Brillouin scattering signal in polymer optical fiber enhanced by exploiting pulsed pump with multimode-fiber-assisted coupling technique

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Received February 6, 2013; revised March 11, 2013; accepted March 25, 2013;
posted March 27, 2013 (Doc. ID 185028); published April 26, 2013

A cost-effective technique for coupling a polymer optical fiber (POF) with 50 μm core diameter to a silica single-mode fiber (SMF) with 8 μm core diameter is proposed, which can, by exploiting a multimode fiber with 50 μm core diameter, avoid the damage or burning at the butt-coupled POF/SMF interface. Using this coupling technique, we also show that the Brillouin signal in a POF can be enhanced by combined use of pulsed pump and an erbium-doped fiber amplifier. When the pulsed pump with average optical power of 18 dBm (63 mW), duty ratio of 15%, and pulse period of 2 μs is launched into a 200 m-long POF, 4 dB enhancement of the Stokes power is obtained compared to that with 18 dBm continuous wave pump. The relatively small enhancement is probably caused by the high Brillouin threshold of POFs. The Stokes power dependence on duty ratio is nonmonotonic, which might originate from a longer phonon lifetime in POFs than that in silica SMFs.

OCIS codes: (060.2370) Fiber optics sensors; (130.5460) Polymer waveguides; (290.5830) Scattering, Brillouin.
http://dx.doi.org/10.1364/OL.38.001467

Brillouin scattering in optical fibers [1] has been the subject of intense research for several decades as a prospective mechanism for various devices and systems [2–9]. Since glass optical fibers are fragile and need to be treated with care, we have focused on Brillouin scattering in polymer optical fibers (POFs) with such high flexibility that they can withstand >50% strain. Up to now, especially for sensing applications, we have investigated some fundamental Brillouin properties of perfluorinated graded-index POFs at 1.55 μm, including Brillouin gain coefficient [10], Brillouin threshold power [10], as well as Brillouin frequency shift [10] and its dependences on strain (relatively small strain [11] and large strain [12]) and temperature [11]. These results indicate that Brillouin scattering in POFs is potentially applicable both to high-precision temperature sensing [11] and to large-strain sensing [12]. However, the Stokes power in POFs is quite low because of their large core diameters (>50 μm), which needs to be enhanced for more detailed investigation of their Brillouin gain spectra (BGSs) [13–15].

Several methods have been developed to enhance the Brillouin signal in POFs. The Stokes power was enhanced simply by employing long POFs [16], but the use of POFs longer than ~50 m has been proved to be of scarcely any effect due to their high propagation loss at 1.55 μm resulting in short effective length. Another way is to induce stimulated Brillouin scattering with a pump-probe technique [17], in which detailed evaluation of the BGS was, however, difficult because it was easily influenced by lock-in configurations. Exploiting the nonlinearity of Brillouin scattering, we have also demonstrated that the Stokes signal in silica single-mode fibers (SMFs) can be drastically enhanced by use of pulsed pump and a low-power erbium-doped fiber amplifier (EDFA) [18]. This method was, however, inapplicable to the enhancement of the Stokes signal in POFs, because the butt-coupled POF/SMF interface was easily damaged or burnt due to the extremely high peak power of the pulsed pump. Inserting a multimode fiber (MMF) with an appropriate mode-field diameter at the POF/SMF interface [19] might be used to avoid the damage, but, when a POF with 50 μm core diameter is used, the corresponding optimal core diameter of the MMF becomes a value that is not commercially standardized.

In this Letter, we develop a new POF-to-SMF coupling technique, which can, with the assistance of an MMF, minimize the damage at the POF/SMF interface. Then we enhance the Brillouin signal in a POF using pulsed pump and an EDFA, which method was unfeasible without the MMF-assisted coupling. The obtained enhancement in the Stokes power is 4 dB, which is relatively small because of the high Brillouin threshold of the POF. The Stokes power dependence on duty ratio is found to be nonmonotonic, which might originate from a longer acoustic phonon lifetime in POFs than that in silica fibers.

In general, the dependence of Stokes power on continuous wave (CW) pump power is nonlinear [1]; namely, the Stokes power begins to grow drastically via electrostriction when the pump power is higher than Brillouin threshold power P_{th}. When pulsed pump with its peak power higher than the threshold is employed, temporally averaged Stokes power can be enhanced compared to that with CW pump with the same average power [18]. Such pulsed pump with high peak power can be generated with a low-power EDFA, which typically has small-signal gain of around 20–40 dB and saturation output power of around 10–20 dBm. So long as the average output power is lower than the saturation output power, an incident optical pulse even with several-milliwatt peak power experiences the small-signal gain. This condition can be satisfied by sufficiently decreasing the pulse duty ratio, leading to the generation of pulsed pump with (sub-)Watt-range peak power.

