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# 1 km hollow-core fiber with loss at the silica Rayleigh limit in the green spectral region

Matthieu Chafer, Jonas H. Osório, Foued Amrani, Frédéric Delahaye, Martin Maurel, Benoît Debord, Frédéric Gérôme, Fetah Benabid

**Abstract**—In this letter, we report on the fabrication of an Inhibited-Coupling guiding fiber with a cladding amorphous lattice of nine tubes exhibiting record loss of 13.8 dB/km in the green spectral region. The fiber has been drawn over a length of 1 km with high stability during the drawing process (outer diameter variation of  $\pm 0.2\%$ ). To our knowledge, this is the first time that loss figures as low as the fundamental Rayleigh scattering limit of silica are reported for a hollow-core optical fiber in the green spectral range. Also, this is the first report on a tubular fiber draw over such a long length. Additionally, this is the lowest loss figure ever demonstrated in any kind of optical fibers in this spectral region.

**Index Terms**—Fiber optics, photonic crystal fiber, hollow-core fiber.

## I. INTRODUCTION

REDUCING the loss of optical fibers has been a major preoccupation since their advent and, therefore, motivates intense research on both solid- and hollow-core optical fibers. In addition to the great attention given to the near- and mid-infrared ranges – whose efforts allowed to attain attenuation levels as low as 0.14 dB/km around 1550 nm for conventional solid-core fibers [1] –, improvements on the fiber optics technology in the visible spectral region are still required for addressing the needs of a wide set of growing application fields, since the loss of solid-core fibers in the visible are much higher than the ones obtained in the infrared due to the greater influence of the Rayleigh scattering for shorter wavelengths. For example, attenuation values in the green spectral range are around 30 dB/km for commercial single-mode fibers and around 20 dB/km for endlessly single-mode photonic crystal fibers [2–4] optimized for the visible range, which are higher than the limit, 13 dB/km, set by Rayleigh scattering in bulk silica. These improvements are particularly important for applications in the green spectral range (GSR) since, for instance, lasers emitting in the GSR are often used in the context of photovoltaic solar micro-processing for scribing and cutting in the solar cell fabrication process [5]. Moreover, lasers emitting in the visible spectral region are increasingly important for biological applications such as cytometry, DNA sequencing and confocal microscopy. Hence, improvements on the transmission capabilities of optical fibers in the visible range would bring ease of use, precision amelioration and cost effectiveness to these applications and, therefore, are highly desirable.

In this context, since the loss in solid-core fibers are fundamentally limited by the Rayleigh scattering of glass, hollow-core photonic-crystal fibers (HC-PCF) appear as a very promising route for obtaining fibers with low loss in the visible region. HC-PCFs can guide light via photonic bandgap (PBG) [6] or by Inhibited-Coupling (IC) [7] mechanisms. In PBG fibers, the core mode is unable to be coupled to the cladding by virtue of avoidance of any propagating mode in the core-guided mode effective index-frequency space [6]. Conversely, in IC fibers, the “uncoupling” to the cladding of core-modes is ensured no longer by the absence of cladding modes but by strongly minimizing the mode coupling between the core and cladding. It is achieved by engineering the fiber cladding so that core and cladding modes exhibit a strong mismatch between their transverse phases and small spatial overlap [7].

The lowest loss figures reported for PBG fibers reached 1.2 dB/km around 1600 nm [8], which is one order of magnitude above the value achieved for solid-core fibers at this wavelength. Furthermore, at visible wavelengths, the minimum attenuation in such fibers is as high as 870 dB/km at 557 nm [9]. Further reducing the attenuation in PBG fibers, however, is prevented by limiting factors such as the strong core-cladding optical overlap, the existence of interface surface modes and the core surface roughness. Furthermore, PBG HC-PCFs guiding in short wavelengths (*i.e.*  $\lambda < 1 \mu\text{m}$ ) require smaller cladding pitches and core diameters, which imposes additional fabrication challenges. This dissolved the ambition of overcoming the Rayleigh scattering limit via the utilization of PBG fibers.

In contrast, the IC guiding HC-PCFs exhibit several orders of magnitude lower core-cladding optical overlap than PBG HC-PCFs and can guide in the visible with much larger core and cladding sizes. Furthermore, they promise to be an alternative able to get rid of the PBG fibers shortcomings thanks to their ultralow loss levels accomplished with the introduction of the hypocycloid core contour (negative curvature) [10, 11]. Indeed, the hypocycloid core contour entailed an impressive reduction of the loss in IC fibers from the decibel per meter (dB/m) level in the first kagomé lattice fiber [12] to the recently reported loss figure of 8.5 dB/km at 1030 nm [13]. Still, at shorter wavelengths, loss levels of 70 dB/km at 600 nm and 130 dB/km at 532 nm remain as the record low ones for kagomé lattice fibers [14].

