Heating Power Feedback Control for CO_2 Laser Fusion Splicers

Wenxin Zheng, Hiroshi Sugawara, Toshirou Mizushima, William Klimowych

Abstract

A novel feedback control method has been developed for an automated splicer using a CO_2 laser as the heating element. The feedback method employs a sensor for laser beam power and CMOS cameras as sensors for fiber luminescence which is directly related to glass temperature. The CO_2 laser splicer with this type of feedback system provides a consistent platform for the fiber laser and bio-medical industry for fabrication of fused glass components such as tapers, couplers, combiners, mode-field adaptors, and fusion splices. With such a closed loop feedback system, both splice loss and peak-to-peak taper ripple are greatly reduced.

Keywords: CO_2 laser splicing, Fiber laser, Fused glass components, Specialty fibers, Controllable glass heating

1. Introduction

Fabrication consistency of fused glass components, such as tapers, couplers, combiners, mode-field adaptors, and fusion splices is critical to the fiber laser industry and bio-medical industry. Due to very high laser powers (in a range from 100 W to 50 kW, see [1-2]) carried by optical fibers, any imperfection in fiber splicing or glass treatment, impairment of fiber coating, and deposits on the fiber surface may cause large power leakage as well as a possible fire hazard and failure. Research of heat source methods for fiber splicing and glass processing has been an ongoing effort for decades. Many different methods have been investigated and commercialized [3-5]. The common heat sources are: flame, arc discharge, filament, and CO_2 laser. These methods are summarized and compared in the following table.

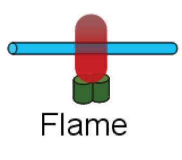
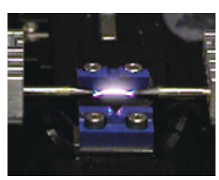
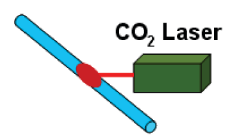
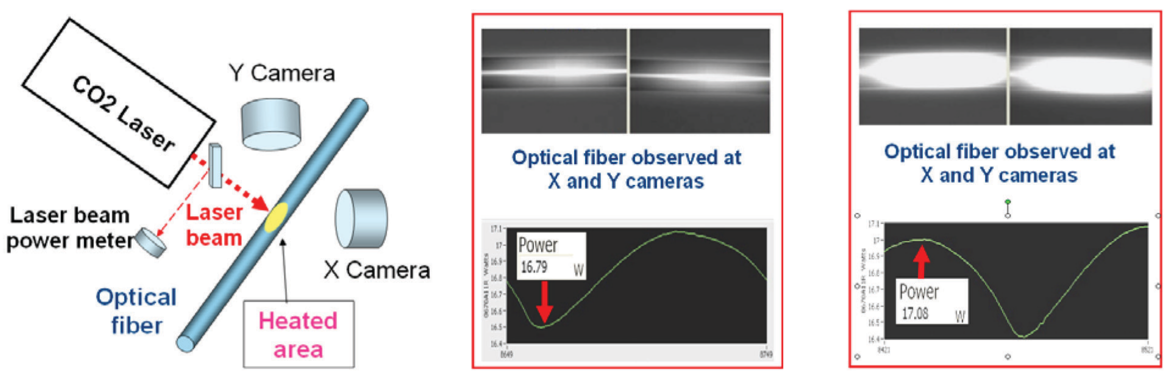
				
METHOD	Flame Torch	Electrode Arc Discharge	Filament Heater	CO_2 Laser
YEAR INTRODUCED FOR FIBER HEATING	Late 1960s	• 2 electrodes—1970s • Multiple electrodes—mid 1980s by NTT	1980s by Vytran and Fujikura	Late 1980s
PRO	Wide heating range (~5 mm)	No need for gas supply	No need for high voltages	Cleanest with no deposits on fiber
CON	Need gas supply system for flame	• Need to clean electrodes after every taper if fiber OD >1.5 mm • Deposit on fibers when electrodes are not clean	• Need change filament after ~50 min of use • Max single run time for tapering is 1 min (un-cooled) • Filament may deposit on fiber • Filament alignment issues	Need eye safety and other considerations

