Lotus Shaped Negative Curvature Hollow Core Fibre with 10.5 dB/km at 1550 nm Wavelength

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Abstract *We present a novel negative curvature antiresonant hollow core fibre design with the potential for low loss and very wide bandwidth. A low loss of 10.5 dB/km at 1550 nm is demonstrated, showing its potential for use in data transmission and high power beam delivery applications.*

Introduction

Due to the unique guidance mechanisms offered by hollow core photonic crystal fibres (HC-PCFs), which enable light transmission in low index media such as gas and liquid, these fibres are great contenders, as compared to solid core counterparts, for applications such as gas based linear/non-linear optics and laser and particle guidance[1]. Furthermore, they also have potential use in telecommunications and high power, ultra-short pulse delivery[2,3]. Based on their guidance mechanism, HC-PCFs are broadly categorised as hollow core photonic bandgap fibres (HC-PBGFs) and hollow core antiresonant/inhibited coupling fibres (HC-ARF). Within the broad HC-ARF category, many different fibre topologies have emerged, such as those with a Kagome cladding (K-HCF)[4], or with a simpler structure with a single ring of touching or non-touching tubes as antiresonant elements[5,6].

To date, HC-PBGFs still offer the lowest loss recorded, although this comes at the expense of the useable bandwidth (only 10s of nm in the lowest loss fibre[7]), and while this can be extended up to ~200 nm, this yields some compromise on the minimum loss[8]. On the other hand, in recent years the loss in K-HCFs, which offer octave wide bandwidth, has improved so much that at certain wavelengths they can already compete with PBGFs, albeit with an increased bend loss[4]. The main reason behind such dramatic recent improvement has been the realization of the importance of imposing a negative curvature hollow core (NCHC) boundary[9,10]. Early works observed that a K-HCF with a negative curvature core wall unexpectedly exhibited reduced attenuation as compared to the standard core geometry.[9]

These fibres were soon followed by attempts to reduce the cladding complexity by using a single ring of non-touching tubes surrounding the core. This was found to allow not only a faster preform preparation compared to PBGFs or Kagome fibres, but also in certain cases a lower transmission loss and a wider bandwidth[6,10]. One of the main practical challenges in the fabrication of non-touching tubes NCHC-ARFs is to achieve the required high uniformity in: (i) the gap between all the non-touching tubular elements and (ii) the size (and for mass conservation the thickness) of each glass tube. An example of a single ring tubular HC-ARF fabricated in our group is shown in Figure 1. Despite the regularity of the antiresonant elements in the structure of the cane (or primary preform), the fabricated fibre shows a somewhat non-uniform gap between the tubes, which prevents narrow gaps to be achieved without some of the tubes contacting each other. Besides, due to pressurisation during fibre draw, which accentuates small initial differences between the tubes, the size of all the tubular elements is also fairly different, with differences of 10-20% typical. The increased gap between the tubes eventually increases the leakage loss in such fibres. In addition to this, difference in the wall thicknesses of the single ring tubular elements will contribute to wider

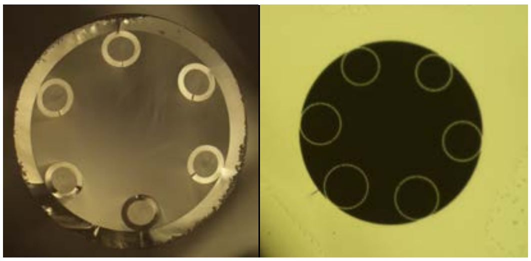

(a) **(b)**

Fig. 1: (a) Microscope image of cane, (b) Microscope image of a typical single ring tubular HC-ARF

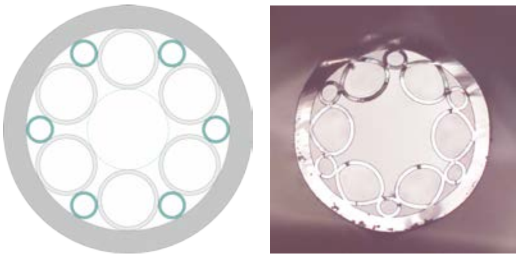

(a) (b)

Fig. 2: (a) Image of preform for cane draw, (b) microscopic image of fabricated cane

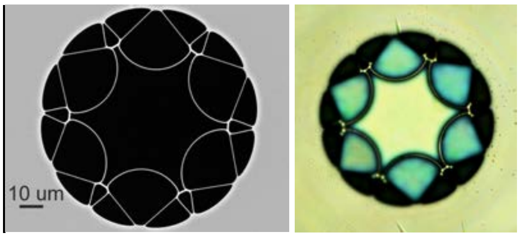
resonance peaks which will narrow the transmission bandwidth.

