

Laser-induced damage to large core optical fiber by high peak power laser

Xiaoguang Sun* and Jie Li

OFS, Specialty Photonics Division, 55 Darling Drive, Avon, CT 06001 USA

ABSTRACT

In this paper we present a study of laser damage to large core multimode glass optical fibers by high peak laser power of up to 175 kW. Fibers samples prepared with polymer coatings having different refractive indices were tested in a two-point bend tester while transmitting laser light. The peak power used in the experiment clearly differentiated the performance among the samples. A polymer coating having lower refractive index significantly improves the fiber resistance to bending while transmitting laser. This observation provides important insight into the damage mechanism for this particular failure mode.

Keywords: laser damage, optical fiber, laser power delivery, reliability

1. INTRODUCTION

Fused silica optical fibers are commonly used for laser power delivery in many medical applications because of the high laser induced damage threshold (LIDT) of the silica glass, high strength, mechanical flexibility and other excellent properties such as low optical loss over a wide wavelength range from UV to Near IR. Silica optical fibers typically exhibit a median strength of more than 5 GPa (725 kpsi) and the LIDT of bulk silica glass on the order of 10 GW/cm². A value of 4 GW/cm² was cited as the LIDT of the cleaved fiber end face [1] at 1064 nm wavelength, and a nanosecond range pulse width. A successful transmission up to 20 MW of peak power by an optical fiber with a 1500 μm diameter core has been reported [2]. The estimated peak power density that the fiber experienced is approximately 1 GW/cm².

In actual medical applications of laser delivery the fiber that is transmitting laser light is also often bent to small diameters. Fiber breaks when the stress, due to bending, exceeds its fracture strength. Transmission of laser power causes the bent fiber to break at even lower stress level [3, 4]. In our earlier studies the polymer coating used to protect the glass fiber was found to be a weakest link determining the breaking diameter of a fiber while in a two-point bend tester while transmitting laser. It is conceivable that bending of the optical fiber results in leaking of some of the optical power out of the core region into the glass cladding, eventually reaching the surrounding polymer coating, which has a much lower LIDT than that of silica glass. Our work has shown that improving the fiber draw process, coupled with the use of coatings having lower refractive indices, can drastically reduce the breaking diameter of the fiber while transmitting laser with power up to 20 kW [4, 5].

* xgsun@ofsoptics.com; phone 1 860 678-6671; fax 1 860 674-8818; www.specialtyphotonics.com

As new medical applications demand still higher peak power and smaller bend diameters, it has become necessary to develop optical fibers that can perform under these stringent conditions. In this paper we compare the performance of a fiber sample, similar to the fiber used in ref [4] and a fiber coated with a lower index coating by measuring the breaking diameters of the fibers in a two-point bend tester while transmitting laser at different peak and average powers (peak powers up to 170 kW). The peak power used was much higher than that used in our earlier study (peak power 20 kW) [4] to differentiate the performance of the fibers with different coatings. The experimental results and conclusions will be discussed.

2. EXPERIMENTAL DESCRIPTIONS

2.1 Sample description

The properties of the two fibers tested are listed in Table-1. Both are step index (SI) fibers with a pure silica core of 272 μm and an F-doped silica glass cladding of 300 μm in diameters. The numerical aperture (NA) of the core is 0.22. This is a commonly used fiber for laser lithotripsy, preferred for its flexibility, as compared to other large core SI fibers and having a core size that is large enough to readily couple light from multimode lasers.

Outside the F-doped glass cladding is a thin layer of HCS[®] fluoroacrylate coating[†]. The HCS coating has a lower refractive index than that of both silica glass and F-doped silica glass cladding. The coating of Fiber-1 has a refractive index of 1.405 at 850 nm while that of Fiber-2 1.386. Both fibers have an ETFE buffer of 400 μm outer diameter. The coating of Fiber-1 has similar structure as the Sample-B in our previous study [4]. The index profiles of the fibers are shown in Figure 1.