Table 1—Summary and comparison of different heating methods for fusion splicers and glass processors

After more than 10 years of study and research at Fujikura and AFL labs, we have concluded that fusion splicers using CO_2 laser heating can provide consistent operation that is contaminant free from metal oxide particles, requires little maintenance due to the absence of electrodes or filaments, possesses an accurate and adjustable heating area, and exhibits uniform heating by absorption of CO_2 laser energy. However, the typical 5% beam power variation found in most CO_2 lasers provides a significant challenge in the production of low ripple tapers and low loss splices. In this article, we are going to discuss a novel approach to greatly improve power stability in CO_2 lasers.

2. Technologies for CO_2 Laser Feedback Control

As shown in Fig. 1 (a), CO_2 beam power variation can be measured simultaneously using a laser beam power meter and a pair of CMOS cameras. Two percent of the laser beam power is sampled for monitoring using a high speed power sensor. The light emitted from the heated fiber is captured by the cameras and the images are processed using a fast CPU board. From Fig. 2 (b) and (c), we can clearly observe that the luminescence of the heated fiber varies tremendously even for a 2% beam power variation. Simultaneous measurement allows both the beam detector and the cameras to be employed as sensors to form two complementary closed-loop feedback methods. The laser beam power detector is very sensitive and has an extremely short response time, but it does not reflect the actual fiber temperature. It works by itself regardless of the fiber appearance in the machine. On the other hand, fiber luminescence monitoring using cameras and the associated image processing has a longer response time due to the image processing latency. This method does, however, directly reflect the fiber temperature during the glass processing. A proper combination of these two feedback control methods has been found to produce a very stable CO_2 beam output at a desired fiber temperature.



(a) (b)

Fig. 1—Measurement setup for CO_2 laser beam power variation

Feedback from the laser beam power detector can regulate the beam power stability. Camera feedback can regulate the beam power level to establish the desired temperature at the glass rod when using an automated splicer. A comparison of measured laser output power with and without the feedback control system is shown in Fig. 2.

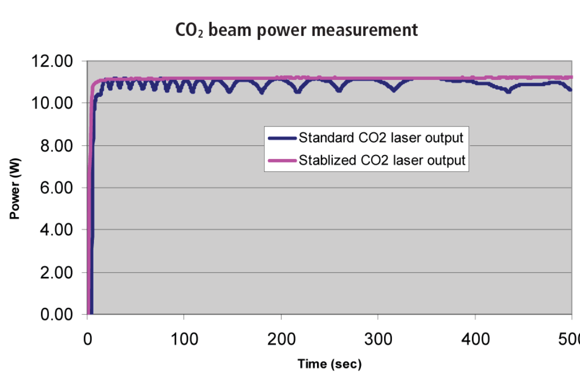


Fig. 2—Comparison of measured CO_2 laser beam power with and without feedback control

3. Feedback Control for Splicing

Based on the feedback control system discussed in the previous section, a splicer utilizing CO_2 laser as heating element, the LZM-100 LAZERMaster (shown in Fig. 3), has been developed and is commercially available. To ensure safety, the CO_2 laser beam of this machine is contained within an enclosure using a triple redundant interlock system. It meets TUV Class 1 laser safety certifications. Protective eyewear is not required when operating this machine. Since the laser power has a very large controllable range, we can automatically splice or process fiber or glass rod from a few microns up to 2.3 mm in diameter.

Fig. 3—LZM-100 LAZERMaster CO_2 laser splicer with 150 mm taper range and up to 2.3 mm fiber diameter capability for automatically fiber aligning, splicing and heat processing.

