Fiber optic cables for transmission of high-power laser pulses

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ABSTRACT

High power pulsed lasers are commonly deployed in harsh environments, like space flight and military missions, for a variety of systems such as LIDAR, optical communications over long distances, or optical firing of explosives. Fiber coupling of the laser pulse from the laser to where it is needed can often save size, reduce weight, and lead to a more robust and reliable system. Typical fiber optic termination procedures are not sufficient for injection of these high power laser pulses without catastrophic damage to the fiber endface. In the current study, we will review the causes of fiber damage during high power injection and discuss methods used to avoid these issues to permit fiber use with high reliability in these applications. A brief review of the design considerations for high peak power laser pulse injection will be presented to familiarize the audience with all the areas that need to be considered during the design phase. The majority of this paper focuses on the proper fiber polishing methods for high power use with an emphasis on laser polishing of the fibers. Results from recently build fibers will be shown to demonstrate the techniques.

Keywords: Laser polishing, fiber optics, pulsed laser, fiber injection, fiber threshold, optical damage

1. INTRODUCTION

Lasers exhibiting high peak power pulses are used in a wide range of high reliability applications from spaceflight to optically initiated explosives. Examples of flight instruments that rely on high power pulsed lasers include LIDAR systems for ranging, autonomous docking systems, and optical communications between satellites and from satellites to ground-based systems. All of these systems require high optical power laser pulses for accurate detection of transmitted or reflected signals. Fiber coupling of the laser pulses can allow locating the laser system in a more favorable location on the overall system. By not forcing the laser to reside on the exterior of the system or be coupled using free space optics, savings in size, weight, and power can be realized. Lasers mounted on the exterior of a system are subjected to larger thermal ranges, higher radiation, and offer less mechanical protection. This results in having to add extra heating and cooling, along with extra shielding to provide the needed safety for the optical components. These problems are compounded as multiple lasers and detectors are added to the overall system. Requirements for many new and upcoming spaceflight systems dictate having multiple lasers and detectors to increase the amount of data collected. A good example of how these concepts of relocating sources and detectors to more favorable locations is on the Lunar Reconnaissance Orbiter (LRO) in which the detector for the Laser Ranging (LR) was shared by the Lunar Orbiter Laser Altimeter (LOLA) instrument. Our group designed, manufactured, tested, and integrated custom fiber optic bundles for both instruments to allow the optical pulses from a ground-based laser, using a small telescope mounted on the high gain antenna, to be routed 10 meters across the spacecraft to LOLA for detection and analysis.[1] While at the same time, our custom five-fiber optical cable on LOLA allowed collection of the five individual laser spots in a single telescope to be routed to five individual detectors.[2] Both of these systems enabled significant size, weight, and power savings over traditional architectures. Similar improvements using remote placement of the laser source have been difficult due to the inability to reliably transmit high-power optical pulses down a fiber.

Optically initiated explosives is another area where there are significant benefits to be gained by using a remotely located laser and firing the explosives using a high power optical pulse. Here the primary benefit is the large improvement in safety by switching to the optically based system. Electrically initiated explosives can be susceptible to

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outside interference, like electrostatic discharge (ESD) or radio frequency pickup, which can cause unintended detonation of the connected explosives. But, by switching to a more insensitive explosive that requires a high peak power optical pulse, the probability of unintentional detonation is greatly reduced. Depending on the distance and number of detonators, there can be a noticeable difference in the weight of the cables leading from the firing bunker to the explosives due to the lighter weight of the fiber cable. The disadvantage of the optically based system is that the fiber-to-fiber connections must be clean before connecting, whereas electrical connections can tolerate some dirt inside the connector.

In this paper, we will discuss many of the aspects that need to be considered when injection high power optical pulses into fiber optic cables. A brief discussion will inform the reader about many of the design constraints that need to be considered when setting up the system. The majority of the paper will then focus on the various methods of preparing a fiber optic cable endface for high power injection.

