Microstructured fibers for high power applications

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ABSTRACT

Fiber delivery of intense laser radiation is important for a broad range of application sectors, from medicine through to industrial laser processing of materials, and offers many practical system design and usage benefits relative to free space solutions. Optical fibers for high power transmission applications need to offer low optical nonlinearity and high damage thresholds. Single-mode guidance is also often a fundamental requirement for the many applications in which good beam quality is critical. In recent years, microstructured fiber technology has revolutionized the dynamic field of optical fibers, bringing with them a wide range of novel optical properties. These fibers, in which the cladding region is peppered with many small air holes, are separated into two distinct categories, defined by the way in which they guide light: (1) index-guiding holey fibers (HFs), in which the core is solid and light is guided by a modified form of total internal reflection, and (2) photonic band-gap fibers (PBGFs) in which guidance in a hollow core can be achieved via photonic band-gap effects. Both of these microstructured fiber types offer attractive qualities for beam delivery applications. For example, using HF technology, large-mode-area, pure silica fibers with robust single-mode guidance over broad wavelength ranges can be routinely fabricated. In addition, the ability to guide light in an air-core within PBGFs presents obvious power handling advantages. In this paper we review the fundamentals and current status of high power, high brightness, beam delivery in HFs and PBGFs, and speculate as to future prospects.

Keywords: Microstructured, holey, photonic crystal, band-gap, fiber, high power, beam delivery.

1. INTRODUCTION

1.1. Introduction

Beam delivery fibers are key components in a wide range of high power application sectors; from medicine and defense through to the industrial machining and processing of materials. Optical fibers offer many practical advantages relative to free space delivery solutions, both in terms of system design and safety, in addition to ease of use. Microstructured fibers (MFs), which are typified by the small, longitudinal air holes that define the cladding region, exploit the unique optical properties that arise in dielectric materials with wavelength-scale regions of high index contrast. In recent years there has been a surge of interest in this research area, fuelled by the many unusual and useful optical properties that have been demonstrated in these fibers, including photonic band-gaps at optical wavelengths, broad-band single-mode guidance, unique dispersion properties and extreme nonlinearities (amongst others)1–2. The wealth of different fiber designs and the wide range of optical properties so far achieved stems from the fact that the optical properties of these fibers are sensitive functions of the cladding configuration, which can, via careful design and fabrication, be tailored to suit a wide variety of application needs. MFs are typically separated into two classes, defined by the way in which they guide light: (1) holey fibers (HFs), in which light is guided by a modified form of total internal reflection and, (2) Photonic band-gap fibers (PBGFs), in which guidance is achieved via photonic band-gap effects generated by the periodic nature of the cladding. Both classes of MF are considered here. MFs are also known as photonic crystal fibers (PCFs), and comprehensive review of these novel fibers can be found in [1, 2].

Both types of MFs offer many attractive qualities for beam delivery applications. For example, the flexibility inherent to the typical methods used to fabricate index-guiding HFs enables almost arbitrary combinations of core size and numerical aperture (NA) to be created. Indeed, the largest mode areas in single-mode fibers, and the highest NAs in

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large core multi-mode fibers have both been reported in HF designs. Furthermore, HFs can be made entirely from pure silica, which may offer power-handling advantages relative to polymer-clad and doped designs. In PBGFs, the mechanism responsible for guidance permits light to be guided in regions of low index. This has enabled the realization of single-mode low-loss hollow-core fibers, which offer obvious power-handling advantages in terms of damage threshold and nonlinear suppression relative to solid core fibers.

However, in order to properly assess the potential of MFs for real-world applications it is essential to consider their performance in terms of practical issues. For example, transmission and bending losses are a key concern in beam delivery applications as they place fundamental limits on the length and flexibility of the delivery fiber, which in turn impact the system design and ease of use. The process of end termination is also key in the integration of fiber-based systems and the ability to reliably achieve high quality cleaves and splices is essential if MFs are to become practical delivery solutions. In addition, the mechanical strength of the fiber is a fundamental consideration in determining reliability and suitability. In the following sections, we present a review of the fundamentals and the current status of high power, high brightness, beam delivery in large-mode-area, single-mode HFs and Hollow-core PBGFs fibers, and explore the merits of these novel fibers, relative to conventional designs, in terms of practical issues such as loss, end termination and mechanical strength.

1.2. Microstructured fiber types for high power applications

1.2.1. Large-mode-area single-mode holey fibers

Large-mode-area (LMA) HFs are typically fabricated from a stack of silica capillaries surrounding a single, central, solid rod. In the drawn fiber, the solid rod forms the core and the surrounding glass capillaries form the microstructured cladding. The cladding holes in a HF are typically arranged on a hexagonal lattice (due to the stacking geometry of round capillaries) and the defining parameters are the hole-to-hole spacing \( \Lambda \), and the hole diameter \( d \), which typically range from 10-20 \( \mu m \) and 5-10 \( \mu m \) respectively in LMA HFs. However, note that cladding periodicity is not a requirement for guidance in this fiber type. An example of a LMA, endlessly single-mode HF in which one central solid rod is used to create the fiber core is shown in Figures 1 (a) and (b).

