measured using a scanning electron microscope (SEM) as shown in Fig. 2(e) and (f).

3. Results and discussion

In an ideal ABFT, transition region angle is small enough to allow light propagation at the core–clade interface of the unperturbed fiber to core–air interface of tapered region without coupling to higher order modes. Therefore light transmits through taper with minimum loss. Main loss is due to light scattering from surface roughness and light absorption by surrounding medium. Here, we show that the tapers fabricated using two-step etching process satisfied the conditions of being an adiabatic tapered fiber. In addition we demonstrate and analyze the reproducibility of our proposed fabrication method.

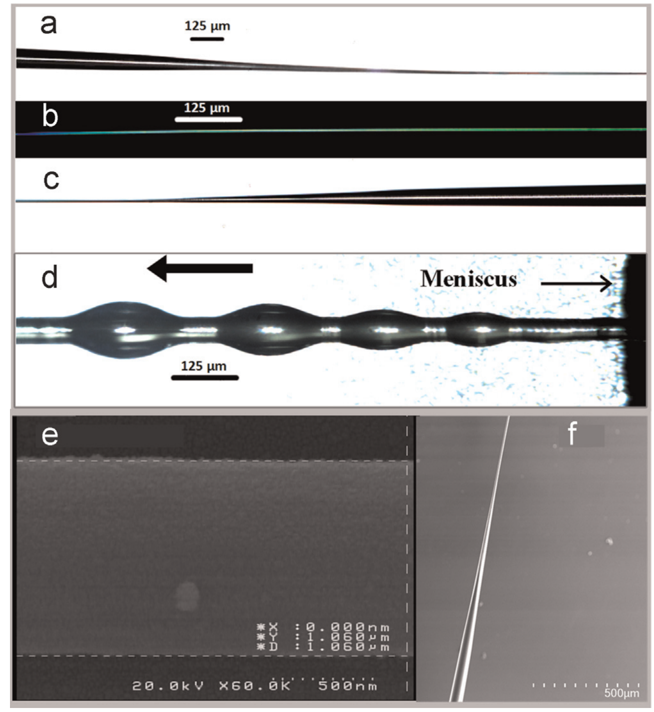

Fig. 2. An optical micrograph of (a–c) transition and waist regions of the fabricated taper with 1.6 µm diameter. (d) Acid microdroplets move along the fiber in arrow direction. SEM image of (e) the smooth surface of fabricated taper using two step etching with 1 µm diameter and (f) graded diameter profile of transition region.

3.1. Tapered fiber profile

The formation of smooth profile of the transition regions is demonstrated in Fig. 2(a), (c), and (f). In the first step, when the acid droplet is placed on the fiber, it stretches along the fiber. In the film of acid that covers the fiber, the evaporation rate of HF is higher than water. Hence, as the film reaches farther positions on the fiber, the concentration of the acid (C) becomes lower and lower, i.e. a gradient of concentrations ($dC/dx < 0$) is created. Since the surface tension of water is higher than HF, higher acid concentrations correspond to lower surface tensions, γ. Thus, a gradient in the surface tension is created along the fiber ($d\gamma/dx > 0$) which causes the further regions of the film have higher surface tensions. Therefore, a flow of acid microdroplets is formed along the fiber, in other words, the acid with lower surface tension moves toward higher surface tension (Fig. 2(d)). This phenomenon is known as *Marangoni flow* [22,25]. The flow of acid from higher to lower concentration along the fiber results in a graded diameter profile formation and elongates the transition regions. Also this process removes surface corrugations so provides a smooth surface [22]. Although in the second step, BHF droplets do not flow along the fiber, the transition region shape remains suitable to transmit light adiabatically. In addition, using BHF etching in second step preserves the surface smoothness (Fig. 2(e)).

Fig. 2(b) shows waist region of a taper with 1.6 µm diameter which appears as blue-green. From interference relation $2nD = m\lambda$ where n is the refractive index of the fiber, D diameter, λ wavelength of visible light and m is an integer number, for a white light incidence on a taper, rainbow colors are observed because of constructive interference for various wavelengths as the thickness varies. In other words, the repetition of the colors shows gradual reduction of the fiber diameter. So, the color of taper region is because of interference effects and cannot provided a means to estimate waist diameter as suggested by [22,24].