A novel technology based on CO_2 lasers for surface finishing and direct fiber fusion of beam delivery optics

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ABSTRACT

A unique technology for the fabrication of high-quality and robust beam delivery optics for fiber lasers is presented. CO_2 lasers are used to reshape the spherical surface of plano-convex fused-silica rod-lenses, and then fuse the optical fiber directly to these lenses. A specific fiber collimating system is presented and analyzed in terms of aberrations, insertion loss, M2, and return loss. Test results are compared to the theoretical modeling, demonstrating the accuracy and repeatability of this technology.

Keywords: fiber collimators, beam delivery optics, fiber fusion, surface finishing, aspheric optics.

1. INTRODUCTION

Recent advances in the development and technology of high-power fiber lasers have created an increasing demand for high-performance, reliable, and robust beam delivery optics. Beam delivery optics is used to gather divergent light emerging from the tip of the fiber and change its divergence depending on the application. Collimators are the most common beam delivery optics in fiber lasers and are used to minimize divergence relative to the output beam size in order to relay the laser beam through free-space or bulk optics. Fiber collimators are used in many applications, including free-space communications, LADAR, target painting, various industrial applications, and telecom.

A very simple and robust beam delivery collimator for fiber lasers can be made by directly fusing a small plano-convex fused-silica rod lens, also known as a C-lens, to the optical fiber, as illustrated in Figure 1. The main advantage of such fiber collimator is that the mode coming out of the fiber expands in the rod lens before encountering an interface, reducing the risk of damage at the exit of the fiber and also lowering the return loss.

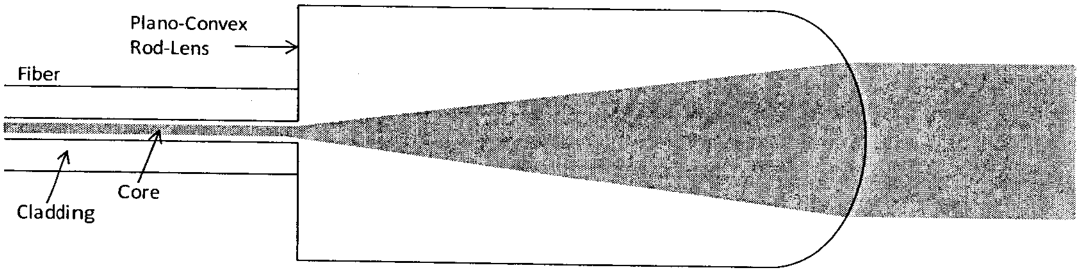

Figure 1: Single fused rod-lens fiber collimator.

We developed a unique technology to fabricate simple and reliable beam delivery optics for fiber lasers, pigtailed laser diodes, and other fiber-ended laser sources. Our technology is based on CO_2 lasers, which are used to reshape the

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convex surface of fused-silica spherical C-lenses, and then fuse the optical fiber directly to these lenses. This paper presents an overview of this novel technology. Also, a specific fiber collimating system is presented and analyzed in terms of aberrations, insertion loss, M^2, and return loss. Test results are compared to the theoretical modeling, demonstrating the accuracy and repeatability of these fabrication processes.

2. BACKGROUND

In many laser applications a laser beam has to be injected into an optical fiber, such as pigtailing a laser diode, as illustrated in Figure 2(a), or taking the light out of an optical fiber to pass it through bulk optical components and inject it back into the fiber, as illustrated in Figure 2(b). In the case of Gaussian beams and single-mode (SM) optical fibers with large numerical aperture (NA), the insertion loss (IL) could be very sensitive to the spherical aberration (SA) in the optical system [1], which increases rapidly (non-linearly) with the fiber NA and also increases linearly with the focal length of the optical system (or the output beam diameter of the collimator). The SA in a SM fiber collimator can also affect the M^2 of the collimated output beam, so correcting the SA can improve the M^2 of the output beam in certain cases. In general, SA can be corrected by using a multi-element design. However, in the case of a C-lens, there is only one refractive surface, so an aspheric surface might be needed to correct the SA in the optical system.