A particular sort of IC fibers which has arisen as an extension of the introduction of the hypocycloid contour concept are the single-ring tubular lattice (SR-TL) HC-PCFs [15]. The cladding structure of the SR-TL HC-PCFs consists of a single ring of tubes which establishes a

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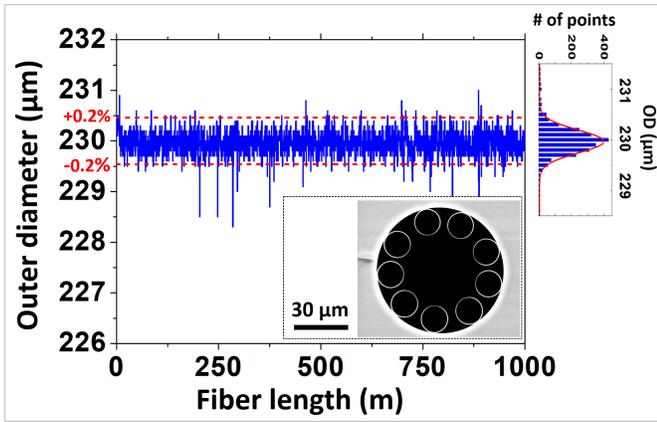


Fig. 1. Fiber cross section and fiber outer diameter (OD) evolution during the fiber draw. Inset plot shows a histogram on the OD values during the fiber draw (red line stands for a fitted gaussian function to the experimental data).

hypocycloid core contour which lacks of any connecting node. As both of these properties favor IC guidance, remarkable results regarding loss reduction have been obtained in the latest years [16-21]. For instance, Debord *et al.* have undertaken a systematic experimental and numerical study on the key physical parameters in designing a low-loss SR-TL HC-PCF to report a loss figure of 7.7 dB/km at 780 nm using a SR-TL HC-PCF with a cladding composed of 8 tubes [16]. This loss figure is only a factor 2 above the loss due to the fundamental scattering limit of silica. Additionally, modified tubular lattice HC-PCFs with so-called conjoined [17] and nested tubes [18] was also demonstrated to offer loss values of 2 dB/km at 1512 nm and 1.3 dB/km at 1450 nm, respectively. For shorter wavelengths, the loss of tubular fibers are reported to achieve 80 dB/km at 532 nm [19], 130 dB/km at 300 nm [20], and 100 dB/km at 218 nm [21]. The progress made in IC fibers is such that, for wavelengths lower than 1  $\mu\text{m}$ , the transmission loss is no longer limited by the cladding design but by the surface scattering loss (SSL) due to surface roughness which can result from capillary waves or instabilities during the fiber draw [16].

Here, we report an IC guiding SR-TL HC-PCF with a 9 tubes cladding structure with record loss of 13.8 dB/km at 539 nm. This loss figure corresponds to the Rayleigh scattering limit of silica at this wavelength. The fiber has been drawn over 1 km with an outer diameter (OD) variation of  $\pm 0.2\%$ , which demonstrates the great stability of the drawing process.

## II. RESULTS

Fig. 1 shows the cross section of the SR-TL HC-PCF we report herein, which was fabricated by the stack-and-draw technique. The cladding of the fiber is composed by a ring of 9 tubes which demarks a 42  $\mu\text{m}$  inner-diameter hollow-core. The cladding tubes have inner-diameter of 11.4  $\mu\text{m}$ . The diameter uniformity of the tubes was found to have a standard deviation of 150 nm. The thickness of the cladding tubes is 610 nm, and the distance between two adjacent tubes ranges from 2.2  $\mu\text{m}$  to 4.0  $\mu\text{m}$ . The choice of a lattice of 9 tubes follows the results reported in [16], which showed that, for the same core radius, the confinement loss (CL) decreases with increasing number of tubes in the fiber cladding. Also, the choice of a 9-tubes lattice fiber allows to keep a good compromise between low CL and a modal content dominated by the  $\text{HE}_{11}$  mode (see [16] for the effect of the tube numbers on the CL and the modal content).

