Robust Low Loss Splicing of Hollow Core Photonic Bandgap Fiber to Itself

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Abstract: Robust, low loss (0.16dB) splicing of hollow core photonic band gap fiber to itself is presented. Modal content is negligibly affected by splicing, enabling penalty-free 40Gbit/s data transmission over > 200m of spliced PBGF.
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1. The need to splice microstructured PBGF

Air guiding hollow-core photonic band-gap fibers (HC-PBGF) are of great interest to next-generation communication systems [1], offering the potential for ultralow nonlinearity, low latency and ultralow loss at 2µm, as well as the possibility to further increase the transmission capacity though higher-order-mode (HOM) multiplexing. As the manufacturing techniques and optical infrastructure for these fibers develops, a key milestone in demonstrating their suitability for adoption in a practical telecoms system is to achieve low loss splices, ideally amenable to being performed in the field using commercially available splicing equipment.

Some concern exists within the optical fiber community that handling issues and high splice losses could potentially hinder a widespread future adoption of HC-PBGF. Here we demonstrate that losses below 0.2 dB are achievable in a splice which can be handled and packaged. We also show that strong modal extinction can be preserved across the splice, enabling single mode transmission through a spliced fiber and potentially enabling multiplexing on discrete modes in the future. As a demonstration, we transmit an on-off-keying (OOK) modulated data signal at 40Gbit/s through spliced HC-PBGF without bit-error rate (BER) penalty.

2. Mechanical effect of splicing and strategies

The microstructured region within a HC-PBGF has fine silica struts (of the order of 100-200 nm thick), which have low thermal mass and are readily deformed under heat-processing [2]. A standard SMF-SMF type splice recipe will apply too much heat, and it is therefore a challenge to join fibers without destroying the microstructure at the splice. Approaches so far considered in order to splice HC-PBGFs to conventional solid fiber (e.g. SMF) have typically focused on reducing the arc current and duration to the minimum to achieve a join, while some degree of collapse in the microstructured region is often associated with this [3]. Such splices may be weak because fibers are only lightly tacked together and the bond is not well fused. To the best of our knowledge, there is no report in the literature on the even more delicate task of splicing a HC-PBGF to itself.

Here we demonstrate an effective novel strategy to splice HC-PBGF with an arc fusion splicer, which is robust enough for handling and packaging in splice protectors, where splices are very rugged. We use a tack stage, enhanced with sweep stage and subsequent short arc pulses. The tack lightly fixes the relative position of the fibers while being then strengthened by sweeping the arc over the splice. When sweeping, the arc dwell time is reduced so that higher currents can be used to encourage fusion near the surface, but the average heating effect at the core is lessened, protecting the microstructure. In the final splice stage, a re-arc of very short pulses with relatively high power is applied, intended to fuse the glass surface at the fiber join to give the splice greater strength, while being rapid enough that the average heat reaching the inside of the fiber is low, again avoiding damage to the microstructure. Figure 1 shows the splice achieved with the strategy described.

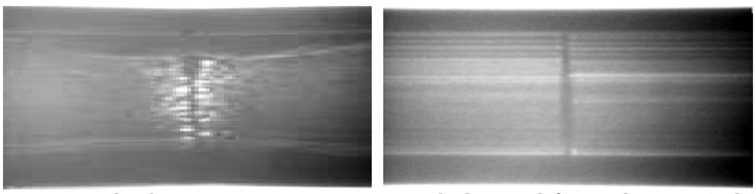
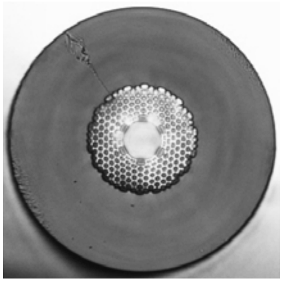


Fig. 1. Spliced 180µm 1550nm HC-PBGF: Standard recipe (left), novel strategy (right)

