Fabrication of submicron-diameter silica fibers using electric strip heater

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Abstract: In nonlinear optical frequency conversion process, it is desirable to maximize the product of the intensity of pump laser and the interaction length in order to achieve maximum conversion efficiency. In this paper, long and unbroken submicron-diameter optical fibers with low optical loss about 0.1dB/cm were fabricated with a new drawing process by heating the conventional single mode fiber using a designed electric strip heater. Pumped by a 532 nm mode-locked pico-second laser, enhanced SRS phenomena can be observed in the submicron-diameter fibers with relative low pump power.

OCIS codes: (060.2280) Fiber design and fabrication; (190.5650) Raman effect; (060.2280) Electric strip heater

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1. Introduction

Nowadays, the 1.5μm wavelength band is generally used in optical communications because it lies in the low-loss window of the fiber [1]. In a conventional single mode optical fiber, the diameter of the fiber core is usually about 8μm, much longer than the optical wavelength. To observe some nonlinear optical effect in the conventional fiber, such as stimulated Raman scattering (SRS), stimulated Brillion scattering (SBS) and four wavelength mixing (FWM), high intensity of beam or very long interactive length is necessary due to the relative large effective area. Especially, SRS is an important nonlinear process in fiber optics, which had contributed to the fabrication of the broadband Raman amplifier and the tunable Raman laser [2,3]. Usually, in order to realize SRS or Raman amplification in the conventional single mode fiber, one must use high input optical power and several kilometers fiber. In past several years, in order to enhance nonlinear coefficient of fiber, the photonic crystal fibers has been fabricated [4] and was employed to generate super-continuum light [5] or as a dispersion compensator [6]. Unfortunately, photonic crystal fibers are rather expensive due to fabrication complexity.

If we can draw the conventional single mode fiber to submicron-diameter dimension and hold the surface uniformity simultaneously, the optical energy will be mainly concentrated in the entire thin fiber, and thus the optical power density is much larger than that in the conventional single mode fiber core and the demand of the pump power and length for nonlinear optics effect will be lower.

The length of submicron-diameter optical fiber in which nonlinear optical frequency generation has been studied is less than 10 cm [5,7,8]. Nonlinear optical frequency generation in longer submicron fibers has not been investigated probably because of the difficulty to draw fibers with long and narrow tapered waist and to couple light into the tapered fiber.

In this paper, we report the fabrication of longer and unbroken submicron-diameter optical fibers by heating the conventional single mode fiber with a designed electric strip heater. We succeed in fabricating a longer freestanding fiber with diameter down to 650 nanometers and optical loss less than 0.1dB/cm. In our experiment, light can be launched into the thin fiber easily by coupling through an objective lens owing to the taper transitions' connecting to the untapered fibers shown in Fig. 1. Pumped by a pico-second laser, enhanced SRS phenomena appeared in these fibers. By comparing it with the conventional single mode fibers with the same length, we believe that the submicron-diameter optical fiber has evident advantage in nonlinear optical frequency generation.

Fig. 1. A schematic diagram of a resulting tapered fiber, depicting a narrow taper waist connected to untapered fibers by rather long taper transitions.

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2. Fabrication of submicron-diameter tapered fibers

More and more applications require taper fibers with micron-scale diameter and several groups attempt to fabricate submicron-diameter wires reported in references [9-15]. So far, almost all the drawing methods are based on a flame-heated melt or a laser-heated melt, but their corresponding disadvantages are the turbulence and the convection of the flame and impractically large laser power requirement to produce nanometer-diameter wires [9].

Recently the fabrication of submicron-diameter silica wires was reported by Tong *et al.* [10] who used a two-step drawing process to get the fabricated samples with diameters down to 50nm and low optical loss. These desirable results aroused renewed interest in the field and ensured that various-diameter nano-tapers could certainly satisfy the transmission loss of tolerable levels for many practical device applications. However, the fact that samples drawn in this way are very short (only tens of millimeters) and have no untapered fiber connection makes it difficult to launch light into them and impractical to be used as optical waveguides and sensors. Furthermore, the evanescent coupling makes some loss of the power.

