Damage of silica-based optical fibers in laser supported detonation

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Abstract. The study of detonation-like mode of laser induced damage propagation is presented. This mode is new investigation object of laser destruction of silica-based optical fibers. The fiber destruction images were obtained in evolution and in static (on saved samples).

1. Introduction
The motion of laser damage in silica-based optical fiber was discovered in 1987 (see review in [1]). Nature of this phenomenon is the propagation of the plasma front (laser absorbing zone) towards the laser radiation source. Plasma appearance causes irreversible damage of optical fiber. The low velocity propagation was named fiber fuse effect (deflagration). In our later work [2] we have reported that silica-based optical fibers can demonstrate a high velocity mode of catastrophic damage. This mode is new object of laser destruction of silica-based optical fibers and study of such bulk damage becomes rather significant due to world progress in optical communication link application.

The damage wave propagated with the velocity $\sim 3 \text{ km/s}$ through the optical fiber core. It is more two orders fast than fiber fuse effect [1,3]. To distinguish this new process from burning we are using the term laser supported detonation (LSD). We have used single mode optical fibers. In these optical fibers the laser intensity distribution (transverse mode) stays constant at every cross-section along the full length of the fiber, so the plasma propagates under steady-state conditions. This is especially important in the case of long laser pulses ($\tau_p > 1 \text{ ns}$) when hydrodynamics gives a significant effect on plasma motion. LSD demonstrates near constant velocities of plasma front during $\sim 200 \text{ ns}$ in the laser peak intensity range of $2-4 \text{ GW/cm}^2$. Here we present experimental study of LSD propagation and irreversible damage treks in silica-based fibers.

2. Experiment conditions and results
We had tested three types of silica-based optical fibers. Parameters of these fibers are described in table 1. There a mode field diameter (MFD) is the $1/e^2$ width of the radial radiation distribution. These fibers were close to the single-mode at used laser wavelength ($\lambda = 1.064 \mu m$). The fiber F3 is Corning SMF-28e. For fiber F2 with a big central dip in the refractive index profile RID is the value for the effective step-index profile.
### Table 1. Characteristics of tested fibers.

| Name | Silica cladding diameter, µm | Core diameter, µm | Refractive index difference | SiO$_2$:GeO$_2$:Al$_2$O$_3$ | MFD, µm |
|------|-----------------------------|------------------|-----------------------------|-----------------------------|--------|
| F1   | 600                         | 9.5              | 0.006                       | 97:1:2                      | 10.5   |
| F2   | 125                         | 7.7              | 0.013                       | 89:11:0                     | 6.13   |
| F3   | 125                         | 8.2              | 0.005                       | 96.5:3.5:0                  | 8.9    |

As in our previous works [2, 3] driving laser pulses were supplied by Nd$^{3+}$:YAG laser ($\lambda = 1.064 \, \mu m$) in Q-switched mode with 5 kHz repetition frequency. Temporal intensity profile was near-Gaussian shape (with FWHM of ~ 250 ns) with a peak intensity of 4 – 4.5 GW/cm$^2$ in the fiber core. To initiate laser supported detonation an output end-face of the optical fiber was touched by a metal absorption surface. The LSD occurs during a middle part of the laser pulse only. LSD had started to move when the laser intensity became greater than ~ 2 GW/cm$^2$. The distance of LSD propagation was around 500 – 700 µm per one laser pulse. Next laser pulse initiated the laser plasma near point of previous stopping. Figure 1 exhibits more details of the region around start and stop points. In these points the immobile plasma brightly glows (figure 1a). Here plasma heating is supplied by laser radiation with the intensity below the fast propagation thresholds. The start-stop area is shown in figure 1b. The distance between these points is about 8.3 µm. Most likely it is determined by moving of laser absorption front during the time between laser pulses as heat front. To measure plasma front velocity the streak camera has been used. The streak camera image of plasma propagation and the oscilloscope picture of the laser intensity are shown in figure 2. We had observed a start point, short acceleration time, then velocity stabilized during around 75% of propagation time and finally deceleration and stop. The constant velocity corresponds to detonation regime (as our definition).