In our previous report [18], by employing the pulsed pump with average optical power of 13 dBm, duty ratio of 20%, and pulse period of 2 μs, the Stokes power in a 1 km-long silica SMF ($P_{\mathrm{th}} = 17$ dBm $= 50$ mW) was drastically enhanced by 25 dB. Each parameter was defined as shown in Fig. 1. In contrast, when the pulsed pump with average power of 19 dBm, duty ratio of 10%, and pulse period of 2 μs was launched into a 2 m-long silica SMF ($P_{\mathrm{th}} = 44$ dBm = 25.1 W), the Stokes power was also raised probably due to the nonlinearity of the Stokes power dependence on CW pump power even within the range below P_{th}, but only by 0.25 dB. Thus, the effectiveness of this method is highly dependent on the Brillouin threshold of the fibers under test (FUTs), which should be lower than the peak power of the pulsed pump.

A 200 m-long perfluorinated graded-index POF with numerical aperture of 0.185, core refractive index of ~1.35, and propagation loss of 250 dB/km at 1.55 μm was used as an FUT (Note that almost the same measurement results are expected irrespective of the POF length, providing it is longer than ~50 m). Following the method that takes the multimode correction into consideration [16,20], its Brillouin threshold was estimated to be 40.2 dBm (=10.4 W). The experimental setup shown in Fig. 2 was similar to that previously used in [18], which was based on self-heterodyne detection for high-resolution BGS monitoring. All the optical paths except for the FUT were composed of silica SMFs. A distributed-feedback laser diode at 1.55 μm was used as a light source. Pulse conversion of the pump was performed with a $LiNbO_3$ intensity modulator having an extinction ratio of over 20 dB. A low-power EDFA with small-signal gain of 35 dB was used to amplify the pulsed pump. The relative polarization state of the Stokes and the reference beams was optimized with polarization controllers.

Conventionally, POFs were butt-coupled to silica SMFs for Brillouin measurement [10], which was subject to physical damage or burning, resulting in inapplicability of high-peak-power optical pulse injection. To resolve this problem, we developed a new coupling technique exploiting an MMF, the concept of which is schematically shown in Fig. 3. The conventional method suffers from the differences in material and in core diameter simultaneously at the POF/SMF interface. Damage is caused not only by the difference in core diameter but also by the slight difference in surface roughness, which cannot be removed by splicing in this case because the two materials to be spliced are quite different (polymer and glass). In contrast, in the new coupling method, a silica MMF with the same core diameter as that of the POF is inserted between the POF and the silica SMF, and spliced to the SMF by arc fusion (both silica glass). Then, the damage originating from the difference in surface roughness can be avoided at the MMF/SMF interface, while no difference in core diameter can mitigate the damage at the POF/MMF interface. To verify whether this coupling method itself has an effect of enhancing the Brillouin signal, BGSs in the POF were measured with and without the MMF-assisted coupling using 12 dBm CW pump, as shown in Fig. 4. The Brillouin frequency shift was approximately 2.8 GHz, which agrees with our previous report [10]. The Stokes power with the MMF was only slightly (~0.25 dB) higher than that without the MMF, which indicates that the MMF-assisted coupling itself has hardly any influence on the Stokes power in POFs. Further research is required to clarify the physical process of reflection and transmission of electromagnetic and acoustic waves along the POF/MMF/SMF structure.

Using the MMF-assisted coupling to avoid the damage at the POF/SMF interface, we applied to the 200 m-long POF the method for enhancing the Stokes signal using pulsed pump. The average power of the pump was set to 18 dBm. The pulse period was fixed at 2 μs, and the duty ratio was varied from 100% (CW) to 5%. During the experiment, the POF/MMF and MMF/SMF interfaces remained undamaged. The microscopic images of the POF ends with and without the MMF after all the measurements are shown in Figs. 5(a) and 5(b), respectively. Burning was observed at the core in Fig. 5(b), which was successfully avoided in Fig. 5(a).

The measured BGS dependence on duty ratio in the POF is shown in Fig. 6(a). With decreasing duty ratio, the Stokes power was raised, probably because of the nonlinear dependence of the Stokes power on CW pump power in the range of $<P_{\mathrm{th}}$. Figure 6(b) shows the Stokes power dependence on duty ratio. The error bars were calculated based on the signal fluctuations in ten minutes. As the duty ratio was reduced, the Stokes power

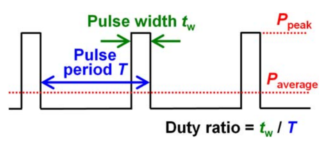


Fig. 1. Definitions of parameters related to optical pulse train.

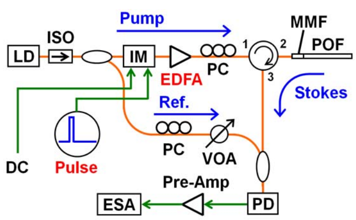


Fig. 2. Experimental setup. DC, direct current; EDFA, erbium-doped fiber amplifier; ESA, electrical spectrum analyzer; IM, intensity modulator; ISO, isolator; LD, laser diode; PC, polarization controller; PD, photo detector; VOA, variable optical attenuator.

