Observation of blowing out in low loss passive optical fuse formed in silica glass optical fiber circuit

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Low loss (less than 1dB) passive optical fuses were realized by inserting 50-μm-thick TeO_2 glass layer into a single-mode silica glass fiber circuit with carbon coating. On the basis of real-time observation of their fusing action, the mechanism of losing its transparency is discussed. The observed loss drop is found to be an overlap of decoupling of the circuit and transient light flux from the burned coating. The critical input power to blow out is expected to be raised by eliminating its insertion loss.

KEYWORDS: optical fiber, tellurium oxide glass, carbon, optical fuse, hybrid device

"Optical fuse" is a switching device whose transparency drops by an excessive incident beam and is used for protecting optical components to be damaged by the beam. Its importance is growing considerably with the recent development of high power light sources. Several passive optical fuses have been proposed[1,2] and they have a common structure in which some thin layers are inserted in a optical fiber circuit and one or some of the layers made of metal absorb propagating light to bring about a permanent loss increase there.

Recently, we proposed a new structure of passive optical fuse,[3] in which transparent soft glass segment (pure TeO_2, $\sim$150μm-long with a necked region, see Fig. 1) is inserted in the circuit (insertion loss: $\sim$2–3 dB) and is coated with carbon-containing paint. In this structure, leaked light from the glass segment is absorbed by the coating to generate heat that deforms the glass segment to reduce its transparency. Although its response time in theory is expected to be much slower than that of the former optical fuses, it is still important to offer several options for constructing fail-safe optical systems. Here we report the improved version of this structure with reduced insertion loss, less than 1dB. On the basis of real-time observation of fusing action, its mechanism to lose transparency is discussed.

Several samples were fabricated by the following procedures, some of which are described in detail elsewhere.[4–6] Two commercial single-mode bare fiber pigtails were placed on fiber holders so that their ends face each other. A droplet of TeO_2 melt on a gold plate with a small electric heater (>700°C) was set between them. Then, the end of the fibers were inserted into the glass melt from its sides and the plate was lowered to leave a small amount of the melt between the two ends. The fibers were immediately moved to an appropriate position to minimize its insertion loss before the melt was solidified.

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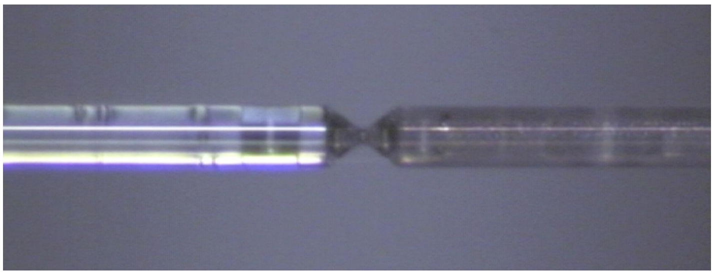

Fig. 1. A necked glass bridge inserted in a silica glass fiber circuit, which is used for making a passive optical fuse in our former work.[3] The diameter of the fiber is 125μm.

Table I. Summary of the results.

Sample	Insertion loss (dB)	Maximum output (W)
E-1	0.95	1.22
E-2	0.82	1.31
E-3	0.61	1.63 (2nd trial)
E-4	0.63	not blown out
R-1	0.80	4.03
R-2	0.71	4.04
R-3	0.66	5.33

We made 7 samples with a 50μm-thick soft glass layer (see Fig. 2(0)), whose insertion loss values are listed in Table I. The variation among these values must be mainly due to that of a little tilted cut at the fiber ends. This fiber circuit was connected to an Er-doped fiber laser (ELD-33-1540, IPG Laser, 1.54μm, 2W max., the samples are denoted as E-1, 2, 3 and 4) or a Raman fiber laser (PYL-10-1480, IPG Laser, 1.48μm , 10W max., denoted as R-1, 2, and 3) and an optical multimeter (8163B, Agilent Tech., averaging time: 1 msec) to measure the variation of its transmitted power. We confirmed that the soft glass layer withstands transmitting the laser power up to its maximum, increased stepwise in about 2 sec or 4 sec for the Er laser (see the dotted line in Fig. 2) or the Raman laser, respectively. Then, the glass layer and adjacent fiber ends were coated with commercial black watercolor, which consists of fine carbon powder and gum arabic in general (Fig. 2(1)).

The laser light was entered to the device in the same way described above and its outer appearance was recorded as a video movie whose sampling rate was 30 images per second. For the samples except E-3 and E-4, a flush suddenly appeared from the glass segment as shown in Fig. 2(2&3), and subsequently the coated carbon burned completely and the glass layer was found to be disappeared between the red-hot fiber ends (see Fig. 2(4&5)). This flush burning of the coated carbon is brought about by the leaked light from the adjacent glass layer which has no waveguide structure.

