Study of optical fiber damage under tight bend with high optical power at 2140 nm

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Abstract

Expanding medical applications of laser power have resulted in an increase in demand for silica optical fibers, but these applications often require the fiber to endure the damaging combination of high laser power levels and increasingly tighter bends. In this study, we examine the damage to step index multimode fibers transmitting Ho:YAG laser light at a wavelength of 2140 nm when bent to a radius down to 5 mm and carrying an average power of up to 100 W. The results of different types of fibers are compared to gain more knowledge about the failure mechanism, among other relevant issues.

Keywords: Step index fibers, laser power delivery, Ho:YAG laser, bend and high power, laser damage

1. Introduction

Damage to the silica optical fiber while transmitting high laser power through a tight bend has become a serious concern as medical applications of silica optical fiber increase [1,2]. This damage raises concerns about the reliability and safety of the optical fiber under these circumstances, because in many cases, bending of fiber is necessary in these applications. For example, to reach the desired location in a patient's body and achieve uniform power distribution at the fiber output end, a section of the fiber must be bent or looped down to several centimeters in diameter, to enhance mode-coupling and to reach an even-modal power distribution.

In a typical laser lithotripsy, Ho:YAG laser power at 2140 nm wavelength is delivered by low-OH silica fiber. The fiber often undergoes sharp bends, down to a bend radius of 1 cm, to reach the lower pole stones in the kidney [2]. The typical fiber for Ho:YAG laser delivery is a step-index multimode fiber that has a pure silica core with F-doped silica cladding or has a Ge-doped silica core with pure silica cladding. The fiber has low-OH content so that the –OH absorption at 2.1 μm is sufficiently low enough.

The fiber fracture has been reported to occur under different laser power levels while being bent to different curvatures. Some occurred while the fiber was bent to a 10 mm of radius of curvature, transmitting a laser with energy as low as 200 mJ [2], while others occurred in a bend diameter of 5 mm of radius of curvature while transmitting kJ levels of laser energy.

In this paper we compare the performance of several fibers transmitting 100 W of Ho:YAG laser power at a wavelength of 2140 nm when bent to a radius down to 5 mm.

2. Experimental

The experimental setup used in our study was comprised of a laser and a two-point bend fiber strength tester, as shown in Figure 1.

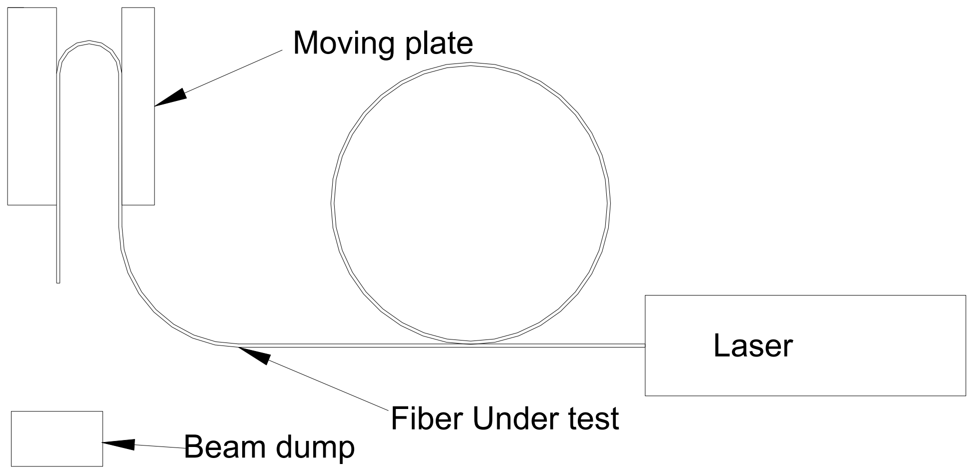


Figure 1 Experimental setup, 100 W of laser power is launched into the fiber when bent, excess fiber was looped into a diameter of 20 cm

The laser is a Lumenis Ho:YAG laser with a center wavelength of 2140 nm. It operates in a quasi-CW mode with a pulse repetition rate of 50 Hz and a pulse energy of 2 J. The two-point bend tester is a device commonly used to measure fiber strength through bending. It consists of a stationary plate and a moving plate which can be moved at defined speed. The fiber breakage is detected by a microphone with a time resolution of ~5 ms.

