On-demand tapered optical fiber

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ABSTRACT

Tapering optical fibers to create nanofibers with submicron diameters enables strong light confinement and enhances nonlinear effects. However, a key challenge in this process is maintaining guided optical modes and minimizing optical losses. Losses primarily arise from mode leakage in the transition regions connecting the standard fiber to the nanofiber. The geometry of these transitions is crucial for ensuring adiabatic mode evolution and achieving low-loss transmission. Current tapering techniques offer limited flexibility in shaping these transitions, restricting optimization. This work introduces a novel approach to fiber tapering using a classical fusion-heat-brush process. This method allows for precise control over the transition shape, enabling fabrication of nanofibers with transitions defined by any decreasing function. By offering enhanced design flexibility, this technique expands the potential applications of optical nanofibers in nonlinear optics and signal processing.

Keywords: Tapered optical fiber, fiber post processing, optical fiber technology

1. INTRODUCTION

Optical nanofibers are sub-wavelength waveguides that offer strong optical confinement, thereby enhancing nonlinear effects. The fabrication of these waveguides, through the tapering of standard optical fibers, has been the subject of numerous studies using different tapering methods.[1–3] The phenomenon of optical losses is a critical aspect to be considered when applying a nonlinear effect.[4] It has been observed that there is a direct correlation between these losses and the leakage of optical modes into higher-order modes, which occurs within regions known as "transition". These regions serve as the interface between the standard optical fiber and the thinned area.[5,6] It has been demonstrated that achieving high optical transmission with nanofibers measuring 1 mm in length is possible, as outlined in the recent work published by Horikawa.[7] In this study, a classical heat-brush technique is employed, in conjunction with a novel algorithm to control diameter reduction. This methodology facilitates precise supervision of the transition shapes using any numerically defined decreasing function. This method offers the possibility to create very long nanofiber lengths with a short transition part. The enhanced flexibility of these nanofibers paves the way for novel applications, including signal processing[8] and nonlinear interactions that necessitate extended interaction lengths.[5,9]

2. ARBITRARY SHAPED TRANSITIONS

Nanofibers are fabricated using a flame-fixed scanning stretching method, where an optical fiber (SMF-28) is positioned between two translation stages and heated by a flame.[10] Then, the cyclic movements of the stages elongate the heated fiber. Traditionally, this method uses a three-phase stage control protocol, which allows the design of adiabatic transitions for the fundamental optical mode. The typical total losses of the nanofibers are around 0,2 dB at a wavelength of 1550 nm.[5] The tapering of an optical fiber is governed by conservation laws[2] related to the stretched length and volume. Length conservation is ensured by the increasing distance between the two translation stages along the fabrication process. Regarding volume conservation, in the three-phase process, a reduction factor is defined for each exponential function. This factor determines the gradual decrease of the function and, consequently, the fiber's diameter. Adhering to these conservation laws is crucial for obtaining high-transmission waveguides.

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The new method involves calculating the reduction factor based on a user-defined transition profile. This approach eliminates the need for predefined functions. The profile is then divided into cycles, each corresponding to a round trip of the translation stages. Between two cycles, the reduction factor ensuring volume conservation is calculated, and the trajectories of the stages are determined.

Figure 1 shows a target theoretical transition profile for a nanofiber, plotted using Bézier polynomial curves in black dots. The transition profile corresponds to a diameter reduction from 125 μm to 30 μm over a length of 20 mm. The red markers correspond to diameter measurements taken along the transition of a nanofiber fabricated using this profile, obtained with an optical microscope. The tapering of standard optical fibers to diameters of approximately several tens of micrometers is of relevance to biological applications. In fact, reducing the diameter of a standard optical fiber by a factor of 2 or 3 enables the creation of fan-out input/output (FIFO) devices for biomedical applications.[11]

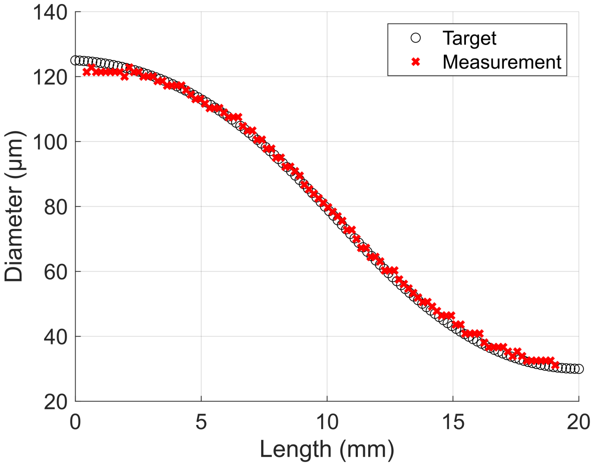

Figure 1. Transition profile in a 30 µm diameter nanofiber. The theoretical target profile is indicated by black circles, and the microscope measurements by red crosses.