Table 1. Sample description

Item	Fiber-1	Fiber-2
Core	Pure silica, 272 μm diameter	
Cladding	F-doped silica, 300 μm diameter; fiber core NA=0.22	
Coating	HCS coating, 330 μm diameter Index of refraction =1.405 @850 nm	HCS coating, 330 μm diameter Index of refraction =1.386 @850 nm
Buffer	ETFE, 400 μm Diameter	

[†] HCS[®] is a registered trademark of OFS Fitel LLC

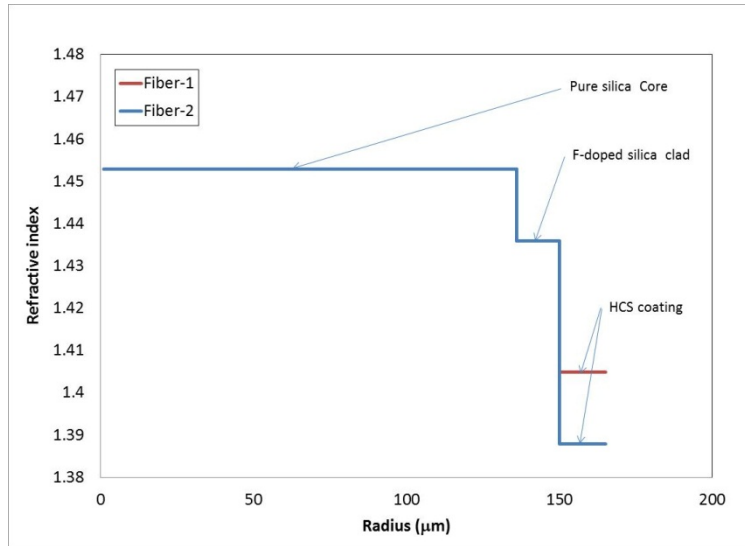


Figure 1. Index profile of Fiber-1 and Fiber-2

2.2 Laser parameters

The laser used in our fiber testing is a pulsed Nd:YAG laser from Lee Laser. The center wavelength of the laser is located at 1064 nm and the pulse repetition rate is set at 6 kHz (Setting-1) and 24 kHz (Setting-2). The output of the laser is focused to a 180 μm diameter spot size with a beam divergence that is 16 degree at full width at half-maximum (FWHM). The coupling loss to the fiber is typically less than 10%, including the Fresnel losses by the two fiber end faces. In the experiment, the pump power of the laser is kept constant. When the pulse repetition rate is increased, the pulse width becomes wider, as shown in Figure-2, resulting in a higher average power. The subsequent pulse peak power is lower with a higher pulse repetition rate. The laser settings and the resulting laser parameters in the experiment are shown in Table-2. The fiber output power was measured using an Ophir FL250A-BB-50 detector with a power accuracy of 3%.

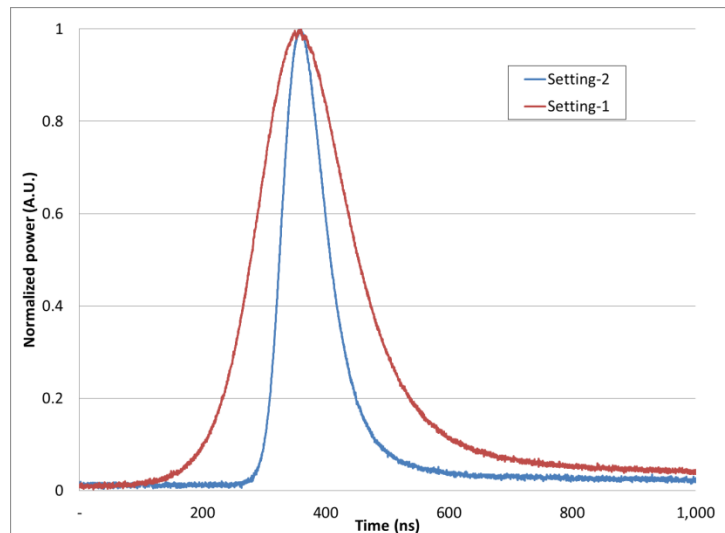


Figure 2. Pulse shape at laser setting-1, 6 kHz repetition rate and setting-2, 24 kHz repetition rate

Table 1. Laser setting/parameter

Laser parameter	Setting-1	Setting-2
Repetition rate (kHz)	6	24
Measured pulse width (ns)	80	170
Measured average power (W)	83	110
Calculated peak power (kW)	170	27

