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Very High Intensity Fiber Transmission Systems

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ABSTRACT

Various applications are currently motivating interest in the transmission of very high laser intensities through optical fibers. As intensities within a fiber are increased, however, laser breakdown or laser-induced fiber damage will eventually occur and interrupt fiber transmission. For a number of years we have been studying these effects during the transmission of Q-switched, Nd/YAG laser pulses through step-index, multimode, fused-silica fiber. We have found that fiber transmission is often limited by a plasma-forming breakdown occurring at the fiber entrance face. This breakdown results in subtle surface modifications that can leave the surface more resistant to further breakdown or damage events. Catastrophic fiber damage can also occur as a result of a number of different mechanisms, with damage appearing at fiber end faces, within the initial "entry" segment of the fiber path, and at other internal sites due to effects related to the particular fiber routing. An overview of these past observations is presented, and issues requiring further study are identified.

1. INTRODUCTION

Applications that are currently motivating interest in high-intensity laser transmission through optical fibers include certain medical procedures, laser acceleration of metal flyers for studies of material behavior under dynamic loading, and prompt initiation of secondary explosives using methods inherently safe from accidental electrical currents. For a number of years we have been examining several of these applications using Q-switched, Nd/YAG laser pulses transmitted through relatively large ($\leq$ 400 µm), step-index, fused-silica fiber. One goal has been to establish how much pulse energy could be transmitted through a given fiber size before the onset of breakdown and damage processes. The various limiting processes that we have observed in these studies are indicated in Fig. 1.

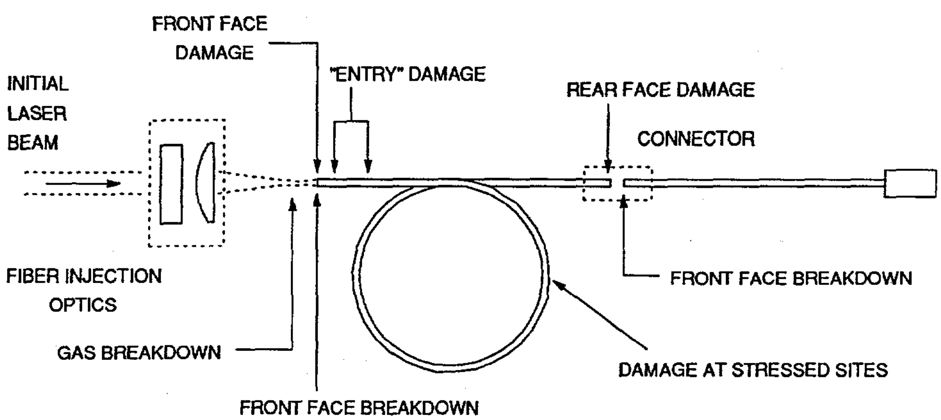

Fig. 1 Breakdown/damage processes in a high-intensity fiber transmission system

We have found that for a given laser and fiber configuration, the particular breakdown or damage mechanism that will dominate and its corresponding threshold will generally depend on three factors: laser characteristics, the design and alignment of laser-to-fiber injection optics, and fiber end-face preparation. Subsequent sections of this paper will address these factors, as well as effects that can arise due to fiber routing. The final section will identify current issues of interest.

