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High Strength, Low Loss, Fusion Spliced Interface Between Fused Silica & Phosphate Glass Fibers

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Abstract

For the first time to our knowledge, high strength fusion splices of a new Er^{3+} doped phosphate glass fiber to a standard telecom fused silica fiber have been achieved. Fusion splicing of single mode, erbium doped phosphate fiber directly to Corning SMF-28™ fused silica fiber is accomplished with standard fusion splicing equipment. Fusion splice parameters and optical power throughput measurements are reported.

Introduction

Optical fibers used in the telecommunications industry are typically manufactured from fused silica due to its unique ability to transmit optical signals over long distances with relatively low attenuation. Fiber amplifiers made from rare earth doped fused silica are readily spliced to standard fused silica transmission fiber using conventional thermal fusion splice technology. The fusion splice process offers significant advantages to the telecom industry including: very low cost per splice, good durability, and low excess optical power loss (eg. < 0.02dB).

Phosphate glass is an attractive amplifier medium because, unlike fluoride and silicate materials, it combines several desirable characteristics such as good chemical durability, ion-exchangeability, high gain per length coefficient, wide gain spectrum, and low up-conversion characteristics [1,2]. Phosphate glass also exhibits an extremely high solubility for rare earth ions, which allows large densities of optically active, trivalent rare earth ions. The high ion density results in significantly shorter gain lengths than can be fabricated from silica based glasses traditionally used for fibers.

Erbium-ytterbium (Er^{3+}, Yb^{3+}) doped phosphate glass technology, in particular, has demonstrated a significant capacity for large gain per length coefficients [2,3,4], in addition to providing the ability to tailor the absorption band by the ytterbium concentration. Furthermore, various experimental devices have been demonstrated for fiber-optic transmission applications supporting data rate capabilities in the multi-Gb/sec range.[5,6,7,8]. These combined aspects of the phosphate glass material and reported gain characteristics support it as a prime candidate for compact, high performance, and cost effective optical amplifiers.

Given that the phosphate fibers can provide effective optical amplification in a commercial environment they must be able to interface with the standard silicate fibers currently deployed. This work is a step toward developing a process of mating the phosphate fibers to standard silicate fibers.

Until recently, successful fusion splicing of different glass materials with different melting temperatures and thermal expansion values was considered very difficult, if not impossible. One method used to accomplish such a task used "splice glass fibers". Thin splice glass fiber sections were reportedly inserted between the dissimilar glass fiber materials to be mated. All three glasses could then be fusion spliced together with the splice glass section in the center acting to buffer the connection between the two different fiber material's expansion and melting point values [9]. In this work, we report on direct fusion splice coupling without splice glass, of single mode phosphate based glass fibers to single mode fused silica glass fibers, resulting in high bond strength and low interface losses.

Phosphate glasses typically exhibit glass transition (T_g) values of ~ 400^{o}C and thermal expansion values of greater than 100 x $10^{-7}/^{o}$C. In contrast, fused silica possesses (T_g) values of ~ 1000^{o}C and thermal expansion values of 5 x $10^{-7}/^{o}$C. The new phosphate glass fiber material (designated QX & MM) exhibits many properties that make it a more "forgiving" fusion splice partner with fused silica fibers. The differences are shown in Table 1. Some of the attributes that allow QX and MM glass fibers to be readily spliced to fused silica include enhanced chemical durability and increased stability against devitrification.

Property	**MM-2**	**QX/ER**	**Fused Silica[10]**	**Ä Value**
Refractive Index at Sodium D Line n_D	1.540	1.538	1.4605	0.0775
Abbe Number, $(n_d-1)/(n_f-n_c)$	64.0	64.5	70.4	5.9
Nonlinear Refractive Index n_2 (10^{-13} esu)	1.20	1.22	2.4	1.18
Thermal Expansion α (10^{-7}/°C)	72	82	5.5	79.5
Transformation Temp T_g (°C)	506	450	1042	592
Deformation Temp T_d (°C)	535	485	1585	1100
Thermal Conductivity (w/m*k)	0.84	0.85	1.30	0.45
Density (g/cc)	2.7	2.9	2.215	0.68

Table 1.

