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# Spectral attenuation limits of silica hollow core negative curvature fiber

Fei Yu\* and Jonathan C. Knight

Centre for Photonics and Photonic Materials, Department of Physics, University of Bath, Claverton Down, Bath, BA2 7AY, UK  
\*fy230@bath.ac.uk

**Abstract:** In this paper we discuss the limits of attenuation of silica hollow core negative curvature fibers in the wavelength range from 800 nm up to 4.5  $\mu\text{m}$ . Both numerical and experimental results are presented and show good agreement. A minimum attenuation of 24.4 dB/km was measured at around 2400 nm wavelength, while 85dB/km was measured at 4000 nm.

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**OCIS codes:** (060.2280) Fiber design and fabrication; (060.4005) Microstructured fibers; (060.2390) Fiber optics, infrared.

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## 1. Introduction

Hollow core fiber (HCF) is a novel form of optical fiber which has lower refractive index in the hollow core than in the cladding. Total internal reflection can therefore not explain confinement of light to the core of a HCF. HCFs can be broadly divided into hollow core photonic bandgap fibers [1, 2] and hollow core leaky mode fibers depending on the optical properties of the cladding structure. HCFs provide a new playground for study of light–gas interaction [3] and have many applications where the fiber material properties would usually become a limiting factor, such as in high power laser pulse delivery [4], mid-infrared and far-infrared wavelength transmission [5, 6], ultrafast laser pulse transmission [7] and so forth.

Leaky mode fibers do not have a photonic bandgap cladding, so that while light may propagate in the core with low attenuation, the modes are not confined to the core. In 1964 Marcatili and Schmeltzer [8] first systematically studied leaky mode properties of HCF and explored the attenuation limits of HCF in theory. To further reduce the attenuation for practical applications, inner-surface-coated hollow core fiber or dielectric coated hollow core fiber was proposed and it soon became an attractive alternative to solid-core fibers in the mid-infrared and far-infrared region [9]. “Kagome” fiber is a more recently-developed leaky mode fiber [3] which exhibits broader spectral transmission bands. Although its cladding exhibits periodicity, it does not possess a photonic bandgap.

Hollow core negative curvature fiber (HC-NCF) is a kind of leaky mode fiber which is defined by the negative curvature of the core boundary. The importance of the shape of the core boundary was first recognized in “Kagome” fibers in 2010 [10]. Later Vincetti and Setti numerically studied the cladding-simplified negative curvature fiber systematically and clarified the mode coupling interaction between the core and cladding [11]. Shortly afterwards Pryamikov et al. fabricated the cladding-simplified HCF which has no “Kagome” cladding lattice but just a negative curvature core boundary [12]. Light transmission through 63 cm length of fiber around 3  $\mu\text{m}$  was detected even though the fabrication material of HCF was fused silica which exhibits relatively high material absorption in this spectral region [13]. Kosolapov et. al. extended the transmission of similar structured HC-NCF to 10.6  $\mu\text{m}$  for CO<sub>2</sub> laser by using chalcogenide glass [14]. In 2012 we demonstrated silica HC-NCF with low loss transmission in the mid-infrared spectral region, with minimum attenuation of 34 dB/km at a wavelength of 3.05  $\mu\text{m}$  measured through 83 m fiber length [15]. Transmission of wavelengths beyond 4  $\mu\text{m}$  was also demonstrated. Later, the delivery of high energy microsecond pulses at 2.94  $\mu\text{m}$  was successfully demonstrated through the HC-NCF, which could be used for minimally invasive surgical laser procedures [6]. THz guidance was also demonstrated in this kind of HC-NCF made of polymethylmethacrylate [16]. Recently Kolyadin et. al. reported a modified silica HC-NCFs with contactless capillary cladding and demonstrated low loss transmission of light in the mid-infrared spectrum range from 2.5 to 7.9  $\mu\text{m}$  [17]. In their work the contactless capillary cladding structure was introduced to reduce the coupling between the core modes and strut modes and measured average attenuations at 5.8  $\mu\text{m}$  and 7.7  $\mu\text{m}$  were 30 dB/m and 50 dB/m respectively.