2.3 Two-point bend testing

The test setup consists of a laser and a two-point-bend fiber tester, as shown in Figure 3. The two-point bend fiber tester has a stationary plate and a moving plate that can be moved at a defined speed. The fiber breaking diameter under power is measured as follows. First the fiber buffer is stripped from a section near the end and the end face is cleaved, then that section of the fiber is held between the two jaws in the two-point bend tester with a 180° bend at a large bend diameter. With the laser turned on, the moving plate travels towards the stationary plate until the fiber breaks at which point the distance between the two plates is recorded. In our testing the initial fiber bend diameter was 32 mm and the speed of the moving plate was 2 mm/s. The fiber breakage was detected by a microphone with a time resolution of ~5 ms in our apparatus, the overall accuracy of the recorded breaking diameter is around 50 μm. The cumulative length of each fiber tested was about 5 m and the excess fiber is coiled to a diameter >30 mm. After each break the fiber was re-cleaved.

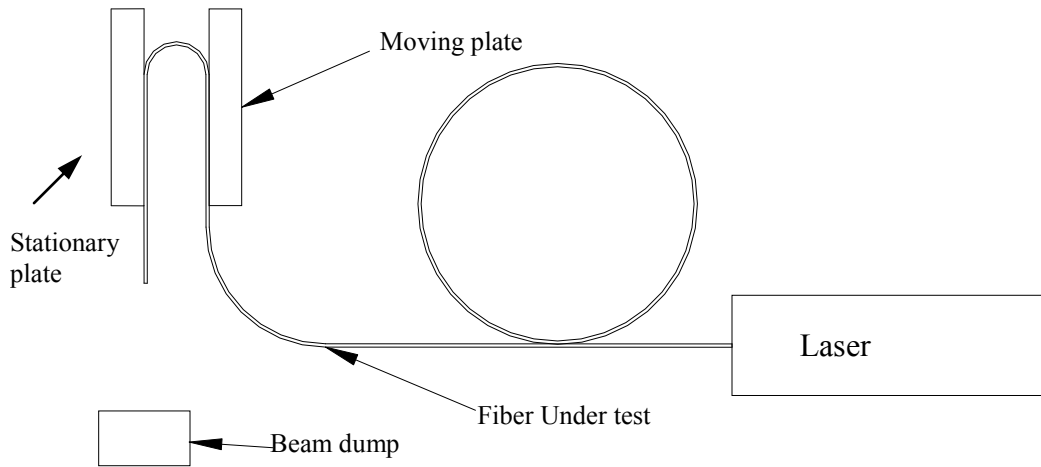


Figure 3. Experimental setup

3. RESULTS AND DISCUSSION

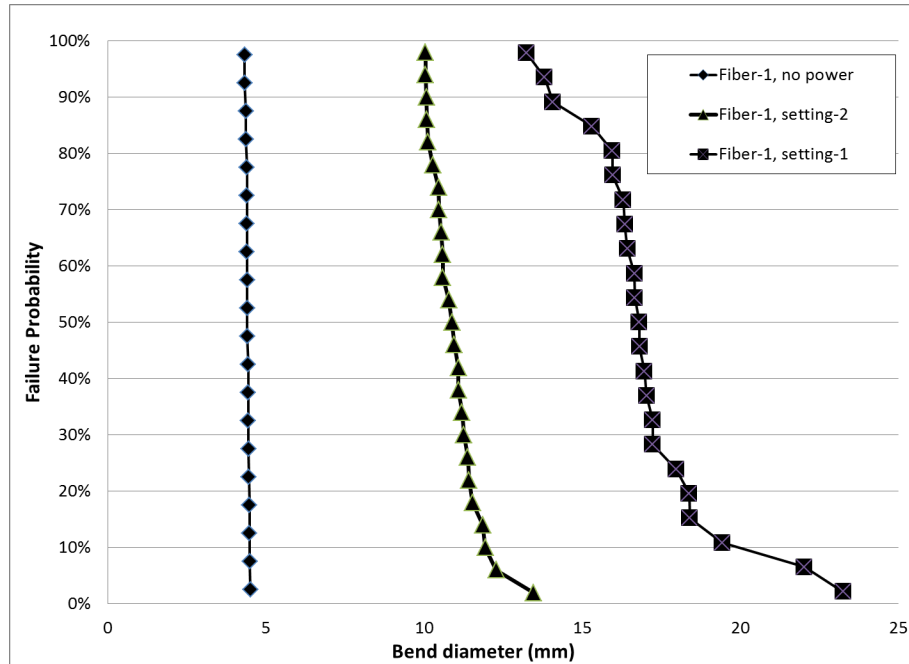
3.1 Breaking diameter of fiber while transmitting laser