The OD evolution during the fiber drawing process is also presented in Fig. 1, which was measured by using a laser diameter monitoring

system during the fiber draw. It can be observed that the 1 km long fiber was drawn with very high OD stability. The inset plot in Fig. 1 presents a histogram on the OD values during the fiber draw. By fitting a gaussian function to the experimental data (red curve), we obtained a  $2\sigma$  value of 0.44  $\mu\text{m}$ , which means a 0.2% variation in the OD values. The two dashed red lines in Fig. 1 main plot identifies the  $\pm 0.2\%$  variation in the OD value. We note that the spikes in the OD curve are likely due to residual dust passing the laser beam of the OD measurement system. The fiber cross section was also checked along the fiber length using a high resolution microscope. The dimensions of the fiber microstructure features show also great stability. For example, the core diameter was measured to have a maximum variation of 0.7%.

The fiber loss was accounted by performing several cutback measurements. The fiber length was wound in several turns to form a coil of 40 cm radius. Fig. 2 shows the transmission spectra for fibers 1 km, 500 m, 200 m, and 5 m long. Additionally, it is shown in the top graph in Fig. 2, the detected transmission bands in the UV range which were measured by launching light from a broadband plasma source and by measuring the transmitted spectrum from a 5 m long fiber with a spectrometer. Transmission bands in the UV region range from 276 nm to 323 nm, and from 335 nm to 424 nm.

The cutback measurement results are shown in Fig. 3. The bottom graph presents the average loss considering all the transmission spectra shown in Fig. 2 (left axis). The average minimum loss was measured to be 90 dB/km at 1700 nm, 11.4 dB/km at 850 nm and 16 dB/km at 550 nm. Moreover, cutback measurements performed by using lasers emitting at 343 nm and 355 nm showed loss figures of 150 dB/km and 75 dB/km at these wavelengths, respectively – these results are shown in Fig. 3 as blue squares; a transmission spectra (T) is

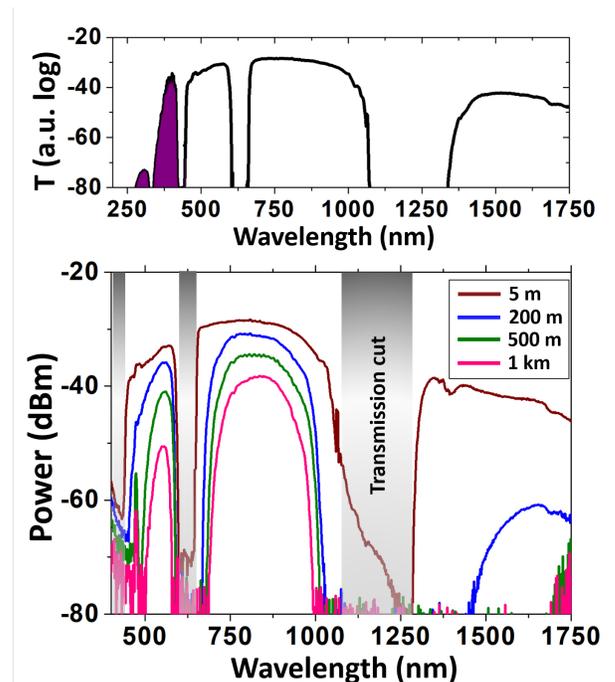


Fig. 2. Fiber transmission spectra for the lengths of 1 km, 500 m, 200 m, and 5 m (bottom graph). Fiber transmission (T) with the detected bands in the UV spectral range for a 5 m long fiber (top graph).

