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Abstract. We report on the development of new state-of-the-art ultralow-loss hollow-core fibers guiding in the short-wavelength range. The new record low attenuation values are as low as 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. Notably, the core roughness levels of the new state-of-the-art fibers are under the thermodynamic equilibrium limit set by the surface capillary waves scenario in amorphous silica.

The accomplishment of next-generation optical fibers for short-wavelengths, namely for the visible and ultraviolet (UV) ranges, are among the pressing needs for future developments in photonics. Particularly, UV photonics assumes a prominent position within the current technological and scientific frameworks, as it encompasses activities entailing or requiring the generation and control of light at wavelengths between 400 nm and 100 nm such as micro- and nano-processing and light transport. Indeed, fiber optics technology experienced remarkable progress in the latest years, as exemplified by the achievements in inhibited-coupling (IC) hollow-core photonic crystal fibers (HCPCFs) science and technology. However, while the results on the performance of HCPCF are noteworthy, new advances should be constrained to the improvement of the core surface quality in HCPCFs, as it hinders further loss decreasing due to scattering phenomena. Whereas the loss of IC HCPCFs guiding in the infrared remains limited by the fiber design (*i.e.*, by the confinement loss, CL), the current HCPCF state-of-the-art for guidance at short wavelengths ($\lambda < 800$-1000 nm) is set by the surface scattering loss (SSL) [1, 2]. Hence, even though the endeavors on cladding design optimization have allowed attaining substantial loss reduction in the infrared range, lessening the loss figures in the visible and UV ranges persists as a more challenging task due to SSL. SSL is determined by the fiber core surface roughness, which in turn arises from frozen-in thermal surface capillary waves (SCW) that are formed during the fiber draw.

SSL is described by $\alpha_{SSL} = \eta \times F \times (\lambda/\lambda_0)^{-3}$ (F: core mode and core contour overlap; λ: wavelength; λ_0: a calibration constant) and relates to the square of the surface roughness root-mean-square (rms) height, $\alpha_{SSL} \propto h_{rms}^2$ [3]. The factor η in α_{SSL} formula depends on the core surface quality and is proportional to h_{rms}^2. Under thermodynamic-equilibrium surface roughness (TESR) scenario, the roughness levels amount to $\sqrt{k_B T_G/\gamma} \sim 0.4$ nm for silica (k_B: Boltzmann constant, T_G: glass transition temperature, γ: interfacial tension). In this context, the reduction of SSL must count on the control of the core surface roughness. Recent results have demonstrated that lessening of roughness along the fiber drawing direction can be attained by controlling the drawing stress during fiber fabrication [4]. Indeed, SSL reduction would allow accomplishing fibers with unparalleled low transmission-loss and solarization-resistance, enabling further UV photonics industrial and scientific applications.

In this paper, we report on HCPCFs with improved core surface quality and ultralow loss in the short-wavelength range. By revisiting the usual HCPCF fabrication methods, we obtained a rms roughness reduction from ~0.4 nm, in fibers drawn with standard methods, to ~0.15 nm, in fibers fabricated by using our new techniques. The latter have, therefore, sub-TESR levels. Such reduction of the core roughness levels allowed obtaining 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. We foresee that our investigation will provide a new panorama for fibers with ultra-smooth core surfaces for the next-generation photonics applications.

Fig. 1 presents the measured loss of the fibers we report herein (F#1 and F#2) and their cross-sections. The fibers are singe-ring tubular-lattice (SR-TL) HCPCF composed of 8 non-touching tubes. Fig. 1 right-hand side plot shows the measured loss values within the wavelength range between 250 nm and 900 nm and the silica Rayleigh scattering limit trend (SRSL). F#1 has

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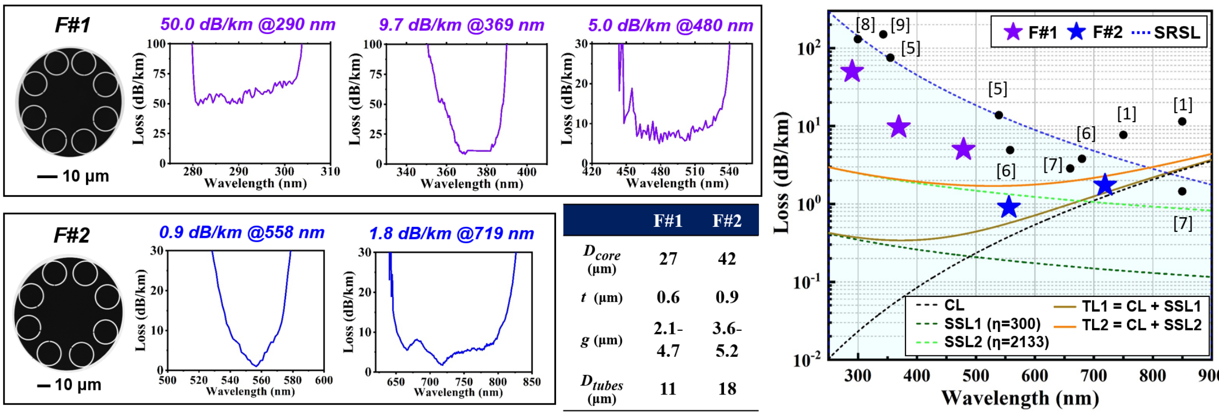

