Current Applied Physics 19 (2019) 1334–1337

Contents lists available at ScienceDirect

Current Applied Physics

journal homepage: www.elsevier.com/locate/cap

Fabrication method for ultra-long optical micro/nano-fibers

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ARTICLE INFO

Keywords:
Micro/nano-fiber
Tapered fiber
Flame-brushing and pulling method
Nonlinear optical effects

ABSTRACT

Nonlinear optical interactions can be enhanced dramatically by tight light-confinement and long interaction-length. Optical fiber tapers with micro/nano-thickness waists considerably increase light-matter interactions in or near their waists. Here, we propose and demonstrate a novel tapering method of fabricating uniform, low-loss, and ultra-long micro/nano fibers. The technique comprises three steps for conventional flame-brushing and pulling, recalibration, and one-directional pulling. Using the proposed method, two strands of tapered fibers are fabricated, having 0.82-μm/1.6-μm diameters, 220-mm/500-mm uniform lengths with < 55-nm/66-nm diameter variances, and high transmittances of 90.2%/91.5%. A figure of merit indicating the nonlinear-optic efficiency is defined and used to compare the results obtained in this study with those for tapered fibers in references. The proposed tapering method will be very useful for the fabrication of tapered fiber devices exploiting nonlinear optic effects, including Brillouin scattering, Raman amplification, and other third-order nonlinearities for supercontinuum generation.

1. Introduction

Optical micro/nano-fibers (MNFs) offer the advantages of tight optical confinement and long interaction lengths, leading to strong evanescent fields for light-matter interaction, excellent coupling efficiencies with disk resonators, high flexibilities, and enhanced nonlinearities [1]. Photonic crystal fibers (PCFs) and tapered optical fibers can be listed as two examples of fibers with micro-diameter cores where strong nonlinear optic interactions occur [2]. However, PCFs are costly and their optical properties are very sensitive to the non-uniform variations of their inner structures along the fiber length, resulting in non-uniform optical coupling strengths in the given fiber lengths. In MNFs tapered from commercialized fibers, their sizes are readily controllable by varying the tapering conditions for heating and pulling [3–5]. The structure of MNF consists of input/output regular single-mode fiber sections, conically tapered sections, and a fine micro/nano-wire filament. During the fabrication process of an MNF by using the heat-and-pull method, the flame (a heat source) is moved along the length of the fiber several times, which is gradually increased via the application of a force at the ends. This causes a progressive decrease of the fiber diameter. The length of the uniform section depends on the target diameter, and a tapered fiber with a small diameter, in general, has a short uniform section and vice versa. Therefore, it is challenging to fabricate a long and fine optical micro/nanofiber with high uniformity as well as low insertion loss.

In this study, we developed a novel technique to fabricate long and uniform tapered optical MNFs. An MNF with the desired diameter is formed using the "flame-brushing and pulling" technique followed by an extra one-way pulling to elongate the MNF to the desired length. The demonstrated two A/B fibers in this study have 0.82-μm/1.6-μm diameters with 55-nm/66-nm tolerances, 220-mm/500-mm lengths, and 90.2%/91.5% transmittances. The length could be increased further if a longer pulling stage is used and the pulling speed is optimized. This new technique can facilitate the production of long and uniform MNFs with high transmittance, which is useful for numerous applications including signal processing by using nonlinear effects and light-matter interaction.

2. Fabrication methods

The desirable properties of MNF devices for strong nonlinear optic effects or evanescent coupling include a small cross-sectional area, uniform diameter, long MNF waist, and high transmittance. To fulfill these requirements, we propose a one-directional fiber-tapering technique as illustrated in Fig. 1. The method in this study mimics a typical fiber drawing process where a preform is melted and pulled to fabricate a long fiber filament. The proposed one-directional fiber-tapering method consists of three steps. The first step is the flame-brushing and pulling process. A short length fiber is slowly pulled in both directions while flame is moved back and forth along the fiber, as shown in

