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Laser-induced damage studies on step-index, multimode fibers

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ABSTRACT

A previous investigation of laser-induced damage mechanisms and corresponding thresholds in step-index, multimode fibers was motivated by an interest in optical systems for firing explosives. In the initial study, the output from a compact, multimode Nd/YAG laser was coupled into fiber cores of pure fused silica. End-face polishing steps were varied between successive fiber lots to produce improved finishes, and each fiber was subjected to a sequence of progressively increasing energy densities up to a value more than 80 J/cm^2. Essentially all of the tested fibers experienced a "laser conditioning" process at the front fiber face, in which a visible plasma was generated for one or more laser shots. Rather than produce progressive damage at the front surface, however, this process would eventually cease and leave the surface with improved damage resistance. Once past this conditioning process, the majority of fibers damaged at the rear end face. Other modes of damage were observed either at locations of fixturing stresses or at a location of high static tensile stress resulting from bends introduced to the fiber.

Although the previous results were encouraging in terms of achieving useful damage thresholds, a number of areas for further study were indicated. In the present study, a similar experimental procedure was used to address these areas. The relative permanence of front-surface laser conditioning was examined by re-testing fibers that had experienced this process at least a year previously. End-face mechanical polishing was again examined by testing fibers prepared using a refined polishing schedule. Attempts to use a single fixture to hold an entire lot of fibers throughout end-face polishing and damage testing met with mixed results, with fiber positions subjected to fixturing stresses likely sites for initial damage. In an effort to prepare fiber faces with the improved damage resistance observed with front faces following "laser conditioning," two schedules for CO_2-laser polishing of end faces were developed and evaluated. Finally, to improve resistance to damage at sites with significant static stresses, fiber samples which passed a much higher tensile proof test during manufacturing were tested.

The current experiments were conducted with a new laser having a shorter pulsewidth and a significantly different mode structure. The beam was injected into the fiber using a geometry that had been successful in the previous study in minimizing a damage mechanism which can occur at the core/cladding interface within the first few hundred fiber diameters. However, the different mode structure of the new laser apparently resulted in this mechanism dominating the current results.

1. INTRODUCTION

Efforts to understand the basic mechanisms and the possible controls for laser-induced damage in optical fibers are motivated by growing interest in fiber applications requiring very high power transmission. Our particular interest is the use of laser-based optical firing systems to initiate explosives, thereby eliminating the risk of inadvertent firing by an unintended current in an electrical firing system. Very prompt initiation of a secondary explosive requires that a strong shock wave be generated in the material, and extensive earlier studies[1] examined the generation of such shock waves using the high power densities available from Q-switched, solid-state lasers.

Transmission of Q-switched laser pulses through optical fibers has only been examined in a few recent studies[2-5]. In our last investigation[5], the power transmission capabilities of a particular step-index, multimode fiber were examined in some detail. This fiber was selected because of its established resistance to attenuation induced by ionizing radiation. A small, rugged, multimode Nd/YAG laser was used in this study because of its similarity to the type of laser required for our firing system application. In preceding studies a common damage site had been at the core/cladding interface near the front fiber face, and to avoid this possibility a diverging beam was introduced into the fiber by positioning the entrance face

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downstream from the focal plane of a focusing lens. The emphasis in our previous study was the significance of surface finish on the fiber end faces, and a number of lots of fibers were tested in which the fiber faces in each lot were prepared following a particular mechanical polishing schedule. Following alignment, each fiber was subjected to a series of progressively increasing energy densities until either damage occurred or a value of 80 J/cm^2 was exceeded. Prior to permanent damage, nearly all fibers experienced a plasma-forming breakdown at the front face. Rather than produce observable damage, this "laser conditioning" process would cease after one to ten laser shots, leaving the front face highly damage resistant. The majority of fibers then experienced permanent damage at the fiber rear face.

In the present study, a number of follow-on activities suggested by the earlier investigation were pursued using similar experimental procedures. Several issues that were addressed are related to the "laser conditioning" process observed at the front fiber face. An important question is whether or not this effect is permanent. This was examined by re-testing fibers that had experienced this conditioning process at least a year previously. A second question is whether the resultant damage-resistant surface can be produced prior to testing by adding an additional processing step to the mechanical polishing schedule. Two schedules for CO_2-laser polishing of fiber end faces were developed and evaluated for this purpose. Because preparation and testing of many fiber samples is very tir.e consuming, we examined the use of a single fixture to hold a lot of fibers throughout polishing and damage testing. A refined schedule for mechanical polishing, intended to minimize subsurface defects that affect rear-surface damage thresholds, was evaluated. Finally, in an effort to improve damage resistance at fiber positions experiencing static stresses, fiber samples that met a much higher tensile proof test during manufacturing were examined. These samples also had an additional buffer layer to minimize handling-related damage. The only significant change in the experimental configuration for the present work was a necessary replacement of the Nd/YAG laser. Although the same model laser from the same manufacturer was used, the new laser had a shorter pulsewidth and a different mode structure. The changes in mode structure proved to be very important in terms of the dominant damage mechanism observed. The details of the experimental configuration and test procedures are briefly reviewed in the following section. The results of these studies are presented and discussed in subsequent sections.

