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Review of Fabrication Techniques for Fused Fiber Components for Fiber Lasers

Invited Paper

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ABSTRACT

Fused fiber components are the key building blocks that enable reliable and efficient operation of high power fiber lasers. In this paper, we review fabrication techniques for the manufacture of such devices, including mode-field adaptors, fiber tapers, fused couplers, and fused combiners. We present the basic equations governing both the optical performance and fabrication requirements for these devices, and demonstrate how these apply to some common fiber laser applications. We then describe and discuss component fabrication techniques and available hardware.

Keywords: Fusion process, specialty fiber, fused fiber components, diffusion, taper, mode adapting, combiner, fiber laser, beam propagation

1. INTRODUCTION

Fiber lasers have been increasingly used for various industrial applications, such as material processing, marking, cutting, and welding because of their high optical-to-optical and overall wall-plug efficiency and excellent output beam quality [1,2]. CW fiber lasers with multi-kW power levels from a single fiber have been demonstrated [1,3], and compact, low cost pulsed fiber lasers with high peak power have been developed [4]. With the availability of fiber Bragg gratings and fiber coupled pump diodes, a fully monolithic (i.e. all fiber) system architecture can be achieved with appropriate fused components. A fully fused system fully exploits the inherent advantages of fiber laser systems, including simplicity, compactness, robustness and reliability. For a typical all-fiber fiber laser system, there are a number of fused components that must be considered, including pump combiners, mode adaptors, output combiners and couplers, and end-caps. Even a basic splice can be thought of as a system component, as splices for fiber lasers are typically between dissimilar fibers and therefore may require some form of mode adaption. There are some unique challenges associated with fiber laser components, beginning with the very high power levels that can be involved. Losses that would normally be considered very satisfactory for typical telecom applications, can lead to catastrophic component failure due to localized heating. In addition, large mode area (LMA) fibers are commonly employed as a means to reduce power densities and subsequent non-linear effects. By design these fibers are very weakly guiding and often support higher order modes. They are therefore very susceptible to bending or kinking, as well as small angular misalignments. Because LMA fibers can effectively be multimode waveguides, it is not simply a matter of ensuring extremely low loss but also beam (fundamental mode) quality.

Further component fabrication challenges arise from the wide variety of fiber types possible, including non-circular, double clad, PM, micro-structured (PCF) and rare-earth doped [9-13]. Mechanical reliability of the fused device is also of a critical concern [6-8] due to potentially harsh field environments and inherent thermal cycling at the power levels involved. Signal feed-through pump combiners [14] and the potential for extreme high power output combining add further challenges. It is easy to see why proper design and fabrication of fused components is a critical challenge for fiber laser systems.

2. FUNDAMENTAL OPTICS FOR FUSED FIBER COMPONENTS

In the fabrication of fused devises for fiber lasers, whether simply splicing together dissimilar fibers or trying to feed a signal through a tapered pump combiner, it is extremely important to understand mode matching and mode transformation. There are two basic methods for locally changing the waveguide properties of an optical fiber: thermal core expansion and physical tapering, shown schematically in Fig. 1. Thermal expansion involves heating the fiber at very elevated temperatures such that the core dopants begin to diffuse. The speed of diffusion is dependant not only upon the temperature at which the fiber is held, but also upon the chemical makeup, or dopants within the core (e.g. Ge, Al, F, or rare-earth elements – Yb, Er, Tm, etc.). For silica based fiber, significant diffusion can take place at typical splicing temperatures of around 2000°C, over time frames of several seconds to several minutes. Dopant diffusion causes the core diameter to increase and the refractive index delta to decrease, resulting in an increase in the mode field diameter (MFD) of the signal. Because this is purely a thermal process, the outside diameter of the fiber stays nominally the same. (Note: processing at very elevated temperatures and/or extended times may cause some OD non-uniformity due to surface tension effects).

By contrast, physical tapering does change the OD of the fiber, and, by simple geometric scaling, the core diameter of the fiber is reduced. The basic process for tapering a fiber is to heat it to an elevated temperature, typically a minimum of 1400°C for silica fibers, and pull. At typical tapering temperatures and times, dopant diffusion is minimal, so the refractive index delta of the core does not change. The change in MFD of the signal is therefore based solely on the reduction in core diameter.

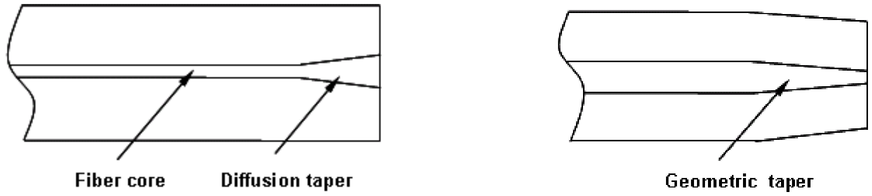


Fig. 1 Schematic of two types of mode modification processes

For both thermal core expansion and physical tapering, the transition characteristics are very important for minimizing losses and maintaining beam quality. The mode transition region needs to be adiabatic and the mode field at the output needs to match that of the interconnecting fiber. A full quantitative description of the optical field propagation through the transition region requires solving Maxwell’s equations with associated boundary conditions based on the actual waveguide property of the fiber and the optical characteristics of the transition region. When light transmits in a weakly guided fiber core, its field components in the fiber are governed by the Helmholtz equation [15]. The interaction between different fields in the fiber transition region can de described by the coupled mode theory. The evolution of the field is a superposition of many Eigen modes [16,17]. Numerically, the Helmholtz equation can be solved using a finite beam propagation method (BPM) with commercially available software, e.g. [18] based on the fiber property and boundary conditions. When a fiber is subjected to a heat treatment, the dopant in the core diffuses and this leads to fiber waveguide property change [19]. The dopant diffusion characteristics at the fiber joint can be analyzed by Fick’s law [20] with *a prior* knowledge of the dopant distribution in the fiber before diffusion.

