Laser Supported Detonation in Silica-based Optical Fibers

Vladimir P. Efremov, Artem A. Frolov, and Vladimir E. Fortov
Joint Institute for High Temperatures of Russian Academy of Sciences
Moscow, Russia

1 Introduction

Silica-based optical fibers demonstrate two regimes of catastrophic damage propagation velocities caused by laser radiation. Sense of this phenomenon is the propagation of laser radiation absorbing zone of the plasma (fracture zone) towards the laser radiation. Low velocity mode was named burning. Here we present experimental study of fast detonation-like mode of laser induced damage propagation. This propagation regime is two orders of magnitude faster than known published data on burning optical fiber. 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.

Recently we had reported the observation of laser-induced damage propagated with the velocity ~3km/s through the optical fiber core [1]. We have used single mode optical fibers. In these fibers the laser intensity profile stays constant at every cross-section along the full length of the fiber. A mode field diameter (MFD) is the $1/e^2$ width of this radial distribution. This property supplies observing wave under steady-state conditions. This is especially important in the case of long laser pulses (τ_p>1ns) when hydrodynamic gives a significant effect on of plasma propagation distance (comparable with core diameter in our case).

2 Measurement techniques and results

We had tested three types of silica-based optical fibers. Parameters of these fibers are described in Table 1. As in the our previous work [1, 2] driving laser pulses were supplied by $Nd3^+$:YAG laser (λ=1.064um) in Q-switched mode with 5 kHz repetition frequency. Temporal intensity profile was near-Gaussian shape (with FWHM of ~ 250ns) with a peak intensity of 4-4.5 GW/cm^2 in the fiber core. To initiate laser supported detonation (LSD) an output end-face of the optical fiber was touched by a metal absorption surface. LSD had started to move when the laser intensity became greater than ~2GW/cm^2 with the velocity around 3km/s. The distance of this wave propagation was around 400-700um per one laser pulse.

The photo of fiber (F1) after LSD propagation is shown in Fig. 1. The damage tracks and corresponding laser pulses are presented in Fig.1. The process is moving during the part of laser pulse. Next laser pulse initiated new LSD near point of previous stopping. Fig. 2 exhibits more details the region of Start and Stop (S&S) points. The immobile plasma glows in Start and Stop points (See Fig 2(a)). At these moments core heating is supplied by laser pulse tails below threshold intensity. Failure picture after process is shown in Fig 2(b). S&S distance is about 8.3um. Most likely this distance is determinated by heat wave propagation between laser pulses.

We have used the streak camera for velocity measurements. The streak camera image of plasma propagation (the frame sizes of 1mm x 350ns) and the oscilloscope picture of the laser intensity are shown in Fig.3. The red dashed line has been drawn throughout the maximums of plasma glow. We had observed short time of acceleration and then velocity stabilizes. Data on the plasma front velocity as a function of average intensity of laser radiation are presented in Fig.4 for fibers F1 and F2 (number in circles correspond to number of fiber). Velocity is slightly increasing with average dissipated laser energy.

An optoelectronic camera (Nanogate-3n, NPP Nanoscan with S-1 photocathode sensitive to a visible light) with a microscope objective (with 10× magnification) was used to obtain micrograph images. A minimum exposure time was 2ns. 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 an angle of 45 degrees. The mirror had the reflectivity of 55% at 530 nm under normal incidence. To make clear LSD features we had applied three types of technique for obtaining images. There were a bright field microscopy for crack formation, thermal emission for plasma zone visualization and a stress-induced birefringence through the crossed polarizers for pressure pulse.

The photo in Fig.5(a) demonstrate the plasma zone glow. Relative blackening along fiber axis represents line 1 and across fiber axis represents line 2 in Fig.5(b). The plasma temperature under our conditions is around 10^4K. The spatial distribution of a wave emission is shown in Fig.5(b). 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 examined a digital convolution of the transversal profile passed through a maximum of the emission and the instrumental function (for the 1.8ns-time window and the object velocity of 2.8um/ns). In high temperature region the convolution curve agrees well with the profile on the front side of the micrograph image Fig.5(b). Thus the plasma front had a nearly spherical shape. In front of plasma zone there is a shoulder in the longitudinal profile, where the brightness exceeds the mount of thermal emission of the plasma. It is an important feature to understand LSD in optical fibers.