![Figure 1 SEMs of LMA silica HFs; (a) and (b) single-rod HF, (c) three-rod HF](image)

Light is guided in the core of a HF as a result of the fact that the air holes lower the volume average refractive index of the cladding, relative to that of the solid core. As such, this guidance mechanism can be thought of as a modified form of total internal reflection and the properties of HFs can, to first approximation, be reasonably well evaluated by considering the cladding as a solid material with an equivalent refractive index. However, unlike conventional fibers, in which the cladding index is only weakly dependent on the wavelength, the effective index of a HF cladding region is a strong function of the wavelength. Essentially, the amount by which the air holes lower the effective index of the cladding depends on the fraction of air "seen" by the light. For wavelength-scale air holes, the fraction of light located in the air can increase dramatically as the wavelength increases, significantly reducing the effective index. Since the index of the solid core region in a HF is only weakly wavelength dependent, the effective index contrast between the core and cladding, (i.e. the NA) decreases rapidly with wavelength. This phenomenon is responsible for a host of optical properties unique to HFs, including endlessly single-mode guidance, whereby only the fundamental mode is guided (if \( d/\Lambda < 0.4 \)), regardless of the relative structure scale. In addition to the obvious advantages for broadband applications, this also provides a route towards arbitrarily large cores in single-mode fibers, simply by creating large values of \( \Lambda \). Furthermore, even larger cores can be created by including multiple solid rods in the center of the preform stack and mode areas of \( \approx 1000 \, \mu m^2 \) have been created in this way. An example of an LMA HF in which three missing air holes form the core is shown in Figure 1 (c).
Although HF’s provide a simple fabrication route for creating arbitrarily large cores in single-mode fibers, making them an attractive solution for high power applications in which good beam quality is a critical issue, the upper limit on practical mode size is fundamentally limited by the bending losses, which increase with mode size. Since the spectral behavior of bend loss in a HF is dramatically different to that of a conventional fiber, it is important to understand how these losses limit practical mode size in HF’s and to consider how these limits compare to those of conventional solid fibers. Recent work has shown that the bending losses of HF’s can be comparable to conventional solid fibers at any given wavelength, and that they can be improved relative to conventional fibers, by altering the hole arrangement. Indeed, mode areas as large as 1400 μm² at 1 μm have been realized in single-mode HF’s.

Assuming the damage threshold is that of bulk silica, HF’s of this size should be able to transmit mJ pulses of ~5 ns in duration (corresponding to peak intensities ~10¹⁰ Wcm⁻²) without suffering damage. However, in solid silica core fibers, nonlinear effects start to become apparent at peak intensities below this value. For example, a small amount of nonlinear effects are reported for light at 1064 nm with ~18.4 kW of peak power per pulse (corresponding to peak intensities within the fiber of ~5.3 x 10⁹ Wcm⁻²), transmitted through ~11 m of LMA HF. The spectrum of this HF shows that ~1% of the output power is located at a wavelength of 1120 nm, which is consistent with a spontaneous Raman shift and indicates that nonlinear effects may start to become restrictive for peak intensities much above ~10⁹ Wcm⁻² in HF’s.

1.2.2. Photonic band-gap fibers

Photonic band-gap fibers (PBGFs) are a class of microstructured fibers in which light guidance is achieved through a fundamentally different mechanism than in conventional or holey fibers. Rather than relying on the refractive index difference between core and cladding regions, PBGFs exploit optical band-gap effects that can occur in periodic dielectric structures and can be made from a variety of materials in many different configurations. The type of PBGF considered here are made entirely from silica using the same basic fabrication techniques described briefly for HF’s in the previous section. As a result, the air holes that define the cladding in this type of PBGF are arranged on a hexagonal lattice, and the defining parameters are once again the hole-to-hole spacing A, and the hole diameter d. For sufficiently large air holes (d/A ≥ 0.95), the microstructured cladding region can act as a two-dimensional photonic crystal with band-gaps at well-defined optical frequencies. Wavelengths within the band-gap cannot propagate in the cladding and are thus confined to the core. The most attractive property of this type fiber is that the core can be defined by a low index material, allowing light to be guided in a hollow core. An example of the type of hollow-core PBGF considered here is shown in Figure 2. In this example, the core is formed by the omission of 7 capillaries from the preform stack, but larger cores formed by the omission of 19, and even 91 capillaries have also been fabricated. For the type of PBGF shown in Figure 2, the width of the band-gap is typically ~10-20% of the central wavelength.

Figure 2 SEMs of 7-cell silica PBGFs, (a) a whole fiber (b) close up of a core region.

Hollow-core guidance has obvious advantages for high-power delivery applications since most gasses, including air, possess intrinsically low values of attenuation and nonlinearity at optical wavelengths and are able to withstand significantly higher optical intensities than silica glass. The potential offered by PBGF’s has been demonstrated in a range of high power applications including ultrashort-pulse compression and soliton generation, in addition to beam delivery, and in many cases, the fluence of laser radiation incident at launch and transmitted within the fiber exceeds the damage fluence of bulk silica by an order of magnitude. Indeed, predictions state that these fibers should enable nanosecond pulses up to the level of tens of millijoules to be transmitted in a single-mode. Similarly, the non-linear coefficients of air-filled hollow-core PBGF’s have been found to be 1-2 orders of magnitude smaller than those obtained in index-guiding HF’s with large mode areas, however, note that the nonlinearity could be further reduced by evacuating the air from fiber core. One other advantage associated with a hollow-core is that these high damage thresholds and low values of nonlinearity can be achieved in relatively small mode areas. Typically, the mode areas of the type of PBGF’s shown in Figure 2 are ~20 μm² at 1 μm and the bending losses are, as a result, negligible for all radii of practical interest.
Investigation of the relative merits of core size in hollow-core PBGFs for high power applications have shown that the smaller 7-cell cores are currently most suitable for the transmission of femtosecond and sub-picosecond pulses, whereas larger core 19-cell PBGFs are better suited for delivering nanosecond pulsed and continuous-wave beams. These conclusions are based on the findings that the fundamental core mode of 19-cell PBGFs are more Gaussian in shape and have less light localized in the silica regions of the fiber relative to a 7-cell PBGF, thus offering advantages in terms of nonlinearity and coupling efficiency. However, 19-cell PBGFs typically have a higher density of surface modes within the band-gap, and so a 7-cell design is more appropriate for shorter (and more spectrally wide) pulse transmission.

2. LOSS IN MICROSTRUCTURED FIBERS

2.1. Introduction

In this section we focus on the losses that occur along the length of the fiber, i.e. transmission and bending losses. Losses that result from interconnection, such as coupling and splice losses are considered in Section 3.