When two fibers are interconnected to each other by fusion splicing, transmission loss typically occurs. To further understand the transmission loss, it is convenient to decompose the total loss at the joint into two parts, mode field mismatch loss and transition loss. As shown schematically in Fig. 1, transition losses occur when the mode transformation of light propagating through the transition region is too rapid, or, by definition, not adiabatic. In addition, mode field mismatch loss occurs at the interface between two fibers because of the waveguide property difference at the vicinity of this interface. To a lesser degree, losses due to light scattering and reflection may also occur at the interface. It is also important to note that the transmission loss is wavelength dependent [12]. To determine the transition loss, it is necessary to solve Helmholtz equation or the coupled mode equation numerically. The mode-field mismatch loss can be estimated based on the overlap integral of the field amplitudes of the guided modes using the following equation,

$$Loss\ (dB) = -10\log_{10}\left[\iint \varphi_A(r,\theta)\cdot\varphi_B(r,\theta)\,dr\,d\theta\right]^2 \ , \qquad (1)$$

where $\varphi_A(r,\theta)$ and $\varphi_B(r,\theta)$ are the normalized field amplitudes of the guided modes for two fibers A and B. For a step-index fiber, the guided modes can be solved exactly [21] to determine the mode-field mismatch loss.

The above discussion has been concerned with optimization of signal losses and beam quality. Another major area of concern for fiber laser components is the fabrication of pump combiners, which are used for scaling the total pump power delivered to the gain fiber. Here multiple multimode (MM) fibers carrying pump power can be fused together and tapered down and spliced to an appropriate output fiber. To ensure lossless transmission in the forward direction, the brightness of the beam needs to be conserved. This conversation of brightness for our discussion is best given as follows:

$$TR \times NA_{in} \leq NA_{out} \tag{2}$$

where NA_{in} and NA_{out} are the numerical apertures of the input and output beams respectively, and TR is the taper ratio, defined as the effective diameter in, divided by the effective diameter out. By effective diameter we are referring to the diameter of a round fiber that gives the equivalent cross sectional area of the actual fiber or bundle (the “glass” area). The taper ratio, as so defined, also ties in to the mechanics of fabricating the physical taper through basic conservation of volume. For a typical taper process where the fiber is pulled out of the heat zone at velocity, V_{out}, and fed into the heat zone at velocity V_{in}. The effective input and output diameters are related as follow:

$$\mathrm{V_{out}} \times \mathrm{D_{out}^2} = \mathrm{V_{in}} \times \mathrm{D_{in}^2} \rightarrow \frac{\mathrm{D_{out}}}{\mathrm{D_{in}}} = TR = \sqrt{\frac{\mathrm{V_{out}}}{\mathrm{V_{in}}}} \tag{3}$$

The shape of the taper (linear, sinusoidal, etc.) can therefore be defined by the rate of change of the square root of the velocity ratio.

3. FABRICATION TECHNIQUES FOR FUSED FIBER COMPONENTS

In this section, we review some techniques for fabricating high power fused fiber components with a focus on mode field adapting between dissimilar fibers and fused fiber combiners.

3.1 Mode Field Adapting

For mode field adapting, the thermally expanded core (TEC) and physical fiber tapering methods are two useful techniques for modifying the modal property of a fiber. The choice of which method to use is typically dictated by the application at hand. If the only consideration is optimal signal matching, then there may be multiple ways to achieve the same result using different combinations of thermal expansion or physical tapering. The choice of which technique to use in such a case may be more based on ease of fabrication or mechanical robustness. When it is also necessary to match the OD’s of the fibers, say due to pump coupling requirements, then the choice of mode adaption method may be limited. It is also important to remember that just matching the mode field diameters (MFD’s) does not mean zero loss. The modal shapes must also match and the mode transition must be adiabatic (lossless). Ultimately, a rigorous analysis of the transition of the refractive index profile along the length of the fiber will determine the optimal mode coupling.

As an example of how thermal core expansion can be used to change the mode field diameter of a fiber, we consider a single mode (SM) 1060 fiber, which is a common signal fiber for seeding a MOPA fiber laser configuration. This fiber has a cut-off wavelength of 920nm and is robustly single mode at 1060nm with an MFD of 6.5µm. For small diffusions, it is possible that simply the heat profile of the fusion source along the length of the fiber is sufficient to provide an adiabatic transition of the mode. For most fusion sources, such as arc discharge or filament fusion, the heat zone is on the order of 100’s of microns. One technique for extending the heat zone and achieving better control over the TEC process is to scan either the fiber or the heat zone back-and-forth axially in a process termed fire polishing. One such fire polish technique involves scanning the heat source back-and-forth in ever increasing distances, given by an incremental distance delta. If for instance 10 passes are performed with a delta of 100µm, the total scan distance would be ±1mm. This scan profile yields essentially a triangular heat profile with the greatest thermal input at the center and decreasing thermal input at the edges. The diffusion is therefore gradually increased over this scan distance.

