Two serendipitous episodes
— How I embarked on fiber fuse research —

S. Todoroki

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Episode I

Early afternoon in Stockholm

I participated in the European Conference on Optical Communication held in September 2004. After having lunch at a sushi bar popular with some locals, I checked the conference notice board and was greatly surprised. My paper had unexpectedly been accepted as a postdeadline paper [1]. "Those photographs are the first in the world for sure, but I wonder why my paper has been chosen when it only provides immature results of the first trial." All the same, I was now scheduled to make a presentation late in the afternoon of the final day. I had to prepare my talk instead of sightseeing in Stockholm.

The poster that brought good fortune

The story really started four months earlier. A salesman called Kazugide Hanaka came to my office without an appointment and took me outside the room to look at a poster showing my latest research results. Then, he said, "Our brand new video camera will surely help you to obtain fascinating results! Would you allow me to take photographs of this phenomenon as a demonstration?"

The phenomenon was the burning of a device called an "optical fuse" which results from excess incident light [2]. As with the fuses that are installed in every electric device for overload protection, optical fuse is designed to protect delicate optical systems.

The photographs that he pointed out had been taken with an ordinary video camera at intervals of 1/30 second (see Fig. 1), and showed the moment of breakdown as a flash. He said that his camera could take up to 4,000 times as many pictures as mine. Very impressive! I promised him that I would request a demonstration once my experimental system was ready.

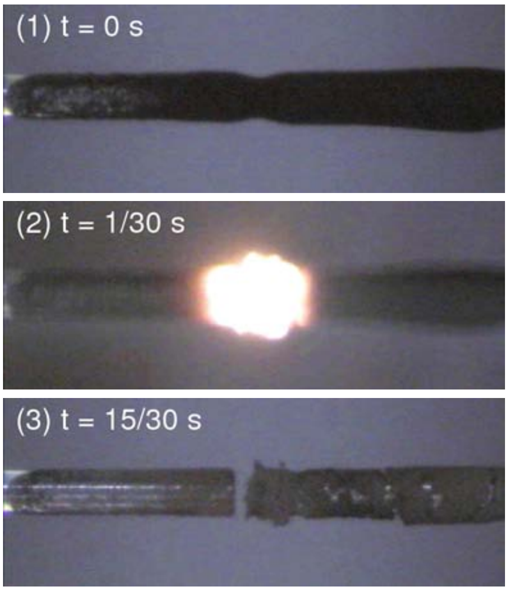

Figure 1: Breakdown of optical fuse. The outer diameter of the optical fiber is 125 μm.

National Institute for Materials Science, JAPAN
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As a matter of fact, his proposal reminded me of another famous phenomenon called "fiber fuse", which was discovered in 1987 [3]. It is widely known among researchers in the fiber optics field but I had never seen a photograph showing it. So if we were successful, it would surely create a sensation.

A fiber fuse is initiated by the local heating of an optical fiber delivering a few watts of light, which generates an optical discharge running along the fiber to the light source at about 1 m/s (see Fig. 2 and 3). This results in the catastrophic destruction of the core region and the discharge continues unless the light source is cut off. The damaged fiber no longer transports light. Thus, it has posed a real threat to every application where high power light is delivered through optical waveguides. However, this phenomenon is not yet fully understood.

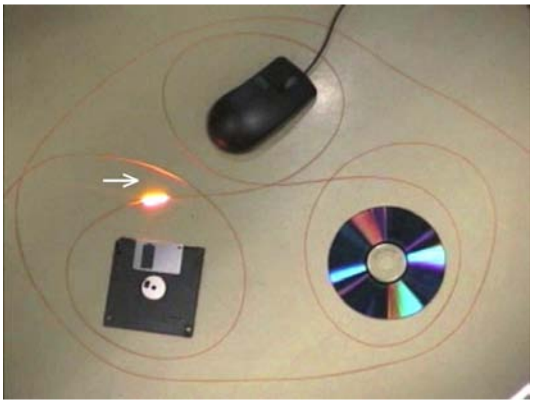


Figure 2: Macroscopic view of fiber fuse propagation through a single-mode silica fiber pumped by a 9.0 W and 1.48 μm laser light.

