Low loss silica hollow core fibers for 3–4 μm spectral region

Fei Yu,* William J. Wadsworth, 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: We describe a silica hollow-core fiber for mid-infrared transmission with a minimum attenuation of 34 dB/km at 3050 nm wavelength. The design is based on the use of a negative curvature core wall. Similar fiber designed for longer wavelengths has a transmission band extending beyond 4 μm.

©2012 Optical Society of America

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

References and links
1. F. K. Tittel, D. Richter, and A. Fried, “Mid-infrared laser applications in spectroscopy,” in Solid-State Mid-Infrared Laser Sources, I.T. Sorokina and K.L. Vodopyanov, ed. (Springer, 2003).
2. B. Jean and T. Bende, “Mid-IR laser applications in medicine,” in Solid-State Mid-Infrared Laser Sources, I.T. Sorokina and K.L. Vodopyanov, ed. (Springer, 2003).
3. B. Gaspare and U. Skaleric, “Clinical evaluation of periodontal surgical treatment with an Er:YAG laser: 5-year results,” J. Periodontol. 78(10), 1864–1871 (2007).
4. O. Humber, H. Fabian, U. Grzesik, U. Haken, and W. Heitmann, “Analysis of OH absorption bands in synthetic silica,” J. Non-Cryst. Solids 203, 19–26 (1996).
5. R. Kitamura, L. Pilon, and M. Jonasz, “Optical constants of silica glass from extreme ultraviolet to far infrared at near room temperature,” Appl. Opt. 46(33), 8118–8133 (2007).
6. J. S. Sanghera, L. B. Shaw, and I. D. Aggarwal, “Applications of chalcogenide glass optical fibers,” C. R. Chim. 5(2), 873–883 (2002).
7. T. Katagiri, Y. Matsuura, and M. Miyagi, “Metal-covered photonic bandgap multilayer for infrared hollow waveguides,” Appl. Opt. 41(36), 7603–7606 (2002).
8. J. Harrington, “A review of IR transmitting, hollow waveguides,” Fiber Int. Opt. 19(3), 211–227 (2000).
9. B. Temelkuran, S. D. Hart, G. Benoist, J. D. Joannopoulos, and Y. Fink, “Wavelength-scalable hollow optical fibres with large photonic bandgaps for CO2 laser transmission,” Nature 420(6916), 650–653 (2002).
10. J. Shephard, W. Macpherson, R. Maier, J. Jones, D. Hand, M. Mohrbait, A. George, P. Roberts, and J. Knight, “Single-mode mid-IR guidance in a hollow-core photonic crystal fiber,” Opt. Express 13(18), 7139–7144 (2005).
11. N. Gayraud, L. W. Kornaszewski, J. M. Stone, J. C. Knight, D. T. Reid, D. P. Hand, and W. N. MacPherson, “Mid-infra-red gas sensing using a hollow-core photonic bandgap fiber,” Optical Fiber Sensors (OFS) 2006 paper TuA5 (2006).
12. W. Rudolph, A. V. V. Nampoothiri, A. Ratanavis, A. Jones, R. Kadel, B. R. Washburn, K. L. Corwin, N. Wheeler, F. County, and F. Benabid, “Mid-IR laser emission from a CH2 gas filled hollow core fiber,” Transparent Optical Networks (ICTON) paper Tu.B2.4 (2010).
13. Y. Wang, F. County, P. J. Roberts, and F. Benabid, “Low loss broadband transmission in optimized core – shaped Kagome Hollow Core PFC,” in Conference on Lasers and Electro-Optics/Quantum Electronics and Laser Science, Postdeadline Papers (Optical Society of America, 2010), paper CPDB4.
14. Y. Y. Wang, N. V. Wheeler, F. County, P. J. Roberts, and F. Benabid, “Low loss broadband transmission in hypocycloid-core Kagome hollow-core photonic crystal fiber,” Opt. Lett., 36(5), 669–671 (2011).
15. A. D. Pryamikov, A. S. Birukov, A. F. Kosolapov, V. G. Plotnichenko, S. L. Semjonov, and E. M. Dianov, “Demonstration of a waveguide regime for a silica hollow-core microstructured optical fiber with a negative curvature of the core boundary in the spectral region > 3.5 μm,” Opt. Express 19(2), 1441–1448 (2011).
16. A. D. Kosolapov, A. D. Pryamikov, A. S. Birukov, V. S. Sharyaev, M. S. Astapovich, G. E. Snopatin, V. G. Plotnichenko, M. F. Charbanov, and E. M. Dianov, “Demonstration of CO2-laser power delivery through chalcogenide-glass fiber with negative-curvature hollow core,” Opt. Express 19(25), 25723–25728 (2011).
17. L. S. Rothman, I. E. Gordon, A. Barbe, D. C. Benner, P. F. Bernath, M. Birk, V. Boudon, L. R. Brown, A. Campargue, J.-P. Champion, K. Chance, L. H. Coudert, V. Dana, V. M. Devi, S. Fally, J.-M. Flaud, R. R. Gamache, A. Goldman, D. Jacquemart, I. Kleinir, N. Lacome, W. J. Lafferty, J.-Y. Mandin, S. T. Massie, S. N. Mikhailenko, C. E. Miller, N. Mouazen-Ahmad, O. V. Naumenko, A. V. Nikitin, J. Orphal, V. I. Perevalov, A. Perrin, A. Predoi-Cross, C. P. Rinsland, M. Rotger, M. Šimečková, M. A. H. Smith, K. Sung, S. A. Tashkun, J. Tennyson, R. A. Toth, A. C. Vandaele, and J. Vander Auwera, “The HITRAN 2008 molecular spectroscopic database,” J. Quant. Spectrosc. Radiat. Transf. 110(9-10), 533–572 (2009).
1. Introduction

