APPLIED PHYSICS LETTERS **104**, 043302 (2014)

Observation of polymer optical fiber fuse

Yosuke Mizuno,[1,a)] Neisei Hayashi,[1] Hiroki Tanaka,[1] Kentaro Nakamura,[1,a)] and Shin-ichi Todoroki[2]
[1]*Precision and Intelligence Laboratory, Tokyo Institute of Technology, 4259 Nagatsuta-cho, Midori-ku, Yokohama 226-8503, Japan*
[2]*Photonic Materials Unit, National Institute for Materials Science, 1-1 Namiki, Tsukuba 305-0044, Japan*

(Received 2 December 2013; accepted 12 January 2014; published online 27 January 2014)

Although high-transmission-capacity optical fibers are in demand, the problem of the fiber fuse phenomenon needs to be resolved to prevent the destruction of fibers. As polymer optical fibers become more prevalent, clarifying their fuse properties has become important. Here, we experimentally demonstrate a fuse propagation velocity of 21.9 mm/s, which is 1–2 orders of magnitude slower than that in standard silica fibers. The achieved threshold power density and proportionality constant between the propagation velocity and the power density are 1/180 of and 17 times the values for silica fibers, respectively. An oscillatory continuous curve instead of periodic voids is formed after the passage of the fuse. An easy fuse termination method is also presented. [http://dx.doi.org/10.1063/1.4863413]

Just over a quarter century ago, Kashyap and Blow[1,2] published their influential paper on the observation of the optical fiber fuse phenomenon: the continuous self-destruction of a fiber by propagating light. High-power light propagating through the fiber results in local heating and the creation of an optical discharge that is then captured in the fiber core and travels back along the fiber toward the light source, consuming the light energy and leaving a train of voids.[3] While fiber fuse propagation is stunningly beautiful,[4] the fiber cannot be used after the passage of the fuse. This effect, along with the Shannon limit,[5–7] nonlinear effects,[8,9] and the optical amplifier bandwidth,[9] is now regarded as a critical factor limiting the maximal optical power that can be delivered.[10,11] The fuse properties must be well characterized so that all possible measures are taken to avoid the creation of a fiber fuse.

The fuse properties in various glass fibers, including standard silica-based single-mode fibers (SMFs),[1–4,12–14] microstructured fibers,[15] fluoride fibers,[16] chalcogenide fibers,[16] erbium-doped fibers,[17] photonic crystal fibers,[18] and hole-assisted fibers,[18] are well documented. The fiber fuse is reported to be typically induced at an input optical power of one to several watts (one to several megawatts per square centimeter) and to have a propagation velocity of one to several meters per second. These properties differ according to the type of glass fiber; the threshold power, for instance, is reported to be much higher in photonic crystal and hole-assisted fibers than in silica SMFs,[18] and nonlinear saturation of the fuse velocity has been observed in erbium-doped fibers.[17] To date, reports detailing similar properties of non-glass fibers such as polymer optical fibers (POFs) have not been published. Several special POFs with relatively low propagation losses and broadband transmission capabilities have recently become commercially available,[19,20] and extensive studies have investigated the implementation of POF-based high-capacity communication systems[19,20] and possible engineering applications of nonlinear effects in POFs.[21,22] Therefore, there is a pressing need to clarify the fuse properties of POFs.

In this Letter, we characterize the POF fuse and discuss its unique properties. The propagation velocity of the bright spot is one to two orders of magnitude slower than that in standard silica SMFs. The threshold power density is 1/180 of the reported value for silica SMFs. We find that, after the passage of the fuse, an oscillatory continuous curve is formed in the POF. We also show that the POF fuse can be easily terminated by local elastic deformation of the waveguide structure.

