

Core Alignment for Large Mode Area (LMA) Fibers

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ABSTRACT

Large mode area (LMA) fiber types are widely used in many different fiber laser systems. Since the core diameter of an LMA fiber is generally larger than the mode field diameter (MFD), LMA fibers can carry a few higher order modes (HOM). When LMA fibers are spliced together (such as a splice of a passive LMA fiber to an active LMA fiber) if the cores are not well aligned it may result in beam shape deterioration and downstream fiber over-heating. An appropriate core alignment method for fusion splicing of LMA fiber is thus essential for the fiber laser manufacturing process, especially for multi-kW systems. A recent study on LMA fiber core alignment is reported in this paper and has been implemented in new firmware available for FSM-100 series fusion splicers.

Keywords: LMA fiber, Core alignment, Fusion splicing, Fiber laser system

1. INTRODUCTION

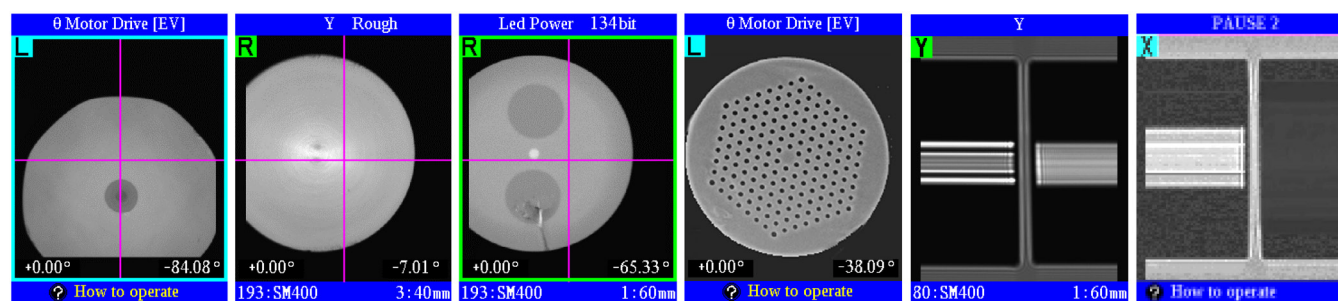
LMA fiber types are widely used in many different fiber laser systems. Since the core diameter of an LMA fiber is generally larger than the mode field diameter (MFD), LMA fibers can carry a few higher order modes (HOM). When LMA fibers are spliced together, if the cores are not well aligned it may result in beam shape deterioration and downstream fiber over-heating. An appropriate core alignment method for fusion splicing of LMA fiber is thus essential for the fiber laser manufacturing process, especially for multi-kW systems. A recent study on LMA fiber core alignment is reported in this paper. New functions and algorithms that enable core alignment of LMA was developed and implemented in commercially available fusion splicers (FSM-100 series).

Fiber lasers have become increasingly important for a wide variety of applications. As developments in fiber lasers have evolved, higher output power has been achieved and fiber laser efficiency has become more important. Large mode area (LMA) fibers are widely used in many different fiber laser designs and are well suited for high power fiber lasers. The core diameters of LMA fibers are typically quite large as compared to conventional single-mode fibers, and alignment of LMA fiber cores has been challenging. Most fusion splicers in the current market have been designed for telecom splicing applications. While some of these telecom fusion splicers are only capable of aligning the fiber cladding (e.g., ribbon splicers utilizing a fixed V-groove passive alignment system), true core alignment telecom splicers are available. These core alignment splicers are in widespread use and provide the capability of aligning the cores of SMF fibers to a sub-micron accuracy. However, as these splicers have been designed for telecom network applications, the core alignment capability only functions properly with standard telecom single-mode fiber types. For LMA fibers, using the existing core alignment algorithms results in either an error message, or random, inconsistent, and unreliable core alignment.

New functions and algorithms that enable core alignment of LMA and multi-mode fiber (MMF) have recently been developed and implemented in commercially available fusion splicers. The new core alignment functions have been verified in different labs and are now being utilized in fiber laser production facilities by updating the firmware in FSM-100 series fusion splicers. In this paper, explanation of the different algorithms for the LMA fiber core alignment is provided, as well as discussion of the different verification methods of core offset at the splice point for different LMA fiber types, including GDF, YDF, EYDF, and TDF with round or octagonal cladding shapes.

1.1 LMA fiber types

There are many different LMA fiber types, such as passive (e.g., GDF, GSF, etc. with round cladding shape), active (e.g., YDF, EYDF, TDF, etc. with octagonal cladding shape), polarization maintaining (e.g., PLMA with Panda stress rods), and photonic crystal fiber (PCF) [1-3]. A few typical LMA images from a splicer (FSM-100P+) end-view system are shown in Figure 1. Their typical properties are compared with standard SMF in Table 1.



(a) TDF 20/400 EV (b) GDF 25/400 EV (c) PLMA 20/400 EV (d) PCF EV (e) TDF to GDF SV (f) PLMA to PCF SV

Figure 1 – End-view (EV) and side-view (SV) images of typical LMA fibers captured from a splicer (FSM-100P+).