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https://doi.org/10.1016/j.cap.2019.08.018
Received 14 June 2019; Received in revised form 16 August 2019; Accepted 20 August 2019
Available online 21 August 2019
1567-1739/

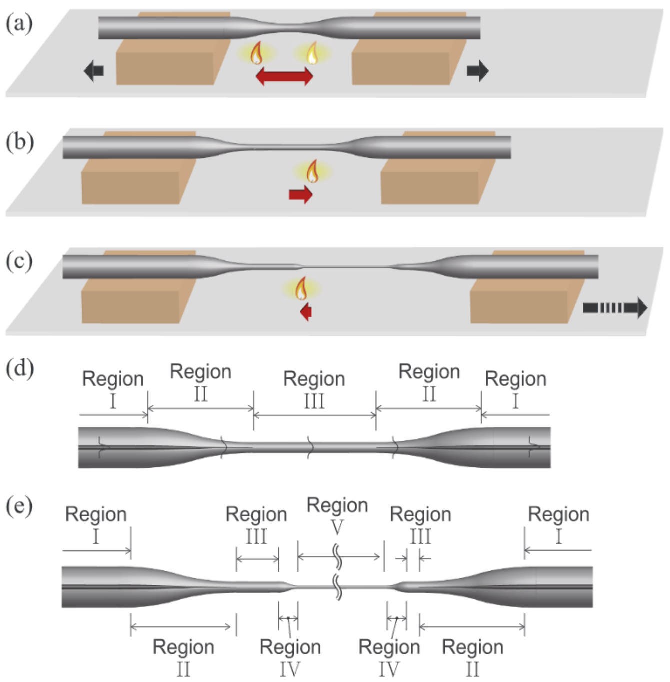

Fig. 1. The three steps of the micro/nano-fiber fabrication technique proposed in this work and schematic diagrams of a tapered fiber. (a) the first step is to create the pre-uniform section with adiabatic regions, (b) the second step involves a recalibration, and (c) the third step of the one-directional pulling approach. The black and red arrows indicate the direction of movement of the stages and flame, respectively. Schematic diagrams of the tapered fiber after (d) the first step and (e) the third step. Region I: the single-mode region with 125 μm /8.2 μm cladding/core diameter, Region II: the adiabatic region, Region III: the pre-uniform region, Region IV: the secondary adiabatic region of the third step, and Region V: the micro/nano-sized diameter region. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Fig. 1(a). During this first step, the size of the fiber core and cladding gradually decrease, yielding a adiabatic change of fiber diameter for high transmission [as seen in Fig. 1(d)]. In the adiabatic region, the incident LP01 (single) mode light leaks out to the cladding region, thereby, supporting higher-order modes. The power transfer between the LP01 mode and one of the higher-order modes repeats with every modal beat length along the fiber, and transmission loss can be minimized if both the length and surface gradient of the adiabatic region are carefully chosen [6]. Fig. 1(d) illustrates a schematic of the fiber after completion of the first step. Region I, II, and III are the single-mode, adiabatic, and pre-uniform regions, respectively.

The second step is referred to as the recalibration process of the tapering method. The position of the flame is relocated to the end of the pre-uniform section that is closer to the right-side translation state as shown in Fig. 1(b). The third step involves flame-brushing and the one-directional pulling process that is designed to create a long and uniform micro/nano diameter fiber. The fiber strand is pulled only in one direction (right-hand side in Fig. 1(c)), while the flame is slowly translated in the opposite direction (left-hand side in Fig. 1(c)). The fiber material in the pre-uniform region is melted and pulled to fabricate a long micro/nano diameter fiber. The black and red arrows represent the direction of movement of the stages and flame, respectively. Fig. 1(e) illustrates a schematic of a micro/nanofiber consisting of (I) a single-mode region, (II) an adiabatic region, (III) a pre-uniform region, (IV) a secondary adiabatic region, and (V) the MNF region. The volume of fiber material in the pre-uniform region determines the length of the MNF region, but practically, the travel range of the translation stage limits the length of MNF. The secondary adiabatic regions should slowly vary for high transmission, and the transmittance after the first step does not change during the second and third steps.

