Ultrahigh-speed videography of fiber fuse propagation: a tool for studying void formation

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ABSTRACT

Ultrahigh-speed videography of fiber fuse propagation through single mode silica fiber revealed that asymmetric, or tailed, optical discharge pumped by more than 2.0 W of CW 1480nm light generates periodic voids, whereas symmetric one gives a thin continuous void. A number of optical micrographs showing front part of fiber fuse damage pumped by same energy were collected and sorted in the order of increasing distance between the top of the first big void and the top of the first regular void. The sorted sequence suggests the periodic void formation by the optical discharge; the discharge forms an asymmetric void and casts off its tail which shrinks to be one of regular voids. This process helps us to understand why the regular void looks like a bullet considering the internal pressure of the optical discharge and the temperature gradient along the fiber.

Keywords: Fiber fuse, Ultrahigh-speed videography, Laser-induced damage

1. INTRODUCTION

Fiber fuse effect was discovered in late 1980s,[1–6] initiated by local heating of optical fiber to generate an optical discharge running along the fiber to the light source (∼W) resulting in catastrophic and strange destruction of core region, i.e. periodic and bullet-shaped void formation. Ever since, nearly 40 papers has been published concerning this phenomenon.[7–37] On the one hand, recent growth of available laser power (>kW) gives rise to an practical need for fiber fuse termination.[6,22,25,31] On the other hand, the mechanism of void formation is not fully elucidated, because only few experimental data was available directly from dazzling and rapidly moving (∼m/s) optical discharge, such as spectrum of backscattered light[4] and single snapshot.[10,19] Therefore, former discussions[18,29] were mainly based on static images of fused damage and macroscopic properties including propagating speed.

Recently, the author reported ultrahigh-speed videography of fiber-fuse propagation and mentioned the relation between the shape of running optical discharge and the morphology of generated voids.[34,35] This paper presents further investigation of this topic to obtain a sequence of photographs demonstrating periodic void formation.

2. EXPERIMENTAL

Figure 1 shows the experimental setup in this study. One end of a commercial single-mode silica glass optical fiber (SMF-28, Corning, core diameter: 9μm) was connected to a Raman fiber laser (PYL-10-1480, IPG Laser, 1.48 μm, 10 W max.). The other end was folded and in contact with a metallic plate in order to initiate a fiber fuse when the laser light entered. The optical discharge was observed in a stripped section of the fiber through a CCD (Charge Coupled Device) camera (ultima APX-RS, monochrome version, Photron Ltd., sensitivity range: 380-790 nm) with an appropriate zoom lens. Pictures with a resolution of 128×16 were taken every 4 μs with 1-μs-exposure time through ND (neutral density) filters (x16 or x32). The fusing phenomenon was terminated by switching off the pumping laser. The time for extinction is less than 100 μs, which is the minimum time resolution of the power meter. Damaged sites were examined by an optical microscope.

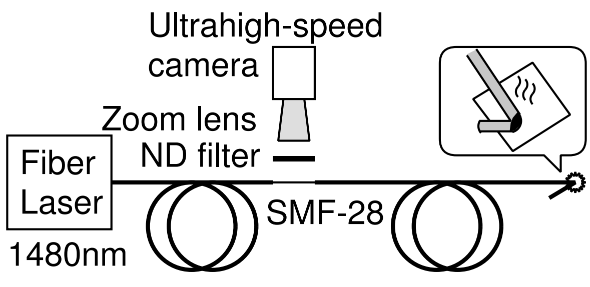

Figure 1. Experimental setup for observing fiber fuse propagation.

