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Low Loss Splices to Dissimilar Optical Fibers

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Splicing between dissimilar optical fibers can lead to unacceptable losses in sensing systems due to mode field mismatch. This is particularly true for multiplexed fiber laser arrays where high splice losses between active and passive fibers reduce the available pump light for lasers furthest from the source. Flame polishing the splice joint can reduce the loss by thermally diffusing core dopants such that the effective mode fields between the fibers are similar. This report describes a technique by which the splice loss between two dissimilar fibers was reduced on average to 0.23 dB. A discussion on the multiplexing limits of fiber lasers using 980 nm pumping will also be provided.

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Optical fiber fusion splicing, fiber lasers, sensors, multiplexing, flame polishing, splice loss, erbium-doped fiber

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LOW LOSS SPLICES TO DISSIMILAR OPTICAL FIBERS

1. INTRODUCTION

Splicing between dissimilar optical fibers can lead to unacceptable losses in sensing systems due to mode field mismatch. This is particularly true for multiplexed fiber laser arrays where high splice losses between active and passive fibers reduce the available pump light for lasers furthest from the source. Flame polishing the splice joint can reduce the loss by thermally diffusing core dopants such that the effective mode fields between the fibers are similar. This report describes a technique by which the splice loss between two dissimilar fibers was reduced on average to 0.23 dB. A discussion on the multiplexing limits of fiber lasers using 980 nm pumping will also be provided.

2. PUMP DEPLETION AND POWER BUDGET

For a fiber laser sensor system, minimizing the splice loss is critical as each splice will deplete the pump power and limit the number of lasers that can be multiplexed along a sensor system. An example system is illustrated in Fig. 1. Because power consumption is a key metric for remote systems, pump diodes operating at 980 nm have been developed that can operate as air-cooled systems. Since active cooling is not needed, the total power requirements for the system is low. While beneficial in terms of overall power consumption, this limits the pump diode's output power to typically 200 mW (500 mA). If more power is needed, coolerless pump diodes with powers up to 600 mW (1.6 A) have been developed or additional diodes can be combined into a single fiber to deliver the necessary power at the cost of consuming more energy. As an alternative, erbium-doped fiber lasers can also be pumped at 1480 nm. While doing so can be advantageous because of lower losses at this wavelength, it is important to recognize that the laser's threshold power is typically greater than when pumped at 980 nm [1].

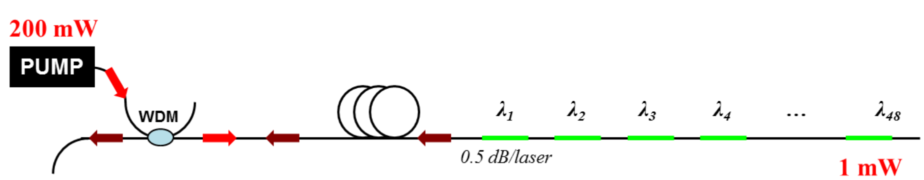

Fig. 1 — Sensor architecture for fiber laser array.

Pump depletion in the fiber array depends on the two factors: pump absorption and splice loss. Pump absorption is governed by the material properties of the fiber. For Nufern's PS-ESF fiber, a photosensitive erbium-doped fiber, the small signal absorption at 980 nm is on the order of 9 dB/m [1]. Therefore, shorter devices or shorter sections of active fiber are often preferred to limit excess absorption of the pump power. At high pump powers, the absorption is actually much lower due to high population inversion. Only when

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the pump is sufficiently depeted will the absorption increase and subsequently decrease the available power for distal lasers.

Given the nonuniform pump absorption along the fiber, splice loss plays the largest role in pump depletion and limits the number of lasers that can be multiplexed in a single fiber array. The threshold of the fiber laser, which depends on factors such as pump mode area and overlap factor, must also be considered. For fibers with a high numerical aperture, the pump mode area is small thereby reducing the pump threshold values to 1 mW.