The fiber breaking diameters were measured at the two laser settings as well as without laser power. The resulting Weibull distributions for Fiber-1 and Fiber-2 are shown in Figure 4, where the x-axis is the breaking diameter and the y-axis is the accumulated failure probability. Approximately 20 measurements were made for each fiber sample at each condition. The failure probability was calculated as follows. The measured breaking diameters were sorted in descending order and assigned a corresponding rank n , where $n = 1, 2, 3 \dots N$ (N was the total number of fiber measurements). The cumulative failure probability F_i at bending diameter ranked at n was calculated using: $F_i = (n - 0.5)/N$. The measured breaking diameters were fit to a Weibull distribution [6] by least a square method:

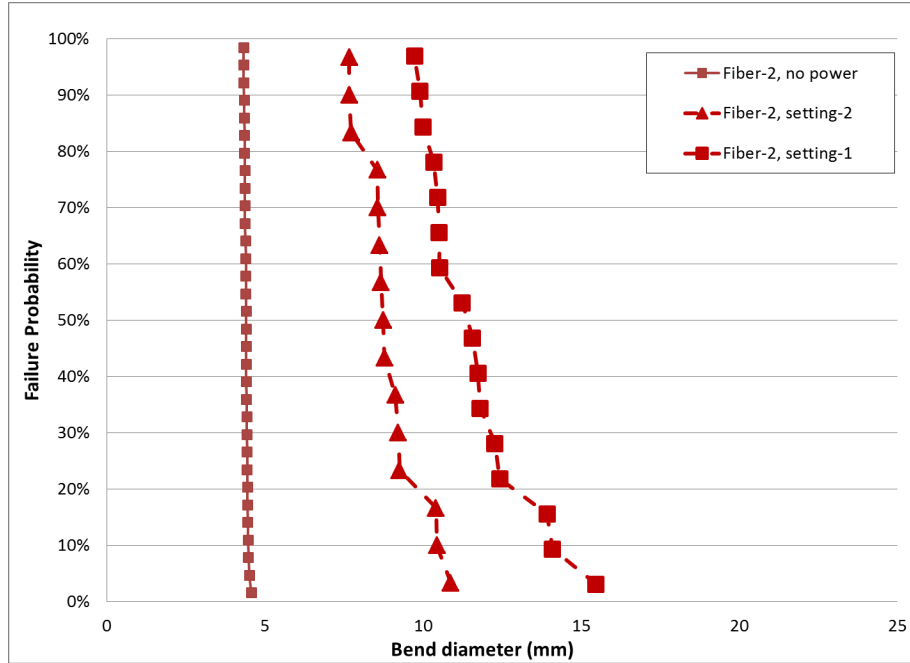
$$F = 1 - \exp\left(-\left(\frac{D_0}{D_f}\right)^m\right) \quad (1)$$

where F is the cumulative failure probability, m is the Weibull slope, D_f the breaking diameter, and D_0 a constant. The median breaking diameter is calculated accordingly. The Weibull slope, m is inversely proportional to the standard deviation and a larger m means a tighter distribution of the breaking diameter.

A summary of the testing results is shown in Table 3.



(a)



(b)

Figure 4. Fiber failure probability vs. bend diameter for Fiber-1(a) and Fiber-2(b).

Table-3 Summary of the fiber breaking diameter

Breaking diameter (mm)	Fiber-1			Fiber-2		
	Setting-1	Setting-2	No power	Setting-1	Setting-2	No power
Average	17.1	10.9	4.4	11.6	8.9	4.4
Standard deviation	2.3	0.8	0.1	1.7	1.0	0.1
Median	16.1	10.4	4.4	10.8	8.5	4.4
Weibull slope <i>m</i>	5.4	16.7	117	8.5	11.7	101

