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ICSO 2010 **Rhodes, Greece**
International Conference on Space Optics **4 - 8 October 2010**

FIBER OPTIC CABLES FOR TRANSMISSION OF HIGH-POWER LASER PULSES IN SPACEFLIGHT APPLICATIONS

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ABSTRACT

Lasers with high peak power pulses are commonly used in spaceflight missions for a wide range of applications, from LIDAR systems to optical communications. Due to the high optical power needed, the laser has to be located on the exterior of the satellite or coupled through a series of free space optics. This presents challenges for thermal management, radiation resistance, and mechanical design. Future applications will require multiple lasers located close together, which further complicates the design. Coupling the laser energy into a fiber optic cable allows the laser to be relocated to a more favorable position on the spacecraft. 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 our new manufacturing procedures that overcome these issues to permit fiber use with high reliability in these applications. We will also discuss the proper methods for launching the laser pulses into the fiber to avoid damage and how this is being implemented for current spaceflight missions.

I. INTRODUCTION

Lasers exhibiting high peak power pulses are used in a wide range of spaceflight applications. Examples 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. A traditional optical system would use transmission and detection systems mounted on the exterior of the spacecraft. The transmission system would comprise a laser and collimation optics to launch the light, along with a receiver telescope and detector to collect the optical signal. This configuration presents many challenges for the spacecraft design. Exterior components experience large thermal changes during flight as they transition from facing toward the sun to facing away from it. Thermal management requires heating and cooling to maintain desired temperatures, which adds weight and uses power. Exterior components also experience higher radiation levels, which necessitates adding shielding, further increasing weight. In addition, mechanical constraints are always present, especially on newer systems that incorporate a larger number of instruments onto the spacecraft. Many of these optical instruments rely on multiple sources and detectors.

One method of overcoming many of these constraints is to re-locate the sources and detectors to preferred locations on the spacecraft. The launch and collection optics must remain in location to direct and collect the light to and from the target, but the light can be routed to other parts of the spacecraft. Fiber optic assemblies have been used to accomplish this on optical receiver systems. Lunar Reconnaissance Orbiter (LRO) is a good example of this, in which custom fiber optic bundles were designed, manufactured, tested, and integrated by our group for both the Laser Ranging (LR) and Lunar Orbiter Laser Altimeter (LOLA) instruments. The fiber bundle used on LR allowed collection of optical pulses, from a ground-based laser, using a small telescope mounted on the high gain antenna and routing the optical signal 10 meters away, across the spacecraft to the LOLA instrument for analysis.[1] The custom five-fiber optical cable on LOLA allowed collection of the five individual laser spots in a single telescope and routing 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.

II. 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, fiber injection system, alignment, fiber preparation, and routing / 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 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. Improved fiber ferrules have been designed to help avoid these issues, as will be discussed in a later section of this paper. 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.

III. HIGH-POWER FIBER OPTIC CABLES

Fiber selection and endface preparation are key 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 spaceflight use, the proper materials, preparation, and termination are still essential for producing a quality product. Not following the proper procedures for manufacturing spaceflight 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 in these defects. If the defects are small enough, there will be no effect on 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.

A. 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. Fig.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.

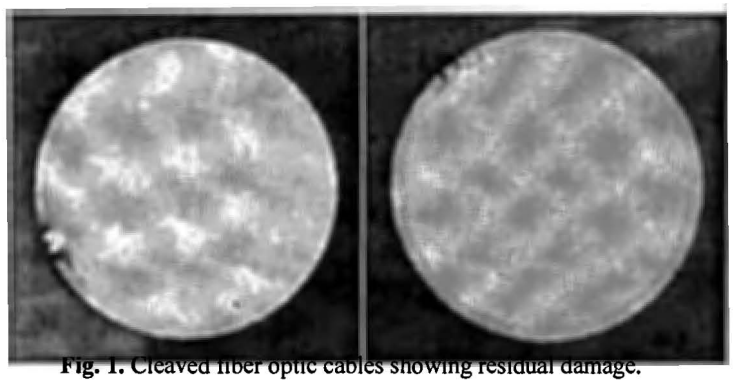

Fig. 1. Cleaved fiber optic cables showing residual damage.

B. 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. Industry standard is around 30 to 15 μm, but for spaceflight use, the roughest grit used 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 top 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 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.

C. 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 also. 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. Fig. 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.

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. Fig. 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. Fig. 4 shows representative examples under optical inspection and interferometry of connectorized fibers exposed for slightly too long.

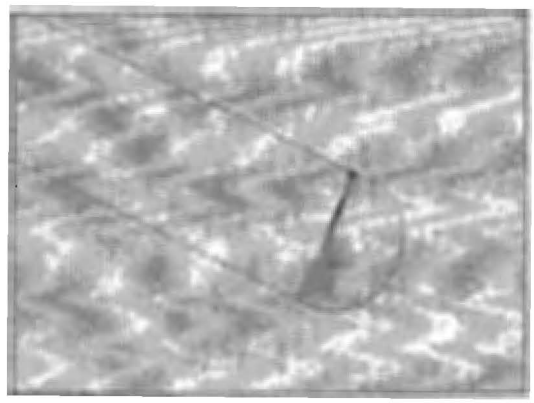

Fig. 3. Bare fused silica step index fiber heated for an extended period of time with a CO_2 laser.