2. EXPERIMENTAL APPROACH

The experimental configuration used for the present studies was described in detail previously[5]. The particular fiber examined continued to be FHP400/440/470 from Polymicro Technologies, Inc. This fiber has a 400-micron diameter core of pure, high-OH^- fused silica, a 440-micron diameter cladding of F-doped fused silica (resulting in a numerical aperture of 0.22), and a 15-micron thick polyimide buffer. The nominal tensile proof test achieved during manufacturing is currently 100 kpsi, but 75 kpsi was the test value for samples evaluated in our previous study. To improve resistance to damage at sites experiencing significant static stresses, one lot of fibers was tested from a production run having a tensile proof test of 150 kpsi. These fibers also had an additional 650-micron diameter buffer layer of acrylate to improve resistance to handling damage. The laser used was a Laser Photonics YQL-102 Q-switched Nd/YAG. This small oscillator-only laser has a folded-cavity design intended to preserve cavity alignment even during rough handling. In the previous study the nominal multimode output energy was 135 mJ at a pulsewidth of 16 ns. The new laser was found to have a nominal output energy of over 150 mJ at a pulsewidth of 13 ns. The mode structure was also found to be significantly different, and will be described in a subsequent section.

The geometry of the focused laser beam entering the fiber is shown in Figure 1. For some tests a plano-convex lens with a 100-mm focal length was used, with the front fiber face positioned 5.5 mm beyond the focal plane. The minimum beam diameter at the focal plane was approximately 250 microns, and the diameter of the diverging beam at the position of the fiber face was approximately 320 microns. In order to increase the beam divergence at the fiber face, some tests used a lens with a 75-mm focal length and the fiber face positioned 4.8 mm beyond the focal plane. In this case the minimum beam diameter was approximately 200 microns, and the diverging beam at the fiber face had the same 320-micron diameter. Figure 2 shows the nominal configuration of the fiber samples, with the likely sites for laser-induced damage identified.

The previous study[5] evaluated fibers prepared following a series of different conventional polishing procedures. Five lots of fibers were prepared, with each lot consisting of approximately twenty fibers polished identically. The two procedures that resulted in the best surface finishes were again used in the present study. In addition, a refined schedule aimed at minimizing subsurface defects was evaluated. The particular fiber polishing steps for these three schedules are listed in Table I. The numbering system in this table was chosen to be consistent with that used in the previous study. If the lot of polished fibers for a particular test had not previously been assembled into a fixture, these samples would be assembled into a linear array of ten to twenty fibers by sandwiching them between either microscope slides or grooved aluminum plates. These assemblies were then attached to optical mounts to provide all the necessary degrees of freedom for alignment. Prior to alignment, the fiber end faces were cleaned using acetone and methanol, and a freon duster. Once a fiber fixture had been carefully aligned with the incoming focused beam, only minor tuning was necessary when the next successive fiber to be tested was translated into position.

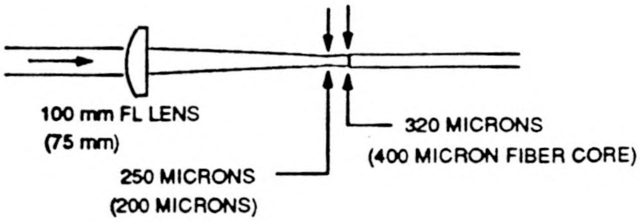


Fig.1. Geometry of the focused laser beam entering the fiber.

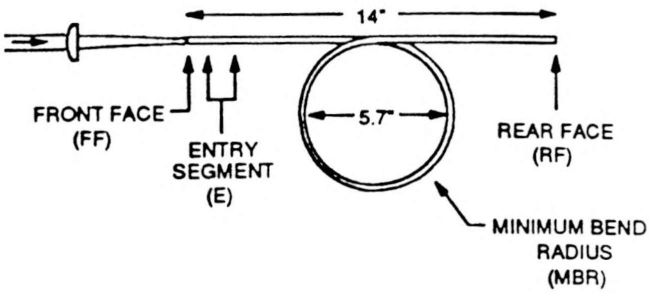


Fig.2. Probable sites for laser-induced damage.

