Simple coupling method for enhancing Brillouin scattering signal in polymer optical fibres

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A simple, efficient, and cost-effective method to enhance a Brillouin scattering signal in perfluorinated graded-index (GI-) polymer optical fibres (POFs) is proposed and demonstrated. In this method, instead of the conventional butt-coupling of a POF to a silica singlemode fibre (SMF), a multimode fibre (MMF) with a proper mode-field diameter of the fundamental mode is additionally inserted between the two fibres to improve the optical coupling efficiency from the POF to the SMF. After theoretical analysis, it is experimentally shown that the Brillouin signal in the POF is clearly enhanced simply by inserting standard MMFs, which are commercially available at affordable cost.

Introduction: Brillouin scattering in glass optical fibres (GOFs) [1] has been an active field of research for several decades, and applied to various devices and systems, such as lasing, microwave signal processing, slow light generation, phase conjugation, and optical storage. Strain/temperature sensing is also one of the useful Brillouin applications, but GOFs are so fragile that they cannot be used as sensor heads to which a large strain of $>10\%$ is applied. One solution to this problem is to implement such Brillouin sensors using polymer optical fibres (POFs), which offer not only high flexibility but also easy connection, low cost, and high safety [2]. Up to now, experimental study has been extensively performed on the Brillouin scattering properties in perfluorinated graded-index (GI-) POFs at 1.55 μm [3–5]. In all our previous experiments, one end of the POFs under investigation was directly butt-coupled to a silica-based singlemode fibre (SMF) for Brillouin detection. Although Brillouin scattering in POFs has been shown to be potentially useful in developing high-precision temperature sensing with reduced or even zero strain sensitivity [4], one of the biggest problems is the extremely low Brillouin Stokes power due to the following three reasons: 1. a propagation loss of GI-POFs (~250 dB/km at 1.55 μm) is much higher than that of silica SMFs, resulting in a short Brillouin effective length [1, 3]; 2. a core diameter of POFs is much larger than that of singlemode GOFs, leading to a high Brillouin threshold [1, 3]; and 3. only some portion of the Brillouin-scattered light caused in the POFs returns back to an SMF for detection, and the rest is lost at the butt-coupled part because of the difference in core diameter [3].

We have so far succeeded in drastically enhancing the Brillouin signal in a POF by inducing stimulated Brillouin scattering (SBS) with low threshold power using a so-called pump-probe technique [5], where two light beams are injected into both ends of the POF. However, this technique requires some expensive devices, including a single-sideband modulator (SSBM), a microwave generator with frequency sweep function, and a lock-in amplifier. We have also developed a method to enhance the Brillouin signal using pulsed pump light and an erbium-doped fibre amplifier (EDFA) [6], which also requires additional expensive devices, such as an optical pulse generator composed of an intensity modulator (IM). Thus, a more cost-effective way of enhancing the Brillouin signal is highly demanded for a wider range of applications.

In this Letter, an extremely simple and low-cost method is developed to enhance the Brillouin scattering signal in a POF only by additionally inserting an MMF at the butt-coupled part. First, we theoretically prove that the MMF to be inserted should have a proper mode-field diameter (MFD) of the fundamental mode in order to resolve the problem 3 described above and to improve the optical coupling efficiency from the POF to the SMF. Then, we experimentally show that the Brillouin signal in the POF with 120 μm-core diameter is clearly enhanced by inserting standard MMFs with 50 μm-core diameter.

Theory: Owing to their large core diameter ranging from 50 to 980 μm, standard POFs are multimode. To simplify the analysis, however, we consider only the Brillouin-scattered light of the fundamental mode of a GI-POF, which is much stronger than that of other modes. This assumption is not exactly the case, but valid for rough analysis (note that even exciting only the fundamental mode of an MMF is experimentally feasible by a so-called centre-launching technique, i.e. by adjusting the input beam profile to match the MFD of the fundamental mode of the MMF [7]). The Fresnel reflection at the boundary between the GI-POF ($n \sim 1.35$) and the silica SMF ($n \sim 1.46$) is negligibly small ($<<0.1$ dB). We define the MFDs of the SMF, the MMF, and the GI-POF as w_{SMF}, w_{MMF} and w_{POF}, respectively. According to Marcuse's equation [8], when the GI-POF and the SMF are simply butt-coupled, the loss which the Brillouin-scattered light causes in the GI-POF suffers in propagating back to the SMF is

$$L_{S\text{-}P} = -10 \log \left(\frac{2\, w_{POF}\, w_{SMF}}{w_{POF}^2 + w_{SMF}^2} \right)^2 [\text{dB}] \quad (1)$$

In contrast, when the MMF is additionally inserted between the GI-POF and the SMF, the total loss is

$$L_{S\text{-}M\text{-}P} = \left\{ -10 \log \left(\frac{2\, w_{POF}\, w_{MMF}}{w_{POF}^2 + w_{MMF}^2} \right)^2 \right\} + \left\{ -10 \log \left(\frac{2\, w_{MMF}\, w_{SMF}}{w_{MMF}^2 + w_{SMF}^2} \right)^2 \right\} [\text{dB}] \quad (2)$$

Fig. 1 shows the dependence of the calculated total loss $L_{S\text{-}M\text{-}P}$ on w_{MMF}, when $w_{SMF} = 10.4$ μm and $w_{POF} = 25$ μm (for example). When w_{MMF} is the same as w_{SMF} or w_{POF}, $L_{S\text{-}M\text{-}P}$ is ~ 3 dB ($=L_{S\text{-}P}$). When w_{MMF} is larger than w_{SMF} and smaller than w_{POF}, there is an improvement of the total loss compared with $L_{S\text{-}P}$; and w_{MMF} has an optimal value w_{opt} (in this case ~ 16 μm) slightly below the average of w_{SMF} and w_{POF}. Thus, by inserting an MMF with a proper MFD of its fundamental mode between the SMF and the GI-POF, the Brillouin signal in the GI-POF should be enhanced.

