Animation of fiber fuse damage, demonstrating periodic void formation

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A series of optical micrographs showing the front region of the fiber fuse damage were obtained to reveal the periodic void formation process. They were collected from a number of samples and were sorted in order of increasing distance between the top of the first large void and the top of the first regular void. The micrographs clearly show that the first large void sheds its tail, which shrinks to form a regular void. This mechanism leads to the formation of bullet-shaped regular voids as the result of the balance between the internal pressure of the optical discharge and the increasing viscosity of the surrounding glass that occurs during pinching off.

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The fiber fuse effect has been a familiar phenomenon since the late 1980s. It is initiated by the local heating of an optical fiber, which generates an optical discharge running along the fiber to the light source (approximately a few watts). This results in catastrophic destruction of the core region, i.e. periodic and bullet-shaped void formation.[1,2] The recent increase in available laser power (to greater than a kilowatt) has led to a practical need to terminate the fiber fuse.[3,4,5] On the other hand, the void formation mechanism is not fully understood and has only been discussed from a theoretical point of view[6,7] and by means of a few direct observations near the bright and rapidly moving (approximately a meter per second) optical discharge.[8,9,10] This Letter describes two types of experimental results that suggest the mechanism behind periodic and bullet-shaped void formation.

The first result is a direct observation of the optical discharge obtained with an ultrahigh-speed CCD camera[8,10] as shown in the upper half of Fig. 1. One end of a commercial single-mode silica glass optical fiber (SMF-28, Corning) was connected to a Raman fiber laser (wavelength: 1.48 μm). The other end was folded and brought into contact with a metallic plate in order to initiate a fiber fuse when a 7.0 W laser light was launched into it. The optical discharge was observed in a stripped section of the fiber through the CCD camera (ultima APX-RS, Photron Ltd., sensitivity range: 380–790 nm) with an appropriate zoom lens. Images with a resolution of 128×16 were taken every 4 μs with a 1-μs-exposure time through neutral density (ND) filters (×16). Since the fiber acted as a cylindrical lens, the images were expanded in the vertical direction. The speed of the optical discharge was calculated to be 1 m/s, as shown in the lower half of Fig. 1. The damaged fiber was examined with an optical microscope to measure the interval of the generated voids, which was found to be 20.2 μm (see the right half of the photographs in Fig. 2). Thus, a void is generated about every 20 μs, i.e., one void per five photographs. A series of cross-sectional views of the front part of the optical discharge, shown in the lower half of Fig. 1, clearly shows that the optical discharge runs at a constant speed during the formation of one void.

The second result is a collection of micrographs showing the front part of the damage train. The samples were obtained by switching off the 7.0 W pump laser after a fiber fuse was generated. It required no more than 7 μs for the emission from the optical discharge to drop to zero. This value is near the resolution of the CCD camera. A typical view is shown at the top of Fig. 2. The vanished optical discharge was originally in the first large void for the following two reasons. Firstly, the asymmetric shape and length of the void ($\sim$ 120 μm) coincide with those in the images shown in Fig. 1. This relationship is also confirmed for samples with different pump powers (1.5–9.0 W).[11] Secondly, the micrographs of a running optical discharge and following voids pumped at more than 5.9 W, which were reported by Bufetov *et al.*[9] and Todoroki,[10] also show similar geometry, that is, an asymmetric luminous region and periodic voids.

The micrograph at the top of Fig. 2 is only one snapshot taken during 20-μs void formation sequence. Other moments can be captured by preparing further samples. A number of micrographs were collected and sorted in order of increasing distance between the top of the first large void and the top of the first regular void (see the rest of Fig. 2). This sorting operation corresponds to a rearrangement in chronological order within the void formation cycle, since the optical discharge runs at a constant rate during the cycle as described above. This rearrangement was also applied to other groups of micrographs with different pump powers (3.5, 5.0 and 9.0 W) to produce similar sequences.

