Observation of stimulated Brillouin scattering in silica graded-index multimode optical fibre based on pump-probe technique

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Based on the pump-probe technique (PPT), stimulated Brillouin scattering (SBS) was observed in a 100 m-long silica graded-index multimode optical fibre with the same core diameter as that of a perfluorinated graded-index polymer optical fibre (PFGI-POF) (=50 µm). The SBS threshold was measured to be ~50 mW, which was much lower than 5.08 W, the SBS threshold obtained for the same fibre without the PPT. This result indicates that the PPT is useful even under multimode conditions and that the difficulty in observing SBS in PFGI-POFs consists not in their physical problems but in their material problems (high propagation loss etc.).

Introduction: Among various kinds of sensors, optical fibre sensors based on Brillouin scattering have especially attracted considerable attention in the area of smart materials and structures [1–5], because distributed strain and temperature sensing along an optical fibre can be performed. Up to now, glass optical fibres (GOFs) have been mainly used as the sensing heads of the Brillouin sensors. However, GOFs are so fragile that they cannot withstand strains of over several per cent. One method of overcoming this disadvantage is to employ plastic optical fibres (POFs) as the sensing heads, which have many advantages such as extremely high flexibility (more than 50% strain can be applied), low-cost connection, and ease of handling. Besides, POFs have a 'memory effect': they can memorise the information on applied large strains due to their plastic deformation [6]. Among several types of POFs, perfluorinated graded-index (PFGI-) POFs have been mainly used because their propagation loss is not too high even at telecom wavelengths.

There are two major techniques for achieving distributed strain and temperature sensing based on Brillouin scattering: time domain and correlation domain. The time-domain techniques are further divided into two types: 'Brillouin optical time-domain reflectometry (BOTDR)' [1], in which incident light is injected into only one end of a sensing fibre, and 'Brillouin optical time-domain analysis (BOTDA)' [2], in which incident light is injected into both ends of a sensing fibre to induce stimulated Brillouin scattering (SBS). The correlation-domain techniques are also divided into two: 'Brillouin optical correlation-domain reflectometry (BOCDR)' [4] and 'Brillouin optical correlation-domain analysis (BOCDA)' [5].

One of the most serious problems in implementing such distributed Brillouin sensors using PFGI-POFs is their weak Brillouin signals [7]. As a result, especially when high spatial resolution is required, a better candidate is not 'reflectometry' but 'analysis', where SBS is induced by the pump-probe technique, leading to drastic enhancement of the Brillouin signals. Although SBS in the PFGI-POFs has already been observed by the pump-probe technique using an experimental setup similar to that of BOCDA [8], the setup including lock-in detection was rather complicated. In order to develop POF-based BOTDA systems, SBS in the PFGI-POFs should be observed with a much simpler setup, but this trial has not been successful [9]. So far we have had no idea whether this difficulty is due to their structural or material problems, which needs to be clarified to proceed to the next step.

In the work reported in this Letter, based on the pump-probe technique without lock-in detection, we observed SBS in a 100 m-long silica graded-index multimode optical fibre (GI-MMF) which has the same core diameter as that of a PFGI-POF, and measured its SBS threshold to be approximately 17 dBm (= ~ 50 mW). This value was much lower than 5.08 W obtained for the same silica GI-MMF without using the pump-probe technique, which indicates that this technique is useful even with multimode nature. Then we conclude that the difficulty in observing SBS in PFGI-POFs consists not in their structural problems (multimode nature, small core diameter etc.) but in their material problems (high propagation loss, small Brillouin gain coefficient etc.).

Theory: When pump light is injected into an optical fibre, backscattered Stokes light is generated due to spontaneous Brillouin scattering (SpBS) [10]. The centre frequency of the Stokes light is known to be lower than that of the pump light. The amount of this frequency shift is called Brillouin frequency shift (BFS), which is, at 1.55 µm, typically ~10.8 GHz for silica singlemode fibres (SMFs) and ~2.8 GHz for PFGI-POFs. In general, the Stokes power grows higher with increasing pump power. When the pump power becomes higher than a certain power called Brillouin threshold P_{th}, the Stokes power begins to drastically increase due to the transition from SpBS to SBS.

For sensing applications, the Brillouin Stokes power should be as high as possible, which leads to high spatial resolution, long measurement range, short measurement time etc. The so-called pump-probe technique is one of the effective techniques to enhance the Stokes power. With this technique, by injecting probe light at the same frequency as the Stokes light additionally into the other end of the fibre, SBS can be induced at much lower pump power, i.e. the Brillouin threshold can be largely reduced. This scheme has been fully exploited in developing SMF-based BOTDA [2] and BOCDA systems [4].

Experiments: As a fibre under test (FUT), we employed a 100 m-long silica GI-MMF with a numerical aperture (NA) of 0.2, a core diameter of 50 µm, a cladding diameter of 125 µm, a core refractive index of ~1.46, and a propagation loss of about 1.0 dB/km at 1.55 µm. Both ends of this silica GI-MMF were coupled to silica SMFs using so-called butt-coupling with air gaps filled with index-matching oil ($n \sim 1.46$) to suppress the Fresnel reflection.

