

Fresnel-assisted self-heterodyne detection for Brillouin gain spectrum characterisation in polymer optical fibres

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It has been experimentally shown that by utilising the Fresnel-reflected light as the reference light, Brillouin signals in polymer optical fibres (POFs) can be observed with a higher signal-to-noise ratio (SNR) than those measured with standard self-heterodyne detection. This method is basically the same in setup as direct detection, leading to an additional advantage of system simplicity. Moreover, it has been demonstrated that the Brillouin signal in a 1 cm-long POF can be observed with a moderate SNR using this technique, indicating a potential feasibility of POF-based distributed Brillouin measurement with a millimetre-order spatial resolution.

Introduction: Brillouin scattering in optical fibres has been applied to various devices and systems, including lasers, optical storages, slow light generators and distributed strain and temperature sensors [1–3]. To improve their performance, Brillouin properties have been extensively studied not only for silica glass single-mode fibres (SMFs), but also for polymer optical fibres (POFs) [4–6]. Instead of direct detection, optical self-heterodyne detection is generally employed to observe the relatively small Brillouin signals in silica SMFs with a higher signal-to-noise ratio (SNR) [1–3]. Accordingly, the same type of self-heterodyne detection has been used to observe and characterise the Brillouin signals in POFs [4–6], which are even smaller because of the larger core diameters and multimode nature. As POF-based optical devices such as circulators and amplifiers are not widely available, almost all the optical paths of the experimental setup for detecting the Brillouin signal in a POF basically need to be composed of silica SMFs. Consequently, as long as a continuous wave (CW) is used as pump light, backscattered Stokes light inevitably includes a Fresnel-reflected component generated at the interface between the silica SMF (refractive index $n \sim 1.46$) and the POF ($n \sim 1.35$).

In this Letter, we experimentally show that, by exploiting the Fresnel-reflected light as the reference light for heterodyne detection and thus by removing an optical coupler for mixing the Stokes light and the reference light, the Brillouin signal in a POF can be observed with a higher SNR than in the previous reports using the standard self-heterodyne detection. This method, which we call Fresnel-assisted self-heterodyne detection, is similar in setup to direct detection, providing an additional advantage of system simplicity, i.e. no need for preparing a reference path including optical couplers, an amplifier and a polarisation controller. We then demonstrate that the Brillouin signal in an extremely short POF (1 cm) can be observed with a moderate SNR using this technique.

Theory: In general, compared with direct detection, optical heterodyne detection enables high-SNR detection of low-power signals through the use of a high-power reference light. The highest achievable SNR is reported to be limited by shot noise and/or photodiode (PD) saturation [7–9], and excessively high reference power results in a reduced SNR; namely, there exists an optimal value for the reference power. It is also known that the optical coupler used to mix the signal light and the reference light should have a high transmission or, ideally, should not be employed, so that most of the signal power is sent to the PD [7–9].

Experiments: Perfluorinated graded-index POFs [10] with a numerical aperture of 0.185, a core refractive index of ~ 1.35 and a propagation loss of ~ 250 dB/km at $1.55 \mu\text{m}$ were used as POFs under test. They had a core diameter of $50 \mu\text{m}$, a cladding diameter of $100 \mu\text{m}$ and an overcladding diameter of $500 \mu\text{m}$. An experimental setup based on standard self-heterodyne detection is schematically shown in Fig. 1a, in which two 3 dB optical couplers were employed along the reference path, whereas that based on the Fresnel-assisted self-heterodyne detection is shown in Fig. 1b. In both cases, the POFs were butt-coupled to the silica SMFs using ‘SC/FC’ adaptors [4]. In Fig. 1b, when a 50 m-long POF was used, irrespective of the incident pump power, the reflectivity of the POF measured via a circulator was ~ -29 dB, which agrees well with the Fresnel reflectivity at the POF-to-SMF interface (-28.1 dB = 0.15%), indicating that the influence of the other

scattering phenomena in the POF such as Rayleigh scattering is negligible. The Fresnel reflection at the open end of the POF (-16.5 dB = 2.2%) was also found to have hardly any influence on the measurement because of the high propagation loss and the low optical coupling efficiency at the POF-to-SMF interface, which was verified by the fact that neither the reflectivity nor the Brillouin gain spectra (BGS) was changed by immersing the POF end into water ($n \sim 1.33$) to match the indices.