I made up my mind to take pictures of a fiber fuse during the demonstration, but the problem was that I had never seen a fiber fuse and did not know how to initiate it. How could I induce it right in front of the camera?

Days of trial and error

A survey of the literature in the field revealed that there were no reports about capturing sequential images of a moving optical discharge. There are various methods for achieving fiber fuse ignition. In essence, local heat must be generated at the end of an optical fiber by bringing it into contact with a light absorber. However, in my case, both the fiber end and the absorber should be within the field of vision; the fiber end should not be covered by the absorber. I began to undertake trials with the components available in my laboratory.

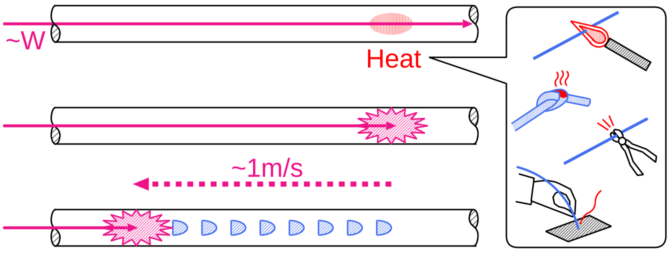


Figure 3: Fiber fuse ignition, propagation and periodic void formation.

How about placing a carbon lead normally used for mechanical pencils in a Pyrex capillary tube as a light absorber? The tube provides a meeting point between the lead and the fiber end. I assembled an observation system that included an ordinary video camera. Launching a 10 W light only resulted in a crack in the tube. I tried to remove the lead from the tube but found that it was firmly stuck. Thus, the temperature must have exceeded 800 °C! The use of a thin tungsten rod instead of the lead only gave a spark.

Then, how about using a glass ferrule for the optical fibers instead of a Pyrex tube? It has a through hole whose inner diameter is the same as the outer diameter of optical fibers. Although the space for the absorber is very limited, it is possible to mount it if it is in the form of fine powder and pressed between two fiber ends in the through hole. I found that cobalt oxide powder generates dark red radiation with the incident laser beam, and induces subsequent cracking in the ferrule. But its behavior varies according to the thickness of the powder layer.

These experiments caused me some degree of stress. This was because I had to shut down the light source as soon as the fuse appeared, or it would reach the expensive laser and break it. In addition, I had never seen a fiber fuse before. Then one evening, I performed the last trial of the day with the thinnest powder layer so far. Soon after I launched the laser beam, the ferrule cracked and a dark red light disappeared. I left the laboratory feeling slightly disappointment as usual.

The next day, I pulled myself together and started a new experiment. I launched the laser and measured the light power passing through the same fiber that I had used the previous day. However, the power meter did not respond. I checked the fiber cable and found a point where the polymer coating had melted. Oh, dear! I must have damaged the fiber without noticing! I removed the damaged segment, and when I spliced the remaining fibers I observed an unexpected image. The fused point had inflated like a balloon. This must have been due to the voids generated by fiber fuse propagation. At last, after struggling for a month, I had succeeded in initiating a fiber fuse.

Counting chickens before they hatch

I immediately requested the demonstration, and it was scheduled for early August. I started to assemble a new observation system including an ordinary video camera to record the fiber fuse ignition and the brand new camera to record the propagation. Then, an interesting plan occurred to me. I was going to attend the European Conference on Optical Communication early in September. I would submit a postdeadline paper if I obtained some interesting results. It would be unlikely to be accepted but "nothing ventured, nothing gained". It would also be fun rather than just attending the conference to hear the presentations.

