Data Transmission Over 1km HC-PBGF Arranged With Microstructured Fiber Spliced To Both Itself And SMF

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Abstract *Validation of novel splicing strategy enabling integration of hollow-core photonic band gap fiber with both itself and conventional SMF is presented. Self-splices are robust and low loss (0.16dB). Penalty-free 40Gbit/s data transmission is demonstrated in 1km arrangement of spliced HC-PBGF.*

Introduction

Hollow-core photonic band-gap fiber (HC-PBGF) is attractive in many applications, from spatial division multiplexing[1] to gas sensing[2], and potentially of particular interest for next generation telecoms infrastructure. These air-guiding fibers offer ultra-low nonlinearity, low latency and a new transmission band in their predicted ultra-low loss window at 2µm wavelength.

HC-PBGF is intrinsically multimode, yet low intermodal coupling means that it can be effectively operated as a single mode fiber[3]. The geometry of air-core and microstructured inner cladding (Fig. 1, left) are critical to the band-gap and guiding properties of the fiber. The microstructure was previously suspected to be too fragile to splice without high loss or modal disruption, detrimental to data transmission[4,5]. However, we have recently demonstrated a splicing strategy overcoming this perceived difficulty[6], and we use this to achieve robust low-loss splices between HC-PBGF without any significant impact on microstructure (Fig 1, right), while it is also applicable when integrating conventional SMF with HC-PBGF. Here we now report data transmission experiments with various configurations of HC-PBGF, that include splices to SMF, with amplification between sections and a total of one kilometer of HC-PBGF within the arrangement. This is to our knowledge the longest length reported for data transmission over HC-PBGF and demonstrates this novel fiber type in a small-scale approximation to a complex telecoms network.

Splice strategy

Conventionally microstructured fibers have been spliced using short arcs at low powers to avoid microstructure collapse[7], but this often leads to weak splices. Transmission configurations tested here are assembled with our recently reported technique to tackle this problem, and fuse microstructured fiber to both itself and solid fiber types. Briefly, we describe the splicing strategy adopted, which comprises three stages.

First, fibers are tacked together with a quick low power fuse. Subsequently the splice is swept with a moderately high power, and then pulsed with a strong arc. Sweeping and pulsing enables intense surface heating to anneal flaws, with a low average heating effect at the core protecting the microstructure (illustrated in Fig 2) and gives a strong circumferential bond.

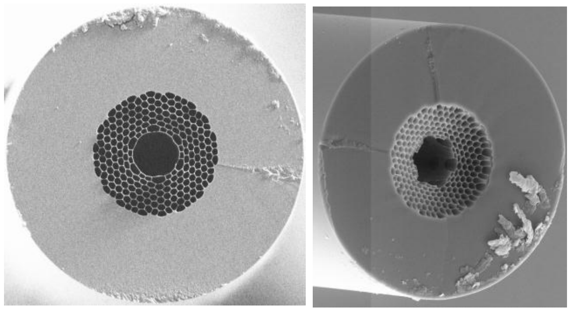

Fig. 1: 180 µm diameter HC-PBGF, cleaved fiber and after splicing, exhibiting no radial microstructure collapse and only ~5 µm of longitudinal discontinuity

Breaking the splice to inspect the microstructure (Fig 1, right) shows that just ~5µm of it is affected by longitudinal withdrawal into the fiber, forming an air-gap, while there is no radial collapse or significant alteration in the microstructure from the freshly cleaved fiber.

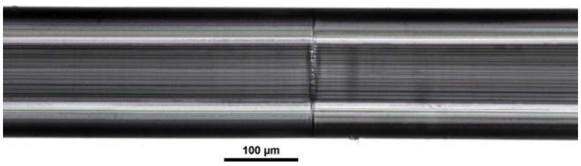

Fig. 2: HC-PBGF spliced with new strategy

Using this technique losses as low as 0.06dB have been achieved, with typical average loss of 0.16 dB per splice.

Transmission testing

Here we consider three different fibers under test (FUT), of the same HC-PBGF design, with closely matched geometries (Tab. 1): FUT A of 206m; FUT B of 234m, and; FUT C of 560m.

Tab. 1: Fiber geometry parameters

FUT	Core dia. [μm]	Λ [μm]	Holey dia. [μm]
A	29	4.4	75.5
B	27	4.5	76.5
C	28	4.4	75.5

We compare the transmission performance of the three sections of HC-PBGF (spliced to telecoms SMF at each end) and then again with a splice made between HC-PBGF and itself in each section. Then the SMF is removed from all but two of the fiber ends, and the three HC-PBGFs are all spliced together into a 1km long continuous span, with SMF spliced at each end; see Fig 6, upper. We also consider a more challenging network configuration where HC-PBGF sections, spliced each end to SMF FC/APC pigtails, are linked in series (with each HC-PBGF section also incorporating HC-PBGF-self splices). In this last test there was also an EDFA connected at mid-span; see Fig 7, upper.