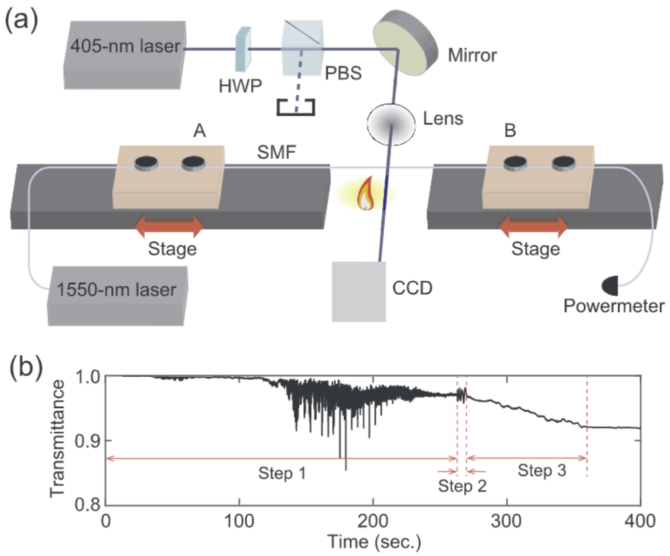

Fig. 2. Experimental setup used for the fabrication of the tapered micro/nanofibers and the measurement of the MNF diameter. SMF (single-mode fiber), HWP (half-wave plate), PBS (polarization beam splitter). (b) The transmittance during the tapering process against time. The times for each step are indicated by red arrows. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

3. Experiment and discussion

Fig. 2(a) illustrates a schematic diagram of the tapering system used for the experiments. The system consists of a fiber-tapering setup as well as fiber-diameter-measurement setup. The homemade fiber-tapering setup comprises a stationary hydrogen-oxygen flame torch and two computer-controlled translation stages, and the whole tapering process is controlled by a Labview code. A strand of a typical single-mode fiber (SMF-28, Corning) is initially mounted and clamped at the two points identified as A and B on each translation stage. The flame torch is located between A and B and its position is fixed during the fabrication process. Instead of moving flame, the two translation stages move back and forth in the same direction with slightly different speeds [7]. The parameters determining the fiber dimension are the gas flow, nozzle size, flame speed, fiber pulling speed, total iteration, and moving time. The gas flows under our experimental conditions are 320 [standard cubic centimeter per minutes: sccm] for Oxygen gas and 160 [sccm] for Hydrogen gas. The flame nozzle diameter was 1 mm for demonstration 1 and 1.5 mm for demonstration 2. The flame speed is the speed of the rear (slower) stage, and the pulling speed is the difference between the speed of the front and rear stages. The parameters used in the experimental demonstrations are summarized in Table 1.

To measure the diameter of an MNF, we employed the forward scattering method with a 405-nm-laser diode ($P = 40$ mW) as a coherent light source [8] as shown in Fig. 2(a). A circular beam from a fiber-pigtailed laser diode is collimated and then passes through a series of half-wave plates and a polarization beam splitter to set a horizontally polarized beam with a polarization that is parallel to the longitudinal axis direction of the fiber. The beam, which is focused by an objective lens, is irradiated onto the fiber, forming a diffraction pattern on the screen behind the fiber. The spot size of the beam at the surface of the fiber is $\sim$250 μm in diameter. An image sensor to extract the diameter values captures the intensity profile on the screen [8]. The measured results obtained by the forward scattering method are in excellent agreement with that obtained using a scanning electron microscope and the difference between the two results was less than 10 nm.

The first step is the flame brushing and pulling process to create the pre-uniform section. Under our experimental conditions, the minimum width of the diameter of the pre-uniform region is approximately 10 μm, which was heuristically determined, and the measured length of the pre-

Table 1
The parameters used in the experimental demonstrations.