2. DESIGN CONSTRAINTS FOR HIGH-POWER LASER TRANSMISSION

Many design constraints need to be considered in order to reliably transmit high-power optical pulses over a fiber optic cable. All of the following need to be understood and controlled to achieve the highest optical fiber damage threshold: laser beam characteristics, laser-to-fiber injection optical design, injection system alignment, fiber preparation, and fiber routing and fixturing.

System requirements usually determine several of the laser beam characteristics, such as wavelength, energy, pulse width, and repetition rate. These will dictate the optical power level of the system. Along with the injected spot size, based on fiber core size, the optical energy density being injected into the fiber is calculated. Typically, the fiber size is selected to give the desired optical energy density. Given these fixed requirements, several other aspects of the laser design will determine the laser beam mode structure. For high-power injection, a uniform spatial beam profile is desired. If the laser beam exhibits small areas of higher intensity, then those will determine the damage threshold of the fiber during injection. The injection system design can be chosen to help smooth the spatial profile of the laser output, such as through the use of diffractive optical elements. The main design criteria for high-power fiber injection are: minimize peak fluence in air before the fiber, minimize peak fluence on the fiber endface, align the fiber axis to the incident beam axis, minimize laser “hot spots,” prevent conditions that lead to focusing within the fiber, and broaden the initial mode power distribution within the fiber. Details of high-power laser injection into fibers is beyond the scope of this paper but has been covered in several other sources.[3-10]

Alignment of the fiber to the optical injection system will play a large role in how the light travels down the fiber. Some injection systems are very sensitive to misalignment, while others show little change in the transmitted beam. It should be noted that when injecting high-power laser pulses, any optical energy that misses the fiber can cause catastrophic damage. Typical fiber connectors use epoxy located in intimate contact with the fiber cladding. Beyond the epoxy is the metal or ceramic ferrule holding the fiber. Light is readily absorbed and reflected by the epoxy and metal. Due to the high optical energy, even a small amount of absorbed light can cause a plasma event that will lead to damage to the fiber or deposition of ejected debris from the ferrule onto the fiber. The next optical pulse will be absorbed by the debris, causing catastrophic damage. Therefore, controlling the stray light, either from misalignment or tails on the injected beam, is essential. Diffractive optical elements can be used to clean up the laser beam profile before injection into the fiber, but often result in higher order diffracted spots. These spots typically are only a few percent of the total optical energy, but can still contain sufficient energy to cause damage if not controlled. Once the optical energy is successfully launched into the fiber, care must be taken to avoid sharp bends in the fiber that cause an increase in localized optical power density on one side of the bend, exceeding the damage threshold of the glass.

Through proper design of the laser, injection system, and routing, a highly reliable system can be produced, assuming the fiber can handle the optical power density without damage. The next section will cover the various methods of fiber design for high-power applications.

3. HIGH-POWER FIBER OPTIC CABLES

Proper fiber selection and endface preparation are essential to producing fiber optic cables with excellent optical damage threshold limits. The majority of fiber used in high-power systems is step index fused silica fiber, however, other fiber types, such as hollow core and custom doped, are under investigation. Due to the high optical power densities, large multi-mode fibers are usually chosen. These fibers can either be used as bare fiber or connectorized into a fiber ferrule. System use will likely dictate whether the fiber is connectorized. Finally, it should be noted that for high reliability applications, the proper materials, preparation, and termination are still essential for producing a quality product. Not following the proper procedures for manufacturing high reliability fibers will result in high optical loss, which will lead to catastrophic failure during transmission of the high-power optical pulse.

Any fiber optic cable will contain very small flaws in the glass matrix. If these flaws are small enough, they will have no effect on the optical performance of the fiber. When injecting a high-power optical pulse, some of the laser energy will be absorbed or scattered by these defects. If the defects are small enough in size and number, there will be no significant degradation of the optical pulse. However, if the defects can absorb enough energy, they will cause a rapid heating and expansion of the glass, which will destroy the fiber endface. Thus, the way to increase the optical damage threshold of the fiber is to eliminate the flaws on and below the fiber endface. The three primary methods of accomplishing this are with cleaving, mechanical polishing, or laser polishing the fiber.

