# Arc-Shaped Multi-Layered Anti-Resonant Hollow-Core Fibre for Reduced Microstructure Diameter and Ultralow Loss

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**Abstract**. *An arc-shaped anti-resonant hollow-core fibre (AR-HCF) is fabricated with the outmost AR layer removed, reducing the microstructure diameter by 16%. A loss level below 0.5 dB/km from 1220 nm to 1340 nm and a minimum loss of 0.28 dB/km±0.1 dB/km @ 1290 nm has been achieved.* 

## Introduction

Achieving ultralow loss has been a long-term goal in the field of fibre optics. Silica-based solid core fibre has almost reached the intrinsic Rayleigh scattering loss (RSL) limit with a loss level of 0.14 dB/km [1], leaving little room for further optimization. Anti-resonant hollow-core fibre (AR-HCF, ARF for short) [2] has been considered as a potential candidate for achieving ultralow loss below the fundamental RSL limit of silica fibre, as more than ~99.9% of light is guided in the air core. In recent years, the attenuation of ARF has reached 0.174 dB/km [3] and it is projected that loss reduction to below 0.1 dB/km is possible in the near future [4]. This could revolutionize the ecosystem in optical fibre communication.

The guidance mechanism of ARF relies on the anti-resonant reflection of both the silica and air layer in the cladding [5]. The most efficient way of reducing the confinement loss (CL) of ARF is by adding more AR layers until CL no longer dominates the total loss and other loss mechanisms take over. For example, the conjoined tube fibre (CTF) [6] and nested antiresonant nodeless fibre (NANF) structure [7] could be considered to have 5 AR layers, while the doube-nested NANF (DNANF) possesses 7-8 AR layers [8]. However, with the increase in the AR layers, the size of the tubular units arranged in a rotationally symmetric pattern surrounding the core is subsequently enlarged, resulting in an increased microstructure diameter. For example, in the 5 tubular-units (5T) NANF structure, with a core diameter of 30 μm, the overall microstructure diameter (MSD) goes well beyond 100 μm. After adding a projective jacket outside the microstructure, the outer diameter reaches 200-250 μm, almost twice that of silica fibre. This makes the handling, such as splicing and cleaving, and deployment of ARF difficult. Reducing the fibre diameter is an efficient way to increase the core density in cables, which helps to increase the bandwidth of the optical transmission links.

In this work, we developed an arc-shaped multi-layered ARF structure which helped to reduce the MSD diameter by 13%-20%. The arc shape is formed by removing the outmost AR layer, which is proved to be inefficient in preventing light leakage. The fabricated arc-shaped ARF exhibits a loss level below 0.5 dB/km from 1220 nm to 1340 nm, with a minimum loss of 0.28 dB/km±0.1 dB/km @ 1290 nm. This loss level is similar to that of the series of 5T-NANF reported in previous studies [7], while showing a reduction in MSD, paving the way for dense optical interconnects in optical transmission system.

## Fibre Design

According to the multi-layered model [5], a typical NANF structure consists of five AR layers (Fig.1a left), including the 1$^{st}$ silica membrane AR layer from the inner part of the large tube, the 2$^{nd}$ air crescent-shaped air layer, the 3$^{rd}$ silica layer from the inner part of the small tube, the 4$^{th}$ air layer of the small tube and the 5$^{th}$ silica layer from the outer part of both the small and large tube. Since the 5$^{th}$ layer is too close to the jacket, it is less efficient than the former 4 layers. Furthermore, the two 5$^{th}$ layers have redundant functions, indicating that one of them could be removed without affecting the leakage loss. To reduce the MSD, the outmost 5$^{th}$ layer from the large tube is removed resulting in an arc-shaped tubular structure shown on the right of Fig. 1a. The removed layer is defined by its central angle, denoted as $\theta$. Simulation is performed using the finite element method (FEM) with Comsol 5.5 to show the variation in CL with degree of $\theta$ increased from 0° to 180°. Note that for each angle, we need to optimize the small tube diameter to minimize the CL. The other parameters are kept fixed, including the intertube gap of 3 μm, silica membrane thickness of 980 nm (operating in the O band with a 2$^{nd}$ order AR window), and core diameter of 30 μm.