2.2. Transmission losses in MFs

Although the transmission losses of both index guiding HFs and hollow-core PBGFs are currently larger than those of conventional fibers, significant advancements have been made in recent years (see Figure 3). The minimum propagation loss in conventional pure-silica core fibers is ~ 0.15 dB/km and is close to the theoretical minimum loss for solid silica (~ 0.14 dB/km), which is limited by fundamental scattering and absorption processes. This value also represents the minimum losses possible in index-guiding pure-silica HFs, assuming contributions from other sources loss, such as confinement loss and waveguide non-uniformity are negligible. In LMA HFs, confinement losses can be reduced to negligible levels simply by using a sufficient number of holes in the cladding (see footnote in Section 2.2.3). However, the roughness of the inside surface of the glass capillaries used to fabricate HFs has been identified as a significant contribution to propagation loss via Raleigh scattering. This can be significantly reduced via etching/polishing techniques and HFs with transmission losses of ~ 0.28 dB/km have been fabricated in this way. The authors note that the losses can be improved further by increasing A in order to increase the scale of the surface roughness relative to the wavelength of light. In typical hollow-core PBGFs, > 99 % of the light can be transmitted in air, making any loss contribution from material scattering and absorption negligible. For this reason, these fibers are considered to promising candidates for ultra-low loss transmission. However, to date, the lowest transmission loss reported in PBGFs is ~ 1.2 dB/km, and surface roughness has been identified as the dominating contribution. In addition, whilst surface roughness can be reduced via etching and polishing techniques, it has been found that it is fundamentally limited by surface capillary waves that are frozen into the fiber during fabrication. However, it has been shown that these losses can be mitigated through fiber design, and that losses of the order of 0.1 dB/km are plausible. This demonstrates that hollow-core PBGFs offer a realistic route towards lower transmission losses than are possible using conventional technology.

Assuming the developments in loss reduction in these novel fibers follows a similar trend to that of conventional fibers, as illustrated in Figure 3, it is probable that losses of < 0.2 dB/km in HFs and PBGFs will soon be achieved. Note that whilst the longest lengths of HF fabricated to date is 100 km, (with losses of 0.55 dB/km at 1550 nm), the fabrication of PBGF is typically more challenging than HF and the longest length of PBGF through which light has been transmitted is currently 345 m.
Bend loss in MFs

2.2.1. Introduction

In any fiber, loss due to curvature typically increases as the mode area becomes larger and as the NA decreases. For this reason, bend loss is a key issue in index-guiding single-mode HF, in which large mode areas are required in order to mitigate damage and nonlinear effects, but does not affect the performance of hollow-core PBGFs, which typically have mode areas much smaller than conventional telecommunication fibers\(^7\), \(^22\) (see Section 1.2.2). As a result, only the bending losses of single-mode HF are considered here. At first glance, one may expect the bending losses of HF to be worse than conventional fibers due to the fact that HF possess two bend loss edges, towards both long and short wavelengths\(^1\). In both fiber types, bend loss increases in the long wavelength extreme as the mode extends further into the cladding, becoming more weakly guided. The additional short wavelength bend loss edge in a HF arises from the fact that the NA decreases towards short wavelengths, resulting in a more weakly guided mode that is more sensitive to bend induced loss. As such, bend loss not only places limits on the maximum practical mode size, but also limits the bandwidth of practicality for broadband applications of HF. However, despite these spectral differences, the bending losses of single-mode HF have been shown to be comparable to those of equivalent step-index fibers at any given wavelength\(^1\). Moreover, it has also been demonstrated that HF can offer significant advantages in the LMA single-mode regime for broadband or multiple wavelength applications\(^1\), and this work is summarized in Section 2.2.2 below. Recent work has also shown that the bending losses of HF can be improved relative to conventional designs by changing the geometry of the cladding\(^1\). The high degree of flexibility offered by HF fabrication techniques means that the size, number and placement of the cladding air holes can be easily modified. Since the optical properties of a HF, including bend loss, are highly sensitive to the exact cladding configuration, there is potential for optimization. Recently, two approaches have been developed for LMA HF, one of which uses a modified core geometry\(^7\) and another which takes advantage of confinement losses to remove unwanted higher order modes\(^3\). These methods of improving bend loss in a HF are explored in Sections 2.2.3 and 2.2.4.

2.2.2. Broadband bend loss in single-mode HF

![Graph](image)

Figure 4 (a) Effective mode area (A_{eff}) as a function of wavelength for a HF with \( A = 12.25 \mu m \) and \( d/\lambda = 0.40 \) and a SIF with \( a = 2.488 \mu m \) and \( \Delta n = 2.316 \times 10^{-9} \). (b) Critical bend radius (R_c), as a function of wavelength for the same fiber pair.

12.25 \mu m \) and \( d/\lambda = 0.40 \). In comparison, the limiting factors in a SIF are the bend loss at the longest design wavelength (since bend loss only ever increases towards long wavelengths in a SIF) and the modedness of the fiber at the shortest

* The critical bend radius is defined as the radius at which half the power is lost for a single loop of fiber.

\(^1\) Note that this value for the maximum tolerable R_c is based on our experimental observations in which fibers with R_c > 15 cm are found to exhibit rapidly fluctuating power levels in response to low level vibrations and air-currents in the laboratory environment. Of course, the definition of tolerable bend radius will differ greatly depending on the application and the way in which the fiber is packaged, but for many applications, critical bend radii < 15 cm are considered practical.
design wavelength. In this case, the largest practical mode size corresponds to a fiber with $R_e = 15$ cm at 1064 nm and a cut-off wavelength of 532 nm, which can be achieved with $a = 2.488 \mu$m and $\Delta n = 2.316 \times 10^{-4}$, resulting in $A_{eff} \sim 115 \mu$m at 1064 nm.

