# In-Situ Observation of Fiber-Fuse Propagation

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Ultrahigh-speed photographs of fiber-fuse propagation in single-mode silica fibers revealed a new factor, other than pumping laser power that affects the morphology of damage sites: the length of the running optical discharge. Nine W pumping of 1480 nm light generated a discharge of ∼130 $\mu$m in half-width moving rapidly and leaving discrete voids along the fiber core, whereas 2-W-pumped discharge was ∼27 $\mu$m long, moved slowly and left nearly continuous thin voids. This is because 9-W-pumped discharge takes a longer time to travel its half-width, about 5/3 times longer than that of the 2-W-pumped discharge, which provides longer interaction time for modifying the fiber core.

KEYWORDS: optical fiber, fiber fuse, ultrahigh-speed photography

The fiber-fuse effect has been a familiar phenomenon since the late 1980s,[1,2] which is initiated by the local heating of silica glass optical fiber to generate an optical discharge moving along the fiber to the light source, resulting in catastrophic destruction of the core region. Although it has attracted the interest of many researchers, its mechanism has not yet been fully elucidated. This is due to the difficulty in observing the rapidly moving bright discharge, which has a speed of about 1 m/s. Thus, the previous discussions have been limited to the pumping power, the speed of propagation and the morphology of generated damage.[3]

Here I propose a new parameter for describing this phenomenon, the length of the running optical discharge, which is obtained by ultrahigh-speed photography. Its propagation was observed under two conditions (pumping laser power: 2W and 9W) and the relationship between the length and the shape of generated damage is discussed. (This paper is based on a post-deadline paper presented at the European Conference of Optical Communication held in Stockholm, Sweden, on September 9th 2004,[4] with some supplementary results and discussions.)

Figure 1 shows the experimental setup used in this study. One end of a single-mode silica glass optical fiber (SMF-28, Corning, core diameter: 9$\mu$m) was connected to a Raman fiber laser (PYL-10-1480, IPG Laser, 1.48 $\mu$m , 10 W max.) via an optical isolator. The other end was stripped off and spliced to another five-meter-long fiber. The spliced section was mounted on a fiber holder equipped with a ultrahigh-speed CCD (Charge Coupled Device) camera (ultima APX, Photron, monochrome version, denoted by A in Fig. 1) and a CCD camera (B) connected to a video recorder. The end of the second fiber was mounted on another fiber holder to another CCD camera (C) connected with the recorder via a channel selector. Each camera was fitted with a zoom lens of appropriate magnification.

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In order to initiate a fiber fuse, the end of the second fiber was inserted into a glass ferrule with a small amount of cobalt oxide powder. Next, laser light was introduced. Ignition and passage of the fiber fuse were recorded through cameras C and B, respectively, in order to determine the time for 5 m propagation. A captured video image (speed: 30 frames per second) of an ignition is shown in Fig. 1. A set of neutral density filters was placed between the fiber and camera A.

Two types of fiber fuse were demonstrated: one pumped by the maximum power of the fiber laser (10 W) and the other by about one fifth of the maximum power. Since the fiber-fuse ignition often failed when the pumping power was below the maximum, the latter condition was realized by decreasing the power during the run in the five-meter-long fiber after an ignition with the maximum power. Considering the total loss of the light path and the decreasing speed of the pumping power, the power supplied to the fuse around the spliced section was about 9 W (14 MW/cm$^2$) and 2 W (3.1 MW/cm$^2$).

The thick lines in Fig. 2 are emission spectra of the discharge measured using a multichannel monochrometer (S-2600, Soma optics) through a fiber probe placed near the spliced section. The wavelength range of the emission coincides with the sensitivity region of camera A, 370–790nm. Although it is generally thought that the local temperature of the optical discharge becomes several thousand kelvins,[1–3] these spectra involve little heat radiation because of the lack of emissions in the range of 800–1100nm. This is clear when these spectra are compared with the theoretical spectra of blackbody radiation at 5400K and 4000K, shown as dashed lines in Fig. 2. This is because the light emission from the optical discharge is dominant compared with its heat radiation.

