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LETTER

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# Measurement of large-strain dependence of optical propagation loss in perfluorinated polymer fibers for use in seismic diagnosis

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**Abstract:** Brillouin scattering in perfluorinated graded-index (PFGI-) polymer optical fibers (POFs) has been extensively studied for structural health monitoring, including seismic diagnosis. Here, we measure the propagation loss of PFGI-POFs at telecom wavelengths as a function of large applied strain (up to 100%) at three optical powers and as a function of strain rate at a constant optical power. The strain dependence of the propagation loss in PFGI-POFs is found to be independent of the incident power (<27 dBm) and the strain rate (<500% $s^{-1}$), indicating that PFGI-POF-based Brillouin sensors are potentially applicable to actual seismic monitoring.

**Keywords:** polymer optical fibers, strain sensors, propagation loss

**Classification:** Fiber optics, Microwave photonics, Optical interconnection, Photonic signal processing, Photonic integration and systems

## References

[1] T. Kurashima, T. Horiguchi, H. Izumita, S. Furukawa and Y. Koyamada: IEICE Trans. Commun. **E76-B** (1993) 382.
[2] T. Horiguchi and M. Tateda: J. Lightwave Technol. **7** (1989) 1170. DOI:10.1109/50.32378
[3] D. Garus, K. Krebber, F. Schliep and T. Gogolla: Opt. Lett. **21** (1996) 1402. DOI:10.1364/OL.21.001402
[4] Y. Mizuno, W. Zou, Z. He and K. Hotate: Opt. Express **16** (2008) 12148. DOI:10.1364/OE.16.012148
[5] K. Hotate and T. Hasegawa: IEICE Trans. Electron. **E83-C** (2000) 405.
[6] M. G. Kuzyk: *Polymer Fiber Optics: Materials, Physics, and Applications* (CRC Press, FL, 2006).
[7] Y. Koike and M. Asai: NPG Asia Mater. **1** (2009) 22. DOI:10.1038/asiamat.2009.2
[8] Y. Mizuno and K. Nakamura: Appl. Phys. Lett. **97** (2010) 021103. DOI:10.1063/1.3463038
[9] Y. Mizuno, N. Hayashi, H. Tanaka, K. Nakamura and S. Todoroki: Appl. Phys. Lett. **104** (2014) 043302. DOI:10.1063/1.4863413
[10] K. Goda, A. Pomonis, S. C. Chian, M. Offord, K. Saito, P. Sammonds, S. Fraser,



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A. Raby and J. Macabuag: Bull. Earthquake Eng. **11** (2013) 141. DOI:10.1007/s10518-012-9371-x
[11] A. Fellay, L. Thevenez, M. Facchini, M. Nikles and P. Robert: Tech. Dig. Opt. Fiber Sens. **16** (1997) 324.
[12] H. Naruse and M. Tateda: Appl. Opt. **38** (1999) 6516. DOI:10.1364/AO.38.006516

## 1 Introduction

Owing to their distributed strain and temperature measurability, fiber-optic sensors based on Brillouin scattering have recently attracted considerable attention as a promising candidate for monitoring the damage of civil structures caused by earthquakes. Researchers have developed various types of sensing schemes, including time- [1, 2], frequency- [3], and correlation-domain [4, 5] techniques. Conventionally, their sensing heads were composed of glass fibers (especially standard silica glass fibers), resulting in fiber fracture at relatively small strains of $\lesssim$3%. To extend the maximal measurable strain, we have been exploring the possibility of using Brillouin scattering in polymer (or plastic) optical fibers (POFs) [6], which can withstand strains of up to 100%.