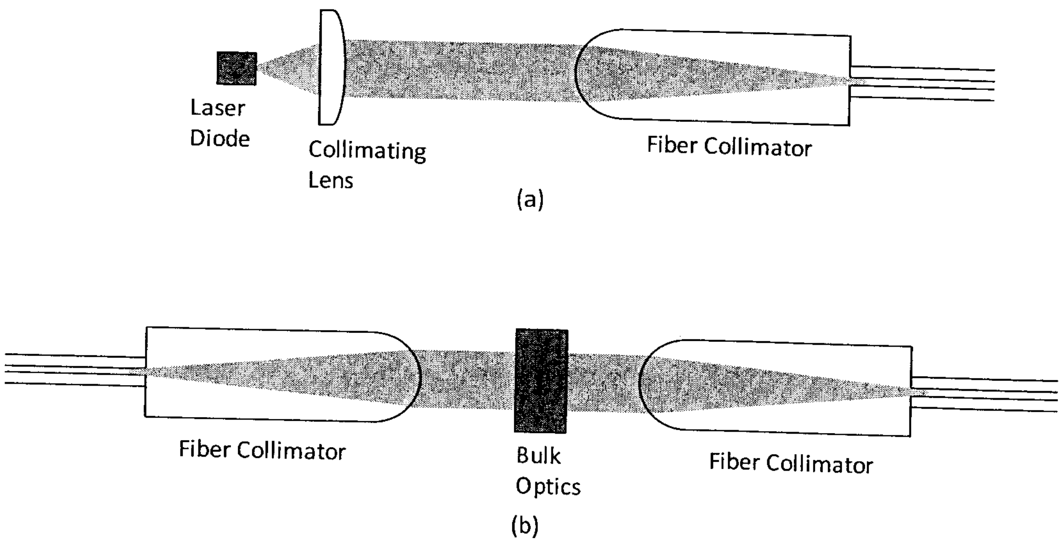

Figure 2: (a) CO_2 micro-shaping apparatus; (b) Glass reflowing process to reshape the surface.

Aspheric surfaces can be fabricated in fused-silica C-lenses by using conventional aspheric grinding and polishing equipment or by using a magneto-rheological fluid (MRF) polishing machine. However, both fabrication methods are relatively expensive and have a low throughput, so they are not very suitable for high-volume production. Also, these fabrication methods are both limited by the size of the tool, and therefore the minimum diameter of the optics is limited. We developed a unique fabrication process that lends itself very well to high-volume production of aspheric C-lenses and is also ideal for application using smaller optics. Since fabrication of spherical C-lenses is relatively inexpensive and available in large volumes, we start with spherical C-lenses as performs in our process. A CO_2 laser beam is focused down onto the convex surface of the spherical C-lens to reshape it into an aspheric surface. This technology is covered in more detail in the following section.

Another important parameter in fiber collimators is the return loss (RL), which is the portion of light reflected back into the fiber due to residual Fresnel reflections at interfaces [2]. In the case of fiber lasers, this light can couple back into the fiber and travel backwards through the amplifications stages, which can cause severe damage to the laser system. The most significant reflection usually occurs at the exit of the fiber, whether this is a glass/air, glass/adhesive, or glass/glass interface. We developed a reliable fabrication process to fuse the optical fibers directly to C-lenses in order to eliminate any physical interface between fiber and lens, and therefore lower the RL. A CO_2 laser beam is focused down at the interface between the fiber and the C-lens to fuse the two together. This technology is also covered in detail in the following section.

3. TECHNOLOGY

Two separate fabrication processes were developed. The first process is aimed at correcting the SA of the optical system in order to improve the IL and M^2 in fiber collimators based on C-lenses. This is done by reshaping the convex surface of a spherical fused-silica C-lens. Ground and polished spherical C-lenses are used as performs in this process since fabrication of such optics is relatively inexpensive and can be done in large volumes. The concept behind the surface reshaping apparatus is schematically illustrated in Figure 3(a). A collimated CO_2 laser beam at 10.6 μm is focused down onto the convex surface of the spherical C-lens through a ZnSe focusing lens. Two motorized scanning mirrors are used to rotate the beam around the mechanical axis of the setup (z-axis) by means of a synchronized combination of tip-tilt around the x and y axes.

