# Advances in Hollow Core Photonic Crystal Fiber Fabrication

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**Abstract:** We review recent advances in the fabrication of both hollow core photonic bandgap fibers and hollow core anti-resonant fibers.
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## 1. Introduction

Hollow core photonic crystal fibers (HC-PCFs) provide low loss, low latency and ultra-low non-linearity and are now considered serious contenders for applications such as telecommunications, high power laser beam delivery and gas-based optics. Even though this novel fiber technology is now relatively well established, new fiber designs are still emerging and several leaps forward have recently been achieved in terms of new record low losses [1, 2], ultra-wide operating bandwidth [3], fabrication of ultra-long uniform fiber lengths [4] and fibers which operate well beyond the transmission window of silica [5, 6]. Furthermore, multi-hollow core fibers have also been reported, either for mode filtering (to achieve single mode operation [7]) or to explore power transfer between adjacent cores for potential applications in fiber-based devices such as couplers and splitters [8].

HC-PCFs are usually divided into two key groups that are defined by the guidance mechanism through which light can be trapped in the hollow core. The first group, hollow core photonic bandgap fibers (HC-PBGFs), are better established and understood and still provide the lowest reported loss at any wavelength (1.2 dB/km around 1550 nm, [9]) over a limited bandwidth (up to ~34% of the central guidance wavelength [4] with a minimum loss ~ 5 dB/km). HC-PBGFs also show exceptional resilience to bending induced loss, as demonstrated in [10]. The second group, hollow core anti-resonant fibers (HC-ARFs), have rapidly evolved over the past 10 years, and can now achieve comparable or better losses than HC-PBGFs below ~1 µm and above ~ 2.5 µm. HC-ARFs also provide wide operating bandwidths and can have low loss in multiple spectral windows. Furthermore, they typically have at least one order of magnitude lower overlap between the guided core modes and the silica cladding as compared to HC-PBGFs, which makes them excellent fibers for ultra-high power beam delivery [11, 12]. However, HC-ARFs typically exhibit significantly higher bend sensitivity as compared to HC-PBGFs. Yet, if attenuation in HC-ARFs continues to decrease, as predicted by modelling of new structures (see e.g., [13]), and the high bend sensitivity is successfully reduced, they may become true competitors with HC-PBGFs for longer range applications, such as telecommunications. Here, we will review recent progress in HC-PCF fabrication, of both fiber types, and compare the key qualities of both fiber types that are relevant to real world applications.

## 2. Fiber Fabrication and Characterization

Regardless of type, HC-PCFs are conventionally fabricated via a two-step stack and draw technique. Four recently fabricated HC-PCFs are shown in Figure 1. Figure 1(a) is a 19-cell HC-PBGF [4]; a record, 11 km length of this fiber was recently fabricated and analysis of the longitudinal uniformity of the fiber showed that the structure was

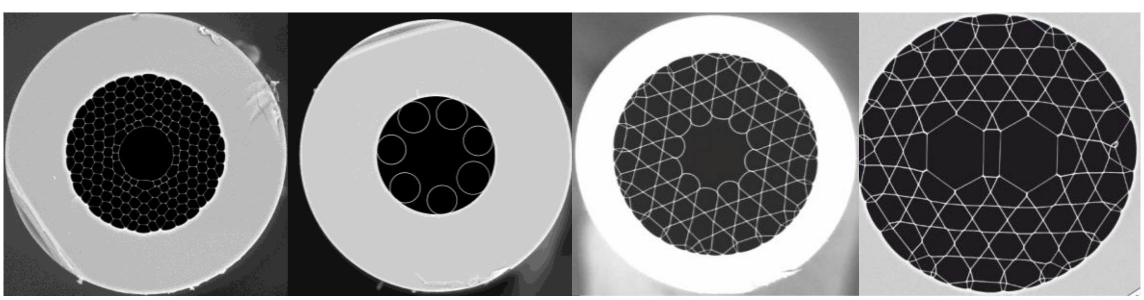

Figure 1: Scanning electron microscope images of HC-PCFs. (a) 19-cell HC-PBGF [4], (b) Tubular, non-contact HC-ARF [3], (c) Kagome HC-ARF [2] and (d) Dual HC-ARF [8].