Table I. Fiber Polishing Procedures

Lot #	Preparation	Surface Finish[a]
4	(a) #600, #800 SiC paper (b) 9, 3, 1 micron Al_2O_3 paper (c) nylon cloth, 5 micron diamond (d) chemomet cloth, 3 micron diamond (e) selvyt cloth, 1 micron diamond (f) selvyt cloth, 0.5 micron diamond	50 ± 15 A
5	(a),(b),(c),(d),(e) (g) selvyt cloth, 0.3 micron Al_2O_3 slurry	50 ± 15 A
6	(a), (b), (c), (d),(e) (h) selvyt cloth, 1 micron cerium oxide suspension	40-50 A

[a]peak-to-valley (Sloan stylus profilometer)

The test procedure for each fiber is the same as that used in the previous study, and is illustrated in Figure 3. After initial alignment with a co-linear HeNe laser, centering of the fiber was finalized by observing the transmitted energy while the Nd/YAG laser was operated at 1 hertz with a low pulse energy (≈3 mJ). After alignment was completed, the fiber sample was subjected to a series of single laser pulses, with the incident energy progressively increased with each pulse. As shown in Figure 3, twenty pulses were used to reach a maximum transmitted energy in excess of 100 mJ, corresponding to power and energy densities of 5.9 GW/cm^2 and 80 J/cm^2, respectively (based on the fiber core area and the 13 ns pulsewidth). If damage was detected prior to reaching the maximum test condition, the maximum transmitted energy before damage and the attempted transmitted energy at damage were recorded, together with the actual transmitted energy. Also shown on Figure 3 is a range of transmitted energies identified by "front face conditioning". In the previous study[5], essentially every fiber tested experienced one or more laser pulses in this energy range which produced a bright plasma at the entrance face. In most cases, however, the plasma formation would not result in observable damage at the fiber face. This process would typically stop occurring after a few pulses, with the fiber transmission returning to normal. Testing with progressively increasing pulse energies would then continue. Figure 4 shows the results obtained with the final lot tested during the previous study. The curve identified as "first transmission reduction" shows the percentage of fibers that reached a particular value of transmitted energy before the onset of "front face conditioning." The box in the figure identifies the sites where permanent damage occurred (Fig. 2), with ten fibers from this lot showing no damage ("ND").

3. INITIAL RESULTS

The initial testing during the present study addressed the permanence of "front face conditioning," the use of single fixtures to support an entire lot of fibers throughout polishing and damage testing, and a refined schedule for mechanical polishing. Figure 5 shows the results obtained using twenty fibers that had been tested at least a year previously. The entrance faces of all these fibers had experienced the conditioning process, and each fiber had subsequently completed the test sequence without evidence of permanent damage. No special care had been taken in storing these fiber samples, and only the standard pre-test cleaning was performed. Temporary front-surface breakdown occurred only once on one fiber sample. However, in contrast to the past results displayed in Figure 4, permanent damage occurred in every fiber at

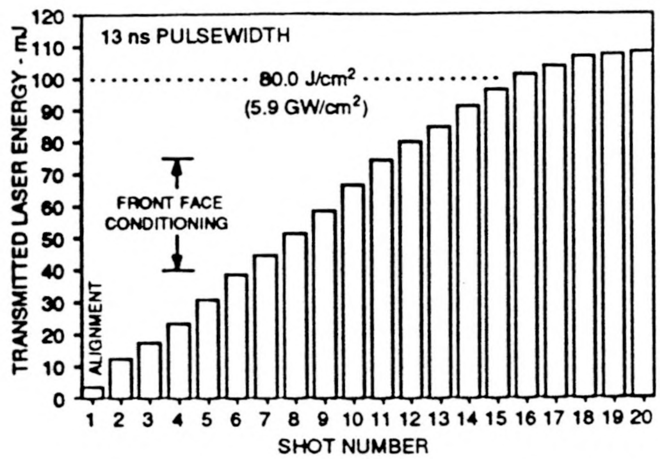


Fig.3. Test procedure used for each fiber.

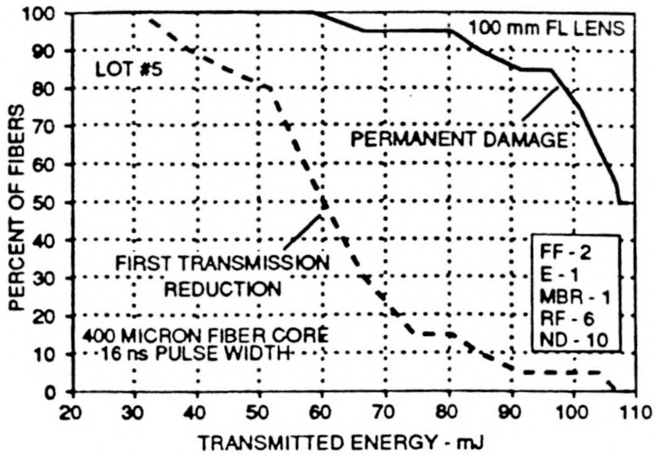


Fig.4. Results from the final lot tested previously[5].

relatively low energies. Most fibers damaged in the "entry" segment (Fig. 2). Because the permanent damage curve was shifted so much towards lower energies, the apparent "permanence" of the laser conditioning process on the front fiber faces is not as conclusive as desired.

