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## ► To cite this version:

J Osório, F Amrani, F Delahaye, A Dhaybi, K Vasko, et al.. Hollow-core fibers with ultralow loss in the ultraviolet range and sub-thermodynamic equilibrium surface-roughness. Conference on Lasers and Electro-Optics (CLEO US), OSA, May 2022, San Jose, United States. pp.SW4K.6. hal-03681684

**HAL Id: hal-03681684**

**<https://hal.science/hal-03681684>**

Submitted on 30 May 2022

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# Hollow-core fibers with ultralow loss in the ultraviolet range and sub-thermodynamic equilibrium surface-roughness

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**Abstract:** We report on hollow-core fibers displaying rms core roughness under the surface capillary waves thermodynamic limit and record loss in the short-wavelength range (50.0dB/km at 290nm, 9.7dB/km at 369nm, 5.0dB/km at 480nm, 0.9dB/km at 558nm). © 2022 The Author(s)

Among the novel frontiers in photonics are ultraviolet (UV) photonics and next-generation optical fibers. The former holds a prominent position within technological and scientific areas, as it includes activities that entail or require the generation and control of light at wavelengths between 400 nm and 100 nm. Such activities encompass materials synthesis, micro- and nano-processing, precision spectroscopy, and light transport. The latter saw a huge progress, exemplified by the latest achievements in inhibited-coupling (IC) hollow-core photonic crystal fibers (HCPCFs) technology. Still, although the recent results on these fibers' performances are remarkable, further advances should rely on the improvement of the HCPCFs core surface quality as it imposes a fundamental hindrance to loss decreasing due to scattering processes. Differently from the IC HCPCFs guiding in the infrared (IR), whose loss remains limited by the fiber design (*i.e.*, confinement loss, CL), the current state-of-the-art in HCPCFs with guidance at short wavelengths ( $\lambda < 800\text{-}1000$  nm) is constrained by the surface scattering loss (SSL) [1]. Thus, although the cladding design optimization efforts have entailed significant lessening of the loss for fibers guiding in the IR, reducing it in the visible and UV ranges lingers as a more challenging task owing to SSL limitation. SSL is set by the roughness of the core surface, which stems from frozen-in thermal surface capillary waves (SCW) that are forged during the fiber draw. SSL takes the form of  $\alpha_{SSL} = \eta \times F \times (\lambda/\lambda_0)^{-3}$  ( $F$ : core mode and core contour overlap;  $\lambda$ : wavelength,  $\lambda_0$ : calibration constant) and scales with the square of surface roughness root-mean-square (rms) height, *i.e.*,  $\alpha_{SSL} \propto h_{rms}^2$  [2]. The multiplying factor  $\eta$  in  $\alpha_{SSL}$  relates to the surface quality and is proportional to  $h_{rms}^2$ . In the thermodynamic-equilibrium surface roughness (TESR) scenario, the silica roughness levels amount to  $\sqrt{k_B T_G / \gamma} \sim 0.4$  nm ( $k_B$ : Boltzmann constant,  $T_G$ : glass transition temperature,  $\gamma$ : interfacial tension). In this context, diminishing the SSL levels must rely on manipulating the surface roughness. Recent results have shown that the roughness along the fiber drawing direction can be lowered by controlling the drawing stress [3]. Furthermore, SSL reduction enables the advent of optical fiber with unprecedentedly low transmission loss and solarization resistance, which, in turn, gives UV-photonics a strong leverage to further industrial and scientific applications.

Here, we report on the fabrication of HCPCFs with improved core surface quality and record low loss in the short-wavelength range. To accomplish it, we revisited the usual HCPCF fabrication methods and obtained a rms roughness reduction from  $\sim 0.4$  nm in fibers drawn with standard fabrication methods to 0.15 nm in fibers fabricated by using an innovative technique. The new fibers have, therefore, sub-TESR levels. The reduction in the core roughness allowed attaining fibers with ultralow loss: 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, 1.8 dB/km at 719 nm. We envisage that our investigation will confer a new panorama for fibers working in short-wavelengths and a new path for attaining ultra-smooth surfaces for next-generation applications in photonics.

Fig. 1a displays the measured loss of the fibers we report here (F#1 and F#2) and their cross-sections. F#1 and F#2 are 8-tube single-ring tubular-lattice (SR-TL) HCPCF. F#1 has minimum loss of 50.0 dB/km at 290 nm, 9.7 dB/km at 369 nm, and 5.0 dB/km at 480 nm. The minimum attenuation values for F#2 are 0.9 dB/km at 558 nm and 1.8 dB/km at 719 nm. Fig. 1b contextualizes F#1 and F#2 minimum loss values within the IC HCPCF framework in the wavelength range between 250 nm and 900 nm. Also, Fig. 1b presents the silica Rayleigh scattering limit trend (SRSL), the CL, SSL, and total loss (TL = CL + SSL) trends, calculated by using the scaling laws reported in [4]. Here, we used  $\eta = 2133$ , corresponding to a fiber with TESR, and  $\eta = 300$ , corresponding to a surface-roughness rms that is 2.7 lower than the TESR rms. The  $\eta$  values have been estimated by adjusting them to the loss of fibers displaying TESR and sub-TESR levels [2, 3, 10]. Remarkably, F#1 and F#2 loss figures are new record low-loss values in the short-wavelength range [1, 5-9] and lies under the SRSL. Table 1 informs the fibers' geometrical parameters.

