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

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Abstract

Silica optical fibers are being increasingly used for delivering laser power in various medical applications. Laser damage to the optical fiber can occur when fiber is bent while transmitting high power laser light, leading to a serious concern for medical application. In many medical applications, small radius bend of the fiber is often required. In this study, we examined the damage of step index multimode fibers transmitting Ho:YAG laser power at wavelength of 2140 nm when bent to a radius down to 5 mm and carried an average power of up to 100W. We compared the results of different types of fiber and fibers made with different manufacture processes in an attempt to gain more knowledge about the failure mechanism. Other relevant issues are also discussed.

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

1. Introduction

Silica optical fibers are used for laser power delivery in the fields of industry, scientific and medical application etc. Damage to the silica optical fiber under bend with high power has been observed in both single mode and multimode fibers[1,2], and this raises concerns about the reliability and safety of optical fiber being tightly bent and under high laser power. Except accidental of bending of the fiber, in many applications of high laser power delivery by optical fiber, bending of fiber is necessary for various reasons. For example, to achieve a uniform power distribution at the fiber output end, a section of the fiber is bent or looped to several centimeters in diameter to enhance mode coupling to reach an even modal power distribution. In many medical applications, the optical fiber for laser power delivery often has to be bent to small radius to reach the desired location in the patient’s body.

In laser lithotripsy, Ho:YAG laser power at 2140 nm wavelength is delivered by low-OH silica fiber, the fiber can undergo sharp bends down to 1 cm to reach the lower pole stones [2]. The typical fiber for Ho:YAG laser delivery is 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 the –OH absorption at 2.1um is low. The fiber fracture has been reported to occur under different laser power levels while being bent to different curvatures. Some occurred while the fiber bent to a 10 mm of radius of curvature is under a laser power level as low as 200mJ [2] and others in a bend diameter of 5 mm of radius of curvature while transmitting kJ level of laser power.

In this paper we will measure the performance of several fibers transmitting 100 W of Ho:YAG laser power at wavelength of 2140 nm when bent to a radius down to 5 mm. We compared results to gain knowledge about the failure mechanism and find an optimized fiber solution for this application.

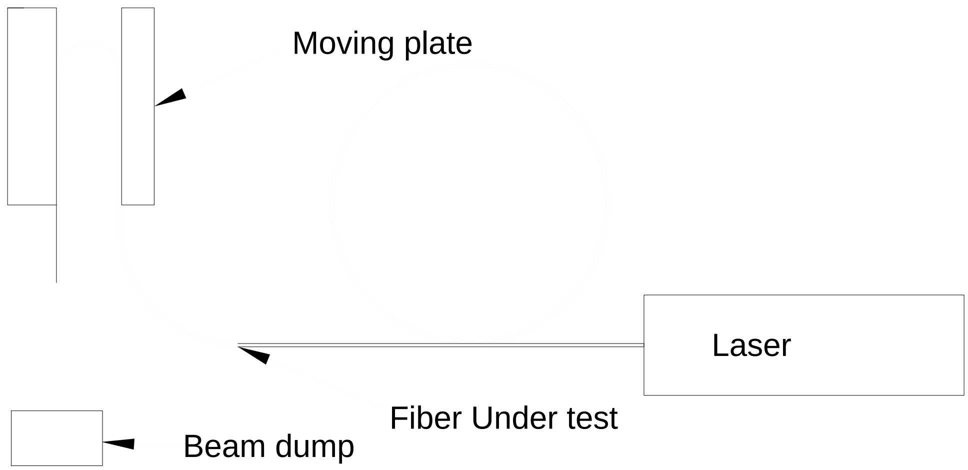

Figure 1 Experimental setup, 100W of laser power is launched into the fiber when bent, excess fiber was looped into a diameter of 20cm

2. Experimental

The experimental setup is illustrated in Figure 1. The laser is a Lumenis Ho:YAG laser with a center wavelength of 2140nm. It operates in qausi-CW mode and the pulse repetition rate is 50Hz and pulse energy of 2J.