The time-varying output power from sample E-2 is shown as the solid line in Fig. 3. The upward

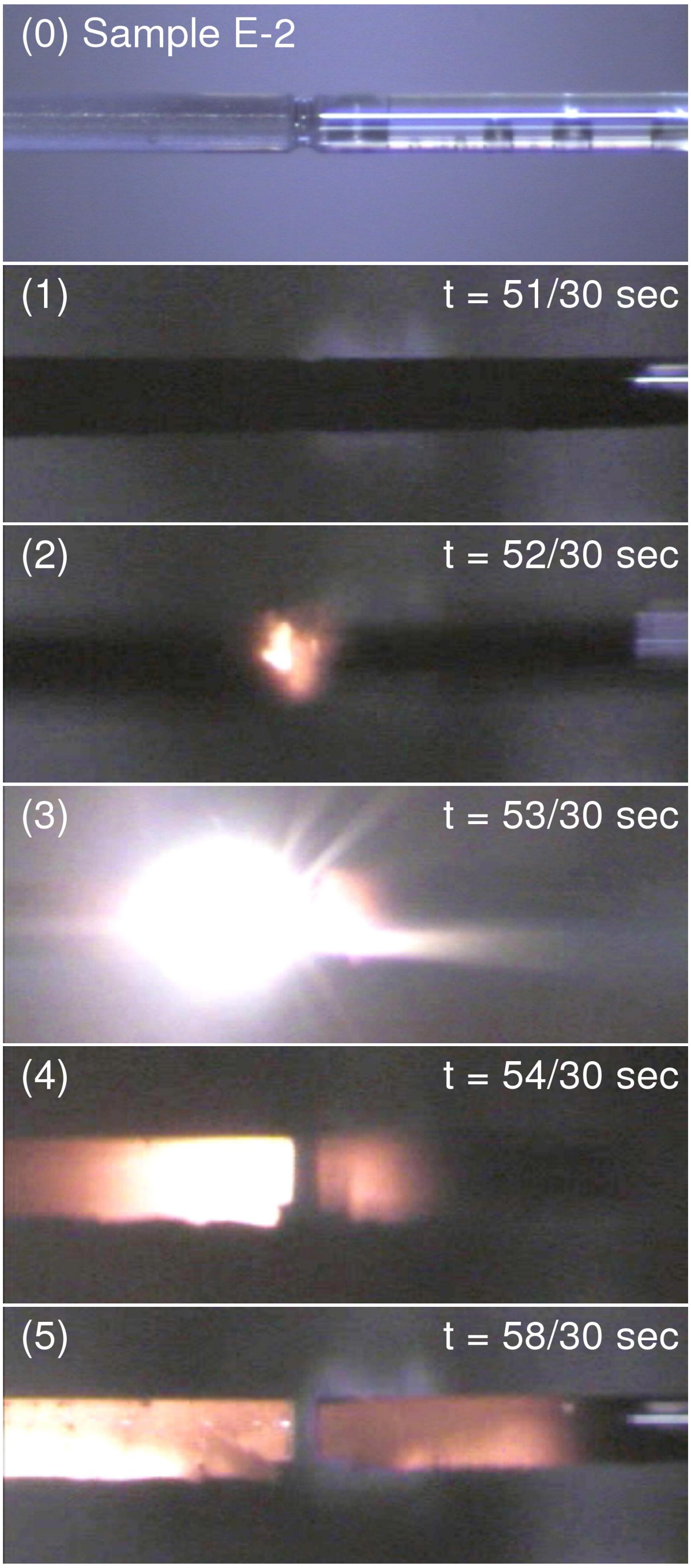

Fig. 2. Captured video images of sample E-2; (0) before and (1–5) after the carbon-coating on TeO_2 glass segment inserted in a silica glass optical fiber circuit. The light source is connected to the right side. Each elapsed time is shown at the top-right corner of each image.