Experiment Descriptions and Results

Single mode fiber samples of Corning SMF-28 (125um OD) and MM-2 (180um OD) were cleaved with an Amherst Ericsson Model #EFC 11-4 Electronic Cleaver and a Fitel Furukawa Model #S323 Manual Cleaver. Single mode (rectangular) double clad and round multimode QX/Er fibers were also evaluated. Good quality cleaved fiber faces were achieved with both cleaving units at Kigre on various test fibers. Initial successes with the Ericsson electronic cleaver unit on the single mode fibers was surprisingly surpassed later on by the quality and consistency of cleaves produced by the simpler Fitel manual cleaver unit. The Ericsson unit provides for fiber tension control. Test cleaving optimization studies with the Ericsson unit presented a trend indicating a requirement for higher tension settings for the production of optimized (flat & smooth) cleaved fiber faces. However, continued studies with the Fitel manual cleaver (which provides for no fiber tension) surpassed all earlier work with very consistent high quality cleaved fiber end faces. The Ericsson unit uses a flat blade that pushes into the side of the fiber (under tension) in order to affect a fiber cleave. The Furukawa unit employs a round blade that slices the fiber barrel (without tension) with a rotated "chop" motion. The same modifications were made to the mounting fixtures on both cleaving units in order to accommodate the 240um x 300um double clad single mode QX fiber.

Initial results of fiber splicing experiments (single mode MM-2 to standard SMF-28 fused silica) were reported by Dr. Chris Good (Sumitomo Electric Lightwave, RTP, NC) and Dr. Conleth Hussey (Feasa Enterprises Limited, Limerick Ireland). Dr. Hussey was able to produce strong splices that exhibited mechanical strengths of 0.5Gpa (~6 Newtons). This is comparable to a standard silica/silica splice. Dr. Good was able to obtain a strong splice with a measured loss of ~ 2.5dB during his initial work.
The arc circuit board in the Sumitomo Type-36 unit was modified so as to increase the heat control resolution and limit the rage to the lowest 10% of the unit's standard scale. The program used by Dr. Good is described as follows: Power setting 1, Gap 10, Overlap 15, Pre-fusion 0.0, Duration 00.15, Arc Spattering duration 0.05s.

Fiber fusion splicing was also performed by Kigre Inc. with a modified Sumitomo Type-36 and an Ericsson Model FSU 995 FA. Experiments were initiated on the Sumitomo Type-36 unit utilizing the settings provided by Dr. Good. As the optimization experiments proceeded, it was found that the Ericsson Model FSU 995 FA provided more flexibility for adjusting the system parameters. For example, the Ericsson system allows the user to adjust 11 independent variables where the Sumitomo system is restricted to 6 settings and a pre-programmed arc pulse shape. Optimum phosphate to fused silica fusion splice settings for the Ericsson system are listed as follows: Pre-fuse time 0.2 sec., Pre-fuse current 3.0 mA, Gap 50.0mm, Overlap 13.0mm, Segment #1 Fusion time 0.1 sec., Segment #1 Fusion current 8.0 mA, Segment #2 Fusion time 1.0 sec., Segment #2 Fusion current 2.0 mA, Segment #3 Fusion time 1.2 sec., Segment #1 Fusion current 2.0 mA, Set Center (offset from 255 arc center) 225. . Figure 1 is a Kigre photo showing a sample fusion splice of SMF-28 to Kigre's MM-2 (180um single mode) fiber.

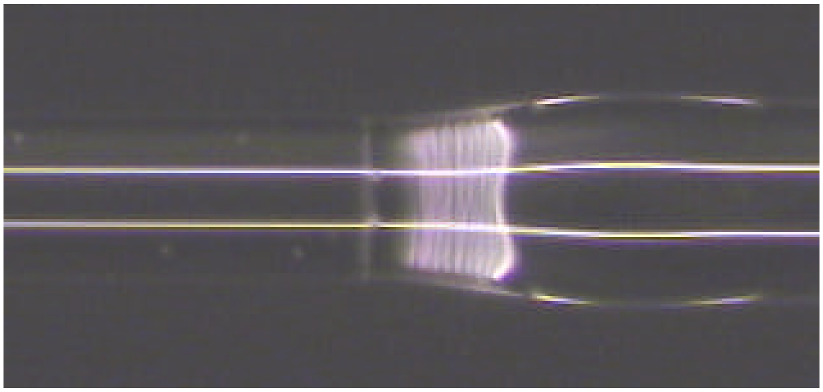

Figure 1 - MM-2 fiber spliced to SMF-28. Estimated Interface Loss ~ 0.25 dB

Harris Corp. independently developed processes for cleaving and fusion splicing single mode phosphate fibers to fused silica fibers. Figure 2 is a photo that is representative of Harris' SMF-28 to Kigre's MM-2 (180um diameter cladding, single mode core) amplifier fiber bonds. Their work included the development of proprietary cleaving, cleaning, and splicing techniques. The strength of the bonds is surprisingly good because the chemical and thermal properties of the two fibers are radically different. Ten splices were examined for breakage characteristics. All of the fractures occurred on the SMF-28™ fiber within 3 mm of the fusion splice (see Figure 3.). As indicated in the following discussion of tensile strength, given a strong fusion splice, we would expect the