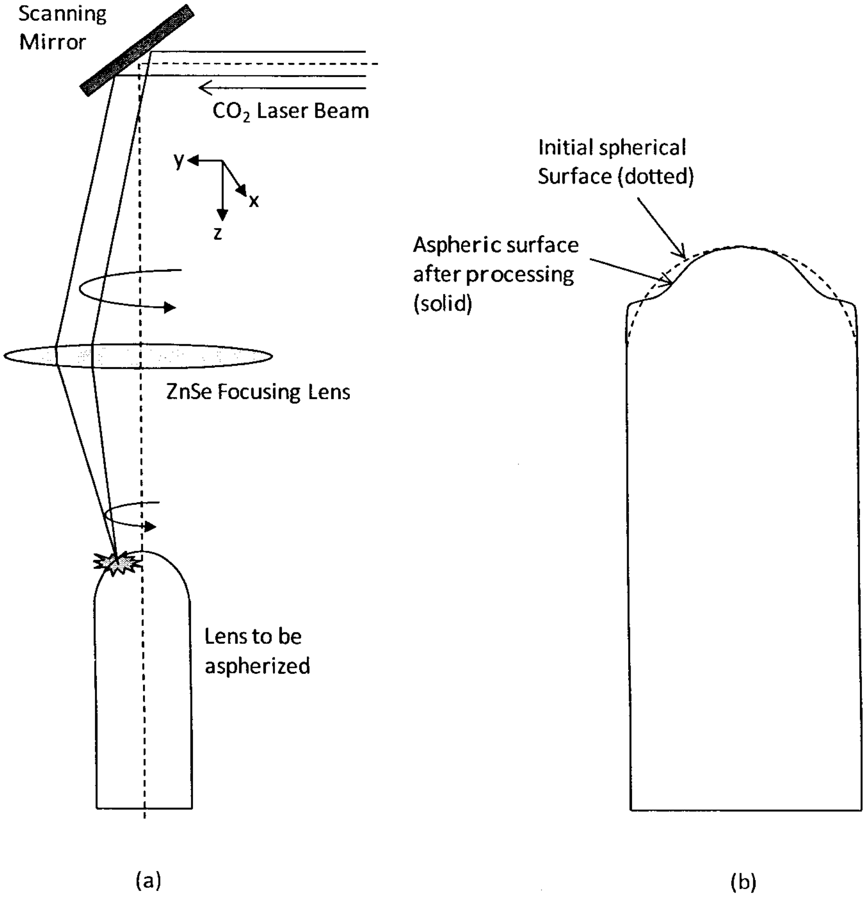

Figure 3: (a) CO_2 micro-shaping apparatus. (b) Glass reflowing process to reshape the surface.

The focused CO_2 laser beam is adjusted such that it will scan the spherical surface in a circular motion to heat up, melt and reflow just enough glass in order to obtain the desired aspheric shape, as shown in Figure 3(b). The surface to be processed has to be heated according to a very precise circular pattern across the clear aperture. The melted glass will flow away from the center of the clear aperture due to gravity and other surface forces. Therefore, the radius of the spherical surface of the C-lens before laser processing has to be slightly larger than the final radius of the aspheric surface. The system has to be aligned and calibrated for every new optical prescription. The intensity and the focus of the CO_2 laser beam as well as the processing time per lens have to be adjusted depending on the volume and the location of surface glass that has to be melted in order to achieve the desired aspheric surface. Once calibrated and started, this process will take an average of about 8 seconds per lens to complete. In production, up to 500 spherical C-lens preforms can be loaded at one time into a precision machined tray placed on an x-y motorized precision stage, and the reshaping process is repeated after each lens is positioned under the CO_2 laser beam.

The second process uses a CO_2 laser beam focused onto the flat surface of the C-lens, at the interface between the bare optical fiber and the lens in order to fuse the fiber to the lens without using any adhesives in the optical path. This process eliminates any interface between fiber and lens, dramatically reducing the RL in the system. The fusion apparatus is schematically described in Figure 4. Just like in the first process, a collimated CO_2 laser beam at 10.6 μm is focused at the fusion point using a ZnSe focusing lens. A similar combination of two motorized scanning mirrors is used to rotate the beam around the mechanical axis of the setup, while keeping the focal point fixed at the fusion joint. The fiber is fed through a small hole in a fixed steering mirror, as illustrated in Figure 4. The intensity and the focus of the CO_2 laser beam as well as the processing time per fusion have to be adjusted depending on the diameters of the fiber core and cladding.

