Applied Physics Express **6** (2013) 076601
http://dx.doi.org/**10.7567/APEX.6.076601**

Fast Flaw Detection in Polymer Optical Fibers with Infrared Thermometer

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Received May 17, 2013; accepted June 11, 2013; published online June 27, 2013

We demonstrate a fast and cost-effective method of detecting flaws in polymer optical fibers (POFs) using an infrared thermometer. The optical loss dependence of the measured temperature at the flaw is found to be linear with a proportionality constant of approximately 0.74 °C/dB when the propagating light is 24.5 dBm (282 mW) at 1.55 µm. The propagating optical power dependence of the measured temperature at the flaw with a fixed loss also shows a linear behavior, which predicts that a high optical input power is preferable to precise estimation of the loss.
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The fabrication technology of widely used silica single-mode optical fibers (SMFs) has matured sufficiently to keep their quality extremely high and stable; and as a result, km-order-long silica SMFs with a propagation loss of as low as 0.2 dB/km at 1.55 µm are common.[1–4)] In contrast, the fabrication technology of polymer optical fibers (POFs) is relatively new. Currently, poly(methyl methacrylate) (PMMA)-based POFs can be fabricated with a stable propagation loss owing to their large core diameters of up to 980 µm.[5–7)] However, the propagation loss of perfluorinated graded-index (PFGI-) POFs with core diameters of as small as 50 µm, which have become commercially available only recently, is largely influenced by the flaw in the core induced during the fabrication process, resulting in the difficulty in producing long PFGI-POFs with stable quality.[8–10)] Such PFGI-POFs with a length of one hundred meters or longer are now highly demanded not only in POF-based high-capacity transmission systems[11)] but also in next-generation distributed sensors exploiting nonlinear effects in POFs.[12–14)] Thus, to develop an effective method of detecting flaws in PFGI-POFs is of substantial significance.

Conventional methods for detecting flaws in optical fibers include optical time-domain reflectometry (OTDR),[15,16)] optical low-coherence reflectometry (OLCR),[17,18)] and optical frequency-domain reflectometry (OFDR).[19,20)] They can measure the accurate loss distribution along the POFs with a high spatial resolution, but suffer from some drawbacks, such as high installation cost required for the devices (photodetectors, specially configured lasers, etc.), long measurement time for signal processing, and the inability to resolve the flaw location at a glance in long POFs.

In this paper, a fast and cost-effective method of detecting flaws in POFs using an infrared thermometer (IRT) is demonstrated, which can overcome the disadvantages of the conventional techniques. Since an optical loss at a flaw in a POF induces the rise in temperature, the loss distribution along a POF can be detected with the IRT as a temperature distribution. First, we show that the locations of the flaws in POFs can be detected, whether the POFs are jacketed or bare. Then, we find the optical loss dependence of the measured temperature at the flaw to be linear with a proportionality constant of ~0.74 °C/dB with the propagating light of 24.5 dBm (282 mW) at 1.55 µm. We also show that, when the loss is fixed, the propagating optical power dependence of the measured temperature at the flaw is linear, predicting that high-power optical power is desirable to estimate the loss precisely.

A blackbody, i.e., a perfect absorber of any radiation incident on it, is capable of emitting radiation.[21)] When heated to a uniform temperature, it generates blackbody radiation, the characteristics of which are determined solely by the temperature. The total radiant emittance W of an object (both blackbody and non-blackbody) is known to be given by Stefan-Boltzmann's law as

$$W = \varepsilon \sigma T^4, \tag{1}$$

where ε is the emissivity of the object (1 for a blackbody), σ is the proportionality constant, and T is the surface temperature of the object.[22)] The surface temperature of an object including a POF can thus be measured with an IRT. The IRT-based method for detecting a flaw, which exploits the rise in temperature induced by an optical loss at the flaw, has such advantages as (1) cost efficiency, (2) real-time measurement, and (3) visual display of the flaw location.

We employed two PFGI-POFs as fibers under test (FUTs), which had a numerical aperture of 0.185, a core diameter of 50 µm, a cladding diameter of 100 µm, a core refractive index of ~1.35, and a propagation loss of ~250 dB/km at 1.55 µm. One FUT, denoted by FUT 1, was a long jacketed PFGI-POF with an inner jacket diameter of 750 µm and an outer jacket diameter of 2.8 mm, in which a flaw had been caused probably during the fabrication process. Both of the jackets were composed of poly(vinyl chloride) (PVC). The other FUT, denoted by FUT 2, was a 60-cm-long bare PFGI-POF, at the middle point of which a flaw was artificially induced by repeating bending and releasing. The loss at the flaw was moderately variable from 2.5 to 20 dB. An IRT (FLIR System; i7) was used to detect the flaws, which had a spectral range from 7.5 to 13 µm, and an image frequency of 9 Hz. The emissivity ε was set as follows: for the jacketed POF, $\varepsilon = 0.98$ (value for PVC[23)]); for the bare POF, $\varepsilon = 0.95$ (value for PMMA[24,25)]). The room temperature was 24 °C. Note that the optical power and/or the loss at the flaw were estimated considering the optical loss caused during the light propagation from one end of the POF to the flaw.

