

# Low Loss, Tightly Coilable, Hollow Core Photonic Bandgap Fibers for Mid-IR Applications

N. V. Wheeler, M. N. Petrovich, A. M. Heidt, N. K. Baddela, E. N. Fokoua, J. R. Hayes, S. R. Sandoghchi, F. Poletti and D. J. Richardson

Optoelectronics Research Centre, University of Southampton, Highfield, Southampton, SO17 1BJ, UK  
e-mail: [nvw1v10@orc.soton.ac.uk](mailto:nvw1v10@orc.soton.ac.uk)

**Abstract**— We describe low loss (50dB/km at 3.3 $\mu$ m) and low bend sensitivity mid-IR hollow core-photonic bandgap fiber. Gas sensing applications are highlighted by a methane spectrum recorded in our fiber.

**Keywords**—Hollow core-photonic bandgap fiber; mid-infrared; gas sensing; spectroscopy.

## I. INTRODUCTION

Advances in optical sources such as quantum cascade lasers, frequency combs and broadband supercontinua operating in the mid-infrared (mid-IR) spectral region ( $\sim 2 - 20 \mu\text{m}$ ) are driving an increasing interest in these wavelengths [1], [2]. The atmospheric transmission window between 3 and 5  $\mu\text{m}$  which overlaps with many fundamental absorption bands of molecular species opens up applications in fields such as environmental and industrial sensing, security and medical diagnostics. For these applications, a low loss optical fiber is highly beneficial; providing access to remote or hazardous areas and the means to fabricate compact, lightweight and portable devices.

Conventional, all-silica solid fibers, while integral to many applications at near-IR wavelengths, are not suited for mid-IR transmission due to the high material absorption of silica beyond 2  $\mu\text{m}$  [3]. Fibers fabricated from materials such as ZBLAN can provide low attenuation [4]; however, they cannot currently provide the combination of durability, bend insensitivity, modal quality and power handling offered by silica fibers in the near-IR. Hollow core photonic crystal fibers (HC-PCFs), consisting of an air core surrounded by a periodic array of air holes defined by a silica matrix, provide an alternative approach, capitalizing on the outstanding properties of silica glass in fiber fabrication while keeping attenuation low due to minimal overlap between the guided optical modes and the silica structure. Recent outstanding results [5], [6] have produced low attenuation fibers in

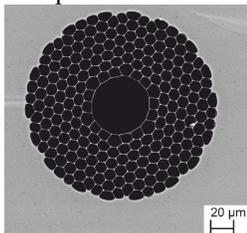


Fig. 1: SEM of an example mid-IR HC-PBGF

remarkably simple fiber geometries.

In this paper we review our recent progress in fabrication of hollow core-photonic bandgap fiber (HC-PBGF, a type of HC-PCF) for mid-IR operation which combines low loss (50 dB/km) with low bend sensitivity [7] and is highly suited for applications in the 3 to 4  $\mu\text{m}$  spectral region such as high power laser delivery as well as gas sensing; this is highlighted by a high resolution spectrum recorded using 1.26m of methane-filled HC-PBGF.

## II. FIBER FABRICATION

The HC-PBGFs have a 19 cell core and were fabricated using the conventional two-step stack and draw process. A thin-walled core surround combined with careful pressure control during the fiber draw enables optimization of the final fiber geometry towards minimizing attenuation and maximizing the fiber's operating bandwidth. A scanning electron microscope image of an example fiber is shown in Fig. 1; the average core diameter is 50  $\mu\text{m}$ , the average hole-to-hole distance is 9.3  $\mu\text{m}$  and the relative hole size is 0.965.

## III. FIBRE CHARACTERISATION

The mid-IR transmission was measured using a custom built supercontinuum source which extends from 0.75 to 4  $\mu\text{m}$  by using a diode seeded picosecond thulium-doped fiber amplifier operating at 2  $\mu\text{m}$  to pump a ZBLAN fiber. For signal detection a monochromator with 5 nm nominal resolution was initially used as it provided the means to detect transmission across the full fiber bandwidth. The fiber attenuation was calculated by a cutback loss measurement. Fig. 2a shows the cutback measurement for the fiber in Fig. 1 which indicates a minimum loss of  $130 \pm 50$  dB/km and sub-dB/m transmission from 3.1  $\mu\text{m}$  to beyond 3.6  $\mu\text{m}$ . This loss result improves on the previous best HC-PBGF operating in this spectral region by an order of magnitude [8]. In the low loss transmission region of Fig. 2a several loss peaks are visible which can be attributed to HCl absorption; HCl is in the fiber due to the presence of chlorine in the dehydrated synthetic silica used as the raw fabrication material. These absorption lines are shown in more detail in Fig. 2b where a high resolution (0.2 nm) optical spectrum analyzer was used for detection. The minimum recorded loss was likely to be limited due to the presence of this species and the limited monochromator resolution, therefore the HCl was removed