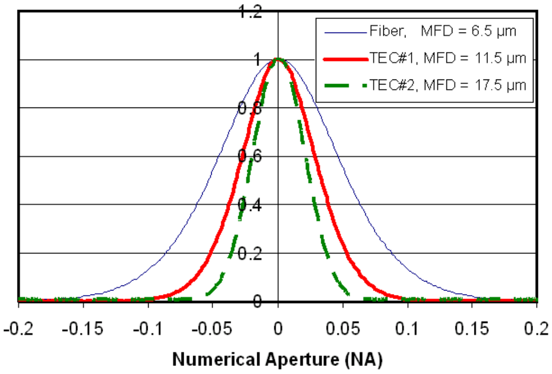


Fig. 2 Mode-field expansion with the TEC method

Figure 2 shows the results of different fire polish processes on the above SMF 1060 fiber. The thermal heat treatment was applied to a continuous length of fiber that was then cleaved at the center of the diffusion region. The mode field diameter was then measured using a far field scanner. (Note that an increase in MFD in the near field yields a reduced profile in the far field.) The original MFD of 6.5µm could be increased to 17.5µm with very low loss and good beam quality. This is approximately a factor of 3 increase in MFD, which is a typical practical upper limit for thermal core expansion.

As an application example of how the above thermal expansion method can be used to minimize the transmission loss between two dissimilar fibers, let's assume the above SM 1060 fiber needed to be spliced to a typical large mode area (LMA) fiber with a MFD of 12.4µm at 1060nm. The theoretical splice loss based on the MFD mismatch is 1.7dB. To optimize the optical transmission between these two fibers, we used a filament-based Vytran FFS-2000 fusion splicing system and actively monitored the transmission loss during the fiber diffusion process. The measured transmission loss change versus the thermal treatment time is shown in Fig. 3. The loss between these two fibers was reduced to 0.02 dB with approximately a three-minute thermal diffusion treatment. In this case the loss is very low even though both fibers are experiencing thermal diffusion. For some applications it may be beneficial to pre-diffuse the smaller MFD fiber first and then splice this to the large MFD fiber using a standard "quick" splice process.

For comparison, the simulated result of transmission loss vs. diffusion time between the above two fibers is shown in Fig. 4. In the calculation, we assumed that the diffusion occurs only in the SM 1060 fiber. Both results have a good agreement. In addition, we show in the simulated result that low transmission can also be achieved between the SM 1060 fiber and a 20-µm LMA fiber via diffusion.

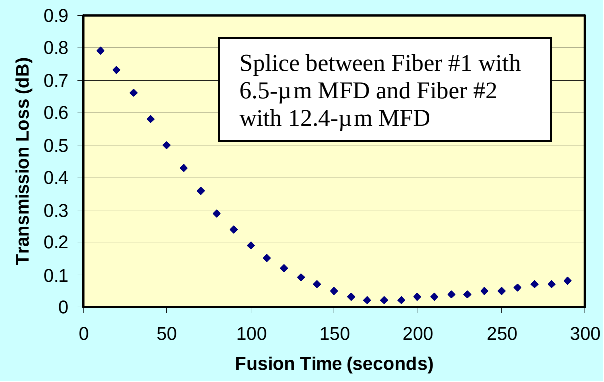


Fig. 3 Optical coupling optimization using the TEC method

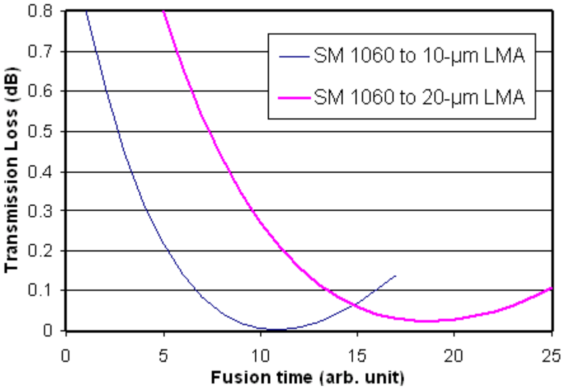


Fig. 4 Simulation transmission loss due to diffusion

While thermal diffusion does change the core size and refractive index difference of a fiber, it does not, to first order, change the V-number of the fiber. This means that a fiber which is single mode before diffusion will stay single mode after diffusion. This is not the case with physical tapering, where the refractive index delta (and hence the NA) stay the same but the core size is reduced. Physical tapering, an example of which is shown in Fig 6, is especially important for making combiners with a center feed-through fiber. For a fiber with a step index profile, the mode field profile of each guided mode can be computed analytically. Fig. 5 shows how the mode field diameter (MFD) varies as a function of core size for different fixed values of refractive index, Δn, or fixed NA. The MFD change has a saddle shape, where, starting at large core diameters, the MFD decreases with decreasing core size. For a given NA there is a certain core size at which the MFD is minimized, after which point any reduction in core size actually causes an increase in MFD. This means that for a given NA fiber, there are actually 2 points where the MFD matches. For example, if a 400 µm diameter LMA fiber with a 20µm, 0.06NA core is tapered down to 125µm (TR=3.2), the core size will be reduced to 6.25µm but the MFD will end up approximately the same at 18µm.

