Fusion Splicing Holey Fibers and Single-Mode Fibers: A Simple Method to Reduce Loss and Increase Strength

M. L. V. Tse, H. Y. Tam, L. B. Fu, B. K. Thomas, L. Dong, C. Lu, and P. K. A. Wai

***Abstract*—We demonstrate a novel method for low-loss splicing Ge-doped holey fibers (HF) with subwavelength core size and high numerical aperture fibers by using a conventional fusion splicer. We found that a large overlap distance of the fibers during fusion would decrease the splice loss and increase the splice strength. The lowest splice loss achieved for a fiber with a core diameter of 1.27 μm and air-filling fraction of $>$0.95 was $\sim$1 dB at 1550 nm, with a bend failure radius of 0.8 cm. With the same method, we also observed improvement in terms of loss and strength with larger core size HF.**

***Index Terms*—Optical fiber connecting, optical fiber splicing, photonic crystal fiber.**

I. Introduction

RECENTLY there has been considerable interest in using small core holey fibers (HF) for nonlinear applications [1], [2]. In order to fully integrate these fibers into device and sensor systems, low-loss robust splicing with conventional single-mode fiber (SMF) is required. Since the first demonstration of splicing HF and standard SMFs [3], many splicing techniques have been used, including the use of a filament splicer, a CO_2 laser [4], and gradient index fiber lenses [5]. However, the most commonly used method is by electric arc fusion, because such splicers are widely available. In this letter, we demonstrate a simple method to splice HF with a subwavelength-diameter core and a high numerical aperture (NA) SMF by using a common arc fusion splicer. A splice loss of 1 dB was achieved.

Highly nonlinear HF often have designs with high air-filling fraction (>0.9). Because of surface tension, the glass–air interfaces within the microstructured region offer less resistance to deformation than the solid glass in the outer cladding of the fiber. A recess is formed in the end-face of the HF when heated in a splicer [6]. Similar behavior may also be found in HF with a badly cleaved end-face. Because of the concave feature, an air gap of up to a few tens of micrometers is created between the cores of the two fibers. We found that a large overlap distance (the distance in which the two fibers is pushed together when softened by the electric arc discharge) will help to reduce the size of the air gap, or may remove the air gap entirely, and hence reduce the coupling loss. This is opposite to what was suggested by Xiao *et al.* in [7], that a large overlap may cause bend misalignment when arc discharge energy is low. To date, all the suggested arc fusion splicing recipes for splicing microstructured fibers and SMF have overlap distances in the range of 1–15 μm [7]–[10]. This is too short for achieving low splice loss in our case presented here. Also, low energy and short overlap distance splicing can only produce splice joint with relatively weak strength.

The ultrasmall core HF used in our experiment has a 1.27-μm diameter core, an effective area of $\sim$1.75 μm^2, mode field diameter (MFD) of 1.5 μm, NA $>$ 0.9, and transmission loss of 78 dB/km, at 1550 nm. The scanning electron microscope (SEM) picture of the fiber is found in the inset of Fig. 1. It has a Ge-doped region of $\sim$60% core diameter, to provide a graded index with a peak Δn of 0.025 [11]. However, we were unable to achieve low splice loss using the method with default discharge parameters suggested by Wang *et al.* in [12]. This may be due to the ultrasmall core size and the doped region. The high NA SMF is the Nufern-UHNA1, which has a quoted MFD of 4.8 μm and NA of 0.28, at 1550 nm. This fiber can be spliced to an SMF patch cord using automatic settings with an estimated splice loss of 0.12 dB. The butt-coupling loss (α) between the HF and UHNA1 was theoretically estimated to be $\sim$4.94 dB by the mode-matching relationship [13]

$$\alpha = -20\log\left(\frac{2\omega_1\omega_2}{\omega_1^2+\omega_2^2}\right) \qquad (1)$$

where ω_1 = MFD of the HF and ω_2 = MFD of the UHNA1. The splice loss can be below this value by adiabatically collapsing of the air holes, and increasing the mode field area [14].

