Optical nanofibers: technology and transmission properties

Alexander Hartung, Hartmut Bartelt
Institute of Photonic Technology, Jena
mailto:alexander.hartung@ipht-jena.de

Optical nanofibers can be prepared by remelting and redrawing of existing light guiding fibers down to much small diameters than common 125µm standard fibers. We introduce our fabrication process by means of indirect laser heating. In addition the transmission phenomena during the tapering process to a diameter well below 1µm are discussed.

1 Introduction

The most common way working with optical nanofibers is to use a submicron diameter waist of an optical fiber taper as a nanofiber (Fig. 1). Though several setups for producing optical nanofibers out of existing optical light guiding fibers have been proposed and implemented, reaching freestanding nanofibers with a diameter well below 1µm is still sophisticated and challenging because of their low mechanical stability and high demands concerning their diameter uniformity. Focussing on these demands we built up an optical fiber taper facility with a CO_2 laser as heat source including a travelling hot zone scheme. A detailed description can be found in section 2.

Several investigations on the properties of optical nanofibers have been already performed and some applications e.g. for super continuum generation or atom trapping and guiding have been proposed. Nevertheless their optical light guiding properties are not yet absolutely understood and require further examination and verification. Because of the taper configuration the observed transmission is always influenced by both the transitions between the untapered sections of the fiber and the nanofiber itself. Therefore the transition properties always have to be taken into account when investigating the waist properties. Discussing the transmission phenomena during the tapering process assists to understand the impact of the taper transitions. This is done in section 3. The paper is summarized in section 4.

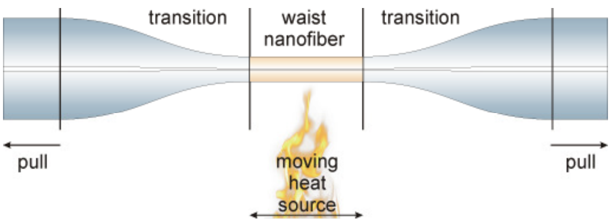

Fig. 1 *Sketch of an optical fiber taper. The submicron diameter waist is used to investigate the properties of optical nanofibers.*

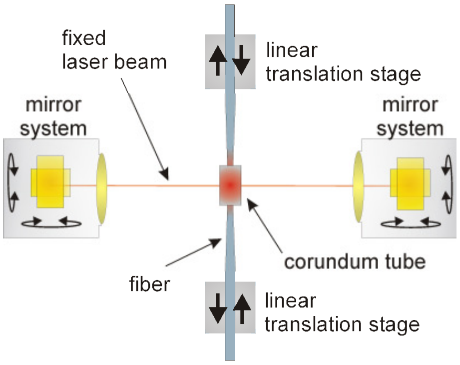

Fig. 2 *Setup of the indirect laser heating method. A corundum tube acts as a micro furnace to overcome absorption problems of the bare fiber.*

2 Experimental Setup

Optical nanofibers are made by tapering existing standard optical fibers because this approach has two advantages. Firstly, the taper transition regions act as a mechanical support that assists in handling the nanofiber. Secondly, the transitions perfectly perform the task of coupling light in and out the nanofiber what would be a serious problem otherwise.

Fiber tapers are produced by a local heat treatment of optical fibers above the transition temperature of silica accompanied by a stretching force along the fiber axis. If the heated section is pointlike one only gets two transitions adjacent to the heat center. A widespread heated section is needed for a waist to be formed.

Variations in temperature inside the taper waist always lead to variations in viscosity and in a non homogeneous diameter distribution. Therefore efforts have to be made concerning the temperature stability within the hot zone in time and space. Normally the heat source exhibits an inherent temperature distribution with a high temperature in the center and a low temperature at the edges of the source as e.g. for a CO_2 laser beam. In this case the heat source has to be moved along the fiber or vice versa to maintain a constant mean temperature within the waist. Due to insufficient power absorption of the CO_2 laser beam (10.6µm wavelength) in silica fibers with a diameter below 5µm, the fiber has to be introduced into a small tube of appropriate material and dimension in order to achieve submicron diameter waists [1]. Now the tube absorbs the laser power and acts as a small micro furnace whose temperature is independent of the fiber diameter. In our setup the micro furnace stays fixed in space. In addition to a pulling motion the taper waist has do adopt an oscillatory movement to maintain a constant mean temperature inside the whole waist (Fig. 2).