Table 1 Properties of fiber tested

	Fiber-A	Fiber-B	Fiber-C
Core	365um, Pure silica		365um, Ge-doped
Cladding	400um, F-doped		438um, pure silica
NA of core	0.22		0.29
Fluoroacrylate coating	HCS®-1	HCS®-2	HCS®-2

The three fibers tested are step-index multimode fibers with a core diameter of 365um, labeled Fiber-A, B and C, as shown in Table-1. Fiber-A and B have pure silica core and F-doped silica cladding with NA of 0.22. Fiber-C has a Ge-doped silica core and pure silica cladding with NA of 0.29. All three fibers have UV cured fluoroacrylate coating and ETFE buffer. The fluoroacrylate coating has a lower refractive index than that of silica, so it also acts a second cladding that will guide light in the silica cladding of the fiber. The index profile of the fibers is shown in Figure 2. Fiber-B and C is made with optimized manufactured process of fluoroacrylate coating for power handling, and the fluoroacrylate coating is labeled as HCS®-2.

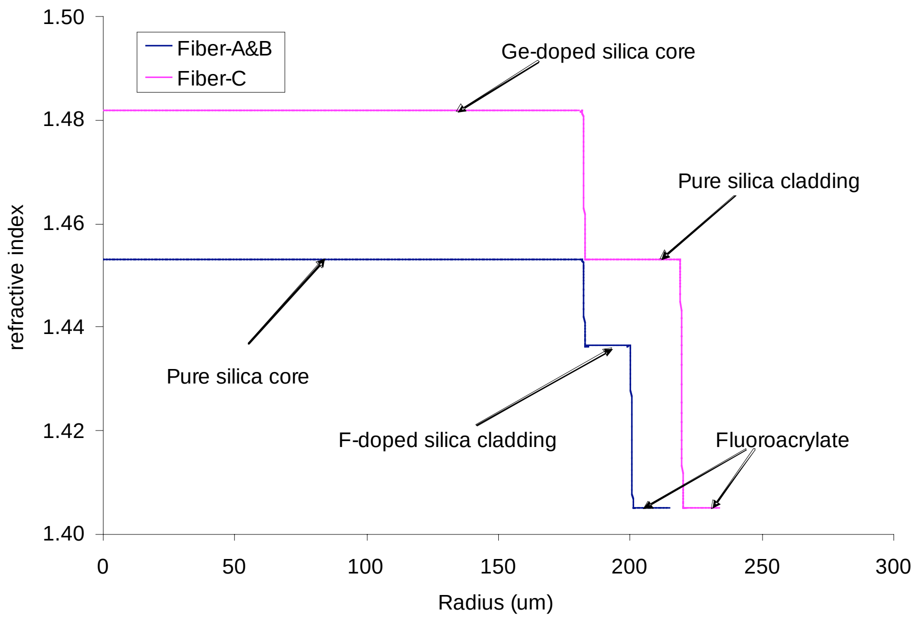

Figure 2 Index profile of Fiber-A, B and C

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

Two types of test were carried out to measure the fiber performance under bend and laser power. The first test measures the breaking diameter at constant jaw moving speed with laser power: the fiber was initially held between the two jaws of a two-point bend tester, spaced at 25mm. Then the laser is switched on and the plate is moved inward at a constant speed of 2mm/s. When the fiber breaks the distance between the plates is recorded as the fiber breaking diameter. 20-30 measurements were done for each fiber sample. Then the breaking diameters were sorted in descending order, then assigned a corresponding rank n, where $n = 1, 2, 3 \ldots N$ (N is the total number of fibers tested). The cumulative failure probability Fi at bending diameter ranked at n is calculated using: $F_i = (n - 0.5)/N$ [3].