In this paper, we present further development of silica HC-NCFs covering the spectral range from 800 nm to 4.5  $\mu\text{m}$ . By analyzing data from HC-NCFs scaled for minimum attenuation in different spectral regions, the limits of HC-NCF attenuation are discussed. Numerical simulations which explain the observed attenuation limits are also presented.

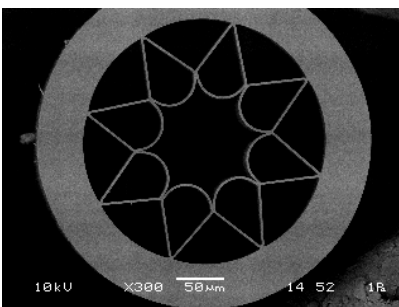


Fig. 1. Scanning electron micrographs of our typical HC-NCF with triangular cladding.

## 2. Numerical simulations

### 2.1 Approximations and analysis

The model of HC-NCF in our numerical simulations is presented in Fig. 2(a), which has cylindrical capillaries comprising the cladding as an approximation of our fabricated HC-NCF in Fig. 1. In photonic bandgap fibers, maintaining the complexity of the cladding is key to obtaining a photonic bandgap and reducing confinement loss [18]. In HC-NCF, simplification of the cladding structure has a negligible effect on the field confinement in the hollow core [19]. By comparing “Kagome” fiber with negative curvature core wall [10] with HC-NCFs [12, 14, 15, 17], it is found that the more complex cladding structures do not result in reduction of fiber attenuation. As a result, in our simulations we use a simplified cladding structure when compared to that shown in Fig. 1. This approximation reduces simulation difficulty including both computational time and complexity.

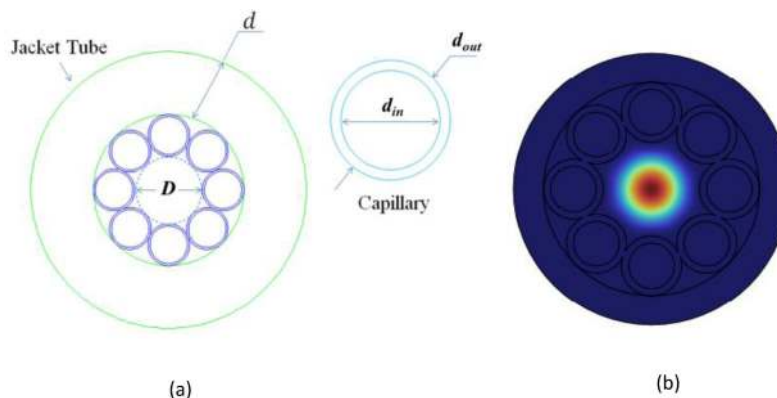


Fig. 2. (a) Simulated model of HC-NCF. (b) Energy flux density distribution of fundamental mode in simulations.

In Fig. 2(a) eight identical capillaries comprise the cladding of the modeled HC-NCF and the core has a closed boundary with negative curvature formed by adjacent capillaries being in contact. The core diameter  $D$  is defined by the shortest distance from capillaries across the core. Capillaries are characterized by their inner diameter  $d_{in}$  and outer diameter  $d_{out}$ . The ratio of inner diameter over outer diameter is defined by  $\eta = d_{in}/d_{out}$ . The external layer surrounding cladding capillaries is a jacket tube with wall thickness  $d$  protecting the fiber structure from the external environment.

To reduce loss, a larger core size is preferred in leaky mode fiber design although it may significantly increase bending loss [8]. Core size of HC-NCF can be increased by increasing the number of capillaries in cladding. To balance the core size and curvature of negative core wall, a design using eight capillaries in the cladding is chosen in our simulations and experiments.