At the same time we see distinguishly more immobile cracks in Fig.6(a). The image demonstrates formation of individual cracks ahead of the plasma front. The cracks are separated by the distance of ~2-3um. They begin on the core-cladding interface and propagate almost radially outwards.

Stress-induced birefringence is used to measure longitudinal stresses in optical fibers. We applied optical microscopy between crossed polarizers to examine stresses arising in the fiber at LSD [3]. Stress waves in the silica cladding as an elastic precursor (EP) 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 (Fig.6(b)). A stress distribution of EP is bell-shaped without a rarefaction region and the wave occupies all the fiber in diameter. On the other hand, in the plasma front a strain localized region is in the fiber core where a GeO_2:SiO_2 glass with a lower elastic modulus than in silica cladding. The position of radial crack formation was observed also in this method. It is possible to properly combine the images obtained by different techniques. Optical absorption, light scattering and plasma fluorescence complicate the interpretation of the obtained pictures. We could estimate the values of longitudinal compressive stress due to birefringence fringes observed in stress wave region. In the linear approximation with optic-stress coefficient $35.5\text{x}10^{-13}\text{Pa}^{-1}$ the compressive axial stress of the core in the crack formation plane was ~4GPa and the maximum of EP was ~2GPa. If the pressure linearly increases in the plasma front the maximum plasma pressure would be evaluated as around 8-10GPa.

After passing LSD fibers were destroyed. Optical fibers with a silica cladding diameter of 125 microns and without a polymer cladding fly away. Polymer-jacketed optical fibers with the diameter of 125 microns and with silica cladding diameter of 600 microns keep integrity. It gives possibility to make analysis of damage tracks by scanning electron microscope. The photo of a saved fiber is shown in Fig. 7. One can see melted and crushability zones. Analyzing the destruction along the track, we can distinguish three areas: acceleration, "detonation", deceleration. Acceleration and deceleration are accompanied by formation of conical cracks (CC) in a silica cladding. The angle between the crack and the axis of the core decreases with increasing velocity of the plasma front. The transition to detonation mode is fixed as the occurrence of radial cracks (RC) in the cladding.

3 Discussion and conclusions

Our measurements had visualized new details of detonation like process of destruction of silica-based optical fibers. Is the concept of detonation applicable here? 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 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 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. Processes of optical absorption increasing are strongly depended on pressure and temperature. It's necessary to note that we had investigated core of fiber consisted of SiO_2 with additives (See table 1) meanwhile most of available data are mainly correspond to pure silica. The question of detonation model applicability remains open still and demands new experiments. Though dominating mechanism of the transparency loss at pressure wave demands additive investigations.

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References

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[2] Dianov E.M., Fortov V.E., Bufetov I.A., Efremov V.P., Frolov A.A., Schelev M.Y., Lozovoi V.I. (2006). Detonation-like mode of the destruction of optical fibers under intense laser radiation. J. Exp.Theo. Phys.Lett. 83(2): 75.

[3] Efremov V.P., Dianov E.M., Fortov V.E., Bufetov I.A., Frolov A.A. (2011). Nanosecond frame photography of quasi-detonation in silica-based optical fibers under laser radiation. Physics of Extreme States of Matter-2011: 41. Institute of Problem of Chemical Physics, RAS, Chernogolovka (ISBN 978-5-91845-007-9).

