Microstructured cladding elements to enhance performance and flexibility of large mode area fibers

Sonali Dasgupta[1a], John R. Hayes[a], Catherine Baskiotis[a], David J. Richardson[a]
[a]Optoelectronics Research Centre, University of Southampton, SO16 7FB, United Kingdom.

ABSTRACT

Large mode area fibers are imperative for scaling up the average power of fiber lasers. Single-mode behavior and low FM loss are the crucial functionalities for these fibers. However, for key applications such as picosecond pulsed lasers, the device length needs to at least a few meters. This makes a certain degree of bend tolerance a prerequisite in the fiber design. While rod-type PCFs have been very successful in offering large mode areas, their rigid configuration limits their application domain. Alternatively, leakage channel fibers (LCFs) have shown a great potential for offering substantial bend tolerance along with large mode areas. However, the proposed use of Fluorine-doped rods in the all-solid version limits their practical design space. Here, we propose a novel design concept to attain single-material, large mode area fibers (mode area >~ 1000µm^2) with effectively single mode operation coupled with bending characteristics comparable to all-solid LCFs and greater design flexibility and easier splicing that is comparable to rod-type PCFs.

Keywords: large mode area fibers, microstructured fiber, single mode, bend radius, leakage channel fibers

1. INTRODUCTION

The development of large mode area (LMA) fibers in the recent past has primarily been driven by the quest to attain higher output powers from fiber lasers. The combination of high peak power (~ MW), high average power (~ kW), excellent beam quality and long working distance obtainable from fiber lasers has transformed the materials processing industry today, with processes such as remote laser welding, precision cutting and marking being routinely used for manufacturing products ranging from automobiles to medical stents. Continuous wave fiber lasers can easily generate multi kilowatt powers [1] with an almost perfect beam quality whereas pulsed fiber lasers in the femtosecond regime can be used to generate up to few millijoules of pulse energies [2]-[3]. However, further scaling of the output power from fiber lasers demands a novel approach to design the large mode area fibers in order to tackle the detrimental effects of excessive thermal load, nonlinear effects, bend loss and higher order mode coupling [4].

The design of LMA fibers for laser applications focuses on attaining the following essential characteristics: single-mode output, low fundamental mode (FM) loss and low bend loss. However, there is always a trade-off between the largest mode area that can be achieved, number of modes supported and the bend loss of the fiber. For example, if the core size of a fiber is increased in an attempt to achieve large mode area, the refractive index difference between the core and cladding must be decreased in order to maintain single mode operation. The reduced index difference (numerical aperture) increases the sensitivity of the fiber to macro bends and associated bend losses, which in turn renders the fiber impractical for packaging. Besides, the lowest numerical aperture is technologically limited to ~ 0.06 by the MCVD process, which imposes an upper limit of ~15um on the core diameter [5][6]. In practice, instead of being truly single-mode, most LMA fibers are in fact designed to support a few higher order modes (HOMs) in addition to the fundamental mode, and effective single mode operation is realized by enabling sufficiently large differential loss between the FM and the HOMs. The most widely employed technique to realize this is bending the fiber in a controlled manner so as to preferentially lose out the power in the HOMs as compared to the FM [6]. Other techniques have also been proposed such as the chirally coupled fibers [7], resonant out-coupling of HOMs [8] etc. although with limited applicability due to issues concerning their fabrication tolerance.

Microstructured fiber technology is the alternate technology platform that has been widely explored due to its potential to offer extremely low numerical aperture. The core of the microstructured optical fibers (MOFs) is typically surrounded by a lattice of air-holes or dopant rods that constitute the fiber cladding. Various designs have been reported that enable LMA fibers with mode areas ~ 1000 µm^2 [9-14]. Amongst these, the rod-type photonic crystal fibers (PCFs)

---

[1] sxd@orc.soton.ac.uk; Phone: +44 23 8059 22825

and the leakage channel fibers (LCFs) represent two of the most successful design platforms that have enabled the design of fibers with mode areas > 4000µm^2 at the wavelength of 1.05µm. More recently, large pitch fibers have also been reported as an attractive route for achieving very large mode area up to ~ 8600µm^2 [11], although they can be considered as a subset of rod-type PCFs.