The transmission (TX) set-up includes a CW source at 1557.3nm modulated with a 40Gbit/s on-off keying (OOK) signal with 2^{31}-1 pseudo-random bit- sequence (PRBS). The receiver (RX) configuration incorporated a variable optical attenuator (VOA) and EDFA with filtered output to optimize the power level and improve the noise characteristics seen at the bit-error-rate tester (BERT), as illustrated in Fig. 3.

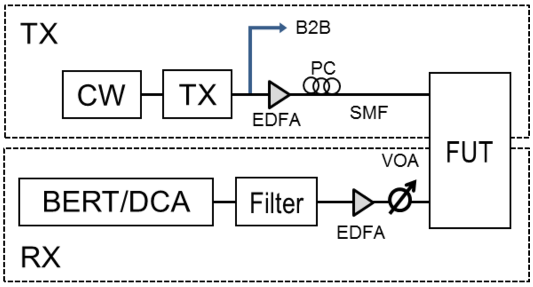

Fig. 3: Transmission & receiver configurations

The resolution of the test was ~ 0.1dB with the BER assessed down to 10^{-11}. The eye observed may be scaled between the back-to-back and transmission case as amplification was adjusted to maintain optimum signal level between tests and manage the usual optical path losses. In all cases the performance of the system was compared with the back-to-back case. Polarization control was used to optimize eye openness. Eye diagrams presented to illustrate each test show the transmission case is just as clear and open as the back-to-back.

Individual fibers, unbroken and spliced

Each HC-PBGF sample was spliced at both ends to an FC/APC SMF pigtail, using the splicing strategy as described, and samples were connected directly into the test.

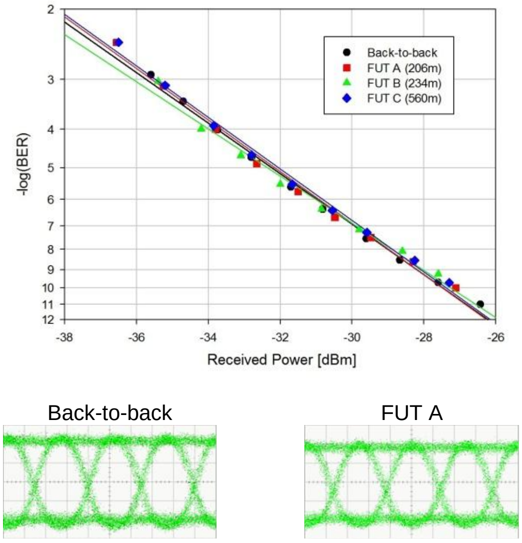

Fig. 4: HC-PBGF, BER plots, eye diagrams

Next, each sample was broken within the HC-PBGF section, near one end, and spliced back together. This transmission test (Fig. 5) through spliced fiber confirms that there is no BER penalty when the network incorporates splices between HC-PBGF and itself.

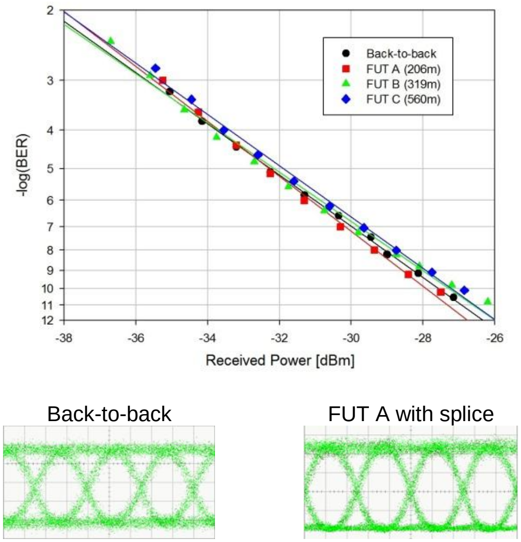

Fig. 5: Spliced HC-PBGF, BER plots, eye diagrams

Spliced Arrangement

Once fiber samples had been tested individually, the SMF sections were removed and the HC-PBGF lengths spliced together (Fig 6.), such that each section was spliced twice, comprising a splice to itself and another fiber from a different fabrication batch - with splices to SMF retained at the input and output of the fiber assembly so constructed. This arrangement might be expected in a typical field deployment of fibers, albeit often with greater spans between splices. No BER penalty is found, at high received powers, when compared to the back-to-back performance. The eye diagrams are open with low noise and jitter, confirming good performance despite the complexity in the assembly of fibers and splices.