On the day of the demonstration, an engineer joined us but we only managed three takes. It took 30 minutes to prepare fiber fuse ignition. In addition, the ignition failed on a number of occasions. The first take was performed as a test run with a slow sampling rate and a long exposure time. We were looking at the the replay in slow motion and discovered a thrilling image. A dazzling fireball moved across the screen followed by scattering points in a line caused by the generated voids (see Fig. 4). What a terrific view! But the image was over-exposed. We had to increase the sampling rate and reduce the exposure time.

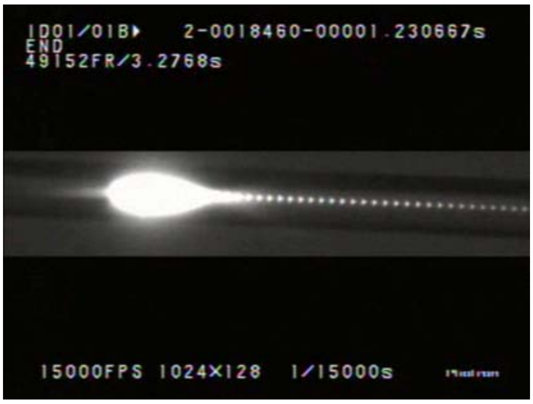


Figure 4: The first captured image of fiber fuse propagation. The image is saturated in spite of the exposure time of 1/15000 second.

However, a faster sampling rate meant an increased number of photographs. I had to find just 50 images from over 100,000 during playback. For the last take of the day, the condition was at the limit of the camera's performance. Nevertheless, the images were still over-exposed. The emission was very strong! The fiber fuse seemed to make fun of the state of the art camera. Was this an egg that would never hatch? Immediately, I proposed my plan for submitting a paper to Mr. Hanaka. "That's a good idea! We can use this camera next week. It's in my company's summer holidays."

Rushing forward at the expense of my summer vacation

There are two ways of preventing over-exposure. One is to mount neutral density (ND) filters on the camera and the other is to reduce the laser power after the ignition of the fiber fuse. In the afternoon of the day before the second demonstration, Mr. Hanaka suddenly appeared in my laboratory carrying the brand new camera. This was because his business had finished earlier than expected. We performed one trial right away using ND filters. Strange as it was, the images obtained were out of focus. Then, I realized that I had to focus the camera after the ND filters had been mounted. However, it was too dark to focus the camera through ND filters without the brilliant fiber fuse. To over come this problem, I spent the rest of the day installing extra lighting behind the fiber.

The next morning, we succeeded in determining the condition for the reduced incident power. However, during the first trial in the afternoon, I carelessly forgot to reduce the laser power. After a short break, we obtained pictures without over-exposure.

There were now only five days left before the deadline. All I had to do was to analyze the data, draw the figures, and write a 2-page paper in English. I wondered whether I could make an attractive discussion from the photographs of the last trial. Therefore, I also analyzed the rest of the data. Then, I found that the second from last trial was also usable; the trial where I forgot to reduce the laser power. These photographs clearly captured the whole shape of the optical discharge although a small portion of the pixels was over-exposed. Thus, I could compare the results under different conditions. In fact, I found a clear difference between the pictures of the voids left in the damaged fibers. The pictures taken in the first demonstration were also usable as proof of the fact that a void is generated just after the passage of the optical discharge. Ultimately, the quality of the discussion became much better than my initial expectation, but it still seemed to be well below the standard required for postdeadline papers. Nevertheless, I was able to submit the paper just before the deadline without any real hope of it being accepted.

The chance cause

On the last day of the conference, the postdeadline paper session began. I was the third speaker. I finished my 10-minute talk with the short movies, and the talk was opened for questions from the floor. The first questioner was Prof. Dianov, a leading figure in fiber optics from Russia. I had spoken with him once before. Eight years ago, at the same conference, he had made a critical comment about my poster presentation. His group had also been working on the fiber fuse phenomenon for years. Will this be another critical comment? All of my attention focused on his voice.

> "What is the new finding of your work?"

Okay, you are right. I would also ask the same question about work that only showed observations. I could only reply, "If we are to prevent accidents caused by a fiber fuse, we need a precise understanding of the phenomenon. I found that the shape of the damage is closely related to the shape of the optical discharge."