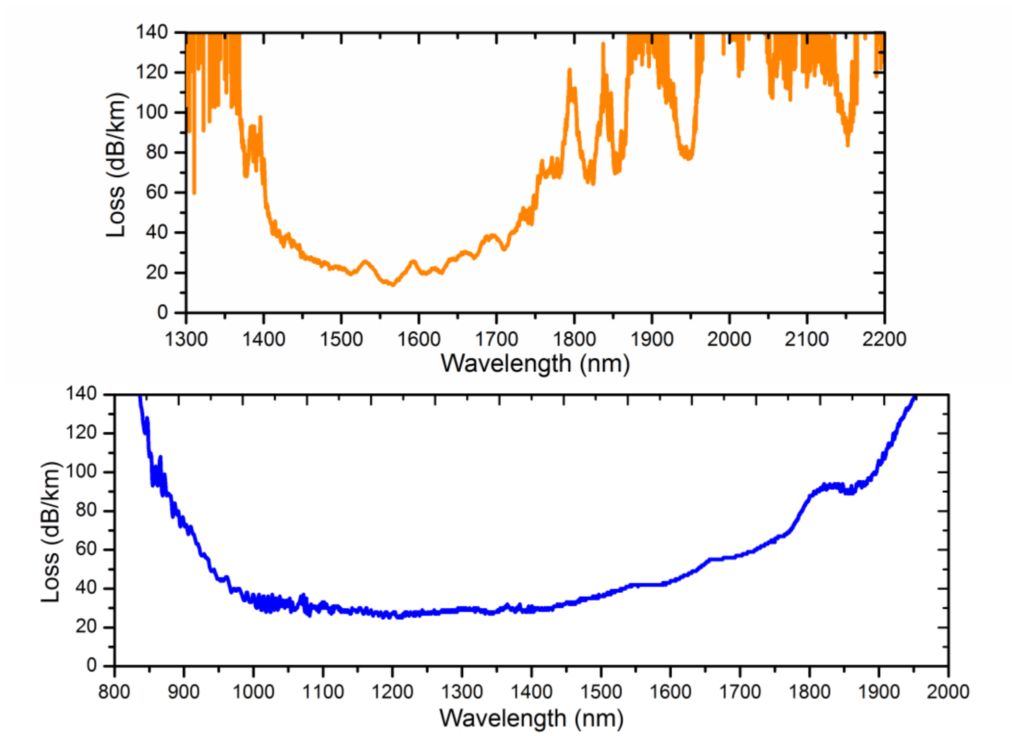


Figure 2: (a) Attenuation of Kagome HC-ARF tailored for operation around 1550 nm and (b) attenuation spectra of tubular, non-contact HC-ARF that shows sub-100 dB/km loss over more than a bandwidth > 1000 nm.

extremely consistent. Figure 1(b) and (c) show two radically different HC-ARF structures (a Kagome fiber [2] and a tubular, non-contact fiber [3]) and the attenuation spectra of these fibers are shown in Figure 2. The minimum loss of the Kagome fibre is 13.9 dB/km, which is a record low loss for any HC-ARF operating around 1550 nm. While this minimum loss is lower than that of this particular tubular fiber, the operating bandwidth of the tubular fiber is far superior as the fundamental guidance window of the Kagome fiber is punctuated by loss peaks due to resonant coupling between the core-guided modes and the nodes in the Kagome cladding structure. Figure 1(d) shows another very different HC-ARF which has two separate hollow cores and was fabricated to explore the coupling efficiency between the two adjacent cores [8]; by changing the fiber structure, it was found that the coupling was highly polarization dependent and that up to 65% of power could be coupled between the adjacent cores. These fibers are representative of some of the most recent advances in hollow core fiber fabrication and highlight the diverse range of structures that are available. In this talk, we will review the properties of these fibers in detail and highlight key fiber parameters, such as loss, bend sensitivity, bandwidth and modal properties that define their potential application spaces.

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## 3. References

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