We obtain a very good agreement between theoretical predictions and experimental measurements, thereby validating the efficacy of the stretching process. However, it should be noted that the measurements carried out do not cover the entire transition, creating uncertainty.

3. ULTRA LONG NANOFIBER

The flexibility provided by this new method for defining transition profiles allows for a reduction in transition lengths compared to the previous procedure. Consequently, the waist length of the nanofibers can be increased, given that the total elongation length is constrained by the maximum displacement of the translation stages. Figure 2(a) shows the designed transition profile for a diameter reduction from 125 µm down to 750 nm for a length of 35 mm. The profile was drawn using Bézier polynomial curves. Figure 2(b) shows a distributed measurement of Rayleigh backscattering obtained with a commercial optical backscatter reflectometer (OBR4600, Luna).

The indicated length is relative, as it depends on the effective index considered. In the region of diameter reduction (0,7-0,1 m), the scattering amplitude gradually increases from -110 dB/mm to a level close to -65 dB/mm. Conversely, as the diameter increases (0,27-0,3 m zone), the scattering amplitude returns to the initial plateau (-110 dB/mm). The nanofiber waist is characterized by a plateau where the scattering amplitude remains constant. This measurement gives us an estimation of the waveguide waist length (up to 15 cm). However, it should be noted that the plate is not perfectly planar, which may reflect variations in diameter uniformity.

4. PERSPECTIVES AND CONCLUSION

In conclusion, we have demonstrated the ability to fabricate optical nanofibers with precise control over the tapering process, ensuring accurate diameter reduction. The enhanced flexibility in transition profile design

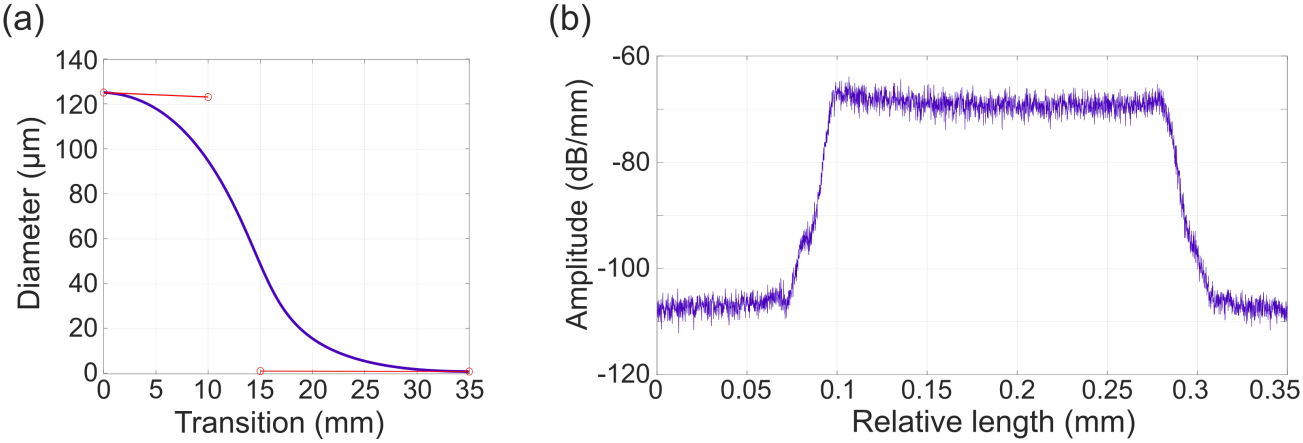

Figure 2. **15 cm waist nanofiber with a diameter of 750 nm.** (a) Theoretical transition profile. (b) Rayleigh reflectometry trace of the fabricated nanofiber.

enables the tailored fabrication of nanofibers for specific applications.[5] Notably, this approach allows for the development of waveguides with extended waist lengths, which are particularly advantageous for nonlinear optics applications. Furthermore, by carefully monitoring the adiabaticity criteria of mode transitions, this technique facilitates the realization of multimode nanofibers or modal filtering structures, broadening the scope of potential applications in optical signal processing and advanced photonic systems.

ACKNOWLEDGMENTS

This work has received funding from the European Union's Horizon Europe research and innovation program under grant agreement uCAIR (101135175), EQUIPEX+ SMARTLIGHT platform (ANR-21-ESRE-0040), EIPHI Graduate School (ANR-17-EURE-0002).

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