Figure 6 shows the results of testing a lot of fibers prepared using the "lot #5" polishing schedule (Table 1). The fibers in this particular lot had been permanently epoxied into a fixture for support throughout the polishing and damage-testing processes. 480-micron diameter holes were drilled through the 5-mm thick aluminum fixture to hold twenty fibers in a rectangular array on 2.5-mm centers, and the complete assembly was easily held in a standard mount for 25-mm diameter optics. The front fiber faces extended 10 mm from the support plate. To provide stress relief for the fibers when they were looped into the test configuration (Fig. 2), flexible plastic tubes approximately 25 mm in length were epoxied to the rear of this fixture to support each fiber individually. The results in Figure 6 show that every fiber in this fixture damaged within the "entry" segment at surprisingly low energies. In fact, the damage sites for all twenty fibers were located within a 7-mm length of the fiber centered approximately 6 mm behind the rear surface of the fixture. This extreme consistency in damage location indicates that fixturing stresses - perhaps due to shrinkage in the epoxy used for the support tubes - were responsible for the onset of fiber damage.

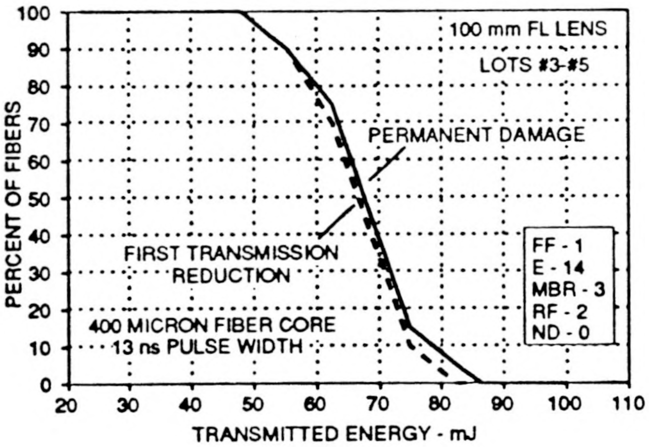


Fig.5. Results from re-testing fibers tested a year previously.

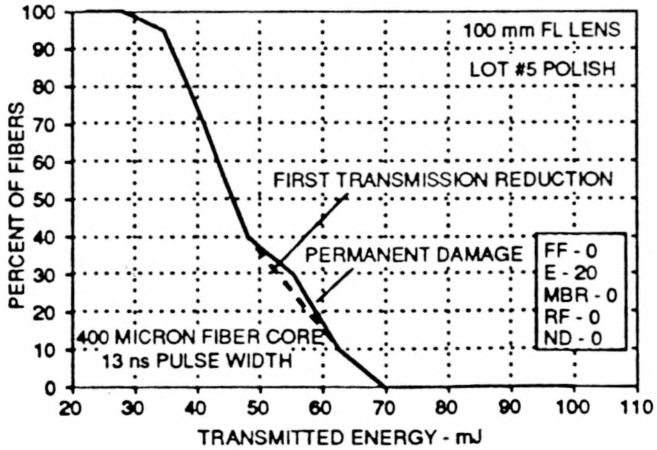


Fig.6. Results from testing fibers in a permanent fixture.

In the previous study the majority of fibers damaged at the rear end face from a mechanism believed to be sensitive to subsurface defects[5]. To minimize the subsurface damage generated during polishing, a lot of fibers was prepared using a cerium oxide suspension in the final polishing step[6]. The results from testing these fibers are shown in Figure 7. Although the permanent damage curve is shifted to higher energies than in Figs. 5 and 6, nearly all fibers damaged in the "entry" segment rather than at the end face. These damage sites varied from 8 to 47 mm beyond the front face, with no apparent relation to the location of the grooved aluminum plates holding the fibers in a temporary linear array for testing.

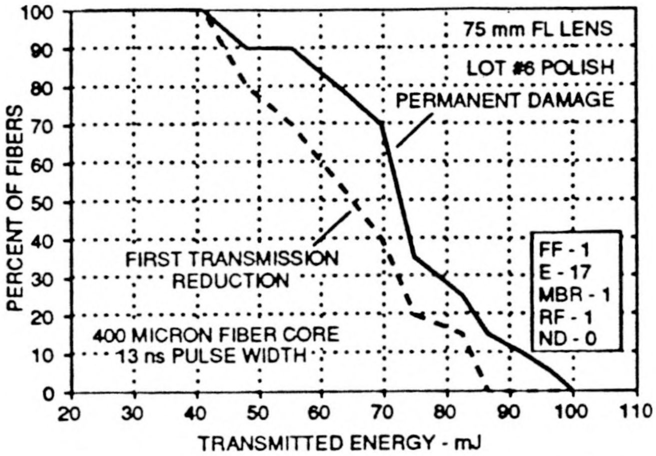


Fig.7. Results from testing fibers with the "lot #6" polishing schedule.

Unfortunately, the dominance of the "entry" damage mechanism minimized the possibility of seeing improvement in rear-face damage thresholds resulting from this refined polishing schedule.

4. RESULTS WITH CO_2-LASER POLISHED FIBERS

An important objective of the present study was to determine whether or not the damage-resistant surfaces produced by the "front face conditioning" process observed in the previous study could be produced by adding a controlled preparation process to an existing fiber polishing schedule. Two likely possibilities for this additional process were flame polishing and CO_2-laser polishing. Of these choices, CO_2-laser polishing of fused silica surfaces had been more carefully examined in previous studies for an effect on laser-induced damage thresholds. Temple et al.[7] found a significant improvement in the damage threshold of bare fused-silica surfaces following an optimized schedule of surface heating by a scanning CO_2 laser beam. Weber et al.[8] also found increased thresholds for fused silica surfaces conditioned with a large-diameter CO_2 laser beam, but noted that non-optimum conditioning could be detrimental.