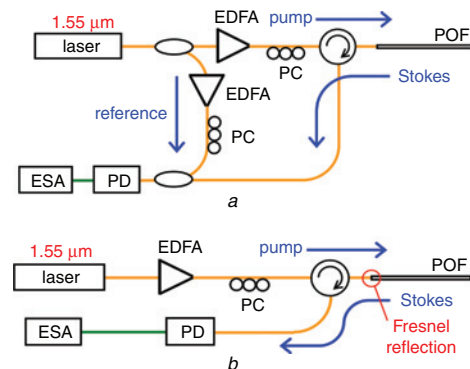


Fig. 1 Schematic setups for detecting Brillouin signals in POFs EDFA: erbium-doped fibre amplifier; ESA: electrical spectrum analyser; PC: polarisation controller; PD: photodiode

- a Standard self-heterodyne detection
- b Fresnel-assisted self-heterodyne detection

Fig. 2 shows the BGS measured using the standard self-heterodyne detection (Fig. 1a) with reference powers of -6.0 , 0 and 3.0 dBm, and without the reference light (>50 dB bending loss was induced). The BGS measured using Fresnel-assisted self-heterodyne detection (Fig. 1b) is also shown. The pump power was fixed at 20 dBm, and the polarisation state was optimised [11]. The Brillouin frequency shift (BFS) was ~ 2.84 GHz, which is in agreement with previous reports [4, 5]. With the standard detection, by raising the reference power, the SNR, i.e. the BGS height (difference in power between the noise floor and the BGS peak) was reduced, which indicates that the Fresnel-reflected power is higher than the optimal reference power in this measurement. In contrast, when the coupler-free Fresnel-assisted detection was used, the SNR was improved by ~ 5 dB. This technique with a higher SNR is suitable for BGS characterisation in POFs, but it cannot be directly applied to the Brillouin optical time-domain reflectometry (BOTDR) [2], in which not CW but optical pulses are used and the Fresnel-reflected light is not detected at the same timing as the Brillouin-scattered light.

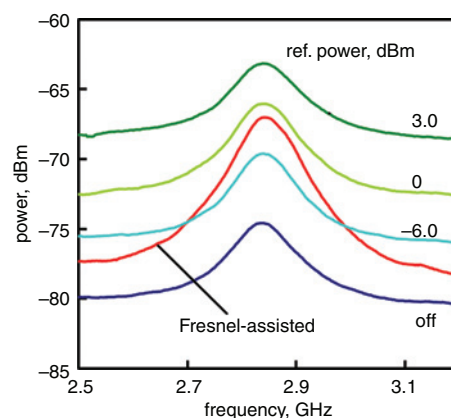


Fig. 2 BGS in 50 m-long POF measured with standard self-heterodyne detection (reference powers of -6.0 , 0 and 3.0 dBm, and without reference) and Fresnel-assisted self-heterodyne detection

Next, a minimal POF length required for Brillouin measurement was investigated using this method. The initial POF length of 20 cm was gradually reduced by cutting the section involving the open end, at which the Fresnel reflection was suppressed by angled cut and water immersion. Fig. 3 shows the measured BGS dependence on the POF length. The pump power was fixed at 23 dBm. With decreasing POF

length, the SNR deteriorated, but even when the POF was as short as 1 cm, a BGS which was sufficiently clear to obtain the peak frequency (i.e. BFS) was observed. The BFS became slightly lower, because the entire length of the 1 cm-long POF was heated [5] (part of the optical coupling loss at the POF-to-SMF interface is turned into heat). This result suggests a potential feasibility of POF-based distributed Brillouin measurement [12] with a millimetre-order spatial resolution. Further increase of the pump power will improve the SNR, but we should note that excessively high pump power may induce burning or damage at the POF-to-SMF interface [6] as well as a fibre fuse phenomenon [13].