The perfluorinated graded-index POF[19] employed in this experiment consists of a core (50 μm diameter), cladding (100 μm diameter), and overcladding (750 μm diameter) encased in polyvinyl chloride. The core and cladding layers are composed of doped and undoped polyperfluorobutenylvinyl ether, respectively. The refractive index at the center of the core is 1.356, whereas that of the cladding layer is 1.342;[23] these values do not depend strongly on the optical wavelength.[24] The polycarbonate reinforcement overcladding reduces microbending losses and increases the load-bearing capability. The propagation loss is relatively low ($\sim$250 dB/km) even at 1.55 μm, and inexpensive erbium-doped fiber amplifiers (EDFAs) can be used to boost the optical power (the standard polymethyl methacrylate POF is optimized for visible light transmission, and its propagation loss at 1.55 μm is higher than 1×10^5 dB/km).

Figure 1(a) depicts the experimental setup, in which 7-dBm (5-mW) output light from a 1546-nm distributed-feedback laser diode (NX8562LB; NEC; $\sim$1-MHz linewidth) was amplified by an EDFA (LXM-S-21; Luxpert Technologies) to up to 23 dBm (200 mW) and injected into a 15-m-long POF. Two optical isolators were inserted to protect the laser and EDFA from reflected or backscattered light. The end of the silica SMF fitted with an "FC" connector was connected to one end of the POF fitted

---

[a)] Authors to whom correspondence should be addressed. Electronic addresses: ymizuno@sonic.pi.titech.ac.jp and knakamur@sonic.pi.titech.ac.jp

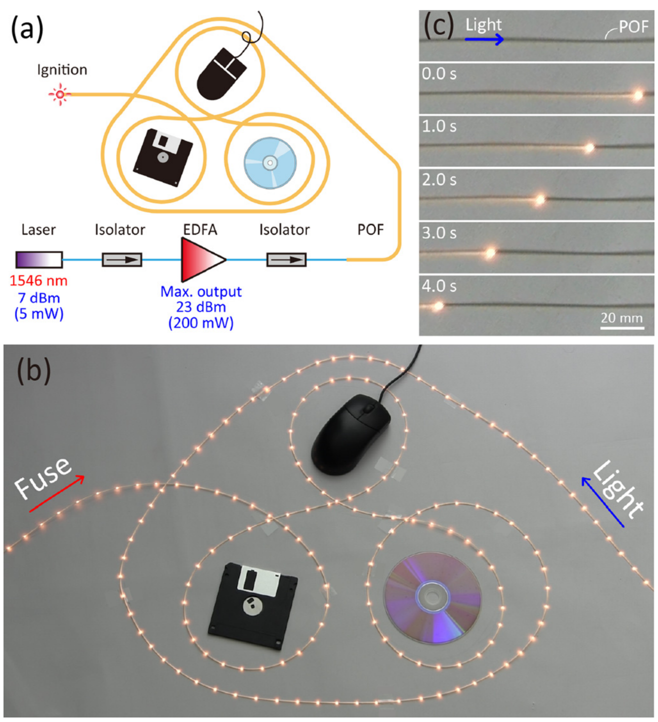

FIG. 1. (a) Schematic of the experimental setup. The silica SMFs are indicated by blue lines. (b) Composite photograph of the fiber fuse propagating along the POF; photographs were taken at 1-s intervals. The light was injected from the right-hand side, while the fuse propagated from the left-hand side. The fiber arrangement was that of Todoroki[4] to allow a direct comparison between the POF and silica SMF. (c) Magnified view of the propagating fuse. The light was injected from the left-hand side.

with an "SC" connector via an FC/SC adaptor (coupling loss ~ 0.3 dB).[21,22] We confirmed that the fiber fuse can be initiated in the same way as in glass fibers[1–4,12–18] by external stimuli such as heating, bending, or bringing the fiber output end into contact with an absorbent material. For the demonstration discussed here, we used a POF end surface polished roughly with 0.5-μm alumina powder.

From observations of the propagation of the fuse along the POF (Fig. 1(b)), the propagation velocity was calculated to be approximately 24 mm/s, which is extremely slow in comparison to Todoroki's[4] result for a silica SMF. The optical power of the propagating light was calculated using the measured power of the injected light, the coupling loss at the SMF/POF interface, and the propagation loss in the POF to be approximately 75 mW, corresponding to a maximal power density of 7.6 kW/cm^2 (Refer to the next paragraph for calculation method). A magnified view of the fuse propagation along a straight portion of the POF is shown in Fig. 1(c) (70.5 mW, 22.8 mm/s).