Rod-type PCFs are essentially based on exploiting the ‘endlessly single-mode’ property of PCFs, which allows single-mode propagation as long as the ratio of the air-holes to the pitch (d/Λ) is less than ~ 0.40 [15]. This has allowed reducing the numerical aperture to values much lower than what is possible through conventional fibers by compensating for the reduced difference with larger air-holes [13]. It is important to note that rod-type PCFs are essentially leaky, multimode fibers that have been tailored to exhibit much higher losses for the HOMS. Thus, as the numerical aperture reduces or the core size increases, they become more susceptible to inter modal coupling, macro bends and reduced effective area in the bent state. Hence, the rod-type PCFs, as their name suggests, rely upon a rigid configuration to avoid the afore-mentioned issues; although this becomes increasingly challenging as core diameters larger than 50µm are targeted. The rigid configuration of the rod-type PCFs also limits their practical device lengths to only few tens of centimeters. While such lengths are sufficient for achieving high peak powers for many applications, they are not appropriate for the generation of short pulse, high average power fiber lasers, which typically necessitate fiber lengths of a few meters.

LCFs, in contrast, exploit differential leakage loss of the modes in a leaky fiber structure to achieve single mode output along with low bend loss for considerably large mode areas [12]. However, the originally proposed air-hole LCFs suffer from the serious issue of mode distortion and high losses during splicing / end termination due to the collapse of the large air holes [12]. A solution was proposed in the form of all-solid LCF, in which the air holes were replaced by F-doped rods [16], which could offer bend losses at par with the air-hole LCFs. Their performance could be improved further if the index difference between the core and the cladding rods could be increased. Larger index difference leads to a higher effective index difference between the modes, a lower mode loss sensitivity to index variations and reduced losses at smaller hole diameter to pitch ratio [16]. However, in practice, the maximum material index difference for F-doped rods is limited to ~ 10^{-3}. Higher levels of F-doping may present issues of poor surface quality and localized defects that can severely compromise fiber quality during the fabrication process due to diffusion and out-gassing of fluorine from the silica glass matrix. Here, we propose a single-material (silica) large mode area fiber design platform based on a novel air-hole lattice structure that avoids the potential issues mentioned above and allows easy splicing to conventional solid fibers while exhibiting bend characteristics that are comparable to all-solid leakage channel fibers.

2. FIBER DESIGN CONCEPT AND PERFORMANCE

The proposed design (Fig.1) consists of 6 microstructured cladding elements that are arranged in a hexagonal lattice and surround the core region (pitch, Λ_1). Each cladding element itself is a hexagonal lattice of ~3-4 rings (n_{rings}) of small air holes (hole diameter, d_2 (~ 1µm), pitch, Λ_2).

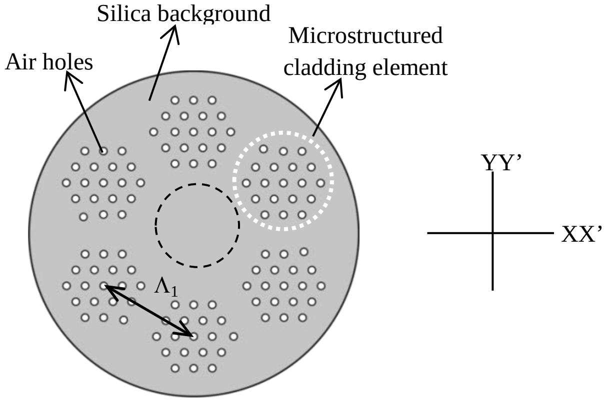

Fig. 1. Schematic of proposed LMA fiber with microstructured cladding elements.

The resultant fiber is a leaky waveguide that allows single-mode output owing to the large differential loss suffered by the HOMs that ‘leak out’ from the ‘silica channels’ in between the cladding elements (similar to LCFs) [12]. The ‘effective’ index difference between the core and the cladding can be controlled by appropriately engineering the lattice of air holes in the cladding elements, and thereby offering a much greater choice over the achievable numerical aperture as compared to the conventional LCF approaches.

Fabrication of the proposed fiber would necessitate a two-step process - the hexagonal microstructured cladding elements would first have to be obtained by the standard stack and draw technique, which would then be drawn into a cane as the first-stage preform. Subsequently, the canes would need to be stacked together with the core element (doped with rare-earth for the active fiber version) within an enclosing silica jacket tube to form a second-stage preform, which would be drawn into the fiber.

2.1 Modal characteristics

The HOM filtering capability (differential loss between the FM and the HOMs) of the proposed fiber is primarily determined by the separation between the cladding elements. Accordingly, we define a structural parameter, $\sigma\,(= \Lambda_1 - n_{rings} * \Lambda_2)$ that is proportional to the width of these channels. For the initial design, we arbitrarily chose a core diameter of 50µm, and air-hole diameter of 1µm in the cladding. We vary the pitch of the lattice structure in the cladding elements, which translates into different values of the channel width, σ, and study its effect on the modal characteristics of the fiber. Figure 2 illustrates the effect on the FM effective area, FM loss and propagation loss ratio between the FM and the first HOM (LP_{11}).