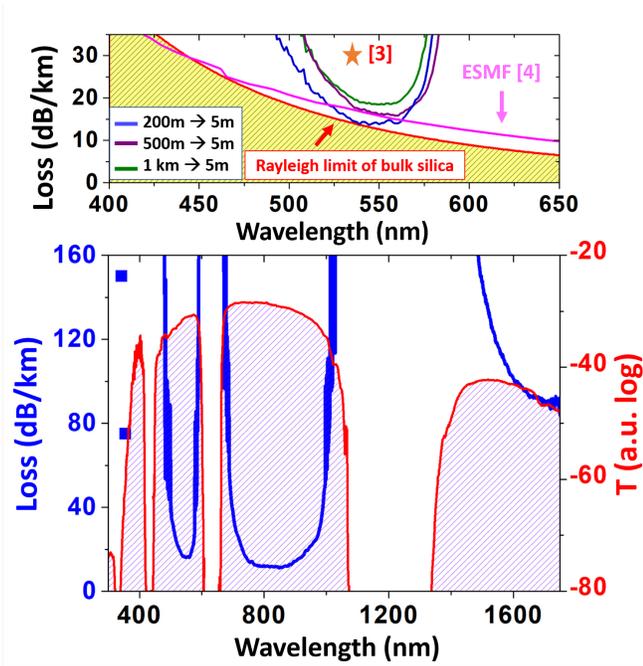


Fig. 3. Cutback measurement results. Bottom graph presents the average loss considering the transmission spectra in Fig. 2 (left axis) and the fiber transmission spectrum ( $T$ ; right axis). Top graph shows the result for the loss measurement between the 1 km and 5 m, 500 m and 5 m, and 200 m and 5 m long pieces (green, purple and blue lines respectively) together with the silica Rayleigh scattering limit curve (red line). The pink line is the loss spectrum of a endlessly single-mode (ESMF) solid-core optical fiber taken from [4] and the star symbol is the loss of a single-mode fiber optimized for the visible range [3] used for comparison.

also shown for better visualization of the 343 nm and 355 nm wavelengths within the fiber transmission band. The measured loss value at 355 nm is lower than the values reported in [20] and [21] for similar wavelengths in the UV range.

The top graph in Fig. 3 shows a close-up of the measured loss between 400 nm and 650 nm for cutback measurements between the 1 km and 5 m, 500 m and 5 m, and 200 m and 5 m long fibers (green, purple and blue lines respectively). Here, we observe that the measured loss are lower for cutback measurements performed with shorter fibers. At 539 nm, for example, the measured loss values are 19 dB/km for the cutback between 1 km and 5 m long fibers, 17.3 dB/km for the measurement using the 500 m and 5 m long fibers, and 13.8 dB/km for the cutback measurement between the 200 m and 5 m long fibers for a 40 cm bending radius. We attribute this discrepancy in the measured loss figures to possible structural non-uniformities in the fiber, in consistency with the observed side scattering points along the fiber length during the transmission measurements. It is noteworthy that the 13.8 dB/km loss figure measured at 539 nm is as low as the fundamental Rayleigh scattering limit for bulk silica (as indicated in the red curve in Fig. 3 inset). To our knowledge, this is the first time that a hollow-core fiber with loss at such level in the green spectral range is reported in the literature. Moreover, this attenuation value is better than any optical fibers including commercial fibers optimized for the visible range, whose loss are around 20-30 dB/km [2- 4]. Fig. 3 shows the loss trend for a endlessly single-mode fiber (ESMF, pink line in Fig. 3) [4] and the loss for a solid-core single-mode fiber optimized for the visible range [3] used for comparison.

In order to account for the macro-bending influence, bending loss measurements were performed. The measurement results are shown

in Fig. 4, where bend loss values are presented as a function of the wavelength for the curvature radii ( $R_c$ ) of 20 cm, 15 cm, 10 cm, 7.5 cm and 5 cm. It is seen that the bending loss increases for shorter wavelengths and smaller  $R_c$ . The top graph in Fig. 4 shows bend loss values as a function of  $R_c$  for selected wavelengths, namely 539 nm and 1000 nm. While at 1000 nm a maximum bending loss figure of 0.15 dB/turn was measured for  $R_c = 5$  cm, at 539 nm the bending loss values range from 0.147 dB/turn to 0.83 dB/turn as  $R_c$  goes from 20 cm to 5 cm. Particularly, at 1550 nm, the maximum bend loss is 0.05 dB/turn for  $R_c = 5$  cm. These results are in good agreement with previously reported results [16]. It is worth saying that, in our fiber, the critical radius at which the bend loss should peak [23] is estimated to be 4.4 cm and 1.2 cm at the wavelengths of 539 nm and 1000 nm, respectively. The bend loss peak, therefore, was not seen in our experiment since the smallest  $R_c$  used in the measurements was 5 cm. Additionally, the near field profiles at the fiber output for the different  $R_c$  values are shown in the bottom part of Fig. 4. It is seen that the output profiles were kept fundamental-like during the measurement.