First, we detected the flaw in the FUT 1 wound on a reel of 20 cm diameter. The incident optical power was 24.5 dBm (282 mW). Figure 1(a) shows its photograph, from which no information on the flaw was derived. In its IR image shown in Fig. 1(b), however, the location of the flaw was roughly but clearly detected despite the thick jackets, which is not feasible only by detecting the scattered visible light with our naked eyes. The maximum temperature was 24.4 °C, and the

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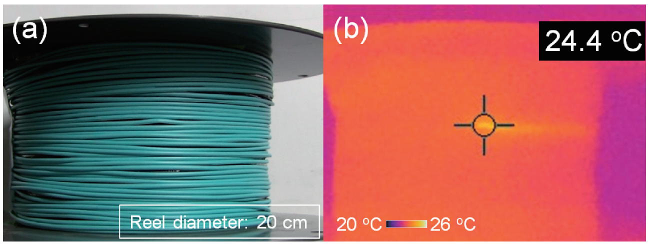

Fig. 1. (a) Photograph and (b) IR image of the jacketed POF with a flaw wound on a reel.

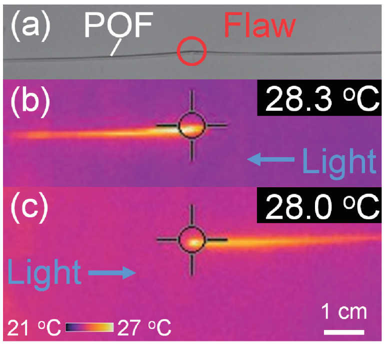

Fig. 2. (a) Photograph of the bare POF with a flaw, and its IR images with light propagating from (b) right to left, and (c) left to right.

high-temperature region had a tail extending toward the left. To clarify this tailing effect, we injected 21.3 dBm (135 mW) light into both ends of the FUT 2, one by one, as shown in Figs. 2(a)–2(c). The optical loss of the flaw at the midpoint of the FUT 2 was fixed at 4.9 dB in this measurement. When the light was injected from the right-hand side, the high-temperature region had a tail extending for approximately 5 cm toward the left, as shown in Fig. 2(b), and vice versa, as shown in Fig. 2(c). This phenomenon can be exploited to identify the unknown direction of the propagating light through the POF. Since the measured maximum temperature of ~28 °C was almost the same in both configurations, the light injection only from one end of the POF appears to be sufficient for rough estimation of the optical loss at the flaw.

Next, we measured the dependence of temperature on the optical loss at the flaw when the incident optical power was fixed at 24.5 dBm (282 mW), as shown in Fig. 3. The error bars calculated from the signal fluctuations for 5 min were ±0.8 °C. As the loss was raised, the temperature was increased linearly with a slope of ~0.74 °C/dB, which is of practical use for the rough estimation of the loss using the measured temperature. We also measured the dependence of temperature on the optical power of the propagating light when the optical loss at the flaw was fixed at 20 dB, as shown in Fig. 4. As the incident power was raised, the temperature was increased almost linearly, which indicates that, by employing high-power light, the measured temperature for a certain loss can be increased. This leads to the enhancement of the proportionality constant between the measured temperature and the loss (see Fig. 3), resulting in a more precise estimation of the loss. The slight decrease in the slope observed in the range of the optical power

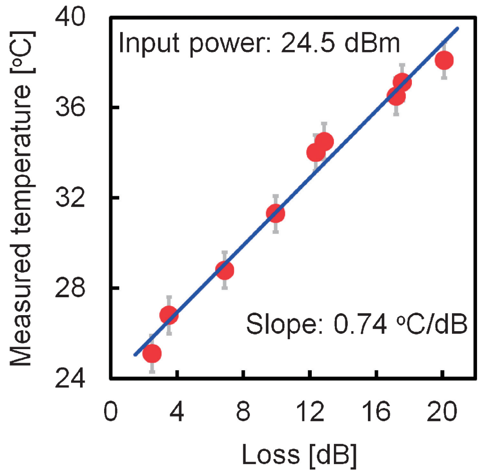

Fig. 3. Measured temperature dependence on optical loss at the flaw.

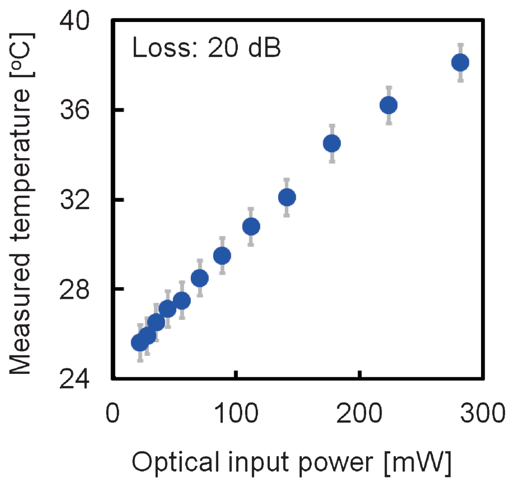

Fig. 4. Measured temperature dependence on optical power of the propagating light at the flaw.

of >200 mW seems to be caused by the heat dissipation effect.

In conclusion, we demonstrated a fast and low-cost detection of the flaws in POFs using an IRT, which can overcome the drawbacks of the conventional techniques. The locations of the flaws were successfully detected, even when the POF was protected by thick jackets. The optical loss dependence of the temperature at the flaw was linear with a coefficient of ~0.74 °C/dB when the optical power was 24.5 dBm (282 mW) at 1.55 μm. The optical power dependence of the measured temperature at the flaw with a fixed loss was also linear, which predicts that a higher optical power is desirable for the loss estimation with more precision. We hope that this method will be of common use, with its fast measurement capability, ease of handling, and cost efficiency, in examining the quality of POFs at the final stage of their fabrication process in the near future.

Acknowledgments 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).

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