3.1 Cleaved Fiber for High Power

Modern fiber cleavers are fairly good at producing high-quality cleaved fiber. The fiber is placed under slight tension and is then nicked, usually with a diamond blade. The tension causes the defect crack to propagate across the fiber. Some machines also allow for cleaving on an angle. Cleaved fibers are best used when they are permanently packaged in a device, as they are very difficult to connectorize after they have been cleaved. Of particular concern is residual damage from the cleaving. Figure 1 shows examples of two fibers that have been cleaved. Note the small damage on the outer edge of the fiber as a result of the cleaving operation. These pictures were shown to highlight this damage, which is often difficult to detect. Care must also be used with the cleaved fiber because the sharp edges are prone to chipping and cracking, which can cause damage into the fiber.

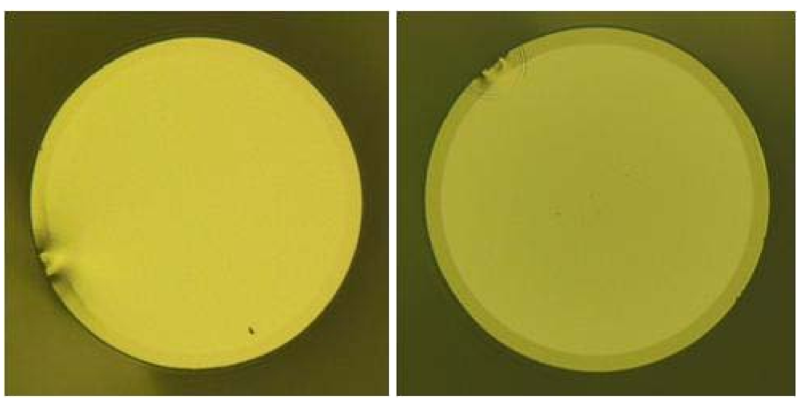

Figure 1: Cleaved fiber optic cables showing residual damage.

3.2 High-Power Mechanical Polish

Most systems will require a fiber optic cable that can be connected and possibly disconnected, making bare cleaved fibers impractical. The traditional method of polishing the fiber ferrule is to use mechanical methods with finer grits on each polishing step. Following cleaving of the excess fiber outside the ferrule, a coarse polishing grit is used to remove excess epoxy and bring the fiber endface close to the top of the ferrule surface. The industry standard starting grit is around 30 to 15 µm, but for high reliability applications, the roughest grit used by our group is 9 µm. Subsequent polishing steps use smaller polishing grits to remove scratches left by the previous step. Following this method, all scratches and other damage that will affect the optical throughput are removed. However, each polishing grit used causes subsurface damage below the endface of the fiber of up to three times the diameter of the polishing grit itself. Thus, a 30 µm grit will produce damage up to 90 µm or more into the fiber. The smaller grits used in subsequent polishing steps will not remove this amount of material from the fiber tip, and the larger subsurface damage will remain. This will reduce the damage threshold of the fiber. Therefore, a high-power mechanical polish starts with a small initial grit and polishes for a long time to accomplish the necessary polishing. This procedure requires more time to complete, but it is the preferred method for producing high-power mechanical polishes. Typically, the largest grit used for a high-power polish is 3 µm. Experience and very good procedures will determine the final fiber geometry.

3.3 Laser Polishing for High Power

Any mechanical polishing procedure will leave subsurface damage in the fiber. The size and amount of subsurface defects will dictate the optical damage threshold of the fiber. Removing these subsurface defects will improve the optical damage threshold of the fiber. One method for doing this involves, after the high-power mechanical polish, reflowing the fiber surface by heating until it just starts to melt. This can be accomplished by various heat sources, such as a heating element, spark discharge, flame, or laser. Heating elements can introduce contaminants into the melted fiber endface, thus lowering the damage threshold. Spark discharge can lead to arcing onto the fiber connector and can present an electrical hazard. Flames present many hazards and can contaminate the fiber endface. Overall, laser heating is the preferred method of melting the fiber endface.