After the session had finished, I left the room and found that Prof. Dianov was waiting for me.

> "Your paper did not gain high points from the other members of the selection committee, but I insisted it be adopted."

Now I understood! My doubt disappeared.

> "As a matter of fact, we're also trying ultrahigh speed videography."

Later I found that his group published their results at a domestic workshop 20 days after my presentation [4]. Their photographic techniques were more sophisticated than ours, but the performance of our camera was clearly superior to theirs. If Prof. Dianov had not insisted that my paper be accepted, I would have no chance to publish my results and his group would be recognized as the first. I have to admire his fairness.

Episode II

Late night in St. Petersburg

"Okay, that camera is the solution."

I woke up before dawn on the day of my trip back to Japan. After finishing my invited talk the day before, I had been thinking about one problem. Now, I had found the way to proceed.

"I have 20 days before the deadline. I will do my best to borrow the camera."

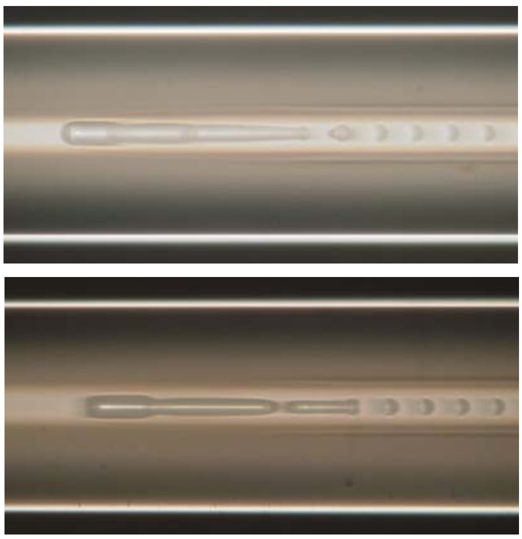
I had to reply to the comments on the paper that I had submitted to a journal. It was a hurdle to be cleared in order to publish what I had just told to the world. Once the business center in the hotel had opened, I sent an e-mail to Mr. Hanaka describing my difficult situation. That was the only action I could take at that time. I would consider remaining ploblems after returning to Japan.

Last summer, I had borrowed a camera from him and successfully recorded fiber fuse propagation in situ for the first time. Then I had a chance to talk about the work at an international conference last autumn. This had led to another chance to go to St. Petersburg in spring [5]. Since I had not been willing to talk about an achievement realized with a borrowed camera, I had continued my research without the camera and discovered an interesting issue. Thus, I had written the paper and submitted it one month before my departure to St. Petersburg.

Enigma left in fused fibers

Despite the new findings obtained by the ultrahigh speed videography, one curious feature was left unexplained. Along the trajectory of the optical discharge, there remained periodic bullet shaped voids (see Fig. 3). No one had ever provided a persuasive reason for the formation of this strange shape, because there had been no way to observe what occurs at the optical discharge due to the strong light emission.

One day I was repeating an experiment that consisted of initiating a fiber fuse, terminating it by switching off the pump laser and observing the voids that were generated. In order to minimize the waste in terms of the fiber cable I was using, I looked for the fiber fuse termination point and cut the cable adjacent to that point. For no special reason, I looked at the termination point through a microscope. I saw a long void followed by regular periodic voids (see Fig. 5 (a)). This was my first view of the top void and reminded me that the optical discharge was there before termination.



(a) (b)

Figure 5: Optical micrographs of fused damage generated by a laser light of 1480 nm, 9.0 W. The images are distorted due to the absence of matching oil. The distance between the two horizontal white lines corresponds to the diameter of the optical fiber, 125μm.

A few days later, I was again repeating the same experiment, and happened to stop the procedure. That was when I observed the termination point. "What is this neck?" (see Fig. 5 (b)) Suddenly, an idea flashed into my mind. It looks like a frame of a movie showing periodic void formation. I'm sure that this neck moves backwards and the long void sheds its tail, which shrinks to form a regular void.