The wavelength dependence of $A_{eff}$ and $R_e$ are plotted in Figures 4 (a) and (b) respectively, for the HF (solid black line) and the SIF (dashed red line). In addition to illustrating the differences between bend loss in HFs and SIFs, these figures show that it is possible to design both fiber types with tolerable bend loss and single-mode guidance for 532 nm < wavelength < 1064 nm. However, these results also show that whilst the $A_{eff}$ of the HF remains relatively constant at ~180 to 195 $\mu$m$^2$ in this wavelength range, the $A_{eff}$ of the optimal SIF design is almost half this value at 1064 nm and falls rapidly to ~23 $\mu$m$^2$ at 532 nm. This demonstrates that while it is possible to design a SIF with broadband single-mode guidance and tolerable bend loss, it only possible to do so if the $A_{eff}$ is significantly reduced relative to a HF design.

2.2.3. Improving bending losses in single-mode HFs: (1)

The core mode(s) in a bent solid-core fiber distort outwards in the direction of the bend at an amount related to the severity of the bend. In the short-wavelength extreme, bend loss in HFs can be explained in terms of the relative scales of the fiber structure and the wavelength of light. Towards short wavelengths in a HF, the distance between each cladding air hole ($\Lambda-d$) becomes increasing large (relative to the wavelength of light) and the distorted mode of the bent fiber is more effectively “squeezed out” between the air holes. As such, it seems logical to suppose that the bend loss could be improved by decreasing the distance between each air hole. Whilst reducing $\Lambda$ also reduces the core size in a traditional HF design, it is possible mitigate this effect by using multiple adjacent rods in the perform stack to form the core. Indeed, studies of a single HF in which three solid rods form the core suggest that the effective mode area of a HF can be enlarged by ~30%, without any additional bend loss penalty in this way. Here, we aim to accurately quantify the improvement in bend loss that can be obtained with this more complex design by comparing suitably matched examples of the three-rod and single-rod HF types at 1064 nm. Note that preliminary results from this study were presented in [30]. The numerical approach used here to model the bending losses of HFs is described in detail in [31]. This model uses an orthogonal function approach together with a conformal transformation to obtain the distorted modal fields of the bent fiber. The bend loss is then extracted by estimating the fraction of the modal field lost to radiation. This model has very few restrictions on the refractive index profile that can be considered and has been experimentally validated for LMA HFs$^{11}$. Note that this approach does not approximate the fiber profile as a step index fiber.

When evaluating the relative bending losses of different fiber types, it is essential to consider fibers that are equivalent in terms $A_{eff}$ and NA at the wavelength of interest to ensure that any predicted improvement does not result merely from a relatively higher NA or smaller $A_{eff}$. Here we compare the bending losses of three-rod HFs and single-rod HFs at 1064 nm with similar values of $A_{eff}$ and NA, the latter of which is defined by the effective cladding index ($n_{Clad}$). Since finding fiber parameters that result in identical values of both $A_{eff}$ and NA for each fiber type is not a trivial task, we consider a

![Figure 5](image_url)
range of structures for both fiber types, each with \( A_{\text{eff}} \approx 190 \, \mu m^2 \) at 1064 nm. Note that smaller holes are required in the three-rod HF's to create matched values of \( n_{\text{FSM}} \) in the two fiber types, due to the fact that \( n_{\text{FSM}} \) decreases as \( \Lambda \) becomes smaller. At 1064 nm, we find that \( d/\Lambda < 0.18 \) is required for single-mode guidance in a three-rod HF, compared to \( d/\Lambda < 0.43 \) in a single-rod HF.

The results from numerical simulations are shown in Figure 5 (i), which shows predicted values of \( R_e \) for the fundamental mode of each fiber considered as a function of \( n_{\text{FSM}} \) at 1064 nm in which the circles correspond single-rod HF's and the triangles correspond three-rod HF's. The fiber parameters are indicated in the caption. Two data points are shown for each of the three-rod HF's and correspond to bends in the \( \varphi = 0^\circ \) and \( 60^\circ \) directions (\( \varphi = 0^\circ \) corresponds to the horizontal direction in the orientation shown, which is the direction of maximum bend loss). The variation in \( R_e \) with respect to \( \varphi \) is < 1% for the single-rod HF's considered here.) The results in Figure 5 (i) show that at the single-mode cut-off, the \( R_e \) of a three-rod HF's is reduced by approximately 20 - 30% relative to the single-rod HF designs of equivalent \( A_{\text{eff}} \) and \( n_{\text{FSM}} \). This corresponds to an increase in mode size of approximately 15 - 20% without any additional bend loss penalty (assuming a bend in the \( \varphi = 0^\circ \) direction). In addition, by comparing the mode shapes of bent fibers C and c (shown in Figure 5 Figure (ii) for \( R = 3.5 \, cm \)), the reason for this improvement can be seen. Essentially, the smaller, more closely spaced holes of the three-rod HF are more effective at confining the mode to the core than the larger, more widely spaced holes of the single-rod HF. This demonstrates that effective index considerations alone are not sufficient to evaluate the bending losses of HF's and that it essential to consider the detailed structure of the cladding.

However, the fabrication of multiple-rod HF's is generally more challenging because a large number of elements are required in order to maintain the extent of the cladding and hence low confinement losses. Indeed, more than 200 additional elements are typically required in the preform of a three-rod HF, which increases the complexity and risk of failure during fabrication. However, such structures have been fabricated, as shown in Figure 6 (c), which shows the core region of a three-rod HF with \( \Lambda = 11.4 \, \mu m \), \( d/\Lambda = 0.20 \) and 10 rings of holes. This fiber has an \( A_{\text{eff}} \approx 400 \, \mu m^2 \) at 1064 nm and the \( R_e \) for the fundamental mode is measured to be \( \sim 10cm \), which is \( \sim 20 \% \) smaller than that measured in a near-equivalent single-rod HF (illustrated in Figure 6 (a)), for which \( A_{\text{eff}} \approx 400 \, \mu m^2 \) and \( R_e \approx 12 \, cm \). This is in excellent agreement with the predicted improvement in the \( R_e \) of the fundamental mode for \( A_{\text{eff}} \approx 190 \, \mu m^2 \), as shown in Figure 5 (i).

