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► **To cite this version:**

Nicholas Traynor, Achille Monteville, Laurent Provino, David Landais, Olivier Le Goffic, et al.. Fabrication and Applications of Low Loss Nonlinear Holey Fibers. *Fiber and Integrated Optics*, 2009, *Fiber Optic Research in France (Part III of III)*, 28 (1), pp.51-59. 10.1080/01468030802272526 . hal-00430322

**HAL Id: hal-00430322**

**<https://hal.science/hal-00430322v1>**

Submitted on 27 Apr 2022

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# Fabrication and Applications of Low Loss Nonlinear Holey Fibers

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**Abstract** *We present the important fabrication issues involved with the realization of low loss, low water peak, nonlinear holey fibers based on the Stack and Draw technique. We have realized fibers with loss performances in the 1.38  $\mu\text{m}$  spectral region that are limited by the intrinsic losses of the raw materials, opening up the possibility of using long lengths of such fibers to demonstrate phenomenon such as Raman amplification and supercontinuum generation using continuous wave pump sources.*

**Keywords** fiber design and fabrication, fiber optics, microstructured fibers, nonlinear optics

## Introduction

Micro-structured optical fibers (MOF) or holey fibers (HF) have found a multitude of applications since their first practical realization in 1996 [1]. Among the benefits of these fibers are the ability to realize waveguides that are effectively single mode for all wavelengths in the silica transmission window and the ability to tune the chromatic dispersion allowing wideband flat dispersion profiles or anomalous dispersion in the visible and near infrared wavelength regions. While endlessly single mode fibers with mode field diameters close to those of standard fibers have been fabricated with losses approaching those of state of the art transmission fibers [2], small core highly nonlinear fibers, which benefit from the increased optical confinement afforded by a silica-air cladding, tend to exhibit losses which are higher than their all-silica counterparts, notably with respect to the  $\text{OH}^-$  absorption peak around 1.38  $\mu\text{m}$ . These highly nonlinear fibers benefit from the possibility to widely tune the chromatic dispersion and there are many reports of wideband supercontinua initiated by picosecond or nanosecond pulse sources operating close to the zero dispersion wavelength of the fiber. Such demonstrations require

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only a few meters of fiber and, as such, are generally insensitive to the magnitude of the fiber loss. Applications requiring longer lengths of nonlinear fiber such as Raman amplification [3] or supercontinuum generation using continuous wave (CW) pump sources [4] have received less attention, most likely due, in part, to the relatively high losses achieved in these fibers.

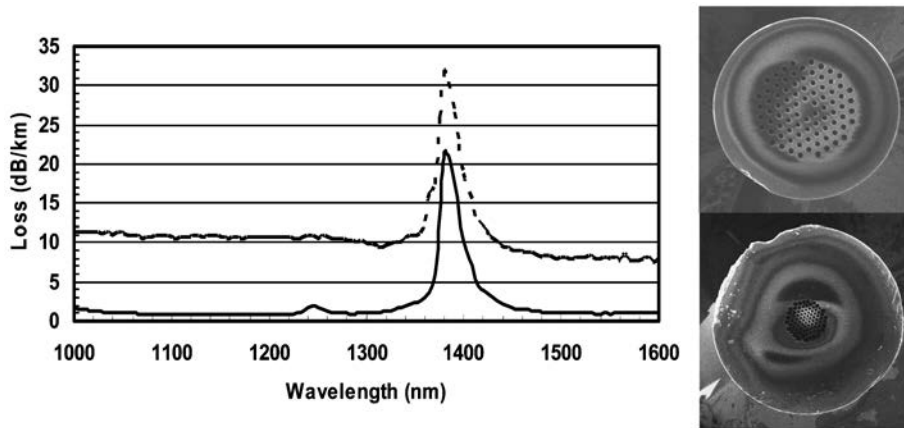
In this article we will discuss the fabrication of nonlinear holey fibers with particular attention given to the control of optical losses, the design tolerances of such fibers and finally demonstrate the utility of these fibers for various optical functions.