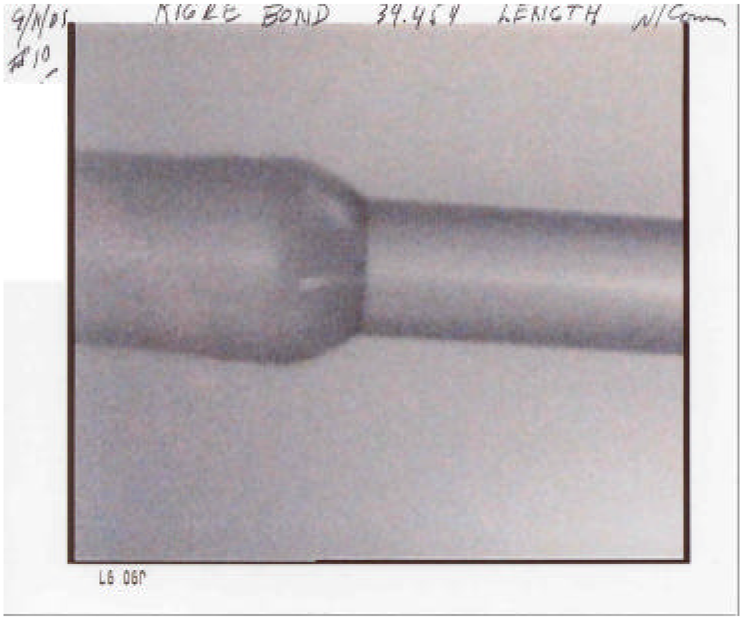

Figure2. MM-2 fiber (left) spliced to SMF-28. Measured throughput loss: 0.20 dB.

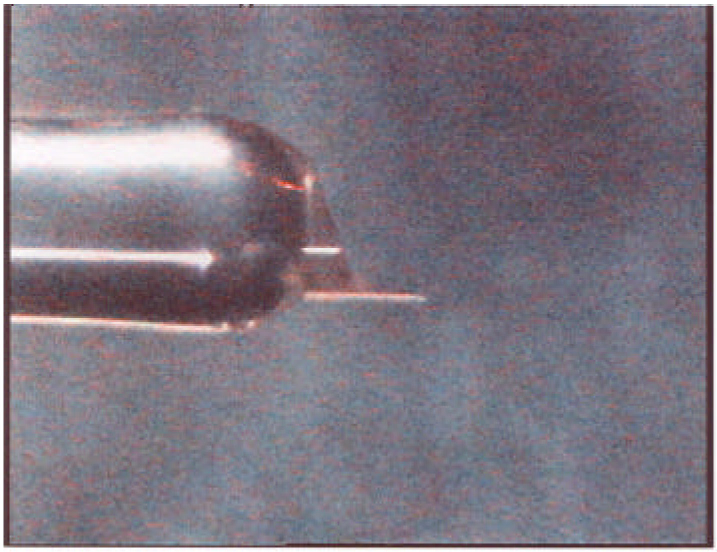

Figure 3 – Photo showing typical result of destruction tests. SMF28™ (right side) fiber fractures near fusion

SMF-28 fiber to fracture due to its smaller diameter (SMF-28 @ 125um, Kigre Fiber @ 180um). *The significant result of the fracture tests is that the fractures did not occur at the fusion splice.*

Tensile Strength

For a first order quantitative measurement of the tensile strength of the MM-2 fiber we employed a loop test and compared the value to that of other fibers [11,12,13,14,15]. In these loop tests, a loop of fiber was drawn by hand. The tensile strength of the fiber is calculated from the radius or diameter of the loop when the fiber breaks. Five separate tests were done and all broke at about the same diameter: 4mm +- 0.5mm. If we assume that the modulus of elasticity of the glass is 10.2 x 10^6 psi (67 GPa), and the fiber diameter was 125 µm, then the strength of the fiber is calculated as:

$$\sigma = 1.198\, E(d / D) = (1.198) \times (10.2 \times 10^6 \text{ psi}) \times (0.125 / 4) = 382{,}000 \text{ psi}$$
$$= 2.6 \text{ Gpa.}$$

382,000 psi is a very high strength for phosphate glass fibers, which can be attributed to Kigre's patented phosphate glass chemistry. In particular, MM2 was developed for high strength characteristics. It is generally found that the strength of small diameter, pristine glass fibers have a ratio of σ/E of 0.05 (that is, a 5% elongation at break)[15]. For example, pristine E-glass ($CaO-Al2O3-SiO2$) fibers, specifically made for reinforcement purposes, are generally found to have a strength of about 500,000 psi and a modulus of elasticity of 10.5 x 10^6 psi.. The above MM-2 fiber shows a ratio of σ/E of 0.0375, or about 75% of what might be expected under ideal conditions.