In order to overcome the shortcomings of the method introduced by Tong *et al.*, we introduce a new drawing method using a specially designed electric stripe heater (certainly, the method of Ref. [8] is also a alternative). As shown in Fig. 2, with one side fixed at the edge of a stationary table, the pulled fiber is placed in an electric strip heater, and the other side of the fiber is fixed at the edge of the revolving table driven by a stepper motor connected with a computer, which could offer elaborate control in the fiber pulling process. Configuration of the electric strip heater is shown in Fig. 3. The pulled fiber passes above the heating cord with length of 15 cm, and the distance between them is about 0.5cm. Long heating region with relatively small volume in the furnace exhibits excellent heat preservation and steady temperature distribution during the drawing. By properly altering the supplied voltage the temperature of the electric furnace can be carefully controlled to achieve more stable taper diameter requirement. The temperature is carefully adjusted by applied voltage from 200-250V. When the voltage reaches 250V, the temperature in the cavity is about 1600℃ measured by a optical high temperature thermometer.

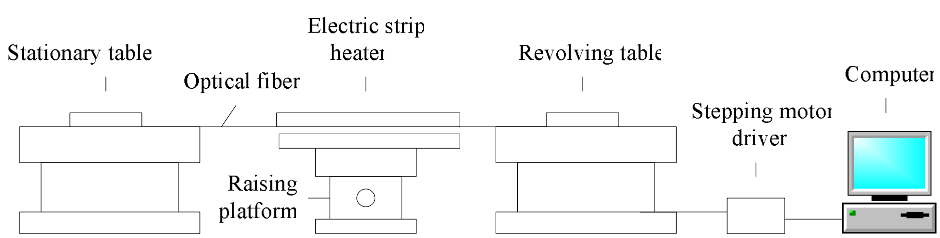

Fig. 2. A novel experiment setup for fabricating submicron-diameter tapered fibers

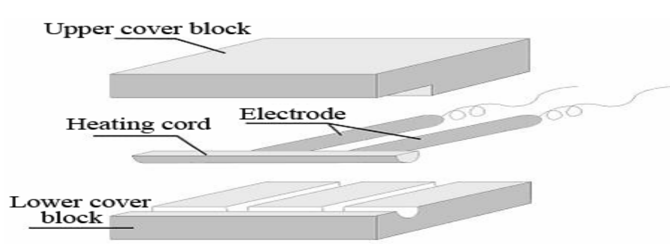

Fig. 3. Configuration of the electric strip heater

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As a result of uniform drawing speed the measurement result shows that taper transitions at both sides of the taper waist are gradual. The typical length of biconical taper transitions fabricated by the electric strip heater is of the order of tens of centimeters, and the gradual transitions ensure little optical loss suffered along the fiber. Using this drawing method, we obtain a tapered fiber with diameter down to 900nm (Fig. 4, measured by scanning electronic microscope, SEM) with length up to several hundred millimeters, which is longer than nanowires drawn in the other ways. Uniformity of the tapered fiber is examined by measuring the diameters at different points of the fiber. It is shown that the diameters have $\pm 5\text{nm}$ error along the 12cm in the center of the tapered fiber. Loss is measured by simply recording transmission before and after tapering. At least 1m of coated fiber is left on the collection arm, which avoids any forward scattering from the taper launch and make it easy to launch light into the fiber connected to a detector. The results show that the optical loss of the taper fibers we got is less than 0.1 dB /cm at 532 nm.

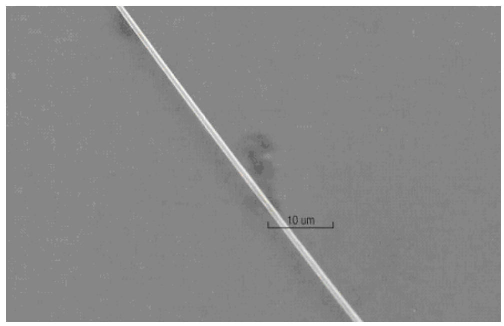

Fig. 4. SEM image of taper waist with a nominal diameter of 900 nm.