## **Fabrication and Characteristics of Nonlinear Holey Fibers**

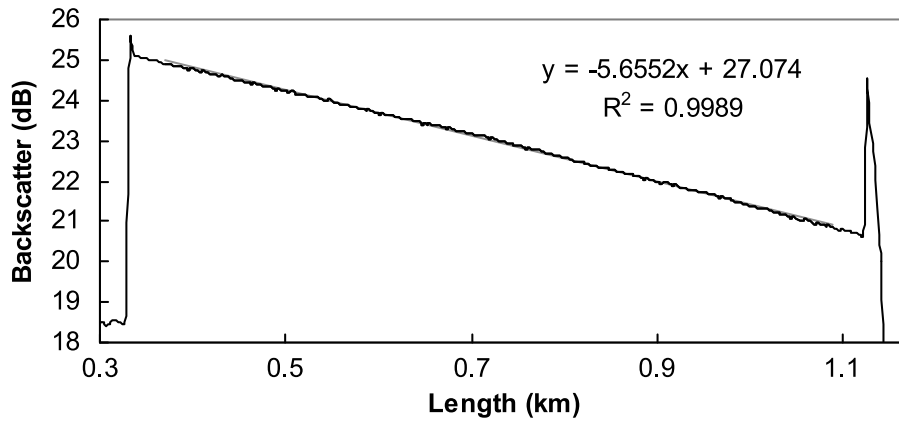
The standard technique in use for the fabrication of holey fiber preforms is the “Stack and Draw” method. High purity silica rods and tubes (in our case F300 silica from Heraeus) are drawn down in a modified fiber draw tower to form uniform capillary tubes and rods of millimeter dimensions. Assuming high dimensional homogeneity of the initial rods and tubes, the dimensional tolerances of the capillaries can be better than 1% over lengths of several tens of meters. The glass capillaries are then stacked inside a glass tube in a hexagonal pattern, with a glass rod that constitutes the central defect forming the final fiber core. For small core fibers this arrangement is then drawn down to form a cane rod of several millimeters that is re-sleeved to achieve the desired core clad ratio for the final fiber. In order to avoid dust and grease contamination of the pre-form, all stacking and sleeving steps are performed in a class 100 clean room environment. Cleaning and polishing steps are extremely important to minimize the optical losses of the final fiber. We use chemical cleaning and polishing techniques which we believe are the key to the low observed fiber losses and, in particular, to avoiding the formation of Si-OH liaisons at defect points around the air silica interfaces which are responsible for the high OH related absorption losses (generally several hundreds of dBs/km) generally observed in small core holey fibers. Finally fiber draw is performed under controlled dry atmosphere conditions in order to avoid extrinsic contamination during this step.

We believe the fiber losses we achieve by these techniques are among the lowest for small core holey fibers. Figure 1 shows the spectral attenuation for two holey fibers. The first is a holey fiber drawn from an initial pre-form (before cane draw) giving a fiber with a final core diameter of 9  $\mu\text{m}$  (solid curve). The second is a holey fiber drawn after cane draw from the same initial pre-form and subsequent re-sleeving to give a final core diameter of 2.5  $\mu\text{m}$  (broken curve). We can clearly see by comparing these two curves that the impact of OH absorption is the same regardless of fiber mode field diameter, indicating that no excess Si-OH liaisons are formed at the air-silica interface for the small core fiber. For both fibers the level of excess attenuation observed around 1,380 nm corresponds to an OH concentration of 0.6 ppm, which is in good agreement with the specified OH content of the raw materials [5]. The attenuation of 0.9 dB/km at 1,550 nm for the large core fiber is more or less limited by the intrinsic losses of the raw materials (0.8 dB/km), while the attenuation of the small core fiber is below 8 dB/km at the same wavelength. Precise control of capillary internal pressure is important to achieve homogeneity of geometry along the fiber, indicated by a very linear optical time domain reflectometry (OTDR) trace for 800 m of the 2.5  $\mu\text{m}$  core holey fiber (Figure 2).