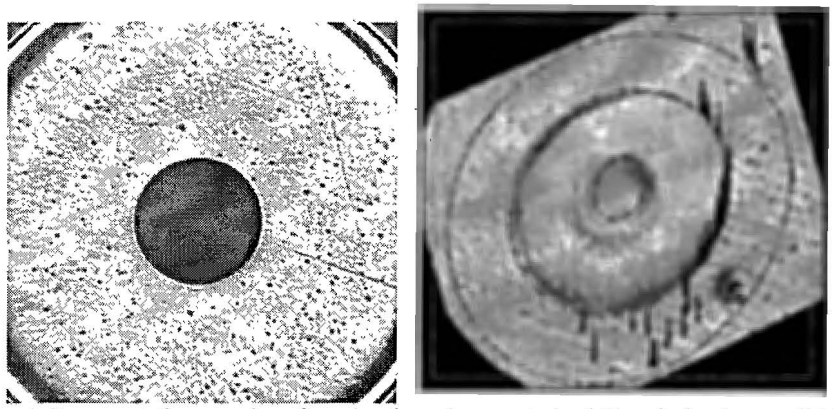

Fig. 4. Representative samples of overheating of connectorized fiber during laser polishing.

D. 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. NASA GSFC is in the process of setting up a high-power laser for performing in-house optical damage testing, so work in this area up to this point has been done in collaboration with Sandia National Laboratories. Fig. 5 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.

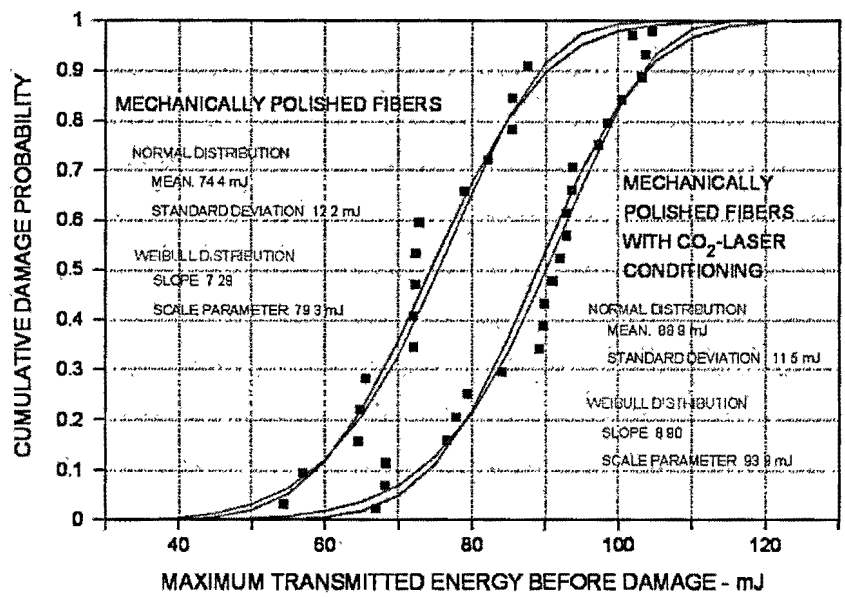

Fig. 5. Comparison of 365 μm core fiber that has been mechanically polished using a high-power polishing process and similar fibers that have undergone a final CO_2 laser polish [11].

IV. NEW HIGH POWER FIBER FERRULES

New fiber optic ferrules have been designed and manufactured that address some of the design constraints imposed when using traditional metal ferrules. The first new type of ferrule uses non-traditional metals on the ferrule endface to provide a highly reflecting surface that should decrease the absorption of any stray light. Ceramic ferrules with a high reflectivity metal insert were manufactured and terminated onto a fiber optic cable. A crimping operation was used to ensure intimate contact of the reflective surface and fiber to avoid any epoxy exposure. The second new ferrule design works in an AVIM connector and provides improved control of the laser heating and mitigates absorption of stray light outside the fiber. Both designs are undergoing testing and are awaiting approval for public release. Information will be available on our website (http://photonics.gsfc.nasa.gov) once approval has been obtained.

CONCLUSIONS

Fiber optic cables capable of transmitting high-power laser pulses offer many advantages for spacecraft designs. 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 polishing provides the highest optical damage threshold. Two new ferrule designs were presented for improving the performance and reliability of the fiber during injection of large optical pulses. These new ferrules, along with the laser polishing, enable coupling of high-power laser energy for future spaceflight designs.

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.

ACKNOWLEDGEMENTS

The authors would like to thank the following: Bob Setchell and Dante Berry at Sandia National Laboratories for collaboration on the high-power laser testing; Fred Taugwalder at Diamond and Matt Showalter at NASA Goddard for collaboration on new high power ferrules.

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