# OPTICAL FUSE MADE OF SILICA GLASS OPTICAL FIBERS SPLICED THROUGH LOW-MELTING GLASS WITH CARBON-COATING

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Light-induced breakdown of low-melting glass with thickness of 50 $\mu$m is demonstrated, which was coated with carbon paint and formed between two end of single-mode silica glass optical fibers. This phenomenon is useful to make irreversible optical limiting devices known as optical fuse. The present structure breaks by 1.2–5.3 W of incident light ($\sim$1.5$\mu$m), exhibits low insertion loss of less than 1 dB, and is formed by dipping-up a small amount of hot glass melt between fibers, aligning the fibers and quenching them. The relation between shape of the captured melt and its insertion loss is discussed.

(Key words: optical fuse, optical fiber, low melting glass, telluria glass, light-induced deformation)

## 1 Introduction

Optical fuses/limiters are switching devices whose transparency drops permanently/reversibly by an excessive incident beam and are used for protecting optical components to be damaged by the beam. Their importance is growing considerably with the recent development of high power light sources, especially for optical fiber circuits. Optical limiters are realized by thermal lensing effect[1, 2], self-focusing due to nonlinear effect[1], or misaligning induced by thermal expansion of waveguides[3]. Although they are practically useful due to their recoverable properties, optical fuses are also attractive in their simple structure. Several passive optical fuses have been proposed[4, 5] 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.

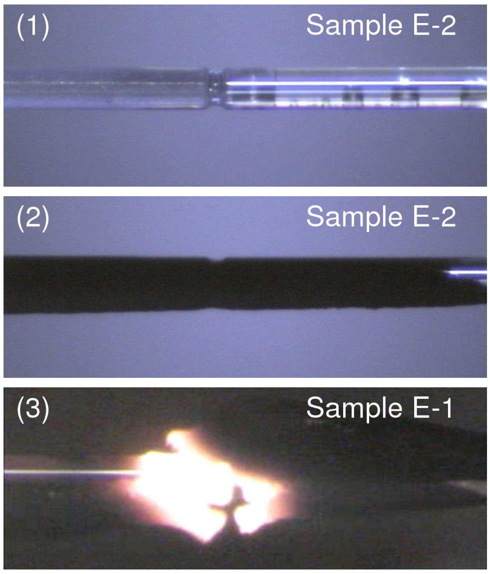
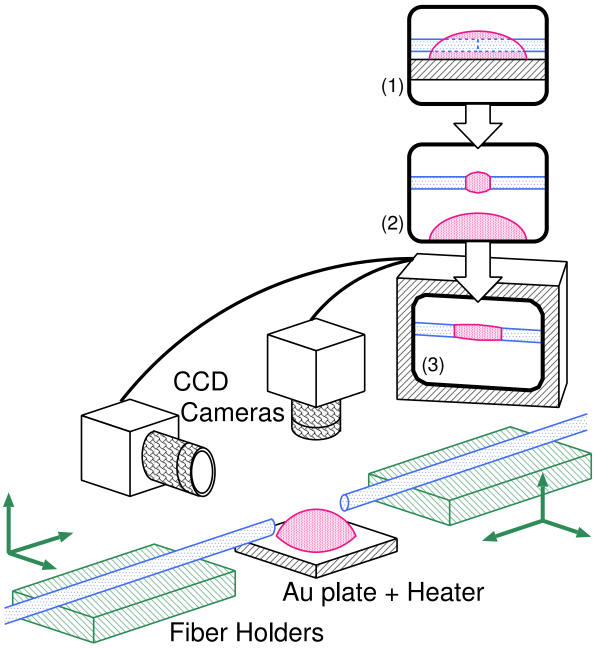



Fig. 1: Photographs of (1) a 50-$\mu$m-thick $TeO_2$ glass layer inserted in a silica glass fiber circuit, (2) carbon-coated spliced region, and (3) light-induced breakdown of this structure. The diameter of the fiber is 125$\mu$m. The light source is connected to the right side.

Recently, we proposed a new structure of passive optical fuse[6], in which transparent soft glass segment (pure $TeO_2$, $\sim$150$\mu$m-long with a necked region) 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[7] (See Fig. 1). On the basis of real-time observation of fusing action, its mechanism to lose transparency is discussed.

From a viewpoint of fabrication, it is very important to splice fibers with low insertion loss. Thus, the effect of soft glass' shape onto the splicing loss is investigated.



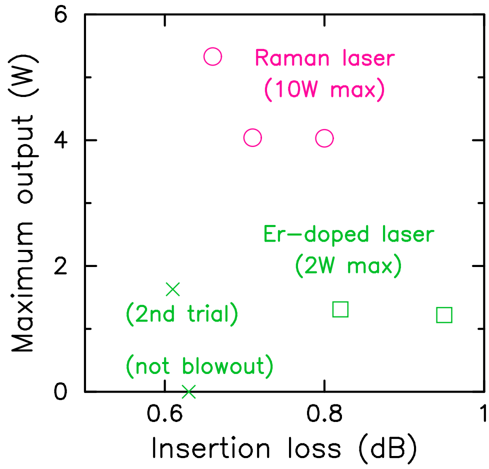




Fig. 3: Maximum output values from the present optical fuses vs. their insertion loss for 1.3$\mu$m.