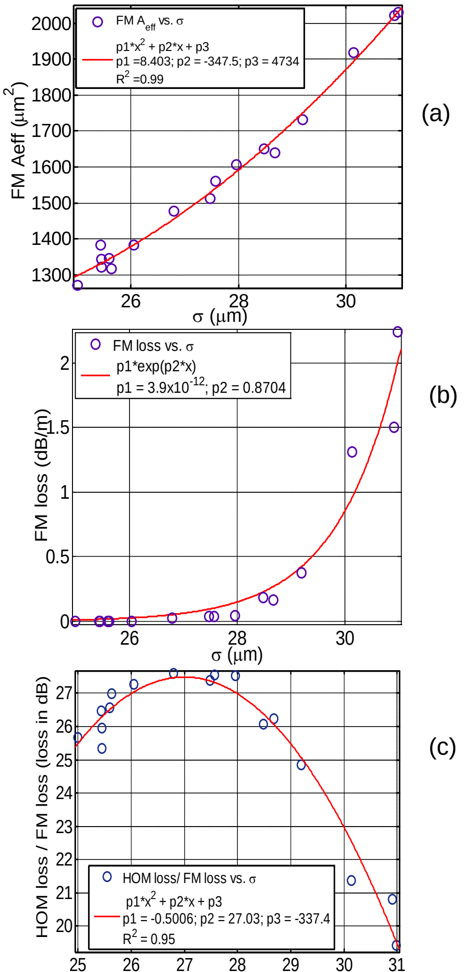

Fig. 2. Effect of cladding element separation,σ, on (a) FM effective area (b) FM loss (c) Ratio of HOM loss to FM loss. Core diameter = 50µm; Air hole diameter = 1µm.

It is clear from Fig. 2(a) that effective area of up to 1900µm^2 can be achieved while maintaining the FM mode loss < 1dB/m along with loss ratios between the FM and the first HOM (LP$_{11}$) > 22. It is also evident that there exists a trade-off between the largest effective area that can be attained, the lowest FM loss and the highest differential loss. Since the FM loss has a much stronger exponential dependence on the channel separation than the differential loss, it ends up being the deciding factor for a particular design choice.

Simulations for fiber designs with larger core diameter (up to 80µm) based on the proposed concept were also performed. They exhibited qualitative behavior similar to Fig.2, thus proving the potential of this scheme to achieve LMA fibers with much larger effective areas. However, as with other previously reported designs [16], the single-mode operation of the proposed design becomes increasingly constrained by the existence of HOMs as the core diameter is increased above ~ 50µm diameters. For example, our simulations showed that the proposed strategy easily allows the design of a fiber that can exhibit an effective area of ~ 4766µm^2, and a FM and HOM loss of 0.11dB/m and 2.7dB/m, respectively (Fig.3). However, the 2nd HOM (LP$_{21}$) of the fiber exhibits a much lower loss of ~ 0.01dB/m (Fig.3). Fortunately, the fractional power of the 2nd HOM within the core region is <30%, while it is above 77% for the FM. By employing additional techniques such as selective launch and preferential doping, it should be possible to mitigate the issues associated with these detrimental HOMs.