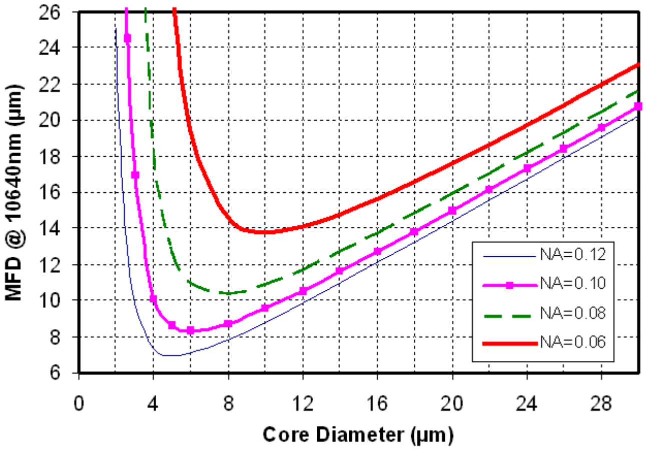


Fig. 5 MFD for fibers with different NAs and core diameter

Although MFD provides a quantitative number to define the fiber modal property, it is important to note that MFD is a highly simplified parameter. Even though two fibers have the same MFD value, it does not necessarily mean that these two fibers have a perfect mode field match. They may have distinct modal profiles and therefore still exhibit significant loss per the overlap integral given in Equation (1).

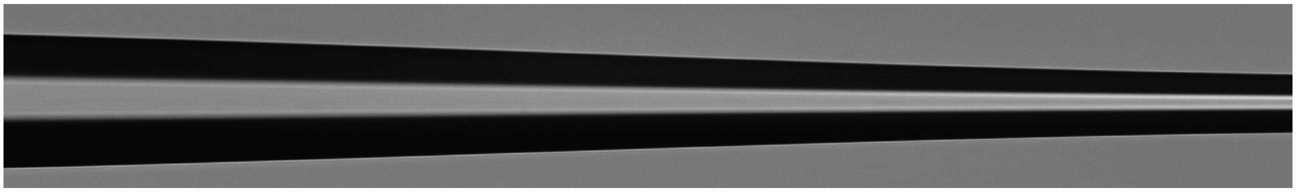


Fig. 6 Typical tapered fiber image

Similar to the thermal diffusion transition region, we need to properly control the physical taper length to ensure that the tapering is adiabatic. A general rule of thumb is that, in order not to excite higher order leaky modes [22], the slope of the taper needs to be gradual enough to meet the criteria shown in Equation 4. This implies that a certain minimum taper length is required to ensure what is effectively a lossless modal transition. While very long taper lengths may ensure low loss, they can make device fabrication more challenging and end up resulting in a package size that is much longer than necessary. So, proper tapering length optimization is required. To estimate the required tapering length for different fibers, we used BeamProp software to calculate the transmission loss due to fiber tapering. In the simulation, the tapered fiber has a tapered section and a straight section. We varied the length of the tapered section at a given tapering ratio (TR) in the calculation, and the length of the straight section was 5 mm in all cases. The results of the calculated transmissions for two cases (Fiber #1: 20µm/0.06NA with TR of 3 and Fiber #2: 10µm/0.08NA with TR of 2) are shown in Fig. 7. This analysis indicates that the minimum tapering length needs to be on the order of 12 mm for these two cases. In addition, we need to be careful not to generate macro or micro bending loss in the tapering process in order to minimize the transmission loss and preserve good output beam quality.

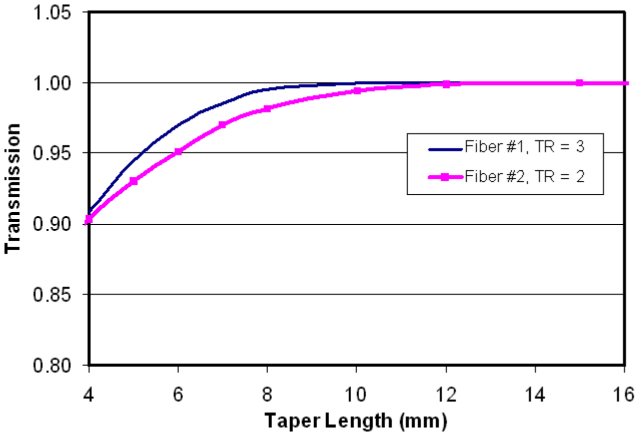


Fig. 7 Transmission loss vs. fiber taper lengths

$$\frac{dr}{dz} < \frac{r}{2\pi}(\beta_1 - \beta_2) \tag{4}$$

where *r* is core radius of the tapered fiber, and β_1 and β_2 are the propagation constants of the core fundamental mode and higher order mode respectively.

Microstructured fibers pose new challenges to the mode field adapting technique because of discontinuity of the material property in transverse direction and presence of air holes in some cases. Several methods have been proposed for optimizing mode field matching of microstructured fibers [23, 24] by properly controlling the fusion temperature and fusion. Another strategy is to match the mode-field of the microstructured fiber using an intermediate solid fiber, e.g. a GRIN fiber lens to achieve both low transmission loss and high mechanical splice strength [11].

3.2 Fabrication of Fused Fiber Combiners

There are a number of different types of fused fiber combiners that may be required in a fiber laser system. These can be divided in two general classes: pump combiners or output combiners. For a typical fiber laser system, the goal of a pump combiner is to deliver multimode pump power to the cladding of a double-clad gain fiber. This can be either via a single fiber delivery in what is termed a side pump configuration, or with very high counts of multiple pump fibers, in what is typically an end-pumped configuration. For many applications, such as MOPA's, amplifiers, or counter-pumping configurations, a center signal feed-through fiber must also be included in the end-pump design. In contrast to a pump combiner, the objective of an output combiner is to combine multiple fiber laser outputs. These can either be incoherently combined, such as bundling multiple outputs on to a power delivery fiber, or coherently combined, through appropriate interactive coupling of the individual laser arrays. In the coherent case, the term output coupler is more appropriately used versus output combiner.