The sorted sequence seems to suggest a void formation process; the first large void sheds off its tail, which shrinks to become the top of regular voids. We have to notice, however, that the shape of the large void may change during the quenching period immediately after stopping the pump laser. However, this does little to undermine the above void formation process for the following reason. It takes less than 7 μs for the emission from the optical discharge to drop to zero. In addition, the viscosity of silica glass is known to increase steeply with decreasing temperature. Since the heated area near the core region is surrounded by a cold and thick cladding layer and polymer coating, the temperature is expected to drop immediately after the laser is switched off. Therefore, considering the period of 20 μs needed for the formation of one void at elevated temperature, the amount of modification in a large void during this shorter quenching period is expected to be smaller in scale than that during one void formation. Consequently, although Fig. 2 is not an in-situ observation, the characteristics of these shapes are sufficient for a discussion of the periodic void formation process.

The void formation sequence helps us to understand qualitatively why the regular void looks like a bullet when we consider the glass bridge generated in the tail of the large void. Figure 3 shows a simplified model of the shape modification of the voids and the glass bridge, which is derived from Fig. 2. As regards a regular void, it is pinched off from the large void at (3) in Fig. 3, shrinks (4,5) and becomes fixed (6). On the other hand, the glass bridge changes its shape in the sequence (a), (b), (c) in Fig. 3.

This action is governed by the internal pressure of the optical discharge and the temperature gradient, i.e., the change in the viscosity of the glass along the fiber. Once a glass bridge appears in the tail, it is pushed backward by the pressure of the optical discharge. 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. 3. Consequently, the front end of the pinched-off void, i.e. the side of the first large void, solidifies after its back end is fixed. This time lag results in the bullet shape. The appearance of the glass bridge is related to a creation of a new free surface at the front end of the optical discharge. The total surface area surrounding the discharge is kept in balance by these actions.

The present results can provide a concrete model for recent work on theoretical approaches and computer simulations[7,12,13,14] and thus help to provide a clear understanding.

In summary, this work has successfully reconstructed the sequence of the periodic void formation that occurs during a fiber fuse from a number of optical micrographs showing the front part of fiber fuse damage. These micrographs were collected from single-mode silica fibers with the pump laser (1.48 μm, 7.0 W) switched off after fiber fuse had been generated. They were sorted in order of increasing distance from the top of the first large void, where there had been an optical discharge, to the top of the first regular void. Although the photographs were not obtained in-situ, the sorted sequence clearly suggests a void formation process; the first large void sheds its tail, which shrinks to become a bullet-shaped regular void. The origin of this shape is the time lag of the solidification between the front and back end of the pinched-off void under the internal pressure of the optical discharge and the temperature gradient along the fiber.

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List of Figures

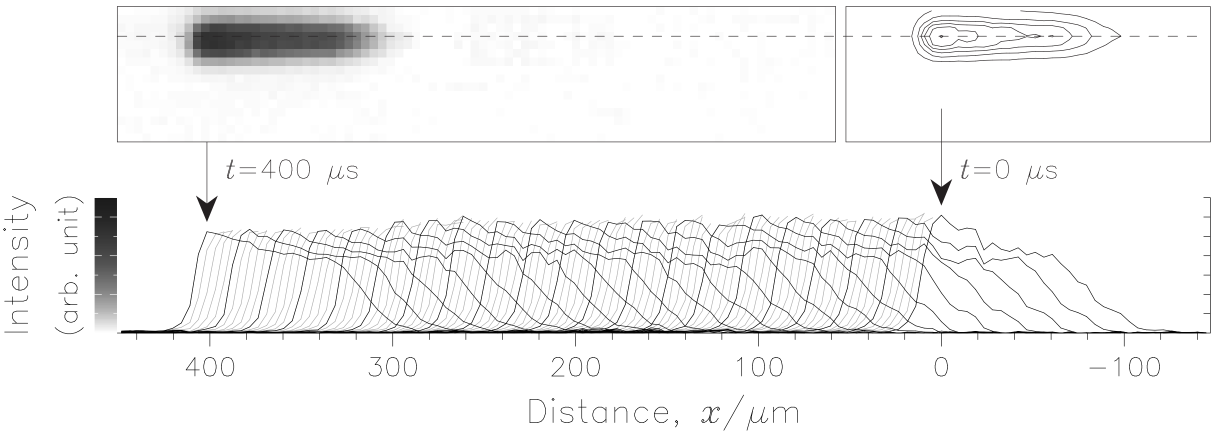

Fig. 1. Photograph and contour map of optical discharge propagating through a single-mode silica glass fiber pumped by 7.0 W light (top) and their intensity profiles every 4 μs along the dashed line in the photo (bottom)