## 2.2 Numerical results

In this section we use *Comsol 3.5*, commercial finite element method software, to calculate numerical results based on the model in Fig. 2(a). No material absorption is used in the simulations. All the attenuation results in this section reflect the leakage rates of fundamental-like mode patterns in HC-NCFs, computed using a perfectly matched layer.

Before starting we verified that the predictions of our model were not affected by the thickness of the outer jacket tube. We then varied the wall thickness of the eight capillaries defining the core. The dependence of the attenuation spectrum on the capillary wall thicknesses is presented in Fig. 3. As the thickness of the capillary decreases, the minimum attenuation is reduced and frequency of the low loss transmission bands reduces as well, as expected. The simulations suggest that thin capillary walls reduce the attenuation. The fluctuations in our simulations have been verified in many different simulations, and we believe that they may relate to electromagnetic states of cladding. In Fig. 3 both  $x$ - and  $y$ -axes are normalized by the core diameter.

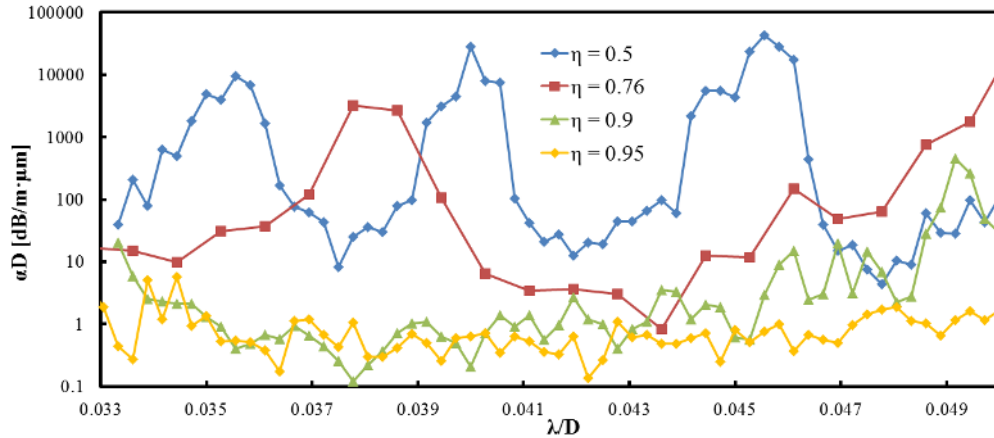


Fig. 3. Simulated normalized attenuation spectra in different condition of  $\eta$ . Neither material absorption nor material dispersion is considered in those simulations.

## 3. Experimental results

One advantage of HC-NCF in comparison with photonic bandgap fiber or “Kagome” fiber is that the simple cladding makes it straightforward to scale fiber size to different dimensions for applications in different spectral ranges. Scaling the entire fiber structure will not only shift the transmission bands and alter the bandwidth accordingly but may also change the absolute attenuation properties of the fiber. To explore the limits of attenuation of HC-NCFs many fibers of different sizes but nominally identical design were fabricated. The eight identical capillaries in the cladding were drawn from thin-walled silica tube (*Suprasil F300*, *Heraeus*) with  $\eta$  of 0.93. Nine fibers with the low attenuation in the first bands of their individual transmission spectra regions were selected as shown in Fig. 4. They span the infrared spectrum from 800 nm to 4500 nm and the minimum attenuation measured is 24 dB/km at 2400 nm wavelength. We attribute such low attenuation to the combined effects of the negative curvature core wall, and to the large core diameter which is 65  $\mu\text{m}$  in that case.

In the measurements, different absorbing regions were found from 2600 nm to 4500 nm. HCl molecules in the core of fiber, apparently originating from our starting material, results in the ro-vibrational spectrum between 3200 nm to 3700 nm [15]. CO<sub>2</sub> molecules in the air cause absorption between 4200 nm and 4400 nm [20]. Absorption lines of CO<sub>2</sub> (in the gas phase) and H<sub>2</sub>O overlap between 2600 nm and 2900 nm [20, 21]. Both molecules in the air and OH<sup>-</sup> in the silica could contribute to losses in this spectral range.