Consider the case where the pump threshold is 1 mW and the pump absorption (worst case) is 9 dB/m (Table 1). For 5 cm of erbium fiber, the loss associated with the pump absorption is 0.45 dB. Therefore, if each splice were 0.01 dB, a total of 48 lasers could be multiplexed with a single 200 mW pump diode (as in Fig. 1). This assumes that the passive fiber between lasers is matched (in MFD) to the active fiber and that the splice loss between the two is minimal. In practice, more pump power is needed to effectively demodulate each laser for sensor applications. This is due to an increase in the noise spectra when the lasers are operating close to threshold. For example, the measured power spectral density at 1 kHz for a typical fiber laser is -72 dB, -80 dB, and -90 dB for input powers of 1.6 mW, 3.2 mW, and 10 mW respectively. Clearly, a 20 dB improvement in SNR is essential for the detection of weak signals. Keeping all other values in Table 1 the same and changing the threshold power to 10 mW, 27 lasers can be multiplexed on a single fiber.

Table 1 — Power Budget for Multiplexed Fiber Laser Arrays

Property	Value	Unit
Pump Power	200	mW
Pump Absorption	9	dB/m
Erbium Length	5	cm
Threshold	1	mW
Splice Loss	0.02	dB per laser (2 splices)
Number of Lasers	48	

Multiplexing density is also dependent on the fiber Bragg grating (FBG) design (apodization/side lobe suppression and grating strength) and Rayleigh backscatter (RBS) of the intermediary and lead fibers [2]. Side lobe and out-of-band reflections, which can cause optical feedback, can be minimized by utilizing strong, apodized gratings. The grating strength helps to reduce back reflection sensitivity while the apodization reduces the side lobes of the spectra. Since back reflections can also be produced by grating inscription errors, suppression of these errors can be achieved through phase compensation during the fabrication process [3]. Similarly, RBS in the passive fiber causes unwanted feedback in the fiber array and leads to increased noise at low frequencies and self pulsing behavior [2]. This effect can be reduced by utilizing low RBS fiber between the fiber lasers, typically with a lower numerical aperture (NA) than the erbium fiber. If the splice loss between these dissimilar fibers is 0.1 dB, the total number of lasers that can be multiplexed drops to 20. However, since the pump absorption is lower at the proximal end of the fiber array, this number is actually a low estimate (as evidenced by the recent fabrication of a 32 channel fiber laser hydrophone array [2]).

3. SPLICE LOSS

3.0.1 Mechanisms

Splicing two dissimilar fibers usually results in a high splice loss. This is chiefly due to the mode field diameter (MFD) mismatch between the two fibers. If the fibers are butt-coupled, the minimum loss is given by [4]

$$\alpha = \left(\frac{2w_1w_2}{w_1^2+w_2^2}\right)^2 \tag{1}$$

where w_1 and w_2 are the mode field radii of the optical fibers. Note that the splice loss between two ends of a fiber might also not be reciprocal if the MFD do not match. This is because all the light from one fiber will not be captured, and loss will occur through cladding, surface, or radiation modes. For a fiber that is transversely misaligned, the splice loss is further affected by an exponential decay of the optical field such that

$$\alpha = \left(\frac{2w_1w_2}{w_1^2+w_2^2}\right)^2 \exp\left(-\frac{2d^2}{w_1^2+w_2^2}\right). \tag{2}$$

Here d is the offset between fiber cores. Finally, we can consider the case when the fibers are angularly misaligned. In such an instance, the loss becomes

$$\alpha = \left(\frac{2w_1w_2}{w_1^2+w_2^2}\right)^2 \exp\left(-\frac{2\left(\pi n_2 w_1 w_2 \theta\right)^2}{\left(w_1^2+w_2^2\right)\lambda^2}\right) \tag{3}$$

where n_2 is the cladding index, θ is the angular misalignment between cores, and λ is the wavelength of light. Experimentally, the loss due to a splice is determined by monitoring the transmission power before (P_{in}), and after, (P_{out}), the splice occurs. Therefore, the loss is given by

