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Hollow-core fibers with reduced surface roughness for record losses and beam delivery in the UV domain

Ali Al Dhaybi¹, Jonas H. Osório¹, Frédéric Delahaye², Kostiantyn Vasko^{1,2}, Foued Amrani², Gilles Tessier³, Luca Vincetti⁴, Benoit Debord^{1,2}, Frédéric Gérôme^{1,2} and Fetah Benabid^{1,2}

¹ GPPMM Group, XLIM Institute, CNRS UMR 7252, University of Limoges, Limoges, France

² GLOphotonics, 123 Avenue Albert Thomas, Limoges, France

³ Institut de la Vision, CNRS UMR 7210, INSERM, Sorbonne University, Paris, France

⁴ Department of Engineering 'Enzo Ferrari', University of Modena and Reggio Emilia, Modena, Italy

Abstract. We report a new generation of HCPCFs demonstrating ultralow loss in the short-wavelength domain by the use of new fabrication process. The process consists of applying a shear stress on the fiber silica core-surround surface. This approach allows a significant silica surface roughness reduction demonstrated by using a home-made picometer-resolution and high dynamic range profilometer. The surface quality improvement is further corroborated by record optical performances measured in the UV spectral range with losses between 50-10 dB/km in the wavelength range of 280-400 nm. As a demonstration of the interest of such fibers, UV laser beam delivery at specific industrial wavelengths including 257/266 nm and 343/355 nm are presented.

1 Introduction

Advancements in optical fiber technology tailored for shorter wavelengths, specifically within the visible and ultraviolet (UV), stand as priorities for the next developments in photonics. The domain of UV photonics holds particular significance within both technological and scientific realms, encompassing activities that involve the manipulation and management of light between 400 nm and 100 nm wavelengths. Notably, recent years have witnessed substantial progress in fiber optics technology, exemplified by breakthroughs in inhibited-coupling (IC) hollow-core photonic crystal fibers (HCPCFs) research and development. Despite notable advancements, there remains a critical challenge concerning the improvement of core surface quality in HCPCFs to mitigate loss resulting from scattering phenomena. While losses in IC HCPCFs guiding infrared light are primarily dictated by fiber design, the current state-of-the-art for guiding short wavelengths ($\lambda < 800\text{-}1000$ nm) is hindered by surface scattering loss (SSL). This SSL is closely tied to the roughness of the fiber core surface, originating from thermal surface capillary waves (SCW) formed during fiber drawing. Under a scenario of thermodynamic-equilibrium surface roughness (TESR), roughness levels are estimated to be around ~ 0.4 nm for silica [1].

Efforts to reduce SSL demand having control over core surface roughness. Recent findings have demonstrated that reducing roughness along the fiber drawing direction can be achieved by controlling drawing

stress during fiber fabrication [2]. A reduction in SSL would enable the production of fibers with significantly lower transmission loss and increased resistance to solarization, facilitating broader applications in UV photonics for both industrial and scientific purposes.

In our recent developments, we demonstrated IC HCPCFs with enhanced core surface quality and remarkably low loss in the short-wavelength range. By revisiting conventional HCPCF fabrication methods, we have managed to reduce rms roughness from approximately 0.4 nm, as observed in fibers produced using standard methods, to around 0.15 nm using our novel techniques. These values have been measured by a homemade optical profilometer developed for fiber roughness characterization with picometer-resolution and high dynamic-range performances.

This reduction in core roughness has then enabled the production of fibers with ultralow loss in the short-wavelength range, namely 50.0 dB/km at 290 nm, 9.7 dB/km at 369 nm, 5.0 dB/km at 480 nm, 0.9 dB/km at 558 nm, and 1.8 dB/km at 719 nm [3]. Additionally, as an example of applications, we report on successful demonstrations of highly efficient UV beam delivery using those HCPCFs, specifically at wavelengths of 343 nm and 266 nm. These realizations demonstrate the capabilities of our new generation of HCPCF to achieve superior endurance and transmission efficiency performances, hence underscoring their transformative potential for acting as a key enabling technology for the next UV photonics advancements.