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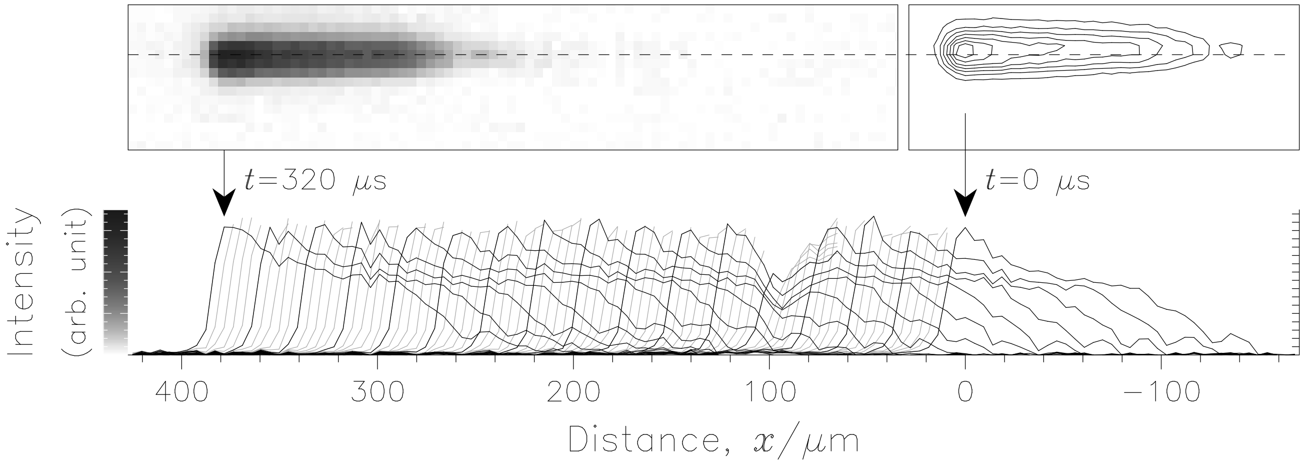
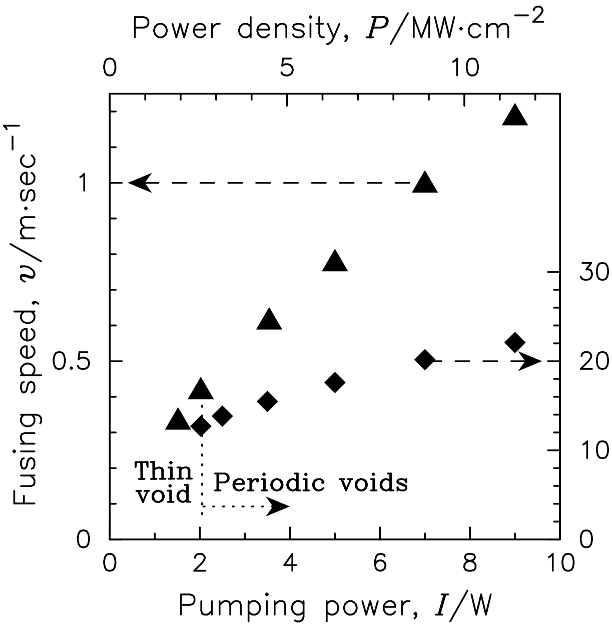


Figure 2. Photograph and contour map of optical discharge propagating through single mode silica glass fiber pumped by 9.0 W light (upper) and their intensity profiles along the dashed lines on the photo at every 4μsec (lower). Photographs of fused fibers under the same condition are shown in Fig. 8.



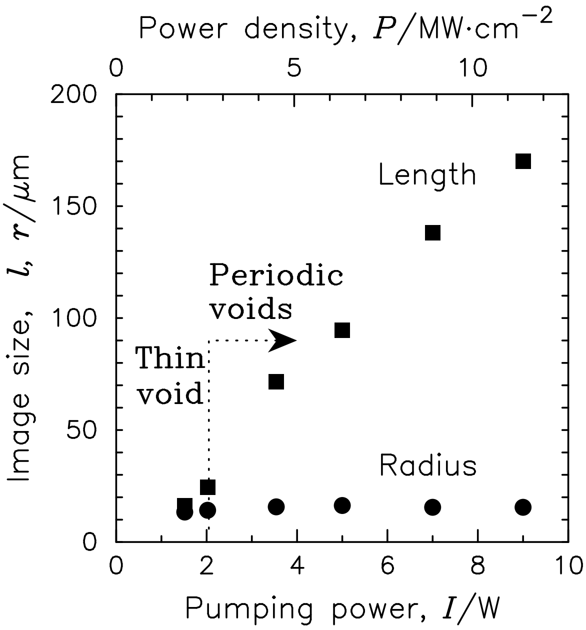


Figure 3. Pumping power dependence of fusing speed (▲) and void interval (♦).