Table 1 Properties of fiber tested

	Sample-A	Sample-B	Sample-C
Core	365 µm, Pure silica		365 µm, Ge-doped
Cladding	400 µm, F-doped		438 µm, Pure silica
NA of core	0.22		0.29
Core/clad ratio	1:1.1		1:1.2
Fluoroacrylate coating	Type I	Type II	Type II
ETFE buffer diameter	550 µm	550 µm	730 µm

The three fiber samples tested were step-index multimode fibers with core diameters of 365 µm, labeled Samples-A, B and C, as shown in Table 1. Samples-A and B had pure silica cores and F-doped silica cladding with an NA of 0.22. Sample-C, however, had a Ge-doped silica core and pure silica cladding with an NA of 0.29. All three fibers had a UV cured fluoroacrylate coating and an ETFE buffer. While Sample-A is made using Type I coating, Samples-B and C are made using Type II fluoroacrylate coating. Sample properties are summarized in Table 1.

The fluoroacrylate coating has a lower refractive index than that of silica, so it can act as a secondary cladding that will guide light propagating in the silica cladding of the fiber. The index profile of the fibers is shown in Figure 2.

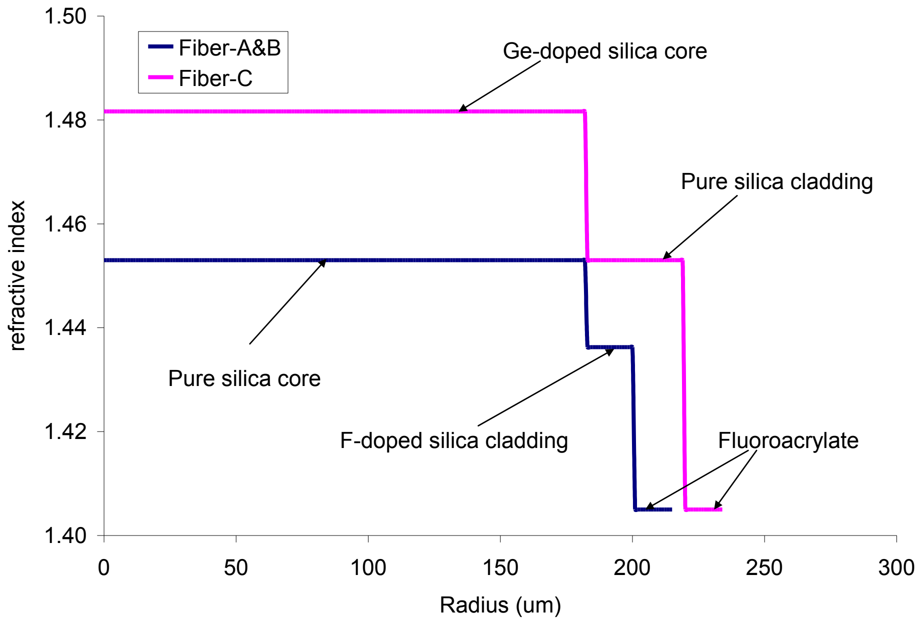


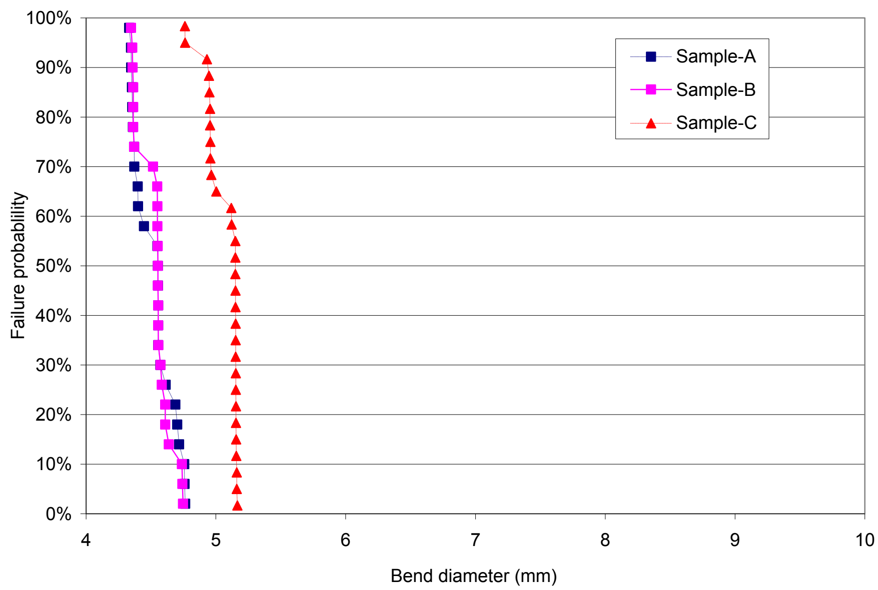
Figure 2 Index profile of Sample-A, B and C

The typical length of the fiber tested is about 5 m and the excess fiber is formed into a loop of a diameter of 20 cm. No section of the fiber was bent to less than a 10 cm radius between the laser launching end and the two-point bend tester.