* Corresponding author: ali.al-dhaybi@xlim.fr

2 Development of a picometer-resolution and high dynamic range profilometer for surface scattering loss assessment

As previously mentioned, SSL is dependent on the HCPCF core surface roughness (SR) quality. Thus, in order to obtain better fibers for the short wavelength range, understanding and characterizing the core surfaces becomes imperative. This characterization is typically achieved by using techniques such as atomic force microscopy (AFM) [1] or optical profilometry [4].

In this framework, we notice that there are very few investigations on the characterization of the SR in HCPCFs. Additionally, the proposed theoretical models are either approximate or based on working hypotheses that need to be confirmed. Besides, the experimental data collected on surface roughness are limited to providing a comprehensive overview of the surface topology. Indeed, this hinders the development of physical models on the dynamics of SR generation inside HCPCFs able to describe its structure on all necessary length scales.

This lack of knowledge is illustrated, for example, by the discrepancy observed between the experimental data and the theoretically expected behavior for low spatial frequencies [5]. This context can be explained in part by the lack of an experimental tool capable of measuring the HCPCF surface profiles with picometric resolution and ranges on the order of millimeters or more. Characterization efforts combining broad dynamic range and fine resolution are therefore necessary for better characterization of HCPCF surface quality and become essential for any future development of HCPCFs with scattering-limited losses [6].

Therefore, we report on the development of a profilometer based on the Normaski interferometer [7], whose principle of operation is schematically shown in Figure 1(a). A 532 nm polarized laser beam is initially directed onto a Wollaston prism. The prism generates two orthogonal polarization beams that are launched to the surface under test. After experiencing reflection, a phase shift is generated between the two beams, which can be interpreted as a difference in height due to the surface roughness of the sample. In sequence, these beams travel the same path back and are directed towards a photo-elastic modulator (PEM). The two polarized beams are hence modulated at a frequency $f = 50$ kHz and the modulated light is then detected synchronously with a lock-in amplifier (a polarizer is set before the photodiode to allow for the beams with orthogonal polarizations to interfere). Lock-in detection allows amplifying the signal at a specific frequency while eliminating all unwanted frequencies by filtering.

To ensure the correct positioning of the sample in the profilometer, an imaging system equipped with a camera was set up. We remark that our optical profilometer is able to measure profiles extending beyond a few millimeters. To obtain such capabilities, we have integrated precision stages to achieve control over all directions. Additionally, we added stages to rotate the sample and to adjust the inclination angles of the sample relative to the system reference plane.

To characterize the operation of the profilometer, we first assessed its sensitivity and stability. In Figure 1(b), we display the height difference measured using a sampling frequency of 255 points per second over 7 minutes on a stationary sample. The results indicate an RMS value of 7 pm, which corresponds to the resolution of our system. Figure 1(c) depicts the Fourier transform of this measured signal versus frequency. The curve demonstrates a $1/f$ trend, suggesting that faster measurements improve system sensitivity. Additionally, Fourier analysis allows determining a sensitivity value of $2 \text{ pm}/\sqrt{\text{Hz}}$. Figure 1(d) shows a surface roughness profile showing an amplitude variation of 1 nm over a record length of 1 cm with a RMS value of $h_{\text{rms}} = 0.54 \text{ nm}$. We mention that, by using our system and an adequate sample preparation procedure (which involves suitable filling of the HCPCF microstructure with index-matching liquid), we can assess different surfaces of the microstructure elements and characterize their inner and outer boundaries (as illustrated in Figure 1(e)).

