High Signal-to-Noise Ratio Stimulated Brillouin Scattering Gain Spectrum Measurement

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Abstract: A technique to measure nonlinear processes, such as stimulated Brillouin scattering, with a very-high signal-to-noise ratio (SNR) is presented. Brillouin gain measurement with 77 dB SNR is demonstrated over a 2m-long section of single-mode fiber.
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1. Introduction

Stimulated Brillouin Scattering (SBS) is a nonlinear process produced by phonon-photon interactions inside a medium when two light beams spatially overlap. In optical fibers, backward SBS occurs when two coherent optical signals counter-propagate at a frequency difference equal to the Brillouin frequency shift of the fiber, such that energy and momentum conservation laws are fulfilled [1]. SBS has currently found diverse applications: it is mostly used to perform distributed temperature or strain measurement along an optical fiber [2-4], to achieve low phase noise Brillouin lasers [5,6], to realize optical signal processing in microwave photonics [7] or to create isolators [8]. Recently, on-chip waveguides is a rapidly growing field in which SBS is expected to play an important role [9,10]. In order to characterize SBS in such waveguides, gain measurements over millimeter-scale distances are required, considering chip dimensions. Since the Brillouin gain is typically of the order of 10^{-3} W^{-1} over such small distances in materials such as silica, dedicated measurement techniques have to be implemented. Several pump-probe interrogation methods have been previously reported:

1. Continuous-wave (CW) stimulated gain measurements are simple but suffer from low frequency noises such as 1/f noise [11].
2. Direct pump intensity modulation schemes are more robust [12]. Nonetheless, in the presence of reflections, a fraction of the modulated pump overlaps with the probe signal and degrades the system performances due to the presence of a single frequency.
3. Wavelength Modulation Spectroscopy (WMS) is readily used for trace gas analysis as it reaches extremely high sensitivities for weak absorption or gain measurement [13,14]. This technique is also well-suited for pump-probe interactions [15]. However, the exact gain profile is difficult to extract from the measurement data by using WMS due to measurement of only one or few of the signal's harmonics. As a result, gain magnitude and width can only be estimated by assuming a given gain distribution (e.g. Lorentzian) [16]. In addition, wavelength modulation inevitably introduces a spurious intensity modulation, generating unwanted harmonics in the detection signal [17].

In this paper, a measurement technique is proposed to overcome these aforementioned issues by intensity-modulating both pump and probe with frequencies very close to each other and, then, using lock-in detection at the harmonic differential frequency. In this way, only nonlinear phenomena, which are proportional to the product of the pump and probe intensities, are detected. Although higher Kerr and thermal-induced phase noise may affect the measurements in the presence of a cavity due to the applied intensity modulations, accurate measurements of the Brillouin gain profile are demonstrated. Furthermore, as both pump and probe are modulated at different frequencies, pump reflections occurring due to imperfect coupling conditions can be spectrally filtered out from the probe, unlike in direct pump intensity modulation. All these features make the method well-suited for measurements of low Brillouin frequency shifts (< 1 GHz) or, in general, in any scheme in which short samples are under test.

2. Proposed method: working principle and experimental setup

The working principle of our proposed method is based on the experimental setup shown in Fig. 1. It consists of two distributed feedback (DFB) lasers with 1 MHz linewidth, which are used to generate the probe signal and pump signal, respectively. Using injection locking, the pump laser frequency is locked at an optical frequency 6 GHz higher than the probe, thereby ensuring that the two lasers keep a stable frequency offset over time [18]. Each laser light is then intensity-modulated by Mach-Zehnder modulators (MZM) in a carrier-suppressed configuration with frequencies f_{ms} and $f_{mp} = f_{ms} - 30$ kHz respectively. The probe modulation frequency f_{ms} is set to 20 MHz, high enough to avoid any thermal modulation of the fiber under test (FUT) but low enough so that the signals' power can be considered uniform along the FUT. Another modulation at a frequency f_s is added on the pump by using a RF mixer to perform a spectral scanning. Then, the pump power is amplified to ~1 W thanks to an erbium-doped fiber amplifier (EDFA), followed by a 100 GHz bandwidth thin film filter (TFF) to broadly filter out the amplified spontaneous emission (ASE) noise. Both pump and probe's polarizations are adjusted by polarization controllers (PC) and launched into each end of the FUT. The probe is collected at the fiber output and filtered by a 5 GHz bandwidth fiber Bragg grating (FBG) to pre-filter potentially strong reflections from the high-intensity pump at the FUT end faces and prevent potential saturation of the detector. Probe light is detected by a photodetector, directly connected to a lock-in amplifier (LIA) and locked at the second harmonic of the frequency $f_{ms} - f_{mp}$ obtained by a RF mixer.

