Destruction of silica fiber cladding by the fuse effect

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The phenomenon of destruction of silica fiber cladding by the fiber fuse effect has been observed for the first time to the authors’ knowledge. Experiments on the optical discharge propagation along a fiber were conducted with fibers of decreased cladding thickness. The destruction of fiber cladding led to expansion of the optical discharge plasma and to a decrease of its density. This resulted in the termination of optical discharge propagation. The section of a fiber with decreased cladding thickness can act as a safety device to halt damage propagation. © 2004 Optical Society of America

The fiber fuse effect (catastrophic destruction of optical fibers) that occurs at relatively low cw optical power (less than 1 W) was observed and described in 1988. If a fiber is locally heated to a temperature of \(\sim 1000\,^\circ\text{C}\), the laser radiation propagating through the fiber is strongly absorbed by the heated part of the fiber, increasing its temperature to \(\sim 10^4\,\text{K}\). This high-temperature region, seen as a bright white spot, moves with a velocity of \(\sim 1\,\text{m/s}\) along the fiber toward a source of laser radiation, causing damage to the fiber core.

At first this phenomenon was considered a curiosity, but now it should be considered a real danger to optical fiber communication systems because of the increase in optical power used in these systems. Various laser sources with output powers of \(\sim 1\,\text{W}\) were developed for pumping Er-doped and Raman fiber amplifiers used in the systems. Any accidents that lead to strong local heating of fibers can initiate the fiber fuse effect and the destruction of kilometers of fiber. Contact of a fiber end with an absorbing substance, an electrical discharge, dust in fiber-optic connectors, and sharp fiber bending are the most typical accidents. A large number of papers (see, for example, Refs. 2–8) have been published on the subject; but one cannot say that all features of this phenomenon are understood well enough. For example, until now there has been much uncertainty in the experimental and theoretical data on the plasma temperature. Moreover, data on the relaxation phase of the optical discharge region are scarce.

In general, the fiber fuse effect can be considered to comprise the formation and propagation of an optical discharge (high-density plasma) along the fiber core. The estimated values of the plasma pressure and temperature are \(\sim 10^4\,\text{atm}\) and \(\sim 10^4\,\text{K}\), respectively.

In standard silica-based fibers with a cladding diameter of 125 \(\mu\text{m}\) this phenomenon results in catastrophic damage of the fiber core manifested as a set of bubbles or long filaments in the core and a change in the refractive-index profile. The silica cladding of fibers is strong enough to withstand the action of the propagating plasma. Reduction of the fiber cladding’s strength in any way can lead to the deformation or even the destruction of the cladding under the high temperature and pressure of the propagating plasma. This can result in changing the character of optical discharge propagation and even in halting it.

In our experiments we achieved the reduction of the cladding’s strength by decreasing its thickness. We etched 2-mm-long stripped sections of fibers with a 20% hydrofluoric acid solution at room temperature to get a number of waist-type samples of fibers with minimum cladding diameter \(d\) in the range 10–60 \(\mu\text{m}\) (Fig. 1). We studied single-mode fibers of different types, but in most experiments SMF-28 fibers were used.

The light source was an Yb-doped fiber laser operating at a wavelength of 1.06 \(\mu\text{m}\) or a Raman fiber laser operating at 1.24 \(\mu\text{m}\). The fibers under investigation were spliced with the output fibers of the lasers. The launched cw radiation power \(P\) was 1.3 to 3 W. We initiated the optical discharge by contacting the end of the fiber with a light-absorbing surface. We tested all the fibers listed in Table 1 to determine the mode field diameter (MFD) at the wavelength of laser radiation and the minimal power \(P_{\text{th}}\) required for optical discharge propagation along a fiber with a silica cladding diameter of 125 \(\mu\text{m}\).