$$\alpha = -10\log\frac{P_{out}}{P_{in}}. \tag{4}$$

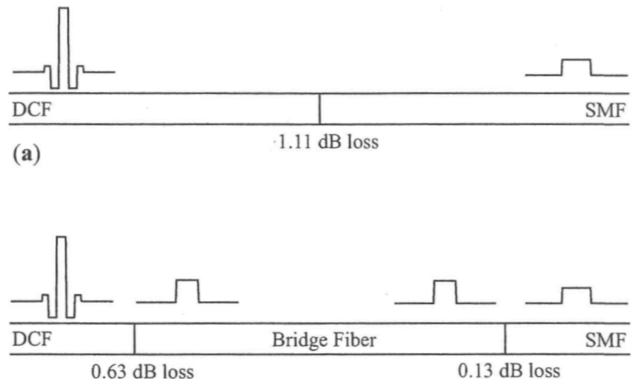

Fig. 2 — Benefits of a bridge fiber. (a) Direct fusion splice between a representative dispersion compensating fiber (DCF) and standard single mode fiber (SMF) exhibiting about 1.11 dB of loss. (b) Step-index bridge fiber exhibits a splice loss of 0.63 dB to the DCF and a splice loss of 0.13 dB to the SMF, reducing the total loss by about 0.35 dB. [6]

3.0.2 Mitigation

One approach to mitigate the excess loss between fibers due to mode field mismatch is through the use of intermediate or bridge fibers [5]. Here an additional fiber is utilized to transition the mode field from one fiber two another with lower loss than if the two fibers were directly spliced. The V-number ($V = 2\pi aNA/\lambda$, where a is the fiber radius and NA is the numerical aperture) of the intermediary fiber is usually between the two fibers of interest. Figure 2 demonstrates this principle [6].

Another approach utilizes tapering of the fiber, whereby the splice joint is heated and pulled such that the fiber is thinned [6]. This modifies the MFDs of the two fibers to be a closer match. This technique could be particularly useful for splices where dopant diffusion is either not practical or the dopant diffusion rates of the two fibers are similar such that post-processing will not improve the splice quality. An example of the tapering process is shown in Fig. 3. Note that tapers can often be structurally weak and can exhibit high loss. It is important to ensure that the taper is adiabatic, i.e. gradual enough so that the guided mode stays confined to the core and does not radiate into the cladding. An advantage of tapering is that it can help reduce the impact of lateral misalignments due to core eccentricity or geometric deformations. The fibers can also be pre-tapered and cleaved prior to splicing.

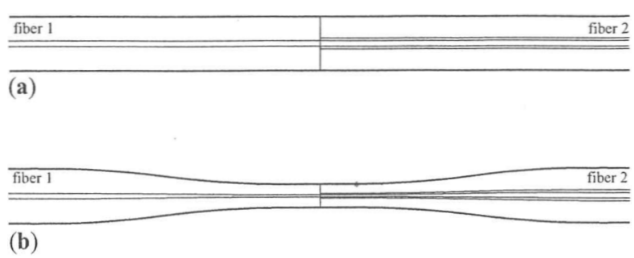

Fig. 3 — Strong tapers can reduce splice loss between highly dissimilar fibers. (a) Completed splice between dissimilar fibers 1 and 2 prior to tapering. (b) Fusion splice following strong taper which converts core guided modes into cladding guided modes at splice joint thus reducing mode field mismatch loss. [6]

Thermal diffusion of the core dopants can also be used to reduce the loss between dissimilar fibers [7], [8], [9]. In optical fiber, dopants are used to alter the refractive index, thermal, and mechanical properties of the glass host. Different dopant species diffuse at different rates when exposed to temperatures characteristic of a fusion splice. Because of this, dopant diffusion can greatly affect the refractive index in the vicinity of the splice joint. This diffusion creates a thermally expanded core which can be beneficial for matching the mode field diameters of the dissimilar fibers. The end result is a lower splice loss because the modal transition between fibers is gradual.

One approach to achieving a thermally expanded core is to employ fire polishing. This process involves scanning a heat source over the splice joint. In addition to thermally driven diffusion, this process relaxes internal tension and repairs surface defects that might increase loss and decrease the joint's strength. The heat source, in this case the plasma arc of the electrode, is confined to a narrow region near the joint and repeatedly scanned back and forth. For erbium-doped fibers spliced to Corning's SMF-28 telecommunication fiber, the small core and high dopant concentration leads to more dopant diffusion of the erbium fiber than the SMF-28 fiber, allowing the two MFDs to get closer to a match through arc scanning.