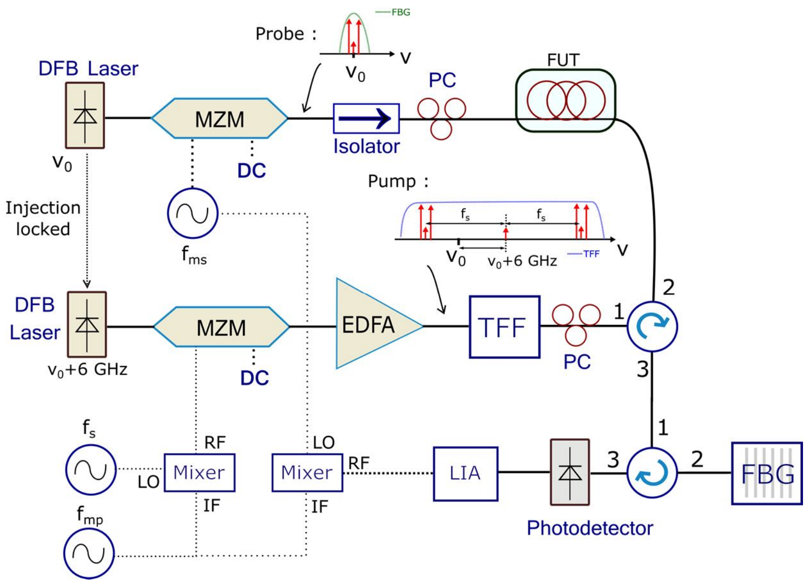

Fig. 1. Experimental setup to measure the Brillouin gain spectral response of very low gain systems. *RF: Radio Frequency, LO: Local Oscillator, IF: Intermediate frequency.*

Due to the carrier-suppressed configuration of the MZM, the frequency separation of the two probe and pump tones are $\tilde{f}_{mp} = 2 f_{mp}$ and $\tilde{f}_{ms} = 2 f_{ms}$ respectively. Therefore, by neglecting the carrier as well as higher order harmonics, the intensity-modulated pump and probe can be respectively approximated as:

$$\begin{aligned} P_P(t) &= \frac{P_{P0}}{2}\left[1+\sin\left(2\pi \tilde{f}_{mp} t + \varphi_P(t)\right)\right], \\ P_S(t) &= P_{S0}\left[1+\sin\left(2\pi \tilde{f}_{ms} t + \varphi_S(t)\right)\right], \end{aligned} \tag{1}$$

where P_{P0} and P_{S0} are the pump and probe average optical powers at the two ends of the FUT and $\varphi(t) = \varphi_P(t) - \varphi_S(t)$ is a slowly time-evolving arbitrarily phase shift caused by the free-running RF frequency sources. Due to the high stability of our RF sources, the temporal evolution of the phase difference is much slower than the signals period and can be neglected. The factor 1/2 in the pump expression is due to the fact that only one sideband of the scanning frequency modulation is used for the SBS interaction. In the following we assume that: (i) polarization controllers have been adjusted to match the polarizations of probe and pump, (ii) the short FUT has well defined linear birefringence axes and (iii) the scanning frequency is set, so that the pump and probe experience Brillouin gain. By considering the FUT's total length L (including circulator's patchcords), effective area A_{eff} and refractive index n, and by defining a z-axis oriented positively along the probe propagation inside the FUT, the stimulated Brillouin interaction reads [19]:

$$\frac{\partial P_S}{\partial z} = \tilde{g}_B P_P(z,t) P_S(z,t), \tag{2}$$

where $\tilde{g}_B = g_B / A_{eff}$ is the Brillouin gain in expressed in $m^{-1}W^{-1}$ and g_B, the intrinsic material Brillouin linear gain in mW^{-1}. Since the probe power is assumed low enough to avoid pump depletion and both pump and probe powers can be approximated to be uniform along the FUT: $P_P(z, t) \cong P_P(t)$ and $P_S(z, t) \cong P_S(t)$, the integration of Eq. (2) is straightforward and gives the probe power after SBS interaction:

