Extruded single ring hollow core optical fibers for Raman sensing

G. Tsiminis*[a], K. J. Rowland[a], H. Ebendorff-Heidepriem[a], N. A. Spooner[a,b] and T. M. Monro[a]
[a]Institute for Photonics and Advanced Sensing and School of Chemistry and Physics, The University of Adelaide, Adelaide, South Australia 5005, Australia
[b]Defence Science & Technology Organisation, South Australia 5111, Australia

ABSTRACT

In this work we report the fabrication of the first extruded hollow core optical fiber with a single ring of cladding holes. A lead-silicate glass billet is used to produce a preform through glass extrusion to create a larger-scale version of the final structure that is subsequently drawn to an optical fiber. The simple single suspended ring structure allows antiresonance reflection guiding. The resulting fibers were used to perform Raman sensing of liquid samples filling the length of the fiber, demonstrating its potential for fiber sensing applications.

Keywords: Microstructured fiber, Raman spectroscopy, fiber sensor, chemical sensing, hollow core fiber

1. INTRODUCTION

Hollow core optical fibers have shown great promise for a number of applications as they provide high overlap of the guided mode and the hollow core, they can carry higher powers than solid core fibers as light is guided in air instead of glass, and they can extend light transmission outside the limits of the fiber material itself.[1-3] The most widespread category of such fibers is hollow core photonic crystal fibers (HC-PCF), where the guiding mechanism relies on a large number of sub-wavelength features periodically arranged around the hollow core, making them costly and difficult to fabricate by capillary stacking.[4, 5] Antiresonance guiding fibers, where optical guiding is achieved by Fabry-Perot reflection off the walls of a waveguide, in the simplest case a thin capillary suspended inside an outer thicker jacket, have emerged as a category of fibers that combines the advantages of HC-PCFs with simpler fabrication,[6] resulting in geometries such as a single suspended ring[7, 8] and negative radius of curvature hollow cores structures.[9] The advantages of these fibers have made them interesting platforms for a range of chemical and biological sensing applications.[10, 11]

In this work we demonstrate the first extruded single ring hollow core optical fibers. Billet extrusion is a relatively simple, automated fabrication technique that allows us to produce fibers with features not easily attainable by capillary stacking. A single ring hollow core fiber was made from lead-silicate (F2) glass with wall thickness of 1.4 μm to support optical guiding in the visible part of the spectrum. We demonstrate the use of these fibers as chemical sensors, performing Raman spectroscopy of methanol solution loaded inside the voids of the fiber. This approach makes use of the enhanced interaction length between the guided optical mode and the sample that hollow core fibers allow. Our results highlight that extruded single ring hollow core optical fibers can enhance Raman signals in comparison to standard non-guided configurations, making them very interesting for use in chemical and biological sensing.

2. EXPERIMENTAL

2.1 Fiber fabrication

Single ring hollow core structures were fabricated using the glass billet extrusion technique. Lead-silicate glass (F2, Schott) was heated to 580°C and a force of 20 kN was applied by a ram to push the softened material through a steel die that incorporates the inverse desired structure, allowing the production of a preform (10 mm diameter) with the required structure. This preform was then directly drawn into a fiber, using internal pressurization to maintain the internal structure while making the core glass ring thinner relative to the outer diameter compared to the preform. Optical loss cut-back measurements were performed on the fiber using a supercontinuum source (NKT Photonics SuperK Compact). The transmitted light was free-space coupled into an optical spectrum analyzer (ANDO AQ6315E).

*georgios.tsiminis@adelaide.edu.au; phone +61(0)883132330; facsimile +61(0)883034380; www.adelaide.edu.au/ipas/

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2.2 Sensing experiments

The experimental setup used in the Raman sensing part of this work is shown in Figure 1. 100 mW light from a 532 nm CW laser (Laser Quantum gem) was reflected on a long-pass Raman filter (Semrock 532 nm long-pass RazorEdge ultrasteep) and focused using a 10x microscope objective. Light from the fiber was collected in backscattering geometry through the same objective and was collected by a multimode patch cable connected to a cooled-CCD spectrometer (Horiba Jobin Yvon iHR320). To enable complete filling of the fiber (20 cm length) and avoid air voids that could affect light coupling, both ends of the fiber were inserted into end cap sample chambers, where the optical window at the face of the fiber was a cover slip and the sealed assembly was subsequently filled with methanol, ensuring both ends of the fiber were in contact with the cover slip and fully immersed in liquid.

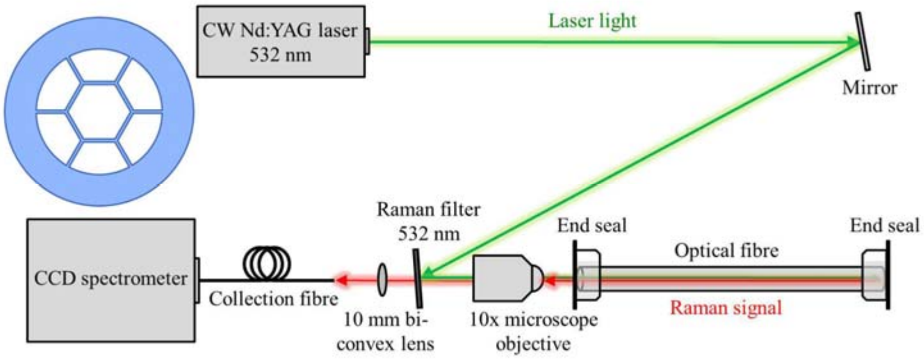

Figure 1. Experimental setup used in Raman sensing experiments with an extruded hollow core optical fiber. The inset shows a schematic of the fiber structure.