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

3. Results and discussion

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

Table 2 Summary of test results

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

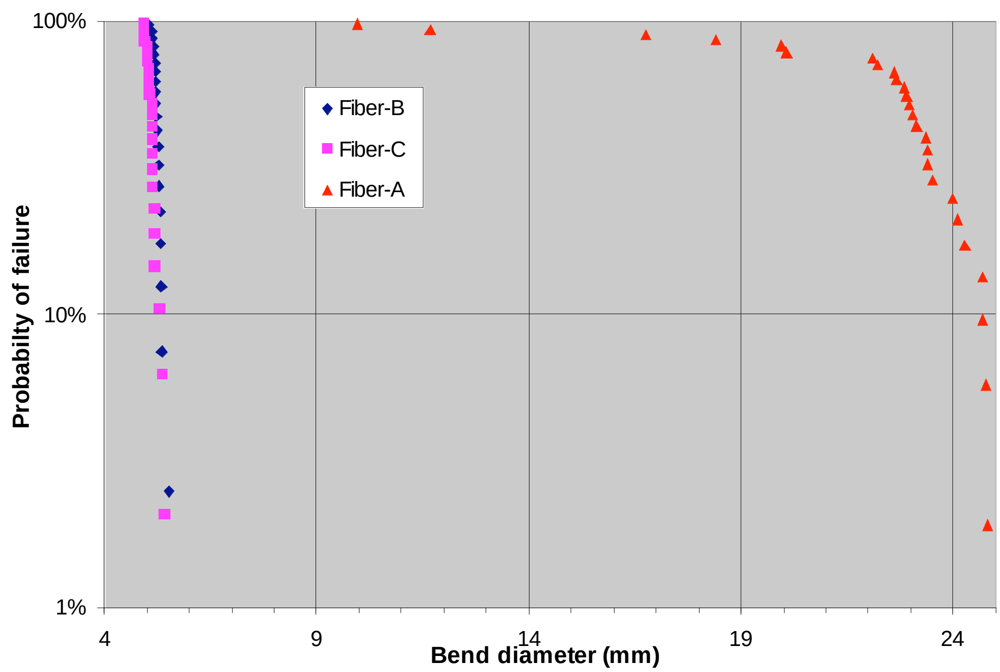

Figure 3 Fiber failure probability vs. bend diameter for Fiber A,B and C with 100W average power

The breaking diameter under power for Fiber-A and Fiber B is very different even though the strength of the two fibers without power is almost identical. The only difference of the two fibers is the fluoroacrylate coating labeled HCS-1 and -2 respectively. This indicates that the polymer coating plays an important role in this damage mode. When optical fiber is bent, light guided inside the core of a fiber can leak into the cladding and reach the polymer layer. Because the polymer typically has higher absorption and lower laser damage threshold than the silica, the polymer material is more susceptible. Since the damage can initiate at the polymer layer in this damage mode, the properties of the polymer can greatly affect the performance of the fiber. For example, the index refraction of the polymer was investigated- a lower-index coating can be improve the performance of single-mode fiber under bend and power[4]. Different polymer materials have similar optical properties can behave differently und high power-HCS fiber is tested to have higher damage threshold than other type of PCS fiber: for 600um core polymer fiber, HCS fiber's damage threshold is >8mJ while PCS is ~1-2mJ[5]. HCS-2 is design and manufactured to reduce the coating absorption and stress, increase the homogeneousness to increase the threshold of laser induced damage.

In Figure 4, we plot the total transmitted power vs. bend diameter for Fiber-B and C. Fiber-A is not shown in Figure 4 because it broke at 10mm instantly when 100W is launched into the fiber. The logarithm of the total energy transmitted and the bend diameter can be fitted linearly.