The wavelength of the heating laser needs to be chosen such that it is readily absorbed on the fiber surface and does not transmit down the fiber. CO_2 lasers at 10.6 µm are an excellent choice for fused silica fiber. Figure 2 shows the laser polishing setup in our lab. The laser incorporates a feedback loop and closed loop chiller to help stabilize the output energy. The duty cycle of the laser pumping can be adjusted to change the output energy. An electronic shutter is used to provide precise exposure durations. An energy meter and beam profiler, installed using pick-off wedges, monitor the energy and spatial profile of the laser beam.

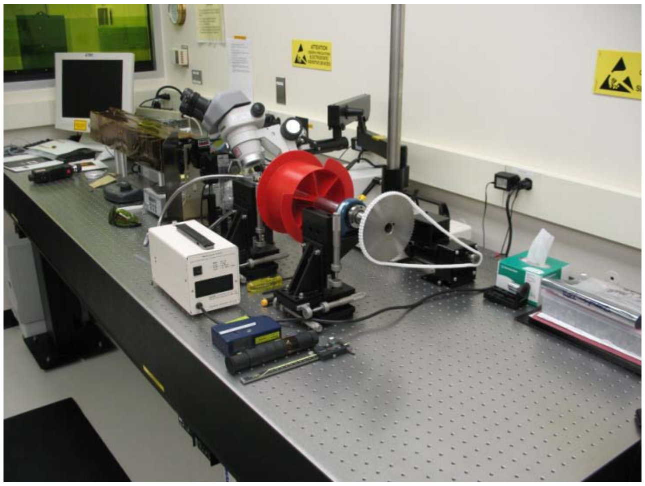

Figure 2: NASA GSFC laser polishing lab setup.

A uniform CO_2 laser beam is incident onto the fiber endface for a controlled duration. As soon as the fiber starts to melt, the laser beam is removed. This causes a melting of the fiber surface, which solidifies upon removal of the laser. The exposure energy and duration are key in producing an ideal surface. If the laser is allowed to remain on the surface too long, the surface tension of the glass will cause rounding of the endface. Figure 3 shows a bare fiber that was heated too long. From the figure, it is clear that the surface tension caused the melted glass to form into a rounded shape. If the exposure is continued, a round glass ball will form on the end of the fiber. Similarly, fibers installed in a connector will exhibit waves on the surface if exposed for too long. The ferrule is constraining the edges of the fiber and acting as a heat sink, so the surface tension will produce waves starting near the center of the fiber. Figure 4 shows representative examples under optical inspection and interferometry of connectorized fibers exposed for slightly too long.

Connectorized fibers in which the fiber is in intimate contact with the metal ferrule, or a thin epoxy line is separating the two, will show rippling on the fiber surface if laser polishing exposures are too long. Heat flowing into and out of the metal endface of the ferrule will affect the laser energy and duration needed to obtain an optimal laser polish. Ferrules from reputable manufacturers tend to have relatively consistent dimensions on the ferrule interior. Therefore, controlling the amount of material removed during the mechanical polishing prior to laser polishing will allow for repeatable laser polishing. If the amount of material removed during mechanical polishing is unknown or uncontrolled, then extreme care must be used to remove the laser irradiation immediately upon melting of the glass at the fiber endface. Optical inspection and interferometry are essential tools to inspect the fibers following laser polishing to check for any residual surface irregularities.

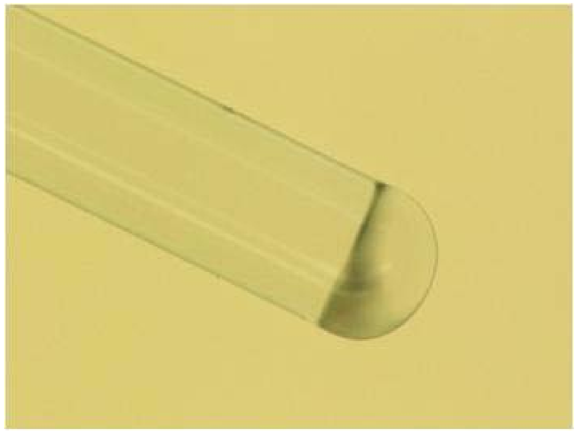

Figure 3: Bare fused silica step index fiber heated for an extended period of time with a CO_2 laser.