1.2 Comparison of splicing properties between SM and LMA fiber types

For aligning the cores before splicing, most factory splicers are equipped with a side-view (SV) and/or end-view (EV) imaging system. From Figure 1, we can see that the GDF and TDF (and similar YDF and EDF) fiber cores can theoretically be aligned by either SV or EV imaging processing, while PLMA and PCF can only be aligned using EV system. Since the EV system is much less popular than the SV system due to its cost, the discussion in this paper is focused on core alignment using the SV system. Due to the major differences in the properties of SMF versus LMA fibers, the corresponding splicing properties are also very different. A comparison of the differences is summarized in Table 1.

Table 1 – The major differences of fiber properties and splicing concerns between SMF and LMA fibers.

COMPARISON BETWEEN SMF AND LMA FIBERS	SMF	LMA
Allowed core to cladding concentricity error	0.5 μm	1.5 μm
Maximum core offset when cladding is aligned	1.0 μm	3.0 μm
Typical accuracy requirement for core alignment	0.2 μm	1.0 μm
Problems induced by core misalignment at the splice	Coupling to cladding	Coupling to HOM & cladding
The light coupled from fundamental mode	Dissipated	Travels in the core & cladding
System impact resulting from core misalignment	Power loss & fiber heat	Bad beam shape & fiber heating

2. THE PROFILE ALIGNMENT SYSTEM

The profile alignment system (PAS) was developed more than 30 years ago [4] for aligning the cores of SMF types with a side-view imaging system to observe either cold fibers or warm fibers [5]. The PAS core alignment method has been widely used for many different fiber types which have a smaller core diameter (< 12 microns), such as traditional SMF G.652, non-zero dispersion shifted fibers G.655, low-loss pure-silica core G.654, as well as bend-insensitive G.657 fiber types. Recently the PAS algorithms have been improved to extend core alignment capability to LMA as well as MMF fibers [6]. An explanation of the PAS system function is useful for understanding of the basic technology of this study.

2.1 PAS optical system structure

A PAS splicer utilizes two orthogonal optical paths to observe the fibers. These two optical observation axes are perpendicular to the axis of the fiber and are commonly referred to as the “X” and “Y” axes (where “Z” is the axis of the fibers). The PAS system is introduced in detail [7] and shown in Figure 2 (with illustration of implementation with a standard G.652 SMF) as background knowledge to this study for LMA fibers.

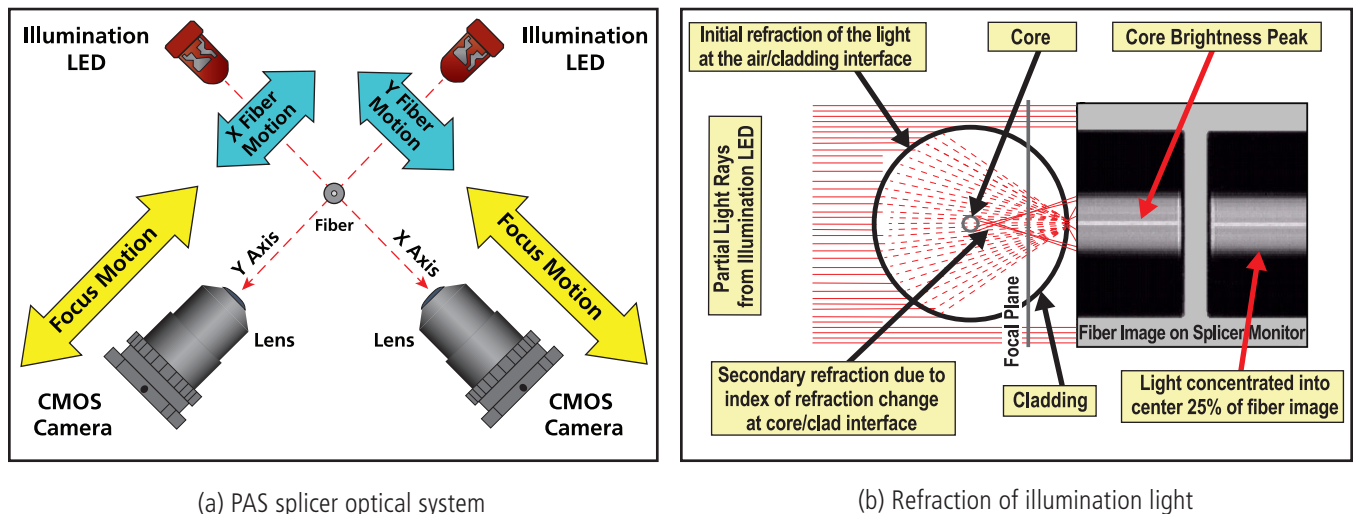


Figure 2 – The profile alignment system (PAS) and refraction of illumination light in a side-view PAS optical system [7]

Each optical axis consists of a high-resolution camera and lens on one side of the fiber, and an illumination LED on the far side of the fiber to provide collimated light which passes transversely through (or above and below) the fiber. The camera and/or lens are motorized to enable precise focusing capability, which is essential to detection and alignment of the fiber cores. If (a) the X/Y motion is finely controlled (as well as camera focus motion), (b) the resolution of the optical system is sufficient, and (c) the alignment algorithms are sophisticated, core alignment to within 0.1 μm is achievable with standard telecom single-mode fibers.