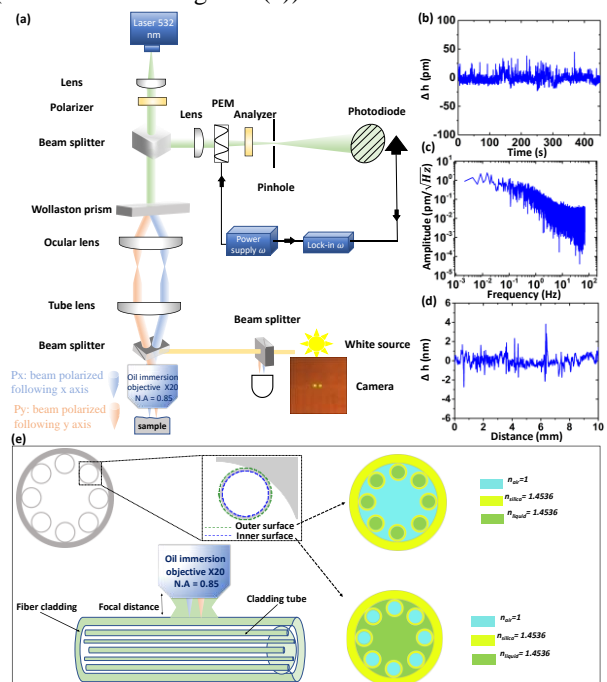


Figure 1: (a) Schematic representation of the optical profilometer setup, (b) Measured difference of height over 7 minutes (stationary sample), (c) the Fourier Transform of the signal, (d) Surface roughness profile over 1 cm measured for a capillary fiber and (e) Sample preparation procedure of HCPCF using an index-matching liquid.

3 HCPCF with reduced surface roughness and ultralow loss in the short-wavelength range

The conventional method for drawing HCPCFs involves pressurizing both the core and cladding regions to achieve appropriate dimensions in the fiber cross-section. In contrast, our recent developments demonstrated that using counter-directional gas and glass flows during the drawing process allow for introducing shear to the glass membranes within the microstructure, thereby achieving smoother core surfaces [3].

To assess the efficiency of this new process, we used the picometer resolution profilometer to measure the core

roughness in two sets of HCPCFs, labelled G#1 and G#2. G#1 fibers were produced using standard procedures, while G#2 fibers were fabricated using our innovative technique. In Figures 2(a) and 2(b), we show typical surface profiles along the axis of G#1 and G#2 fibers. The peak-to-peak roughness of G#1 fibers measures at 1.5 nm, whereas for G#2 fibers, it is approximately 0.5 nm. In turn, Figure 2 (c) illustrates the rms roughness of G#1 and G#2 fibers. The rms roughness of G#1 fibers fluctuates around 0.4 nm, indicating adherence to the TESR standard. Conversely, G#2 fibers exhibit a rms roughness of around 0.15 nm, significantly lower than the TESR limit imposed by the SCW scenario.

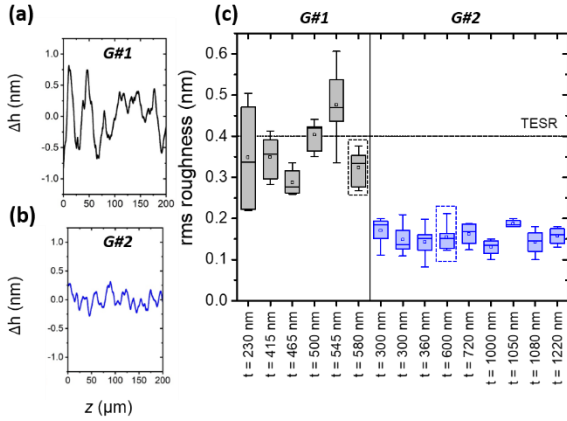


Figure 2: (a) and (b) typical roughness profiles along the fiber axis for samples in G#1 and G#2. (c): Rms roughness obtained for fibers in G#1 and G#2 (sample according to silica thickness of the tube).