The experimental configuration shown in Figure 8 was assembled in order to investigate the possibility of preparing improved fiber end faces. Conditioning was achieved by subjecting fiber faces to a CO_2 laser beam whose power was increased with time up to some peak value, then returned to zero. The faces were positioned beyond the focal plane of a 125-mm focal length lens, with the position varied to control the uniformity of the incident intensity. A magnified video camera was used to help align the fiber and to observe the conditioning process. The fiber face was also examined during conditioning using a Vanzetti pyrometer. Because of temperature variations across the face and a marginal instrument response time, the pyrometer provided only a qualitative measure of surface temperature. The laser output power and the pyrometer output were recorded for each fiber using a dual-channel, strip-chart recorder. Examples of these signals are shown in Figure 9, together with nominal values for two schedules that were used on fiber lots for damage testing. The first schedule had less intensity variation across the fiber face, and a lower pyrometer response. The second schedule would typically leave a fiber face with significant rounding near the edge (within the cladding layer), and possibly a slight deviation from planarity across the core. The first schedule produced only slight edge rounding.

Figure 10 shows the results of damage testing the first lot of CO_2-laser polished fibers. Only the entrance faces were conditioned using the first polishing schedule. This lot of fibers was mounted in a single fixture throughout the polishing and testing processses (as described in the previous section), but with this fixture no modifications were made in an attempt to provide external stress relief. As can be seen in Fig. 10, the additional processing with the CO_2 laser did not prevent front-surface breakdown ("first transmission reduction") from occurring. In fact, these fibers showed this effect at the lowest energies of any lot tested. This lot also showed the unexpected result of permanent damage occurring at the minimum bend radius for most fibers. Figure 11 shows the results of damage testing an identical lot of fibers, except the front faces had been conditioned using the second CO_2-laser polishing schedule. Only one curve appears in this figure, because none of the fibers showed front-surface breakdown prior to permanent damage. Damage at relatively low energies within the "entry" segment again dominated the results, preventing a more definitive statement on the usefulness of the CO_2-laser conditioning.

Figure 12 shows results obtained with a lot of fibers that had passed the higher (150 kpsi) tensile proof test during

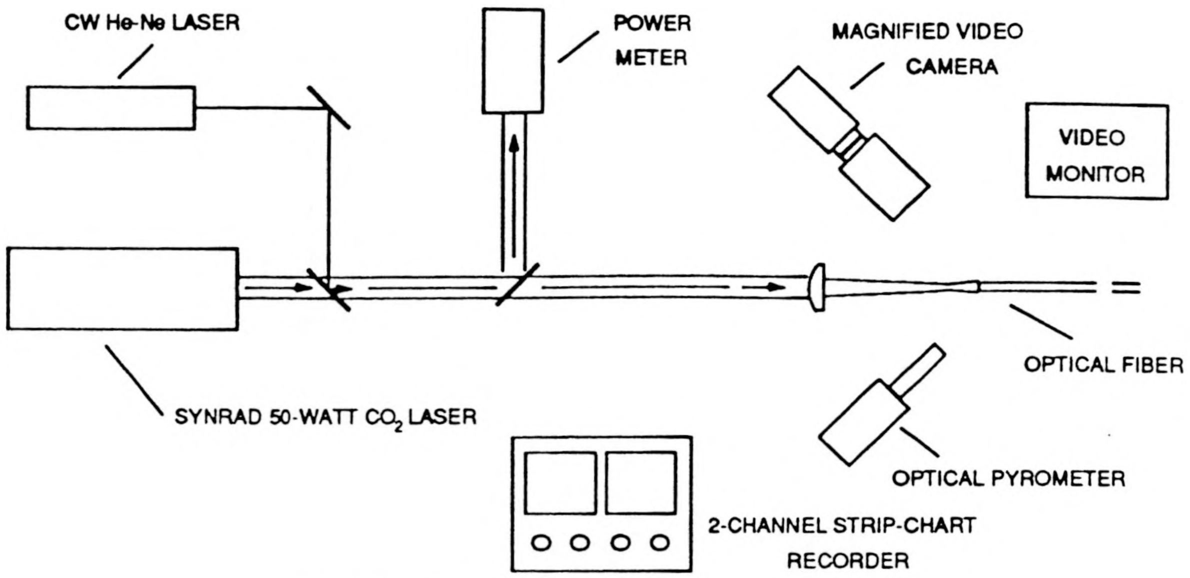
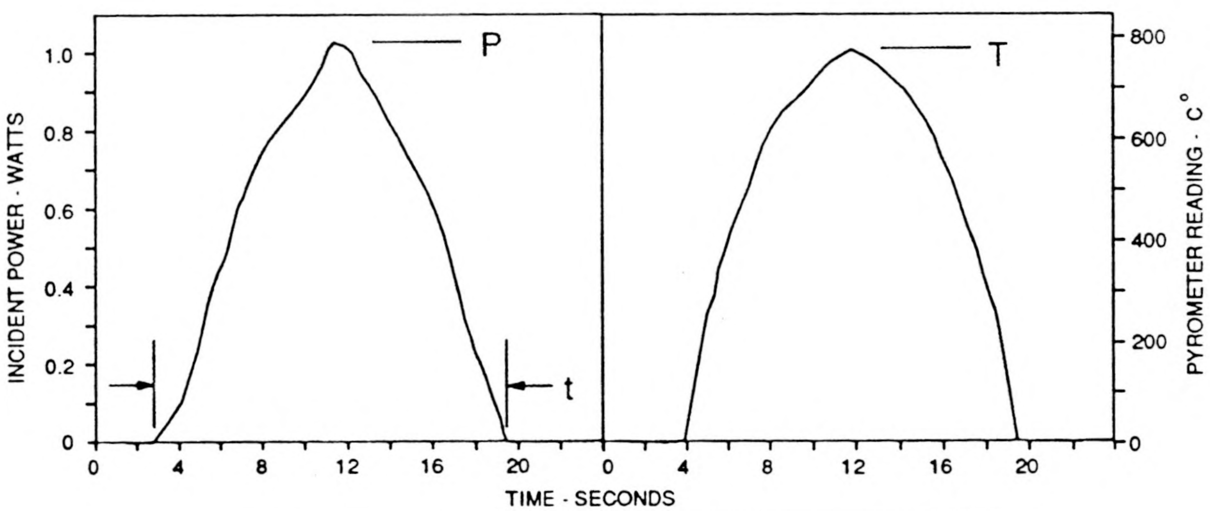