Except for the side-pumped case, the fabrication method is similar for the other devises and involves the following steps: bundle, taper, cleave, splice. One method that has proven to be a fairly convenient way to bundle multiple fibers is to use a silica capillary tube. By selecting a silica “starting tube” with an ID that matches the bundle diameter of the coated fibers, the starting tube then also becomes part of the final combiner “package”. Fig. 8 illustrates this concept for a 7:1 combiner. The selected starting tube is first tapered down such that it has a straight section with an ID that will match the OD of the stripped fiber bundle. The fibers are then stripped, cleaned, and loaded into the starting tube. If a feed-through fiber is required, it must obviously be loaded correctly at the center of the bundle. The fibers in the cladding section are then tapered down by a given taper ratio (TR) over a prescribed taper length. A straight section length is often added to allow for cleaving the fused bundle. This cleaved bundle end face is then splice to an appropriate output fiber, perhaps with some TEC mode adaption thrown in as required. End-view images of 7:1 and 19:1 fused fiber combiners fabricated with a Vytran GPX 3400 glass processing system are shown in Fig. 9.

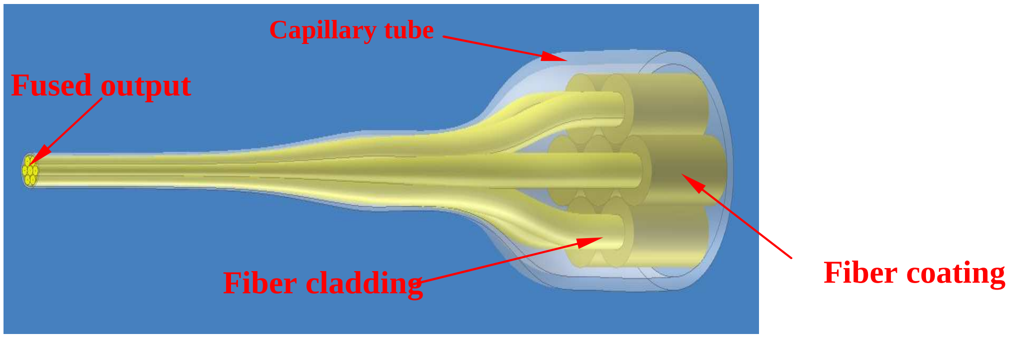
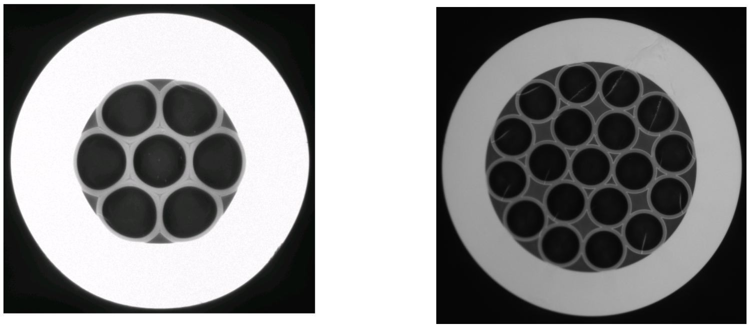


Fig. 8 Schematic of a fused 7:1 fiber combiner



(9a) 7:1 combiner

(9b) 19:1 combiner

Fig. 9 End-view images of two fused fiber combiners

For pump combiners, the brightness of the MM pumps needs to be conserved for lossless pump light transmission. If there is no loss in the device there will be no heating. This means that thermal management really comes down to NA management. If a fiber or bundle is tapered down such that the NA of the pump light increases beyond the carrying capacity of the fiber, then loss will occur. It is very important then to characterize the NA distribution of the incoming pump power. It is this NA distribution of the pump, not the NA of the fiber that will determine the optimal combiner design and the actual pump losses. The overall goal is to minimize the taper ratio, however, and as such it is important to reduce the area of “dark fiber”. By “dark fiber” we are referring to any cross sectional areas that do not carry power, such as the fiber cladding or capillary starting tube. To further reduce the brightness loss, it is therefore often quite advantageous to use hydrofluoric (HF) acid to etch away any “unwanted” dark fiber.

For pump combiners with a center feed-through, the waveguide property of the center fiber changes as it is tapered along with the surrounding pump fibers. The signal fiber may need to be specially designed or selected so that the modal properties of the fiber before and after tapering match those of the input and output fibers respectively. Pump combiners with a PM fiber feed-through can be especially challenging as the stress applying members of a PM fiber are typically low index structures and may interfere with the mode transition within the taper.

For output couplers, the coupling characteristics of the input beams depend on the taper length, taper ratio, and the length of the straight (interaction) section. In addition, the degree of fiber fusion can be controlled to alter the fiber coupling characteristics. Fig. 10 shows how surface tension can be used to vary the degree of fusion in a 7:1 output coupler, from almost completely interstitial, to completely round. This degree of fusion is also an important consideration for pump combiners, as the more collapse within the bundle, the lower the taper ratio required.

Recently, coherent beam combining has been of great interest for both power and brightness scaling [25]. While most coherent beam combining has been demonstrated in free space, it is also possible to achieve this in all-fiber via an appropriately designed output coupler. Fig. 11 depicts the simulated results with a 7:1 coupler when seven input lasers are combined incoherently and coherently. When the lasers are combined incoherently, the total output power scales with the number of lasers combined without brightness improvement. However, if the lasers are combined coherently, both output power and brightness are up-scaled proportionally to the number of lasers combined.