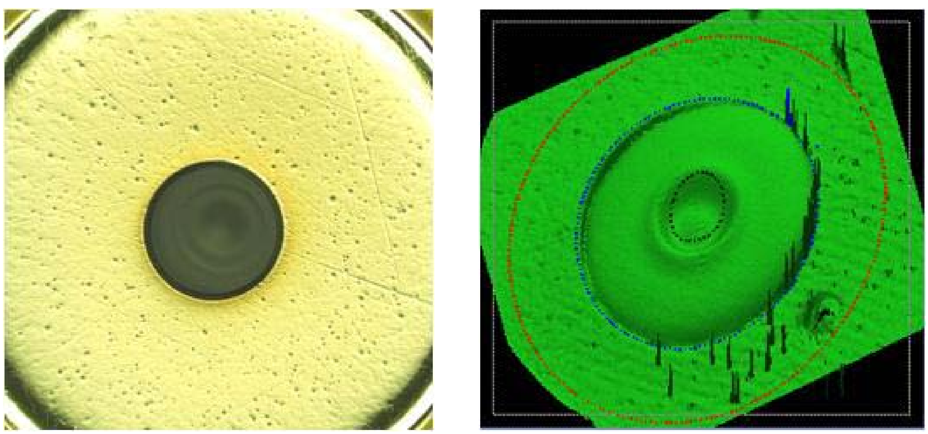

Figure 4: Representative samples of overheating of connectorized fiber during laser polishing. Left image is taken with an optical microscope, while the right image was taken using an interferometer.

Any portion of the laser beam that does not impinge directly onto the fiber endface can lead to unintended heating in areas besides the fiber tip. Many high power connectors utilize a recessed ferrule in which the fiber is suspended in air and held in the connector a short distance behind the fiber tip. Recessed ferrules are useful during high power injection because if the injected high power laser beam misses the fiber endface, due to misalignment, vibration, etc., it is allowed to expand before striking the metal ferrule. The beam's energy density is lower since it expanded further before impinging on the metal, and any ablated material has a lower probability of landing on the fiber endface. Since these recessed connectors are designed for high power injection, they are excellent candidates for laser polishing. There is no epoxy or metal in intimate contact with the fiber endface, so heat flow into and out of the metal around the fiber tip will not affect the polishing energies or durations. But, care must also be taken with these types of connectors because any laser energy that misses the fiber will likely cause heating at the back of the recessed portion of the ferrule. The CO_2

laser used for polishing is collimated and will not diverge significantly between the fiber endface and back of the ferrule recess. Laser energies sufficient to melt the fiber tip can also cause melting inside the recessed portion. Figure 5 shows examples of fibers that were polished inside a recessed ferrule and then removed for inspection. From the figure it is clear that the laser polishing resulted in melting of the fiber at the metal-to-fiber interface at the back of the recess. These effects can be avoided with proper control of the laser beam spatial and temporal profile along with the fiber connector and laser beam alignment.