Fig.8. Experimental configuration for CO_2-laser polishing of fiber faces.



SCHEDULE:	#1		#2	
	mean	std dev	mean	std dev
PEAK POWER - P	1.32	0.06	0.97	0.09
PEAK TEMPERATURE - T	695	75	795	21
TOTAL TIME - t	21.2	0.4	16.1	0.4
FIBER FACE POSITION	FOCUS + 10 mm		FOCUS + 5 mm	

Fig.9. Laser power and pyrometer characteristics for two polishing schedules.

manufacturing, and that also had an additional acrylate buffer layer to minimize handling damage. This lot was also conditioned using the second CO_2-laser polishing schedule. Only one fiber showed front-surface breakdown, and the permanent damage curve is shifted to higher energies than in the previous figure. Damage within the "entry" segment occurred in nearly every fiber.

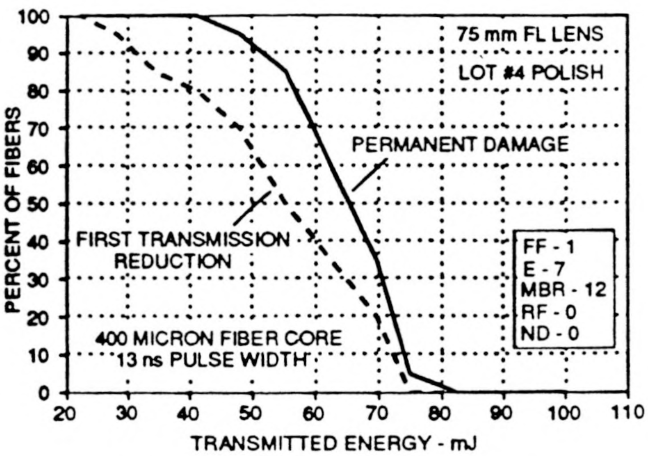


Fig.10. Results using the schedule #1 CO_2-laser polish.

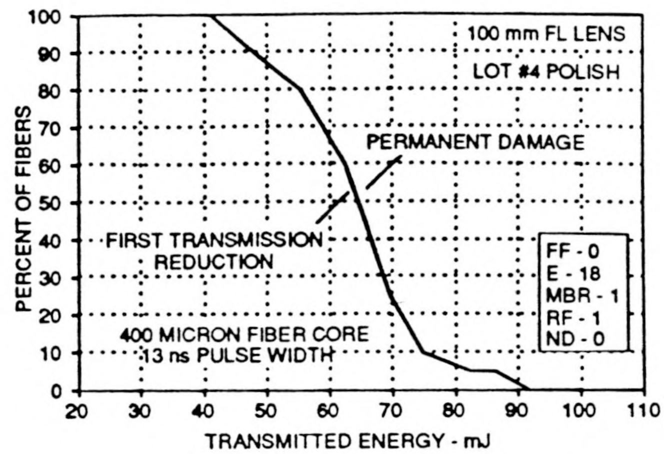


Fig.11. Results using the schedule #2 CO_2-laser polish.