The mid-infrared (mid-IR) wavelength range, which is usually defined as being between 2 μm and 25 μm wavelength, is characterized by the strong vibrational absorption lines of various molecules, and as a result is also known as the ‘molecular fingerprint’ region [1]. With the emergence of new generations of mid-IR laser sources, there is increasing interest in this spectral window for applications in spectroscopy and medicine [1–3]. Consequently the availability and performance of optical fibers with transmission in this spectral range is of great interest.

Material absorption has always been one of the limitations on fiber performance in the mid-IR. Fused silica, the most common optical fiber material, exhibits extraordinary mechanical and chemical durability but is limited by its high attenuation (above 60 dB/m) at wavelengths longer than 3 μm [4, 5]. Soft glasses, such as chalcogenides and fluorides, which possess a much lower absorption, have been widely adopted as optical fiber materials for the mid-IR [6]. However, compared with the mature state of silica fabrication, the processing routes for purification and fiber drawing still need much improvement to achieve the theoretical performance limits for many of these materials [6].

Hollow core waveguides have been investigated as an alternative transmission medium in the mid-IR spectral region [7–9]. In hollow core fiber, the optical damage threshold is raised while the material absorption problem is reduced. Current industrial laser delivery systems using inner-surface-coated hollow core fiber have attenuation as low as 0.1 dB/m and can transmit continuous-wave 10 μm wavelength CO₂ laser powers as high as 2.7 kW [7]. However, the fabrication technique of coated hollow fiber is more complicated than other hollow fibers such as photonic crystal fiber (PCF) and the transmission suffers from high bending sensitivity. Silica hollow core PCF for mid-IR transmission was first reported in 2005 with attenuation of 2.6 dB/m between 3100 nm and 3200 nm, and exhibited excellent bending loss characteristics [10]. PCF for 3 μm transmission has since been reported with less than 1 dB/m attenuation [11]. “Kagome” fiber filled with acetylene gas was reported for mid-IR laser generation recently, guiding pump light of 1521 nm and two laser lines at 3123.2 nm and 3162.4 nm at same time [12], although the attenuation was high (20 dB/m).

Benabid and colleagues [13] described the importance of the curvature of the core wall in their “Kagome” fibers in 2010 and they recently extended this work [14], while Pryamikov et al. reported measurements on a 63 cm long hollow silica fiber without a photonic band gap or a “Kagome” cladding but with a negative curvature core wall, and demonstrated transmission bands extending to beyond 4 μm wavelength [15]. Likewise, a later paper used chalcogenide glass to demonstrate a negative-curvature fiber which extended the transmission region to 10.6 μm for CO₂ laser transmission [16]. Our work describes long, low-attenuation hollow core fiber formed from silica with a negative curvature core wall in the mid-IR spectral region. We demonstrate that such fibers can provide attenuation as low as 34 dB/km at a wavelength of 3.05 μm. Transmission of wavelengths beyond 4 μm was also achieved.