Fig.1b shows the simulation results. Without removing the outmost layer (0 degree), the MSD is 101 μm and the CL is at a level of 0.15 dB/km with small oscillations. These oscillations are probably due to the overlap of the small and large tubes which could cause Fano-resonance at some wavelengths. By removing the outmost layer of 60°, 90° and 120°, the MSD are reduced to 98 μm, 94 μm and 88 μm, respectively, while the losses are all reduced to below 0.1 dB/km (with a minimum figure of 0.06-0.07 dB/km). The removal with 120° is probably the optimum choice since both the CL and MSD are greatly reduced. Removing the layer by 150° to 160° further reduces the MSD to 82 μm and 80 μm. In this case, the loss is in the same level with the 0° one. Given the fact that with such a core diameter to wavelength ratio of 23, the microbending loss and macrobending loss could also contribute to the total loss [4], we believe that a CL level below 0.15 dB/km plays a minor role on the total loss. Further removing the outmost layer by 170° and 180° reduces the MSD to 77 μm and 74 μm but the CL is subsequently increased to 0.2 - 0.3 dB/km. With a MSD of 74 μm, it is possible to have a jacketed fibre diameter of 150 μm. In short haul applications when dense cabling is required, it is probably worth sacrificing CL to some extent in order to achieve such smaller diameter.

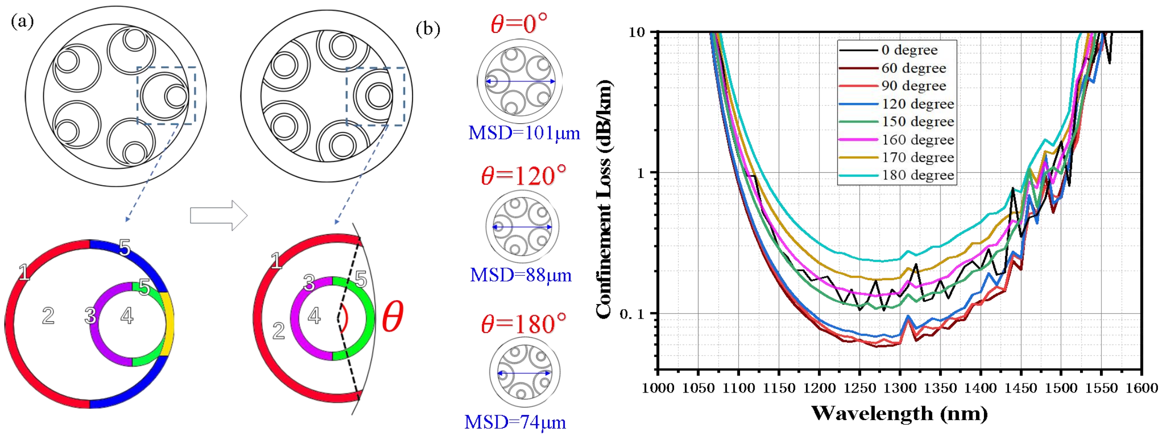


**Fig. 1:** The design of arc-shaped multi-layered ARF structure with reduced MSD. (a)The full tube design (left) and the design with the outmost layer removed by $\theta$ degree. The numbers 1 to 5 labels the AR layers. (b) The corresponding confinement loss curve simulated using Comsol with different $\theta$.

**Fibre Fabrication and Characterization**

To fabricate such arc-shaped ARF, a modified stack-and-draw technique is applied where the tubes are pre-cut at a certain angle using high power lasers before stacking. Figure 2a shows a scanning electron microscopy (SEM) image of the cross section of the fabricated fibre. The core diameter, inter-tube gap and averaged silica membrane thickness are measured to be 30 µm, 4 µm and 900 nm. The angle $\theta$ of the removed layer is measured to be 130° and the MSD is 85 µm. Compared with the MSD of 101 µm for full tubular structure, this reduces the MSD by 16%. The dimensional parameters are consistent at both ends of the fabricated 1.06 km fibre with <5% variation. Simulations show such variations have a negligible influence on the fibre's optical performance.