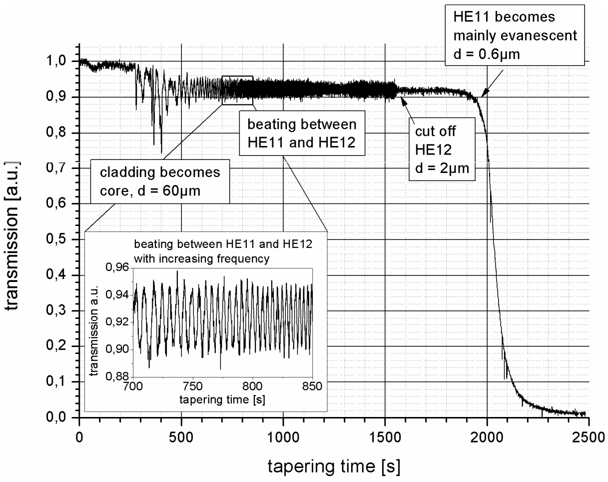

***Fig. 3** Characteristic evolution of transmission during the tapering process.*

3 Transmission phenomena

Because the nanofiber is located between two transition zones, the transmission properties can be observed during the drawing process of the nanofiber. The typical behavior of transmission is shown in figure 3. The untapered fiber is single mode at the investigation wavelength of λ=1550nm and the fiber diameter is reduced by a factor of 2 nearly every 250s.

Optical waveguides that change their geometry in the propagation direction of light do not own any modes that can pass the waveguide without distortion. In this case one may divide the waveguide in short sub waveguides of e.g. constant radius ρ in optical fiber tapers and describe the propagation approximately with local modes and local mode coupling. To maintain as much power as possible in all the local fundamental modes of the taper and hence to retain transmission as high as possible one has to assure that the effective index difference Δn between two local fundamental modes of adjacent local waveguide sections is significantly smaller than the index difference between the fundamental mode and a higher order mode of same azimuthal symmetry. Because the coupling strength is indirect proportional to Δn, the strongest mode coupling in this case occurs between the local fundamental modes and little power is lost to higher order modes or even to leaky modes. More detailed investigations summarize this concept in the adiabaticity criteria [2]:

$$\left|\frac{d\rho}{dz}\right| < \frac{\rho\Delta n}{\lambda} \tag{1}$$

In the beginning of the tapering process this condition is met and transmission stays nearly fixed. Regarding the effective index, the fundamental mode is well separated from higher order modes which are all located in the cladding. Reduction of the cross section leads to a vanishing influence of the core on the guiding properties of the fundamental mode and the effective indices of fundamental and higher order modes approache each other. Calculations point out a diameter region with smallest index difference and hence strongest mode coupling between different modes in the range between 60µm to 50µm. Mode coupling can hardly be avoided and first declines in transmission can be observed. Afterwards the effective indices of different guided modes diverge again and mode coupling becomes less critical.

After the HE_{11} has excited the HE_{12}, an oscillation with constant amplitude and increasing frequency can be observed. This is due to a beating phenomenon. Without power transfer the two modes travel through the waist and depending on the accumulated phase shift more or less power can couple back to the fundamental mode of the untaperd fiber. Frequency increases because the beat length changes with fiber diameter. Oscillation stops when the fiber diameter reaches 2µm - the cut off diameter of the HE_{12}. Afterwards transmission stays constant until the effective index of the fundamental mode approaches to the value of 1 occurring at a fiber diameter of 0.6µm. Smaller diameters repeatedly lead to a steep decline in transmission and losses in the range of dB/mm probably caused by rising evanescent fields. At the end of the process shown in fig. 3 the taper has reached a final waist diameter around 200nm.

4 Summary

With an indirect laser heating method nanofibers with diameters down to 200nm have been achieved. High transmission is possible down to a diameter to wavelength ratio of 0.4. Fibers with smaller ratios exhibit losses of several dB/mm which are acceptable for short length fiber applications.

Literatur

[1] A.J.C. Grellier et al: „Heat transfer modeling in CO_2 laser processing of optical fibers“ Opt. Commun. **152**, 324-328 (1998)

[2] J.D. Love et al: “Tapered single-mode fibers and devices, Part 1: Adiabaticity criteria” IEE Proc. **138**, 343-354 (1991)