Commercially available POFs are classified into two types: poly(methyl methacrylate)-based (PMMA-) POFs [6] and perfluorinated graded-index (PFGI-) POFs [7]. The former predominantly transmit visible light at ~650 nm, while the latter transmit both visible light and telecom-wavelength light at ~1550 nm. As some of the optical devices (high-power amplifiers, circulators, etc.) required for these measurements are extremely difficult to design for operation at visible wavelengths, Brillouin scattering has been experimentally observed only in PFGI-POFs [8]. However, the Brillouin signal in PFGI-POFs is quite weak because of their large core diameters, multimode nature, and relatively high losses (~250 dB/km at 1550 nm). In order to extend the measurement range or to improve the signal-to-noise ratio of the sensors, we need to transmit high-power light of sub-watt order (note that transmitting light above watt-order power raises the probability of POF fuse initiation [9] and should be avoided for sensing purposes). To date, no report has been provided on the large-strain dependence of the propagation loss in PFGI-POFs with such high-power propagating light. Meanwhile, in actual great earthquakes, such as the Great East Japan Earthquake in 2011, several-Hz shaking of components was reported to have caused tremendous damage to civil structures [10]. To verify that POF-based sensors can detect strains applied at such frequency or velocity (corresponding to ~200% $s^{-1}$, if we assume the use of a 1-m-long sensing fiber [11, 12]), the dependence of propagation loss on strain rate also needs to be clarified.

In this paper, we investigate the propagation loss of PFGI-POFs as a function of a large applied strain (up to 100%) at three different optical powers. The strain-rate dependence of the loss at a constant optical power is also reported. Irrespective of the strain magnitude, the propagation loss of PFGI-POFs is found to remain relatively low even when high-power light is propagating or when the strain is


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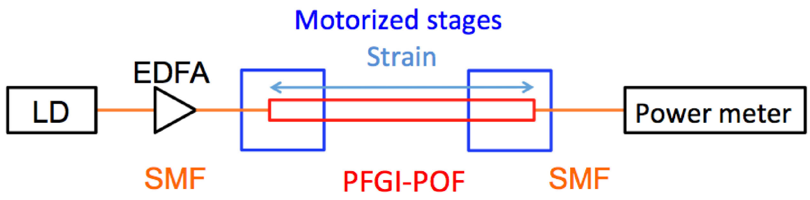


**Fig. 1.** Schematic of experimental setup. EDFA, erbium-doped fiber amplifier; LD, laser diode; PFGI-POF, perfluorinated graded-index plastic optical fiber; SMF, single-mode fiber.

applied at a high rate (up to 500% $s^{-1}$). This result suggests that Brillouin sensors using the PFGI-POFs may have potential as a practical monitor for earthquakes.

## 2 Experimental setup

We employed 4-cm-long PFGI-POFs (Fontex, Asahi Glass) with a core refractive index of 1.35, a numerical aperture of 0.185, a core diameter of 50 µm, a cladding diameter of 70 µm, and an overcladding diameter of 500 µm. The core and cladding layers were composed of doped and undoped polyperfluorobutenylvinyl ether, respectively, and the reinforcement overcladding layer consisted of polycarbonate.

The experimental setup is shown in Fig. 1. The output of a laser diode (LD) at 1552 nm was amplified with an erbium-doped fiber amplifier (EDFA) and injected into the PFGI-POF, which was fixed on motorized stages. The transmitted power was monitored with an optical power meter. The PFGI-POF was connected to silica single-mode fibers (SMFs) by butt-coupling [8], namely, the ends of the SMFs (fitted with 'FC' connectors) were connected to both ends of the POF (fitted with 'SC' connectors) via 'FC/SC' adaptors. Strains were applied to the whole length of the PFGI-POF at an arbitrary rate using a vertical machining center (Vertex 550-5X, Mitsui Seiki; a strain rate up to 500% $s^{-1}$ was achievable thanks to the short fiber length). The operating temperature was 27°C.

## 3 Experimental results

Fig. 2(a) shows the measured propagation loss dependences on strain at 1.5, 15, and 27 dBm incident powers. The strain rate was fixed at 0.33% $s^{-1}$. Some negative values were measured as losses, which probably originated from the error caused by the vibration of the system. Regardless of the incident power, at a strain of ~90%, the loss increased drastically, resulting in the fracture of the POFs. A magnified view of the strain at <80%, shown in Fig. 2(b), also indicates that the incident power has no quantifiable influence on the observed loss.