As the collimated light from the illumination LED enters the fiber, it bends (refracts) through an angle that is dependent upon the difference in index of refraction between air and glass, and the incident angle. Hence, the illumination light that enters the fiber toward the outer edge of the cladding refracts inwards at a greater angle than elsewhere due to the greater incident angle. In effect, the illumination light fans inwards radially toward the center of the fiber due to the higher refractive index of the glass cladding relative to air. This is illustrated in Figure 2 (b). For clarity, this figure shows only a single observation axis, and that axis is shown horizontally.

As the illumination light passes through the fiber, bending of the light path occurs anywhere a difference in refractive index is encountered. In Figure 2, a G.652 single-mode fiber with a very simple refractive index structure is shown. In this case, the only additional change in refractive index within the fiber is at the interface between the pure silica cladding and the higher index Germanium-doped core. At this point, secondary refraction of the light occurs. The refraction is again radially inward toward the center. The position of the camera and lens focal plane is optimized to achieve an image pattern that enables detection of the position of the single-mode fiber core relative to the cladding. In the fiber image (as seen on the right side of Figure 2) the radial inward bending of the illumination light concentrates all the light that entered the fiber from the splicer’s LED into the center of the fiber. Therefore, the outer part of the fiber image is completely black. Typically, the focus position is chosen such that the illumination light is concentrated into an area approximately 25% of the fiber diameter for a G.652 standard fiber. The ratio of the bright width of the center area relative to the entire fiber cladding diameter is

normally known as Focus Width or Focus Ratio. For the best core alignment accuracy, the Focus Ratio must be optimized for different fiber types. For example, the best Focus Ratio for the fiber type used in Figure 2 is 0.25, i.e., 25%. The secondary bending of the illumination light at the fiber's core/cladding interface produces a brightness pattern with a very sharp peak brightness near the center of the bright (concentrated light) region. Detection of this peak brightness position indicates the position of the fiber core for a G.652 standard fiber.

2.2 Brightness intensity profile and core alignment

Figure 3 shows the representative brightness intensity profile from a single vertical scan line from the splicer camera image plotted below the corresponding fiber image. This vertical scan line is plotted horizontally, with the vertical axis representing relative brightness. The background brightness of the illumination LED is therefore to the right and left of the fiber in the brightness intensity profile. In the bright area of the brightness intensity profile, the brightness peak(s) shows the core position, whereas the outer edge of the totally dark region shows the position of the outer cladding.

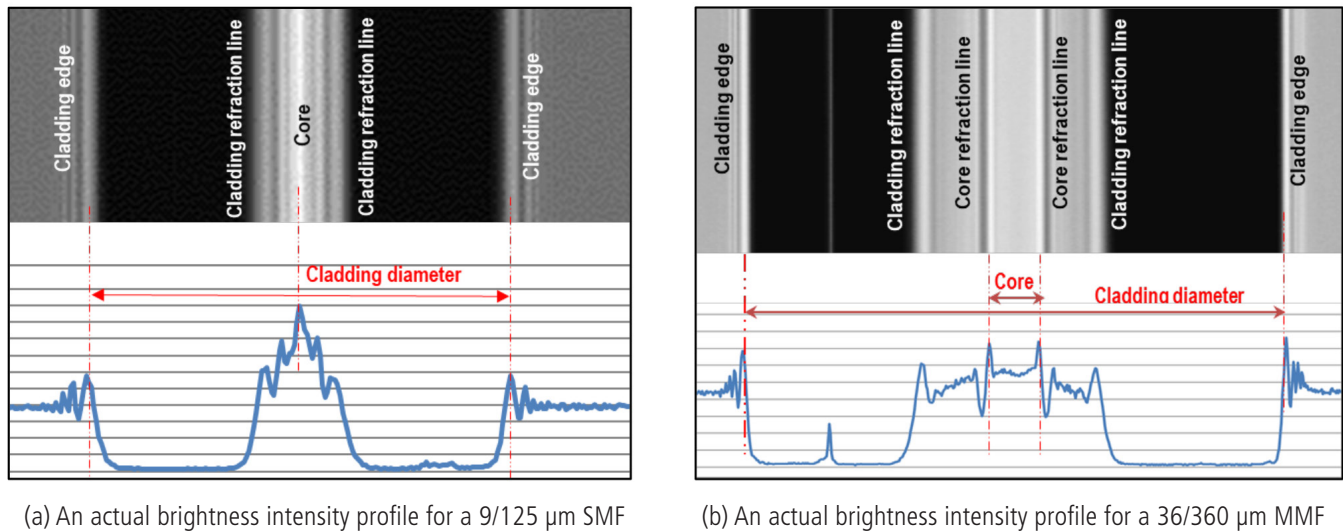


Figure 3 – Brightness intensity profiles of SMF (a) and a MMF (b). The fiber images (rotated to vertical orientation) are shown above the corresponding brightness intensity profiles for each fiber type.

The typical brightness intensity profile for a standard G.652 telecom SMF is shown in Figure 3 (a) and the quite different profile for a MMF is shown in Figure 3 (b) together with their camera images above each brightness intensity profile. An actual brightness intensity profile may have significant noise due to dust on the fiber surface and electronic signal interference. In practice, multiple brightness intensity profile data plots (at different locations along the length of both left and right fibers and in both X and Y camera views) are analyzed to average out the noise and enable extrapolation of the core position relative to the outer diameter of the fiber cladding.