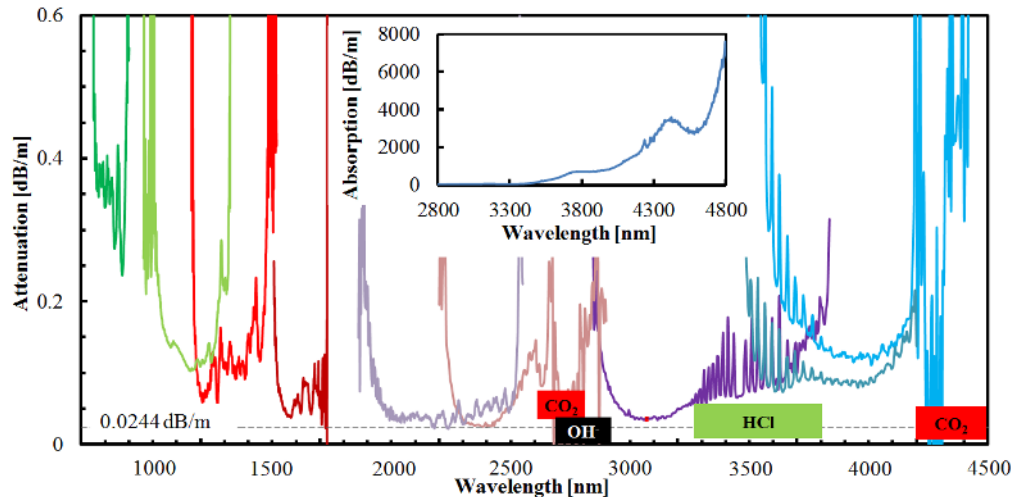


Fig. 4. Measured attenuation curves of the fundamental mode in the first transmission band in 9 different fibers. The absorption features between 3200 nm and 3700 nm are from HCl molecules in the fiber core [15], and between 4200 nm to 4500 nm are from CO<sub>2</sub> molecules [20]. Gas-borne CO<sub>2</sub> and H<sub>2</sub>O molecules and OH<sup>-</sup> in the silica material contribute to the absorption feature between 2600 nm to 2900 nm [20, 21]. Inset: Measured material absorption of F300 synthetic fused silica used as fabrication material.

Figure 5 shows the minimum attenuations measured in the fibers from Fig. 4. In the short wavelength region from 700 nm to 1300 nm, the minimum measured attenuation scales approximately with the wavelength  $\lambda$  as  $\lambda^{-3.6}$  as shown. Fibers in this spectral range are smaller and more difficult to fabricate. We attribute the observed rapid increase of attenuation below 1  $\mu\text{m}$  to a combination of surface scattering [18] and decreased structural integrity.

In the wavelength range between 1  $\mu\text{m}$  and 3  $\mu\text{m}$ , confinement loss dominates the attenuation, varying as  $1/\lambda$  [18]. A fit to our data finds scaling with wavelength  $\lambda$  as  $\lambda^{-0.998}$ , consistent with this assumption.

At long wavelengths beyond 3500 nm, material absorption from silica rises rapidly from tens of dB/m to thousands of dB/m [13]. Our own measurement of material absorption of the F300 synthetic fused silica used in our work (Fig. 4. inset) shows that the material absorption already exceeds 865 dB/m at 4  $\mu\text{m}$  wavelength. We simulate the effect of material absorption on fiber loss by using *Comsol*, and predict that fiber attenuation will be around 7000 times less than the material absorption due to the very low overlap of the guided mode with the glass at these long wavelengths (Fig. 5. inset). By scaling the measured material absorption by this factor and adding it to the predicted confinement loss from *Comsol*, the total fiber loss (orange dashed line in Fig. 5) is found to increase rapidly with material absorption and to dominate the attenuation of HC-NCF in this spectral range. Measured attenuation for our best fiber was found to be 85 dB/km at 4  $\mu\text{m}$  wavelength, which is 10000 times less than the measured bulk glass absorption.