As a result of this decrease in core roughness, we have been able to manufacture fibers with remarkable low loss in the short-wavelength spectrum. This includes loss figures of 50.0 dB/km at 290 nm, 9.7 dB/km at 369 nm, 5.0 dB/km at 480 nm, 0.9 dB/km at 558 nm, and 1.8 dB/km at 719 nm as presented in Figure 3 (a). Finally, Figure 3 (b) contextualizes our results within the state-of-the-art HCPCF framework in the visible and UV ranges.

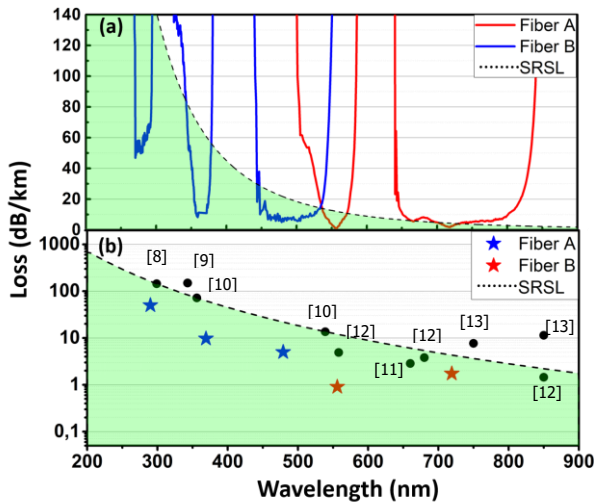


Figure 3: (a) Loss measurement results for fibers fabricated by the methods reported in [3]. (b) IC HCPCF state-of-the-art framework and the SRSL (silica Rayleigh scattering limit) trend.

4 Highly efficient UV laser beam delivery in HCPCF

In the last section, the IC-HCPCFs with reduced surface roughness were tested to deliver a high-power high-energy UV lasers. Indeed, the low-loss air guidance of those novel fibers make them ideal for UV transport as the usual limitation of the silica material absorption and the undesirable solarization effects can be here completely removed. As a first example, a hollow-core fiber with a 27 μm core diameter and optimized losses at 343 nm (< 50 dB/km) was used to deliver 23.3 W (155 μJ) nanosecond pulse laser [14]. This figure corresponds to an improvement of 2 orders of magnitude in the power handling of fibers in the UV range. A second example was demonstrated at 266 nm from a laser source emitting 1 ns wide and 37 μJ energy pulses. A transmission rate of 96% was achieved at the output of a 2-meter-long fiber sample. The stability of the UV delivery and the resilience against solarization were then studied by continuously coupling the UV laser beam to the hollow-core for over 680 hrs. The results show excellent stability in transmitted power (fluctuations of less than 5%) and in mode quality as shown in Figure 4. To our knowledge, this is the first fiber guidance of DUV laser beams combining high energy handling and long lifespan.

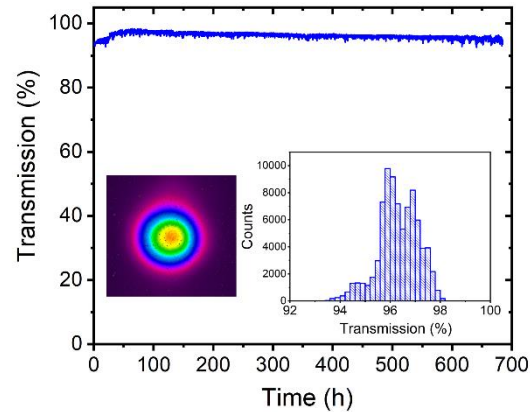


Figure 4: Transmission efficiency of a nanosecond 266 nm laser beam through a state-of-the-art HCPCF as a function of the time. The insets show a histogram corresponding to the transmission efficiency data and an image of the output beam intensity profile.

5 Conclusions

To conclude, the recent advances in IC-HCPCF with reduced surface roughness and ultralow loss in the short-wavelength range open the way to the next UV-DUV photonics applications which have been until now scarcely addressed by the optical fibers technology. In particular, the last results obtained in this communication mark a major milestone in the adoption of hollow-core fibers for UV laser beam delivery by the industrial community.

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