Depending upon the fiber type, the bright area at the center of the brightness intensity profile may be more complicated. In some cases, there are multiple local brightness peaks, especially for LMA or MMF. This is often the case with fibers with more complicated refractive index profiles, such as fibers with a ring structure or a large core diameter. This complicates the analysis required for precise core alignment. In practice, while the PAS concept is relatively simple, successfully applying the PAS method to provide true, accurate, and high precision core alignment capability on a reliable and repeatable basis is difficult. The analysis and alignment algorithms must be sophisticated to properly deal with dust on the fiber, the variety of fiber types with various refractive index profiles (which result in a variety of brightness intensity profiles), the need to compensate for fiber core/cladding eccentricity (since during fusion splicing the

cladding of the heated and semi-molten fibers tends to self-center due to surface tension), and many other factors. Many fusion splicers which claim to provide core alignment capability are incapable of consistent and accurate core alignment.

2.3 Core alignment for LMA fiber types

The major design differences between SMF and LMA fibers are not only the large diameter of the LMA core, but also the lower refractive index difference between the core and inner cladding of the LMA fiber. In the case of a standard SMF, a well-defined brightness peak near the center of the bright area reveals the core position. The large core diameter of the LMA fiber results in a side-view image with two dark parallel lines but without a well-defined peak brightness line. The lower refractive index difference of LMA makes the core refraction line much dimmer than that of SMF and MMF structures and more difficult to distinguish from the background noise. A set of images of an LMA GDF 25/400 μm fiber at different Focus Ratios are shown in Figure 4 and a comparison and their corresponding brightness intensity profiles at different Focus Ratios are plotted in Figure 5.

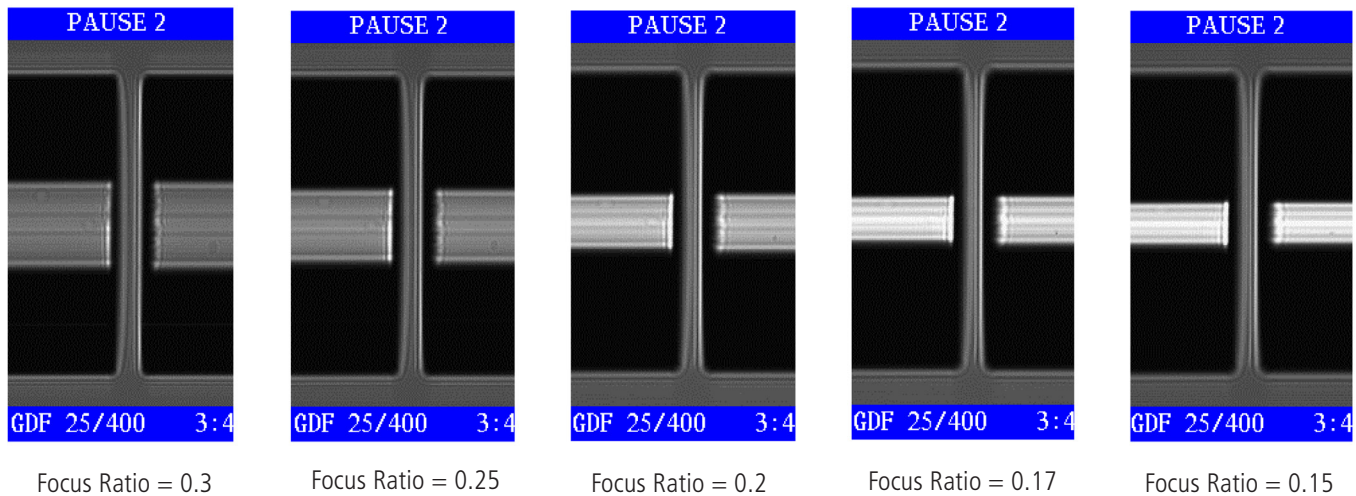


Figure 4 – Typical images for LMA GDF 25/400 μm taken with an FSM-100P+ splicer at different Focus Ratios.