It is necessary to be discussed here that how the modes in these taper fibers as shown in Fig. 1 look. In the front untapered region, the diameter of the fiber core is about 8μm, almost all of optical power is confined in the core layer. When the fiber becomes thinner and thinner. the power of the guided-mode decreases, and in the mean time the cladding mode gets more and more. When the diameter of the fiber reaches to about 1μm, the core diameter is about as small as 60nm. In this case, the power of the light almost entirely propagates in the cladding layer. So the taper waist part of the fiber can be regarded as a new air-clad wire-waveguide with submicron-diameter core. The detailed information of the mode in such kind of fiber is given in reference [16].

3. SRS generation in submicron-diameter tapered fibers

SRS generation requires high power intensity that can be obtained by decreasing the fiber diameter. However, as the size of fiber core decreases, the amount of power in the evanescent field will increase and eventually exceed the power in the core, which leads to lower peak intensity in the nonlinear core region although the core size is reduced [17]. Recently the balance between core size and power confinement was investigated with the aim of maximizing nonlinear interactions in high core-cladding index difference waveguide. It shows that the optimal core size is sub-wavelength and that structures with asymmetric cross-sections maximize the effective nonlinearity [17]. Also low dispersion is the key to efficient SRS, because optimum dispersion can release the need for high intensity [8]. From the reference we find zero dispersion wavelength for diameters of ~900 nm that is 532 nm. In our experiment, the whole fiber length is about 1m with a tapered region of 12cm in length. The 532 nm light from a mode-lock pico-second pulse laser is coupled into the fiber by an objective lens with attenuator. The pulse width is 50ps with repetition rate of 10 Hz. Nonlinear

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optics spectrum from the fiber is measured by an optical spectrum analyzer (OSA).

In order to investigate the enhanced nonlinear effect, such as SRS, in the tapered fiber, a conventional untapered fiber with the same length (1m) is used as a reference. A laser beam with average power of 1.5 μW is launched into the untapered and tapered fibers by lens coupling. Some nonlinear optical effect such as SRS, four-wave mixing (FWM) will occur due to relatively high peak intensity in the fibers. In the experiment, the spectrums are recorded using an OSA by choosing the average result based on scanning 10 times, and distinct generated lines can be observed. If the scanning times are high enough, the spectrum recorded by the OSA will be a continuum. On the contrary, with the low scanning times some spectrum lines may be lost because the repetition rate of the pump laser is only 10 Hz. The results are shown in Fig. 5. Figure 5(a) shows the output spectrum from the untapered fiber. Besides pump lines, other two obvious lines with wavelength of 525nm and 538nm are observed. We believe that these two lines are generated through FWM process ($\omega_p + \omega_p \rightarrow \omega_s + \omega_a$) by phase-matching between guided-modes in fiber, where ω_p, ω_s and ω_a are pump, stokes and anti-stokes lines. We don't find the obvious SRS lines because the peak pump power is not high enough to exceed the threshold for SRS generation in the untapered fiber. When the same pump power is coupled into the tapered fiber, more generated spectrum lines are observed as shown in Fig. 5(b). 525nm and 538nm lines are produced by FWM process that is the same as shown in Fig. 5(a). In the front untapered region of the tapered fiber, FWM process has already occurred. Incorporated with pump lines (532nm), three beam of lines enter the tapered regions (900nm in diameter and 12cm in length), SRS happens owing to the high pump intensity and the low SRS threshold in the narrow region. As indicated in the Fig. 5(b), 545nm and 577nm are the first and third order stokes lines of 532nm lines while 518nm is first order anti-stokes line. In an additional, 551nm and 564nm are the first and second order stokes lines of 538nm; 564nm is also the third order stokes lines of 518nm line. We don't find the second order SRS stokes lines of 532nm possibly because scanning times of the OSA for optical communication is just ten times. Some spectrum lines may be omitted due to certain scanning periodicity of the OSA and low repetition rate of the pump laser. In order to grasp all the possible spectrum lines, we choose the average result of scanning 500 times, and SRS is observed. The generated supercontinuum spectrum is shown in Fig.5(c). Compared with nonlinear optics spectrum in untapered fiber, more generated lines are achieved in the tapered fiber. It is concluded that the tapered fiber with submicron-diameter has enhanced nonlinear optical effect and may have potential applications in laser frequency conversion and generation, for example, developing extremely low-power integrated broadband SRS amplifier or the tunable Raman laser for currently used fiber-optic communication system.