Figures 3(1-a) and 3(2-a) show ultrahigh-speed photographs of fiber fuses pumped by 2 W and 9 W, respectively. The height of these views has a 32-pixel resolution and covers the fiber diameter, 125 $\mu$m. Thus, 10 pixels correspond to approximately 45 $\mu$m. Since the fiber acts as a cylindrical lens, we should note that the image near the core region is nonlinearly expanded in the vertical direction. The same goes for the photos in Fig. 1, Fig. 4 and Fig. 5. Unfortunately, the center of the fiber-fuse image in Fig. 3(2-a), consisting of 3x7 pixels, was off-scale. Figures 3(1-b) and 3(2-b) show the intensity profiles along the black lines on the photos, including those for 5 successive frames taken every 10 $\mu$s. For each case, the traveling distance within one frame is smaller than the width of optical discharge. Therefore, these are regarded as static images.

Figure 4 shows overexposed images of the fiber fuse pumped by 9 W. Discrete scattering points are clearly seen immediately after the optical discharge. These scattering points are likely to be due to void generation. One scattering point is generated about every 20$\mu$s.

The propagation speeds were calculated to be 0.45 m/s for (1) and 1.3 m/s for (2), respectively, from the time they remained in the field of vision and the length of the field. On the other hand, the averaged speeds in the five-meter-long fiber were calculated to be 0.64 m/s and 1.1 m/s, respectively. In the former case, the difference between these values is mainly due to the change in pumping power after fuse ignition. The difference in the latter case of constant pumping power implies variation and fluctuation in the propagation speed, possibly due to some variations in the conditions such as curvature of the waveguide and the energy balance between pumping and dissipation.

Figure 5 shows optical microscope images of the damaged fibers near the observation point of Fig. 3, focused on the generated voids inside. A series of discrete voids at an interval of about 23 $\mu$m are seen for (2), whereas thin and nearly continuous voids are observed for (1). In addition, an examination over several segments in the five-meter-long fiber for (1) revealed that the voids just after the ignition are the same as those in Fig. 5(2), and the void interval decreases as the traveling distance increases, i.e., the pumping laser power decreases.

Atkins *et al.* reported that the fuse speed and the bubble spacing decreased with reduced input power.[3)] They also commented that near the lower limit of the pumping power of fiber-fuse propagation ($\sim$2MW/cm$^2$), "the bubble tracks become less regular and eventually evolve into aperiodic cavities $\sim$30 $\mu$m long." Thus, our results in Fig. 5 are consistent with theirs.

Considering the intensity profiles of the optical discharge shown in Fig. 3(1-b) and 3(2-b), the optical discharge with the narrow and symmetric profile (half-width: $\sim$27$\mu$m) left thin and nearly continuous voids whereas the broad and asymmetric one ($\sim$130$\mu$m) left discrete voids (see Fig. 5). The width of the latter is more than the length of six voids. In addition, their durations, i.e., the times for traveling their half-widths, are estimated to be 60 $\mu$s and 100 $\mu$s, respectively. These results are summarized in Table I.

From this table, it is clear that although the propagation speed of the 9-W-pumped optical discharge is faster than that of the 2-W-pumped optical discharge, its duration is also longer due to its larger width. This means that from the standpoint of a short segment of the silica fiber (e.g. less than half-width of the optical discharge), the interaction time with the optical discharge pumped by 9W is longer than that of the optical discharge pumped by 2 W. Thus, both the pumping power and the fusing duration are related to the morphology of generated damage, which will surely prompt further research activities on this phenomenon.

In summary, ultrahigh-speed photographs ($10^5$ frames per second with an exposure time of 4 $\mu$s) of fiber-fuse propagation along single-mode silica fibers, pumped by about 2 W and 9 W of 1480 nm laser light, reveal that the morphology of fiber-fuse damage is affected not only by the pumping power but also by the length of the running optical discharge.

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## References


1) R. Kashyap and K. J. Blow: Electron. Lett. **24** (1988) 47.
2) D. P. Hand and P. S. J. Russell: Opt. Lett. **13** [9] (1988) 767.
3) R. M. Atkins, P. G. Simpkins and A. D. Yablon: Opt. Lett. **28** [12] (2003) 974.
4) S. Todoroki: *Proc. 30th European Conf. Optical Communication Post-Deadline Papers, Stockholm, 2004* (Kista Photonics Research Center, Sweden, 2004) p. 32. (Th4.3.3).