Here, we derive an equation for the maximal power density I in the core when light with a certain power P is injected into the graded-index POF. We consider a refractive index in the core that takes a parabolic profile.[19] Under the assumption that all modes propagate with equal attenuation without coupling, the optical power profile is given, in the same way as the refractive index profile, by[25]

$$p(r) = p(0)\left(1 - \left(\frac{r}{R}\right)^{g}\right), \tag{1}$$

where r is the radial distance from the core center, R is the core radius, and g is the refractive index profile coefficient. Consequently, the maximal power density I can be calculated as

$$I = \lim_{r\to 0} \frac{P}{\pi r^2} \frac{\int_0^{2\pi} d\theta \int_0^{r} \left(1 - \left(\frac{r}{R}\right)^{g}\right) r dr}{\int_0^{2\pi} d\theta \int_0^{R} \left(1 - \left(\frac{r}{R}\right)^{g}\right) r dr} = \frac{P}{\pi R^2}\frac{g+2}{g}. \tag{2}$$

By assuming $g \approx 2$ in the graded-index POF,[19] Eq. (2) can be further simplified as

$$I = \frac{2P}{\pi R^2}, \tag{3}$$

which indicates that the maximal power density in the graded-index POF with an incident power P is equal to the average power density in a step-index POF of the same core diameter with twice the incident power. For instance, for $P = 75$ mW and $R = 25\ \mu$m, I is calculated to be 7.6 kW/cm^2.

We found that the fuse propagation velocity in the POF, measured at 1.55 μm, had an almost linear dependence on the maximal power density with a slope of 1.59×10^6 mm·s^{-1} MW^{-1} cm^{-2} (Fig. 2(a)). The power density at which the fuse ceased, i.e., the threshold power density, was 6.6 kW/cm^2 at a propagation velocity of 21.9 mm/s. Comparing these results with those of silica SMFs (Fig. 2(b); results[12] at 1.48 μm and the theoretical line[13] at 1.55 μm) revealed that at 1.55 μm the slope in the POF data (corresponding to the efficiency of the velocity control) was 17 times as steep as that in the silica SMF (9.41×10^4 mm·s^{-1} MW^{-1} cm^{-2}), and the threshold power density of the POF was 180 times lower than that of the silica SMF ($\sim$1.2 MW/cm^2). The minimal propagation velocity achieved at 1.55 μm was 11 times as low as that experimentally obtained in a silica SMF at 1.48 μm (250 mm/s).[14]

Digital micrographs taken after the passage of the fuse disclose the extent of the damage to the fiber. The fuse was initially triggered by exploiting the rough surface at the end of the POF (Fig. 3(a)) and was verified to be induced at the center of the core, which supports the assumption in our calculation that the maximal power density in the fiber cross section affects the fuse induction and can be used to determine the threshold power density. The passage of the fuse (Fig. 3(b)) appeared as a continuous black carbonized curve that oscillated periodically along the length of the POF, which is considerably different from the bullet-shaped voids observed in glass SMFs. The oscillation period was approximately 1300 μm, which is in general agreement with the theoretical oscillation period of the ray.[26] Figure 3(c) shows the position where the fuse ceased after the incident optical power was reduced to that below the threshold; since the fuse remained at this point for several seconds, it melted a relatively large area of the POF, which resulted in the observed bending.

Optical propagation loss in the POF after the passage of the fuse was measured for incremental cutbacks from 30 cm to 20 cm (Fig. 3(d)) and a fixed input power of