In this work we use a Fujikura FSM-100P splicer. Our technique involves no cleaning arc, and gapping the fibers at the minimum 5µm with cladding alignment. Typical recipe parameters would prefuse for 400ms at STD-5.0mA followed by a special function sweep with three passes 250/500/750um at 0.5µm/ms either side of the splice at STD-3.5mA. Then a re-arc is applied with around five 200ms arc pulses at STD current. To optimize for strength, the swept power may be adjusted, typically a few mA up or down, below the collapse threshold, depending on PBGF design and geometry, while the intensity of the pulsed re-arc can be increased to enhance melt characteristics at the circumference of the join. We find that these splices can survive a machine imparted proof test of 2N for 200ms or more, and some will survive through the elevated strains imparted by a machine reset.

In HC-PBGF to SMF splices, it is known that an air gap of a few tens of micrometers is formed between the fiber cores due to the action of surface tension during fusion [4]. We seek to minimize this effect with our splicing strategy and observe ~10µm separation, meaning each fiber end-face has withdrawn just 5µm or so due to this surface tension effect. In the Fig. 2 below we compare the end face of cleaved fiber with that at the splice junction and show the moderate funneling of the microstructure a few microns back into the fiber. We infer that there is no bond across the microstructure, and as the splice breaks cleanly there is a very narrow annealed circumferential region, perhaps with a few other bonded regions elsewhere across the end face. While the splices are strong in tension and can be handled into splice protectors, the splices are weaker than fully fused solid fiber splices if the fiber is bent or twisted, as cracks in the microstructure will readily propagate across the splice join.



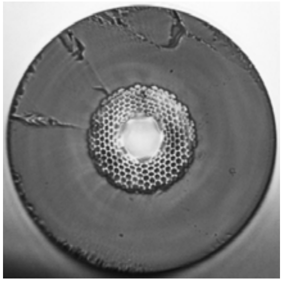
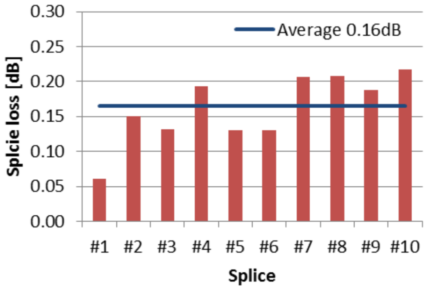


Fig. 2. Cleaved 180µm HC-PBGF (left), Spliced 180µm HC-PBGF at break (right)

3. Loss and modal effect when splicing PBGF to self, S^2

Where there is a need to join two fibers, there is always some degradation in transmission. Ten splices were made between a 180µm OD HC-PBGF operating at 1550nm and itself, obtaining an average loss of 0.16dB (Fig 3.) with standard deviation of 0.05dB. Using the same strategy, we obtained a 0.2dB splice loss (at 1950nm) with 220µm OD HC-PBGF designed for operation at 2µm.

For a fiber capable of propagating HOMs it is also of interest to consider the intermodal crosstalk generated at the splice point. We compare the extinction between an excited fundamental mode and HOM content, and consider how this is preserved across the splice. We use an S^2 approach [5,6] involving autocorrelation of an ASE source, sampling at discrete spatial points in the mode-field image plane, to collect spatial and phase information about the modal content coming out of the fiber. Modal transmission through 10.5m of a low loss (3.5dB/km) 1550nm HC-PBGF was assessed with the S^2 technique and measurements made: (1) on the unbroken fiber; (2) cleaved fiber ~ 0.5m from input, ends gapped & aligned; (3) splice after sweep stage; (4) splice after re-arc stage. The input and output conditions were preserved, and the differential group delay (DGD) plot (each offset 10dB) for these cases shows the impact on relative modal content in each case (Fig. 3).