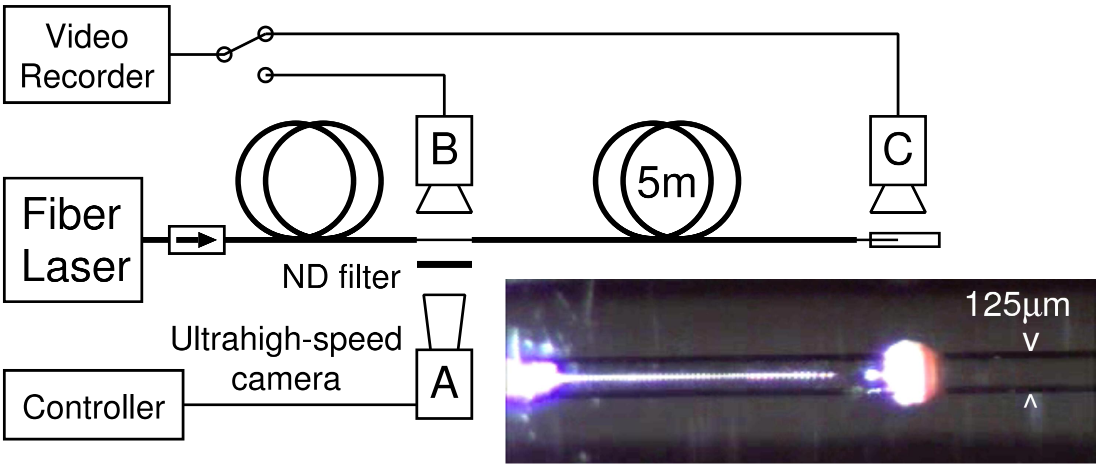


Fig. 1. Experimental setup and a captured video image of fiber-fuse ignition taken from camera C.

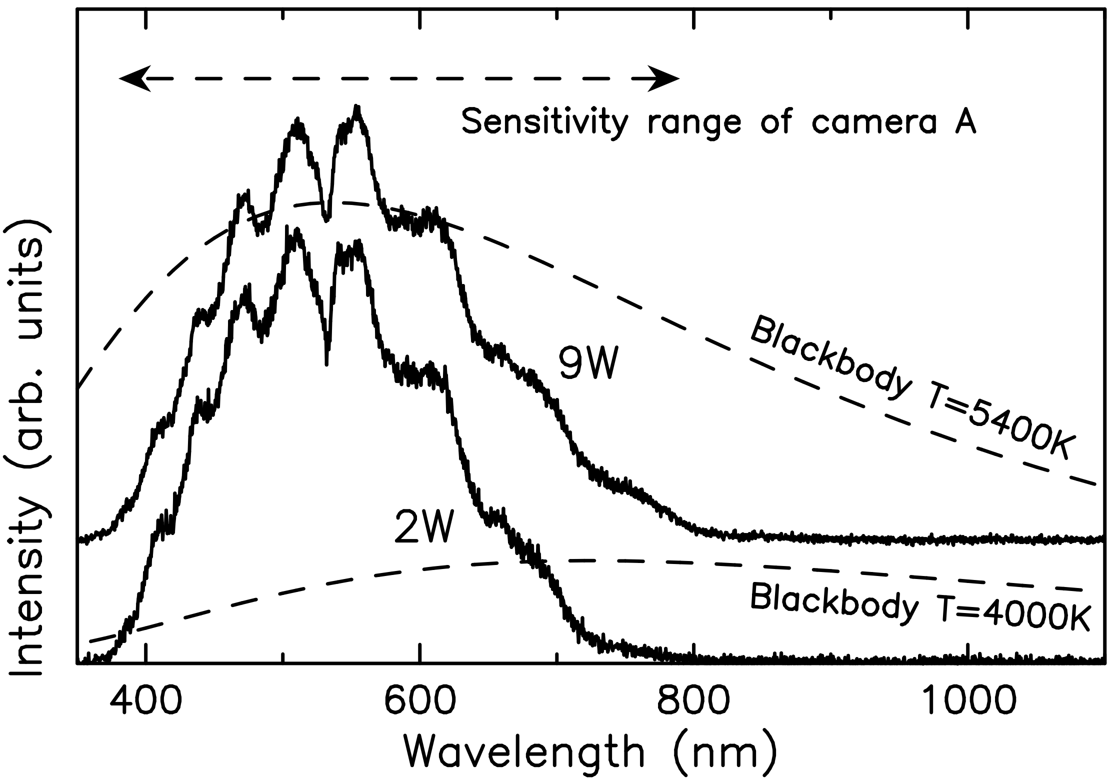


Fig. 2. Emission spectra of the optical discharge measured near camera B. Their intensities are normalized so as to be equal in height. The horizontal arrow indicates the sensitivity range of ultrahigh-speed camera A. The dashed lines are theoretical spectra of blackbody radiation at 5400K and 4000K.