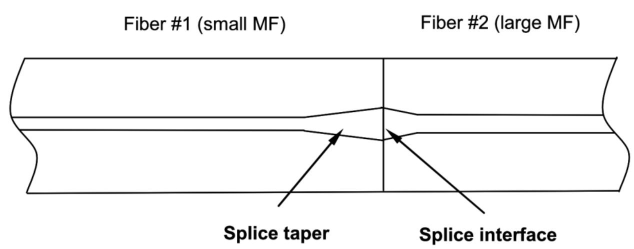

Fig. 4 — Schematic of a splice joint formed by fusion splicing of two dissimilar fibers. [10]

3.0.3 Characterization

To form the fiber samples, 900 μm tight buffered patchcords (SMF-28) were used. Before splicing, these patchcords were measured for their transmission loss at 1310 nm using an EXFO Maxtester FOT-920, an 818-IR Detector, and a Newport Optical 840 Power Meter. The transmission power was measured at 1310 nm to 1) prevent bend losses from affecting the measurements and 2) limit the attenuation of active fiber (which is absorbing at 1550 nm). Each cord was then cleaved into two pieces of equal length, measured again for losses, then subsequently spliced to either PS-ESF or PS-GSF. The specifications for all fibers can be found in Table 2.

Table 2 — Properties of Fibers Used in Fiber Laser Samples

Property	SMF-28	PS-GSF	PS-ESF
Cutoff Wavelength	1260 nm	920±50 nm	920±50 nm
Core Diameter	8.2 μm	3.0 μm	3.0 μm
Mode Field Diameter (1550 nm)	10.4±0.5 μm	5.0±1 μm	5.0±1 μm
Attenuation(1550 nm)	0.2 dB/km	N/A	8.5±1 dB/m
Numerical Aperture	0.14	0.28	0.28

Table 3 lists the results from the various splice loss measurements. The first four entries reflect the nominal splice losses in a Fujikura 70s fusion splicer for the different fibers. Once these baselines were established, these fibers were spliced using the 3SAE large diameter splicer (LDS II). The splice routine utilized a 5 μm gap and active alignment to limit lateral and angular misalignments during the push phase (25 μm for a total stuff of 20 μm). As can be seen from the table, the SMF-28 to SMF-28 splices are comparable to those made with the 70s. Conversely, the splices made to the PS-GSF fiber are considerably worse (2.42 dB vs. 1.63 dB). This is likely due to non-optimized splice parameters. To further reduce the splice loss from SMF-28 to PS-GSF, flame polishing of the splice joint was employed.

Table 3 — Measured Splice Losses for Various Fiber Combinations

Fiber Set (Instrument)	Average Loss (dB)
SMF-28 to SMF-28 (70s)	0.02
SMF-28 to PS-GSF (70s)	1.63
PS-GSF to PS-GSF (70s)	0.04
PS-GSF to PS-ESF (70s) [a]	0.04
SMF-28 to SMF-28 (LDS II)	0.03
SMF-28 to PS-GSF (LDS II)	2.42
SMF-28 to PS-GSF (LDS II) [b]	0.23

[a] estimated
[b] with flame polishing

To determine the appropriate splice parameters for flame polishing, we first measured the change in transmission power as a function of arc current. Several trials were executed with initial arc power values of 25 to 45 in increments of 5. The electrodes that generate the plasma field (”ring of fire” or ROF) were scanned at a speed of 1 mm/s over a 200 μm distance. From this data, the optimum arc current was determined to be 40. Next, sequences were tested whereby the initial arc current was varied, then ramped to a final value of 40. The results showed that the initial arc current did little improve the quality of the splice, only serving to prolong reaching the ultimate transmission value.