Table and Figures

Table 1: Characteristics of silica-based optical fibers

Name of fiber	F1	F2	F3
Silica cladding diameter, um	600	125	125
Core diameter, um	9.5	7.7	8.2
Refractive index difference (RID)	0.006	0.013	0.005
Composition SiO_2:GeO_2:Al_2O_3	97:1:2	89:11:0	96.5:3.5:0
Mode field diameter at 1064 nm, um	10.5	6.13	8.9

For fiber F2 with a big central dip in the refractive index profile RID is the value for the effective step-index profile; the fiber F3 is Corning SMF-28e™

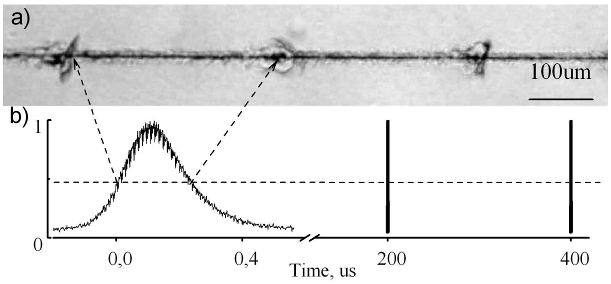

Figure 1. The damage track in optical fiber under the laser pulse train: a) the micrograph of the damaged F1, b) the temporal dependence of the laser intensity (in arbitrary units). The laser radiation propagated from right to left.

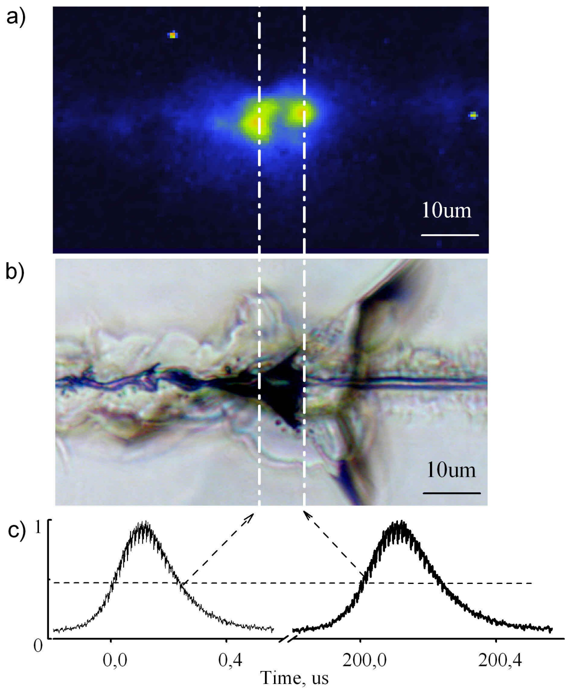

Figure 2. The micrographs of the region with the start and stop points: a) the plasma glow during damaging F3

(the 1s exposure time), b) the failure picture after process in F1, c) the temporal dependence of the laser intensity (in arbitrary units).

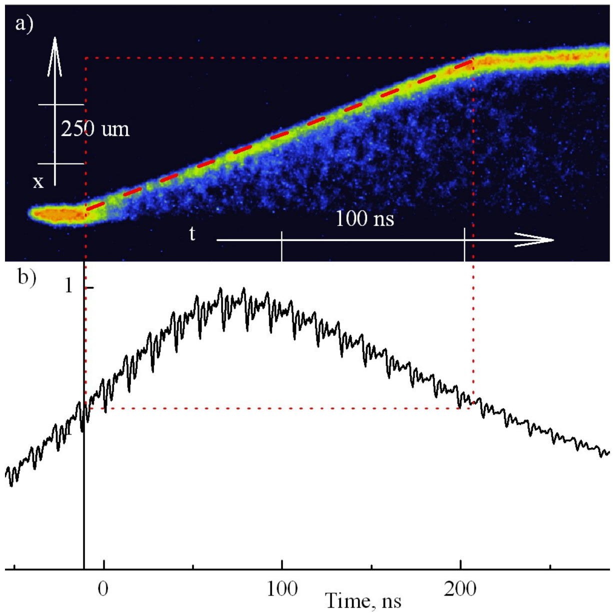

Figure 3. The plasma propagation in the F2 fiber core under laser pulse: a) the streak camera image, b) the oscilloscope picture of the laser intensity (in arbitrary units). The red dashed line has been laid throughout the maximums of plasma glow.