Additionally, spectral and spatial imaging technique ( $S^2$  technique) [22] was employed to account for the modal content of the fiber. The  $S^2$  measurement setup includes a tunable laser with wavelength range between 1030 nm and 1070 nm (10 pm resolution) and a camera which has its image acquisition controlled by a computer. Fig. 5 bottom graph shows a typical  $S^2$  measurement result obtained by testing a 5 m long fiber set in a coil of 40 cm radius.  $LP_{11}$ -like mode contributions are seen at the delays of 5.0 ps and 5.9 ps, and present multi-path interference (MPI) values of -33.5 dB and -35.2 dB, respectively. This corresponds to a quasi-single-mode operation in this fiber. Moreover,  $M^2$  measurement was performed and values of 1.01 and 1.09 were obtained for the x- and y-axes respectively (ISO

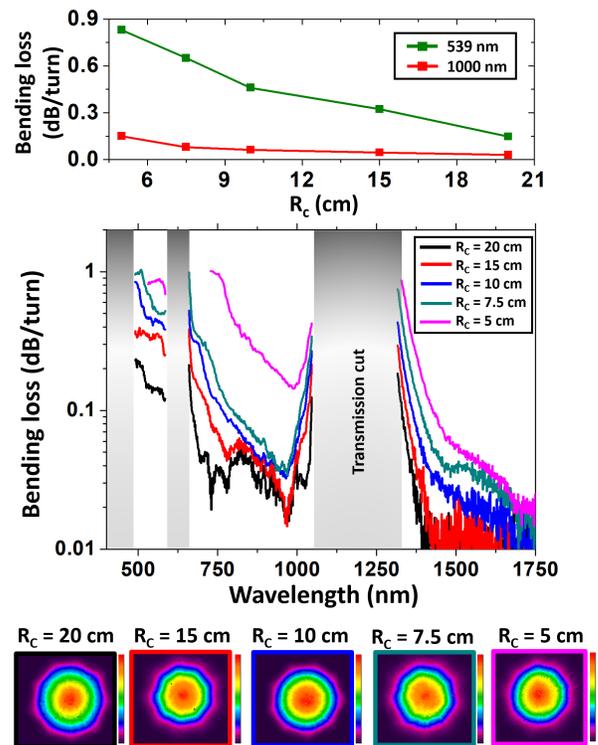


Fig. 4. Bending loss measurement. Upper graph shows the bending loss value as a function of the curvature radius ( $R_c$ ) at selected wavelengths (539 nm and 1000 nm). Bottom part presents the near field profile in the green spectral range.

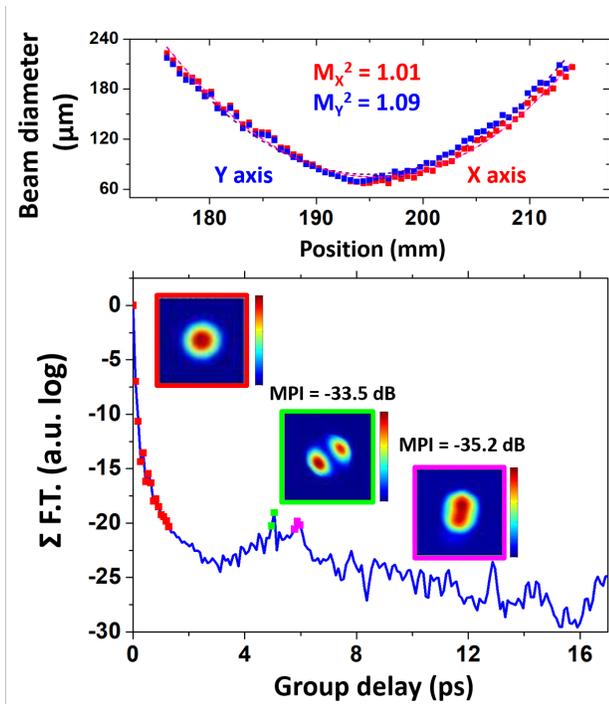


Fig. 5.  $S^2$  measurement result for a 5 m long fiber. The reconstructed mode field profiles are presented with the corresponding MPI values (bottom graph). The top graph presents the  $M^2$  measurement results.

standard, Metrolux LPM 200). The top graph in Fig. 5 shows the  $M^2$  measurement data, which were accounted at the wavelength of 515 nm. Finally, the fiber polarization extinction ratio (PER) was measured by launching laser light (at 515 nm) and by measuring the optical power at the ports of a polarizing beam splitter. A maximum value of 19 dB was obtained for a fiber 5 m long.

### III. CONCLUSION

In summary, we here reported the successful drawing of a 1 km long IC guiding SL-TL HC-PCF with 13.8 dB/km loss at 539 nm. The obtained loss figure is as low as the fundamental Rayleigh limit of silica. To our knowledge, this is the lowest loss value for a hollow-core fiber in the green spectral range ever reported in the literature. Moreover, this is the first report of a tubular fiber draw over such a long length. Further improvement in the fiber core surface roughness levels will allow to attain even lower loss values in future fibers.

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