Next we determined whether there was an advantage to increasing the scan distance from 200 μm up to 1 mm. Experiments showed that at extreme distances (greater than 500 μm), the effect of flame polishing decreased. For a constant scan speed of 1 mm/s this makes sense since the further the arc has to travel, the less heat at any given moment on the fiber (and the longer it takes to reach optimum transmission). This also agrees with the observation that highly localized heat tends to improve the splice quality. We did find that there was a slight improvement by moving to a wider scan after initially scanning over a shorter distance. Here we scanned the ROF for 200 μm for roughly a minute, then switched to 400 μm. The average splice loss was 0.23 dB with a total scan time less than 5 min.

In performing these experiments, there was a noticeable decrease in the arc intensity over time. This was attributed to soot from the splice process depositing on the electrode. As a result, the fiber did not receive the same heat as when the splice process began. While this can be somewhat mitigated by regularly cleaning the electrodes, for long scan times this can be problematic. To address this issue, we monitored the fiber glow approximately 500 μm from the splice joint during the scan using the splicer’s onboard cameras and kept the pixel intensity constant throughout the flame polishing sequence (by increasing the arc current).

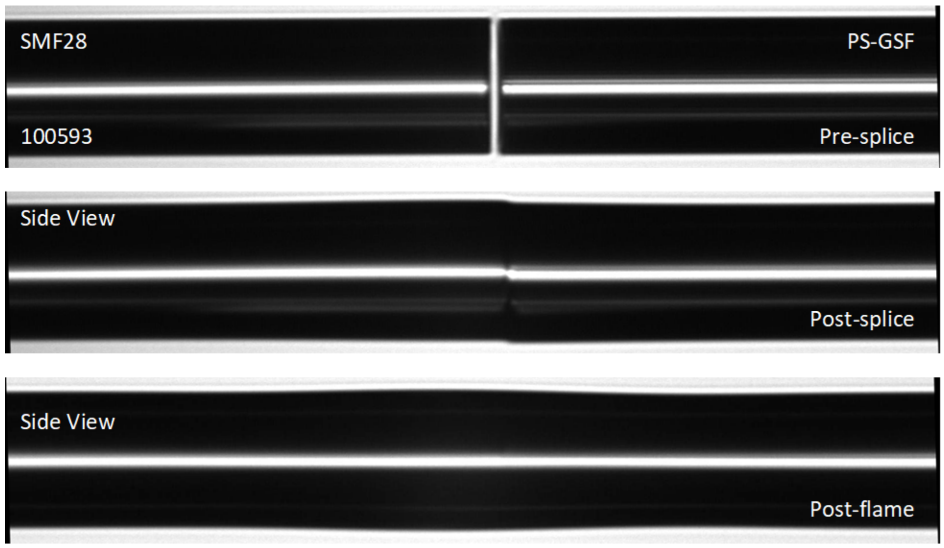

Fig. 5 — Microscope images of a two fibers at various stages of the splice procedure. (top) SMF-28 and PS-GSF fibers priors to splicing. (middle) The fibers immediately after automated splicing. (bottom) The splice joint after flame polishing using pixel observation and a 250 μm sweep.

Figure 5 displays images from a splice at different stages of this splicing routine. Of note is the smoothing of the joint (caused by a lateral offset of the fibers) during the flame polishing stage.

Figure 6 shows the change in splice loss for each trial of three flame polishing techniques and their corresponding scan times. The circles represent the increased scan distance technique (200 μm to 400 μm), the squares correspond to pixel observation with a 250 μm sweep, and the diamonds relate to pixel observation with a 500 μm sweep. In all instances, the sweep speed was 1 mm/s. The average change in splice loss is roughly uniform across all techniques (0.23 dB), and all methods achieve similar final transmission values. One unmistakable difference between the various techniques is the time to achieve the final transmission value. Not surprisingly, the approaches that incorporated the widest sweeps took the most time.