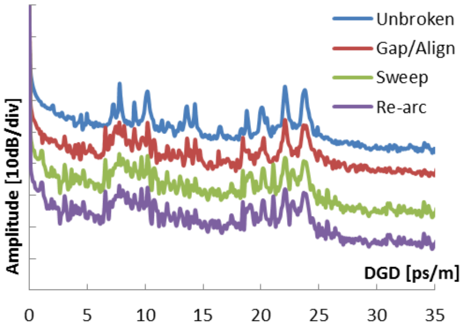


Fig. 3. Splice results (left), DGD plot showing peaks in amplitude corresponding to HOM modal content in fiber output (right)

As the fundamental mode of the HC-PBGF was selectively excited, the S^2 technique can determine whether propagation of the fundamental is disturbed through excitation of HOM content due to the splicing, where an ideal splice would have no effect on the modal content seen. We then analyzed the various DGD plots and considered the sum of all modal energy not in the fundamental mode, in this case all HOM up to 35ps/m delay (Table 1 below). Besides, to understand the extinction between the fundamental and any HOM present in the output we also measured the multi-path-interference value (MPI) of the dominant HOM peak.

Table 1. MPI values for modal content assessed before and after splicing stages

	Sum HOM MPI [dB]	**Peak HOM MPI [dB]**
(1) Unbroken	-24.29	-31.31
(2) Gapped & aligned	-24.03	-31.81
(3) Sweep	-24.36	-34.97
(4) Re-arc	-24.39	-34.94

The total HOM content remains largely unchanged with an MPI around -24dB, demonstrating that the majority of energy is preserved in the fundamental mode and the splice is not significantly disturbing the propagation. We do also observe that the amplitude value of the dominant HOM peak decreases, which indicates that energy has been mixed out to other HOM, as can be seen in the difference between DGD plots. A key result is that there is no change between the sweep and re-arc stages, which demonstrate it could be possible to put extra energy in as rapid, high-intensity pulses without affecting propagation within the fiber – something that may enable the strength of the splice to be further improved.

4. Data transmission in spliced HC-PBGF

To verify the previous conclusion that the splice does not introduce significant intermodal cross-talk, we have also compared transmission of a 40Gbit/s on-off keying (OOK) signal in three samples of 1550nm HC-PBGF (length >200m), each with SMF28 spliced to its input and output ends. No power penalty (within the resolution of the test ~ 0.1dB) on the BER assessed down to 10^{-11}, was observed for the transmission through all the HC-PBGFs in comparison to the back-to-back case, i.e. without the HC-PBGFs. Similar performances were also achieved when a splice of the HC-PBGF to itself was introduced ~ 50cm from one end and transmission retested, launching from both fiber ends in turn. Fig. 3 shows the corresponding eye diagrams for the back to back, unbroken HC-PBGF, and spliced cases. Moderate polarization dependence in the BER curves and eye diagrams, managed with a polarization controller at the fiber input, was observed to be introduced by the splice in some instances.

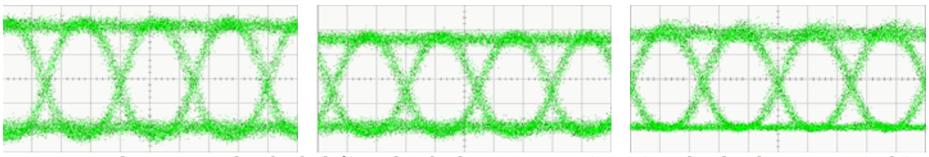


Fig. 3. Eye diagrams: Back to back (left), with unbroken HC-PBGF (center), with spliced HC-PBGF (right)

5. Conclusions

We propose and demonstrate for the first time to our knowledge an effective splicing technique for joining fragile microstructured HC-PBGFs together. The technique involves arc sweeping and rapid duty cycle to pulse power and prevent microstructure collapse. This enhanced strategy allows low-loss (average 0.16 dB per splice), mechanically strong splices to be achieved which are found to introduce negligible intermodal crosstalk and allow single mode transmission without any significant BER penalty.

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