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# Hole-assisted fiber based fiber fuse terminator supporting 22 W input

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ABSTRACT

We investigated the air hole structure in hole-assisted fiber (HAF) with the aim of terminating fiber fuse propagation. We focused on two structural parameters $c$/MFD and $S_1/S_2$, which are related respectively to the position and area of the air holes, and mapped their appropriate values for terminating fiber fuse propagation. Here, MFD is the mode field diameter, $c$ is the diameter of an inscribed circle linking the air holes, $S_1$ is the total area of the air holes, and $S_2$ is the area of a circumscribed circle linking the air holes.

On the basis of these results, we successfully realized a compact fiber fuse terminator consisting of a 1.35 mm-long HAF, which can terminate fiber fuse propagation even with a 22 W input. In addition, we observed fiber fuse termination using a high-speed camera. We additionally confirmed that the HAF-based fiber fuse terminator is effective under various input power conditions. The penetration length of the optical discharge in the HAF was only less than 300 µm when the input power was from 2 to 22 W.

## 1. Introduction

A fiber fuse is a phenomenon whereby an optical discharge propagates toward a light source resulting in the catastrophic destruction of the optical fiber [1,2]. Since the propagation threshold of a fiber fuse $P_{th}$ in conventional single-mode fiber (SMF) is as low as 1.3 W at 1480 nm, in the near future the fiber fuse phenomenon will pose a real danger to wavelength-division-multiplexing (WDM) based optical communication systems [3]. Several approaches have been proposed for avoiding the catastrophic damage caused by a fiber fuse. These approaches include complex systems that can rapidly detect a fiber fuse by monitoring the light or heat from the fiber fuse and terminate it by shutting down the light source [4–6]. It has been also reported the use of fiber fuse terminators with a tapered fiber [7], with a etched small cladding fiber [8], and a thermally diffused expanded core (TEC) fiber [9]. The use of fiber fuse terminators is a simple and attractive solution. However, their effectiveness were confirmed only when an input power was less than 2 or 3 W [7–9]. It is naturally desirable for a fiber fuse terminator to be effective over wide input power ranges. Although the small cladding fiber type will probably work equally at higher input power levels, it was necessary to reduce the diameter of the waist of the etched section to about 30 µm [8]. Therefore, we think that the mechanical strength probably decreases, and it leads to a reduction in long-term reliability and handling difficulty. In addition, it is difficult to use a tapered fiber, a small cladding fiber and a TEC fiber as a transmission line of sufficient length.

Recently, it was reported that the $P_{th}$ in hole-assisted fiber (HAF) can be much higher than that in conventional SMF [10,11]. The propagation characteristics of the fiber fuse in HAF depend on the relationship between the diameter of an inscribed circle linking the air holes $c$ and the diameter of the melted area $D_{melted}$ [10,11]. The melted area is the result of fiber fuse propagation and $D_{melted}$ is assumed to be almost the same size as the optical discharge. When $c$ is much smaller than $D_{melted}$, the fiber fuse does not propagate even at a maximum input power of 15.6 W [11]. Moreover, the mode-field diameter (MFD) of HAF can be tailored so that it becomes comparable to that of SMF. Sufficient mechanical strength comparable to that of SMF with a cladding diameter of 125 µm can be also expected. Therefore, the splice loss between the HAF with a well-designed air hole structure and SMF can be reduced, and it can be applied as a compact fiber fuse terminator in SMF transmission line. In addition, a well-designed HAF with a high $P_{th}$ value can be utilized as a transmission line for high power use, although fabrication processes of drilling a fiber preform and controlling the diameter of air holes during drawing are required.

In this paper, we report the air hole structure in HAF designed to terminate fiber fuse propagation. We focused on two structural parameters $c$/MFD and $S_1/S_2$, which are related respectively to the position and area of the air holes, and mapped their appropriate values for

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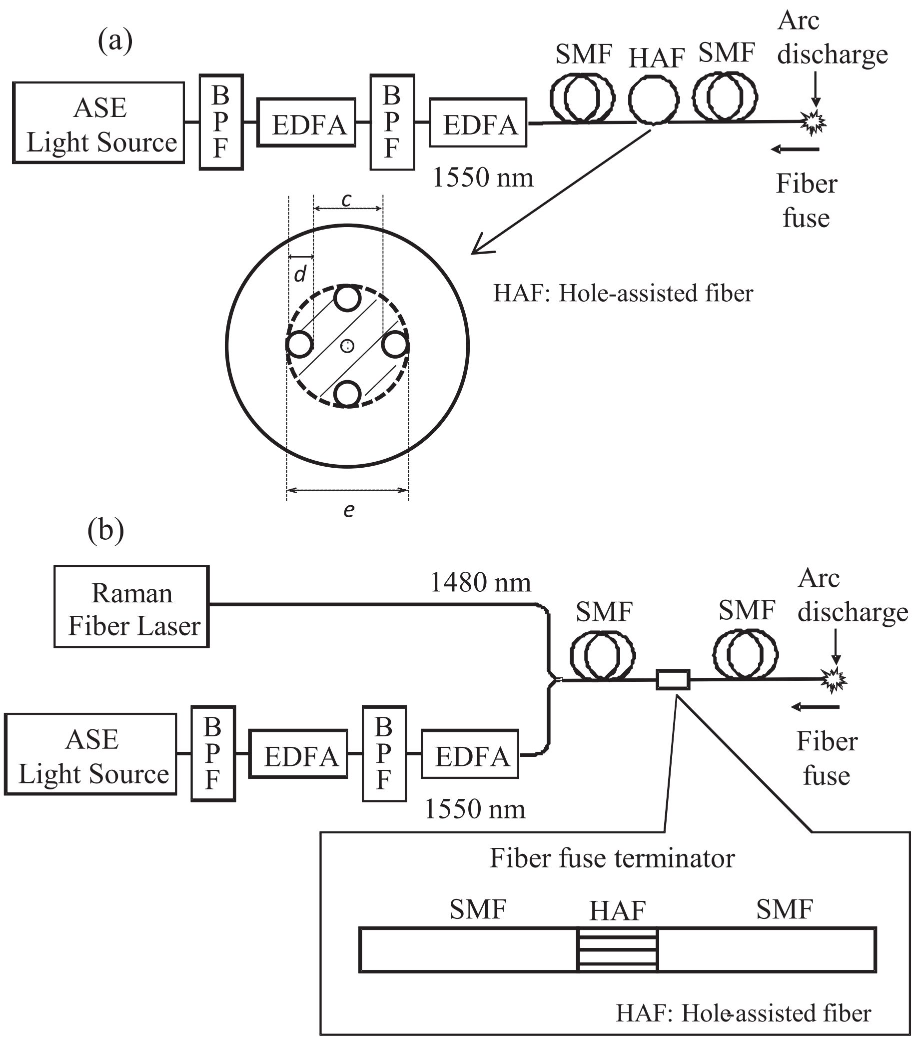