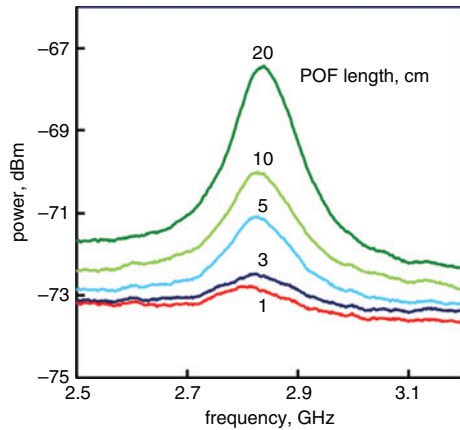


Fig. 3 BGS in 20-, 10-, 5-, 3- and 1 cm-long POFs measured with Fresnel-assisted self-heterodyne detection

Conclusion: Fresnel-assisted self-heterodyne detection was experimentally shown to provide a higher SNR of Brillouin measurement in POFs than standard self-heterodyne detection. System simplicity is another advantage. The Brillouin signal in a 1 cm-long POF was then observed with a moderate SNR, indicating a possible millimetre-order spatial resolution in POF-based distributed Brillouin measurement. Even though it cannot be directly applied to BOTDR, we believe that this method will be a useful tool for characterising the Brillouin properties in POFs.

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

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References

- 1 Agrawal, G.P.: 'Nonlinear fiber optics' (California Academic Press, San Jose, CA, 1995)
- 2 Kurashima, T., Horiguchi, T., Izumita, H., Furukawa, S., and Koyamada, Y.: 'Brillouin optical-fiber time-domain reflectometry', *IEICE Trans. Commun.*, 1993, **E76-B**, (4), pp. 382–390
- 3 Mizuno, Y., Zou, W., He, Z., and Hotate, K.: 'Proposal of Brillouin optical correlation-domain reflectometry (BOCDR)', *Opt. Express*, 2008, **16**, (16), pp. 12148–12153
- 4 Mizuno, Y., and Nakamura, K.: 'Experimental study of Brillouin scattering in perfluorinated polymer optical fiber at telecommunication wavelength', *Appl. Phys. Lett.*, 2010, **97**, (2), p. 021103
- 5 Mizuno, Y., and Nakamura, K.: 'Potential of Brillouin scattering in polymer optical fiber for strain-insensitive high-accuracy temperature sensing', *Opt. Lett.*, 2010, **35**, (23), pp. 3985–3987
- 6 Mizuno, Y., Hayashi, N., and Nakamura, K.: 'Brillouin scattering signal in polymer optical fiber enhanced by exploiting pulsed pump with multimode-fiber-assisted coupling technique', *Opt. Lett.*, 2013, **38**, (9), pp. 1467–1469
- 7 Oliver, B.M.: 'Signal to noise ratios in photoelectric mixing', *Proc. IRE*, 1961, **49**, (12), pp. 1960–1961
- 8 Yuen, H.P., and Chan, V.W.S.: 'Noise in homodyne and heterodyne detection', *Opt. Lett.*, 1983, **8**, (3), pp. 177–179
- 9 Holmes, J.F., and Rask, B.J.: 'Optimum optical local-oscillator power levels for coherent detection with photodiodes', *Appl. Opt.*, 1995, **34**, (6), pp. 927–933
- 10 Koike, Y., and Asai, M.: 'The future of plastic optical fiber', *NPG Asia Mater.*, 2009, **1**, (1), pp. 22–28
- 11 Mizuno, Y., Hayashi, N., and Nakamura, K.: 'Polarisation state optimisation in observing Brillouin scattering signal in polymer optical fibres', *Electron. Lett.*, 2013, **49**, (1), pp. 56–57
- 12 Hayashi, N., Mizuno, Y., and Nakamura, K.: 'First demonstration of distributed Brillouin measurement with centimeter-order resolution based on plastic optical fibers'. *OptoElectron. Commun. Conf.* 2014, Melbourne, Australia, July 2014
- 13 Mizuno, Y., Hayashi, N., Tanaka, H., Nakamura, N., and Todoroki, S.: 'Observation of polymer optical fiber fuse', *Appl. Phys. Lett.*, 2014, **104**, (4), p. 043302