II. Splicing Method

A Furukawa FITEL-S177 fusion splicer and a Fujikura CT-30 cleaver were used to splice and to cleave the fibers, respectively. We programmed two parameters in the splicer, the arc power, and the arc duration. We set the arc power = 2 steps (note that, the SMF–SMF power settings = 100 steps) and the arc duration = 200 ms, to avoid substantial collapse of the air holes at the end-face of the HF. The rest of the parameters such as "Gap,"

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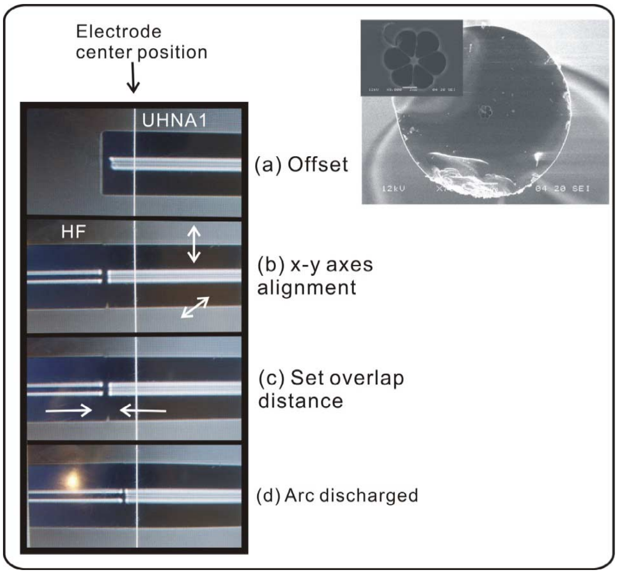

Fig. 1. (Color online) Images of the splice joints during the splicing process, as viewed from the screen of the splicer, for an overlap distance of 35 μm: (a) UHNA1 is positioned at an offset distance of 50 μm from the electrode center position. (b) HF and UHNA1 at butt position. Alignment of the fibers in the x-y plane is done manually with 0.1-μm steps. (c) Overlap distance is set by pushing the fibers together. The fibers are under compression. (d) Fibers fused together after the first arc discharge. The interface is clearly shifted toward the electrode center position, and the diameter of the fibers is slightly larger at the splice region. Inset: SEM images showing the end-face of the HF.

"Z Push Distance," "Re Arc Interval," and "Re Arc Power," etc., were all set to zero. The "Z Push Distance" is equivalent to the overlap distance, which we manually controlled as part of the fiber alignment process.

The splicing process is illustrated in Fig. 1. First, we positioned the fibres with an offset of 50 μm between the joint and the electrode, bias toward the UHNA1. To align the fibers, we monitored the transmission power, and manually adjusted the micro-positions in the x and y axes at the butt position. Due to the extreme small core size of the HF, the x-y alignments were done in steps of 0.1 μm. The averaged butt-coupling loss was 5.2 dB. Next, we manually introduce an overlap distance by pushing the fibers together. At this point, we found that the coupling loss was either reduced or unchanged. Pressure was applied longitudinally to the fibers by the mechanical force exerted from the splicer's micro-positioning blocks. The fibers were pressed (spliced) together by this force when softened by the initial arc discharge. Finally, additional arc discharges (the power and the duration were unchanged) were applied to optimize the loss by collapsing the air holes. In order for the glass to be fully solidified, the time between each arc discharge was over 5 s. If there was residue pressure left in the fibers after the initial arc discharge, the fibers may be pressed together further during the second and subsequent arc discharges. This action may further reduce the coupling loss and increases the mechanical strength of the splice joint.

III. Experiments and Results

The HF (short length) were spliced to UHNA1 ($\sim$0.5 m) at both ends and connected to SMF patch cords. The patch cords were then connected to the light source and detector via fiber connectors. For better accuracy, the splice loss was measured as the difference of the transmitted power between the splice linkage of SMF + UHNA1 + SMF and the spliced linkage of SMF + UHNA1 + HF + UHNA1 + SMF. The measured splice loss for one HF–UHNA1 fiber pair is then estimated to be half the difference. We also checked for the power difference between the launch of the light from both ends. We found that the transmitted power was essentially the same, suggesting the splices were reciprocal, as expected from two SMFs.

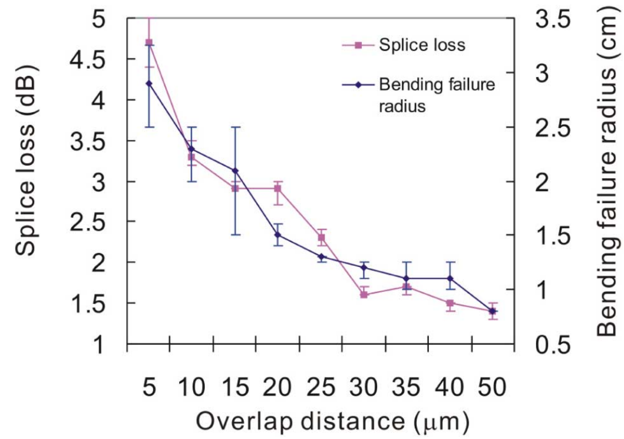

Fig. 2. (Color online) Optimum splice loss and the bending failure radius for different overlap distances.