With traditional fiber splicers, there are many different methods available for power calibration such as the meltback method, the cladding offset reduction method, etc. [6-8]. With the CO_2 laser as the heating source, we can easily adapt those existing calibration methods without using the camera image feedback control. However, the beam detector feedback control is necessary. Without this control, at the moment the fibers touch during the splicing process, the fiberend temperature will be random due to the typical 5% beam power variation. If the fiber ends are too hot, they will result in slight meltback, and will neck down at splicing point. If the fiber-ends are too cold and therefore rigid, once they make contact, an angle between the two fiber axes will be generated. In both cases, high splice losses will be observed.Splice test results for SMF28 fiber are shown in Fig.4. It can be seen that the feedback controlled CO_2 laser exhibits remarkable stability and consistency.

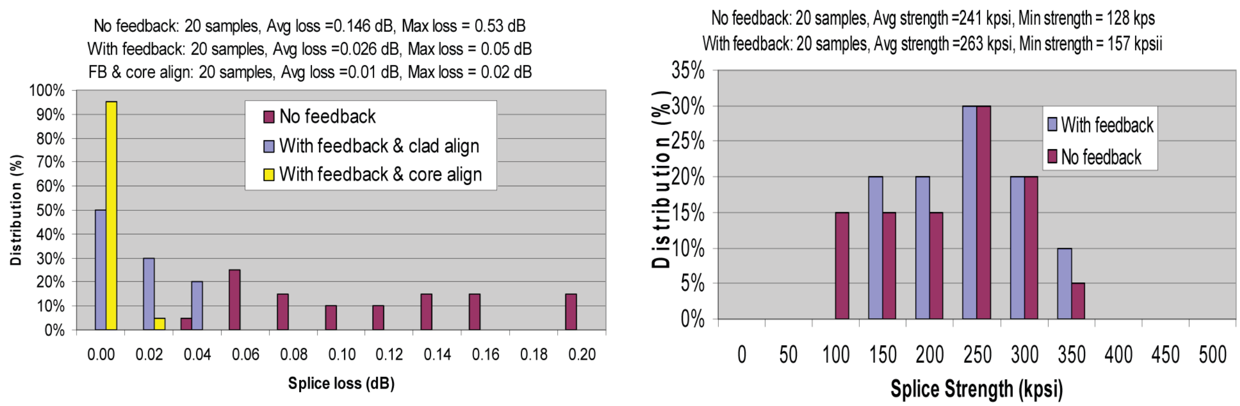


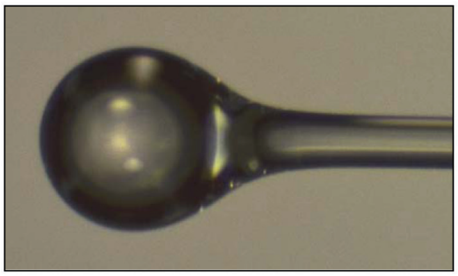
Fig. 4—SMF28 splice loss and strength comparison. Without feedback control, max splice loss is 0.53 dB. With feedback control, max splice loss is 0.05 dB for cladding alignment and 0.02 dB for core alignment. Splice strength is not greatly impacted by feedback control.

With the feedback controlled CO_2 laser, it is possible to splice fibers with extremely large diameter differences. For example, splicing a 2 mm diameter end-cap glass rod to a 0.125 mm diameter LMA fiber is a tremendous challenge for all conventional heating sources. In order to soften the 2 mm rod, very high power must be applied. But high power may completely melt the 125 µm fiber, vaporizing the fiber or creating a ball end. On the contrary, this type of splice is a relatively straightforward process when using the CO_2 heating source. The fiber heating mechanism of a CO_2 laser is fundamentally different from all other heating methods such as flame, arc discharge, and filament. The silica based optical fiber is heated by its absorption of the 10.6 um wavelength CO_2 laser energy, while all other heating methods use radiation and heat conduction. A large diameter fiber has a larger absorption surface, while a small diameter fiber has a smaller absorption surface. Thus, the power of the CO_2 laser does not need to be so different when splicing two fibers with different diameters. The splice of 2 mm glass rod to 125 µm fiber is illustrated in Fig. 5.