Demo. #	Step	Flame speed (mm/s)	Fiber pulling speed (mm/s)	Total iteration	Moving time per iteration (sec.)
1	Step1	4.7	0.016	52	4.5
	Step2	5	0.019	1	7
	Step3	0.01	2.35	1	90
2	Step1	4.7	0.016	52	4.5
	Step2	4.7	0.016	1	8.5
	Step3	0.03	2.3	1	220

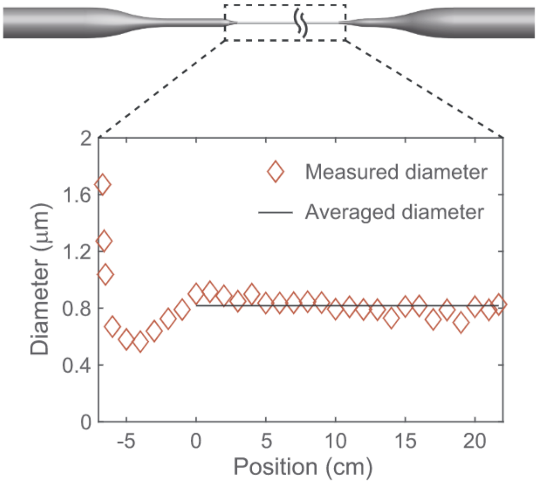

Fig. 3. The diameter of a tapered MNF as a function of position. The red diamonds represent the measured diameter along the tapered fiber and the black horizontal line indicates an averaged value of 0.82 μm over the 22 points (217 mm) on the flat MNF region. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

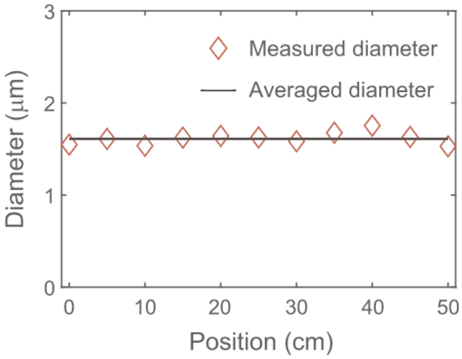

Fig. 4. The diameter of the 50-cm-long micro-fiber measured at fixed intervals.

Table 2
The previously reported results of MNF fabrication and the figure of merit for the efficiency of the nonlinear effects in the tapered fibers.

Method	L [mm]	D [μm]	T [%]	$\rho\ [\frac{mm}{\mu m^2}]$	Ref. #
Flame brush	5	43	–	–	[7]
Ceramic heater	300	112.5	–	–	[10]
Flame brush	4	0.26	20.9	27.1	[11]
Flame brush	90	2	95.5	22.0	[12]
Stabilized Flame	20	0.32	99.7	186	[13]
Flame brush	1	0.8	99.7	1.6	[14]
Flame brush	100	1.2	97.7	68.6	[15]
Flame brush	150	0.9	75	160	[16]
Flame brush	300	1.3	97	176	[17]
Flame brush	250	1	97	242	[18]
Flame brush	120	0.61	50	228	[19]
Flame brush	217	0.82	91.5	324	Current work
Flame brush	500	1.6	90.2	185	Current work

uniform section is 1 cm. The tapering conditions for the minimum loss can be found experimentally by monitoring the transmission of the fiber during the whole tapering process. The transmittance of the tapered fiber is monitored as seen in Fig. 2(b) using a continuous wave light source (Santec, TSL-550, P = 20 mW, λ = 1550 nm) and InGaAs power sensor (Thorlabs, S154C). The transmitted power during step 1 fluctuates due to the modal beating and becomes stable after 250 s, indicating no modal beating and slow diameter variance [6]. The transmittance after the first step is approximately 97% and can be improved by optimizing the flame speed, fiber pulling speed, total iteration, and moving time. The transmittance during step 2 wavers due to the strong vibration of the fiber, but this vibration causes no transmitted power drop after completing step 2. The one-directional pulling process induces the changes of the fiber diameter (Region IV in Fig. 1(e)), but the transmitted power drops neither at the beginning nor end of step 3 in Fig. 2(b). This proves that the adiabatic change condition is alleviated when the fiber thickness is about several μm. The transmittance decreases slowly and linearly during step 3 due to the scattering loss of the evanescent wave [9]. When the whole process is completed, the power stays constant, as shown in Fig. 2(b).