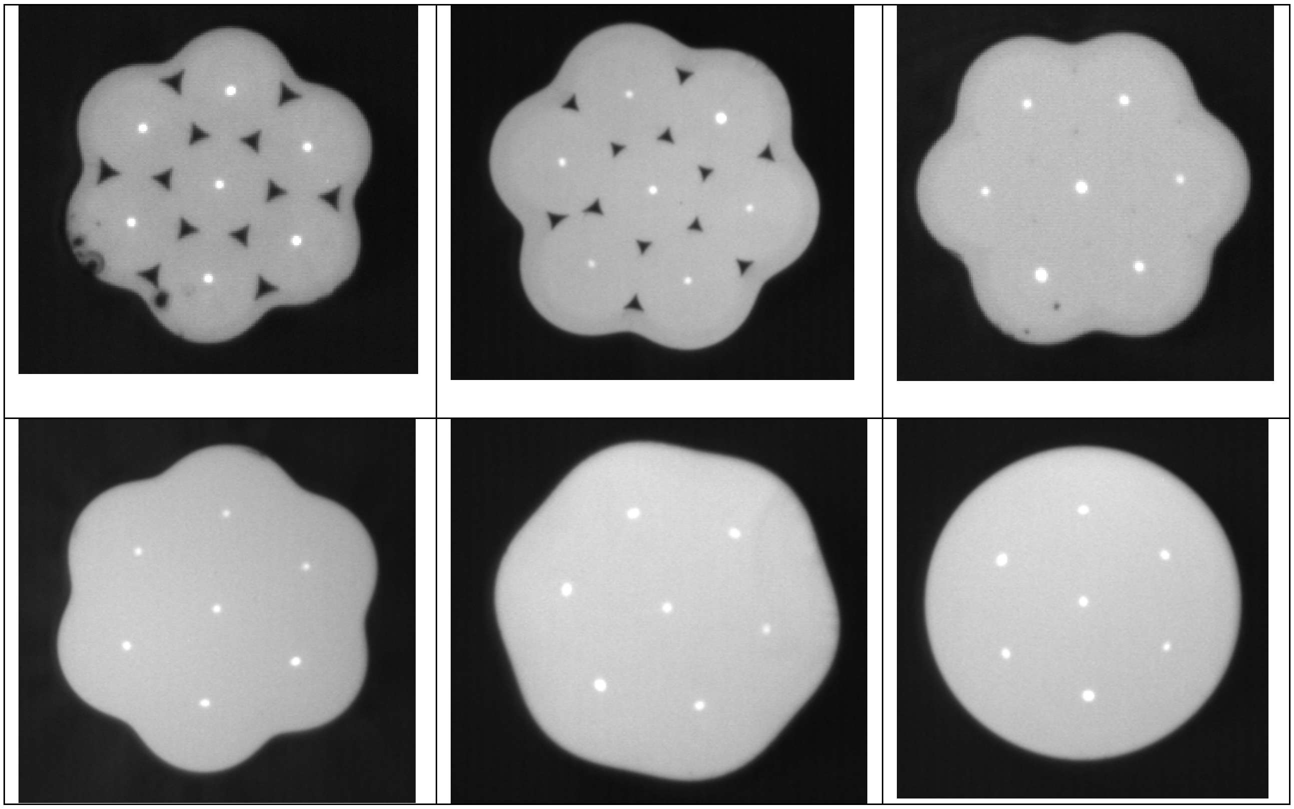
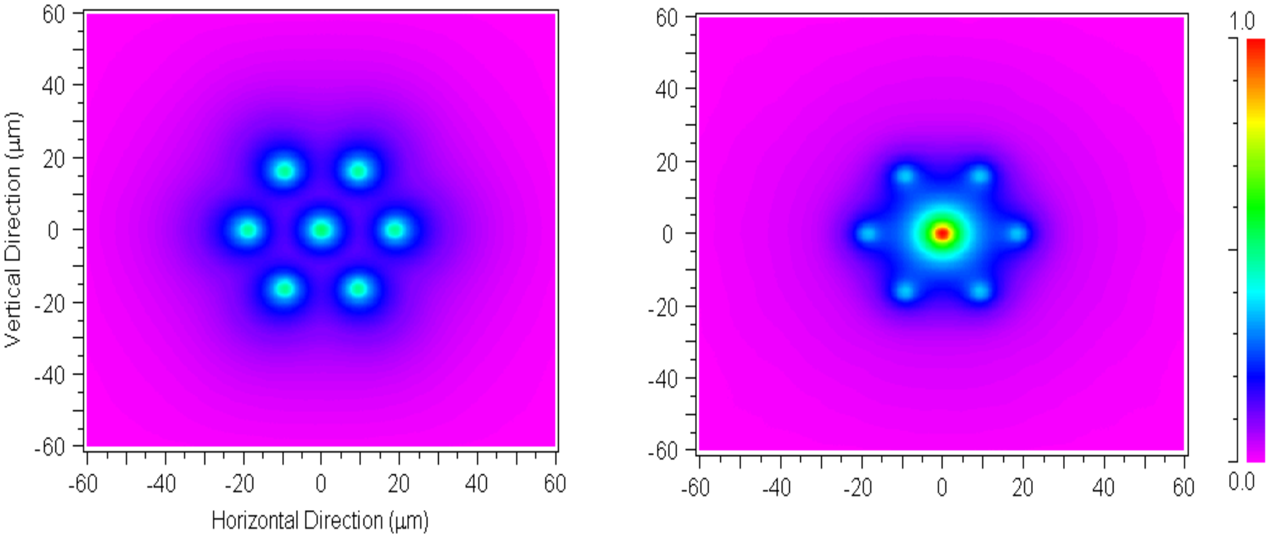


Fig. 10 End-view images of fiber couplers with different degrees of fusion



(11a) incoherent launch

(11b) coherent launch

Fig. 11 Simulated results of with seven lasers launched incoherently and coherently

Cleaving is one of the most critical process steps required for splicing not only fused fiber bundles, but also even standard LMA fibers. This is because as the mode field diameter of the fiber becomes larger, the sensitivity to angular misalignment dramatically increases. For example, a one half degree angular misalignment on a standard telecom fiber with a 6µm MFD results in a loss of 0.06dB. This same angular misalignment on a 20µm MFD LMA fiber results in a loss of 0.69dB. This implies that cleave angles of much less than 0.5 degrees are required.