	F#1	F#2
D_{core} (µm)	27	42
t (µm)	0.6	0.9
g (µm)	2.1-4.7	3.6-5.2
D_{tubes} (µm)	11	18

Fig. 1. Measured loss for F#1 and F#2, the fibers' cross-sections, and a table with the fiber parameters. The plot on the right-hand side situates the results reported herein among other results in the literature together with the CL, SSL and TL trends.

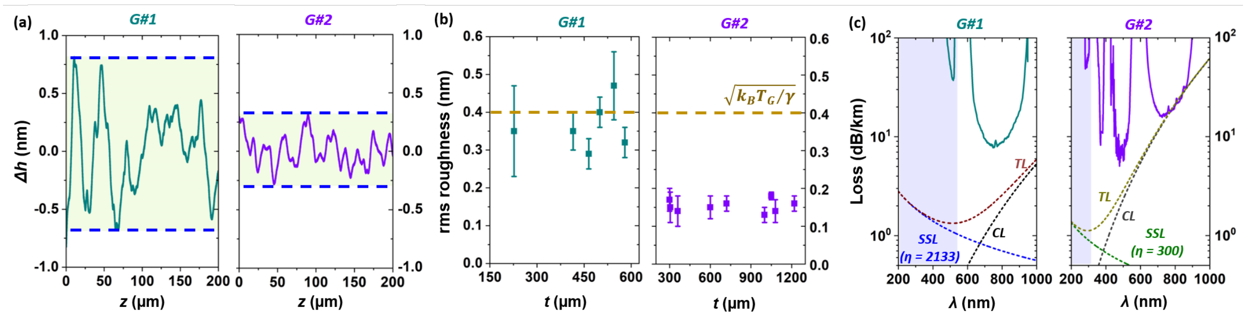

Fig. 2. (a) Typical core surface roughness profiles (Δ*h*: roughness height variation) and (b) rms roughness for fibers in G#1 and G#2 with different lattice tubes thicknesses, *t*. (c) Typical loss spectra for fibers in G#1 and G#2; CL, SSL, and TL trends.

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. Remarkably, such values are new record low-loss figures in the short-wavelength range [5-10] and are under the SRSL. The table in Fig. 1 lists the fibers' geometrical parameters (*i.e.*, their core diameter, D_{core}, the thickness and diameter of the cladding tubes, t and D_{tubes}, and the spacing between the lattice tubes, g).

The plot on Fig. 1 right-hand side situates the new state-of-the-art fibers within the framework of previously reported IC HCPCFs. Additionally, this graph exhibits the CL, SSL, and total loss (TL = CL + SSL) trends, calculated by using the scaling laws reported in [11]. Here, we used $\eta = 2133$, corresponding to a TESR fiber surface, and $\eta = 300$, corresponding to a surface-roughness rms that is 2.7 lower than TESR rms. The η values have been estimated by adjusting them to the loss of fibers displaying TESR and sub-TESR levels [2, 4, 12].

The noteworthy ultralow loss described above could be obtained due to an amelioration of the core surface conditions via the control of the shear stress acting onto the cladding microstructure during fiber fabrication [4]. To investigate the effectiveness of the new methods, we measured, by using a picometer resolution profilometer [13], the core roughness in two groups of SR-TL HCPCFs, G#1 and G#2. G#1 fibers have been fabricated by using standard procedures and G#2 fibers have been fabricated by employing an innovative technique.

Fig. 2a shows typical surface profiles along the axis of G#1 and G#2 fibers. The peak-to-peak roughness of G#1 fibers amounts to 1.5 nm while, for G#2 fibers, it has values around 0.5 nm. Fig. 2b presents the rms roughness of G#1 and G#2 fibers with different cladding tube thicknesses (t). The rms roughness of G#1 fibers oscillates around 0.4 nm. G#1 fibers have, thus, TESR. Instead, G#2 fibers have rms roughness around 0.15 nm, which is considerably lower than the TESR limit set by the SCW scenario (Fig. 2b). Fig. 2c shows the typical loss spectrum for G#1 and G#2 fibers with similar tubes thickness. The loss in the reported G#1 fiber (D_{core} = 41 µm) has a significant increase for $\lambda < 750$ nm due to the SSL. In the reported G#2 fiber (D_{core} = 27 µm), a decreasing loss trend is observed even for $\lambda < 750$ nm. Fig. 2c also shows the CL, SSL, and TL trends calculated by considering the scaling laws reported in [11]. One sees that the TL turning point occurs at shorter wavelengths for smaller SSL. The difference between the loss trends in G#1 and G#2 fibers is a signature of the SSL lessening in the new fibers.

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