Fig. 3 shows the profile of the fiber diameter measured at every 2-cm point along the length of the fiber by the forward scattering method. The data in Fig. 3 includes the uniform micro-diameter region as well as parts of the secondary adiabatic region. From the data points obtained from the secondary adiabatic region, the measured surface gradient of this region was 4.4 mrad. The average value of the measured diameters over the 22 points on the uniformly tapered waist was 0.82 μm with a standard deviation of 55 nm (~λ/28 in telecom C-band). The entire length of the uniform-width section is about 217 mm, and the measured transmission including the pigtail connector loss is 91.5%. Note that the measured diameters from −5 to 0 cm increase rapidly. The position from −5 to 0 cm represents the region where unintentional pulling occurs during the elimination of the flame after the whole fabrication process, indicating that immediate turn-off of the flame is necessary at the end of step 3.

Note that the length of the micro-fiber that can be fabricated by the one-directional fiber-tapering technique is practically limited by the travel range of the translation stage in Fig. 2(a). Because the available travel range of the stage in the third step is 50 cm, up to 50-cm-long MNF can be fabricated. Fig. 4 shows the fiber diameter profiles that were measured at 5-cm intervals along the length, and the average value of the measured diameters over 11 points in the uniform tapered waist is 1.6 μm with a standard deviation of 66 nm. The speeds of the pulling stage and flame movement for step 3 are 2.3 mm/s and 0.03 mm/s, respectively. In this case, the length of the uniform micro-width region is 50 cm. The measured transmission including the pigtail connector loss is 90.2%.

Given that the advantage of fabricating MNFs is the enhancement of nonlinear effects, a figure of merit to characterize the efficiency of nonlinear effects in tapered fibers is defined as $\rho \equiv L\sqrt{T}/d^2$, where L, T, and d denote the tapered length of the uniform-width section, total transmittance, and diameter of the MNF region, respectively. Longer and finer micro-fibers with lower loss will have larger ρ values. Assuming that the loss occurs only in the adiabatic regions, the inner power of the MNFs is proportional to $\sqrt{T}$, which represents the transmittance after the input adiabatic region. Even if the effective mode area differs from d^2 for sub-wavelength diameter fibers, it is a good approximation to treat d^2 as the mode area for the comparison of different MNF cases. The figure of merits of the recently reported results including that in this work are summarized in Table 2. The values of ρ in the current work are the best results, demonstrating the superiority of the proposed tapering method for the fabrication of ultra-long micro/nanofibers and for potential applications involving nonlinear optical effects, including strong four wave mixing, super-continuum generation, Brillouin scattering, Raman scattering, and mode-locked fiber lasers.

4. Conclusion

We propose the one-directional fiber-tapering method, a novel way to fabricate ultra-long, uniform, low-loss, and micro/nano-sized fibers. The demonstrated fiber with 217-mm long and 0.82- μm thick shows the highest potential among the reported optical fibers to date to enhance nonlinear effects in the fiber. With optimized pulling speed conditions and longer pulling stages, the tapering length could be even larger. In the future, we will explore the optimized conditions for higher transmittance, smaller and uniform diameter, and long waist length and prove that our one-directional fiber-tapering method will improve various nonlinear effects for potential applications in the fields of nonlinear optics as well as quantum optics.

Acknowledgement

This work was supported in part by National Research Foundation of Korea (NRF) grants funded by the Korean Government (No. NRF-2016R1A4A1008978, NRF-2017R1C1B2011113, and 2019R1F1A10-63937).

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