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Extending the transmission of a silica hollow core fiber to 4.6 μm

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Abstract: In this work, an anti-resonant hollow core fiber was designed for 3-5 μm transmission and fabricated from fused silica. Due to strong core confinement, low transmission loss was measured in the MWIR, with only 0.128 dB/m loss at 4.05 μm and 0.316 dB/m loss at 4.63 μm. This pushes the usable transmission windows and the potential application areas for silica-based ARHCF beyond what has previously been shown to be possible.

1. Introduction

Silica-based optical fiber is the standard for most applications due to its high optical purity, mechanical strength, and the maturity of the manufacturing process. For applications requiring guidance in the mid-infrared wavelength region, however, less conventional glasses must be used due to the high absorption of silica beyond 2-3 μm [1–4]. Alternatively, guiding light in a hollow core fiber enables transmission beyond the absorption limitations of the fiber material. For example, anti-resonant hollow core fibers (ARHCFs) have been shown to guide light with low loss at wavelengths significantly beyond the limit of the fused silica absorption [2,5–9]. Yu and Knight presented a silica-based ARHCF with a loss of only 32 dB/km around 3 μm [5], followed by a fiber with a loss of 85 dB/km at 4 μm [6]. A loss of 50 dB/km was achieved by Kolyadin et al at 3.39 μm [7]. Klimczak et al. showed a nested ARHCF with a propagation loss of 1.5 dB/m and low bend loss from 3.6 to 4 μm [8]. The guidance of mid-wave infrared (MWIR) light in these silica-based fibers is possible due to the strong confinement of the fundamental mode within the air core, allowing for very little overlap of the light with the glass structure of the fiber [2,10]. The anti-resonant hollow core design enables the use of a mature and robust glass for the fabrication of optical fiber in applications requiring transmission in the MWIR region of the spectrum, such as biochemical sensing, infrared countermeasures, and various medical applications.

Some applications, such as infrared countermeasures, require lower loss guidance up to 5 μm. Previous work has shown MWIR guidance nearing this wavelength through a fused silica-based ARHCF, including Pierscinski et al. with 8.5 dB/m at 4.57 μm [11], and Nikodem et al. with 6 dB/m at 4.54 μm [12]. While these loss values are relatively low for fused silica in this wavelength range, they are still too high for many applications. In this work, we focused on designing an ARHCF with guidance throughout the MWIR, pushing the region of low loss further into the MWIR than has been previously shown.

An ARHCF design was optimized for transmission in the 3-5 μm spectral region using Comsol Multiphysics. Low propagation loss, low bending loss, and high single mode purity were the three properties prioritized in the design.

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2. Fiber characterization

The fabrication of the ARHCF is based on the well-stablished stack and draw method, which is a stable and very controlled drawing process. Using this technique, we can achieve long fiber sections whose structure is unaltered along their length. The glass used for our fiber was high purity synthetic silica glass (Heraeus F300). The application of accurate differential pressure was used during the drawing process to achieve the final structure for the desired transmission window. An SEM cross section of the drawn fiber is shown in Fig. 1. It has a core size of approximately 100 µm, capillary diameters of 65 µm, and capillary thicknesses of 930 nm.

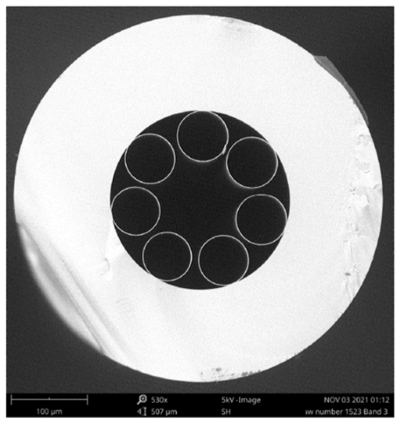

Fig. 1. SEM cross-section of ARHCF drawn at Univeristy of Central Florida.

The transmission through the ARHCF was measured using a Leukos Electro-MIR 4.8 supercontinuum source and a Thorlabs OSA205C. Top and bottom of Fig. 2 show the normalized transmitted spectra through 4.4 m and 25.7 m, respectively, coiled with a 35 cm diameter. Absorption lines can be seen around 3.5 µm and 4.3 µm due to HCl and CO_2, respectively [6].