![Figure 6 (a) and (b) show SEM image and near field modal intensity profile of a single-rod HF with \( \Lambda = 19.6 \, \mu m \) and \( d/\Lambda = 0.44 \) respectively. (c) and (d) show SEM image and near field modal intensity profile]

### 2.2.4. Improving bending losses in single-mode HF's: (2)

This method takes advantage of the fact that each mode of a HF has an associated confinement loss that increases with the mode order and is highly sensitive to the cladding configuration. By careful choice of the cladding parameters, it is possible to design a multi-mode passive fiber in which the confinement and bending losses of the higher-order modes are sufficiently high to ensure that they are not observed in long coiled lengths, whilst maintaining reasonably low confinement and bend losses for the fundamental mode. In this example, a single ring of large air holes (\( d/\Lambda \sim 0.8 \)) is used to create a large core fiber (core dimension 63 x 56 \( \mu m \)) that has a fundamental mode area of \( \sim 1400 \, \mu m^2 \) at 1 \( \mu m \) with low bend loss (\( R_e < 5 \, cm \)). In this fiber the confinement and bending losses of the higher-order modes are sufficiently high to enable an M\(^2\) of \( \sim 1.15 \) to be measured from a 4m length coiled with a radius of 5 \( cm \). In addition, while this approach is only suited for fiber operation over a narrow wavelength range, the design can be scaled to suit the application wavelength. For example, by scaling the design reported in(2), effectively single-mode fibers with core areas of \( \sim 130 \, \mu m^2 \) at 300 nm and over 3000 \( \mu m^2 \) at 1.55 \( \mu m \) should be possible. However, it should be noted that the

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8 Numerical calculations made using a multiple method predict negligible confinement losses (< \( 1 \times 10^{-5} \, dB/\text{km} \)) for the fundamental mode of a single-rod holey fiber with \( \Lambda = 12.7 \, \mu m \) and \( d/\Lambda = 0.45 \) at 1064 nm with 6 to 7 rings of holes, which are typical. To achieve a similar level of mode confinement in a similarly sized three-rod HF (\( \Lambda = 7.4 \, \mu m \), \( d/\Lambda = 0.20 \)), 8 to 9 rings of holes are required.
transmission losses of the fiber fabricated in [3] are a few dB/m at the bend radius required to achieve low values of $M^2$ (5 cm). As such, this fiber design is restricted to applications in which short lengths of delivery fiber are required. Furthermore, as we show in the following section, the mode area of a bent HF can be reduced relative to the straight fiber even when the bend loss is negligible. This will correspond to an increase in the peak intensity, thus limiting the power-handling capabilities of the bent fiber.

2.2.5. Mode size in bent HFs

As discussed above, it is possible to design a HF with large air holes that is effectively single-mode due to the large confinement and bend losses of the higher-order modes present in the fiber. However, it is important to consider what happens to the modal distribution of the fundamental mode in the bent fiber for the case of large air holes. In Figure 7 (a)-(p) contour plots of the modal intensity and the refractive index profile (contours separated by 2dB) for a selection of HFs with $A_{eff} \sim 190 \mu m^2$ at 1064 nm are shown. Each row corresponds to a different fiber with the leftmost plots showing the modal intensity in the straight fiber and increasingly distorted modal intensity as the bend radius is reduced towards the right-hand plots. The radii in the right-most plots correspond to radii close to $R_c$. For specific details of the fiber and bend parameters please refer to the figure caption. The graph in Figure 7 (q) shows the fractional change in the effective mode area of the fundamental mode (normalized to the value in the straight fiber), plotted as a function of bend radius for some of the HFs shown in Figure 7 (a)-(p). Together, these results illustrate how the hole size influences the size and shape of the fundamental mode in the bent fiber. For small air holes, we see that the mode area increases as the bend is tightened. However, for larger hole sizes, the mode area can actually be reduced in the bent fiber as the mode becomes squashed against the inside of the first ring of holes. For a relative hole size of 0.63, which was the largest considered here, the mode area is reduced to $\sim 85\%$ of its value in the straight fiber for radii at which the bend loss is negligible. For the fiber considered in ref [3], this reduction would correspond to a mode area of $< 1200 \mu m^2$ and is obviously something to be further considered.

Figure 7 (a)-(p) Modal intensity (contours separated by 2dB) of four HFs at 1064 nm. (a) - (d); $\Lambda = 9.0 \mu m$, $d/\Lambda = 0.20$ for (a) straight fiber, (b) $R = 15$ cm, (c) $R = 14$ cm and (d) $R = 12$ cm; (e) - (h) $\Lambda = 10.7 \mu m$, $d/\Lambda = 0.28$ for (e) straight fiber, (f) $R = 9.4$ cm, (g) $R = 8.4$ cm and (h) $R = 7.4$ cm; (i) - (l) $\Lambda = 12.2 \mu m$, $d/\Lambda = 0.42$ for (i) straight fiber, (j) $R = 4.4$ cm, (k) $R = 4.2$ cm and (l) $R = 4.0$ cm; (m) - (p) $\Lambda = 15.0 \mu m$, $d/\Lambda = 0.63$ for (m) straight fiber, (n) $R = 2.0$ cm, (o) $R = 1.9$ cm and (p) $R = 1.8$ cm. For the straight fiber, $A_{eff} \sim 190 \mu m^2$ at 1064 nm in each case. Note that the radii in the right-most plots correspond to radii close to $R_c$. (q) Fractional change in $A_{eff}$ (normalized to the value in the straight fiber), as a function of bend radius for five HFs. Fiber parameters are indicated on figure.
3. INTERCONNECTION

3.1. Introduction

In order for MFs to offer practical beam delivery solutions it must be possible to integrate them into real-world systems in a robust, efficient and reproducible way. The novel geometry of a MF introduces new challenges to the process of interconnection as the issues of end face treatment such as cleaving, polishing and splicing are more complex. Furthermore, the modal fields of a MF are typically slightly hexagonal in shape and may raise issues for coupling efficiency. In this section, we discuss how these issues affect the process of interconnection for MFs.