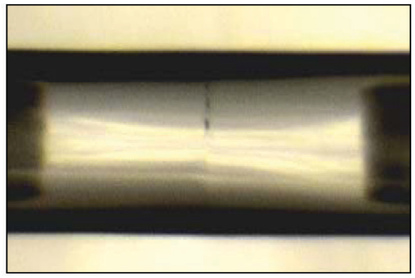
Before Splicing | **During Splicing** | **After Splicing** | **From Microscope**

Fig. 5—Splicing SMF28 (125 µm) to a 2 mm glass rod using the LZM-100. The left 3 images are captured directly from the LZM-100. The warm fiber image taken during splicing shows the two fibers are heated evenly. The right hand picture was taken with a microscope after splicing.

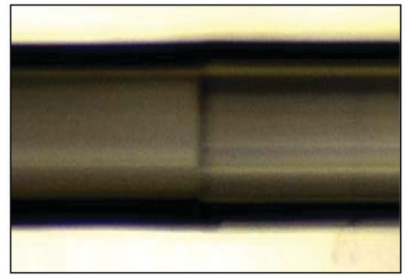
Under feedback control, CO_2 laser power is very stable throughout the entire adjustable range. With this large dynamic range, we are able to make a ball lens with ball diameters up to 2.5 mm, as well as having the ability to splice heatsensitive fibers with a much lower melting point (less than 700°C). Photonic crystal fiber (PCF) can also be spliced easily with or without collapsing the air hole depending on the desired applications. Some examples are shown in Fig. 6a.



Ball lens made with very high laser beam power



PCF spliced with hole collapsed using moderate laser power



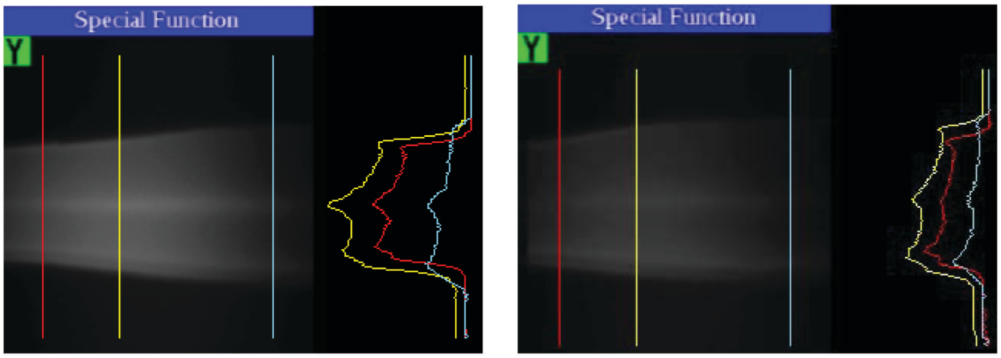
PCF spliced without hole collapsed using very low laser power

Fig. 6a—The large dynamic range of the stabilized CO_2 laser in the LZM-100 is easily adapted to different applications.

4. Feedback Control for Tapering

Fiber tapering is one of the key processes when making combiners, mode field adapters (MFA), fiber sensors, and fiber probes. During tapering, the fiber diameter varies by controlling the pulling and feeding speed of the motors. Thus, the heating power must also vary with the fiber diameter to balance the heating process. Overly heated tapers exhibit large ripple or kinking and may introduce high loss. Insufficient heating power results in lower tensile strength and higher stress. To accurately control heating power, we need to find a reliable and consistent method to measure the relative fiber temperature. As discussed in Sec 2, the fiber temperature can be indirectly measured by the brightness of the warm fiber image via the cameras in the LZM-100. On the other hand, it can also be indirectly measured by the load-cell in the machine which can monitor the fiber softness during heating and tapering.

The warm fiber images are used extensively in the power control for fiber splicing and loss estimation in conventional splicers (see [8, 9]). The brightness of light emission from heated fiber is directly related to fiber temperature and dopant material inside the fiber. In Fig.6b, two warm taper images (WTI) are shown with brightness profiles plotted on the right side of the images. The higher the laser beam power, the higher the maximum brightness value observed. However, it is important to pay attention on the digital images. Since auto gain control is employed in most cameras to avoid image saturation, the brightness of the different images will not reveal the correct fiber temperature unless the gain level of the camera is known when the images are taken. To properly control the fiber temperature, the auto gain control of the camera should be switched off, and the camera gain or exposure time should be controlled by the laser power feedback system. This is important for WTI feedback control since most tapering is performed at a very low power to reduce taper ripple. Without properly setting the camera gain and exposure time, the WTI images appear either very dark or very bright and saturated, and are therefore not usable.



