Low Loss, Large Bandwidth Antiresonant Hollow-Core Fiber Design for Short-Reach Links

William Shere, Gregory T. Jasion, Eric Numkam Fokoua and Francesco Poletti
Optoelectronics Research Centre, Faculty of Engineering and Physical Sciences, University of Southampton, UK
whws1g14@soton.ac.uk

Abstract: We present antiresonant hollow-core optical fibre designs for VCSEL-based short-reach transmission applications in the 850nm band. Our simulations show that lower loss and twice the bandwidth of solid, multi-mode, graded index fibres are possible.

1. Introduction

For short-reach data transmission applications, solid-core, multi-mode, graded-index (GI) are often preferred since their larger cores simplifies connections and allows them to be used with low-cost sources such as vertical cavity surface emitting lasers (VCSELs) which are also typically multi-moded [1, 2]. The data rates of these systems are limited by the fibres' modal dispersion. Although better fabrication tolerances have brought improvements to the OM (optical multi-mode) family of fibres, fundamental limits imposed by their practical minimum loss and dispersion are now in sight. Current Ethernet standards achieve 100 Gb/s transmission by deploying bundles of 4 or 8 GI fibres, each carrying 50 or 25 Gb/s, up to 100 m [3]. The latest, OM5, standard seeks to achieve higher data rates through wavelength division multiplexing (WDM) but the usable optical bandwidth is limited by dispersion and loss specifications. Emerging requirements for 200 and 400 Gb/s Ethernet require a new approach to achieve the required bandwidth over useable distances and without an excessive increase of the already substantial hardware infrastructure.

Air guidance presents the potential to transform short-reach optical links by providing ultra-low latency, wider optical bandwidth and lower losses [4]. The latest generation of nested antiresonant fibres (NANF) in particular has seen remarkable progress in recent years: going from a pure numerical concept a few years ago to now achieving losses of 0.65 dB/km over the C and L bands [5]. These fibres exploit coherent reflections from a microstructured cladding formed of thin glass capillaries to guide light in a hollow core. The simplicity of this structure means that their key optical properties can be engineered by adequate choice of membrane thickness and tube dimension. Unlike in standard fibres where loss is mostly imposed by material properties and changes little amongst modes, guidance in a hollow-core often results in large differential properties between the various core-guided modes (e.g. loss and group delay). This is often a helpful feature, which can be exploited to produce effectively single-mode fibres with large core-sizes, but no work to date has addressed the question of whether multi-mode hollow core fibres with low differential loss can be designed.

Here we use comprehensive numerical simulations to show that antiresonant fibres can be designed to support several modes with relatively low differential losses. The structures we explore are similar in concept to the NANF but feature a pair of tubes nested within a larger one, a design known as antiresonant leakage inhibited fibre (ALIF), to achieve better intermodal control. Our simulations indicate that a VCSEL-compatible large core fibre design able to support the first 7 mode groups with less than 0.6 dB/km loss around 850 nm and over twice the optical bandwidth of GI fibre should be possible. When added to the other unique advantages of ultralow latency and chromatic dispersion, our designs emerge as a promising alternative to GI fibres in many short reach applications.

2. Fibre Design

Figure 1 shows cross-sections of example antiresonant hollow-core fibres, the NANF and the ALIF which is the subject of the present study. In these fibres, the thin tubular membranes behave as Fabry-Perot resonators in the transverse direction and provide effective reflection to confine light into the central core. As such, the typical transmission spectrum of the fibre consists of broad low-loss regions (antiresonance windows) separated by high loss peaks (resonances) determined by the membrane thickness. It is now well-known that the air regions enclosed by the tubular membranes support lossy modes which can strongly couple to the core-guided modes when a phase-matching condition is met (i.e. when they have a similar effective index), resulting in very high attenuation. ALIFs are a modification of the NANF concept replacing the nested element with a pair of nested capillaries inside the primary tube. They have been shown to achieve over two orders of magnitude reduction in confinement loss versus NANFs [6]. Most importantly for us, the ALIF modification provides a further degree of freedom to partition the microstructured cladding and control its modal properties whilst maintaining low-loss operation for all core modes. By choosing the size and position of the nested tube pair appropriately, we can reduce the higher order mode (HOM) coupling to cladding modes, resulting in the fibre guiding many low-loss modes in the core region.