3.2. Cleaving, polishing and splicing

One of the most basic issues when preparing MFs for use in a laboratory environment is the removal of the protective polymer coating from the fiber. For MFs with a standard outer diameter (125 μm), mechanical fiber strippers can be used with excellent results. However, when the outer diameter is a non standard size, as is frequently the case, it is often necessary to use a solvent based stripper to remove the coating. In this case, it is essential for the end of the fiber to remain free of the solvent, which would otherwise be drawn up into the fiber via capillary action, thus disabling the guidance mechanism.

The simplest way to cleave MFs is by hand; by using a small fiber tile to score to the outside of the fiber before tapping/pulling a section of fiber away to reveal a fresh surface. However, this process requires skill and practice, and mechanical cleavers designed for conventional solid fibers can also be used if the parameters such as tension and force are optimized. The optimal parameters required for cleaving MFs in this way are found to be strongly dependant on the fiber geometry, but once optimized for a given fiber, high quality cleaves can be reproducibly achieved\(^3\). Optimum cleaving parameters have been determined for a number of HF's with different air-filling fractions and outer diameters\(^3\). In this study, it is found that cleaving should ideally be performed with a variable force system so that the tension can be kept constant as the fracture propagates, resulting in high quality fiber end faces. However, if the cleaving parameters are non optimal (for both mechanical and hand cleaves) small cracks propagating from each hole in the direction of the applied force are often observed\(^3\). Whilst these flaws cannot be removed using conventional polishing techniques (since the small particulates in the abrasive pastes may penetrate into the air holes), several methods have been proposed to either remove or avoid fracture damage during cleaving. One approach is to chemically etch the exposed surface in 48% hydrofluoric acid for ~ 2 seconds\(^3\). This was shown to effectively eliminate the structural flaws caused by non-optimal cleaving without degrading the general surface quality, but the sharpness of the hole edges was found to be slightly reduced. In another approach, the HF end face is ruggedized prior to polishing by filling the end section with a UV curable liquid resin (via capillary action)\(^4\). Once cured, the solid fiber end can be polished using conventional processes and even angle polishing can be realized\(^4\). In this technique, the length of the filled fiber is found to be accurately reproducible and it is possible to reduce the length of polymer filled HF to a very thin cap layer, thus sealing the fiber end without noticeably affecting the waveguiding properties. In a similar approach, the end face of a HF can also be collapsed/tapered via a heat treating process, which results in a solid glass end-face that can be cleaved, connectorized and polished in the same manner as a conventional fiber\(^5\). This end-sealing process also results in tapered air holes and creates a beam expansion region, which may offer advantages in terms of the fiber end face damage threshold. One other technique avoids all mechanical processes and instead uses high power CO₂ laser light to cleave MFs\(^6\). The process of laser cleaving is advantageous as it results in high quality fiber end faces that do not require additional mechanical polishing. Indeed, previous studies have shown that a CO₂ laser treatment step can significantly increase the laser induced damage threshold of mechanically polished solid core fibers\(^7\).

For beam delivery of fiber based sources, fusion splicing offers many advantages over free space coupling in terms of compactness and robustness. For MFs it also offers the additional advantage of hermetically sealing the fiber ends thus preventing moisture or detritus from degrading the transmission or end face properties. However, when applied to MFs, conventional fusion-splicing technology inevitably reduces the size of the air holes within the cladding or, in many cases, results in their total collapse at the splice interface\(^8\). Since the air holes of a MF are solely responsible for creating guidance this can result in high splice losses. One way to mitigate this effect is to reduce the temperature and duration of the splice. However, this typically results in a fragile splice and hence low long-term reliability\(^9\). Another approach, which offers much improved performance, in terms of both strength and loss incorporates a small GRIN lens
within the splice region\textsuperscript{40}. In this technique, a GRIN lens is fused in the middle of the splice region, creating a system that is analogous with free space coupling, in which the diverging beam in the collapsed hole region is re-focused, thus improving the slice loss. This technique has been used to create high strength (> 100 kpsi) splices with losses of ~ 0.4 dB and 0.34 dB in HF-to-HF and HF-to-SIF splices respectively\textsuperscript{40}.

Whist these techniques have so far only been reported for solid-core HF\textsubscript{s}, there is no fundamental reason why they cannot also be applied to hollow-core PBGF\textsubscript{s}. However, note that additional loss may result from reflection at the air/glass interface at a splice boundary between a hollow-core PBGF and a solid core fiber.

3.3. Coupling efficiency

Assuming Gaussian input beam/mode shape, the optimal coupling efficiencies for a free space coupling arrangement and a direct splice with a conventional fiber should be comparable at any given wavelength. The maximum theoretical coupling efficiency in this case can be calculated from the overlap function between a Gaussian of optimal width and the fiber mode. For a LMA HF, the maximum coupling efficiency is typically in the region of ~ 95 – 97% depending on the relative size of the cladding air holes. The reason for this variation can be seen in Figures 7 (a),(c),(f) and (m), which demonstrates how the mode shape become less filamented and more Gaussian in shape as d/\lambda increases. For endlessly single-mode LMA HF\textsubscript{s} with d/\lambda ~ 0.4 (see Figure 7 (j)), the optimal coupling efficiency is typically ~ 96%.