Two common methods of fiber cleaving are: tension-and-scribe and scribe-and-bend. While cleaving is an extremely quick and convenient method of end face preparation, mechanical polishing or even perhaps laser shaping could also be considered. The tension-and-scribe method of cleaving is the most applicable to large diameter fibers and bundles, and also allows for the option of performing angled cleaves through the additional of a torsional component on top of the standard tension. The reason torsion induces an angle is because the crack propagates perpendicular to the applied stress field. This means that in order to achieve an extremely flat, perpendicular cleave, the stress field applied to the fiber must be perfectly in line with the fiber axis. Even with perfect mechanical alignment, internal residual stresses within the fiber itself may make ultra-low cleave angles difficult to achieve. One variation of the standard tension-and-scribe cleave method that seems to help when cleaving bundles and specialty fibers, is what is termed a sub-critical cleave process. In this process the initial applied tension is held at a level below which a crack can immediately propagate. A scribe is then carefully applied, generally with the aid of a backstop to support the fiber. Tension is then slowly increased, perhaps over several minutes, until the cleave completes. This method is especially useful when cleaving inhomogeneous materials, such as lightly fused fiber bundles or micro-structured fibers. Examples of cleaved fused fiber surface using this technique are shown in Fig. 9 and 10.

4. HARDWARE FOR FUSED FIBER COMPONENTS

4.1 Fusion Heat Sources

The processing temperature for silica based fibers ranges from a minimum of 1200C for tapering applications, to over 2100C for true fusion applications where the viscocity of the fiber must be reduced sufficiently to allow surface tension to flow the glass together. There are a very limited number of heat source options based on these very high temperatures required. In addition, the heat zone needs to be precisely controllable, not only in level and stability, but also in size and location. The most common heat source for fusion splicing applications is based on an arc discharge method, where a high voltage is applied across two electrodes separated by an air gap. A current flows across the gap and heats the surrounding air which, primarily through conduction, heats the fiber. While the arc discharge method is a very convenient heat source for field splicing applications, it can be difficult to control precisely due to environmental variations such as temperature, humidity and barometric pressure. There are also limitations on how large a fiber or bundle can be accomodated, since the fiber is effectively an insulator placed between the electrodes. Recently a three electrode arc discharge method has been developed to try to overcome this size limitation and to provide better uniformity of the heat zone [28].

The other commonly used commercial heat source for splicing fibers is termed filament fusion, and is based on a resistively heated element. At the temperatures required there are very few options for refractory metals, and historically tungsten has been used as it has the highest melting point at 3410C. In order to achieve a uniform heat zone around the fiber and yet still allow for the spliced fiber to be removed, a ribbon shaped into an inverted Omega is typically used, Fig. 12. While tungsten does have a very high melting point, it does oxidize, and therefore an inert purging gas (typically argon) must suround the filament. As with the arc fusion method, the fiber is predominately heated by conduction from the surrounding environment. Because of the need for a purging gas, filament fusion is typically not used in field splicing applications. It does however, offer significant advantages in control and consistency over arc dischage, and can be more readily scaled to larger diameter fibers and bundles. In fact, a resistive heating element is what is typically used in fiber draw towers to fabricate fiber in the first place.

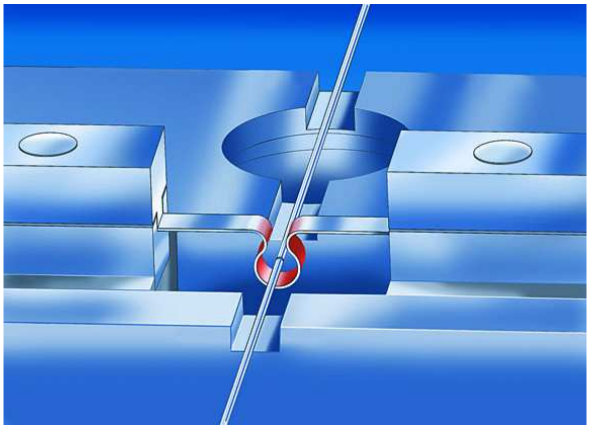


Fig. 12 Schematic of Ω shaped filament for fiber fusion

In addition to arc and filament, two other classes of heat sources are also potential choices for fusion splicing and glass processing: flame and laser. While not used on commercial fusion splicing equipment, the flame method is commonly used in the fabrication of telecom couplers. Here either a direct flame, such as propane or oxy-hydrogen can be used, or, in order to tailor the heat zone and minimize perturbances due to the gas flow, a flame can be used to heat a “crucible” that surround the fiber. Flame fusion, while perhaps a bit more challanging to work with, can provide very good flexibility and long term stability. The final heat source option is that of a laser. Because silica based fibers are of such high purity and transparance in the visible and near infrared, the best choice for laser fusion appears to be CO2, which at a wavelength around 10 microns is well absorbed by silica. Since the fundamental heating method of laser fusion is by radiation, the thermal dynamics are very unique comapred to arc, filament or flame. This presents some challenges to the sucessful implimentation of laser fusion.