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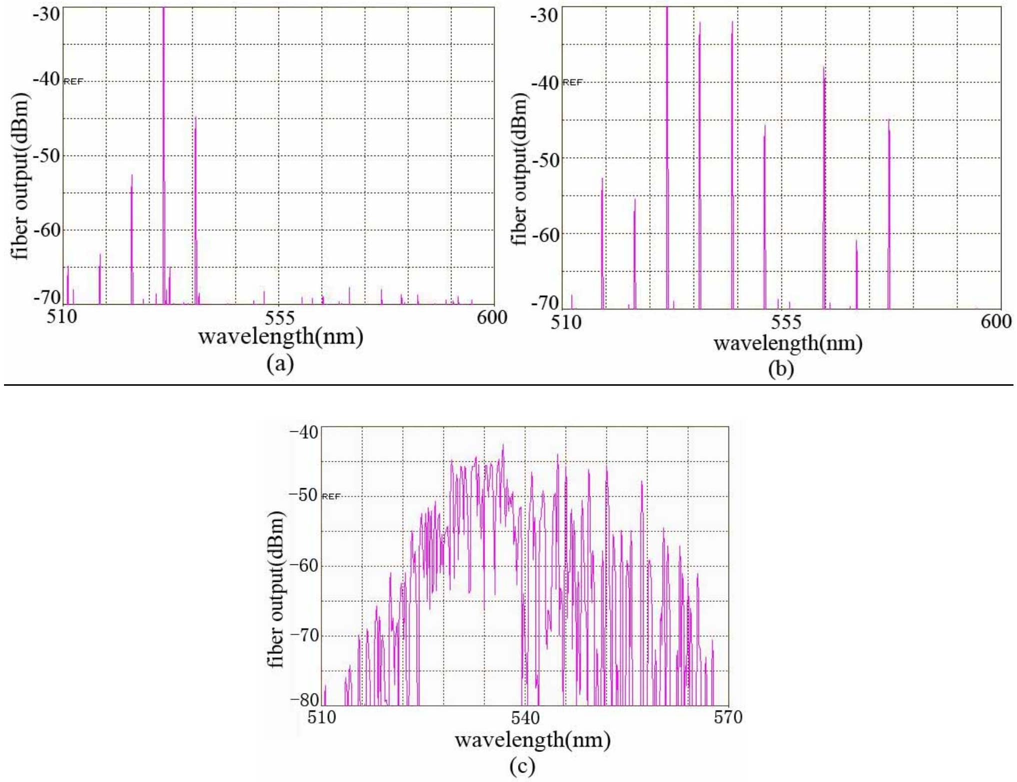

Fig. 5. (a) Spectrum generated by a conventional fiber for diameter, length and average laser power of 125µm, 1m and ~1.5µw. (b) Spectrum generated by taper waists for diameter, length and average laser power of 900 nm, 12cm and ~1.5µw. The whole fiber length is about 1m. (c) Spectrum generated by tapered fiber under the average of 500 scanning times. The parameters of fiber are the same as shown in (b).

4. Conclusion

In conclusion, we have reported a new fabrication method of what as for as we are aware is the longest submicron taper fiber ever produced for the investigation of nonlinear optical frequency generation. The long, submicron-diameter taper fiber has been fabricated in a simple furnace cavity using a new ‘clean and stable’ electric heater. The small area of the taper fiber core makes those taper fibers have larger power density and nonlinear coefficient, and the long length of the taper fibers increase the relative interaction length. Pumped by a pulsed laser, we find enhanced SRS generation in such long air-silica fiber of submicron diameter in comparison with the untapered fiber with the same length. We believe these taper fibers produced by this way should pave the way for the integration of the photonic devices for various application areas including sensors, lasers, biology and chemistry.

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