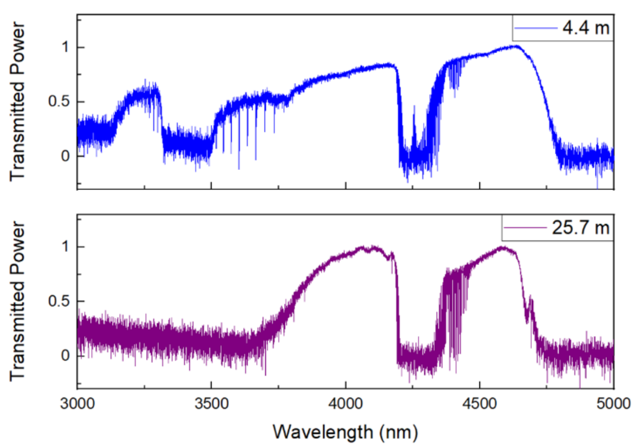

Fig. 2. Transmitted spectra through 4.4 and 25.7 m of ARHCF, measured with a Leukos Electro-MIR 4.8 supercontinuum source and OSA.

Apart from this absorption, strong transmission can be seen from 3.2-4.7 µm, even at relatively long fiber lengths. The strong absorption of HCl around 3.5 µm moves the transmission edge up

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to ~3.9 µm when transmitting through longer fiber lengths; however, Yu et al. was able to purge their fiber and eliminate the absorption caused by HCl [5].

The transmission drop below 3.2 µm is caused by the coupling of the fundamental core mode to a capillary mode, due to the bend in the fiber [13]. Figure 3 shows the simulated loss spectrum, along with modes images at 2.3, 2.7, and 3.3 µm when the ARHCF is bent to a 35 cm diameter in the + x direction. From ~2.5-3 µm the fundamental mode (FM) in the core couples to an outer capillary mode, resulting in very high power leakage. This is what causes the loss below 3.2 µm in the 4.4 m transmission spectra shown in Fig. 2.

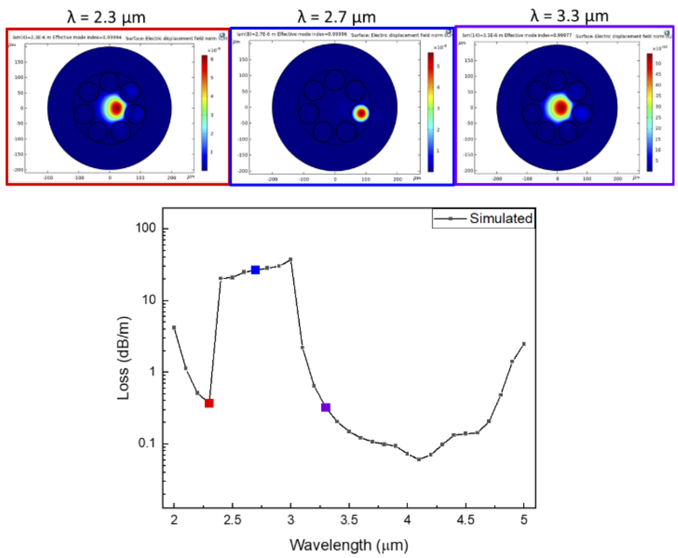

Fig. 3. Simulated loss spectrum, with mode images at 2.3, 2.7, and 3.3 µm.

As the bend diameter increases, the wavelength mode coupling occurs at decreases, widening the mid-infrared transmission window. This effect is demonstrated in Fig. 4 where simulated FM loss spectra are shown for various bend diameters in the -y direction. At larger diameters, the loss in the 3 - 4 microns window drops significantly leading to a widened IR transmission range when the FM core mode no longer couples into the capillary mode. This ARHCF was designed to obtain high transmission from 3-5 µm. If a lower loss at the low wavelength end is desired, the coupling to capillary modes can be mitigated by simply using larger bend diameters. At a bend diameter of 90 cm, the coupling resonance is eliminated from the transmission window, and the simulated loss at 3 µm drops below 0.01 dB/m. There is, however, a tradeoff with mode purity and bend loss. For example, at a bend diameter of 35 cm and a wavelength of 4.05 µm, the first higher order mode has a loss of about 2 dB/m, giving a higher order mode (HOM) extinction ratio of 30. When the fiber is straight, the first HOM loss is only 0.35 dB/m, and the HOM extinction ratio drops to 13. The fundamental mode losses and HOM extinction ratios were calculated for three wavelengths in both straight and bent configurations, and are shown in Table 1 below. The fundamental mode loss and HOM extinction ratio were not calculated for the bent fiber at 3 µm, as an LP_{11}-like mode was the lowest loss mode for this configuration.