One disadvantage to using flame polishing to improve the splice loss is the tendency of the fibers to deform under prolonged treatment. Figure 7 shows three splices from each investigated flame polishing technique. As reflected in the images, the longest heat exposure (330 sec for the 500 μm sweep) caused the most significant tapering and bulging of the fiber. This makes the splice less durable and more susceptible to premature failure. As expected, the technique with the shortest exposure time exhibits the least amount of deformation (250 μm sweep). It is conceivable that a change in the sweep behavior of the ROF at the turn-around points will eliminate this bulging (i.e. to speed up). Based on these results, the most efficient flame polishing sequence (after the initial splice) used pixel observation at a 250 μm sweep distance and 1 mm/s scan speed. This technique provided the lowest loss and least amount of deformation in the shortest time.

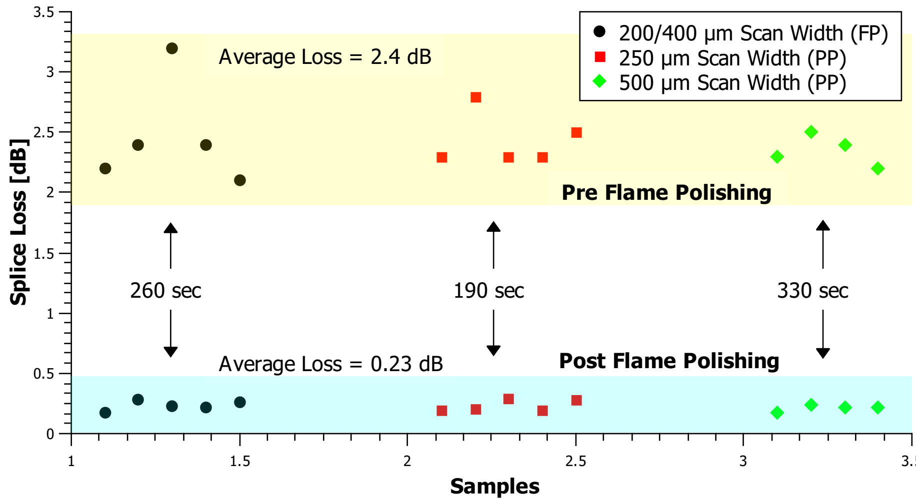

Fig. 6 — Summary of flame polishing techniques used to reduce the splice loss of dissimilar fibers.

4. CONCLUSIONS

Low loss splices to dissimilar fibers were achieved using a flame polishing technique. Thermal diffusion of the core dopants enabled the mode field diameters to more closely match. By monitoring the process and observing the real-time pixel values of the fibers, the arc current was continuously adjusted to ensure a consistent plasma field on the splice joint. The routine was optimized for low losses and high speeds with little deformation to the optical fibers. In doing so, the splice loss was reduced by more than 2 dB over the initial splice to almost 0.2 dB. In terms of realistic multiplexing, the attained splice loss shows that if the pump absorption is negligible (as in the high pump power regime), 32 lasers can be multiplexed on a single fiber.

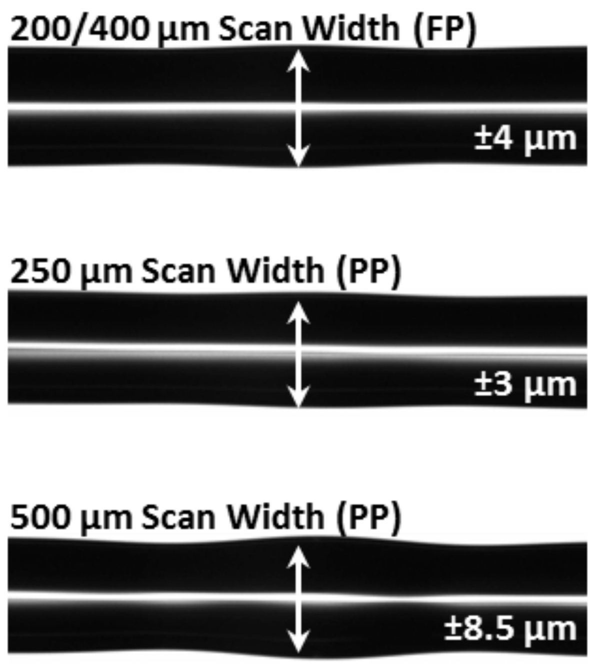

Fig. 7 — Bulge and tapering at the splice joint due to flame polishing the splice joint.

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