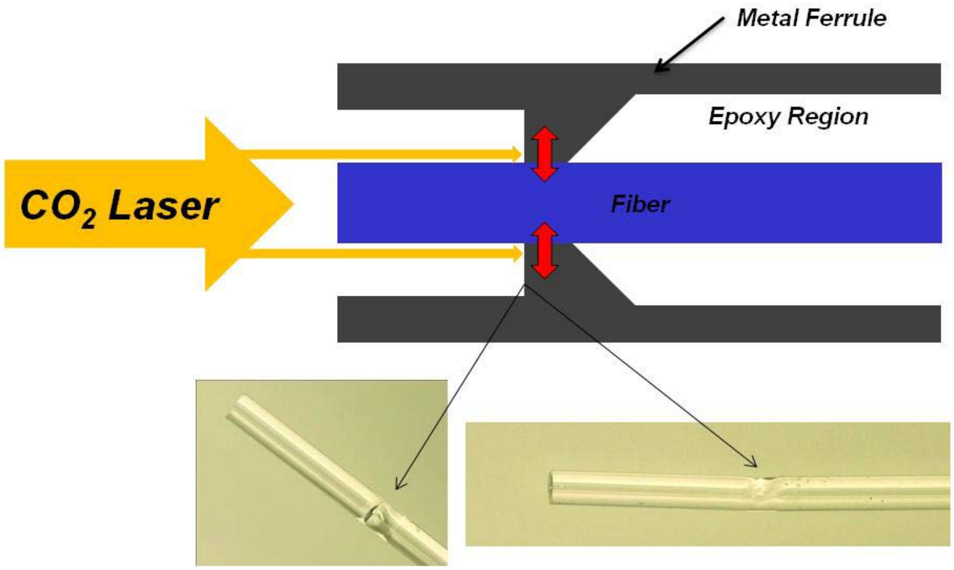

Figure 5: Damage at back of recess in high power connector due to CO_2 laser polishing. This type of damage can be avoided through proper control of laser parameters and fiber-to-laser alignment.

3.4 Comparison of High-Power Mechanical Polish and Laser Polish

Extensive studies have been done comparing the optical damage threshold of cleaved fibers, traditional mechanically polished fibers, high-power mechanically polished fibers, and laser-polished fibers. The results show that fibers polished using traditional polishing routines exhibit damage at relatively low optical powers. Cleaved fibers and those polished using high-power techniques show substantially improved damage thresholds. Fibers polished using a final CO_2 exposure show the best optical damage threshold. Our group at NASA GSFC has recently installed a high-power laser for performing in-house optical damage testing, but is in the process of testing samples to develop statistics needed to show the improvements obtained by high power polishing. Work on optical damage testing up to this point has been done in collaboration with Sandia National Laboratories. Figure 6 shows a comparison of fibers polished using a high-power mechanical process with those undergoing a similar process followed by CO_2 laser polishing. From the figure, it is clear that the laser polishing improved the optical damage threshold. This means that more energy could be injected into the fiber, with a lower probability of causing a damaging event to occur. This data was taken by Bob Setchell and Dante Berry at Sandia National Laboratories using bare fibers. Fiber core diameter was 365 µm and testing was conducted using a 1064 nm pulsed laser.

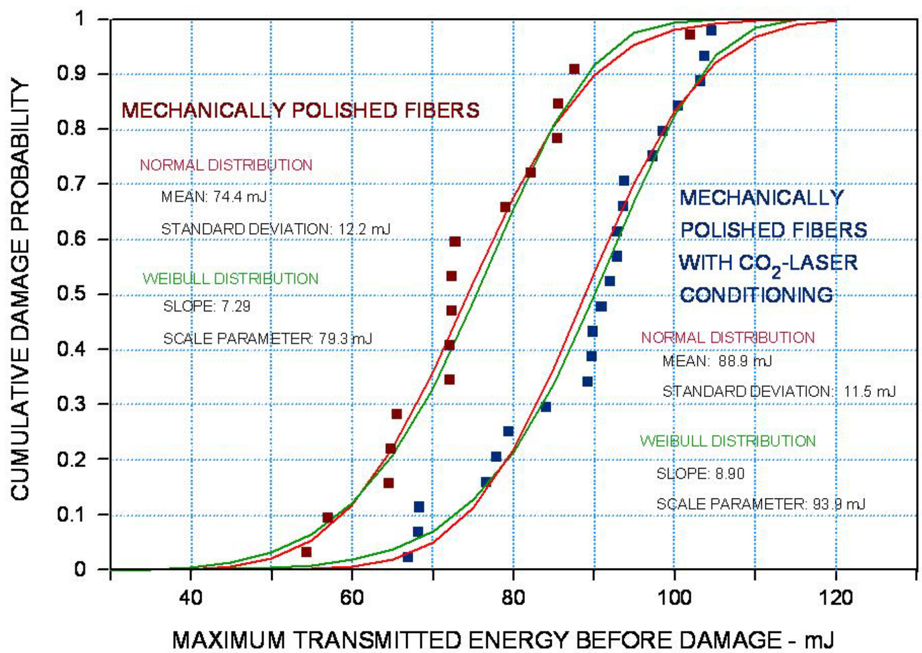

Figure 6: Comparison of 365 µm core fiber that has been mechanically polished using a high-power polishing process and similar fibers that have undergone a final CO_2 laser polish.[11]