One of the major considerations in the choice of heating method for fiber laser components is the fact that the outside surface of the fiber or component may “see” some extremely high power levels. Even very minute levels of contamination left on the surface of the glass may act as local absorbers that can create very large thermal loads. For example, deposits either from the electrodes of an arc splicer, or from the heating element of a filament splicer, can cause local hot spots on the surface of the fiber. While the loss induced by such deposits may be almost unmeasurable, the local thermal loads can be extreme.

4.2 Glass Processing

There are many varied requirements for a glass processing system for the fabrication fused fiber components. As discussed above, the heat source must be extremely well controlled, uniform and “clean”. The heat source must also be able to be tailored in size for the application at hand. For example, a very wide heat source may be ideal for certain tapering applications, but would be almost impossible to use for some a splicing application. Recently, a filament fusion method based on a graphite element has been developed to address some of these demands. The graphite runs very clean over a wide range of operating conditions and has been demonstrated to have minimal heating effect on the processed fiber. In addition, because the graphite is machined and not formed, it can be fabricated in a wide variety of shapes, including almost completely circular as shown in Fig. 13. While this closed loop design is not practical for splicing together long lengths of fiber, it does provide very uniform heating around the diameter of a fiber or bundle, and is very useful in component fabrication where the device can typically be slid out through the graphite loop.

Because of the wide range of techniques that may need to be implemented on a glass processing system, flexibility is probably the single biggest key. High resolution, core-imaging optics and precision alignment stages are critical for splicing applications. For non-circular fibers and bundles, the ability to view and orientate (rotate) the fiber based on its end-view is also of great benefit for accurate core imaging or PM alignment. It is also very beneficial to have some form of adjustable registration between the glass processing system and the cleaving system. This greatly simplifies the fabrication of end-caps for example, where a fiber is cleaved, the end-cap material is spliced on, and then the fiber is returned back to the cleaver for a prescribed re-cleave (end-cap) length. An example of a commercial glass processing system is shown in Fig. 14. Based on the taper ratio formula, Equation 3, a very convenient computer taper interface can be established where it is a simple matter of defining the physical taper characteristics, Fig 15. The correct process conditions can then be dialed in by monitoring the tension in the fiber during the tapering process. This tension monitoring is especially beneficial for bundle applications where the degree of collapse needs to be tightly controlled.

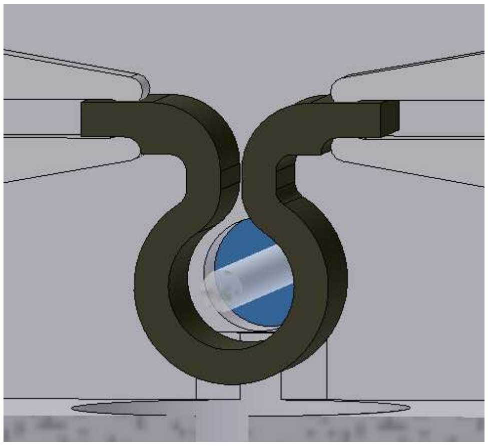


Fig. 13 Circular graphite filament

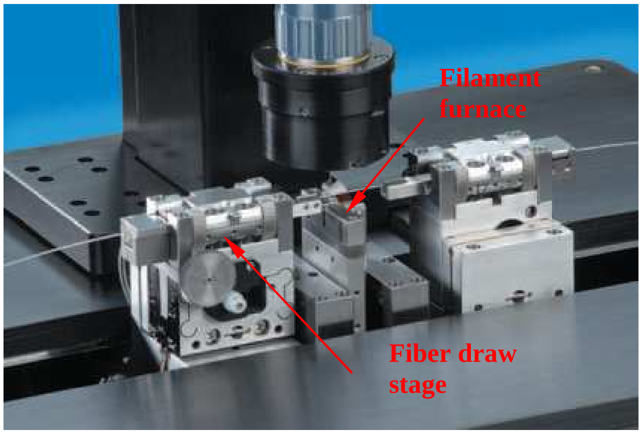
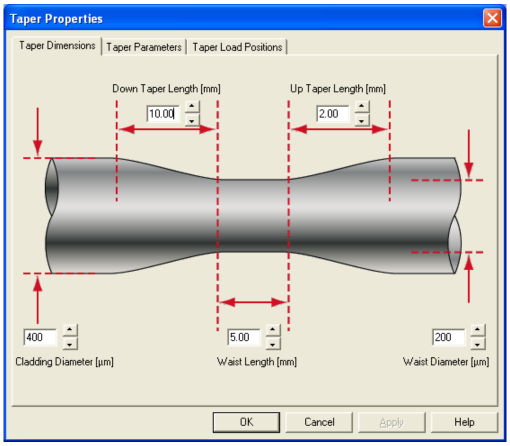


Fig. 14 Glass processing system for fabricating fused fiber components



Down Taper Length [mm] 10.00
Up Taper Length [mm] 2.00
Cladding Diameter [µm] 400
Waist Length [mm] 5.00
Waist Diameter [µm] 200

Fig. 15 Computer taper interface

5. CONCLUSIONS

Fused fiber components are essential for realizing the full potential of fiber laser systems. Low loss transmission of the light through these components is essential for manufacturing high performance and reliable fiber lasers. It is essential to ensure that any modal transitions (both thermal diffusion and physical taper) are adiabatic and that modal properties are matched between dissimilar fibers. Optical design of the fused components and optimization of the fusion process are critical to achieving optimal performance. In addition, glass processing hardware needs to have significant flexibility to address the manufacturing challenges associated with the fabrication of fused fiber laser components.

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