In Figure 4 (a), Fiber-1, with a higher refractive index coating than Fiber-2, exhibits a strong dependence of its breaking diameter on the laser power it is transmitting. The distribution without laser power is virtually a vertical line, indicating a small bend diameter (high strength, ~700 kpsi) and tight distribution (Weibull slope, $m = 117$). The fracture stress of the fiber in bending can be easily estimated from its breaking diameter using the following formula: $\sigma = E (d/D)$ where σ is the fiber fracture stress, E Young's modulus for silica glass (72 GPa or 10440 kpsi), d fiber diameter, and D breaking diameter. When laser power was applied (Setting-2, 27 kW), the Weibull distribution widened and shifted to the greater breaking diameter, indicating a significant decrease in strength (from the original ~700 kpsi to ~300 kpsi), and a decrease in the Weibull slope (from 117 to 16.7). A decrease in Weibull slope implies the originally tight distribution of fiber strength has become wider. When the peak power was further increased to 170 kW (Setting-1), the Weibull

distribution widened further and shifted to the greater breaking diameter further, indicating a further reduction in fiber strength (to ~ 200 kpsi) and a decrease in the Weibull slope (to ~5.4).

In Figure 4 (b), Fiber-2, with a lower refractive index coating than Fiber-1, exhibits less dependence of its breaking diameter on the laser power it is transmitting than did Fiber-1. The distribution with the laser turned off is virtually a vertical line, indicating a small bend diameter (high strength, ~700 kpsi) and tight distribution (Weibull slope, $m = 101$). When the laser was turned on and the peak power was set at 27 kW (Setting-2), the Weibull distribution widened and shifted to the greater breaking diameter, indicating a significant decrease in strength (from 700 kpsi to ~370 kpsi) and a decrease in the Weibull slope (from 101 to $m=11.7$). When the peak power was further increased to 170 kW, the Weibull distribution widened further and shifted to the greater breaking diameter further, indicating a reduction in fiber strength (to ~ 300 kpsi) and a decrease in the Weibull slope ($m=5.4$).

From the results shown in Figure 4, the distributions of the breaking diameters of Fiber-1 and Fiber-2 without laser power are essentially the same and no effect of refractive index was observed. The observed degradation in strength for both Fiber-1 and Fiber-2 is approximately 50% when the laser peak power was at 27 kW. However, when the peak power was increased to 170 kW, the degradation in fracture strength represented by the increase in breaking diameter was greater than 70% for Fiber-1 and less than 60% for Fiber-2. The median strength for Fiber-1 and Fiber-2 were 200 kpsi and 300 kpsi respectively when the peak power was at 170 kW. The improvement in fracture strength by ~100 kpsi along with the improvement in Weibull slope is considered significant for this particular failure mode.

We may conclude that refractive index of a coating does not contribute to the fiber fracture strength in the absence of laser power. However, the effect of the refractive index of the coatings on fiber breaking diameter becomes clear as the peak power increases.

It is also worth noting that the worse degradation was observed at high peak power when the average power was low. We can conclude that the peak power rather than average power is a determining factor for fiber performance in bend while transmitting laser power.

4. SUMMARY

In summary, we have investigated the bending performance of SI optical fiber for the delivery of high peak power laser energy. Our results indicate that peak power, not average power, is a determining factor for this failure mode. At some peak power level above a certain threshold, degradation in fiber fracture strength occurs. Fibers coated with lower refractive index coating provide better resistance to laser-induced damage.

ACKNOWLEDGEMENT

The authors would like to thank Steve Allen, Adam Hokansson, and Deb Simoff for their review of the manuscript.

REFERENCES

- [1] James A. Harrington, "An overview of power delivery and laser damage in fibers," Proc. SPIE Vol. 2966 (1997)
- [2] T. Schmidt-Uhlig, P. Karlitschek, G. Marowsky and Y. Sano, "New simplified coupling scheme for the delivery of 20MW Nd:YAG laser pulses by large core optical fibers," Appl. Phys. B, 72, (2001) 183.
- [3] Knudsen BE, Glickman RD, Stallman KJ et al, "Performance and safety of holmium: YAG laser optical fibers," J. Endourol, 1092 – 1097 (2005).
- [4] Xiaoguang Sun, Jie Li, Adam Hokansson, "Study of optical fiber damage under tight bend with high optical power at 2140 nm," Proc. SPIE, Vol. 6433 (2007).
- [5] Xiaoguang Sun, Jie Li, Adam Hokansson, Dan Whelan and Michael Clancy, "Study of laser-induced damage to large core silica fiber by Nd:YAG and Alexandrite lasers," Proc. SPIE, Vol. 7173 (2009)
- [6] R.D Maurer, "Behavior of flaw in fused silica fibers" in Strength of inorganic glass, Charles R. Kurkjian, ed. (Plenium Press 1985)