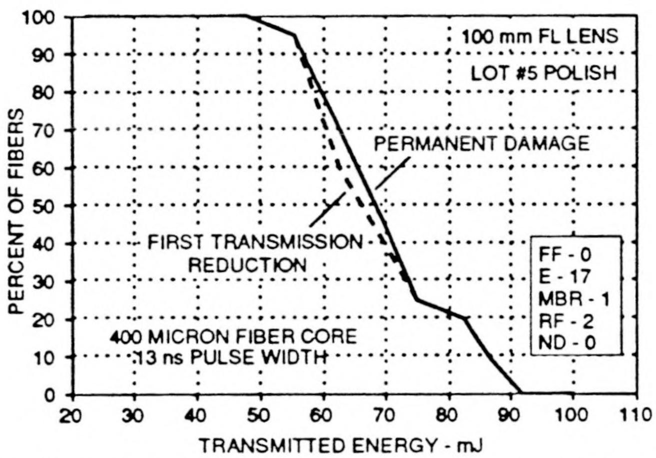


Fig.12. Results with the high tensile strength fiber, with schedule #2 CO_2-laser polish.

5. DISCUSSION

As was noted in our earlier study[5], the logistical difficulties in working with optical fibers limits the practical number of fibers that can be tested, and results in a test procedure that can not determine damage thresholds as typically defined when many one-on-one tests can be performed. The testing results can be dependent on the characteristics of the multimode laser used, as well as on the particular geometry used to introduce the beam into the fiber. The dependence on laser characteristics is very evident in comparisons between the current and previous results. All aspects of the experimental approach were preserved in the current study except the laser used for damage testing. In the previous study the dominant mechanism for permanent damage was cratering or edge fracturing at the rear fiber face, but in the present study most fibers damaged within the "entry" segment at significantly lower energy densities. Earlier fiber studies[2-4] that had encountered this damage mechanism attributed it to high intensities formed locally within the core during initial reflections at the core/cladding interface. This mechanism was apparently enhanced by better beam quality (near-Gaussian instead of multimode), fiber entry with a collimated beam (instead of divergent), and beam misalignment with the fiber axis. The current study shows that using a multimode laser injected with high divergence and good alignment into a fiber is not sufficient to prevent this damage mechanism from prevailing.

To provide some further insight into laser characteristics that can result in this damage mechanism, the mode structure of our current laser was examined using a GE Model TN2509 solid-state camera and Big Sky Software beam profiling software. In addition to near-field and far-field profiles, an imaging system with a magnification of ten was used to obtain beam profiles in the region where the fiber entrance face is positioned during damage testing. Figure 13 shows intensity contours from some of the profiles obtained, together with contours from a beam profile that had been obtained with the previous laser. The near-field characteristics of the previous laser are depicted in Figure 13a. The two regions of higher intensity near the top of the beam typically showed peak values less than 50% above average intensities across most of the cross section. Figure 13b shows the near-field characteristics of the laser used in the current study. This beam is less symmetric, with regions of higher intensity in the upper-right and lower-left quadrants. Peak values in these regions are typically 70-80% above average intensities across most of the cross section. Figure 13c shows beam characteristics at the position where the laser enters the fiber face during damage testing. The "horseshoe" pattern appears to preserve features seen in the near-field profile (Fig. 13b). Regions of higher intensities can be seen in the same two quadrants, with peak values in the upper-right quadrant now exceeding average intensities by a factor of three. This pattern continued in profiles taken farther from the focal plane, as shown in Figure 13d. The far-field pattern showed the same general shape and the same two regions of higher intensities as evident in the the other profiles. The mode structure shown in Figures 13b-13d is an example of laser characteristics that will result in damage within the "entry" segment of a fiber. The characteristics that a multimode laser must have to ensure that this damage mechanism will not dominate is clearly a relevant question, and a challenging subject for further studies.