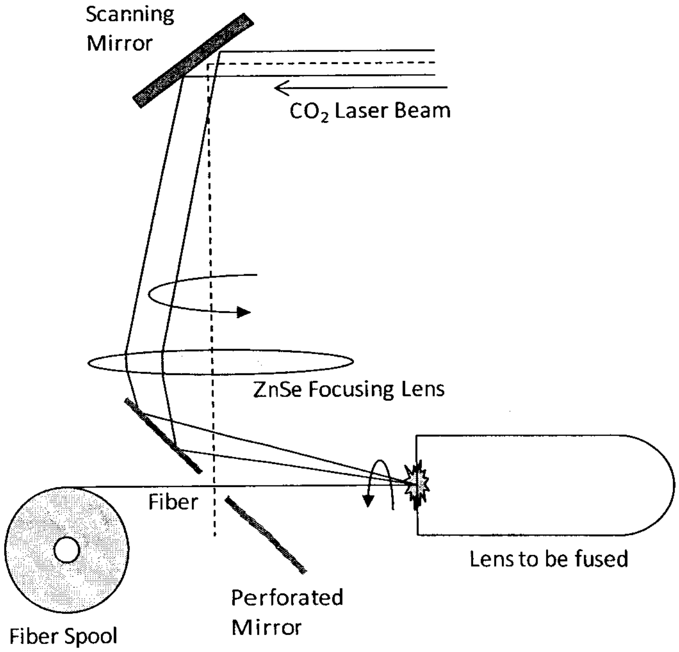

Figure 4: CO_2 fiber fusion apparatus.

4. EXPERIMENTAL RESULTS

A specific application was chosen for a closer study in order to evaluate the C-lens surface reshaping and fusion processes. The application is a fiber collimator to be used in a symmetrical paired configuration, similar to the one shown in Figure 2 (b). The optical fiber is Corning SMF-28 operating in SM at 1550 nm, with a nominal mode-fielddiameter (MFD) of 10.4 μm at 1550 nm. The C-lens design was based on a desired nominal beam diameter of 0.56 mm and a working distance (WD) of 100 mm. The WD is defined as the optimal distance between the two collimators where the IL of the system is minimized. In a symmetrical configuration, the WD is equal to twice the distance from collimator to the beam waist. The beam diameter and WD requirements resulted in a fused-silica C-lens with a center thickness (CT) of 4.42 mm and a radius of curvature (RoC) of 1.352 mm. The CT determines the beam size and the RoC determines the waist position. The diameter of the C-lens was set to 1.25 mm. However, in the case of a spherical design, the wavefront aberration in the system affects the nominal IL and M^2, as shown in Table 1. Therefore, a conic constant of -0.48 was added to the convex surface of the C-lens to correct the SA and reduce the IL and M^2. The peak-to-valley wavefront error (P-V WFE), IL, and M^2 nominal values are compared in the first two columns in Table 1 for the spherical design and the aspheric design. The SA was entirely corrected by the aspheric design, resulting in zero nominal IL and a nominal M^2 of 1.

	Nominal Spherical Design	Nominal Aspheric Design	Experimental Aspheric
P-V WFE [waves]	0.21	0.08	Not measured.
IL [dB]	0.48	0.00	0.25
M^2	1.15	1.00	1.08

Table 1: P-V WFE, IL, and M^2 (nominal and experimental values).

A batch of 100 spherical C-lenses with a nominal radius of 1.376 mm were aspherized using the CO_2 laser reshaping process to obtain aspheric C-lenses with a nominal radius of 1.352 mm and a conic of -0.48, according to the aspheric design. Then, SMF-28 optical fiber was fused to the aspheric C-lenses using the CO_2 fusion process. Twenty fiber collimators were randomly sampled from this batch to evaluate their optical and mechanical performance. The strength of each fusion joint was successfully tested by a pull test of 0.5 Kg. The RL was measured to be less than -65dB for all collimators, and the transmission was higher than 99% (C-lenses were AR coated on the convex surface). Then, the IL and M^2 were measured for each collimator. The IL was measured using a flat mirror in front of every collimator, by adjusting the mirror for minimum IL at 50 ± 10 mm, which represents half of the WD. The tolerance on the WD accommodates the variation in the RoC, which is set by the tolerance on the initial polishing of the spherical surface. The average values for the IL and M^2 are listed in the Table 1, and are a clear improvement from the nominal spherical design.

5. CONCLUSION

We presented two unique processes to fabricate fiber collimators in large volumes starting from fused-silica spherical C-lenses. Our technology is based on CO_2 lasers, which are used to reshape the convex surface of the spherical C-lenses, and then fuse the optical fiber directly to these lenses. A specific fiber collimating system was presented and analyzed in terms of aberrations, IL, M^2, and RL. Test results were compared to the theoretical modeling, demonstrating the accuracy and repeatability of these fabrication processes. The pull test and the experimental transmission and RL measurements proved the strength and the quality of the fusion joint. The experimental values for the IL and M^2 for the collimators with aspheric C-lenses were clearly better than the nominal values for the spherical design, showing that even with the typical fabrication tolerances, an aspheric C-lens fabricated by our process can definitely improve the performance over a spherical C-lens.

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