The plasma front velocity in detonation mode as a function of average laser intensity is presented in figure 3 for fibers F1 and F2 (a number in circle corresponds to the fiber). The average laser intensity was calculated for the detonation time. The velocity is slightly increasing with average dissipated laser energy. This is rather unexpected results.

An optoelectronic camera with S1 photocathode and minimum exposure time of 2ns (NPP Nanoscan) and a 10x microscope objective was used to obtain micrograph images of LSD in glycerol immersed bare fibers. As backlighting the beam of second-harmonic generation (532nm) from the driving laser was applied. An image was projected onto the camera photocathode by a selective dielectric mirror mounted at the angle of 45°. The mirror had the reflectivity of 55% at 530 nm under normal incidence. To make clear LSD features three imaging techniques had been applied. There were a plasma thermal emission for visualizing energy deposition zone, a bright field for observing cracks and a crossed polarizers imaging for detecting stresses. The 2ns exposure time image of propagating plasma is demonstrated in figure 4. Relative blackening is represented by curve 1 along fiber and curve 2 across fiber. The plasma temperature under our conditions is around $10^4$ K.

One can see that the high temperature domain has a rather small size therefore there is motion blur in the longitudinal direction due to the plasma front propagation during the exposure time of the camera. To get the inherent longitudinal profile of the emission we have applied a digital convolution of the transversal profile (2, figure 4b) passed through a maximum of the emission and the instrumental function (for the 1.8 ns-time window and the object velocity of 2.8 µm/ns). In high temperature region the convolution curve (3, figure 4b) agrees well with the profile on the front side. Thus the plasma front had a nearly spherical shape. In the front there is a
shoulder in the longitudinal profile, where the brightness exceeds the amount of plasma thermal emission. It is an important feature to understand LSD in optical fibers. A damage trek looks like a remelted core region with hollow channel inside. In F2 fiber hollow channel diameter was 2.5 \( \mu m \) around start and 3.5 \( \mu m \) in the middle of the path, for example. Remelted core layer is surrounded by crushability zone and cracks around. The images on figures 5a and 6a demonstrate formation of individual cracks around the front edge of the plasma. The cracks separated by the distance of \( \sim 2–3 \mu m \) are beginning on the core-cladding interface and growing outward. However, between these images there is a significant difference in the position of the crack front (the first crack in driving direction, i.e. the leftmost one on the pictures). We can see radial cracks before plasma front in figure 5a and conical cracks attached directly to the plasma edge in figure 6a.

Stress-induced birefringence is used to measure longitudinal stresses in optical fibers. We applied crossed polarizers technique to examine stresses arising in the fiber at LSD [4]. Two stress waves in the silica cladding (as an elastic precursor) and in the fiber core (as a plastic deformation) propagate before the plasma front. These waves were observed as light regions where a stress-induced birefringence rotates a plane of the light polarization (figure 5b). A

**Figure 1.** The micrographs of the region with the start and stop points: a) the plasma glow during damaging F3 (the 1s exposure time), b) the failure picture after process in F1, c) the temporal dependence of the laser intensity (in arbitrary units).
**Figure 2.** The plasma propagation in the F2 fiber core under laser pulse: a) the streak camera image, b) the oscilloscope picture of the laser intensity (in arbitrary units).

**Figure 3.** The dependence of the LSD velocity vs. the average laser intensity during LSD.

stress distribution in the elastic precursor is bell-shaped without a rarefaction region and the wave occupies all the fiber in diameter. On the other hand, plastic deformation results from a
Figure 4. The high-speed micrography of the laser plasma in the core of F3: a) the 2ns exposure time micrograph of the plasma propagated from right to left with speed of 2.8 μm/ns, b) the glow intensity curves (1, 2) and the convolution curve (3).