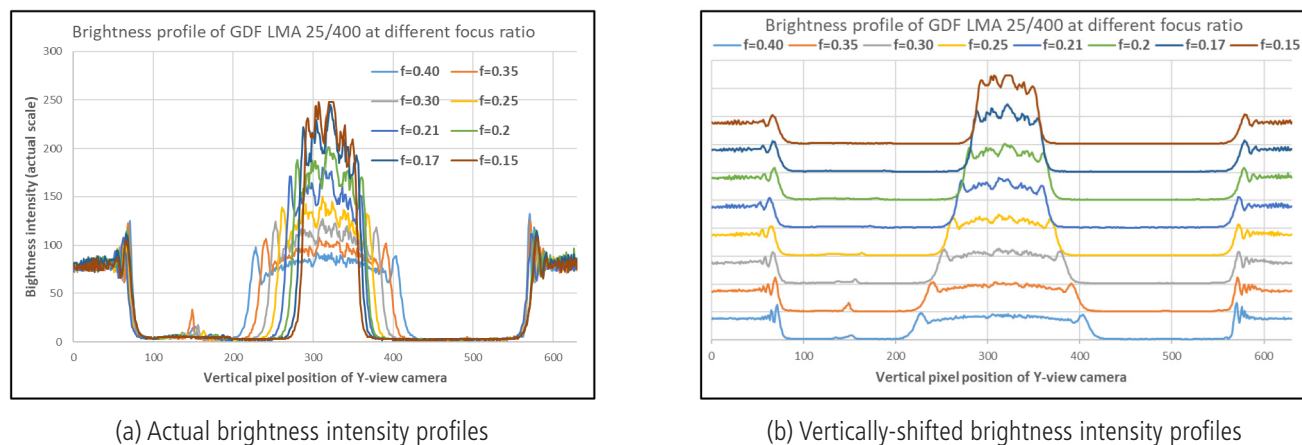


Figure 5 – Brightness intensity profiles of a group of images from LMA GDF 25/400 μm at different Focus Ratios. The profiles are shifted vertically in (b) to demonstrate the shape of the profiles more clearly for each Focus Ratio.

From Figure 5, we can clearly observe that the larger core diameter and smaller index difference of the LMA fiber induces more significant challenges for the core identification algorithm and also complicates optimization of the search routine used to determine the most suitable Focus Ratio for successful core alignment. Optimization is strongly fiber type dependent. For the LMA type shown in Figure 5, the two dark parallel lines of core refraction are getting closer and closer as the Focus Ratio drops from 0.3 to 0.2. A well-defined brightness peak near the cladding center can be recognized at a Focus Ratio = 0.17. At a smaller Focus Ratio = 0.15, the brightness intensity peak is truncated because the intensity value is over 255 for an 8-bit analog-digital converter, causing camera saturation. Therefore, the position of the brightness peak cannot be determined. By selecting a Focus Ratio = 0.17 in the splice recipe for this fiber, the conventional SMF algorithm for searching for the peak brightness intensity can be extended to provide core alignment of a large core LMA fiber.

3. VERIFICATION FOR A VALID CORE ALIGNMENT

To ensure that a splicer provides valid core alignment, the calculation accuracy of the core offset between the left-side and right-side fibers must be verified. There are a few methods for the verification, such as (1) a core offset repeatability test, (2) active loss measurement, and (3) plotting data for core offset versus fiber rotational position with the cladding aligned.

3.1 Core offset repeatability test

The core offset repeatability test is the most frequently used method to achieve a quick analysis of the quality of a core alignment algorithm. Using identical fiber types on the left and right of the splicer, alignment data is collected by either (a) performing core alignment while measuring cladding offset (misalignment) or (b) utilizing cladding alignment while measuring resultant core offset. Repetition (without re-cleaving or reloading the fibers) enables verification of the consistency and repeatability of the readings. For this test method, at least one fiber in the pair should have sufficient core-to-cladding concentricity error (CCCE) to enable measurements that are not in the noise level of the measurement system. Moreover, one of the fibers in the pair should be rotated to search for the maximum core offset between the left and right fibers. Some test results are shown below for four fiber types using the latest FSM-100 core alignment algorithm.

Table 2 – The repeatability error of the core offset after cladding alignment.

FIBER TYPE	CCCE (μm)	ROTATION ANGLE (DEG)	MEASURED CORE OFFSET (μm)	REPEATABILITY ERROR (μm)	SAMPLE NUMBER
SMF28 (G.652) 9/125 μm	L=0.2, R=1.3	L=0°, R=0 to 360°	Min=1.1, max=1.5, avg=1.4	STD (sigma)=0.10	63
LMA (G.654) 12/125 μm	L=0.1, R=0.7	L=0°, R=0 to 360°	Min=0.5, max=0.9, avg=0.8	STD (sigma)=0.25	26
LMA GDF 20/400 μm	L=0.7, R=1.5	L=0°, R=0 to 360°	Min=0.8, max=2.3, avg=1.5	STD (sigma)=0.23	91
LMA GDF 25/400 μm	L=0.6, R=0.6	L=0°, R=0 to 360°	Min=0.1, max=1.3, avg=0.8	STD (sigma)=0.25	240

3.2 Active loss measurement

Active loss measurement is very convenient for core alignment performance verification for SMF fiber types. The loss variation can be measured during the core alignment process by connecting one fiber to a stable light source and the other fiber to a power meter. If the core offset is correctly measured by the splicer, the measured loss should go to minimum when core alignment is performed, assuming the eccentricity correction function (ECF) of the splicer is disabled. However, this method does not work well if the CCCE of left and right fibers are both very small, since cladding alignment can achieve a similar result to that of core alignment. In the case of LMA fibers, the loss variation is small and difficult to measure for most LMA fiber types even if the core offset is more than 1 micron, as can be seen in Figure 6 on the following page.