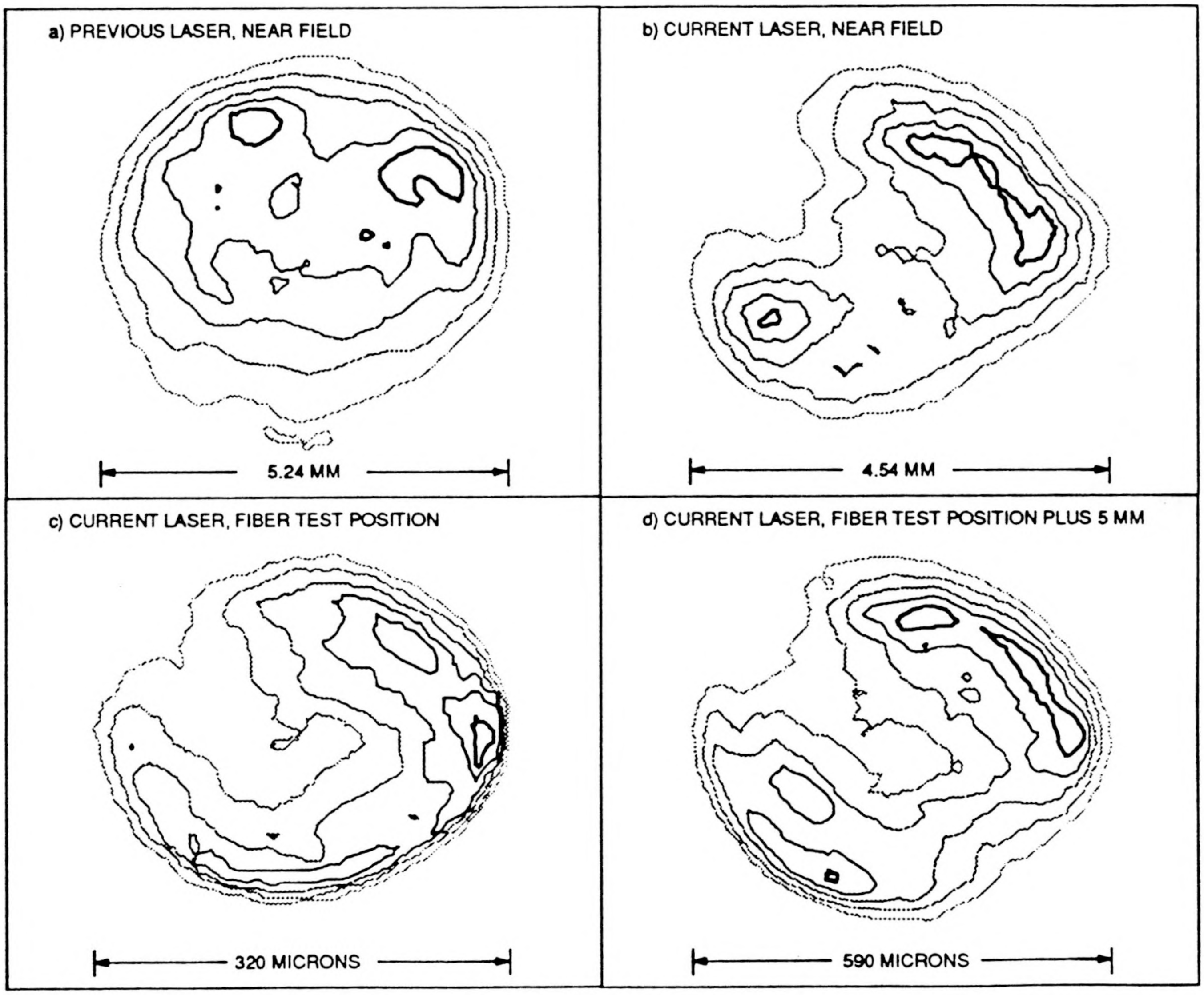


Fig.13. Beam profiles of lasers used in previous and current studies.

Because of the dominance of the "entry" damage mechanism in the present studies, a number of current objectives were not satisfactorily met. The "permanence" of the front-face conditioning effect observed in our previous study (Fig. 5), the value of a refined polishing schedule (Fig. 7), the potential benefits of CO_2-laser polishing (Figs. 11 and 12), and the advantages of higher tensile strength fiber (Fig. 12) were all unresolved to some extent because "entry" damage was occurring at relatively low energy densities. CO_2-laser polishing, in particular, appears to be attractive for further investigation. The absence of front-face breakdown during the testing summarized in Figures 11 and 12 is especially encouraging considering the severe "hot spot" at this surface (Fig. 13c). An important possible benefit that remains to be demonstrated is an improvement in rear-surface damage thresholds due to CO_2-laser conditioning. Such an improvement could result from a reduction in subsurface defects that may be responsible for rear-surface damage once the finish of this surface is fairly good[5]. To investigate this possibility, fiber faces that had experienced the two CO_2-laser polishing schedules (Fig. 9) were examined microscopically following removal of approximately one micron of material by timed etching in a 15-percent solution of hydrofluoric acid. Control fibers that had only experienced the same mechanical polishing procedures were also examined. As was noted in similar studies of fused silica substrates[8], the CO_2-laser polished samples showed fewer subsurface remnants from the mechanical polishing. The results shown in Figures 11 and 12 indicate that an appropriate laser-polishing schedule can probably be developed to achieve significant benefits with respect to front-surface breakdown, and a similar schedule should be pursued to establish if measurable benefits at rear fiber faces can also be achieved.

A final note concerns the surprisingly consistent damage that occurred in fibers that apparently experienced unusual fixturing stresses (Fig. 6). These results and previous findings[5] clearly indicate that fiber positions having significant static stresses can be sites for laser-induced damage at relatively low energy densities. Damage occurring at stressed fiber sites may be related to the presence of defects such as microcracks at those sites. Fiber manufactured with a higher tensile proof test (Fig. 12) will have fewer defects formed during the fiber drawing process, and should be more resistant to growth of these defects in time. The relationship between local stresses, time-dependent local defects, and damage thresholds is obviously an important area for further study. Practical applications will require that the nominal energy densities to be transmitted through fibers have a clear margin with respect to damage thresholds, and that this margin be maintained throughout the projected lifetime of the system.

6. ACKNOWLEDGMENTS

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