Figure 4. Pumping power dependence of the length (■) and radius (●) of the first big voids, some of which are shown in Fig. 5. The radius values are larger than the actual size, $\sim 9\mu$m, (see Fig. 6) because the fiber acts as a cylindrical lens.

3. RESULTS

Figure 2 shows a typical results of ultrahigh-speed videography. The lower half shows a time-varying intensity profile of the optical discharge along the dashed line shown in the upper photos. The depression near $x = 100$ is due to a dust on the fiber surface blocking the emission. Propagation speed of the optical discharge was calculated from this result. Pumping power dependence of the speed is plotted in Fig. 3 as closed triangles.

Periodic void generation was observed for the damaged fibers pumped by more than 2.0 W, and their intervals are plotted in Fig. 3. Only thin continuous void was observed in the fiber pumped by 1.5 W, and both periodic voids and thin continuous voids were observed for the 2.0 W condition. Thus, pumping power of 2.0 W is the lowest limit for periodic

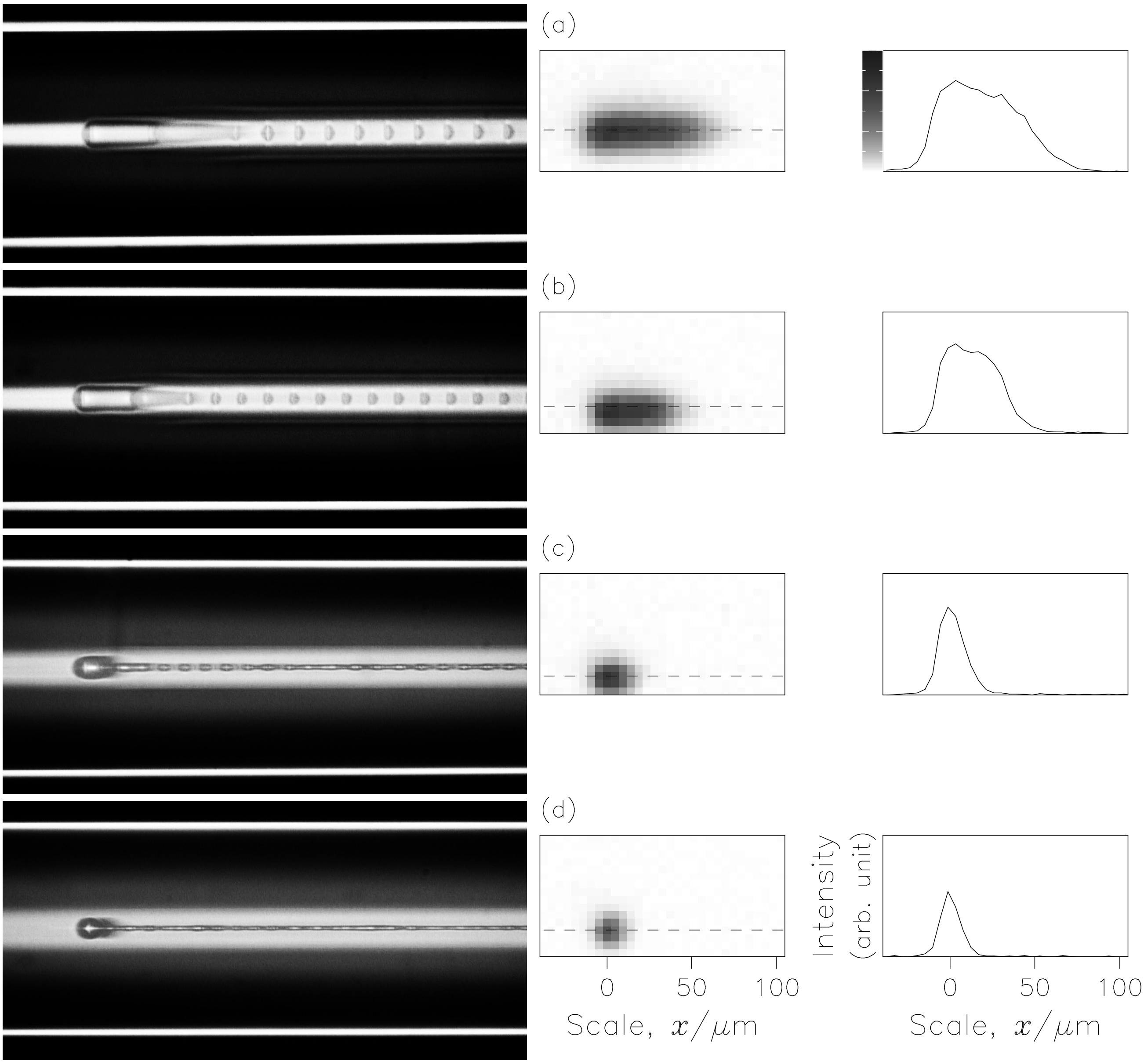