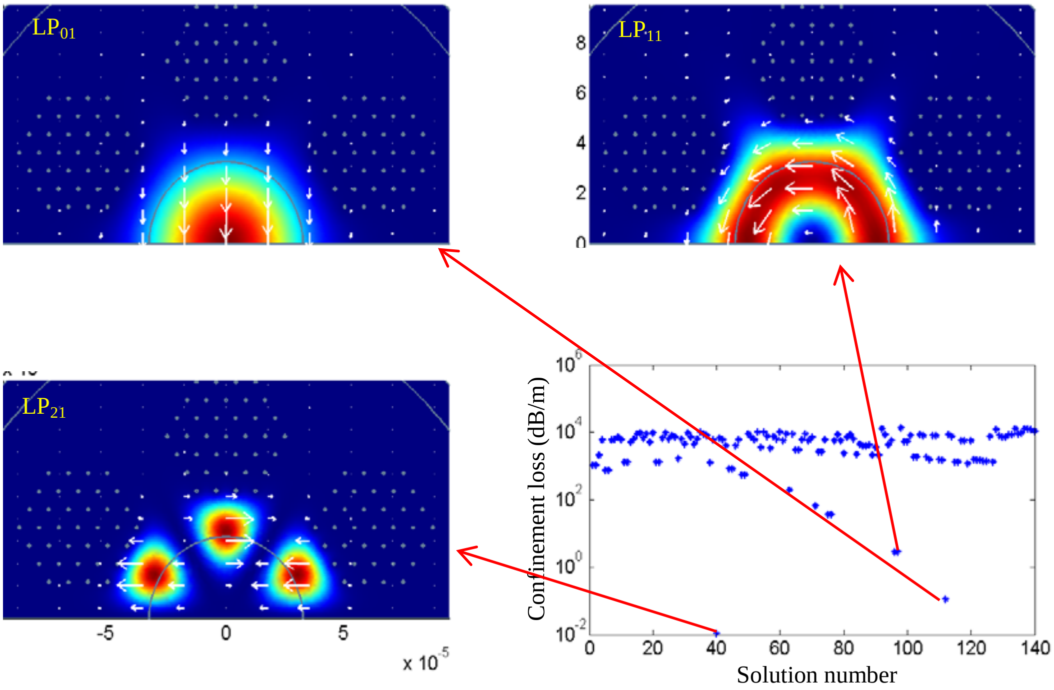

Fig.3. Optical mode characteristics of the proposed fiber with a core diameter of 80µm: (a) FM; (b) LP$_{11}$ mode (c) LP$_{21}$ mode; (d) fractional optical power of various modes within the core region. FM effective area ~ 4766 µm^2; FM loss ~ 0.11dB/m; LP$_1$ mode loss = 2.7dB/m, fractional power within core: 77% (FM); 53% (LP$_{11}$); 32% (LP$_{21}$).

2.2 Bend performance

Based on Fig.2, we choose a LMA design that offers an effective area of ~1606µm^2 at 1.05µm, with a FM and HOM loss of 0.05dB/m and 1dB/m, respectively. We study the bend performance of this design to analyze its usability for applications that require a few meter lengths of the fiber such as picosecond pulsed lasers. Figure 4 illustrates the change in the effective area and loss of the FM of the fiber in the bent configuration (*Rc* is the bend radius); assuming the bend to be along the XX' plane (clf. Fig.1). Bending the fiber along the orthogonal YY' plane yields losses that are in line with the qualitative observations for all-solid LCFs [17]. Fig. 4(a) shows that the fiber can be bent down to a radius of ~ 40cm with ~25% reduction in the effective area and FM loss slightly above 1dB/m. Tighter bends lead to more significant reduction in the effective area besides much higher propagation losses of the FM. Interestingly, bending the fiber does not seem to have a significant effect on the differential loss although there does exist an optimum bending radius that offers the largest ratio of loss between the FM and the first HOM. Further detailed calculations on other fiber designs revealed that either the bend loss or the reduction in effective area will have to be compromised in order to achieve larger effective areas.

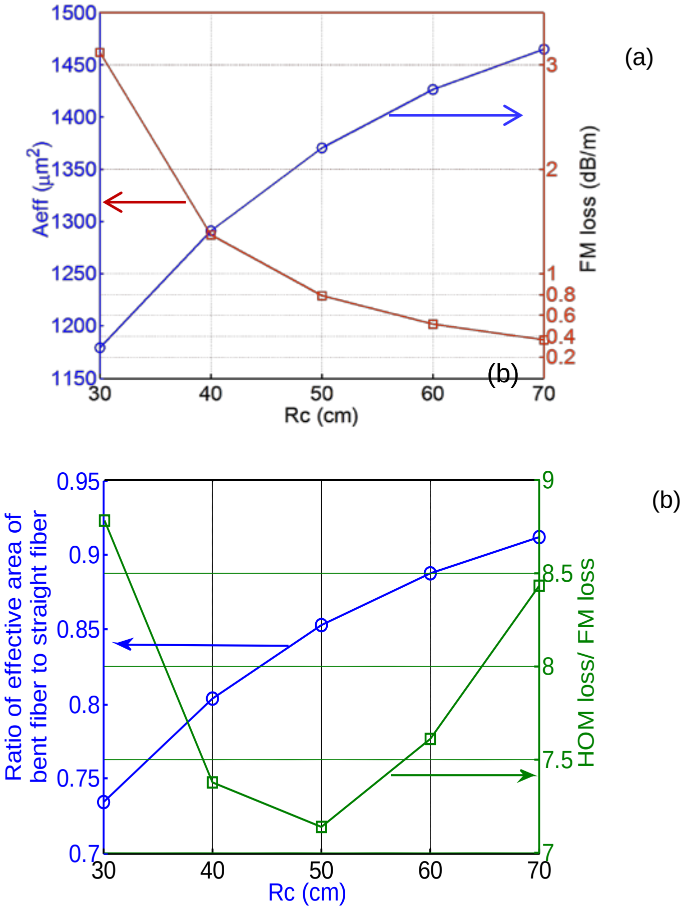

Fig. 4. Effect of bend radius on (a) FM effective area and propagation loss (b) Reduction in effective area and loss ratio between FM and HOM

3. CONCLUSION

In conclusion, we have presented a new design strategy that combines the desirable bending characteristics of all-solid LCFs with the splicing and handling advantages of single-material rod-type PCFs. The novel design is based on employing microstructured cladding elements that allow single-mode output due to the presence of ‘leakage’ channels within these elements. The use of the air-holes in the cladding elements also offers a greater control over the index difference between the core and the cladding, which should be beneficial in the active fiber design where precise control over the index profile is imperative.