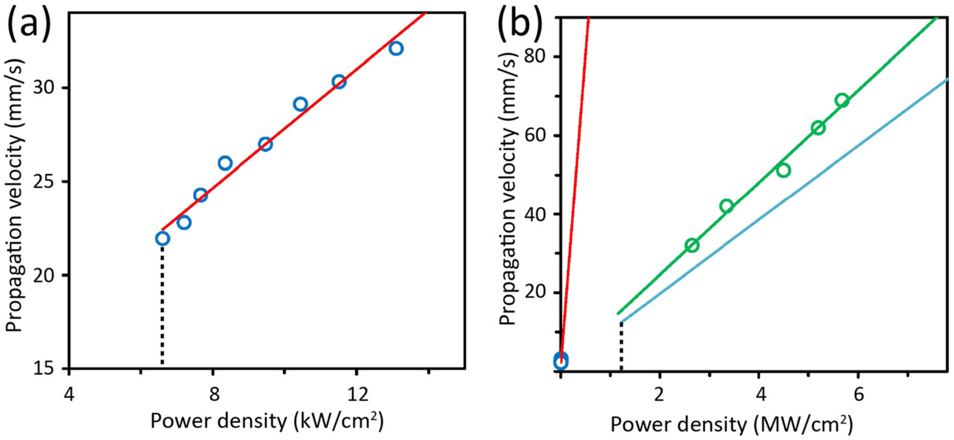

FIG. 2. (a) Propagation velocity of the fiber fuse in a POF measured at 1.55 μm as a function of the maximum power density in the core. Measured data are shown as blue circles, and the red line is a linear fit. The slope of the line is 1.59×10^6 mm·s^{-1} MW^{-1} cm^{-2}, and the threshold intensity is 6.6 kW/cm^2. (b) Propagation velocities of the fiber fuse as a function of the power density. The measured data for the silica SMF at 1.48 μm (data extracted from the literature[12]) are shown as green circles, and the green line is a linear fit (slope of 1.17×10^5 mm·s^{-1} MW^{-1} cm^{-2}); the theoretical threshold power density[13] is 1.16 MW/cm^2. The blue line is a theoretical prediction[13] for the silica SMF at 1.55 μm (slope of 9.41×10^4 mm·s^{-1} MW^{-1} cm^{-2}). The data in (a) are also reproduced for comparison.

10 dBm (10 mW) at 1.55 μm. A loss of 1.4 dB/cm indicates that, unlike silica SMFs,[1–4,12–14] light can propagate through the POF for several tens of centimeters after the passage of the fuse. We believe this is because undamaged regions remain in the core and cladding layers as these diameters are relatively large, which is a unique characteristic of POFs. Yet this propagation loss is somewhat significant for communication applications, and so once the fuse is induced, it is crucial to stop the propagation as soon as possible.

Several methods for terminating fiber fuses have been developed for glass fibers,[18,27–29] which are, in principle, also applicable to POFs. One method is to thin the outer diameter of the fiber at a certain position while maintaining the core diameter;[28] this can reduce the internal pressure and arrest the propagating fuse via deformation. In silica SMFs, this structure is fabricated using hydrofluoric acid as an etchant,[28] but in a POF, chloroform could be used to etch the overcladding layer.[30] An even easier method, which we present here, is to pressure-bond a small metal ring around