4. INSPECTING LASER POLISHED FIBERS

Fibers polished using a mechanical polish for high power followed by laser polishing exhibit improved optical damage thresholds if done correctly. In this section we will review the inspection criteria used to perform optical inspection of the fiber endface. This assumes that the mechanical and laser polishing procedures have been verified using damage threshold testing with a high power laser at the desired wavelength of operation because techniques discussed are not able to completely examine under the surface of the fiber. Correct mechanical and laser polishing procedures will ensure that residual subsurface defects are minimized.

Figure 7 shows a recessed fiber optic connector in which the fiber has been laser polished. After mechanical polishing the fiber will exhibit sharp edges, which can be seen during inspection at a glancing angle across the connector endface. During laser polishing the fiber tip will begin to show curvature at the edges due to surface tension. The curvature should not extend into the fiber core and be confined to the cladding region, as seen in the figure. Curvature on the fiber tip will cause focusing of the optical pulse inside the fiber and the increasing laser pulse power density will result in damage to the fiber. Since the injected laser pulse should be confined in the core region, so it can propagate down the fiber, curvature in the core region is to be avoided. If no curvature is observed at the edges of the fiber, then the laser energy and/or duration of exposure were too low to melt the fiber endface. Without melting, the laser polishing was not successful and no benefit will be gained in the fiber optical damage threshold. Typical fiber inspection techniques such as interferometry and optical inspection should to used to ensure the fiber endface geometry meets specifications. The fiber should be verified to be free of any scratches. Our typical inspection criterion for high power use is scratch-free at 400x magnification. If the fiber was laser polished where the laser beam was incident in line with the fiber, an inspection should be performed to look for distortion of the fiber at the back of the recess where the metal meets the fiber. The images in figure 7 are of the same fiber and pass inspection.

Figure 8 gives an example of a fiber that failed inspection due to excessive melting of the fiber in one region of the endface. The excessive curvature extends into the fiber core region and will cause distortion of the injected laser beam, thus lowering the optical damage threshold of the fiber. The remainder of the fiber endface shows good melting and would be acceptable. Control of the laser beam profile, energy, and exposure duration in conjunction with fiber-to-laser alignment are essential to avoid over-exposure of any portion of the fiber during laser polishing.