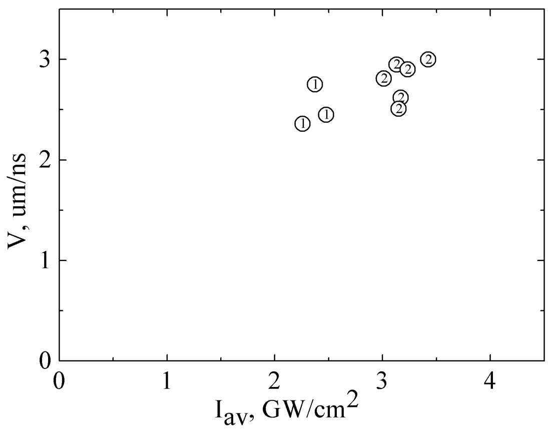

Figure 4. The dependence of the LSD velocity vs. the average laser intensity during LSD.

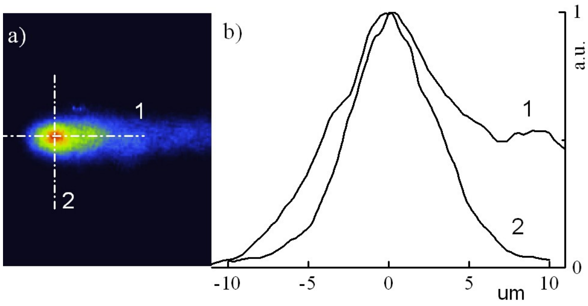

Figure 5. The high-speed micrography of the laser plasma in the core of F3: a) the 2ns exposure time micrograph of the plasma propagated from right to left with speed of 2.8um/ns, b) the glow intensity curves.

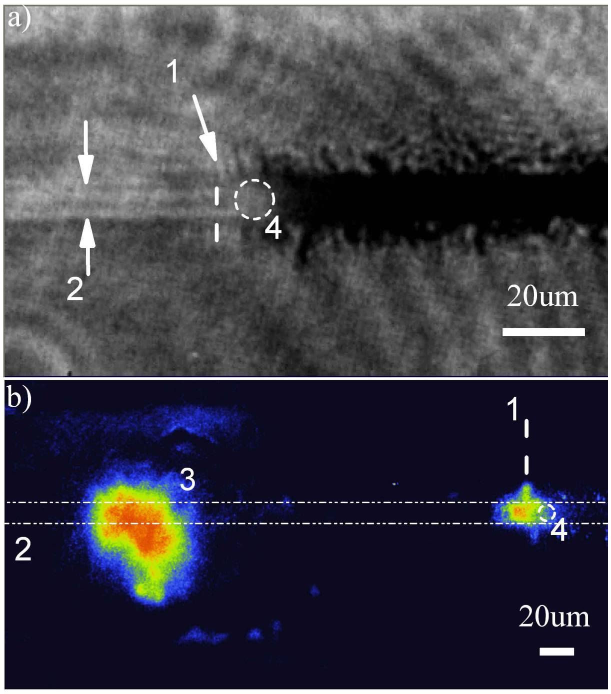

Figure 6. The high-speed micrography of LSD (the 2ns exposure time): a) shadow picture of F2, b) in-crossed-polarizers picture of F3. 1 - the cross-section plane of the radial crack appearance (dash line), 2 - the fiber core, 3 - the elastic precursor, 4 - the laser plasma (dotted circle).

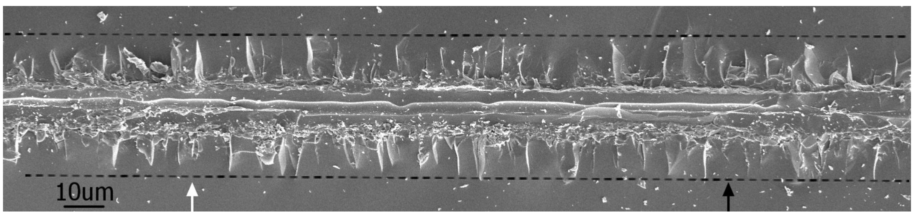

Figure 7. Radial cracks on the detonation channel in F2. Middle of detonation treck is marked with a black arrow. Dotted lines are drawn through the ends of the RC. A change in the length of the RC pointed white arrow. Destruction moves from right to left.