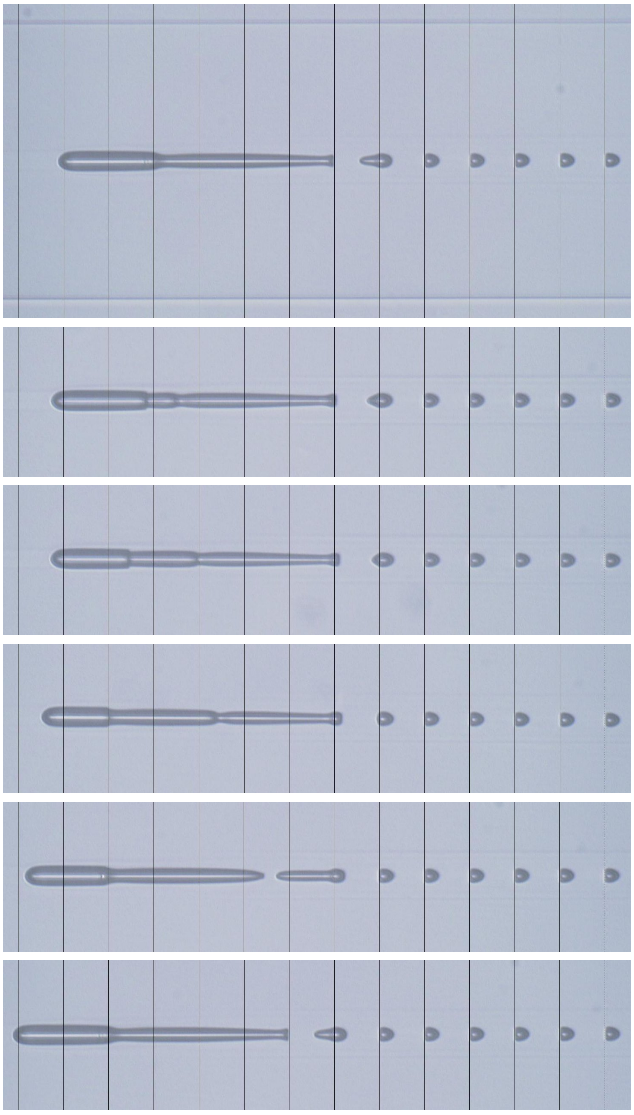

Fig. 2. Series of optical micrographs showing the damage generated in 7.0 W pumped fibers, focusing on the voids inside the fiber. The interval of the vertical lines is 20 μm. The photograph at the bottom is the same as that at the top, shifted 20 μm to the left.

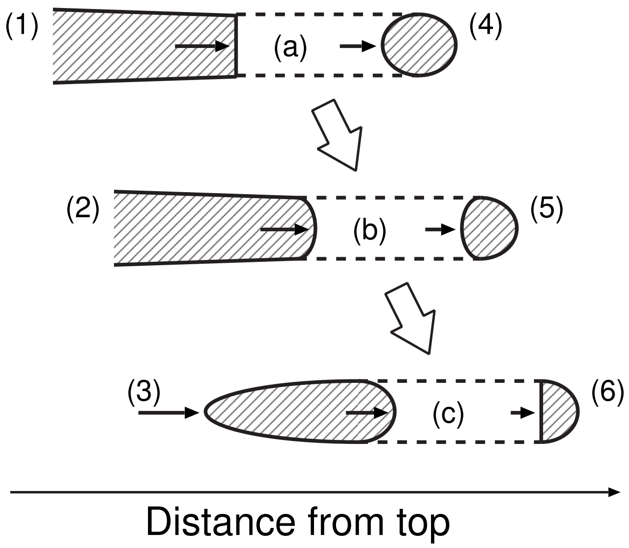

Fig. 3. Transformation of the void generated during fiber fuse.