Figure 5. Optical micrographs showing front-void of fused fibers (left column), captured images of optical discharge by the ultrahigh-speed videography (middle column), and intensity profiles along the dashed line in each image (right column). Pumping powers are (a) 5.0 W, (b) 3.5 W, (c) 2.0 W, and (d) 1.5 W. The scales given in the bottom left are also valid for the photographs on the left.

void generation.

Figure 5 shows optical micrographs of the front part of generated damage and captured video images of optical discharge. Pumping power dependence of the length and radius of the front void is plotted in Fig 4. The actual radius of the front-void pumped by 5.0 W is determined to be about 9μm from the cross-sectional view shown in Fig. 6.

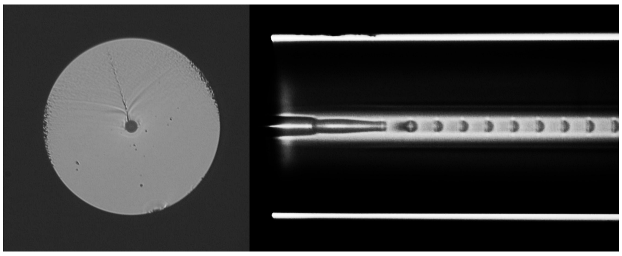


Figure 6. A cross-sectional view of a front-void generated by 5.0-W-pumping, showing the radius is about 9 μm.

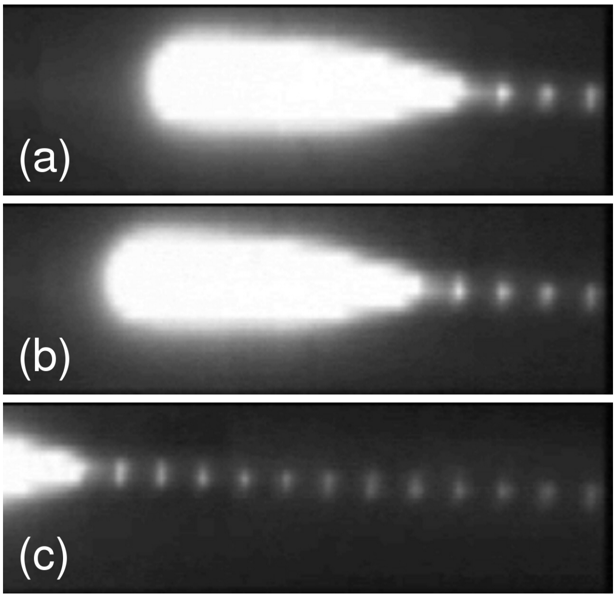


Figure 7. Overexposed images of 9.0-W-pumped optical discharge propagating a single mode silica siber.[35] Exposure time is 4 μs. (a) $t = 0$ μs, (b) $t = 20$ μs, and (c) $t = 180$ μs. The scale given in the bottom in Fig. 2 is also valid for these.