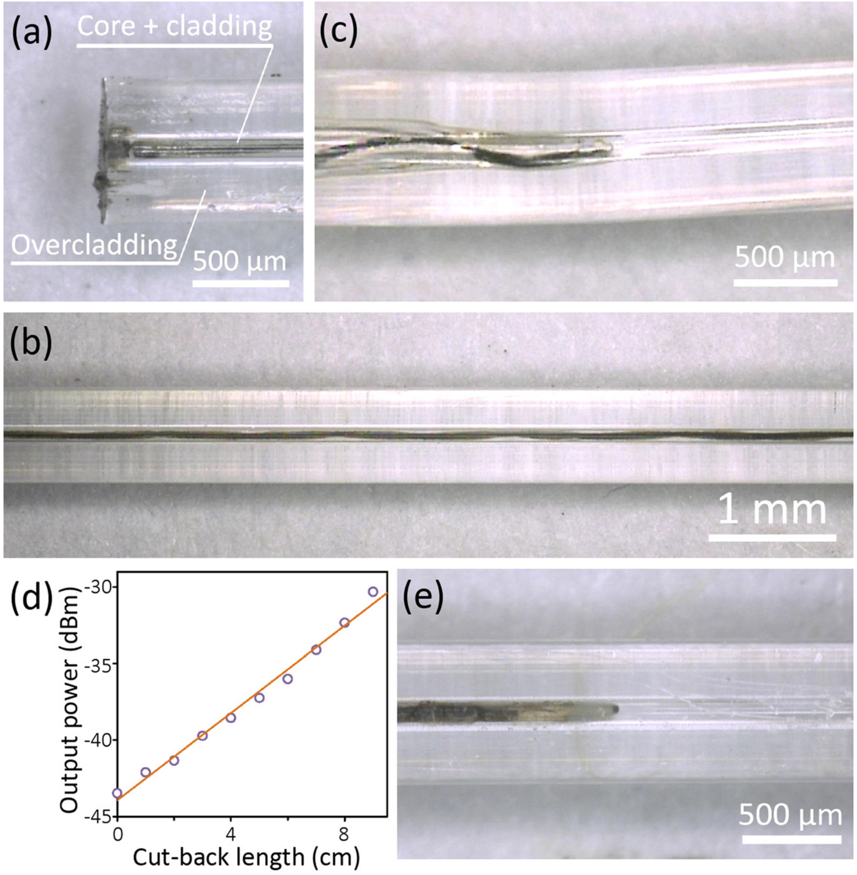

FIG. 3. (a) Digital micrograph of the POF end at which the fuse was initiated by exploiting the rough surface. (b) The path of the fuse in the POF. (c) The point at which the fuse was terminated by decreasing the input optical power. (d) The dependence of the output power on the cut-back length. The open circles are measured points, and the solid line is a linear fit. The slope of the line is 1.4 dB/cm. (e) Image of the fuse termination in the POF at the position of a nickel ring.

the fiber; this method is only applicable to POFs with an extremely high flexibility.[31] The optical power of the particular propagating mode that provides the bright spot with energy is decreased below the threshold by deformation, and the propagating fuse is thus terminated. The resulting induced optical loss is negligibly low, and an image of the fuse termination at the position of the ring (Fig. 3(e)) shows that bending did not occur. Once the ring is detached, the polymer material will return to the original configuration (elastic deformation).

In conclusion, we have experimentally demonstrated a POF fuse propagation velocity of 21.9 mm/s, which is 1–2 orders of magnitude slower than that in standard silica fibers. The achieved threshold power density and proportionality constant between the propagation velocity and the power density are 1/180 of and 17 times the values for silica fibers, respectively. We have found that a unique oscillatory continuous carbonized curve is formed after the passage of the fuse, which can be terminated easily. Future work will focus on understanding the detailed mechanism of the initiation and propagation of the POF fuse. We believe that these results serve not only as a valuable guideline for the development of POF-based high-capacity transmission systems and engineering applications of nonlinear effects in POFs but also as a strong impetus for the on-going research relating to fiber fuses and material sciences.

The authors thank Hirotsugu Yoshida (Sekisui Chemical Co., Ltd.) for his helpful discussions, Richard Nedelcov (Department of Language Arts, Tokyo University of the Arts) for his English editing, and Akitoshi Okino, Takahiro Iwai, Ken Kakegawa, Yosuke Watanabe, Yukiko Ishihara, Yoshitaka Utsunomiya (Department of Energy Sciences, Tokyo Institute of Technology), Hideki Hosoda, Tomoya Inamura, Masaki Tahara, Taku Aoki, Hyunbo Shim, Masatoshi Ii, Wei Qiu, Kazunari Minakawa, and Mingjie Ding (Precision and Intelligence Laboratory, Tokyo Institute of Technology) for the experimental assistance they offered. This work was partially supported by a Grant-in-Aid for Young Scientists (A) (No. 25709032) from the Japan Society for the Promotion of Science (JSPS) and by research grants from the General Sekiyu Foundation, the Iwatani Naoji Foundation, and the SCAT Foundation. N.H. acknowledges a Grant-in-Aid for JSPS Fellows (No. 25007652).