The experimental setup for observing SBS with the pump-probe technique is schematically shown in Fig. 1. Two laser diodes (LDs) were used; one was for providing pump light, and the other was for probe light. The pump light at frequency ν_0 was amplified with an erbium-doped fibre amplifier (EDFA) and injected into the silica GI-MMF. The probe light was, after being amplified also with an EDFA, injected into the other end of the silica GI-MMF, the frequency of which was swept around ν_0 – BFS by controlling the driving temperature of the LD. Part of the Stokes light was converted into an electrical signal with a photodetector (PD) and monitored with an electrical spectrum analyser (ESA); by comparing 1. the beat signal between the Stokes light and the Rayleigh-scattered pump light with 2. the beat signal between the probe light and the Rayleigh-scattered pump light, the frequency of the probe light was accurately adjusted. The rest of the Stokes light was directed to an optical powermeter (OPM), the output of which was acquired as Brillouin gain spectrum (BGS), i.e. as a function of the frequency difference between the pump light and the probe light.

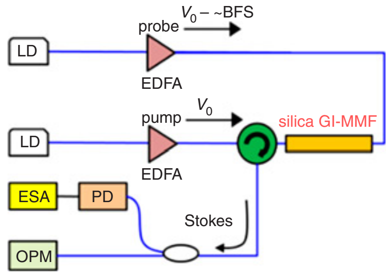

Fig. 1 *Experimental setup for observing SBS in silica GI-MMF with pump-probe technique*

EDFA: erbium-doped fibre amplifier; ESA: electrical spectrum analyser; LD: laser diode; OPM: optical powermeter; PD: photodetector

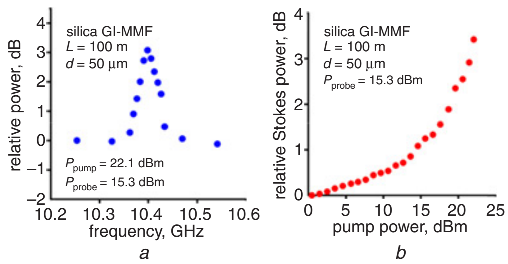

Fig. 2 *Experimental results*

a Relative BGS in silica GI-MMF with pump-probe technique
b Relative Stokes power dependence on pump power in silica GI-MMF with pump-probe technique

The BGS in the silica GI-MMF measured with the pump-probe technique is shown in Fig. 2*a*. The pump power and the probe power were set to 22.1 dBm and 15.3 dBm, respectively. A clear peak was observed at 10.40 GHz (which differs from 10.43 GHz in our previous experiment [11] probably due to the difference in room temperature [12]). Here we should note that the BFS of the silica SMFs connected to the GI-MMF was 10.80 GHz, which is outside the range of Fig. 2*a*.

Fig. 2*b* shows the relative Stokes power against pump power when the probe power was fixed at 15.3 dBm. The Stokes power was drastically enhanced when the pump power was higher than the Brillouin threshold P_{th} of ~17 dBm (= ~50 mW). This value is much lower than 5.08 W (obtained without the pump-probe technique) [11], which indicates that the pump-probe technique is effective even when FUTs are multimode with large core diameters.

The experimental results above imply that the difficulty in observing SBS in PFGI-POFs with the pump-probe technique does not consist in their structural problems, because SBS was successfully induced for the silica GI-MMF with the same length and core diameter. Thus we speculate that the difficulty lies in the material problems of the PFGI-POFs, including their high propagation loss, small Brillouin gain coefficient etc. (Note that the previously reported value of g_B for PFGI-POFs (3.09×10^{-11}m/W) [7] was estimated partially based on the physical parameters for bulk poly(methyl methacrylate) (PMMA), on which point further study is needed.)

Conclusion: By using the pump-probe technique without lock-in detection, SBS in a 100 m-long silica GI-MMF was observed. Compared to the Brillouin threshold of 5.08 W theoretically obtained when the pump-probe technique was not used [11], with this technique it was experimentally found to be as low as ~17 dBm (= ~50 mW), indicating that the pump-probe technique is effective even with multimode nature. Based on the results above, the difficulty in observing SBS in PFGI-POFs appears to consist not in their structural problems but in their material problems, such as the high propagation loss and the small Brillouin gain coefficient. We believe that this Letter provides significant information for developing POF-based BOTDA systems in the near future.

Acknowledgments: This work was partially supported by a Grant-in-Aid for Research Activity Start-up (24860029) from the Japan Society for the Promotion of Science (JSPS), and by research grants from the Murata Science Foundation, the Hattori-Hokokai Foundation, the Mazda Foundation, and the Foundation of Ando Laboratory.

18 November 2012
doi: 10.1049/el.2012.4017
One or more of the Figures in this Letter are available in colour online.

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