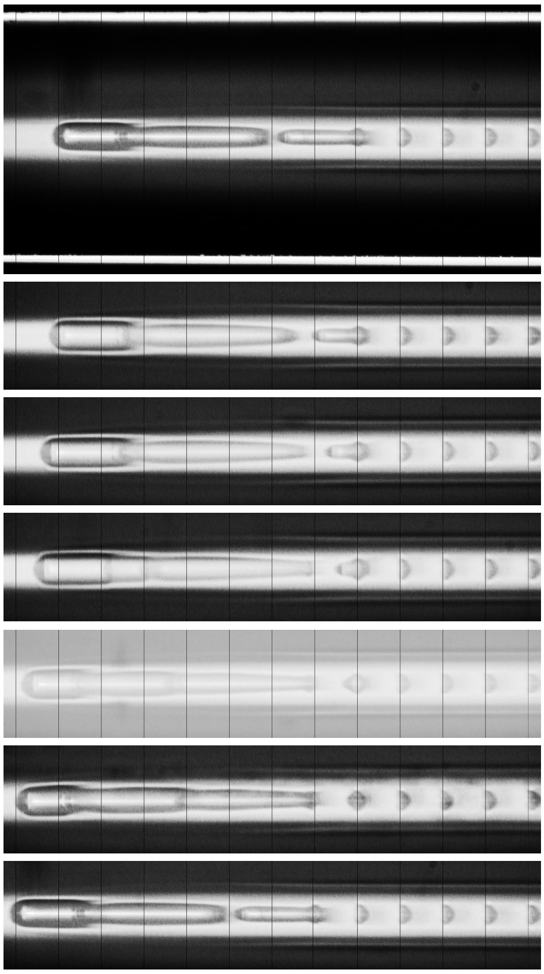


Figure 8. A series of optical micrographs showing fiber fuse damage in 9.0-W-pumped fibers. The interval of vertical lines is 22 μm. The photo in the bottom is the same as the top, shifted by 22 μm to the left. The scale given in the bottom in Fig. 2 is also valid for these.

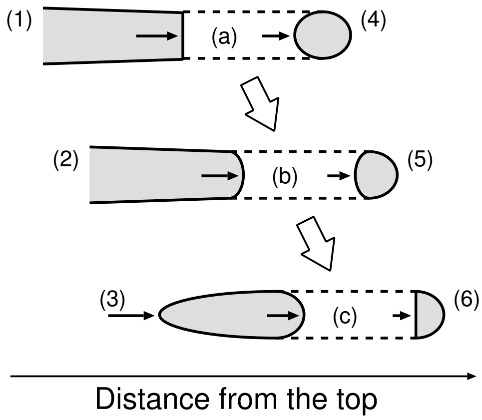


Figure 9. An illustration showing a scheme of transformation of the generated void during fiber fuse.

4. DISCUSSION

4.1. Optical discharge and front void

As shown in Fig. 4, the length of the front-void increases with an increase of the pumping laser power whereas its radius remain nearly constant. Similar tendency is also found in the snapshots of optical discharge shown in Fig. 2 and Fig. 5. Thus, it is reasonable to conclude that the optical discharge used to be located in the first big void. This is also supported by another result of overexposed ultrahigh-speed videography[35] (see Fig. 7) showing that discrete scattering points are clearly seen immediately after 9.0-W-pumped optical discharge whereas no scattering points are seen in front of the discharge. Moreover, the length of this optical discharge and the interval of scattering points coincide with those of voids shown in Fig. 8, which is generated by 9.0-W-pumped fiber fuse. (Note that Fig. 7 and Fig. 8 are printed in the same scale.)

Constancy of the void radius means that optical discharge is strongly enclosed in core region. Thus, the length of the front void, i.e. that of optical discharge, increases linearly with increasing pumping power (see Fig. 4). As shown in Fig. 5, the shape of the optical discharge becomes asymmetric along the fiber length with an increase of pumping power. As for the front void, its shape changes from simple ellipsoid to tailed cylinder (see left half of Fig. 5). Thus, the appearance of tail is the origin of this asymmetric shape. In addition, periodic voids are generated when the front void has a tail. Therefore, the tail must be a key player to form periodic voids.