We then investigated the strain dependence of the propagation loss at strain rates of 0.33, 13.3, 42.6, 200, 420, and 500% $s^{-1}$, as shown in Figs. 3(a) and (b). The incident power was fixed at 27 dBm. The measurement error tended to increase proportionally with the strain rate. The propagation loss remained relatively low at strains of <80%, and the loss characteristics were not influenced by the strain rate (at least in this range). This result suggests that PFGI-POFs can propagate light even when large strains are applied at a rate of ~200% $s^{-1}$ (corresponding to seismic vibration).


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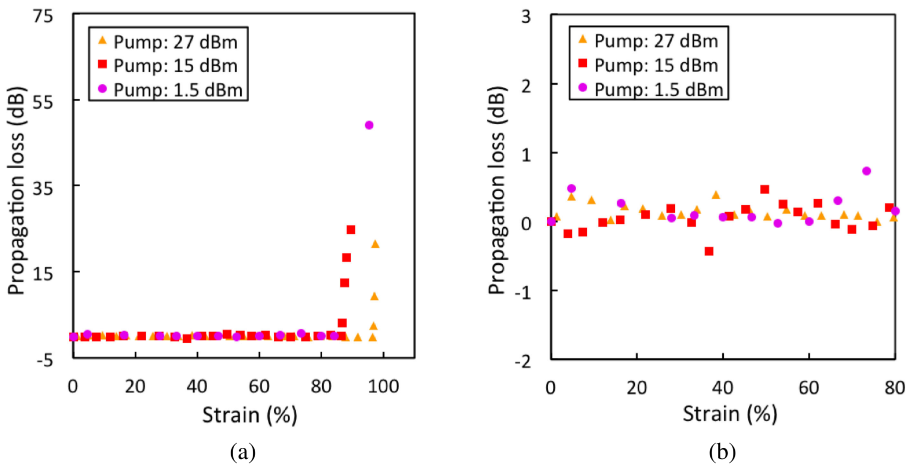


**Fig. 2.** (a) Propagation loss *vs* applied strain at three different optical powers, and (b) a magnified view of the strain from 0 to 80%.

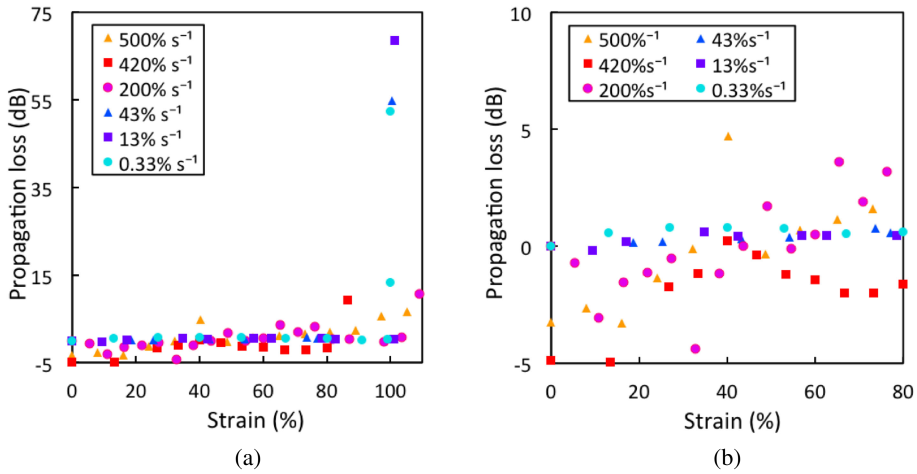


**Fig. 3.** (a) Propagation loss *vs* applied strain at six different strain rates, and (b) its magnified view in the strain range below 80%.

## 4 Conclusion

The propagation loss of the PFGI-POFs was measured as a function of a large applied strain (up to 100%) at three different optical powers and as a function of the strain rate at a constant optical power. The strain dependence of the propagation loss in PFGI-POFs was affected by neither the incident power (<27 dBm) nor by the strain rate (<500% $s^{-1}$). This fact implies that high-transmission-power Brillouin sensors using PFGI-POFs are potentially applicable in the monitoring of strains of several hundred percent per second, which could occur in civil structures during earthquakes.

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