Fig. 2: Fabrication apparatus of splicing optical fibers via low-melting glass.

## 2 Experimental

Commercial optical fiber cables (single mode, core diameter: 10$\mu$m, 3m-long with FC connectors) are used in this study. Bare fibers were cut by a fiber cleaver (York FK10). Two fibers were placed on fiber holders so that their ends face each other, as shown in Fig. 2[8, 9, 10]. A gold plate with a small heater was set between the two ends of the fibers. Their relative positions were controlled by a personal computer with a resolution of 1 $\mu$m. The heater was kept at a constant temperature over 700 °C which was monitored through a thermo couple placed on the back. The glass melt was supplied by putting a small amount of $TeO_2$ powder (5N, Shinko Chemical Co.,Ltd.) on the gold plate. The droplet was observed through video cameras placed from its top and side. Two fibers were inserted into the droplet from its side((1) in Fig. 2). Then, the plate is lowered to leave a small amount of the melt between the two ends(2). Lastly, the fibers were immediately moved to an appropriate position before the melt was solidified(3). $TeO_2$ melt easily vitrified in this method because of its high quenching rate, estimated to be as large as that in twin-roller quenching method, $\sim 10^3$ K/s[9]. In spite of a large gap in thermal expansion coefficient among these glasses, 2 orders of magnitude, no fracture was observed due to small interfaces.

The thickness of the inserted glass was measured by a High-Resolution Reflectometer (AQ7410A, Ando Electric Co.,Ltd.) which consists of a Michelson interferometer and a laser of 1.31 $\mu$m. Its resolution is 20 $\mu$m. Transmittance of the laser light through the optical coupling structure was measured by an optical multimeter (AQ-2140, Ando Electric Co.,Ltd.).

## 3 Results

### *3.1 Optical fuse*

We made 7 samples with a 50$\mu$m-thick soft glass layer (see Fig. 1(1)), whose insertion loss values are plotted along the horizontal axis of Fig. 3. 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, 1.54$\mu$m, 2W max., the samples are plotted as $\times$ and □ in Fig. 3) or a Raman fiber laser (PYL-10-1480, IPG Laser, 1.48$\mu$m , 10W max., denoted as ◯) and an optical multimeter (8163B, Agilent Tech., averaging time: 1 msec) to measure the variation of its transmitted power. We confirmed

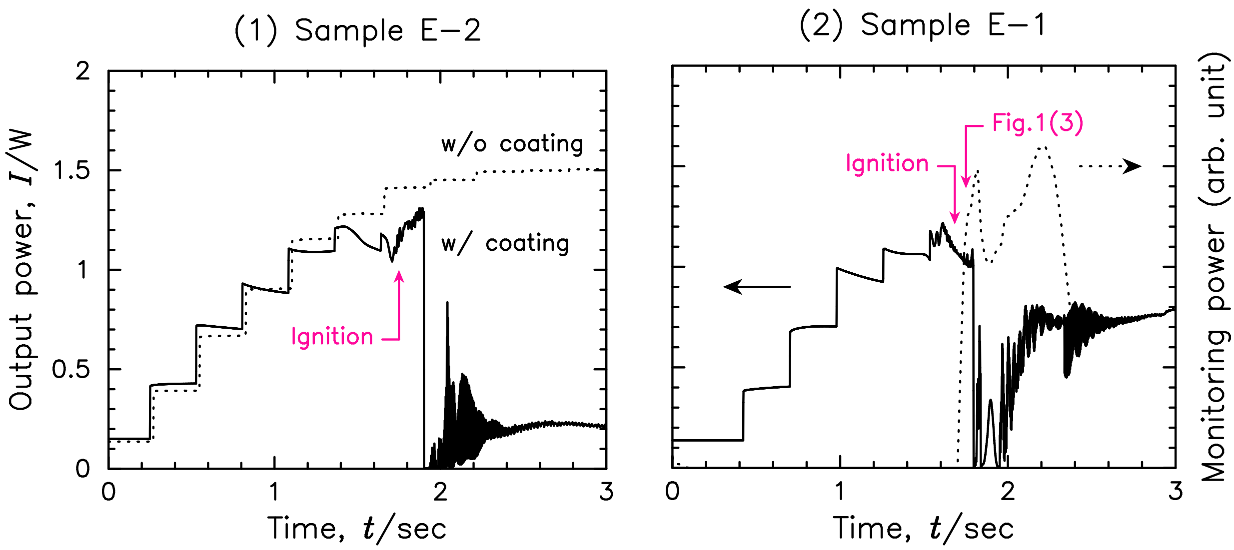



Fig. 4: Time-varying output power from the samples plotted as □ in Fig. 3, to which 1.54$\mu$m CW light from a fiber laser is coupled. The beam intensity increased stepwise to a predetermined value. The dotted line in the left represents the data for the sample without carbon-coating, which is proportional to the incident light. The solid line is the one for coated. The dotted line in the right represents the light from carbon burning, the intensity of 650mn. The vertical arrows represent the time at which flash appeared or the video image of Fig. 1(3) was captured.