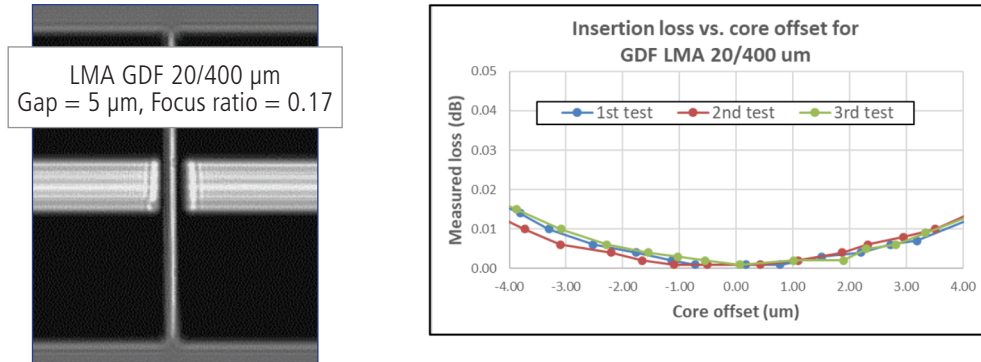


Figure 6 – Measured insertion loss at 1060 nm vs. core offset for LMA GDF 20/400 μm double clad fiber

If the fiber under test is a double clad fiber type, the connection of the laser to the fiber core must be aligned very precisely to avoid launching cladding modes. The output beam shape and numerical aperture should be measured. If cladding modes are launched, they should be removed with a cladding mode stripper. Although loss measurement may not be the best method to judge the quality of the core alignment for a large core LMA, it is stable and useful for a smaller core LMA fiber, such as an LMA 12/125 μm silica core fiber with CCCE 0.7 μm . In testing, 30 splices were performed with this fiber using core alignment. An average splice loss of 0.016 dB and a maximum 0.043 dB were achieved while using the core alignment algorithm. Since the theoretical predicted splice loss for cladding alignment is 0.07 dB, the capability of the core alignment method has been validated for this fiber. The splice loss distribution is illustrated in Figure 7.

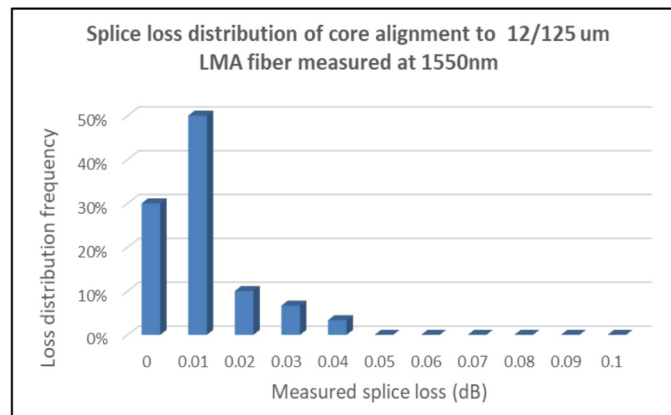


Figure 7 – Splice loss distribution of a 12/125 μm LMA fiber with CCCE 0.1 μm and 0.7 μm

3.3 Core offset versus fiber rotational position

By rotating the fiber on one side (such as the right-side fiber) step-by-step and measuring the core offset after alignment of the cladding, a curve of the core offset vs. the rotation angle can be plotted. Theoretically, this curve can be used to identify whether the core positions are correctly measured and how big the noise level is in the core recognition system.

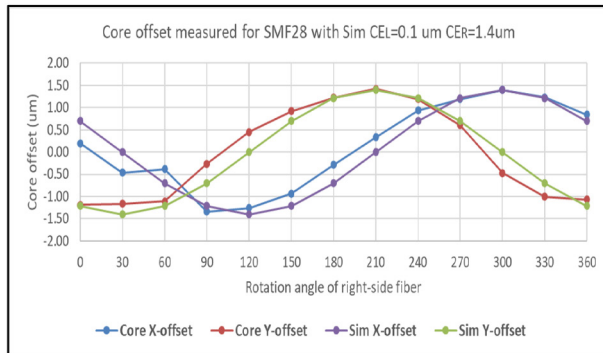
Assuming the concentricity error of the left and right fibers are CE_L and CE_R , the initial rotation angles of the left and right fibers are θ_L and θ_R , and the fiber on the right side is rotated to angle θ , after perfect cladding alignment the core offset δ may be simulated using the following formulas:

$$\delta = (\delta_x^2 + \delta_y^2)^{1/2}, \text{ where } \delta_x \text{ and } \delta_y \text{ are core offset in X-view and Y-view, respectively}$$

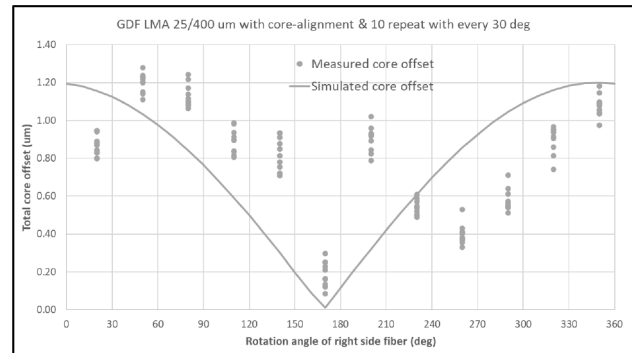
$$\delta_x = CE_L \cdot \cos \theta_L - CE_R \cdot \cos (\theta + \theta_R)$$

$$\delta_y = CE_L \cdot \sin \theta_L - CE_R \cdot \sin (\theta + \theta_R)$$

At every rotation step for the right-side fiber, the fiber cladding is re-aligned and the core offset is measured. The measured core offset values are compared with simulated curves for different fiber types and shown in Figure 8.