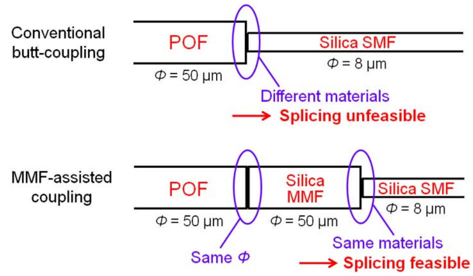


Fig. 3. Concept of MMF-assisted coupling.

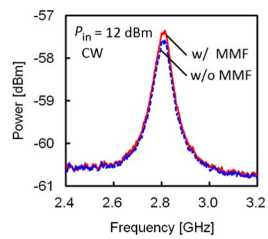
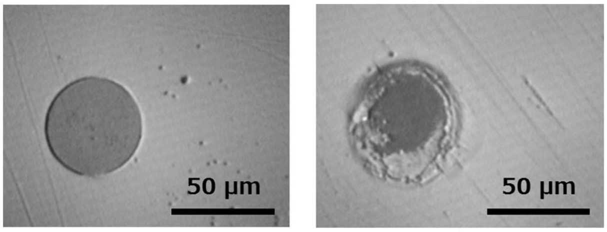
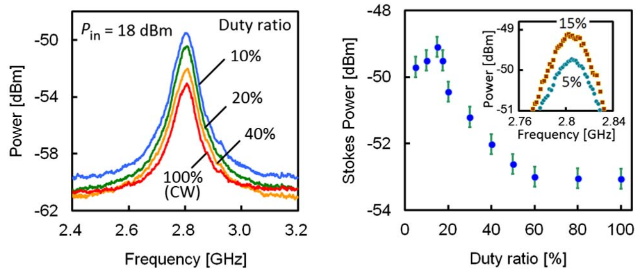


Fig. 4. Measured BGSs with and without MMF-assisted coupling.



(a) (b)

Fig. 5. Microscopic images of POF ends after measurements (a) with and (b) without MMF-assisted coupling.



(a) (b)

Fig. 6. (a) Measured BGS dependence on duty ratio and (b) Stokes power as a function of duty ratio. The inset in (b) shows the measured BGSs with 5% and 15% duty ratio.

was enhanced, which is the same behavior as that with a long silica SMF [18]. At 15% duty ratio, a maximum enhancement of 4 dB was obtained. This value is much smaller than that with a silica SMF [18], which is natural because the calculated peak power of ~26.3 dBm (=420 mW) is much lower than the Brillouin threshold of 40.2 dBm (=10.4 W). More drastic enhancement will be achieved by, to lower the threshold, using a longer POF at shorter wavelength such as 1.1 and 1.2 μm, where its propagation loss becomes minimal (≅ 10 dB/km). If a 1 km-long POF is used, its P_{th} is calculated to be 472 mW, which is comparable to the peak power under the measurement conditions above (Note that, to demonstrate this experimentally, most of the optical devices need to be replaced with those suitable for the shorter wavelength).

When the duty ratio was reduced below 15%, the Stokes power began to decrease slightly, as is recognized in the inset of Fig. 6(b). The reason for this behavior, which was not observed in our previous silica-based experiments [18], has not been clarified yet, but it might originate from a longer rising time of acoustic phonons, which is basically proportional to a phonon lifetime [21], in POFs. Although the Brillouin linewidth, which is in inverse proportion to the phonon lifetime [1], of POFs is reported to be ~100 MHz [10,16] [also see Fig. 6(a)] and is broader than that of silica SMFs (typically, several tens of MHz [1]), considering the multimode nature of the POFs, we cannot simply conclude that the phonon lifetime in POFs is shorter than that in silica SMFs. This point needs to be studied further.

In conclusion, first, we proposed an MMF-assisted POF-to-SMF coupling technique, with which damage or burning at the conventional butt-coupled POF/SMF interface can be avoided. Then, by use of this coupling technique, we demonstrated at 1.55 μm that the Stokes power in a POF can be enhanced by using pulsed pump and an EDFA. In the experiment, 4 dB enhancement of the Stokes power was obtained. This amount can, in principle, be increased by employing a kilometer-order-long POF at shorter wavelength to lower the Brillouin threshold. The Stokes power dependence on duty ratio was nonmonotonic, which might be caused by a longer phonon lifetime in POFs than that in silica SMFs. We believe that the MMF-assisted coupling will be a standard POF-to-SMF coupling technique for high-power light injection (including, but not limited to, Brillouin applications) with its low cost and capability of minimizing the risk of burning at the POF/SMF interface. We also hope that the Brillouin signal in POFs enhanced with the pulsed-pump technique will in the near future be of great use in characterizing their BGS in detail, and that our result will trigger further research on Brillouin dynamics in POFs.

This work was partially supported by a Grant-in-Aid for Research Activity Start-up (24860029) from the JSPS, and by research grants from the Hattori-Hokokai Foundation, the Mazda Foundation, and the JFE 21st Century Foundation.

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