2. LASER CHARACTERISTICS AND INJECTION OPTICS

Relevant laser characteristics can be divided into three areas: basic parameters (wavelength and pulsewidth), transverse mode characteristics, and spectral linewidth. Threshold fluences for breakdown and damage generally decrease with decreasing wavelength and pulsewidth.[1] For high-intensity transmission through fibers, use of either a TEM_{00} beam or a multimode beam with undesirable mode characteristics can lead to difficulties. Three concerns arise when using TEM_{00} lasers: breakdown or damage at a focus within the laser-to-fiber injection segment, damage within the initial portion of the fiber path due to a narrow initial mode power distribution generated in the fiber, and the onset of nonlinear effects within the fiber. In our applications we have been able to avoid these TEM_{00} concerns by using oscillator-only, highly multimode lasers. However, we have found that undesirable transverse mode characteristics can also result in severe limitations. Strong "hot spots" in the output profile of a multimode laser can lower thresholds both for laser breakdown and for laser-induced damage within the initial portion of the fiber path.[2] We try to mitigate such "hot spots" through laser cavity design and alignment, and through the design of injection optics. Using beam-profiling methods, a figure of merit for cavity design and alignment can be established by measuring the ratio of the total beam energy to the peak local fluence. This ratio, which has units of area, will be much smaller for a profile with strong "hot spots" in comparison to its value for a fairly broad, flat profile. In practice, design changes and alignment are typically used to increase this ratio as much as possible for the laser's far-field profile without reducing the pulse energy below required values.

The spectral linewidth of a laser depends on the lasing medium's gain profile and the number of axial cavity modes within that profile. A smaller linewidth corresponds to greater temporal coherence, which enhances interference between propagating modes in a fiber. The intensity distribution across the exit face of a relatively short fiber (a few meters) can then have strong interference maxima and minima,[3] which may be undesirable for some applications. For longer fiber paths ($\geq$ 10s of meters) a smaller spectral linewidth will result in earlier onset of nonlinear effects, particularly stimulated Brillouin scattering.[4]

Once laser characteristics are fixed, the next factor that can influence breakdown and damage thresholds is the design and alignment of the laser-to-fiber injection optics. The simplest approach is to use a single plano-convex lens to focus the beam to a diameter less than the fiber core diameter, and then position the fiber entrance face as far downstream as possible without overfilling the fiber core. One obvious limit to this approach is the onset of gas breakdown in the focal plane. Nevertheless, previous studies have established that certain damage processes can be inhibited if the beam is diverging when entering the fiber.[5] These "entry" damage processes typically occur within an initial length of the fiber path corresponding to 50-100 fiber core diameters, and result from very high local fluences due to internal focusing of the beam by the fiber walls. Poor alignment between the laser beam axis and the fiber axis can also produce this damage mechanism. Ideally, a laser beam should be injected into a fiber in such a manner as to quickly establish a broad, axisymmetric mode power distribution. This is very difficult in practice, and typically some propagation distance involving multiple wall reflections is necessary in order to mix fiber modes sufficiently to avoid local focusing and damage. The focal lengths of injection lenses should be as short as possible, as having higher beam divergence at the fiber entrance face enhances this mode-mixing process. The fast-developing field of diffractive optics is introducing a number of possibilities for injection optics designs that may offer far better beam characteristics entering the fiber than can generally be achieved with a simple lens.

Thresholds for breakdown and damage at the fiber entrance face will depend on the peak incident fluences on this fiber surface. By the use of magnified beam-profiling, the actual fluence distribution on a fiber entrance face resulting from a particular laser and injection optics combination can be established. One figure of merit for conditions at the fiber entrance face can be defined by the following "peak-to-average" ratio:

$$P/A = \frac{\text{peak local fluence}}{(\text{total incident energy})/(\text{fiber core area})}$$

One goal for a high-intensity fiber system is to achieve as low a value for this ratio as possible. Figure 2 shows fluence profiles at fiber entrance faces for different laser and injection optics configurations. In each case the complete profile is nearly axisymmetric. The corresponding values for the "peak-to-average" ratio range from 3.1 to 3.5. Figure 2a shows a multimode, "quasi-Gaussian" Nd/YAG laser focused with a single plano-convex lens. In Fig. 2b the same laser is used with a different lens and a