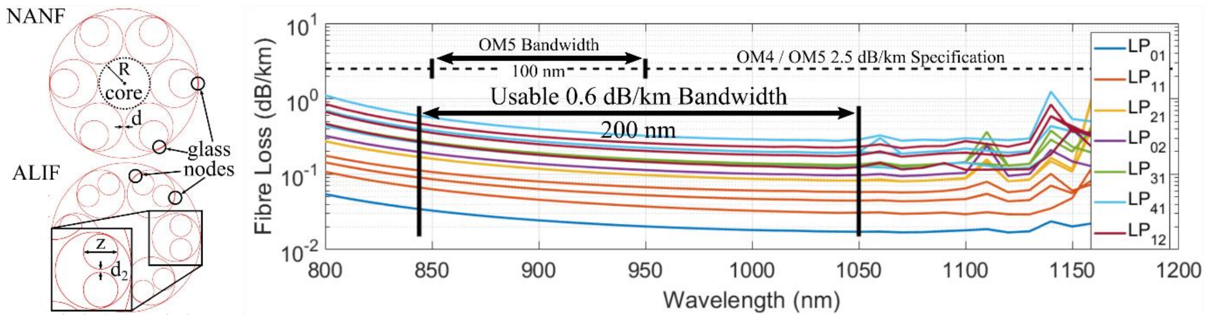

Fig. 1: A comparison of the NANF (top-left) and ALIF (bottom-left) structures and the loss spectrum of the 10-element multimode ALIF geometry shown in Fig. 2. In the ALIF, careful choice of the nested tube diameter z and their separation distance d_2 allows control of the loss and modal content of the fibre.

The key geometrical design parameters of the ALIF are described in Fig. 1. Here we chose a core diameter of 50 μm (similar to OM4 and OM5) and a membrane thickness of 330 nm for all the designs explored, giving a first resonance around 660 nm and a fundamental antiresonance window covering our wavelength band of interest, 850 nm. We used the commercial fully-vectorial mode solver COMSOL for our modelling. We restricted our studies to structures featuring an even number of cladding elements to exploit their symmetry and minimize computation time (modelling only a quarter structure). We calculated loss as the sum of leakage and surface scattering contributions [7], assuming in this study a negligible microbending contribution. Every permutation of the boundary conditions on the quarter structure was performed to ensure all the fibre's modes were solved for.

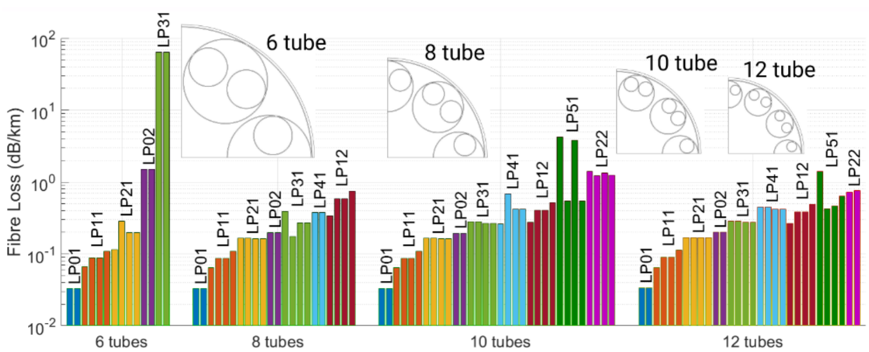

Fig 2: Losses of the core guided modes of the shown fibre geometries. The core diameter and tube wall thickness of every fibre is 50 μm and 330 nm respectively.

We first sought to optimize a six-element ALIF for multi-mode guidance. We found that different partitions of the cladding allowed to select which core modes coupled strongly to lossy cladding modes. However, this was limited by the size of the outer tubes. With the largest nested elements possible there were still large air regions in the cladding (see the highlight in Fig. 1), and as a consequence the fibre could at best support the first four mode groups (LP_{01}, LP_{11}, LP_{21} and LP_{02}) with reasonably low-loss.

To further decrease the loss of HOMs, we increased the number of outer tubes in order to reduce the size of the air regions in the cladding. We identified through this process that a 10-element ALIF could provide sub dB/km loss for the first seven mode groups over the widest bandwidth. The loss of this fibre is plotted in Fig. 1 and the results at 850 nm for the other fibres explored are summarized in Figure 2. Reducing the size of the air regions in the cladding effectively lowers the propagation constant of the modes they support, and thus reduces the possibility of phase-matching to core modes. Fibres with more elements therefore support more core modes and the confinement losses of HOMs are decreased. For the lowest order modes, we found that scattering loss is the dominant contribution in such a large core, with leakage making increasingly large contribution as the order of the mode increases.

We note that the trend of higher order mode loss reduction continues as we add further elements. However, we found that the trade-off was the reduction in bandwidth induced by the spurious resonances which can be seen beyond 1100 nm in Fig. 1. These are introduced by the glass nodes (where tubes are fused together) which have long been known to negatively affect the performance of antiresonant fibres [8]. These sharp spikes in the loss spectrum are more pronounced for HOMs. Although they can be mitigated by moving the nodes further away from the core, we found this strategy relatively ineffective when the design featured more than 10 elements.

For the 10-element fibre the glass resonances limit the usable bandwidth to 1050 nm. For the 12 tube fibre the effect is more pronounced and appears at shorter wavelengths. The 10-element geometry is therefore chosen as the best trade-off between few-moded operation and bandwidth. It supports 7 mode groups (a total of 24 modes) all with a loss (scattering + leakage) under 0.6 dB/km over a bandwidth of 200 nm. This is almost 2 dB/km below the specification of the OM4 and OM5 standards and over twice the bandwidth of OM5.