To address these limitations, in this work we have included additional smaller size capillaries in between the original tubes to help maintain a uniform gap between the antiresonant elements and add mechanical stability to the preform stack. The novel NCHC-ARF presented here clearly shows that as a result of the additional tubes a uniform gap distribution and size of the tubular elements can be achieved very controllably. A consequence of this is that the loss can be very significantly reduced, from ~30 dB/km at telecom wavelengths of Ref.[6] to only ~10 dB/km in this work. The compromise observed with this structure is some additional resonance peaks at specific wavelengths due to the presence of small nodes in the cladding.

Fibre design and fabrication

The NCHC-ARF presented here is fabricated using the standard two stage stack and draw method. The stack design and the fabricated cane are shown in Figure 2. We chose 6 identical capillaries to make the preform which eventually forms the main antiresonant tubular elements and a further 6 additional capillaries (smaller by a factor of 2) are included between the larger capillaries and the jacket tube. The fabricated fibre is shown in Figure 3. As can be seen, a small and very uniform gap between the large tubes could be achieved, which is essential to minimise leakage through the gaps. The critical fibre parameters such as the core radius, core wall thickness, microstructure radius and the fibre outer diameter are controlled by modifying the draw parameters. The fibre core diameter is around 40 µm and the average tube thickness is ~425 nm.

One notable aspect of this NCHC-ARF (and a downside of having the additional small spacing tubes) is the presence of additional nodes where big and small capillaries come in contact. These nodes can act as independent waveguides, introducing additional resonances in the spectrum. However, the negative curvature core wall helps to physically isolate or move away the core modes from these high loss modes and significantly reduces coupling between them.



(a) (b)

Fig. 3: Images of fabricated fibre: under (a) Scanning electron microscope, (b) Optical microscope

Fibre attenuation and bend loss

A 111 m long sample was used for the loss measurement via the cut back technique. The fibre was loosely coiled on the measurement bench to a diameter of ~30 cm. Using a white light source, light was launched into the fibre through a butt-coupled launch fibre with a mode field diameter of ~20 µm. An optical spectrum analyser (OSA, 400-1750 nm) was used to measure the transmission spectrum. The measured transmission and loss spectrum are shown in Figure 4. The lowest loss measured is 9.8 dB/km at 1612 nm and a loss of 10.5 dB/km is observed at 1550 nm. This presents the lowest loss recorded at a wavelength of 1550 nm with a NCHC-ARF, a considerable improvement over our previous result[6], which increases the appeal of this fibre for low latency data transmission at telecom wavelengths.

The two high loss peaks seen around 1245 nm and 1332 nm are resonance peaks due to the struts and nodes where two big and small tubular elements join. The observed total attenuation in this fibre is a combination of confinement loss and the loss due to micro and macro bend, which needs further quantitative study.

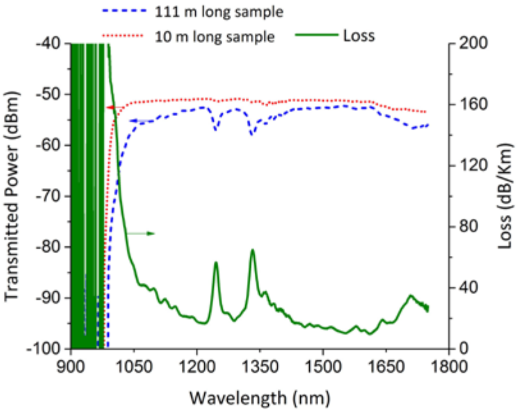


Fig. 4: Measured transmission spectra of 111 m (blue-dash) and 10 m (red-dots) cut back length with the calculated cut back loss (green)