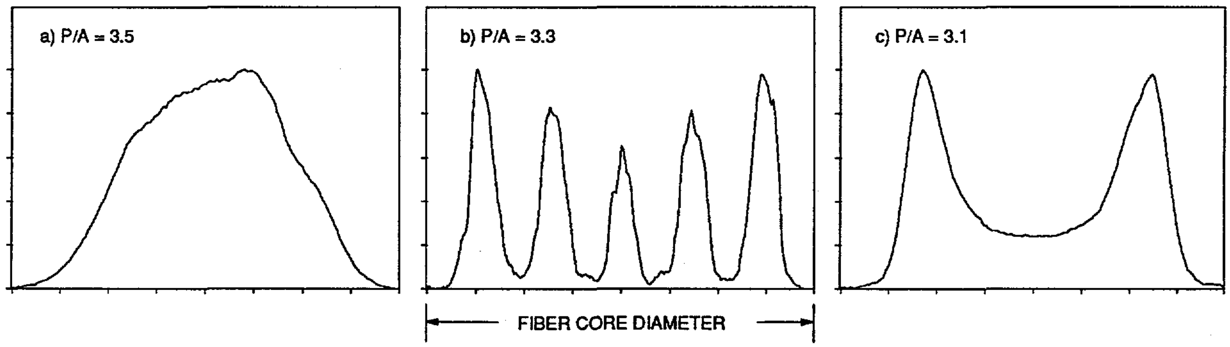

Fig. 2 Fluence profiles (horizontal scan through centroid) at the fiber entrance face for different laser and injection optics configurations

diffractive optical element. This diffractive element is designed to spread any "hot spots" in the laser's near-field profile into multiple locations on the fiber face. The "doughnut" profile shown in Fig. 2c is a commercial Nd/glass laser focused with a single plano-convex lens. This profile was the result of cavity changes and realignment that reduced the P/A ratio by more than a factor of two with no loss in output energy.

In several studies we found that fiber routing can affect the onset of internal damage mechanisms.[6,7] A standard configuration we have used in fiber testing consists of simple lens injection into fibers held in plastic fixtures. These fixtures are machined to carefully control the fiber path. A nominal plastic fixture introduces a 360°, 15-cm diameter loop to the fiber path following a straight entrance segment 18 cm in length. Various injection optics have been used with these fixtures in different studies. When a lens with a relatively long focal length was used for laser injection, internal damage was consistently observed within the fiber segment that transitions from the straight entrance path to the constant-diameter bend. The cause of this damage was determined to be very high local fluences at the "outside" of the bending fiber (farthest from the center of curvature) resulting from "whispering gallery" ray propagation in this fiber segment. Inspection of damaged fibers showed that damage consistently originated at defects near the core/cladding interface at the "outside" fiber position where local fluences were elevated. Such a damage process can be avoided by broadening the mode power distribution prior to the transition segment either by different injection optics or by mechanical mode mixing in the entrance segment.

3. FIBER END-FACE PREPARATION

Our earlier studies emphasized the role of fiber end-face preparation in determining breakdown and damage thresholds at the fiber end faces. If a good surface finish has been achieved through mechanical polishing at a fiber exit face, damage at this face will typically result from the presence of subsurface defects remaining from early polishing steps.[5] We have also observed exit face damage with cleaved surfaces, possibly due to subsurface fractures created during the cleaving process. This dependence on subsurface features for exit face damage results from a standing wave pattern during the laser pulse that produces peak intensities at discrete depths into the silica. In contrast, only the finish and composition at the silica/air interface will govern damage and breakdown at fiber entrance faces.[2,3,5] Figure 3 shows a summary of testing results in which different methods of end-face preparation were used.