(a) Core offsets δ_x and δ_y in X/Y views for SMFs with concentricity errors $CE_L = 0.1 \mu m$ and $CE_R = 1.3 \mu m$



(b) Total core offset δ for LMA GDF 25/400 μm with concentricity errors $CE_L = CE_R = 0.6 \mu m$. The process was repeated 10 times to obtain the repeatability errors.

Figure 8 – Measured core offset compared with simulation for (a) SMF and (b) LMA fiber

Comparing charts (a) and (b) in Figure 8, we observe that the agreement between the measurement and simulation is much better for SMF than the LMA fiber. Other than the large core size and blurred core edges in the LMA fiber image (due to the low index difference between core and cladding as we have discussed), core non-circularity may also contribute to this discrepancy at a few rotation angles. In the simulation formula, the core position is assumed to be shown as a single peak brightness center line. This approximation is sufficient for the SMF side-view images. However, this is not true for LMA or MMF fiber types in which we must consider the two core edge lines (without a distinct center bright line). The larger the core size for LMA fiber, the larger the discrepancy will be relative to the simulation. Although the measured core offset data does not agree well with the simulation, the repeatability for the 10 measurements at each rotational position is quite good (with error in repeatability of $\sim 0.22 \mu m$). Considering this fact, we may consider a rotational core alignment method instead of the conventional X/Y core alignment. The benefit of the rotational core alignment is (a) there will be no cladding offset after splicing and (b) since there is no cladding offset, there is no self-centering (to eliminate cladding offset) due to

surface tension of the molten glass during fusion, and therefore this method does not introduce core deformation. However, the lowest core offset by the rotational alignment is the absolute difference between the left and right fiber concentricity errors $|CE_L - CE_R|$. If one of the two fibers has zero eccentricity error, independent of how large the concentricity error of the other fiber is, the misalignment of the fiber cores will be equal to that CCCE.

4. CORE ALIGNMENT FOR LMA FIBER WITH OCTAGONAL CLADDING

For most non-circular cladding LMA fibers, core alignment using side-view (SV) images is not possible since the core position is either not visible or not correctly measurable from both X and Y views. Random rotational orientation of the non-circular fiber shape relative to the splicer's SV camera system will result in random refraction of the splicer's illumination light that passes through the fiber, and therefore no consistent or discernible SV image will be achieved. The non-circular fiber will not produce a predictable and repeatable refraction of the illumination light (as will a circular fiber as illustrated in Figure 2). Octagonal cladding LMA is an exception. To measure the core position of an octagonal shape active LMA fiber, the fiber must first be rotated so that flat surfaces of the fiber face toward the splicer cameras, parallel to the focus plane. Before the core alignment process, an automated fiber rotation alignment method (IPA or IPA2 [8]) is applied to rotate the fiber to the correct rotational orientation. The typical IPA2 profile for octagonal fiber is shown in Figure 9 (a) for the rotational alignment to enable core recognition. Side-view images of an LMA TDF 20/400 μm (left fiber) to an LMA GDF 20/400 μm (right fiber) are shown in Figure 9 (b) and (c).

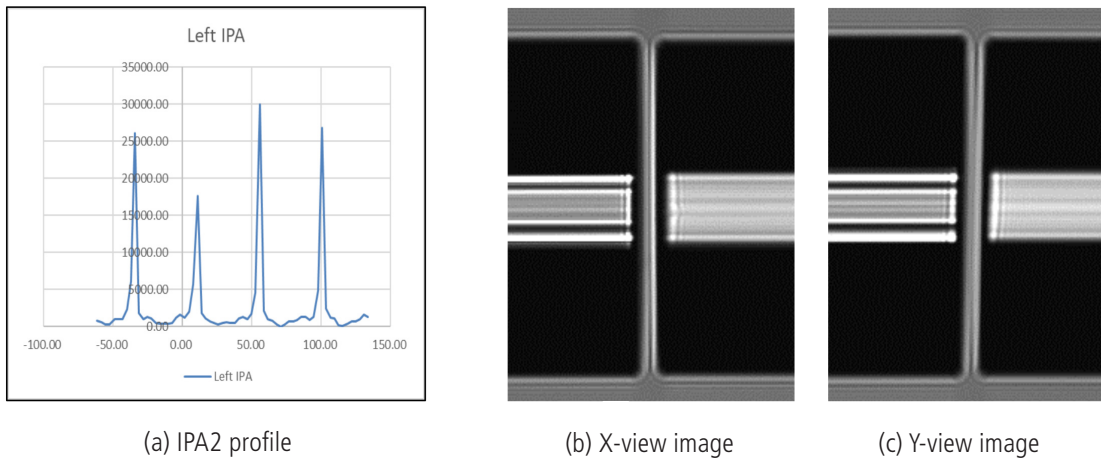
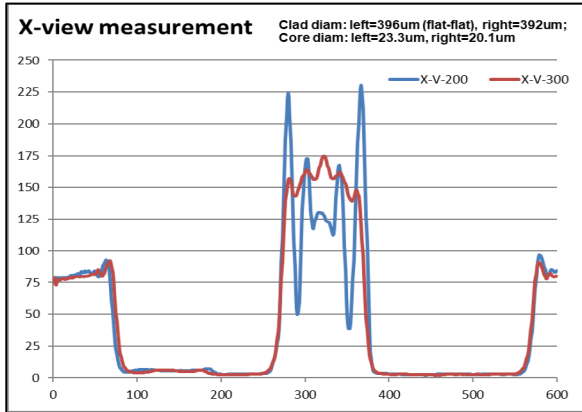
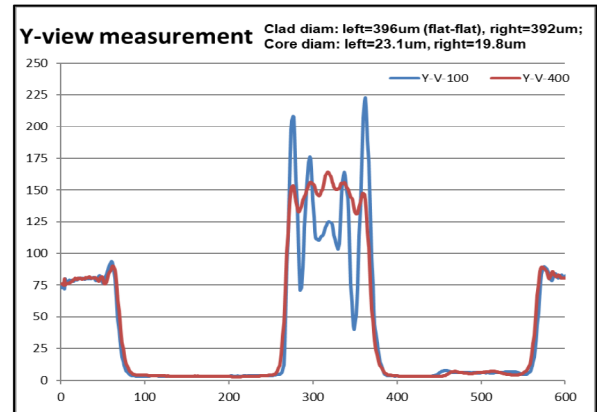