Although PBGF\textsubscript{s} of the type shown in Figure 2 typically support more than one core mode, the fundamental mode can be preferentially selected via optimal launching condition and the output of these fibers can be near-Gaussian in shape at wavelengths well within the band-gap and away from avoided crossings with surface modes\textsuperscript{18}. As an example, the optimal coupling efficiency for an idealized 7-cell PBGF with \lambda = 4.7 \mu m, d/\lambda = 0.98 (parameters from Ref. [21]) is calculated here for wavelengths within the band-gap. For this structure, the A\textsubscript{eff} of the fiber remains relatively flat across the band-gap, falling from ~ 82 – 70 \mu m\textsuperscript{2} in the wavelength range 1.4 – 1.7 \mu m. The optimal coupling efficiency correspondingly varies from ~ 94 – 90% within this wavelength range (for Gaussian with spot size between 4.6 – 3.9 \mu m). However, it has been shown that the Gaussian overlap can be larger in a PBGF with a 19-cell core, in which a typical Gaussian overlap is ~ 96%\textsuperscript{18}. This value is more comparable with the typical Gaussian overlaps of single-mode LMA HF\textsubscript{s}, as discussed above.

4. MECHANICAL PROPERTIES OF MICROSTRUCTURED FIBERS

4.1. Introduction

Mechanical strength is an important consideration in determining the reliability of fiber-based systems. In conventional solid fibers, mechanical failure occurs at discrete points where small defects or flaws within the fiber and on the outer surface act to lower resilience to stress/strain. Since HF\textsubscript{s} have a much larger surface area than solid fibers, one may intuitively expect the mechanical strength of HF\textsubscript{s} to be lower than that of solid fibers. Studies to date have shown that, in general, the mechanical properties (tensile strength and dynamic fatigue) of HF\textsubscript{s} are slightly reduced relative to conventional solid fibers\textsuperscript{41, 42}. In addition, and perhaps unsurprisingly, the mechanical strength of HF\textsubscript{s} is found to depend on the fiber cross section and has been shown to increase as the width of solid outer cladding increases and as the air holes decrease in size\textsuperscript{42}. However, so far, no direct comparison has been made between the mechanical properties of holey and conventional fiber types that are similar in both physical size and with similar modal properties. Here we consider the case of a comparable HF and SF pair that have been designed specifically for high power single mode applications, with large-mode-areas and low values of numerical aperture.

4.2. Methodology

Silica microstructured fibers share many similarities with conventional solid fibers; both are similar in dimension, typically possess a single, central core, consist almost entirely of pure silica and are coated with similar materials. As a result, many of the characterization techniques and assumptions that enable the properties of traditional solid core fibers to be evaluated can also be applied to microstructured silica fibers. In studies of conventional fibers, a Weibull distribution is typically used to describe the statistical nature of the fiber flaws that result in failure\textsuperscript{43}, and for uniaxial tensile loading, the cumulative probability of failure is given by:
\[ F(\sigma) = 1 - \exp\left[-\left(\frac{\sigma}{\sigma_0}\right)^m\right] \]  

(1)

where \( \sigma \) is the failure stress, \( \sigma_0 \) is a normalizing constant and \( m \) is the Weibull modulus, which is an inverse measure of the width of the strength distribution. This representation is useful as it can be transformed into a linear format of the form:

\[ \log[\log(1/[1 - F])] = m \log(\sigma/\sigma_0) \]  

(2)

In which \( m \) can be extracted from the modulus of \( \log[\log(1/[1 - F])] \) vs. \( \log(\sigma) \), where \( F \) is defined as

\[ F_i = (i - 0.5)/N, \quad \text{where} \quad i = 1, 2, 3, \ldots N \]  

(3)

in which \( i \) denotes the \( i \)th sample, ranked low-to-high by the value of \( \sigma \) and \( N \) is the total number of samples tested. For conventional telecommunications fiber \( m \) is found to vary between ~5 for weak to >100 for pristine silica. Ideally, high absolute strength and high \( m \) values are desired, representing a consistently strong fiber.

Many different techniques have been developed for conventional fibers that enable the evaluation of the Weibull statistics, which typically involve measuring the stress required to cause the fiber to fail through tensile or bend measurements. Unfortunately, the majority of these techniques require many long lengths of fiber, which are not well suited to the fibers considered here, as they are not fabricated in commercial production quantities. The approach used here is known as a two-point bend test, in which the mechanical strength is assessed by measuring the bend diameter at which a \( \frac{1}{2} \) loop of fiber fails. This approach is chosen primarily because only short sample lengths (a few cm) are required (since the failure diameter is typically small) but also has the advantage that there is no need to bond the fiber to the set-up, as is required in tensile measurement techniques. Note that this is a dynamic strength test and that it assumes a uniform distribution of flaws along the fiber. As a result, this method would be unsuitable for characterizing damaged samples or splice strengths, for example. It should also be noted that approach cannot be used to infer the reliable long term strength (or aging) but that it is well suited to comparing the dynamic strengths of different fiber samples. This is ideal for our purposes, in which we aim is to determine how LMA HF's compare, in terms of mechanical strength, to their conventional solid counterparts.

The two-point bending set-up used in this study comprises two parallel plates driven by a motorized micrometer and is illustrated in Figure 8. In this arrangement, a short section of fiber is bent into a \( \frac{1}{2} \) loop and is placed in the gap between L-shaped plates A and B. The fiber is held in place by a groove on the inner surface of each plate, which has a radius of curvature slightly larger than the overall diameter of the test fibers. Plate A is stationary, whilst plate B is mounted on a micro-positioning stage, driven by a motorized micrometer. The stage, which is driven by an Oriel 18009 control unit, can be driven at variable speeds and enables plate B to be accurately positioned to within 1 \( \mu \)m. For the results presented here, the stage was driven at a relatively low constant velocity of \( \sim 7.6 \ \mu \text{m/s} \). Plate B is driven towards the right-hand edge of plate B until failure of the fiber occurs, which is detected by the acoustic transducer. At this point, the motor is automatically halted, and the width of the gap between plates A and B is recorded. The bend diameter, at which failure occurs (D), is related to the maximum stress at the apex of the bent fiber (\( \sigma \)), by the following equation:

\[ \sigma = 1.198Ed_f/(D - d_c) \]  

(4)

Where \( E \) is the Young's modulus of the fiber material, \( d_f \) is the diameter of the fiber and \( d_c \) is the diameter of the fiber coating. The Weibull modulus \( m \) can then be determined from Eq. (2). Here we assume that the Young’s modulus of the HF is equal to solid silica, which \( \sim 72 \ \text{GPa} \).