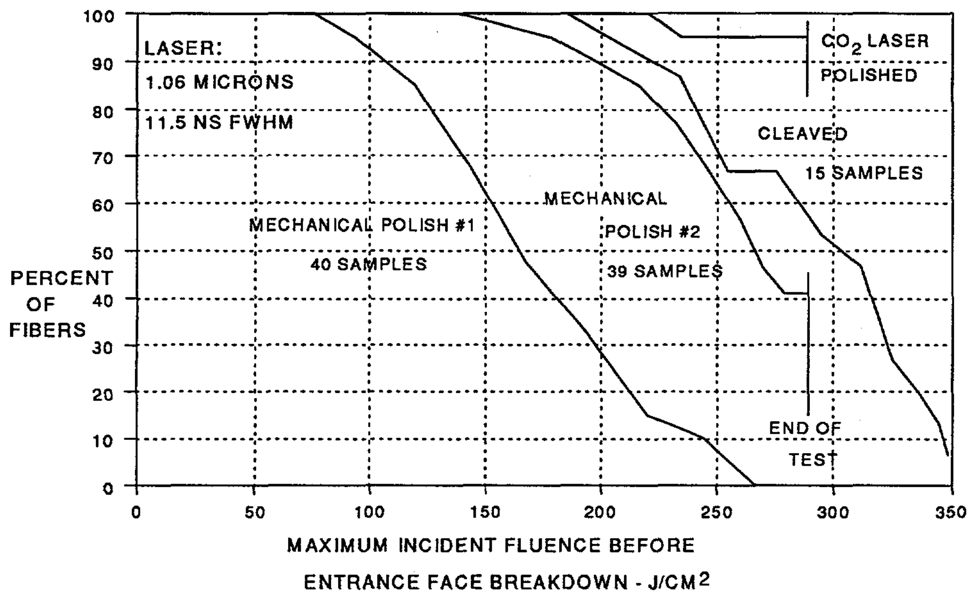

Fig 3. Fiber entrance face breakdown thresholds

In these tests, each fiber was first aligned with the focused laser beam at a very low pulse energy. The pulse energy was then progressively increased in subsequent single-pulse tests until entrance face breakdown - which occurred before any other breakdown or damage process - was observed. The curves show the percentage of fibers from a given test lot that survived up to a particular peak incident fluence before breakdown occurred. The "P/A" ratios at the fiber entrance faces during these tests ranged from 3.3 to 4.1, and most tests were performed on fiber having a 400 μm core diameter. For this fiber diameter and for P/A = 3.5, a peak incident fluence of 200 J/cm^2 corresponds to an incident pulse energy of 72 mJ. For a laser pulsewidth of 11.5 ns (FWHM), this corresponds to a peak power of 6.2 MW and a peak intensity of 17 GW/cm^2. The average fluence and the peak intensity within the fiber core (well beyond the entrance face) for this case are 57 J/cm^2 and 5.0 GW/cm^2, respectively.

4. ISSUES FOR FURTHER STUDY

The various curves in Fig. 3 indicate that surface conditions on fiber entrance faces can have a strong effect on the breakdown process that often limits transmission in a high-intensity fiber system. Despite numerous studies, a fundamental understanding of this process that can lead to threshold predictions is incomplete. A serious hurdle is the difficulty in describing the relevant characteristics of a surface that may have been ground and polished with a number of different compounds, then cleaned with different solvents, then exposed to an ambient atmosphere with constituents that will adsorb to, react with, and diffuse into the surface. For the best results we have obtained to date, a CO_2 laser was used to condition fiber end faces that had previously been polished mechanically.[3] The beneficial effect depended on the particular conditioning schedule that was followed, and some preliminary schedules actually lowered breakdown thresholds. Recently we have obtained some very promising results with a mechanical polishing schedule that uses colloidal silica in the final step. In the absence of better fundamental understanding, such empirical results must be relied upon to establish end-face preparation procedures that may still be far from optimum.

The factor that may ultimately limit most high-intensity fiber applications is the difficulty in injecting a laser beam into a fiber in a relatively benign way. Perhaps the most benign condition would have beam characteristics at the fiber entrance face that are essentially the same as would be found at the fiber exit face after a lengthy propagation distance. Solutions using conventional refractive optics are not likely, particularly if a broad spectrum of laser beam characteristics must be considered. As mentioned previously, the fast-developing field of diffractive optics may offer the means for minimizing this difficulty. To date we have evaluated several prototype elements that were designed to improve one or two aspects of injection, but each had serious drawbacks. Continuing work on the design and fabrication of new diffractive elements that will further improve fiber injection capabilities could prove to be especially useful.

5. ACKNOWLEDGMENTS

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