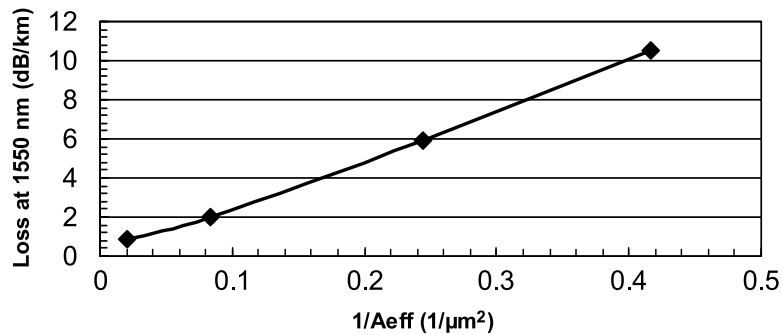
Considering small core fibers with different core sizes we find a more or less linear relationship between the best achieved optical losses at 1,550 nm and the inverse of the nonlinear effective area (Figure 3), suggesting that the nonlinear figure of merit of the



**Figure 1.** Optical attenuation of two holey fibers drawn from the same initial pre-form (left). The solid curve is the attenuation obtained for a holey fiber with a  $9 \mu\text{m}$  core (photo top right) and the broken curve is the attenuation obtained for a holey fiber with a  $2.5 \mu\text{m}$  core (photo top left).



**Figure 2.** OTDR trace of 800 m of a  $2.5 \mu\text{m}$  diameter core holey fiber.



**Figure 3.** Variation of optical attenuation against  $1/A_{eff}$  for various optical fibers, where  $A_{eff}$  is the nonlinear effective area. Results are shown for fibers with  $A_{eff}$ s of  $2.4, 4.1, 12$  and  $50 \mu\text{m}^2$ .

fibers, which we define as  $1/A_{eff} \cdot \alpha$ , is relatively constant for nonlinear effective areas down to  $2.4 \mu\text{m}^2$  (core size of  $1.8 \mu\text{m}$  with  $d/\Lambda = 0.9$ ). The figure of merit for the largest core fiber presented ( $A_{eff} = 50 \mu\text{m}^2$ ) is lower since the losses are limited by the intrinsic loss of the raw materials.

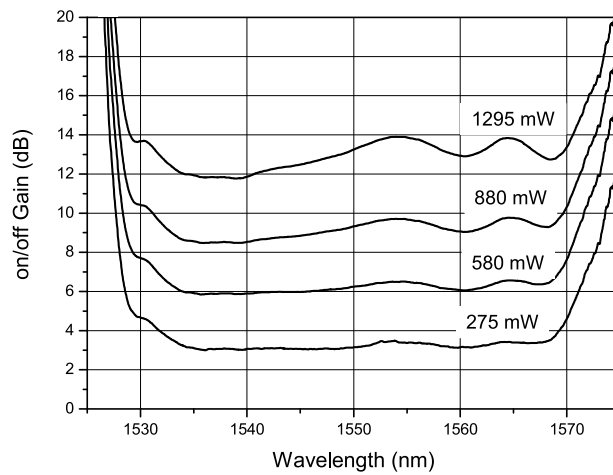
Given the extremely small mode field diameters of these fibers, splicing loss to standard fibers is a particularly important issue. We use high numerical aperture intermediate fibers and controlled tapering to minimize the splicing losses using standard arc fusion splicers. By these methods we are able to achieve a total splice loss of around 0.7 dB between standard single mode fiber and holey fiber with an effective area of  $12 \mu\text{m}^2$  and around 1 dB for holey fibers with an effective area of  $4 \mu\text{m}^2$ .