Cutback measurements were done at two discrete wavelengths using QCLs of 4.05 µm and 4.63 µm. The fiber was bent to a diameter of 35 cm for all measurements. Due to limited fiber length, the cutback at 4.05 µm was measured with only two lengths, 29 m and 5 m, but was repeated for higher accuracy. The measured loss was 0.128 dB/m at 4.05 µm and 0.316 dB/m at 4.63 µm, shown in Fig. 5. These measured values are also shown as green triangles in Fig. 4

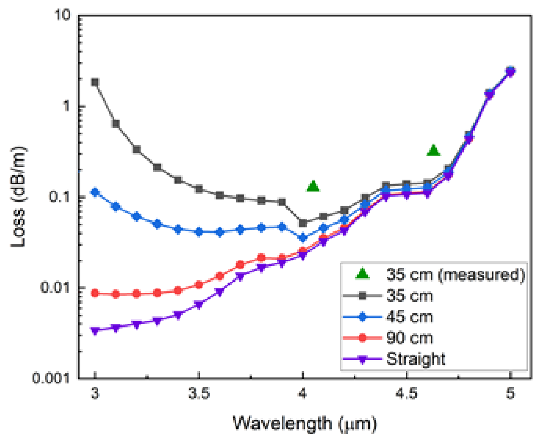

Fig. 4. Simulated loss spectra at various bend diameters, compared to measured loss values (green triangles).

Table 1. Simulated losses and HOM extinction ratios

Wavelength (μm)	Straight		35 cm	
	LP_{01} loss (dB/m)	HOM extinction ratio	LP_{01} loss (dB/m)	HOM extinction ratio
3	0.0034	22.67		
4.05	0.027	12.98	0.055	29.49
4.63	0.121	8.51	0.153	56.23

and can be directly compared to the propagation loss estimated by Comsol for the same bending diameter of 35 cm. The measured loss values agree rather well with the simulated spectrum and are about a factor of 2 higher than the calculated losses of 0.07 dB/m and 0.165 dB/m for 4.05 μm and 4.63 μm, respectively. The slightly higher measured loss values are to be expected due to non-uniformities in the as-drawn fiber compared to the perfect fiber version used in the simulations.

As shown in Fig. 4, at 4.05 μm a bend dependent loss is predicted by simulation. This was tested experimentally through bending ~5 m of the ARHCF to various bend diameters while monitoring the transmitted power at both 4.05 and 4.63 μm. It was observed that the transmitted power increased with increasing bend diameter for both wavelengths, see Fig. 6. While this was expected from Fig. 4 for 4.05 μm, the simulation predicted a low bend sensitivity at 4.63 μm. It was speculated that the unexpected bend loss came from some higher order mode content in the core of the fiber. Table 1 shows that the HOM extinction ratio is low enough that with only ~5 m of fiber length, some HOM content is possible. To support this theory, the bending loss was calculated for the LP_{11} modes, and combined with the LP_{01} bending loss at varying ratios in order to match the measured loss. The results are shown in Fig. 7. The calculated loss from the cutback measurements done at 35 cm were combined with the relative losses measured at various diameters shown in Fig. 6, leading to estimated losses at each of the measured bend diameters (green triangles). It should be noted that the loss of this ARHCF drops below 0.1 dB/m and 0.2 dB/m at 4.05 and 4.63 μm, respectively, when bent to larger diameters. The measured loss is compared to the simulated losses of the fundamental mode and the mixture of the LP_{01} and LP_{11} modes. A close approximation of the measured loss was achieved with the addition of 0.05% and 0.1% of LP_{11} mode content for 4.05 and 4.6 μm, respectively.

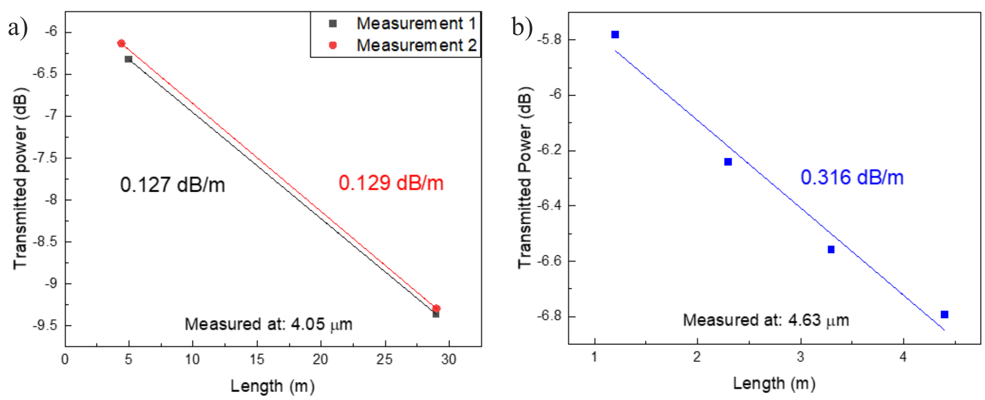

Fig. 5. Cutback measurement at a) 4.05 μm and b) 4.63 μm, both coiled to a 35 cm diameter.