To understand the bend robustness in this fibre and also to explore the possibility of using this fibre for beam delivery applications, macro bend loss measurements were carried out. For this experiment, before including a bend, the transmission for the straight condition is measured with an OSA. Without disturbing the input coupling and the output port, the fibre is bent on a board having different bend radii ranging from 20 cm down to 4 cm. The bend loss as a function of wavelength is shown in Figure 5. Down to bend radii of 8 cm, the attenuation due to bends for 1550 nm does not change significantly while there is a considerable shift of

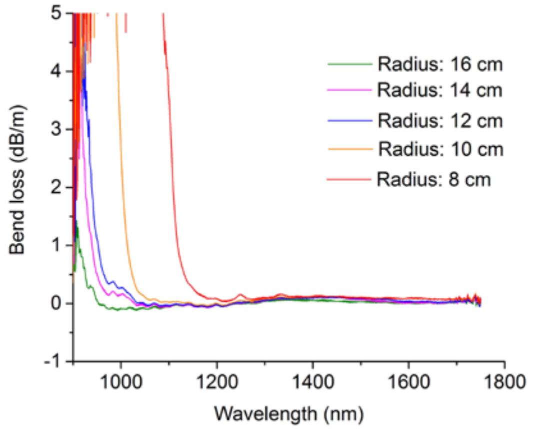
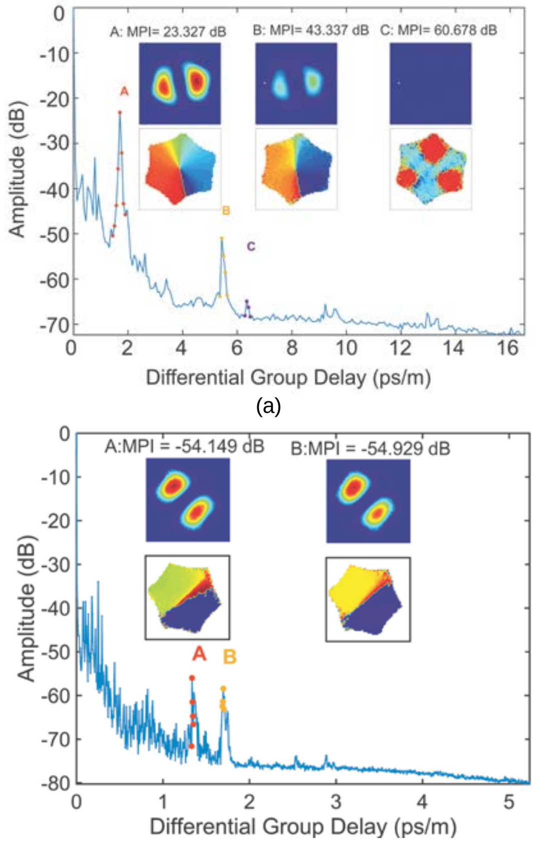


Fig. 5: Bend loss as a function of wavelength

the short wavelength edge. Also note that the cut back loss measurement performed was with a coiled fibre diameter of ~30 cm, which has already shown significantly low loss at 1550 nm.

S^2 measurement

As in any conventional large core fibre, HC-ARFs support higher order modes (HOM). It is known however, that a mode stripping mechanism exists that significantly attenuates most HOMs. To quantify the degree of HOM existence in this fibre, S^2 measurement for a short (23.5m) and long (76.5m) length samples were performed at 1550 nm. The measured results are shown in Figure 6. As can be seen, there is some residual LP_{11} mode after 23.5 metre length, however it becomes practically inexistent (down to over 60dB) after 76.5 metres, indicating that on long enough lengths (a few tens of metres) the fibre is essentially single moded.



(a)

(b)

Fig. 6: Group delay curve showing the mode content of the fibre (a) 23.5 m length, (b) 76.5 m length

Conclusions

We have demonstrated a novel negative curvature hollow core antiresonant fibre with a lotus shaped core, showing very low transmission loss at 1550 nm for this type of fibre structure. The additional capillaries in the cladding structure allow uniform distance between the antiresonant elements and uniform tube size to be achieved. The results from bend loss and S^2 measurements show that this fibre, with further optimisation, will prove promising for applications including data transmission and beam delivery.

Acknowledgements

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