The transmission loss is measured using the cut-back method from 1060 m to 50 using a supercontinuum (SC) source and an optical spectral analyser (OSA) (Fig. 2b). The fibre is wound on the standard drum with a diameter of 32 cm. To avoid the excitation of high order modes, a mode field adaptor is inserted between the SMF 28 fiber from the SC source and the ARF. The measured loss spectrum shows a < 0.5 dB/km attenuation level from 1220nm to 1340 nm. The minimum loss value reaches 0.28 dB/km @ 1290 nm. Due to the limited fibre length and the OSA's resolution, we evaluate the uncertainty of such loss measurement to be 0.1 dB/km. This loss level is higher than the simulated one in Fig.1 indicating the CL is probably not dominating the total loss. The asymmetric loss spectrum which is higher at short wavelength range and lower at long wavelength range also indicates that the bending loss (including microbending and macrobending) plays the major role.

To evaluate the effects of the macrobending loss, part of the fibre is wound off from the drum and bent to 10 cm and 5 cm radius for 100 turns. The spectra before and after bending are recorded by the OSA. For a bending radius of 10 cm, no difference can be distinguished before and after bending. For 5 cm radius, the difference before and after bending is deduced and plotted in Fig. 2c

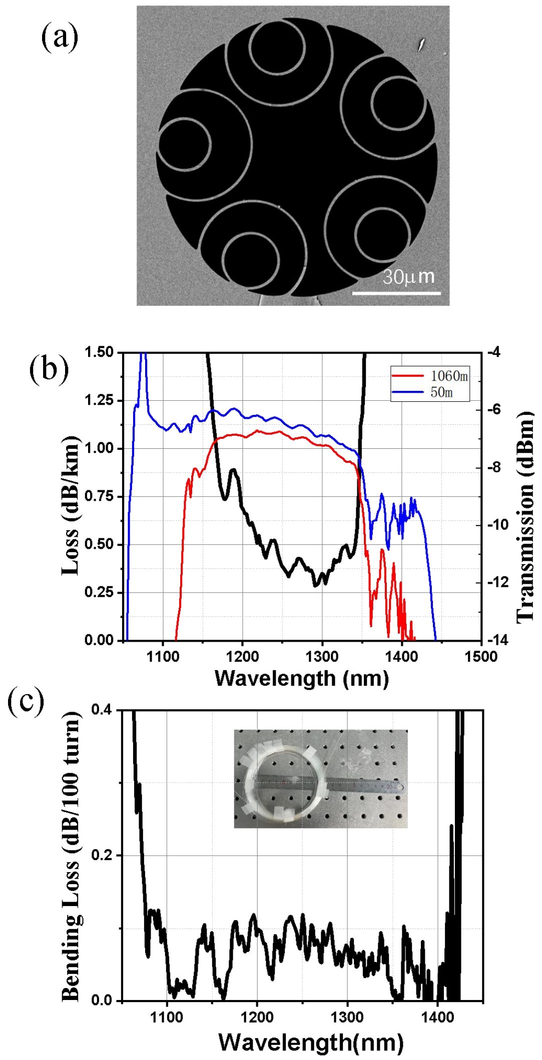


**Fig. 2**: (a) SEM image of the fabricated fibre. (b) Transmission spectra (right axis) of the 1060 m (red) and 50 m (blue) fibre as well as the deduced loss spectrum (black, left axis). (c) Bending loss spectrum for a bending radius of 5 cm.

showing a bending loss of only < 0.1 dB/100 turns. This indicates the fibre's macrobending can be ignored for radius >10 cm, as in the case of Fig. 2b. We thus suspect the dominate effect of the loss spectrum is probably the microbending loss, which is difficult to evaluate and depends on the coating material, the coating thickness, the jacket thickness and the winding tension. [4] Further optimizing of the microbending loss is possible and under investigation.

## Conclusions

The removal of the outmost AR layer in the multi-layered ARF structure resulted in a smaller MSD, reducing the handling and deployment difficulties while maintaining the ultralow loss performance. The fabricated fibre represents the state of art loss level of 5AR layer structures at this wavelength.

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