$$P_S(t) = P_{S0} e^{G(t)L} \cong P_{S0}\left(1+G(t)L\right), \tag{3}$$

where the small gain approximation has been assumed. $G(t)$ contains the following frequency components: DC, $2f_{ms}$, $2f_{mp}$, $2(f_{ms} + f_{mp})$ and $2(f_{ms} - f_{mp})$. Since the lock-in detection is set at the second harmonic of the frequency difference, all the terms except the latter are filtered out. By only keeping the remaining term, we find:

$$G(t) = \frac{\tilde{g}_B P_{P0}}{4} \cos(2\pi f_D t + \varphi), \quad \text{where } f_D = 2(f_{ms} - f_{mp}). \tag{4}$$

Signal attenuation now needs to be taken into account. But since P_S depends on the product of pump and probe, only the total probe attenuation has to be considered. The probe signal then only depends on the probe average detection power at the photodetector. Finally, combining Eqs. (3) and (4) and multiplying by the photodetector's optical power-to-voltage conversion factor ρ yields to the lock-in voltage amplitude:

$$V = \rho \frac{\tilde{g}_B P_{P0} P_{S,d} L}{4}, \tag{5}$$

where $P_{S,d}$ is the probe's average power at detection. By knowing the FUT's effective area, the intrinsic Brillouin gain can be obtained by measuring the lock-in amplifier voltage amplitude. Note that the presence of intensity modulation for both pump and probe signals generates two pump-probe beatings at the Brillouin frequency plus/minus a frequency difference $f_D/2$. Thus, in order to limit gain distortion, f_D should be kept much smaller than the Brillouin gain width. In our experiments, f_D is set to 60 kHz.

3. Experimental results

A. High SNR single-mode optical fiber gain.

To evaluate the performance of the experimental setup, a 2.1 m segment of ITU G.652 single-mode optical fiber was used as FUT. The resulting Brillouin gain measurement are presented in Fig. 2. The measured peak voltage amplitude of the Brillouin gain is 5032.7±0.7 µV. By using the following parameters: P_{P0} = 250 mW, $P_{S,d}$ = 15.8 µW, ρ = 40 kV/W, A_{eff} = 80 µm^2, the peak Brillouin gain can be estimated to be 2.12×10^{-11} mW^{-1}. As pictured in Fig. 2, five higher order acoustic modes are also observed in addition to the main Brillouin peak. Since these modes present a very low overlap with the optical field, their amplitude is strongly reduced with respect to the fundamental mode. The Brillouin gain spectral profile has been measured over a 1.1 GHz frequency range, 1 MHz frequency step, 1.25 Hz lock-in amplifier equivalent noise bandwidth (ENBW) and a 14 minutes measurement time limited by the lock-in amplifier's time constant. The estimated standard deviation over 100 data points at frequencies above 11.5 GHz gives a noise of $\sigma_N \cong$ 668 nV, leading to a Brillouin gain SNR of 77.5 dB at the main resonance peak, calculated as the peak gain value over the noise standard deviation. The gain-length product value of the experimental setup is $\tilde{g}_B L < 7.6\times10^{-5}$ W^{-1}, corresponding to a minimum detectable peak gain of 1.7×10^{-5} Hz$^{-1/2}$, therefore allowing, for instance, gain measurement in an optical fiber or waveguide as short as one millimeter or longer fibers but with much reduced Brillouin gain. As for on-chip waveguides the effective area is usually much smaller than for optical fibers, the sensing capability would be further enhanced.