The remarkable ultralow loss reported above could be attained thanks to an amelioration of the core surface quality, which was accomplished by controlling the shear stress acting onto the cladding microstructure during the draw [3]. To study the effectiveness of the new fabrication approach, we assessed, by using a picometer resolution

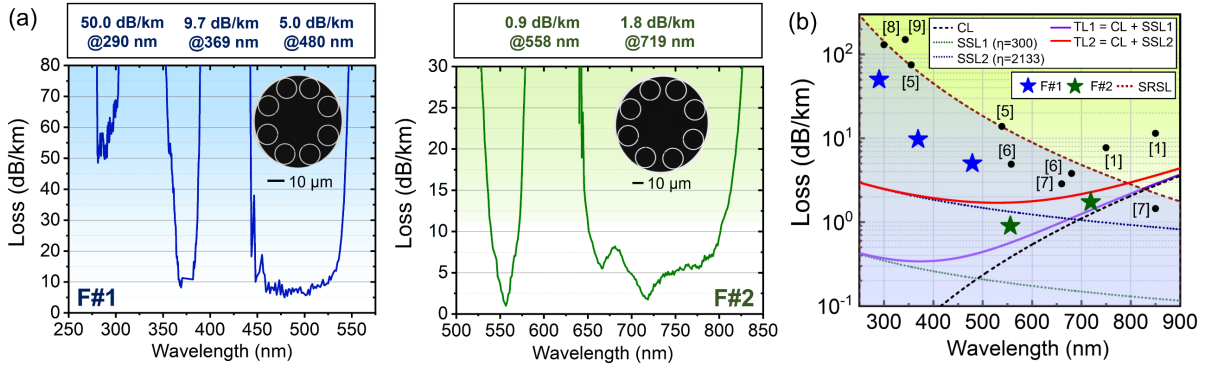


Fig. 1. (a) F#1 and F#2 measured loss and cross sections. (b) IC HCPCF state-of-the-art scenario together with SSSL, CL, SSL, and TL trends.

Table 1. F#1 and F#2 geometrical parameters.  $D_{core}$ : diameter of the core;  $t$ : tubes' thickness;  $g$ : gap between the cladding tubes;  $D_{tubes}$ : diameter of the cladding tubes.

Fiber	$D_{core}$ ( $\mu\text{m}$ )	$t$ ( $\mu\text{m}$ )	$g$ ( $\mu\text{m}$ )	$D_{tubes}$ ( $\mu\text{m}$ )
#1	27	0.6	2.1 – 4.7	11
#2	42	0.9	3.6 – 5.2	18

profilometer [11], the core roughness in two groups of tubular amorphous lattice cladding HCPCFs, G#1 and G#2. G#1 fibers have been drawn by using the standard procedure and G#2 fibers have been drawn by using our new methods. Fig. 2a exhibits typical surface profiles along the HCPCF axis of G#1 and G#2 fibers. Fig. 2a appraises that the peak-to-peak roughness of G#1 fibers has values around 1.5 nm while, for G#2 fibers, values around 0.5 nm. Fig. 2b displays the rms roughness of G#1 and G#2 fibers with different cladding tube thicknesses estimated from several surface roughness measurements. The rms roughness of G#1 fibers fluctuates around 0.4 nm. G#1 fibers have, thus, TESR. In turn, G#2 fibers have rms roughness around 0.15 nm, which is considerably lower than the TESR limit set by the SCW scenario in amorphous silica (Fig. 2b, dotted line). Fig. 2c shows the typical loss for G#1 and G#2 fibers with similar tubes thickness. The distinction between the loss trends is patent. The loss in the reported G#1 fiber ( $D_{core} = 41 \mu\text{m}$ ) presents a considerable loss increase for  $\lambda < 750 \text{ nm}$  due to SSL influence. In the reported G#2 fiber ( $D_{core} = 27 \mu\text{m}$ ), a decreasing loss trend is observed even for  $\lambda < 750 \text{ nm}$ . Fig. 2c also shows the CL, SSL, and  $\text{TL} = \text{CL} + \text{SSL}$  trends calculated by considering the scaling laws in [4]. It is seen that the TL turning point happens at shorter wavelengths for smaller SSL. The difference between the loss behaviors of G#1 and G#2 fibers is, hence, a signature of SSL reduction in the new fibers.

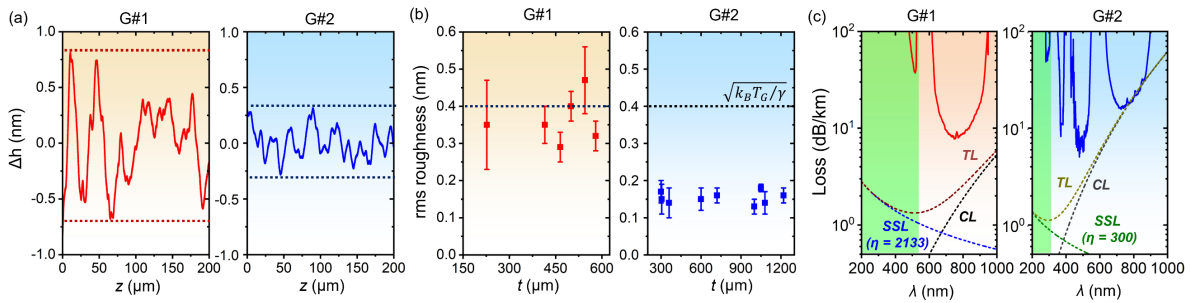


Fig. 2. (a) Typical core surface roughness profiles ( $\Delta h$ : roughness height variation) and (b) measured rms roughness. (c) Typical loss spectra for fibers in G#1 and G#2; CL, SSL and TL trends.

In summary, we developed HCPCFs exhibiting ultralow loss at short wavelengths by improving the fiber cores' surface quality and by attaining sub-TESR levels. We envision that our research will provide a new scenery for the next HCPCFs for the visible and ultraviolet ranges and a new avenue for attaining next-generation photonic devices with ultralow surface roughness levels.

This research was funded through PIA program (grant 4F) and la region de la Nouvelle Aquitaine.

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