2. Fiber fabrication

The fiber was fabricated by using the stack and draw technique, which has been extensively adopted in fabricating photonic crystal fiber. Eight identical capillaries were drawn from thin-walled silica tube (Suprasil F300, Heraeus) and inserted into a larger jacketing tube. By precisely adjusting parameters in the drawing process, we were able to control the core size and core wall thickness as well as the curvature of the core wall, which together determine the
guidance properties. A scanning electron micrograph of one of the fibers is shown in Fig. 1. The core as shown in Fig. 1 is 94 μm across the narrowest diameter and the average core wall thickness is 2.66 μm.

![Fig. 1. Scanning electron micrograph of a hollow fiber with negative curvature of the core wall. The core diameter is 94 μm and the average strut thickness around the core is 2.66 μm.]

Attenuation in these fibers is limited by the rate at which light in the core can couple to the modes of the surrounding structure. In our fiber (Fig. 1) light in the core could couple to modes of the uniform curved core wall, and also to modes of the glass waveguides formed within the cladding structure at the nodes where the adjacent capillaries touch. The inscribed circle of the core roughly determines the extent of the modal distribution of the guided light. Increasing the core wall curvature increases the distance from the inscribed circle to the cladding nodes, and hence decreases the coupling between the modes of the core and those of the cladding, reducing the attenuation of the fiber. During fiber fabrication the curvature of the core wall was intentionally increased to reduce the fiber attenuation. The curvature of the core wall is 26° μm−1 as shown in Fig. 1.

3. Demonstration of mid-IR guidance

Spectral characterization of the fiber was carried out by using a Bentham T3c300 Monochromator, with a 300 lines mm−1 grating and a liquid nitrogen cooled InSb detector. The fiber was filled with nitrogen during the draw, and it was stored in a desiccator after being rewound from the drawing drum. It was removed from the desiccator for measurements but replaced afterwards, to avoid ingress of atmospheric air into the fiber length.

4.1 Attenuation measurement

The attenuation was determined by cut-back measurements. A tungsten halogen bulb was used as a broadband light source. The total fiber length in the measurement was 83 m which was cut back to 3.1 m. The resolution of the monochromator was set to 10nm. As Fig. 2 shows, the lowest attenuation was measured to be 34 dB/km at 3050 nm, and the low-loss band spans over 900nm from 2900nm to 3850nm. A second measurement in which we cut the fiber from 79.9 m to 78 m gave a similar minimum attenuation of 32 dB/km at 3050 nm.

In the attenuation spectrum, a high loss region appears from 2500 nm to 2800 nm (high loss region I in Fig. 2). Within this band we could not reliably record a transmitted signal even for shorter fiber lengths. This region overlaps with a known OH absorption band in silica [4]. However, we believe that the very high attenuation in region I is not due to OH absorption, as the transmitted light would be in the nitrogen-filled core. Instead, we attribute it to a structural loss feature – a resonance of the core wall – which coincides with the OH absorption band in this particular fiber (see section 4.4). Beyond 3800 nm (high loss region II), no light could again be detected over the full 83 m of fiber, although shorter lengths showed transmission as far as 4 μm. We attribute this to the rapid increase in the absorption of silica in this range (see section 4.4).
We have performed a laser transmission measurement through the 79 m fiber to verify the spectral transmission band found in the cut-back measurement, using a Thorlabs H339P2 infrared Helium-Neon laser with 3392 nm wavelength. The detected wavelength of the transmitted HeNe laser in the inset of Fig. 2 is 3388 nm, offset by 4 nm from the known value, presumably due to a small miscalibration of our spectrometer.

As seen in Fig. 2, absorption peaks appear in the transmission band from 3300 nm to 3700 nm. By comparing the measured absorption spectrum with known gas absorption spectra from the HITRAN 2008 database [17, 18], we found an excellent match in both the peak wavelengths and the relative strengths to HCl. The presence of trace amounts of HCl in our fiber would appear to be reasonable given that our starting material is F300 synthetic fused silica, which the manufacturers state contains 1450ppm of Chlorine [19], and our measurement is over 80 m of path length. Analysis of the observed absorption lines’ positions and strengths compared to those from the HITRAN database is shown in Fig. 3.