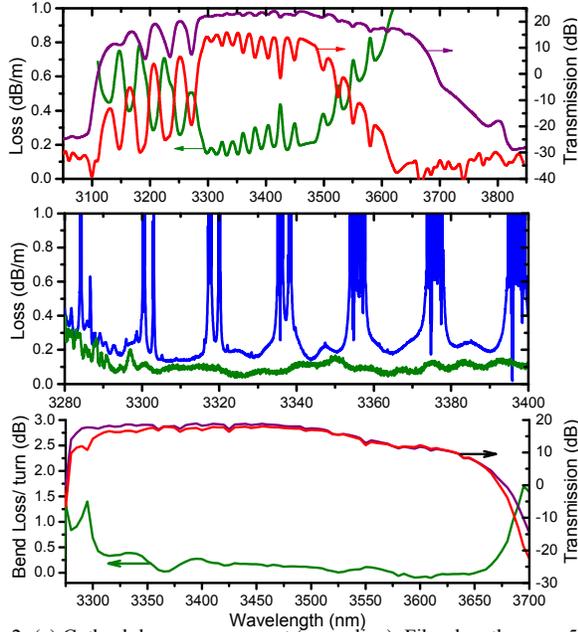


Fig. 2: (a) Cutback loss measurement (green line). Fiber lengths were 58 and 5m, shown by red and purple lines respectively, (b) Cutback loss measurements recorded with 0.2 nm resolution before and after purging fiber to remove HCl (blue and green lines respectively), (c) Bend loss per 5 cm turn (blue line) calculated from transmission of 5 m of HC-PBGF with five coils of 5 cm diameter in the fiber (red line) and with the fiber loosely coiled (purple line).

by purging the fiber with Argon gas. The cutback measurement was then repeated (also shown in Fig. 2b and at 0.2 nm resolution) and the minimum loss was found to be 50 dB/km. From extensive modelling of the fiber, further loss reduction and the ability to push the transmission window further into the mid-IR is expected through increasing the core diameter, e.g., by using a 37 cell HC-PBGF design [9].

The bend loss was found by comparing the transmission of 5 m of loosely coiled fiber, with the same fiber spooled to include five coils with 5 cm diameter. Fig. 2c shows that the resultant bend loss per turn is  $<0.25$  dB/turn over a 300 nm bandwidth; this is significantly lower than that reported recently for anti-resonant HC-PCFs designed for operation in the mid-IR showing that this fiber is suitable for applications requiring a compact device footprint.

#### IV. APPLICATION: GAS SENSING

Hollow core fibers are particularly interesting for gas sensing as the fiber can act as the host for the gas species under investigation as well as the optical waveguide. Use of fundamental molecular absorption bands present in the mid-IR increases the potential sensitivity of a gas sensing device by orders of magnitude compared to the use of weaker, near-IR absorption bands. As an example of the sensitivity achievable using gas-filled HC-PBGF we filled 1.26m of a fiber with a similar design to that in Fig. 1 with 1000 ppm of methane in nitrogen. The transmission spectrum, shown in the lower part of Fig. 3, is in excellent agreement with data from HITRAN (shown in the top part of the figure). By using longer fibers in combination with more sophisticated

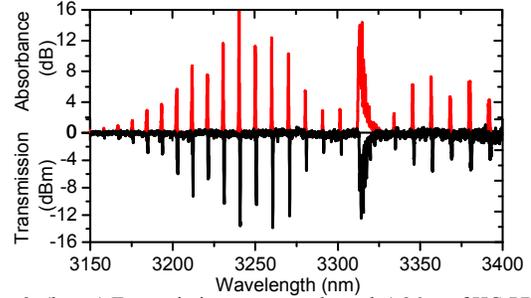


Fig. 3: (lower) Transmission spectrum through 1.26 m of HC-PBGF filled with 1000 ppm  $\text{CH}_4$  in  $\text{N}_2$ , (top) theoretical transmission of filled fiber using data from the HITRAN database [10].

detection techniques we envisage that sensitivity levels of the order of ppb will be easily achievable in these fibers.

#### V. CONCLUSIONS

We report fabrication of low loss (50 dB/km) and low bend sensitivity HC-PBGFs for operation in the mid-IR. Potential applications of these fibers include gas sensing and high power laser delivery. We anticipate that further loss reduction can be achieved through optimization of the core geometry, in particular by increasing the core diameter to minimize modal overlap with the silica fiber framework.

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