Tapering with higher power **Tapering with lower power**

Fig. 6b—SMF28 (125 µm) during tapering with different power levels in the LZM-100. The vertical straight lines are cursors showing the positions where the image brightness is measured. The corresponding brightness profiles (with the same color as the matching cursor) are plotted on the right side of each picture. The bright Germanium doped core is shown as a peak in the brightness profile.

Separate from the WTI brightness feedback system, the load-cell in the LZM-100 provides a third independent feedback loop. It monitors the fiber tension in real-time during fiber processing, such as tapering and thermal core expansion. From an abnormal fiber tension reading we can easily determine a case of over heating or under heating. By using the load-cell readings in conjunction with WTI luminescence monitoring, the range of feedback control can be very much extended beyond the control limitation of the camera gain and the exposure time.

We have been performing process development and optimization in our lab to make a variety of glass components. Some preliminary components produced with LZM-100 are shown in Fig. 7, 8, and 9.

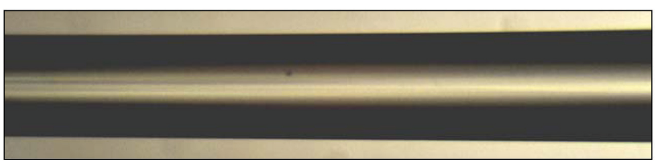


Fig. 7—Mode field adapter (MFA) made with the LZM-100 by tapering, thermal core expansion, and splicing.

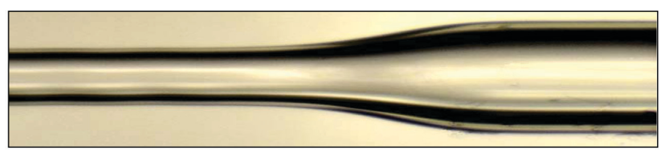
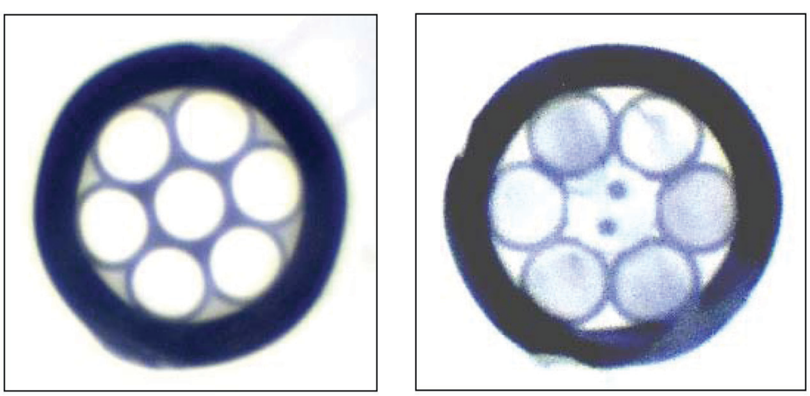


Fig. 8—Tapered capillary made with the LZM-100.



Cross section of 7 into 1 combiner **Cross section of 6+1 PM combiner**

Fig. 9—Preliminary test run of combiners with the LZM-100 and manual cleaving

5. Summary

A feedback controlled CO_2 laser exhibits remarkable stability and consistency. There is a significant difference in splice loss results between using a stabilized versus non-stabilized CO_2 laser splicing system. Moreover, the feedback control system can keep peak-to-peak taper ripple under 5 µm. A glass processor using a stabilized CO_2 laser as the heating source, the LZM-100, has been developed and is commercially available. This new machine provides a significant advancement in fusion splicing technology, and provides a new platform for fused glass component development and mass scale production. Many possibilities are available as we continue developing new and innovative methods of processing glass and fiber.

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