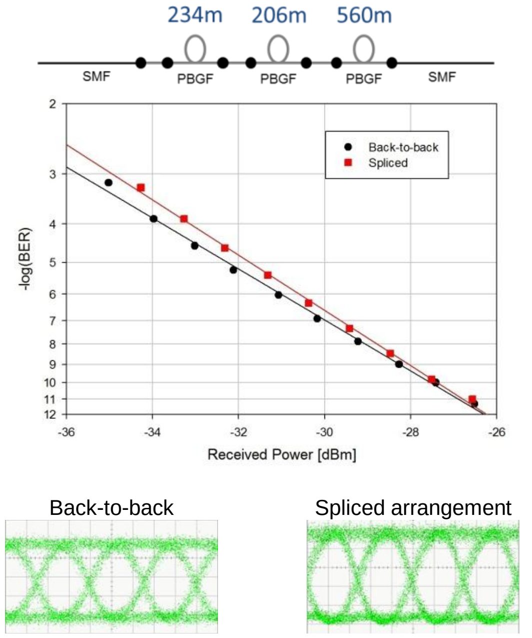

Fig. 6: Spliced HC-PBGF arrangement, BER plot, eye diagrams

We have also demonstrated transmission of data in a small-scale test arrangement more akin to a network expected in the field. This is a complicated arrangement with discrete sections of HC-PBGF, spliced to SMF, and linked by connectors (FC/APC) through in-line amplification. The arrangement incorporates an EDFA between the first and second long spans of HC-PBGF (Fig. 7), with several splices between HC-PBGF to itself and SMF either side of the EDFA. Polarization controllers (not shown in the schematic) are used at the input of each connected section to optimize transmission. There is a power penalty of less than 1dB over the back-to-back case with this connectorised configuration, while the eye diagram for the transmission case remains open with low noise.

Conclusions

We demonstrate data transmission over complex spliced arrangements of HC-PBGF, also confirming the suitability of a splice strategy enabling integration of microstructured HC-PBGFs into next generation telecoms systems.

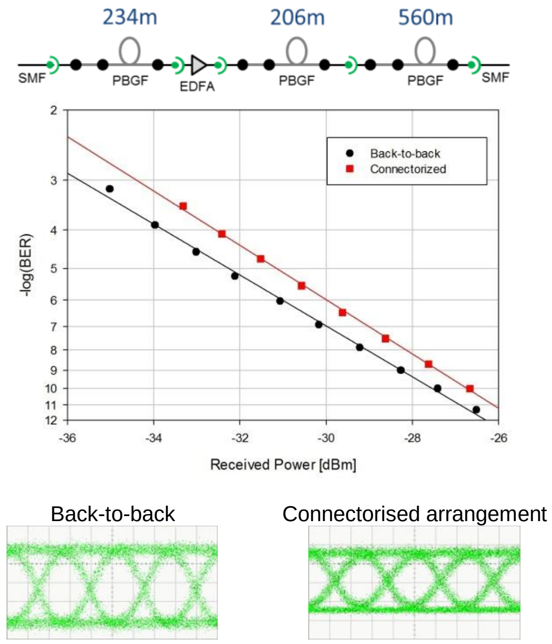

Fig. 7: Connectorised HC-PBGF array, BER plot, eye diagrams

Splicing involves arc sweeping and rapid power pulsing which prevents microstructure collapse. HC-PBGF can now be spliced together with robust low-loss splices (average 0.16 dB) which permit singlemode transmission without any significant BER penalty in an arrangement comprising many such splices, with the first demonstration of transmission over a record 1km of HC-PBGF and a link with mid-span amplification.

Acknowledgements

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References

[1] Y.Jung, et al., Proc. OFC'13, PDP5A.3, (2013)
[2] T. Ritari et al., Optics Express, 12 (17), 4080 (2004)
[3] F.Poletti, et al., Nature Photonics, 7(4), 279 (2013)
[4] P.J. Bennett, et al. Optics Lett. 24(17), 1203 (1999)
[5] Carvalho, J.P., Solid State Phenomena, 161, 43 (2010)
[6] J.P.Wooler, et al., Proc. OFC’13, OM3I.5, (2013)
[7] B.Bourliaguet et al.,Opt. Express. 11(25), 3412 (2003)