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. 4(1)) 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. 1(2)).

The laser light was coupled 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 the ones plotted as × in Fig. 3, a flush suddenly appeared from the glass segment as shown in Fig. 1(3), and subsequently the coated carbon burned completely and the glass layer was found to be disappeared between the red-hot fiber ends. 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 the samples plotted as □ are shown as the solid line in Fig. 4. In addition, light flux from carbon coating was monitored by a multichannel spectrometer (Soma Optics, S-2600) through a fiber probe placed at near the fuse. A broad spectrum of 550–1050nm is obtained from the burning light and its time-varying intensity at 650nm is plotted as the dotted line in Fig. 4(2). The vertical arrows near the line represents the times at which flash appeared or the image in Fig. 1(3) are captured. The maximum output power for each measurement is plotted in Fig. 3, as a function of insertion loss.

In the present experiment, so-called fiber fuse[11] 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.

### *3.2 Splicing loss*

We made several tens of splicing structure with various shape of joining glass, including pot-belly, no waist and waisted as illustrated in the upper right of each figures in Fig. 5, and distances between fibers, whose insertion loss values are plotted in Fig. 5. For each groups, averaged slope is calculated by least square method to be 28, 21 and 20 dB/mm, respectively.

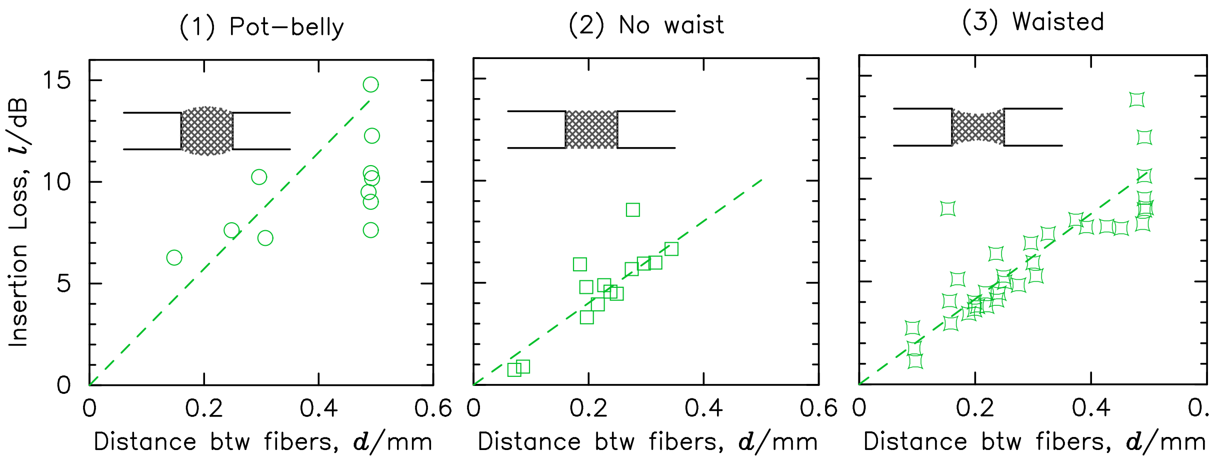



Fig. 5: Insertion loss values for spliced fibers via $TeO_2$ glass as a function of distance between the fibers, $d$, classified into three groups according to the shape of inserted glass, (1) pot-belly, (2) no waist, and (3) waisted. Dashed lines are drawn by least square approximation, whose slopes are 28, 21 and 20 dB/mm, respectively.

## 4 Discussion

### *4.1 Optical fuse*

From the result of time-varying output power from the sample shown in Fig. 4, 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. This, the maximum output power for each measurement plotted in Fig. 3 are not the maximum power of the propagated laser light but the sum of the light flux from the laser and the carbon-burning. 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.

For the samples whose insertion loss is less than 0.63, plotted as × in Fig. 3, a carbon-burning is observed only after the second trial of laser irradiation (max. 2W), or not observed during two trials. Considering that these two samples show smaller insertion loss values compared with the other samples, 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 including the ones connected with the Raman laser (max. 10W), plotted as ○ in Fig. 3.

### *4.2 Splicing loss*

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[8], (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 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[12]. 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[8].

The last factor can be eliminated by a matured fabrication technique. In fact, the results shown Fig. 5 clearly shows that the shape of captured melt should not be pot-bellied to reduce the loss. The reason turns out to be clear when we think of surface tension of the melt. The pulling strength between the two fibers in such a shape is expected to be smaller than that in other shapes, which aligns the fibers.

## 5 Conclusion

Passive optical fusing action was demonstrated in the devices having a structure of 50-$\mu$m-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$1.5$\mu$m, 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. The latter is found to be affected by the shape of inserted glass layer, which is related to the alignment between the fibers in fabrication process.

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