3. Dispersive Properties

The single channel data rate in multi-mode links is limited by the dispersive properties of the fibre. The ALIF structures presented here offer a significant advantage over solid-core multi-mode fibres in terms of latency and chromatic dispersion. For the 10 element ALIF we optimised, we plot in Figure 3 the chromatic dispersion of the first seven mode groups. As can be seen, they are all lower than 10 ps/nm.km across the bandwidth of interest, an order of magnitude lower than what is typical in GI fibres.

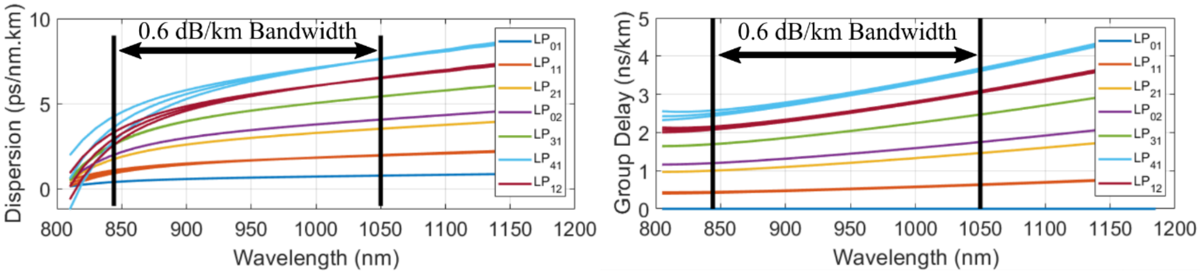

Fig. 3: The DGD (left) and chromatic dispersion (right) of the 10 tube fibre shown in Fig. 2.

We found however, that our ALIF designs may suffer from larger intermodal differential group delay (DGD) than typical OM fibres. Indeed, intermodal dispersion is the limiting factor for GI fibres and its impact is traditionally minimized by careful selection of the refractive index profile of the fibre. For OM3 fibres, for example, maximum DGD is of the order of 0.22 ns/km [9]. For our ALIF, our approach to reducing differential loss does not result in commensurate improvements in the differential group delay. We calculated for the optimised 10 tube structure that the DGD at 850 nm between the fundamental (LP_{01}) and the 7th mode group (LP_{12}) is as high as 2.5 ns/km. This makes DGD a potentially limiting factor for single wavelength, high baud rate transmission in these fibres, if these are to be used with multi-mode VCSELs. However, we believe that DGD itself can be reduced for example by employing a larger core diameter. Further, the impediments induced by DGD can be circumvented by launching light into only a subset of the modes, a technique employed by the OM specifications in their encircled flux requirements.

Besides, one might think of exploiting the wide optical bandwidth and low chromatic dispersion of the fibres to implement WDM at low baud rates, in combination perhaps with higher order modulation techniques that can address the limitations imposed by such relatively high DGD. Orthogonal Frequency Division Multiplexing (OFDM) for example, is a format that is known to be resilient to multipath interference [10].

4. Conclusions

We have presented an approach to achieve low loss, multi-mode operation of hollow-core, antiresonant fibres based on the ALIF structure. Using this approach, a series of fibres were designed with increased multi-mode content. A fibre with twice the bandwidth of the current generation of GI fibre targeting WDM for short-reach datacoms was chosen as the best trade-off. This geometry guides 7 mode groups, or a total of 24 modes, with losses under 0.6 dB/km. Although the single channel data rate is likely inferior to DGD optimised GI fibre due to a large DGD, the proposed fibre has the potential to achieve 100 Gb/s data rate or better using WDM over its increased bandwidth. OFDM is suggested as a modulation format to mitigate the effects of DGD in which case the bandwidth could be used to achieve 200 Gb/s or greater data rates.

The authors gratefully acknowledge the support of the UK RAEng and of an ERC fellowship (grant agreement no. 682724).

References

[1] J. Heinrich, E. Zeeb, and K. J. Ebeling, *IEEE Photonics Technol. Lett.*, vol. 9, no. 12, pp. 1555–1557, 1997.
[2] R. Michalzik, *VCSELs: fundamentals, technology and applications of vertical-cavity surface-emitting lasers*, vol. 166. Springer, 2012.
[3] IEEE standard 802.3bm, 2015.
[4] F. Poletti, *Opt. Express*, vol. 22, no. 20, p. 23807, 2014.
[5] T. D. Bradley *et al.*, *Eur. Conf. Opt. Commun.*, vol. 1, pp. 1–4, 2019.
[6] G. T. Jasion, D. J. Richardson, and F. Poletti, in *Optical Fiber Communication Conference (OFC) 2019*, 2019, p. Th3E.2.
[7] E. N. Fokoua *et al.*, in *Optical Fiber Communication Conference (OFC) 2014*, 2014, pp. 1–3.
[8] A. N. Kolyadin *et al.*, *Opt. Express*, vol. 21, no. 8, pp. 9514–9519, 2013.
[9] P. Pepeljugoski, D. Kuchta, Y. Kwark, P. Pleunis, and G. Kuyt, *IEEE Photonics Technol. Lett.*, vol. 14, no. 5, pp. 717–719, 2002.
[10] A. James Lowery and J. Armstrong, *Opt. Express*, vol. 14, no. 6, pp. 2079–2084, 2006.