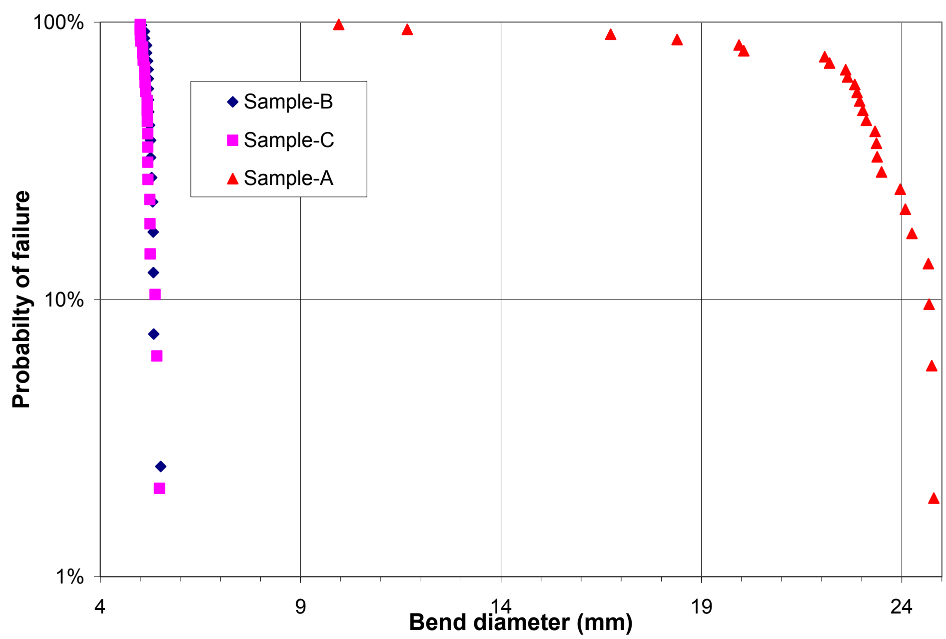
Two types of tests were carried out to measure the fiber performance under bend and laser power. The first test measured the bend diameter at the point of fiber breakage. Initially, the fiber is held between the two plates of the two-point bend tester, spaced at 25 mm. Then, the laser is switched on and the plate is moved inward at a constant speed of 2 mm/s. When the fiber breaks, the distance between the plates is recorded as the fiber breaking diameter. Between twenty and thirty measurements were performed for each fiber sample. Then the breaking diameters were sorted in descending order, and assigned a corresponding rank n, where $n = 1, 2, 3 \dots N$ (N is the total number of fibers tested). The cumulative failure probability, F_i, at bending diameter ranked at n is calculated using: $F_i = (n - 0.5)/N$ [3].

The second test measured the total transmitted power before the fiber fractured when it is bent to a fixed diameter. The fiber is bent to 12 mm, the laser is switched on, and then the total power transmitted before the fiber fractures is recorded. This procedure is repeated at a bend diameter from 6.5 mm to 5.5 mm. The total transmitted power vs. bend diameter is then plotted.

3. Results and discussion



(a)



(b)

Figure 3 Fiber failure probability vs. bend diameter for Sample-A, B and C

(a) No power (b) with power

In Figure 3 the Weibull distributions of the breaking diameter with 100 W of power for Sample-A, B, and C are plotted. The mechanical strength of the three fibers is close, as is shown in Table 2. Because Sample-C has larger buffer and glass diameters, the median breaking diameter appeared to be larger. When under 100 W of laser power, the median breaking diameter for Sample-A increased to 23.5 mm and had a wider distribution. The breaking diameter of Sample-B changed from 0.9 mm up to 5.47 mm, while there is almost no change in the breaking diameters of Sample-C with and without power.