We conducted a number of experiments to investigate the features of plasma propagation along etched fibers with various waist diameters. If the minimal diameter of the etched section was large enough, i.e., much more than some critical value \(d_c\) (\(d > d_c\)), the

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Fig. 1. Waist-formed section of etched fiber and the fuse’s stopping point.
Table 1. Parameters of the Fibers Investigated

<table>
<thead>
<tr>
<th>Fiber Number</th>
<th>MFD (μm)</th>
<th>$P_{th}$ (W)</th>
<th>$d$ (μm)</th>
<th>$P$ (W)</th>
<th>$d_c$ (μm)</th>
<th>Fuse Stopped</th>
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<tr>
<td>1$^a$</td>
<td>9.5</td>
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<td>10.5</td>
<td>2.0</td>
<td>33</td>
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<td>17</td>
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<td>3.0</td>
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<tr>
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<td>60</td>
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</tr>
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</table>

$^a$SMF-28 fiber.

The character of the discharge propagation was practically the same as in a standard fiber (Table 1, fibers 10 and 11). $d_c$ is the diameter of the etched fiber at the point where the optical discharge propagation is halted (Fig. 1), and it is determined experimentally. When the diameter of the waist was only slightly larger than $d_c$, the character of the fiber damage was changed dramatically (Fig. 2). If in a nonetched section of the fiber the damage represented a periodic set of bubbles (region 3), the damage of the etched section took the form of a long capillary (region 2). After passing the etched section, the optical discharge formed a periodic structure of the damage again (region 1). When $d < d_c$, the optical discharge could not pass through the etched section of the fiber (Fig. 3). The high temperature and pressure of the plasma caused cladding deformation and the formation of a large bubble at the cross section of the fiber with the cladding diameter equal to $d_c$. The expansion of the absorbing plasma results in a decrease of its density and radiation absorption, which disturbs the necessary condition for the discharge propagation, and so stops it. Sometimes we observed the complete destruction of the fiber at the place where the fuse stopped (Fig. 4). Note that the observed increase in the threshold of fuse damage in microstructured fibers is also connected to the density reduction of the optical discharge plasma because of its expansion.\(^5\)

The value of $d_c$ may be estimated as follows: Assume that the fiber’s destruction is caused mainly by the pressure of the optical discharge occupying a cylinder with its diameter equal to the MFD. Then the minimum diameter $d_c$ of the etched section of the fiber required for balancing plasma pressure can be estimated as $d_c = \text{MFD}(1 + p/\sigma)$, where $\sigma$ is the breaking strength of silica glass and $p$ is the plasma pressure. Taking $\sigma \approx 10^9$ Pa and $p \approx 10^4 \text{ atm} \approx 10^9$ Pa, we obtain the reasonable estimation $d_c \approx 2 \times \text{MFD}$ (Table 1). However, this is just a rough estimation. Actually, $d_c$ is defined in a complicated manner by the cladding properties, plasma pressure, and temperature. The pressure and temperature are determined by the power of radiation. A simple qualitative consideration indicates that the plasma pressure and temperature are monotonically increasing functions of the laser power. The value of $d_c$ is an increasing function of the plasma pressure and temperature. Thus $d_c$, at least, does not decrease with laser power. Our experimental data (Table 1), however, show that the value of $d_c$ does not practically depend on the power of the laser radiation for the particular fiber. All these facts indicate that it is possible to use the observed phenomenon of the optical discharge termination to protect optical fiber systems.
from catastrophic damage when an accidental optical discharge occurs. One needs just to put into the fiber line a small waist-formed length of fiber with a minimal cladding diameter slightly less than \( d_c \), which will not allow any further propagation of the optical discharge.

The fact that the value of \( d_c \) does not decrease with the laser radiation power (Table 1) means that such a protective device will also effectively operate at higher laser powers, unlike the device\(^3\) that is based on a local increase of MFD in single-mode fiber tapers. The etched section of the fiber has no additional optical losses either.

In conclusion, we have shown that the diameter of a fiber silica cladding can substantially influence the process of the optical discharge propagation in a fiber. The observed phenomenon of destruction of silica fiber cladding by the fiber fuse effect is a direct confirmation of the high-density plasma formation in the fiber core, which is necessary for the discharge propagation. Plasma expansion during cladding destruction results in termination of the optical discharge. This phenomenon allows one to use the section of a fiber with reduced cladding strength as a protective device against the detrimental propagation of an optical discharge in a fiber system.

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References