In order to verify this, I needed to obtain pictures of the top void at different times within the formation period of one regular void and to sort them in order of time. It is impossible to take such pictures intentionally. Luckily, however, the fiber fuse left many reference points; that is, periodic regular voids.

Another day, I made many fused fibers under the same condition and sorted the photographs in order of distance between one of the regular voids and the top void. The result was exactly as I had expected (see Fig. 6).

Walk on a tightrope

When writing my paper, I was very sensitive about one issue, namely that these photographs were not in situ observations of active optical discharges but merely cast-off voids. There is a very short transition time from a very high temperature state to a frozen state. There is no proof that the shape of the top void remains unmodified. I carefully added some indirect evidence for the absence of modification to the manuscript.

Of the three referees who reviewed my work, one accepted the paper without reservation and one was positive and offered some constructive comments. However, the third noticed the weak point. He asked me to provide the decay time of the pump laser power when switching-off. If the time had not been short enough, the shape of the frozen voids would have experienced some modification.

I had to respond within 30 days. One third of the period was taken up by the conference in Russia. I do not have any system for obtaining the requested data and had no idea from where to borrow it. I decided to come up with an argument against the comment during the business trip. Finally, I decided that a better way was to borrow that camera again.

After returning to Japan, I found some good news from Mr. Hanaka. Ten days before the deadline, he was scheduled to demonstrate the same camera near my institute. He gave me 2 hours before the demo to use the camera. What a chance! He gave me a way out of the dead end.

However, there is still one more problem. The camera is sensitive only to visible light but the pump light is invisible. I thought of converting it to visible light but found that it was not feasible for this experiment. Consequently, there was only one approach left; to capture the moment of fiber fuse termination.

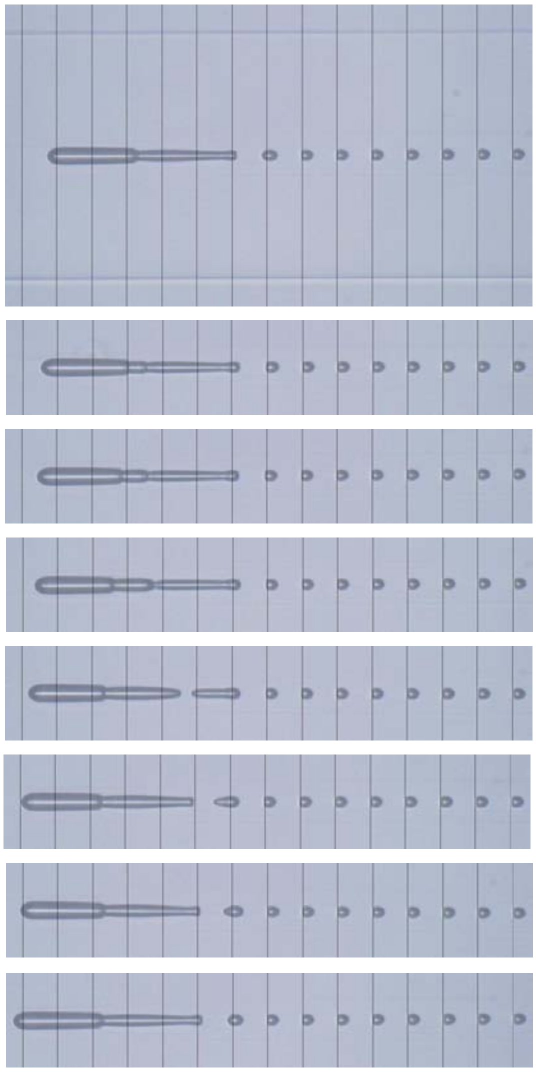

(a) (b) (c) (d) (e) (f) (g) (h)

Figure 6: A series of optical micrographs showing the damage generated by 5.0 W laser light. The interval of the vertical lines is 17.8 μm. The micrograph at the bottom is the same as that at the top, shifted 17.8 μm to the left.