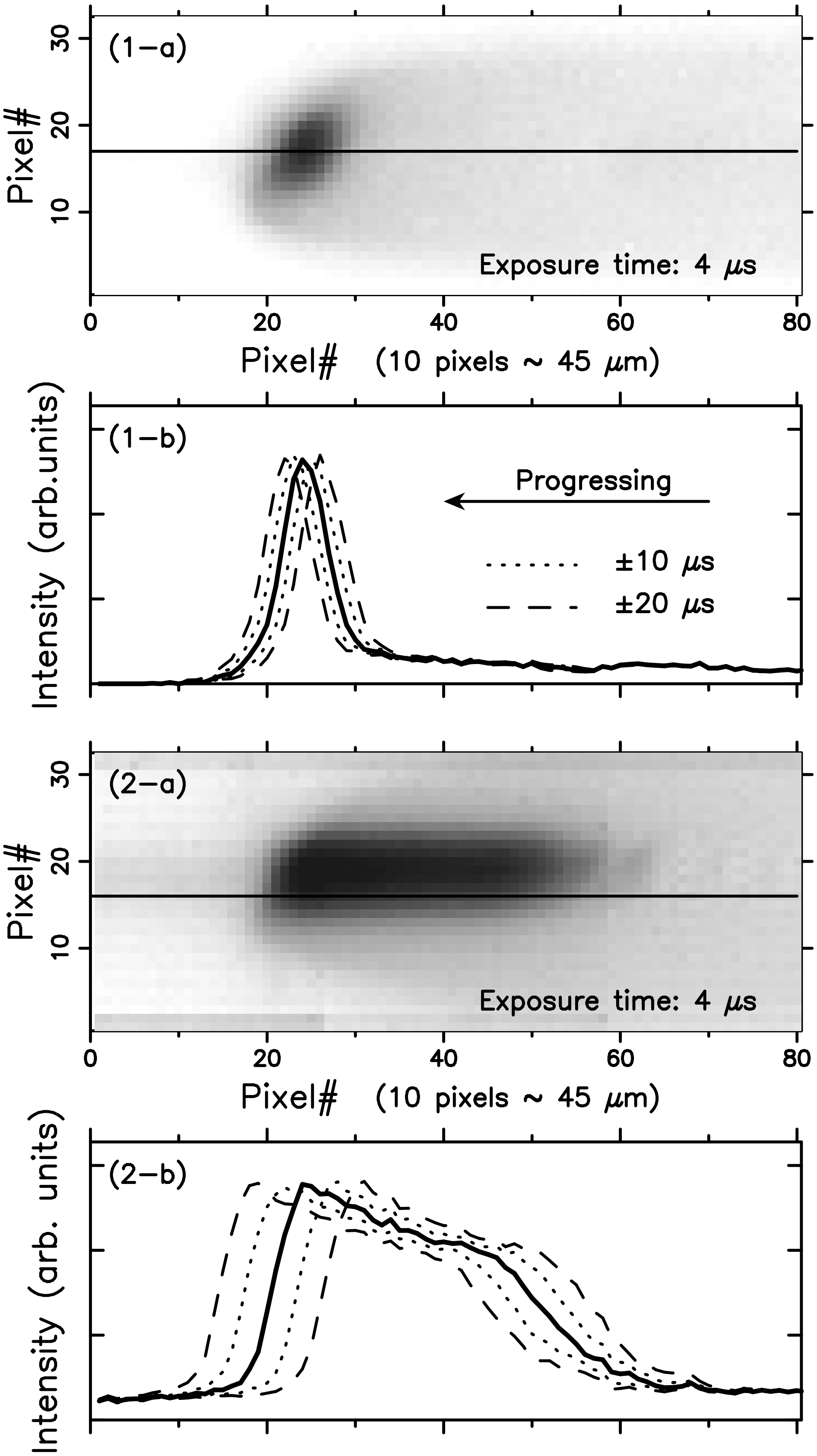


Fig. 3. Photographs of fiber-fuse propagation from the camera A (1-a & 2-a) and intensity profiles along the black lines on the photos for 5 successive frames (1-b & 2-b). The intensities of the laser ($\lambda$=1480 nm) coming from the left were about 2 W (1) and 9 W (2).