Figure 9 – IPA rotational profile for octagonal fiber, and X/Y camera images for an octagonal LMA TDF 20/400 μm (left fiber) and round LMA GDF 20/400 μm (right fiber) after core alignment

Brightness intensity profiles of the octagonal left fiber (blue data plot) and the round right fiber (red data plot) are shown in Figure 10 (a) and (b) for the X-view and Y-view, respectively, with fiber diameter data measured from the profiles by image analysis. The end-view image of this octagonal fiber is shown in Figure 1 (a).



(a) Profiles of left and right fibers for X-view alignment



(b) Profiles of left and right fibers for Y-view alignment

Figure 10 – Brightness intensity profiles for octagonal LMA TDF 20/400 μm (left fiber, blue data plot) and round LMA GDF 20/400 μm (right fiber, red data plot) after core alignment for both X and Y camera views

5. SUMMARY

Core alignment methods of the profile alignment system (PAS) have been studied for different types of LMA fiber and compared with SMF types. Due to the major differences in the fiber design of the LMA compared to SMF (especially the LMA fiber's large core diameter, the low refractive index delta between the core and the cladding/low NA, and the dimmer core refraction lines in the PAS images), the core alignment of LMA fiber types is much more challenging than that for SMF. In the different verification studies for our core alignment methods for LMA fibers (including core offset repeatability, active loss measurement, beam shape measurement, and core offset versus fiber rotational position tests), we conclude that the capability for core alignment for LMA fibers with side view PAS has been achieved, but with much lower accuracy compared to that for SMFs. Since our labs are not equipped with multi-kW high power laser systems, we have not studied issues relative to fiber heating due to LMA fiber core misalignment. Such testing will no doubt be performed by fiber laser manufacturers as they implement the new LMA core alignment capability into their fiber laser production activities.

The newly developed core alignment function for LMA fibers has been released into the splicer firmware for FSM-100 series splicers in response to the market requirements, especially the needs for manufacturing fiber lasers. Further studies concerning the improvement of the image processing, algorithms, focus automation, etc. are continuing for additional fiber types, as well as study of the robustness in fiber laser production use. These methods will be further refined and introduced into future splicer types especially used for fiber laser industry.

REFERENCES

1. T. Feng, et al., "Arc fusion splicing effects in large-mode-area single-mode ytterbium-doped fibers," *APPLIED OPTICS*, Vol. 52, No. 32, 10 November 2013. pp. 7706-7711 (2013).
2. C. Jollivet, et al., "Design optimization of Tm-doped large-mode area fibers for power scaling of 2 μ m lasers and amplifiers," *Proc. SPIE*, Vol. 10083, 100830I-1 (SPIE LASE, 2017).
3. L. Xiao, et al., "Fusion Splicing Photonic Crystal Fibers and Conventional Single-Mode Fibers: Microhole Collapse Effect," *JLT*, VOL. 25, NO. 11, NOVEMBER 2007, pp. 3563-3574, (2007).
4. T. Yamada, et al., "Arc fusion splicer with profile alignment system for high-strength low-loss optical submarine cable," *JLT*, VOL. 4, NO. 8, pp. 1204-1210, (1986).
5. W. Zheng, et al., "Core alignment technique based on image processing of warm fibers," *Optical Fiber Communication Conference 1992*, Th15, p. 230, (1992).
6. W. Zheng, "Control system and method for aligning multimode optical fibers," US Patent 10,996,397 B2, May 4, 2021, <https://patentimages.storage.googleapis.com/2f/02/33/4965427a456eae/US10996397.pdf> (2021).
7. D. Duke, et al., "Issues Concerning Dissimilar Single-mode Splicing," *Proceedings of the 66th IWCS*, 2017, pp. 648-656, (2017).
8. W. Zheng, et al., "Interrelation Profile Analysis Method for Alignment of Polarization-Maintaining Fiber," *OFC/NFOEC2010*, March 25, (2010).



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