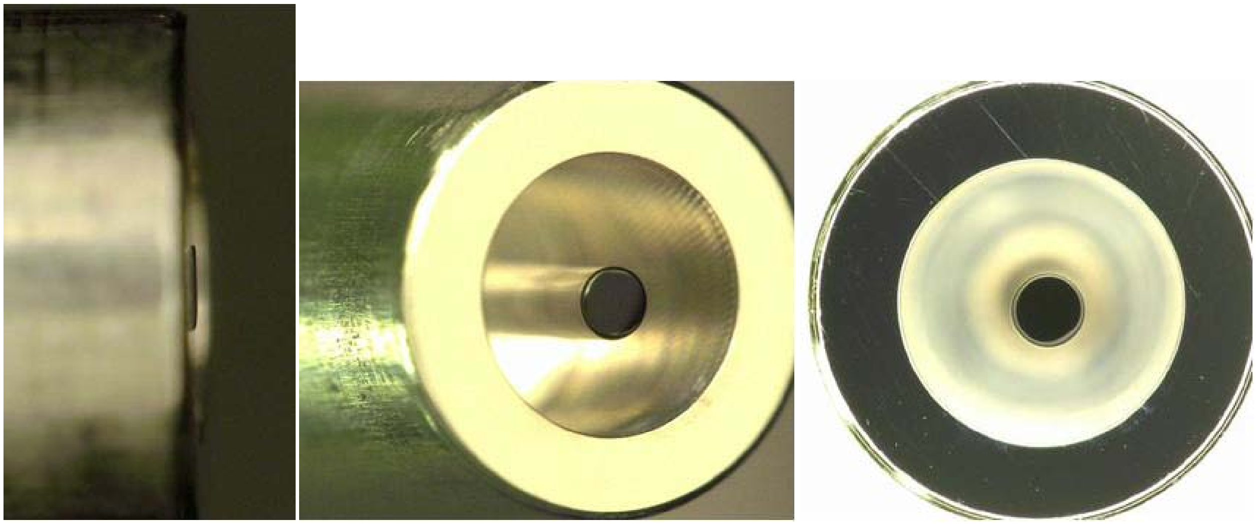

Figure 7: Example of a laser polished high power recessed ferrule fiber connector.

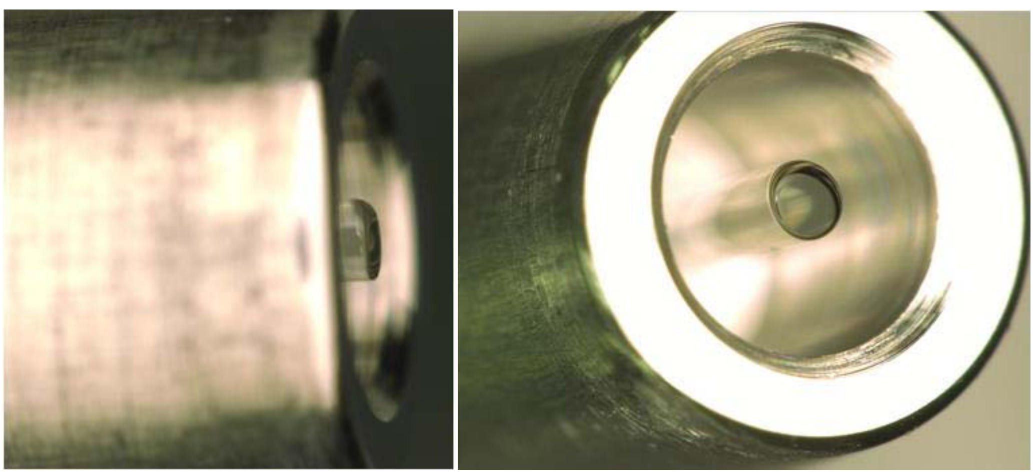

Figure 8: Example of fiber that failed visual inspection due to over-exposure on top edge during laser polishing.

5. CONCLUSIONS

Fiber optic cables capable of transmitting high-power laser pulses offer many advantages in the design of optical systems and provide improved immunity to outside interference compared to electrically-based systems. Reliable transmission of large optical pulses requires proper design of the laser and injection system, fiber selection and preparation, and correct routing and fixturing. Laser polishing the fiber endface following a high-power mechanical polish provides the highest optical damage threshold.

As a general rule of thumb for system design, the following general categories are given: Below approximately 1 GW/cm^2, standard flight fiber terminations and simple laser injection systems are sufficient. From 1 – 3 GW/cm^2, high-power design implementations are necessary. From 3 – 9 GW/cm^2, extreme care must be taken to ensure stable laser output, beam homogeneity, proper injection into fiber, and correct high-power fiber manufacturing. Above 9 GW/cm^2 is very difficult to implement outside of a laboratory environment. The intrinsic damage threshold of fused silica glass is around 12 to 14 GW/cm^2. For most high-power laser systems that are injected into a fiber, an attempt is made to keep the energy density below 6 GW/cm^2. It should be noted that other outside influences may affect the power handling of the system over its lifetime, such as radiation-induced darkening or thermal-induced transmission changes.

All of the presented methods and data for transmitting high power optical pulses down fibers assumes that the fibers have been properly inspected, cleaned, and re-inspected until no contaminants or debris are present on the fiber endface. Debris in the connector that is not on the fiber endface should also be avoided as much as possible so that it does not migrate onto the fiber endface during operation. The surface energy of the clean fiber endface will cause particles to preferentially stick to the fiber, so cleanliness of the entire connector is highly recommended to ensure high power operation over the life of the connector.

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