4.2. Sequence of periodic void formation

Let us consider the period for one void formation. This is calculated from the propagating speed of optical discharge and the void interval, which are shown in Fig. 3. The values vary from 31.0 μs (2W) to 18.7 μs (9W), and are much larger than a cycle of ultrahigh-speed videography, 4 μs. Under the 9.0-W-pumping condition, optical discharge runs at a constant speed during the period of one void formation, as shown in lower half of Fig. 2. This is also valid for other conditions.

What is clear as of now is that the top of optical discharge moves at constant rate whereas a small void is generated every few tens of μs. Then, the photographs shown in left half of Fig. 5 are only one snapshot during the period of one void formation. Therefore, one can capture other moments by further sample preparation. A number of photographs were collected and sorted in a manner of increasing the distance between the top of the first big void and the top of the first regular void[37] (see Fig. 8). This sorting operation corresponds to a rearrangement in chronological order within the void formation cycle.

The sorted sequence seems to suggest a void formation process; the first big void casts off its tail which shrinks to be the top of regular voids. In this process, the tail acts as a source of regular voids. Thus, it is natural that optical discharge with no tail, pumped by less than 2.0 W, produces a continuous thin void.

We have to notice that there is a possibility that these shapes were modified within the quenching period immediately after stopping the pumping laser. The author thinks, however, that it hardly undermine the void formation process discussed above, because of the following reason. If the time for decreasing the pumping energy to zero were much longer than the period of one void formation, the void interval near the big void would decrease gradually, since the interval has been reported to decrease when reducing the pumping power.[18] This is also shown in Fig. 3. Such a reduction of the interval was not observed in the present study. The author confirmed that at least for 20 mm from the big void, the interval was constant. This distance corresponds to be few tens of ms for travelling. Thus, the modification during quenching is likely to occur within the last cycle of void formation, few tens of μs. Moreover, the viscosity of silica glass is known to increase steeply with decreasing temperature (for example, see Yakovlenko's paper[29]). Thus, the modification is expected to be smaller in scale than the one-void formation.

4.3. Mechanism of periodic void formation

The sequence of void formation helps us to understand qualitatively why the regular void looks like a bullet when we think of the glass bridge generated in the tail of the big void. Figure 9 shows a simplified model of shape-modification near the top of regular voids and the glass bridge, which is extracted from Fig. 8. From a viewpoint of the regular void, it is pinched off from the big void at (3) in Fig. 9, and shrinks (4,5) to be fixed (6). On the other hand, the glass bridge changes its shape in the sequence of (a), (b) and (c) in Fig. 9.

This action is governed by the internal pressure of the optical discharge and the temperature gradient, i.e., a change in viscosity of the glass, along the fiber. Once a glass bridge appears in the tail, it is pushed backward by the pressure of optical discharge (note that the discharge is strongly enclosed in the core region as discussed above). As the distance from the top of the optical discharge increases, the temperature decreases and the viscosity of the glass increases. Therefore, the displacement of the interface between the glass and the void decreases, as shown by the horizontal arrows in Fig. 9. Consequently, the front end of the pinched-off void solidifies after its backward is fixed. This time lag brings about the shape of bullet.

The appearance of the glass bridge is related with a creation of new free surface at the front end of the optical discharge. The discharge keeps its total surface area in balance by these actions.

The present results can provide a concrete model to the recent works of theoretical approach and computer simulation[20, 27, 29, 32] toward a deeper elucidation of this phenomenon.

5. CONCLUSION

Ultrahigh-speed videography of fiber fuse propagation and microscopic observation of fiber fuse damage revealed that asymmetric, or tailed, optical discharge generates periodic voids. A sequence of periodic void formation during fiber fuse is generated by sorting a number of optical micrographs showing front part of the damage. The sequence seems to suggest a void formation process; a glass bridge appears in the tail of optical discharge and is pushed backward to form a bullet shaped void. The origin of this shape is the time lag of solidification between the front and back end of the generated void under the internal pressure of the optical discharge and the temperature gradient along the fiber.

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