We have confirmed that purging the fiber with nitrogen removes the absorption lines, and that for a shorter piece of fiber (e.g. 10 m) they disappear after the fiber is stored in the desiccator for 24 hours.
4.2 Confinement in the core

We investigated the confinement of the guided light by using a fiber butt-coupling technique. The tungsten lamp was used to excite a 79.9 m length of fiber, which was then butt-coupled to a second 3 m length of identical fiber coupled directly to the monochromator. The transmitted signal was then recorded at the wavelength of 3115 nm as we translated one fiber relative to the other. The recorded data (Fig. 4) are consistent with the guided light being confined to the hollow core. No deconvolution has been applied.

![Graph](image)

Fig. 4. Results of the mode-field experiment using linear and logarithmic scales. The data shown were recorded at a wavelength of 3.15 µm. The core diameter is 94 µm.

4.3 Bending loss

Bending loss was measured by bending a 2.3 m fiber into a semicircle. One end was excited using the tungsten lamp and the other end was connected directly to the monochromator. We scanned the transmission spectra with different bend diameters D.

![Graph](image)

Fig. 5. Bend loss measurements. Light from a tungsten halogen lamp is coupled into 2.3 m fiber and the output spectrum is measured with monochromator. The middle of fiber is bent in a half circle of different diameters D and both ends are kept straight as shown in the inset.

Figure 5 shows that, with D above 40 cm, bending loss does not affect the transmission spectrum significantly, although there is some evidence of loss at shorter wavelengths. When D becomes smaller than 40 cm, the shorter-wavelength spectral regions in the transmission band are substantially attenuated before the longer wavelengths. For bend diameters of 30 cm and less there was substantial attenuation over much of the bandwidth. Bend loss is expected in this fiber in which there are no truly confined modes. The increased attenuation at smaller
bend radii may be associated with conversion of the guided light to higher-order modes with higher attenuation.

4.4 Anti-Resonance shift

The fiber reported here does not have a photonic band gap cladding. Instead, the leakage rate from the core is reduced (when compared to that expected from a standard capillary) whenever the propagation constants of the core modes do not match any modes in the core surround [20]. According to the model if we change the core wall thickness, the high loss regions would shift, with the resonance (high-loss) wavelengths $\lambda_{res}$ given by

$$\lambda_{res} \sim \frac{2d}{m} \sqrt{n_{clad}^2 - n_{air}^2},$$  \hspace{1cm} (1)

where $d$ is the thickness of the core wall, $m$ is a positive integer and $n_{clad}$ is the refractive index of silica, which is taken as 1.419 [21] for the mid-IR region around 3 µm. For $m = 2$ and $d = 2.66$ µm this gives 2.68 µm as a high-loss wavelength. In a second similar fiber of length 7 m which we drew with a core diameter of 108 µm and an average core-wall thickness of 3.0 µm, Eq. (1) would give 3.02 µm, in agreement with observations (Fig. 6). The spectral features associated with the OH band are now apparent in the transmission spectrum through this shorter piece of fiber, and are distinct from the high-attenuation region. Although 7 m of fiber was too short for us to accurately measure the minimum attenuation, a cutback measurement showed that the attenuation at 4 µm wavelength was below 0.5 dB/m.

![Transmitted spectrum through 7 meters of fiber with 108 µm core, with dashed line representing the theoretical resonant (high-loss) wavelength. The OH absorption lines are unresolved in this 10 nm resolution scan.](image)

Fig. 6. Transmitted spectrum through 7 meters of fiber with 108 µm core, with dashed line representing the theoretical resonant (high-loss) wavelength. The OH absorption lines are unresolved in this 10 nm resolution scan.

5. Conclusion

We have described the a silica based hollow core fiber with a low loss (34 dB/km) transmission window in the mid-IR. We have confirmed that the light was confined to the hollow core and we explain the spectral dependence in terms of resonances of the core wall. Bend loss was low for bending diameters greater than 40 cm. Future work will focus on bend loss reduction, polarization and modal content of the guided light and power transmission.

Acknowledgment

This work was partly funded by the UK Engineering and Physical Sciences Council under EP/I011315/1. Further funding from Heriot Watt University (under EP/G039097/1) is gratefully acknowledged.