Optical Measurements

Optical probing is a straightforward method to measure the loss contribution of a fusion splice. There are three major contributors to the total loss through a section of spliced fiber: Fresnel loss, splice loss, and optical absorption. The refractive index difference between fused silica (1.460) and MM-2 phosphate (1.540) glass fibers introduces a Fresnel loss at the splice boundary. The calculated Fresnel loss at the fusion interface for these materials is 0.003 dB and 0.2 dB for the air interface at the unspliced end of the phosphate fiber. The MM2 material absorption at 1318nm is 0.47 dB/cm.

Loss measurements were taken on several samples of single-end fusion spliced Kigre fibers. A two-foot length of SMF-28 fiber was fusion spliced to each sample and a high quality APC connector was installed on the loose end of the SMF-28 fiber. Single mode 1318nm light, with known power, was injected into the APC connector of the SMF-28 fiber and the output power of the open end of the Kigre fiber was measured with a broad area detector.

The length of the spliced samples was about 5.0 cm. Expected total throughput loss at 1310nm for a 5 cm spliced Kigre fiber is 2.6 dB. We found the throughput loss, for a single-end splice, to have significantly lower values than expected, e.g., the throughput loss ranged from 2.54dB to 0.03dB, with a mean of about 0.6dB for 12 samples. An explanation for the unexpectedly low loss is developed in the following discussion.

Several samples were also prepared with SMF-28 fiber fusion spliced to both ends of a Kigre fiber. The total throughput loss of these samples was significantly higher than expected. The throughput loss ranged from 2.4dB to over 10dB with a typical value of about 7dB. This throughput loss was only slightly direction dependent, ie, launching the 1318nm from either end produced loss measurements within 1 dB of each other.

The mode diameter in the phosphate fiber has been extensively measured at various wavelengths and it closely matches that of SMF-28 fibers. Therefore, the excess optical power loss is likely due to some combination of core-to-core misalignment and diffusive expansion of the phosphate fiber core resulting from the high temperature fusion process.

Mode field imaging of a single-end fusion splice shows that more light than expected is propagating in the cladding of the phosphate fiber (Figure 4). The mode imaging experiment is inconclusive as to the reason for leakage into the cladding.

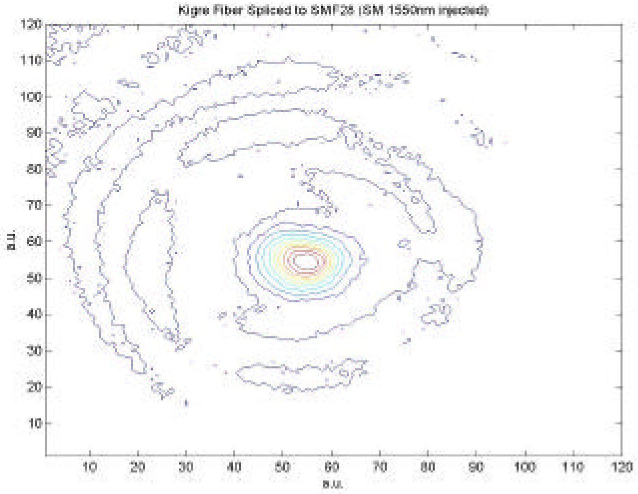

Figure 4. 1550nm mode field image through 45mm long phosphate fiber spliced to SMF-28

Summary

Three labs have independently produced strong fusion splices of erbium doped phosphate fibers (Kigre MM-2 type) to silicate based SMF-28™ fibers. The fusion splices were performed with commercially available equipment. Splice parameters are given. *Destruction tests, by bending, showed that the fusion splices are exceptionally strong and that destructive fractures did not occur at the fusion splice.*

Optical throughput tests, performed at Harris Corp., indicate a significant loss of core-guided light, most likely due to either core misalignments or core diffusion from the high temperature fusion process. Experiments are in progress to determine and correct the optical throughput loss mechanism.

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