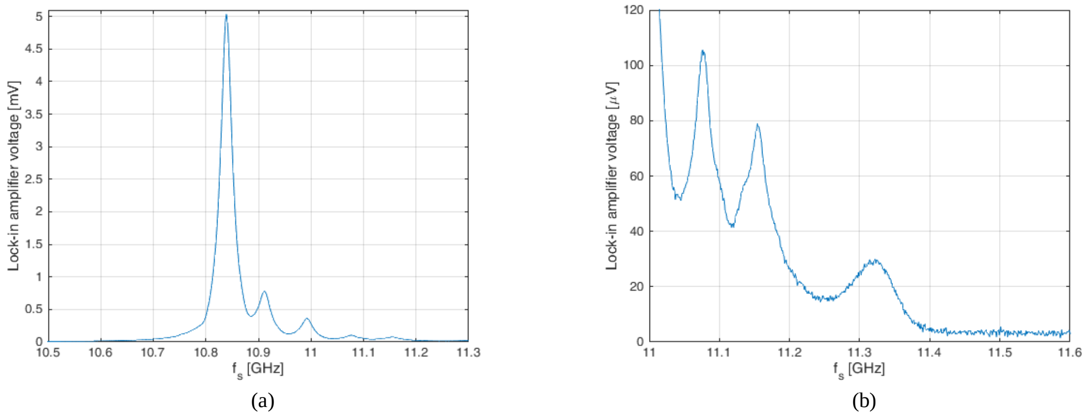

Fig 2. Measured Brillouin gain spectral profile of a 2.1 m single-mode optical fiber. (a) Full spectrum and (b) close-up view on 3rd to 5th higher order acoustic modes with visible noise level.

B. High numerical aperture (NA) fiber through a low-finesse cavity.

In order to challenge the measuring system and evaluate the SNR degradation due to the introduction of a cavity, the Brillouin gain profile of a 4 cm long high NA fiber in series with a 5 mm low-finesse cavity (finesse ≈ 1.5) has been measured. The cavity converts Kerr and thermal-induced phase noise into intensity noise, which degrades the sensor sensitivity. The Brillouin gain corresponding to the second-order acoustic mode of the high NA fiber is shown in Fig. 3. The peak Brillouin gain value of this second-order acoustic mode is 62×10^{-3} m^{-1}W^{-1}, roughly 25% of a standard single-mode fiber gain amplitude. The measurement parameters are the same as in the previous experiment. In this case, the measured noise standard deviation for 100 data points is now $\sigma_N \cong 2.8$ µV, leading to a SNR of 17 dB. As noticed, the presence of the cavity increases the noise standard deviation by a factor 4.

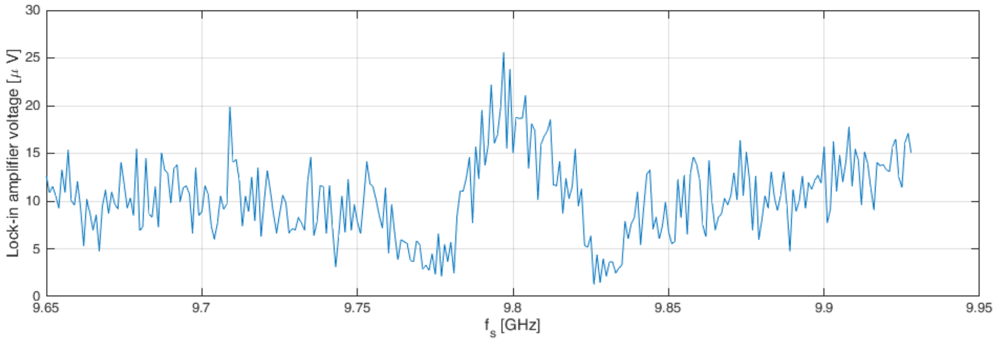

Fig. 3. Second acoustic mode of a 4 cm long high NA fiber in series with a low-finesse cavity.

4. Conclusion

We have proposed and experimentally demonstrated a novel pump-probe interrogation system with the capability to directly retrieve the spectral profile of a nonlinear interaction with a very high SNR. This system is capable of measuring Brillouin gains with a very high sensitivity, potentially enabling gain-length product as low as $\tilde{g}_B L < 7.6\times10^{-5}$ W^{-1} to be measured with unity SNR. The Brillouin gain of a 2.1 m single-mode optical fiber has been measured with an SNR exceeding 77 dB. The potentially degrading presence of a cavity, as frequently experienced in on-chip measurements, has also been tested. Results have shown that, although the strong phase-to-intensity noise induced by the cavity affects the measurements, performances are only degraded by a factor 4. This method can represent a powerful tool to measure effects not yet revealed, such as optoacoustic interactions in novel waveguide materials and even much weaker Brillouin gains as those observed in fluids.

5. Funding Information

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6. References

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