Mind like water

It was to be a very difficult experiment. I had to adjust the timing of the termination so that it occured as soon as the optical discharge running at about 500 mm/s came within range of the camera whose width was 5mm. This situation required that the laser be switched off with a precision of 1/100 second and without any trigger signals for adjustment. But there was no other way to go, or the paper would be rejected. I practiced many times to achieve termination at the desired position, although I had no way to judge the results.

It was the early morning of a fine day in May. I arrived at a station square to meet Mr. Hanaka and an engineer and we went by car to my laboratory. I had prepared only 11 samples, which was the maximum number for a 2-hour experiment. However, I was completely free of anxiety. Very strangely, I believed groundlessly that I would succeed. I must have had a "mind like water", which is a Zen expression.

I performed two trials to determine the proper photographing condition. For further trials, each recordings was replayed in slow motion to confirm whether the termination had been captured or not. In the beginning, either nothing was recorded or a light spot passed across the view. When I replayed the 7th trial, a light spot appeared at the edge of the screen but suddenly disappeared (see Fig. 7).

Great! We've done it.

We shook hands with each other. Having no time to enjoy the taste of success, Mr. Hanaka and the engineer left to perform their second demonstration.

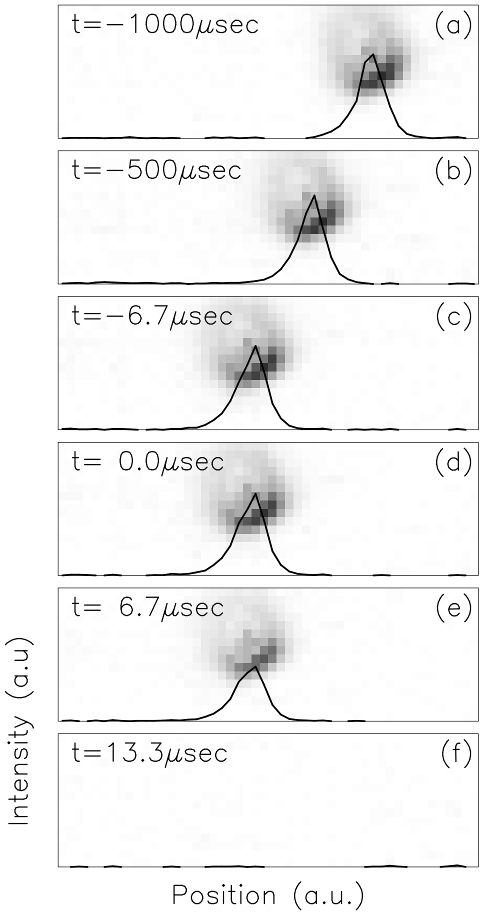


Figure 7: A series of photographs capturing the moment of fiber fuse termination (d–f). The doughnut shape is the result of the image being slightly out of focus.

All's well that ends well

I obtained the decay time of the fiber fuse termination, which was less than 7 μs. The paper was accepted for publication [6]. At each stage I felt as though I were on a tightrope, but my serendipity and the people who have appeared in these episodes helped me along the road to success.

Here I express my sincere thanks to Mr. Kazuhide Hanaka, Mr. Akira Sakamaki and Mr. Keisuke Aizawa (Photron Ltd.) for helping with the ultrahigh-speed videography experiment, Prof. Evgueni Mihailovich Dianov and Dr. Igor Alekseevich Bufetov (General Physics Institute of the Russian Academy od Sciences) for giving me some valuable comments, and the late Prof. Sergey Ivanovich Yakovlenko for inviting me to the International Conference on Lasers, Applications, and Technologies 2005.

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Annotation

- Video clips corresponding to Figures 1, 2 and 6 are available at http://www.geocities.jp/tokyo_1406/node9.html

- The original articles were published in Japanese as shown below.

  Episode I: Electric Glass, **35**, pp. 14-18 (2006).

  Episode II: Industrial Materials, **55** [4], pp. 97-101 (2007).