Figure 5. The high-speed micrography of LSD (the 2ns exposure time): a) shadow picture of F2, b) in-crossed-polarizers picture of F3. 1—the cross-section plane of the radial crack appearance (dash line), 2—the fiber core, 3—the elastic precursor, 4—the laser plasma (dotted circle).

plasma pressure and locates in the fiber core where GeO$_2$:SiO$_2$ glass has lower elastic modulus in comparison with the silica modulus. The position of radial crack formation was observed also in this method. We could estimate the values of longitudinal compressive stress due to birefringence
Figure 6. Acceleration regime of LSD in F2 fiber: a) the high-speed micrography (shadow picture), b) the SEM picture (negative) of destroyed silica cladding. 1—the laser plasma, 2—the conical cracks, white arrows—the first radial crack cross-section, \( \alpha \)—the characteristic angle of crack. LSD moves from right to left.

Figure 7. SEM pictures of damage trek in the detonation regime (a) (negative) 1—the long crack zone, 2—the short crack zone. The nanospheres on the channel surface (b) and (c). LSD moved from right to left, F2 fiber.

fringes observed in stress wave region. In the linear approximation with optic-stress coefficient \( 35.5 \times 10^{-13} \text{ Pa}^{-1} \) the compressive axial stress in the fiber core F3 on the crack front was \( \sim 4 \text{ GPa} \) and the maximum of the elastic precursor was \( \sim 2 \text{ GPa} \). If the pressure linearly increases in the plasma front the maximum plasma pressure would be evaluated as around 8–10 GPa.

The bare optical fibers (F2 and F3) were fragmented by LSD. But a polymer jacket of fiber can save separated pieces inside. A remarkable fact was that the LSD split the fiber strictly along into 2–4 parts. It gives possibility to make analysis of damage treks by scanning electron microscope. Analyzing the destruction along the treks, we also can distinguish three regimes: acceleration, detonation and deceleration. Acceleration and deceleration are accompanied by formation of conical cracks in a silica cladding. They were more distinguishable (more regular) in the acceleration part of the trek. The apex angle \( 2\alpha \) decreased with increasing velocity of the plasma front. For the trek on figure 6b the angle was in the range from 74 to 120°. The maximum apex angle was 130° at stop point.

The fiber destruction at detonation is characterized by transverse cracks in a silica cladding observed as radial cracks (see figure 7a) and central hollow channel inside of the remelted core (see figures 7a and 7b) and formation on the channel surface nanospheres with sizes from 60 to 350 nm (figure 7c). At observable stabilization of plasma velocity the picture of damaged fiber
(figure 7) shows influence of absorbed laser energy.

We note that a larger absorbed energy corresponds to longer cracks, wider channel and a less concentration of nanospheres (see figure 7a, zone “1”), but the lower energy corresponds to short cracks, narrower channel and a greater concentration of nanospheres (see figure 7a, zone “2”).

3. Discussion

Our measurements had visualized new details of destruction of silica-based optical fibers in detonation-like process. It was found that damages in this case have amazing difference in comparison with fiber fuse effect (deflagration). Mainly this is essential crushability and remelted zones, long cracks and appearance nanostructures. But at the same time, the question of detonation model applicability remains open still. Detonation model assumes that absorption of laser radiation in material begins as a result of hydrodynamic processes induced by energy deposition in laser plasma. If the propagation velocity was greater than sound speed the usage of the model would be apparent. Now we have some deviations from ideal detonation. Obtained regime has curved front (not flat), propagation velocity less than sound velocity in pure silica and wave structure of front is complex. Front of obtained regime demonstrates two wave structure (plasma zone and precursor). In addition silica properties under loading are rather complicated what creates difficulties in the interpretation. The cores of investigated fibers consisted of SiO$_2$ with additives (see table 1) meanwhile most of available thermodynamic data are mainly correspond to pure silica. Dominating mechanism of loss of transparency under pressure requires further analysis.

4. Conclusion

Investigation of detonation-like mode of laser induced damage propagation detected in works [2,4] has been continued in this study. This new propagation regime is more than two orders of magnitude faster than known published data on burning fiber glass [1]. The condition of optical fiber and enough long laser pulse let us obtain laser induced damage propagation during hundred own core diameters during pulse. The fiber destruction images were obtained in evolution and in static (on saved samples).

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