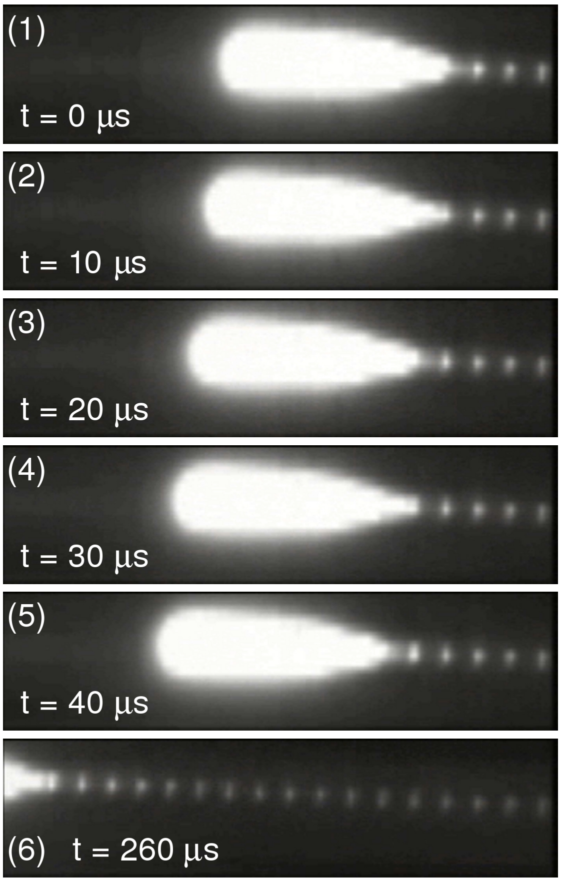


Fig. 4. Ultrahigh-speed photographs of fiber-fuse propagation for the 9 W condition. The view is the same height as that of Fig. 3(2-a).

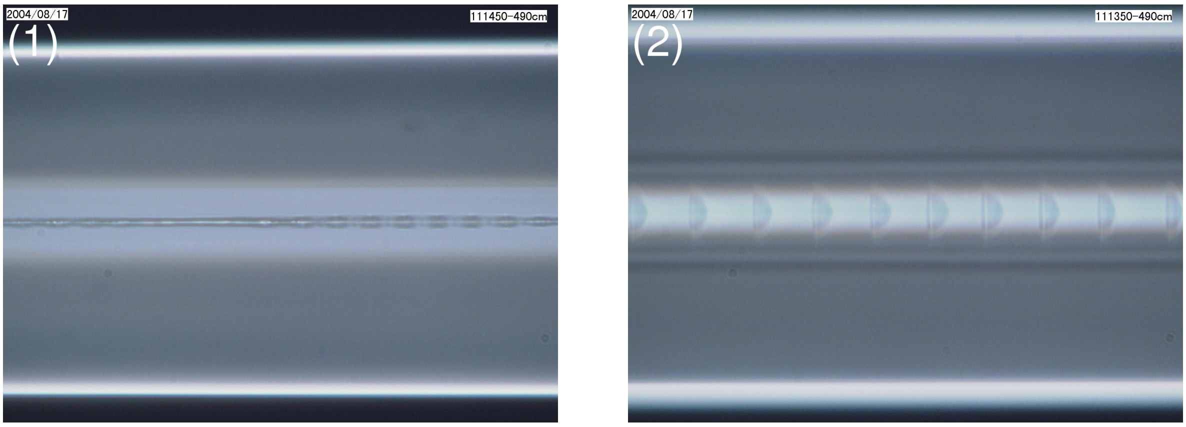


Fig. 5. Optical microscope images of the fiber-fuse damage. The voids on the right appear at intervals of about 23 $\mu$m, which is in good agreement with that for the scattering points shown in Fig. 4.

Table I. Summary of the results.

| | | |
|---|---|---|
| pumping power (W) | 2 | 9 |
| Velocity (m/s) | 0.45 | 1.3 |
| Half-width ($\mu$m) | 27 | 130 |
| Duration ($\mu$sec) | 60 | 100 |
| Shape of the voids | discrete | thin & nearly continuous |