Following the above procedure, we investigated the splice loss and the mechanical strength with different overlap distances. We varied the overlap distance from 5 to 50 μm. For each distance, the optimum averaged splice loss and bending failure radius were measured from four splice attempts; the result is presented in Fig. 2. In general, it shows that as the overlap distance increases, the splice loss and the bending failure radius decrease. For an overlap distance of 5 μm, the splice loss increases after the second arc discharge (no additional push between arc discharges); this may due to the inefficient fusion of the two fibers by the initial arc discharge, and the diffusion of dopants from the UHNA1 to the core of the HF [15]. Similar splice loss is found for an overlap distance of above 30 μm. Moreover, for large overlap distances, the holes collapsed more gradually during the repeated arc discharge process. There are little changes to the splice loss near the optimum number of arc discharges applied, forming a flat bottom in the graph (see Fig. 3). This suggests that the core region is well shielded by the silica cladding at the joint after the initial arc discharge. We noticed that, for an overlap distance of above 50 μm, the fibers may be shattered under high compression; therefore, the experiment ceased at that point. The splice with the lowest loss (1.4 dB) was found for an overlap distance of 50 μm. The experimental result is summarized in Table I.

From Table I, the average increase in the transmitted power after the initial arc discharge from that at the butt position was the greatest with an overlap distance of 25 μm. We modified the procedure slightly, in which, an initial overlap distance of 25 μm is applied, and an additional push of 5 μm between each additional arc discharge. By following the refined method,

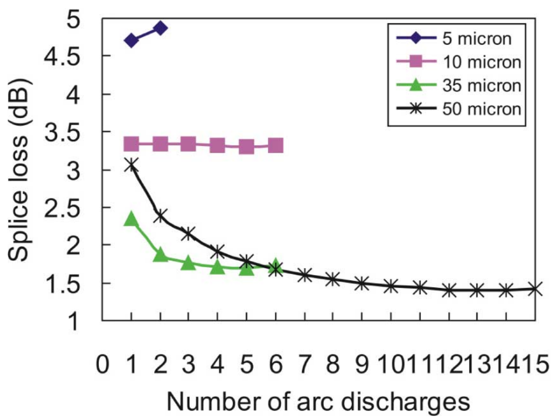

Fig. 3. (Color online) Splice loss against the number of arc discharges for overlap distances of 5, 10, 35, and 50 μm.

TABLE I
SUMMARY OF THE SPLICE LOSS AND MECHANICAL STRENGTH RESULTS FOR DIFFERENT OVERLAP DISTANCES. (STANDARD DEVIATION (STD. DEV.) IS FOUND USING THE STDEV FUNCTION IN MICROSOFT EXCEL XP)

Overlap distance (μm)	% increase in the transmitted power after the 1st arc discharge	Optimum splice loss (dB)	Std. Dev. (dB)	Bending failure radius (cm)	Std. Dev. (cm)
5	10	4.7	0.3	2.9	0.4
10	33	3.3	0.1	2.3	0.2
15	40	2.9	0.1	2.1	0.5
20	33	2.9	0.1	1.5	0.1
25	58	2.3	0.1	1.3	0.0
30	58	1.6	0.1	1.2	0.1
35	48	1.7	0.1	1.1	0.1
40	56	1.5	0.0	1.1	0.1
50	40	1.4	0.1	0.8	0.0

the average splice loss of 1.3 dB with the standard deviation of 0.2 dB were achieved from ten attempts, with an average bending failure radius of ∼1 cm. A precise x-y axes alignment and a well cleaved HF end-face were crucial for achieving the lowest splice loss.

Following our splicing method, we were also able to achieve low splicing loss for an SMF and a polarization-maintaining HF (Crystal Fibre A/S, PM-1550–01). An average splice loss of 0.20 dB with standard deviation of 0.05 dB was achieved with light coupling from the SMF to the PM-1550–01, and 2.02 dB with standard deviation of 0.23 dB in the opposite direction, and the bending failure radius was ∼0.5 cm. Low splicing loss was also achieved for an SMF and a hollow core bandgap fiber with core diameter of 10 μm (Crystal Fibre A/S, HC-1550-02), with a splice loss of ∼1 dB from SMF to HC-1550-02, and bending failure radius of ∼0.5 cm. Both of the results are better than the ones previously reported in [7].

IV. CONCLUSION

We demonstrated a simple method to splice HF with an ultrasmall core diameter and standard SMFs, using a commercial fusion splicer with manual settings. By introducing a relatively large overlap distance, splice loss of as low as 1 dB is achieved.

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