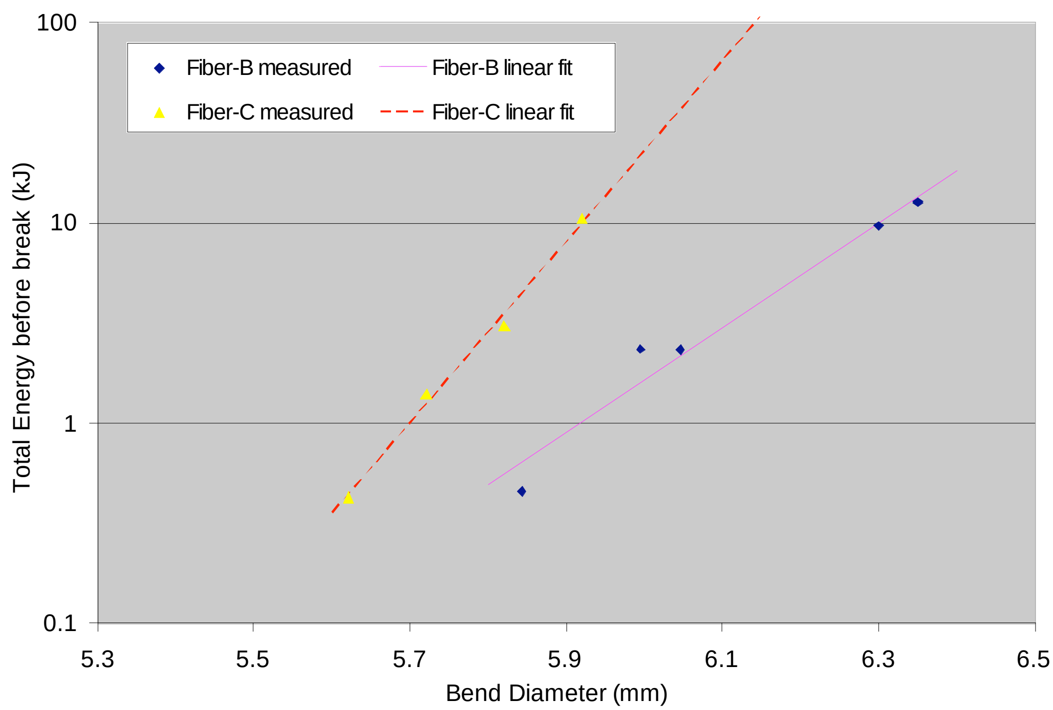

Figure 4 bend diameter vs. total transmitted energy

Fiber-C can transmit more power when bent to a fixed diameter than Fiber-B can: for instance, when bent to 6mm Fiber-B can transmit 2kJ before break while Fiber-C can transmit more than 20kJ. The difference of Fiber-B and Fiber-C lies in the fiber structures as shown in Figure 2: a) the NA of the fiber-C is higher; and b) the index difference of the glass cladding and the polymer coating of Fiber-C is higher than that of Fiber B. Thus the bend loss from the core is lower in Fiber-C than Fiber-B[6]. We measured the bend loss in a two point bender at 2.14um. The light is launched into the two fibers with a piece of fiber with a core size of 365um and NA of 0.22. The result is shown in Figure 5. At 6mm bending diameter, bend loss of fiber-B and Fiber-C is 38% and 12% respectively.

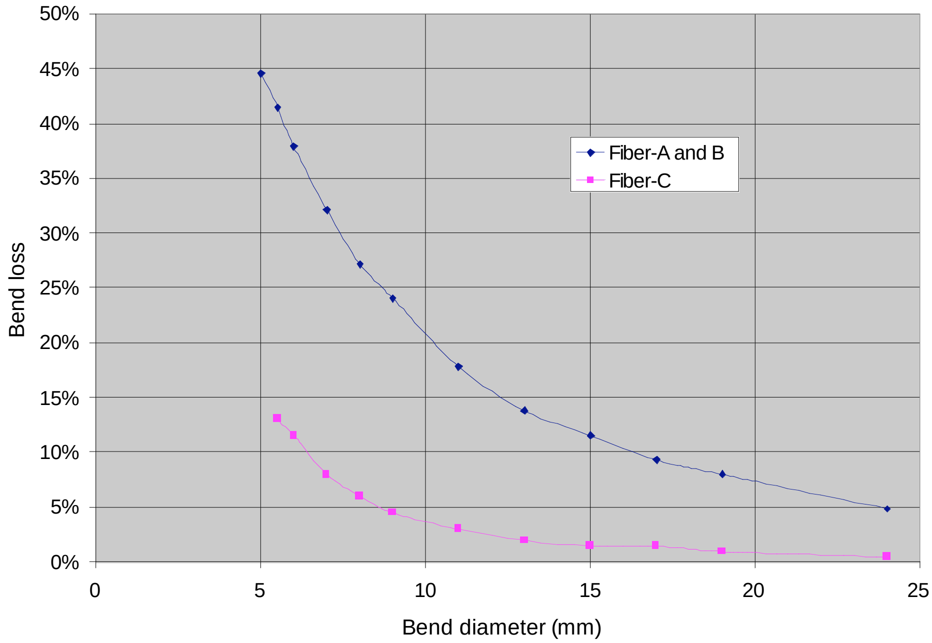

Figure 5 bend loss of Fluosil and Ultrasil fiber 272 at 2.1um with 0.22NA launching

4. Summary

In summary, we investigated the performance of fiber under bend and high power at 2140nm, Fiber-c with a lower bending loss and optimized low-index coating is better suited for laser power delivery under tight bend.

5. References

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