3. RESULTS AND DISCUSSION

The resulting fiber (Figure 2 inset) had an outer diameter of the fiber is 250 μm, a 40x reduction in size in comparison to the preform, with the hexagonal single ring core being 48 μm across (side-to-side distance). The average core wall thickness was 1.4 μm, supported by six struts of 820 μm average thickness. The measured optical loss of the fiber is shown in Figure 2 and at the excitation wavelength of 532 nm was measured to be 41 dB/m. The minimum confinement loss predicted by modelling a single suspended glass ring[12] of the same dimensions is 13 dB/m but this ignores deviations from the cylindrical geometry, surface scattering and material absorption.[13]

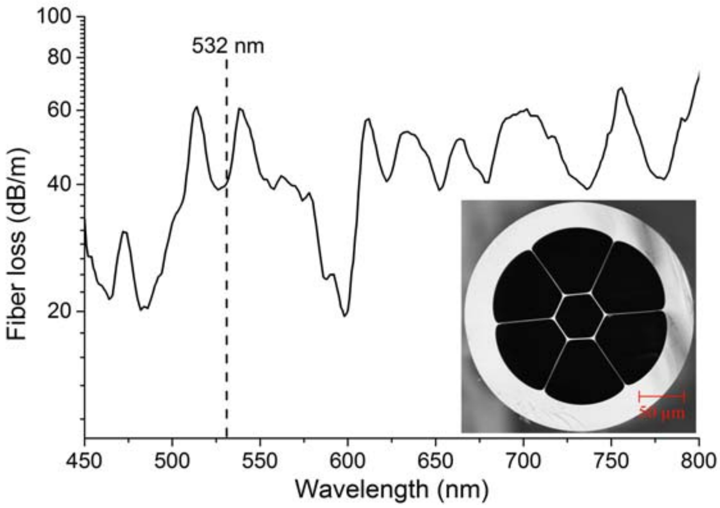

Figure 2. Measured optical loss from an extruded single ring hollow core optical fiber. The inset shows a scanning electron microscope image of the fiber.

Initially the sealed fiber assembly was filled with methanol and the pump beam was not coupled into the fiber but rather into the free liquid volume surrounding the fiber. The collected spectrum shows a weak contribution from the front glass window of the setup, visible as a broad peak below 500 cm^{-1} but the spectrum is dominated by the strong Raman methanol peaks[14] at 1033, 1448, 2832 and 2940 cm^{-1}, as well as the broader peak around 3330 cm^{-1}, as shown in Figure 3. When the pump light is primarily coupled into the outer jacket of the fiber the signal, as expected, contains an overwhelming contribution from the glass Raman background, visible as a broad peak below 750 cm^{-1}, a smaller peak at 800 cm^{-1} and a strong double peak at 1005 and 1060 cm^{-1}, with the methanol signature still visible. The glass contribution is much reduced when light is coupled into the hollow core of the fiber, while at the same time the methanol signal is enhanced by a factor of 2 times in comparison to the signal collected from the liquid free volume under the same confocal configuration.

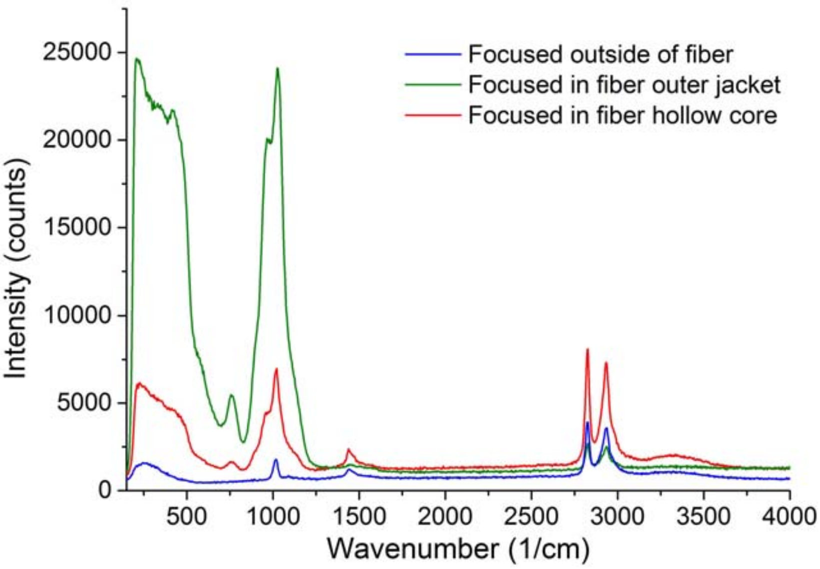

Figure 3. Raman spectra collected using an extruded single ring hollow core optical fiber for 532 nm excitation. The horizontal axis shows the wavenumber difference between the pump light and the observed signal, in units of 1/cm.

These results show an enhancement of sensitivity in Raman sensing in comparison to bulk measurements, a direct result of the extended light-sample interaction along the length of the fiber allowed by the guiding mechanism.

4. CONCLUSIONS

In this work single ring hollow core optical fibers are fabricated using the extrusion technique for the first time. The final dimensions and geometry of the fibers demonstrate the feasibility of the design and fabrication technique. These fibers are used as Raman sensors to detect methanol as a first step towards deploying them in more demanding chemical sensing applications such as explosives detection. These first results show a 2 times enhancement of the collected Raman signal in comparison to bulk measurements, despite the high optical loss of the fiber. By improving the design and fabrication of these extruded fibers to reduce the wall thickness of the core and increase mode confinement we aim to greatly reduce their optical losses towards the theoretical limits, increasing the overall signal enhancement and creating a flexible and customizable platform for optical fiber sensors.

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