Table 2 Summary of test results

		Median Breaking Diameter (mm)	Median Fiber strength (kpsi)	Weibull slope
Sample-A	No Power	4.52	995	28.5
	With 100W	23.5	-	17.6
Sample-B	No Power	4.53	993	46.5
	With 100W	5.47	-	63.6
Sample-C	No Power	5.15	1025	41.8
	With 100W	5.17	-	50.2

The breaking diameter under power for Sample-A is significantly lower than that for Sample-B despite having an essentially identical strength without power. The difference between these two fibers is the fluoroacrylate coating type. This comparison clearly indicates that the polymer coating plays an important role in determining the damage behavior of the fiber.

When optical fiber is bent, light guided inside the core of a fiber can leak into the cladding, and in turn, reach the polymer layer. Conceivably, with a higher absorption coefficient and lower laser damage threshold than the silica glass, the polymer material is more susceptible to laser damage, and therefore the mode of fiber failure may be caused by the polymer coating. Consequently, the properties of the polymer can greatly affect the performance of the fiber. It has been reported that lowering the index refraction of the polymer can improve the performance of single-mode fiber while under power and under bend [4]. Different polymer materials have similar optical properties and can behave differently under high power. A 600 µm core HCS fiber is tested to have a higher damage threshold of >8 mJ while another type of PCS fiber is at ~1-2 mJ [5]. Although the exact failure mechanism of this damage mode is yet to be understood, the comparison strongly suggests that the polymer coating plays an important role.

The second test, shown in Figure 4, measures the total transmitted energy before the fiber fractures when it is bent to a fixed diameter. The total transmitted energy is plotted as a function of the bend diameter for Samples-B and C. Sample-A is not shown in Figure 4 because it broke at 10 mm instantly when 100 W was launched into the fiber. The logarithm of the total energy transmitted and the bend diameter can be fitted linearly, and using the fitting result we can calculate the transmitted energy at any other bending diameter.

Sample-C can transmit more energy when bent to a fixed diameter than Sample-B can: for instance, when bent to 6 mm, Sample-B can transmit 2 kJ before breaking, while Sample-C can transmit more than 20 kJ. The difference of Sample-B and Sample-C lies in the fiber structures as shown in Figure 2: a) the NA of Sample-C is higher, and b) the index differences of the glass cladding and the polymer coating of Sample-C are higher than those of Sample-B. Thus, the bend loss from the core is lower in Sample-C than Sample-B [6]. We measured the bend loss in the two-point bend tester at 2.1 μm. The light is launched into the two fibers with a piece of fiber with a core size of 365 μm and NA of 0.22. The result is shown in Figure 5. At a 6 mm bending diameter, the bend losses of Sample-B and Sample-C are 38% and 12%, respectively.