**Fig. 1.** Our experimental setup. (a) Setup for test fibers, (b) setup for fiber fuse terminator.

**Table 1**
Results of fiber fuse experiment in test fibers.

| No. | *d* (μm) | *c* (μm) | *N* | MFD (μm) | *c*/MFD | $S_1/S_2$ | Result |
|---|---|---|---|---|---|---|---|
| 1 | 4.8 | 20.0 | 6 | 9.9 | 2.0 | 0.16 | Terminated |
| 2 | 4.9 | 17.1 | 6 | 9.7 | 1.8 | 0.20 | Terminated |
| 3 | 5.0 | 9.4 | 6 | 6.9 | 1.4 | 0.40 | Terminated |
| 4 | 8.3 | 20.2 | 6 | 10.1 | 2.0 | 0.31 | Terminated |
| 5 | 5.1 | 20.2 | 6 | 10.0 | 2.0 | 0.17 | Terminated |
| 6 | 4.5 | 30.8 | 6 | 10.1 | 3.0 | 0.08 | Not Terminated |
| 7 | 3.2 | 20.8 | 6 | 10.1 | 2.1 | 0.08 | Not Terminated |
| 8 | 4.0 | 20.5 | 6 | 10.0 | 2.1 | 0.12 | Not Terminated |
| 9 | 4.1 | 20.4 | 6 | 9.9 | 2.1 | 0.12 | Not Terminated |
| 10 | 16.6 | 21.2 | 4 | 10.4 | 2.0 | 0.37 | Terminated |
| 11 | 18.0 | 38.7 | 4 | 10.8 | 3.6 | 0.23 | Not Terminated |
| 12 | 8.3 | 22.8 | 10 | 9.9 | 2.3 | 0.44 | Terminated |
| 13 | 5.9 | 22.4 | 10 | 10.1 | 2.2 | 0.30 | Terminated |
| 14 | 4.4 | 21.7 | 10 | 10.0 | 2.2 | 0.21 | Terminated |
| 15 | 3.4 | 20.3 | 10 | 10.1 | 2.0 | 0.16 | Terminated |
| 16 | 2.0 | 14.9 | 10 | 10.3 | 1.4 | 0.11 | Terminated |
| 17 | 3.4 | 22.0 | 10 | 10.1 | 2.2 | 0.14 | Not Terminated |
| 18 | 2.7 | 22.0 | 10 | 10.0 | 2.2 | 0.10 | Not Terminated |
| 19 | 2.2 | 20.0 | 10 | 10.0 | 2.0 | 0.08 | Not Terminated |

terminating fiber fuse propagation. On the basis of the results, we successfully realized a fiber fuse terminator consisting of a 1.35 mm-long HAF, which can terminate fiber fuse propagation even with a 22 W input. We also observed fiber fuse termination using a high-speed camera. We demonstrated that the HAF-based fiber fuse terminator was effective over wide input power ranges, from 2 to 22 W.

## 2. Air hole structure dependence of fiber fuse propagation

Fig. 1(a) shows the experimental setup we used to investigate the air hole structure dependence of fiber fuse propagation. The light source used for the initiation and propagation of the fiber fuse was an amplified ASE operating at a wavelength of 1550 nm. The amplified ASE was obtained using an ASE light source, bandpass filters (BPFs), and EDFAs. The cw light was guided into a test fiber through an SMF. We initiated a fiber fuse with an arc discharge by heating another SMF that was spliced to the test fiber. SMFs and the test fiber were spliced together by using a fusion splice. We observed the fiber fuse propagation or its termination in a test fiber, whose length was about 5 m. We set the input power at a relatively low value (2 W), which is just above the propagation threshold of a fiber fuse in conventional SMF.

We used nineteen HAFs with different air hole structures as test fibers. The core and cladding diameters of the HAFs were 9 and 125 μm, respectively. Their air hole number *N* was four, six or ten. Fig. 1(a) also shows a typical cross-section of a HAF. The diameter of the inscribed circle linking the air holes *c*, the diameter of a circumscribed circle linking the air holes *e* and the hole diameter *d* are defined as shown in the cross-section.

Table 1 shows the air hole structure dependence of fiber fuse termination. Here, we used the MFD value measured at 1550 nm. The fiber