In conventional solid core fibers, the attenuation is limited by Rayleigh scattering and by multi-phonon absorption at short and long wavelengths, respectively. However, in hollow core fiber, due to small overlap between core mode and fiber material those effects are significantly reduced [18]. In the long wavelength range beyond 3  $\mu\text{m}$ , phonon absorption starts to dominate the loss as the material absorption rises above hundreds of dB/m. Below 1  $\mu\text{m}$ , the increased attenuation accompanies decreased structural integrity. In this spectral range, we speculate that surface scattering is increased as the overlap between the core mode and core boundary increases. At intermediate wavelengths, and away from the OH<sup>-</sup> absorption bands in the silica matrix [21], attenuation is limited by confinement losses.

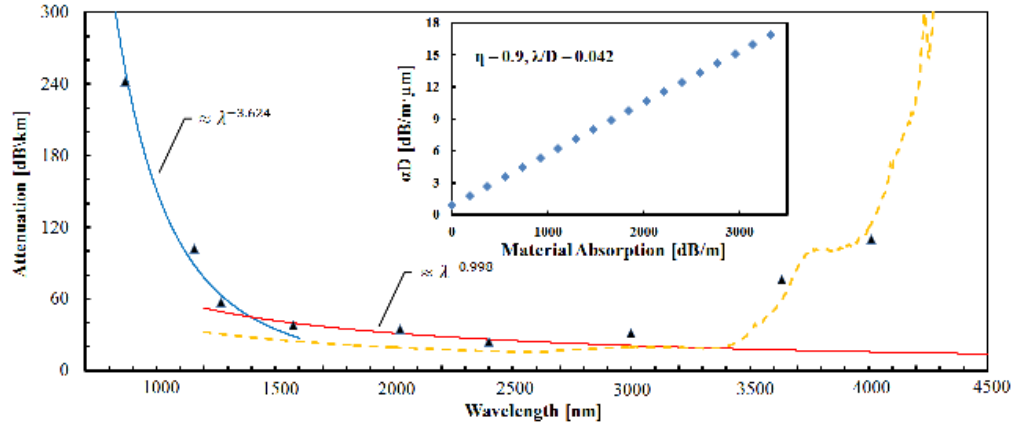


Fig. 5. Scaling of minimum attenuations with wavelengths. Measured data is shown as triangles. The blue and red solid lines represent fits to selected points of attenuation =  $A \cdot \lambda^x$  with a resulting  $x$  of  $-3.642$  and  $-0.998$  separately (blue curve fitting data points between 700 nm and 1300 nm; red curve fitting points between 1500 nm to 2500 nm). The orange dashed line is total attenuation based on predictions of confinement losses from *Comsol* and scaled absorptive loss. Inset: Simulation showing simulated variation in fiber attenuation as silica material absorption increases.

#### 4. Conclusions

In this paper both numerical and experimental results are presented to determine the limits of attenuation of HC-NCFs at mid-IR wavelengths. Numerical simulations indicate that the capillary wall thickness greatly influences the attenuation of HC-NCF. By tuning the wall thickness, low loss transmission can be obtained in HC-NCF. Different NCFs were designed and fabricated for coverage of various spectral regions. The scaling of minimum attenuation with wavelengths reveals that surface scattering and structural imperfections, confinement loss and material absorption dominate attenuation properties of HC-NCFs in different wavelength ranges. We measure attenuation of 24 dB/km at 2.4  $\mu\text{m}$  wavelength (limited by confinement) and 85 dB/km at 4  $\mu\text{m}$  wavelength where the material absorption is about 865000 dB/km. Future work will focus on exploring other properties of HC-NCFs such as loss property from bending, core mode polarization and resonance coupling between core mode and cladding mode and higher order band transmission. Further work is required to fully understand the relationship between the core wall curvature and the observed low attenuation.

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