In two-point bend testing only half of the fiber cross-section is under tensile loading and the stress distribution over that plane is highly non-uniform. Consequently, \( \sigma \) in this study corresponds to the stress over a very small gauge length at the bend apex and tensile testing of longer fiber lengths may give different strength results. However, this approach still
provides valuable information on the strength distribution (via the Weibull modulus) and is well suited to studying the relative strength performance of different fibers\(^5\).

![Acoustic transducer](acoustic_transducer.png)

**Figure 8** Schematic of the two-point bending experimental set-up

### 4.3. Results and discussion

Two fibers were characterized using the set-up shown in Figure 8, one HF and one solid fiber (SF). Both fibers are made from the same grade of silica, are of similar size, are coated in identical materials and are comparable in terms of mode size and beam quality, thus enabling a direct comparison of their mechanical properties. The fiber parameters are listed in Table 1 below. The effective mode area (\(A_{eff}\)) was measured using a far-field knife-edge technique and the critical bend radius (\(R_c\)) corresponds to the radius at which half the power is lost in a single loop. Note that the HF is endlessly single-mode and the SF is observed to be single-mode for radii < 6 cm. Optical images of these two fibers are shown inset in Figure 9 (b).

<table>
<thead>
<tr>
<th>Fiber</th>
<th>Outer diameter</th>
<th>Coated diameter</th>
<th>Core diameter</th>
<th>Other parameters</th>
<th>(A_{eff}) at 1064 nm</th>
<th>(R_c) at 1064 nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>HF</td>
<td>240 (\mu)m</td>
<td>315 (\mu)m</td>
<td>~20 (\mu)m</td>
<td>d/A ~ 0.33</td>
<td>210 (\mu)m(^2)</td>
<td>~7 cm</td>
</tr>
<tr>
<td>SF</td>
<td>220 (\mu)m,</td>
<td>330 (\mu)m</td>
<td>~24 (\mu)m</td>
<td>NA ~ 0.044</td>
<td>190 (\mu)m(^2)</td>
<td>~3 cm</td>
</tr>
</tbody>
</table>

**Table 1** Parameter of fibers characterized via two-point bend test shown in Figure 8.

![Graphs](graphs.png)

**Figure 9** (a) Cumulative probability of failure vs. failure stress for the SF and the HF, (b) plot of \(\log(\sigma)\) vs. the LHS of Eq. (2). Optical images of the HF and SF used in these tests are shown inset in (b).
In the results presented here ~ 20 fiber samples were tested for each fiber considered, each of ~ 5 cm in length with the fiber coating intact. The cumulative probability of failure (F) is plotted against the failure stress (ε) in Figure 9 (a) for both fibers. The value of stress for which F = 0.5 (ε₅₀), and the associated bend diameter (D₀₅) are useful measures of fiber strength and are often used in comparative studies. From Figure 9 (a) it can be seen that the HF and SF have similar values of ε₅₀ of ~ 4.28 and 4.37 GPa respectively, indicating that the two fibers are comparable in terms of absolute strength. These values of ε₅₀ correspond to a D₀₅ of ~ 5 mm for each fiber. However, note that this is not a measure of the practical long term bend radius, for conventional telecommunications fiber is ~ 2 cm, and increases with increasing OD. In Figure 9 (b), log[ln(1/(1-F))] is plotted against log(σ), which enables the Weibull modulus (m) to be extracted (See Eq. (2)). The Weibull modulus (m) is found to be ~ 74 and 128 for the HF and SF respectively, demonstrating that the SF is a consistently strong fiber, as expected, but that the HF has a wider distribution of results. However, note that none of the HF samples failed at strengths lower than those spanned by the SF samples. In addition, on closer inspection of the data, it can be seen that the HF results are not evenly distributed between maximum and minimum values as in the SF case. Instead, the data is grouped into several sets, with one most notably localized around the ε₅₀ value, which, taken by itself has m ~ 150. One possible explanation for this distribution is the non-circularly symmetric nature of the “holey” cladding; in the HF considered here, the cladding is approximately hexagonal in shape, resulting in a varying thickness of solid silica in the outer part of the fiber. As mentioned above, it has been shown that the tensile strength of microstructured fibers increases as the distance between the outermost air holes and the outer surface of the fiber increases. Consequently, it is possible that the Weibull modulus could be increased by creating a HF with a more circular cladding extent.

In summary, a simple two-point bending method has been used in order to determine the comparative strength of a LMA HF and conventional solid fiber. These two fibers, which possess similar mode areas, outer diameters and coating materials, are found to show a comparable range of failure strengths, demonstrating that HF technology represents a practical alternative to conventional fibers. Although the HF results show a greater statistical spread, it is thought that this may result from the non-circularly symmetric nature of the “holey” cladding, which can be simply modified. Similar studies are in progress to determine the comparative strength of hollow-core PBGFs. However, as the microstructured region is located deeper inside the fiber in this case, one may expect the strength of PBGFs to be between those of HFs and solid fibers.

5. CONCLUSION

In conclusion, the results presented here show that with comparable performance in terms of loss, end termination and mechanical strength, index-guiding HFs represent a real, practical alternative to conventional technologies for high power beam delivery applications and also offer significant advantages over conventional technologies for broadband applications in terms of mode size for single-mode operation. In contrast, although hollow-core PBGFs offer orders of magnitude improvements in terms of power handling and nonlinear suppression, and potentially offer lower transmission losses than is possible to achieve in solid core fibers, further work is required to assess the practical performance of these fibers. However, it is probable that the mechanical performance of hollow-core PBGFs (in terms of strength and end face preparation) will not differ significantly from those of index guiding HFs, indicating that hollow-core PBGFs offer real promise for the fiber delivery of intense laser radiation in real-world systems.

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