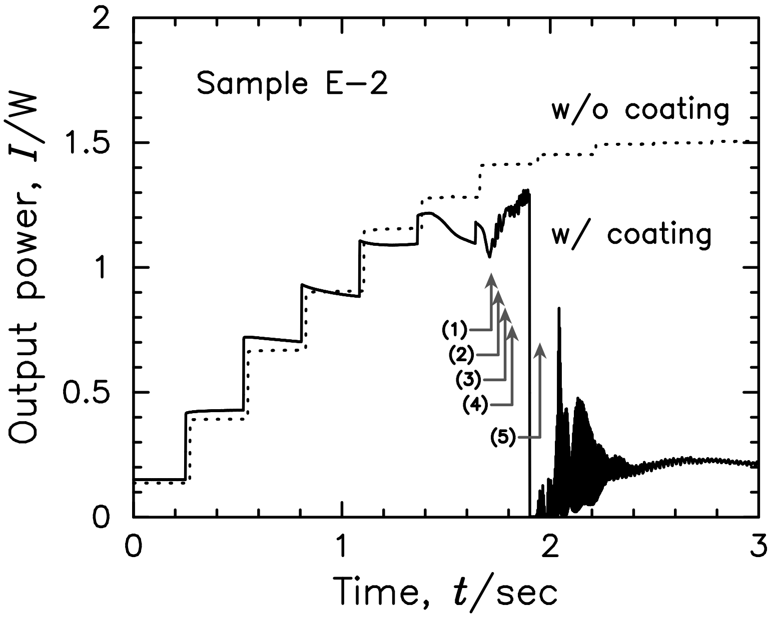

Fig. 3. Time-varying output power from sample E-2, to which 1.54μm CW light from a fiber laser is coupled. The beam intensity increased stepwise to a predetermined value. The dotted line represents the data for the sample without carbon-coating, which is proportional to the incident light. The solid line is the one for coated. Each upward arrow represents the time at which each video image in Fig. 2 was captured.

arrows near the line represents the times at which the images in Fig. 2 are captured. Then, the following three facts become obvious. (1) The output power drop was observed about 0.1sec after the beginning of the flush burning; (2) after the flush, the output power varied irregularly, on which some fine structures were superimposed; and (3) before the flush, a slight reduction of the power had been observed and this trend grew with time until the flush occurred.

The first fact suggests that the observed power drop is not directly related with the disappearance of the glass layer which is brought about by the flush burning. The second fact means that the light from the burning enters to the output fiber. Therefore, it is reasonable that a loss increase due to the absence of the glass layer is buried in the transient light flux of burning, and the observed power drop must be due to an overlap of extinction of the burning and induced misalignment of the fiber ends. The third fact implies that the soft glass layer is somewhat modified before the flush burning. This is brought about by the generated heat at the carbon-coating absorbing the propagating light.

The maximum output power for each measurement is listed in Table 1. It should be noted that these values are not the maximum power of the propagated laser light but the sum of the light flux from the laser and the carbon-burning.

For sample E-3, a carbon-burning is observed only after the second trial of laser irradiation. Sample E-4 did not show any flushing during two trials. Considering that these two samples show smaller insertion loss values compared with those of the sample E-1 and E-2, it is reasonable to consider that an ignition of carbon-burning needs a certain amount of leaked light from the glass layer. In fact, in a separate experiment, samples with thinner glass layer showed smaller insertion loss and absence of carbon-burning with the use of the present Er-doped fiber laser (max. 2W), and samples having thicker glass layer are easy to be burned and showed higher loss value. Thus, the critical input power to cause fusing action is expected to be increased by eliminating the amount of leaked light from the glass layer. This trend is roughly observed in the samples of R-1, 2 and 3.

The insertion loss of the present structure is affected by the following factors. (1) Fresnel reflection loss at the interface of silica fiber and the glass layer, which is estimated as 0.18 dB per an interface,[4] (2) decoupling loss due to the absence of waveguide structure in the glass layer, and (3) another decoupling loss due to a misalignment between the two fiber pigtails and a little tilted cut at the fiber ends. The last factor can be eliminated by a matured fabrication technique. The first loss is suppressed if the refractive index gap at the interface is reduced by using another soft glass with lower refractive index and/or by introducing refractive index gradient coating at the end-face of the fibers.[7] The second loss can be reduced by decreasing the thickness of the glass layer or by using TEC (Thermally Expanded Core) fibers to collimate the propagating light.[4]

In the present experiment, so-called fiber fuse[8] was not observed in spite of carbon-painting near the fiber ends. The absence of fiber fuse is because the fiber core is shielded from the carbon particles by the inserted glass layer.

In summary, passive optical fusing action was demonstrated in the devices having a structure of 50-μm-thick transparent TeO_2 glass layer inserted in a single-mode silica glass fiber circuit with carbon coating. The device is blown out by an incident CW beam of $\sim$1.5μm, about 1–5W. On the basis of the time-varying output power data and the simultaneous video recording of the device's appearance, the mechanism of losing its transparency is discussed before and after the flush burning. The critical power for blowing out is expected to be controlled by the thickness of the glass layer and/or the insertion loss of the device.

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