## Applications of Nonlinear Holey Fibers

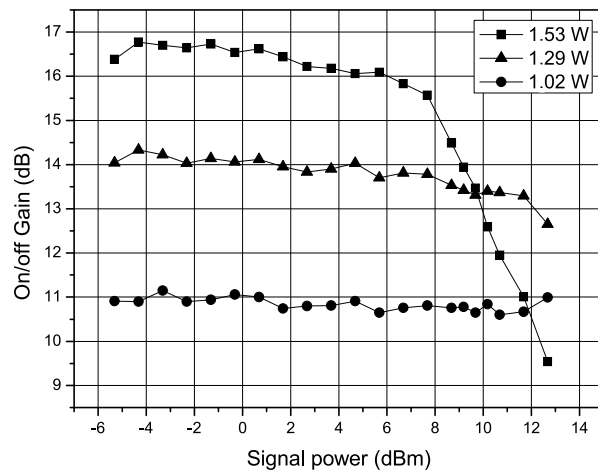
### *Raman Amplification*

Efficient Raman amplification in the telecoms communications window has received little attention due to the high losses in these fibers, especially around 1,385 nm and demonstrations have been limited to the extended *L* band where the Raman pump wavelength lies far from the water absorption peak. Here we demonstrate Raman amplification in the *C* and the *L* band using a 720 m of a low loss 2.5- $\mu\text{m}$  core holey fiber with a measured nonlinear effective area of  $4.1 \mu\text{m}^2$  and an OTDR measured loss of 5.7 dB/km. Two different pump sources were used in the experiments. Both were un-polarized Raman lasers with emission wavelengths of 1,453 and 1,480 nm, respectively. These were injected into the HF via an appropriate wavelength division multiplexer (WDM) and a high numerical aperture intermediate fiber. The total splice loss (single mode fiber [SMF] to HF) was around 1.2 dB. The signal source (counter propagating) was a broadband source (signal input power:  $-20 \text{ dBm}$ ) for the 1,453 nm pump and an external cavity laser diode at 1,570 nm amplified by an EDFA (variable signal input power) for the 1,480 nm pump. Figure 4a shows the on/off signal gain for the 1,453 nm pump source. The indicated powers are launched pump powers in the HF. We obtain an on/off gain of 14 dB for 1.3 W of launched pump power. Figure 4b shows the on/off gain as a function of both input signal power and launched pump power for the 1,480 nm pump. The maximum gain achieved was 17 dB for 1.5 W of pump. At higher input signal power ( $+8 \text{ dBm}$ ) we observe the onset of strong Brillouin scattering that occurs for a signal output power of around  $+19 \text{ dBm}$ . In both cases the observed gain was insensitive to the polarization state of the signal input. Using the measured values of gain,  $A_{eff}$ , fiber loss, and pump power we are able to estimate the Raman gain coefficient,  $g$ , (non polarized pump) to be  $2.5 \pm 0.2 \text{ m/W}$ , which is in good agreement with previously measured values in HF [6], and indicates good confinement and overlap of the pump and signal modes. As can be seen the observed Raman gain values are insensitive to pump wavelength indicating that the OH absorption has little or no effect on Raman gain at 1,453 nm.

The lumped amplifier gain (taking into account fiber loss) is around 12.5 dB for 1.5 W of pump power, or 8.3 dB/W. This gain value compares very favorably with previous experiments using small core holey fiber which achieved 6 dB/W with a polarized pump (equivalent to 3 dB/W un-polarized) and which used a Raman pump far from the water peak at 1,536 nm [3].



(a)

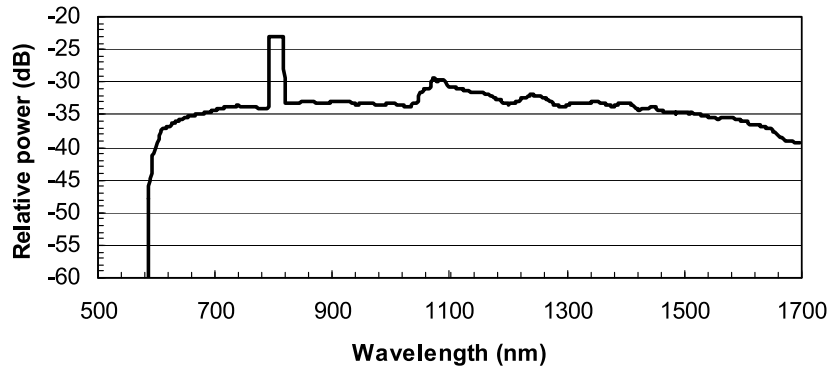


(b)