[1] R. Kashyap and K. J. Blow, Electron. Lett. **24**, 47 (1988).
[2] R. Kashyap, Opt. Express **21**, 6422 (2013).
[3] S. Todoroki, *Selected Topics on Optical Fiber Technology* (InTech, Croatia, 2012), pp. 551–570.
[4] S. Todoroki, Opt. Express **13**, 6381 (2005).
[5] C. E. Shannon, Bell Syst. Tech. J. **27**, 379 (1948).
[6] F. Poletti, N. V. Wheeler, M. N. Petrovich, N. Baddela, E. N. Fokoua, J. R. Hayes, D. R. Gray, Z. Li, R. Slavik, and D. J. Richardson, Nat. Photonics **7**, 279 (2013).
[7] G. Smith and J. Yard, Science **321**, 1812 (2008).
[8] J. M. Kahn and K. P. Ho, Nature **411**, 1007 (2001).
[9] P. P. Mitra and J. B. Stark, Nature **411**, 1027 (2001).
[10] T. Morioka, Y. Awaji, R. Ryf, P. Winzer, D. Richardson, and F. Poletti, IEEE Commun. Mag. **50**, s31 (2012).
[11] M. Jinno, Y. Miyamoto, and Y. Hibino, Nat. Photonics **1**, 157 (2007).
[12] R. M. Atkins, P. G. Simpkins, and A. D. Yablon, Opt. Lett. **28**, 974 (2003).
[13] Y. Shuto, S. Yanagi, S. Asakawa, M. Kobayashi, and R. Nagase, IEEE J. Quantum. Electron. **40**, 1113 (2004).
[14] S. Todoroki, in *Proceedings of Optical Fiber Communication/National Fiber Optic Engineers Conference*, Anaheim, USA, 2013, paper No. JW2A.11.
[15] E. M. Dianov, A. A. Frolov, I. A. Bufetov, Y. K. Chamorovsky, G. A. Ivanov, and I. L. Vorobjev, IEEE Photonics Technol. Lett. **16**, 180 (2004).
[16] E. M. Dianov, I. A. Bufetov, A. A. Frolov, V. M. Mashinsky, V. G. Plotnichenko, M. F. Churbanov, and G. E. Snopatin, Electron. Lett. **38**, 783 (2002).
[17] F. Domingues, A. R. Frias, P. Antunes, A. O. P. Sousa, R. A. S. Ferreira, and P. S. Andre, Electron. Lett. **48**, 1295 (2012).
[18] N. Hanzawa, K. Kurokawa, K. Tsujikawa, T. Matsui, K. Nakajima, S. Tomita, and M. Tsubokawa, J. Lightwave Technol. **28**, 2115 (2010).
[19] Y. Koike and M. Asai, NPG Asia Mater. **1**, 22 (2009).
[20] J. Clark and G. Lanzani, Nat. Photonics **4**, 438 (2010).
[21] Y. Mizuno and K. Nakamura, Appl. Phys. Lett. **97**, 021103 (2010).
[22] Y. Mizuno, N. Hayashi, and K. Nakamura, Opt. Lett. **38**, 1467 (2013).
[23] M. Naritomi, H. Murofushi, and N. Nakashima, Bull. Chem. Soc. Jpn. **77**, 2121 (2004).
[24] T. Ishigure, Y. Koike, and J. W. Fleming, J. Lightwave Technol. **18**, 178 (2000).
[25] D. Gloge and E. A. J. Marcatili, Bell Syst. Tech. J. **52**, 1563 (1973).
[26] G. P. Agrawal, *Fiber-Optic Communication Systems* (Wiley-VCH, Hoboken, 2010).
[27] D. P. Hand and T. A. Birks, Electron. Lett. **25**, 33 (1989).
[28] E. M. Dianov, I. A. Bufetov, and A. A. Frolov, Opt. Lett. **29**, 1852 (2004).
[29] K. S. Abedin, M. Nakazawa, and T. Miyazaki, Opt. Express **17**, 6525 (2009).
[30] R. Gravina, G. Testa, and R. Bernini, Sensors **9**, 10423 (2009).
[31] N. Hayashi, Y. Mizuno, and K. Nakamura, Opt. Express **20**, 21101 (2012).