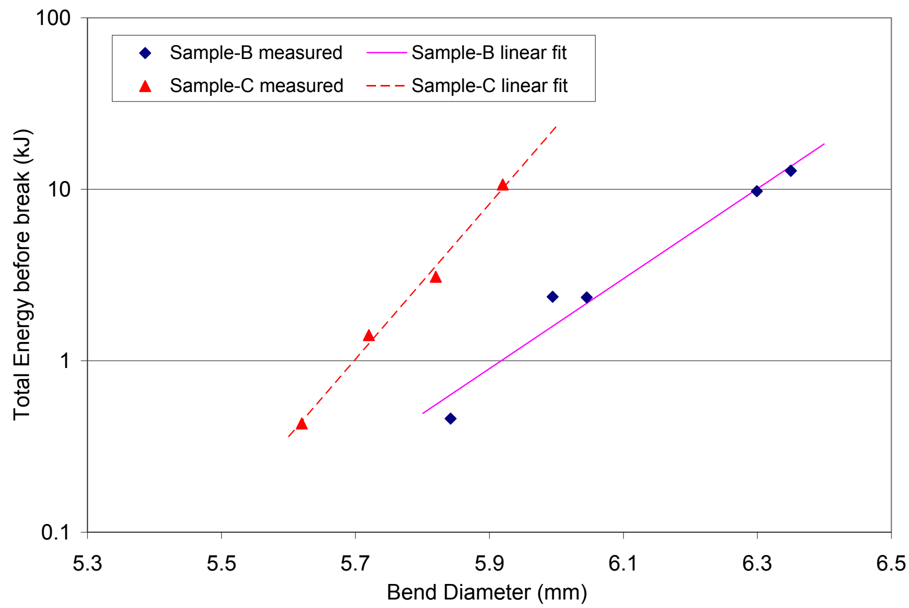


Figure 4 bend diameter vs. total transmitted energy

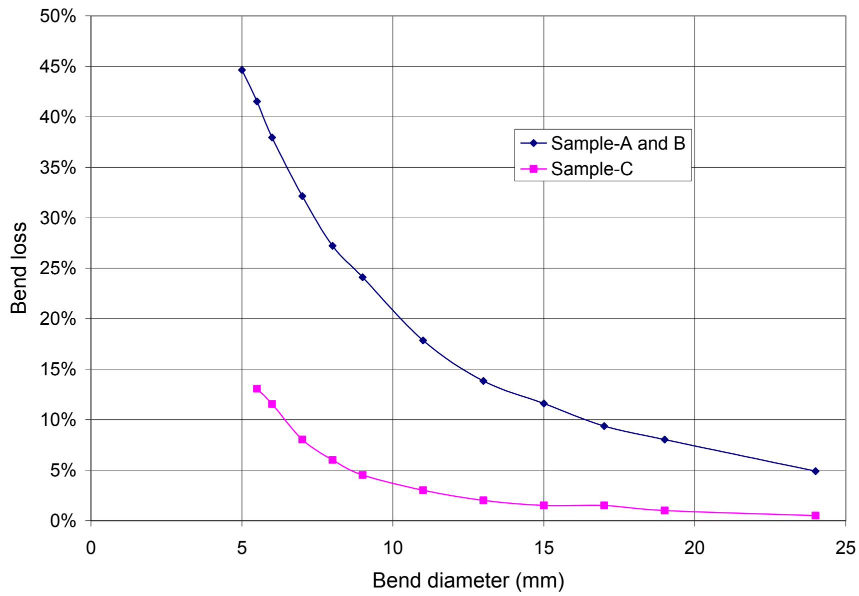


Figure 5 Bend loss of Sample-A, B and C at 2.1 um with 0.22 NA launching

In this experiment, the laser launching spot size was about 270 µm in diameter with a NA of less than 0.22. The transmission of the fiber with connector is more than 97% (excluding the reflection loss of the fiber ends), so most of the laser energy is in the fiber core. Thus, a higher NA with a low bending loss can reduce light leakage from the core when the fiber is bent, and improve the fiber performance under power, as we can see from the comparison of Sample-B and C.

4. Summary

In summary, we investigated the performance of fiber under bend and high power at 2140 nm. Polymer coating plays an important role, and by designing and manufacturing the coating to increase the threshold of laser induced damage, we could improve the fiber's performance under power. Clearly, Sample-C has shown a more superior performance and this fiber design is better suited for laser power delivery under a tight bend.

In the medical laser delivery application, especially laser lithotripsy, laser energy continues to increase, while the diameter of the mechanical bends the fibers are expected to make continue to decrease. Today, flexible endoscopes are drastically different than the semi-rigid scopes these fibers were originally designed to be used with. The improved fiber performance can improve overall safety and system performance.

5. Acknowledgement

6. References

[1] Knudsen BE, Glickman RD, Stallman KJ et al.”Performance and safety of holmium: YAG laser optical fibers”. J Endourol 2005;1092-1097.

[2] R. M. Percival, E. S. R. Sikora, and R. Wyatt, “Catastrophic Damage and Accelerated Ageing in Bent Fibres Caused by High Optical Powers,” Electron. Lett., 36 [5] 414–6 (2000).

[3] FOTP-028C “Measuring Dynamic Strength and Fatigue Parameters of Optical Fibers by Tension”

[4] G. Scott Glaesemann,w Michael J. Winningham, Donald A. Clark, Jeffrey Coon, Steven E. DeMartino,Stephan L. Logunov, and Ching-Kee Chien, “Mechanical Failure of Bent Optical Fiber Subjected to High Power”. J. Am. Ceram. Soc., 89 [1] 50–56 (2006)

[5] S. W. Allison, G. T. Gillies, D. W. Magnuson, and T. S. Pagano, "Pulsed laser damage to optical fibers", Appl. Opt., 32, 291 -297, 1993

[6] A. A. P. Boechat, D. Su, D. R. Hall, and J. D. C. Jones, "Bend loss in large core multimode optical fiber beam delivery systems," Appl. Opt. 30, 321-327 (1991)