**Figure 4.** On/off gains for (a) the 1,453 nm pump source and (b) for the 1,480 nm pump source.

***Supercontinuum Generation***

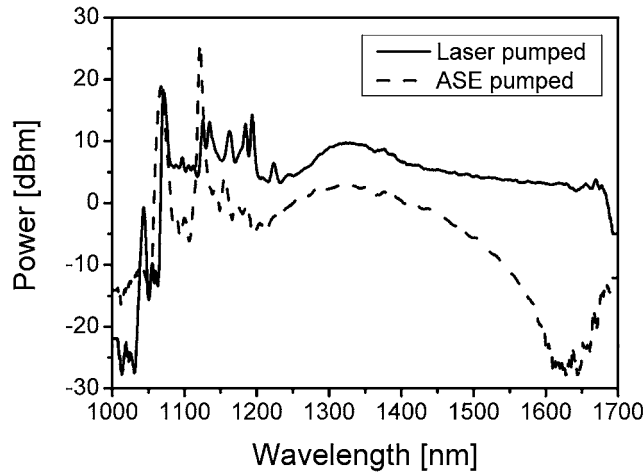
The possibility to widely tune the chromatic dispersion in holey fibers has led to numerous demonstrations of the generation of supercontinuum sources spanning the visible to the near infrared region. The most widely used optical configuration is the use of a Q-switched semiconductor pumped Nd:YAG micro-laser producing ns optical pulses at 1,064 nm injected into a nonlinear holey fiber designed to have a zero dispersion wavelength in the 1  $\mu$ m spectral region. Figure 5 shows a typical optical spectrum generated using such a scheme. One ns optical pulses at 1,064 nm with a peak power



**Figure 5.** Supercontinuum spectrum generated in 20 m of 4  $\mu\text{m}$  core holey fiber using 20 kW, 1 ns pump pulses at 1,064 nm. The observed spectrum is limited by the operating wavelength range of the OSA.

of around 20 kW were injected into 20 m of holey fiber with a core diameter of 4  $\mu\text{m}$  and a zero dispersion wavelength of 1,040 nm (inset). The generated spectrum spans a wavelength region from below 500 nm to beyond 1,700 nm (the displayed spectrum is limited by the spectral response of the optical spectrum analyzer (OSA) used to make the measurement; the peak observed at 808 nm is residual light from the semiconductor laser used to pump the Nd:YAG crystal). The supercontinuum spectrum shows a better than 10-dB flatness over the entire range and has an average output power of around 20 mW.

Certain applications for broadband sources, such as optical coherence tomography (OCT) may benefit from sources that have higher spectral power and lower intensity noise, such as may be offered by continuous wave (CW) pumping of supercontinuum sources. However, such demonstrations require much longer fiber lengths and the high losses generally observed in small core holey fibers, in particular the high OH related losses at 1.38  $\mu\text{m}$ , are detrimental to efficient supercontinuum generation extending beyond 1.4  $\mu\text{m}$ . In [7] we have demonstrated broadband super-continuum generation using CW pumping. We used 200 m of a 2.7  $\mu\text{m}$  core diameter holey fiber with a zero dispersion wavelength of approximately 0.9  $\mu\text{m}$  and optical attenuation of less than 15 dB/km from 1  $\mu\text{m}$  to 1.6  $\mu\text{m}$  and less than 40 dB/km at 1,380 nm. We used two pump sources for the supercontinuum generation: a fiber grating-based single mode Yb fiber laser and a broad linewidth source based on direct amplification of a pre-shaped amplified spontaneous emission (ASE) source (master-oscillator power amplifier scheme [MOPA]). Both sources were coupled into the holey fiber via a standard single-mode fiber with a splicing loss of 1 dB. The output spectrum for both pump sources with a pump power of 13 W is shown on Figure 6 (solid line—laser pump, broken line—ASE pump). Supercontinuum generation in this case is based on the interplay between soliton formation via modulation instability and Raman gain. It is notable that for both spectra we see no spectral dip associated with water absorption around 1.38  $\mu\text{m}$ . With the laser pump source modulation instability is easily self starting due to the intensity noise associated with the longitudinal mode beat signal, resulting in a flat output spectrum extending to beyond 1.6  $\mu\text{m}$ . The broadening with an ASE pump source is more strongly dominated by Raman effects as evidenced by the presence of strong Stokes indicating the onset of Raman lasing, thus limiting the



**Figure 6.** Supercontinuum spectra obtained with 13 W pumping in the HF, with the laser (blue) and ASE (red) sources.

bandwidth of the output spectrum. The output powers were 3.2 and 2.3 W for laser and ASE pumping respectively.

## Conclusion

We have described the fabrication of small core holey pre-forms and fibers and the critical issues that must be addressed in order to minimize optical attenuation and water contamination. The resulting optical fibers have been used in the demonstration of optical functionalities otherwise difficult to realize, notably efficient Raman amplification at telecom wavelengths and supercontinuum generation using continuous wave optical sources. The application domains open to these fibers extend beyond the few realizations presented here, notably in optical switching and optical regeneration for high data rate transmission and efficient parametric amplification from the visible to the infrared wavelength regions.

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