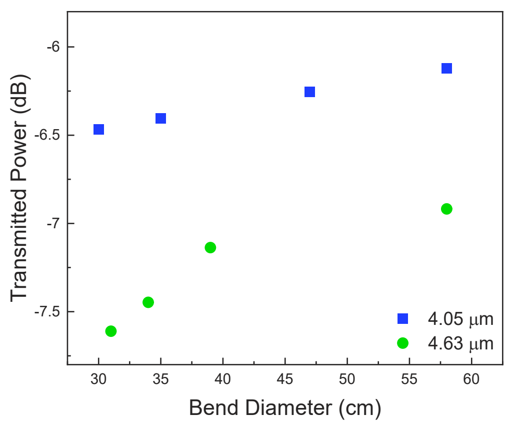

Fig. 6. Transmitted power vs. bend diameter through ~5 m of ARHCF at 4.05 and 4.63 μm.

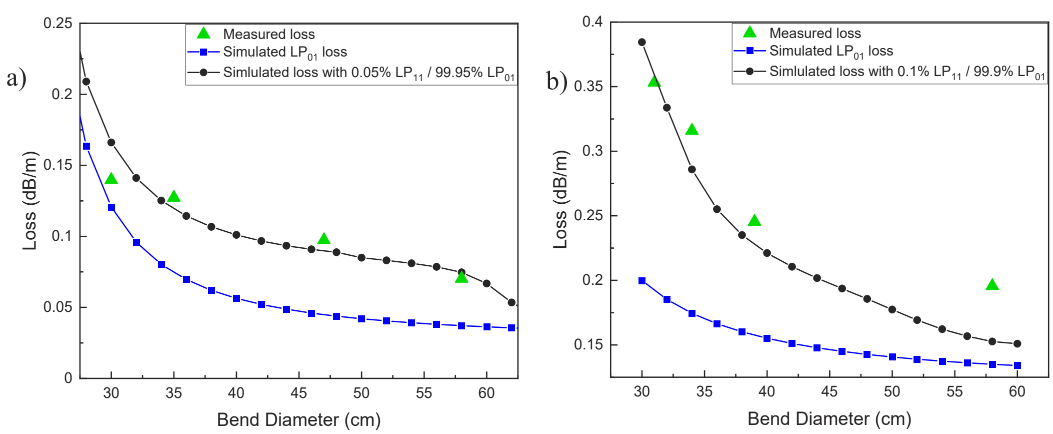

Fig. 7. Comparison of measured bend loss to simulated loss at a) 4.05 μm and b) 4.63 μm.

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3. Discussion

The loss of this fiber shows improved transmission above 4 µm over previous work. For example, a silica-based ARHCF was shown by Yu et. al, with a low loss of only 0.04 dB/m at 4 µm. However, this fiber had no transmission above 4.2 µm [14]. The measured loss value of 0.316 dB/m at 4.63 µm is significantly lower than previously published values in the 4.5-4.6 µm wavelength range for silica-based hollow core fibers (8.5 dB/m at 4.57 µm [11] and 6 dB/m at 4.54 µm [12]). When compared to IR glass fibers, this value is similar to that of commercially available single mode InF fibers, ~0.25 dB/m at 4.5 µm [4], and only slightly higher than state of the art chalcogenide fibers at 0.1-0.2 dB/m [15]. While the losses achieved with these fibers are similar to this work, silica fiber manufacturing is mature and silica fiber is significantly more robust and environmentally stable than InF or chalcogenide fiber, with recent reports showing the capability to draw up to 1.7 km of ARHCF with very low loss [16]. In order to achieve transmission at wavelengths above 5 µm, ARHCF has been fabricated with Tellurite, with losses of 8.2, 4.8 and 6.4 dB/m at 5 µm, 5.6 µm and 5.8 µm, respectively [17]. The authors attribute the high losses to fabrication difficulties, which lead to non-uniformities in the capillaries, but predict that values under 0.3 dB/m could be achieved with improved extrusion techniques.

The reason for such low propagation loss at a wavelength where the silica absorption is ~1500 dB/m is the strong core confinement, which was calculated to allow only 0.005 percent overlap of the fundamental mode power with the glass. Such strong confinement enables pushing the transmission bandwidth of a fused silica-based fiber well beyond its traditional limits.

In conclusion, we have shown a silica-based ARHCF with guidance up to 4.6 µm, relatively low loss below 1 dB/m in the MWIR, and acceptable bending losses. This shows that the wavelength region where alternative fiber glass materials need to be used can be pushed to longer wavelengths than previously considered. Therefore, silica-based ARHCF can be a viable option for MWIR transmission in the 3-5 µm region, an important atmospheric window for applications such as infrared counter measures and remote sensing [18].

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Disclosures. The authors declare no conflicts of interest.

Data availability. Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

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