4. REFERENCES

[1] Y. Jeong, A. J. Boyland, J. K. Sahu, S. Chung, J. Nilsson, and D. N. Payne, “Multi-kilowatt single-mode ytterbium-doped large-core fiber laser,” J. Opt. Soc. Korea **13**, 416 (2009).

[2] A. Malinowski, A. Piper, J. H. V. Price, K. Furusawa, Y.Jeong, J. Nilsson, and D. J. Richardson, “Ultrashort-pulse Yb3+-fiber-based laser and amplifier system producing >25W average power,” Opt. Lett. **29**, 2073 (2004).

[3] F. Röser, T. Eidam, J. Rothhardt, O. Schmidt, D. Schimpf, J. Limpert, and A. Tünnermann, "Millijoule pulse energy high repetition rate femtosecond fiber chirped-pulse amplification system," Opt. Lett. **32**, 3495-3497 (2007).

[4] D. J. Richardson, J. Nilsson, and W. A. Clarkson, 'High Power Fiber Lasers: Current Status and Future Perspectives', J. Opt. Soc. Am. B, **27**, B63 (2010).

[5] M. Li, X. Chen, A. Liu, S. Gray, J. Wang, D. T. Walton, and L. A. Zenteno, "Limit of effective area for single-mode operation in step-index large mode area laser fibers," Journal of Lightwave Technology **27**, 3010 (2009).

[6] M. E. Fermann, "Single-mode excitation of multimode fibers with ultrashort pulses," Optics Letters **23**, 52 (1998).

[7] S. Lefrancois, T. Sosnowski, C. Liu, A. Galvanauskas, and F. Wise, "Energy scaling of mode-locked fiber lasers with chirally-coupled core fiber," Opt. Express, **19**, 3464 (2011).

[8] Y. Tsuchida, K. Saitoh, and M. Koshiba, "Design of single-moded holey fibers with large-mode-area and low bending losses: The significance of the ring-core region," Optics Express **15**, 1794 (2007).

[9] M. Laurila, M. M. Jørgensen, K. R. Hansen, T. T. Alkeskjold, J. Broeng, and J. Lægsgaard, “Distributed mode filtering rod fiber amplifier delivering 292W with improved mode stability,” Opt. Express **20**, 5742 (2012).

[10] M. M. Vogel, M. Abdou-Ahmed, A. Voss, and T. Graf, "Very-large-mode-area, single-mode multicore fibe," Optics Letters **34**, 2876 (2009).

[11] F. Jansen, F. Stutzki, T. Eidam, J. Rothhardt, S. Hädrich, H. Carstens, C. Jauregui, J. Limpert, and A. Tünnermann, "Yb-doped Large Pitch Fiber with 105µm Mode Field Diameter," in Optical Fiber Communication Conference, OSA Technical Digest (CD) (Optical Society of America, 2011), paper OTuC5.

[12] L. Dong, X. Peng, and J. Li, "Leakage channel optical fibers with large effective area," J. Opt. Soc. Am. B, **24**, 1689 (2007).

[13] J. Limpert, O. Schmidt, J. Rothhardt, F. Röser, T. Schreiber, A. Tünnermann, S. Ermeneux, P. Yvernault, and F. Salin, "Extended single-mode photonic crystal fiber lasers," Optics Express **14** (2006).

[14] J. Limpert et. al., "High-power rod-type photonic crystal fiber laser," *Opt. Express* **13**, 4 (2005).

[15] T. Birks, J. Knight, and P. Russell, "Endlessly single-mode photonic crystal fiber," Opt. Lett. **22**, 961 (1997).

[16] L. Dong, T. Wu, H. A. McKay, L. Fu, J. Li, and H. G.Winful, "All-glass large-core leakage channel fibers," IEEE Journal of Selected Topics in Quantum Electronics **15**, 47 (2009).

[17] T.Wu, L. Dong, and H. Winful, "Bend performance of leakage channel fibers," Optics Express, **16**, 4278 (2008).