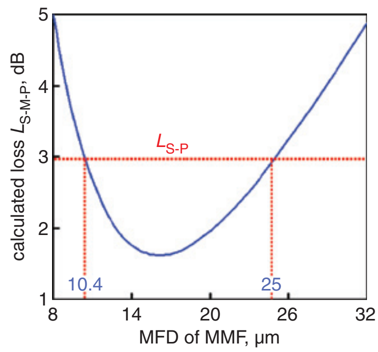

Fig. 1 *Calculated total loss against mode-field diameter of fundamental mode of MMF*

Experiments: We experimentally confirmed the effectiveness of this method. As depicted in Fig. 2, between a 1 m-long silica SMF (pigtail of an optical circulator) with 9.3 μm MFD at 1.55 μm and a 100 m-long perfluorinated GI-POF with 120 μm core diameter, the following three kinds of MMFs with 50 μm core diameter were employed: a 100 m-long silica SI-MMF, a 100 m-long silica GI-MMF, and a 1.2 m-long perfluorinated GI-POF. Index-matching oil ($n \sim 1.46$) was used to fill the airgap between the fibre ends. The experimental setup for observing the BGS in the GI-POF in this experiment was basically the same as our previous setup with self-heterodyne detection [3]. The wavelength of the light source was 1550 nm, and the optical input power to the 120 μm core GI-POF was set to 17.6 dBm for all the measurements, which is much lower than the Brillouin threshold power of the MMFs. The polarisation state was optimised with a polarisation controller (PC). When the silica SI- and GI-MMFs were inserted, the Brillouin signal caused in the two fibres has no influence on the BGS measurement, because the Brillouin frequency shift (BFS) in the GI-POF is ~2.8 GHz [3], which is about four times lower than that in the silica fibres (typically 10.9 GHz) [1]. However, when the 50 μm core GI-POF was inserted, its BFS is the same as that in the 120 μm core GI-POF under investigation; in order to separate their Brillouin signals, making use of the BFS dependence on temperature [4], we placed the 50 μm core GI-POF on the heater and raised the temperature up to 80°C.

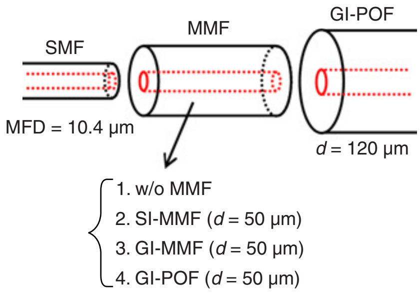

Fig. 2 *Experimental configuration; three kinds of MMFs inserted between SMF and GI-POF*

Fig. 3 shows the measured BGS with and without the three MMFs. A peak at ~2.6 GHz is the Brillouin signal of the heated 50 μm core GI-POF, which is rather broad probably due to its temperature non-uniformity. We can clearly see that the Brillouin Stokes power was enhanced by inserting MMFs, especially when the SI-MMF and the GI-POF were employed. This result can be well explained by assuming that the MFDs of the fundamental mode of the SI-MMF and the GI-POF are close to the optimal value w_{opt} in this experiment.

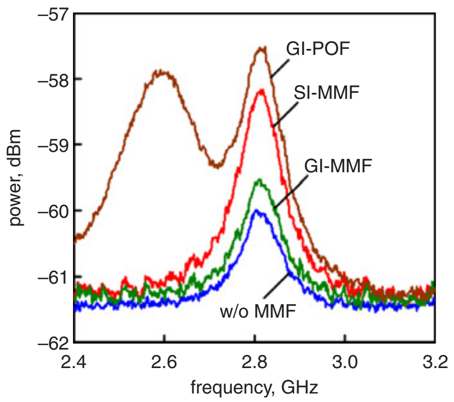

Fig. 3 *Measured BGS with and without three kinds of MMFs*

Conclusions: A simple cost-effective method has been demonstrated to enhance the Brillouin scattering signal in the GI-POF by inserting an MMF between the GI-POF and the silica SMF. First, we have theoretically shown that the MMF for this purpose should have a proper MFD of the fundamental mode to improve the optical coupling loss from the POF to the SMF. Then, we experimentally confirmed the effectiveness of this method by showing that the Brillouin signal of a 120 μm core GI-POF was efficiently enhanced by employing a 50 μm core silica SI-MMF or a 50 μm core GI-POF. We should note that silica MMFs with various core diameters (namely, various MFDs) are commercially available at relatively low cost. Thus, we believe that this method will become a standard technique in exploiting the Brillouin scattering in POFs owing to its simplicity and low cost.

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One or more of the Figures in this Letter are available in colour online.

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