Self-Referenced Method to Measure Brillouin Gain Coefficient in Optical Fibers

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Abstract This paper presents a simple, original, self-referenced single-end method to measure accurately Brillouin Gain coefficient in optical fibers. Measurements performed on Corning SMF28 optical fiber confirmed theoretical description.

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Introduction

Stimulated Brillouin scattering (SBS) in optical fibers is a nonlinear effect that has been thoroughly investigated for many years [1]. For many applications, such as optical fiber communication systems or high-power fiber lasers, SBS effect induces optical power limitations. On the other hand, SBS effect can be advantageously exploited in numerous applications such as slow-light, Brillouin fiber ring lasers or distributed optical sensors. A precise knowledge of Brillouin gain coefficient g_B is required to determine the fiber sensitivity to SBS. A significant variation in g_B coefficient appears in literature. In this paper we present a new method to measure g_B with an accuracy of ~2% never reached until now to the best of our knowledge.

Overview of amplified spontaneous Brillouin scattering theory

When an incident wave (so-called pump wave at ν_0 frequency) propagates inside a long optical fiber (high total birefringence) following z-axis, the Stokes and anti-Stokes backscattered photon numbers (N_S and N_{AS}) can be determined as a function of frequency shift ν from the pump wave, by the following 2 equations (neglecting linear losses):

$$-\frac{dN_s(\nu_0-\nu)}{dz} = \frac{1}{2}\cdot g(\nu)\frac{P_p(z)}{A}N_s(\nu_0-\nu)+(1+\bar{n})\cdot\frac{1}{2}g(\nu)\frac{P_p(z)}{A}$$
$$-\frac{dN_{as}(\nu_0+\nu)}{dz} = -\frac{1}{2}\cdot g(\nu)\frac{P_p(z)}{A}N_{as}(\nu_0+\nu)+\bar{n}\cdot\frac{1}{2}g(\nu)\frac{P_p(z)}{A} \qquad (1)$$

where $g(\nu)$ is the Brillouin gain spectrum, P_p is the pump power and $\bar{n}$ the average thermal phonon number ($\bar{n}\approx 600$ at $\nu = 10$GHz). According to the theory related in [2], A is not the optical mode effective area but the acousto-optic coupling effective area (A computation can be found in [3]). Neglecting pump depletion, each equation leads respectively to an expression of Stokes and anti-Stokes photon numbers where L is the optical fiber length:

$$N_s(\nu_0-\nu) = (1+\bar{n})\left[\exp\left(\frac{1}{2}g(\nu)\frac{P_{p0}}{A}L\right)-1\right]$$
$$N_{As}(\nu_0+\nu) = \bar{n}\left[1-\exp\left(-\frac{1}{2}g(\nu)\frac{P_{p0}}{A}L\right)\right] \qquad (2)$$

Experimental set-up

A self-heterodyne detection is generally used for measurement of amplified spontaneous Brillouin scattering [4]. Unfortunately, the detected Stokes and anti-Stokes waves in the electrical domain are overlapped. Since $\bar{n} >> 1$, we could access to g_B which corresponds to the maximum of the Brillouin gain $g(\nu)$ from:

$$PSD_{elec}(\nu) = \gamma\cdot\left[N_s(\nu_0-\nu)+N_{As}(\nu_0+\nu)\right]$$
$$\approx 2\gamma\cdot\sinh\left[\frac{1}{2}g(\nu)\frac{P_{p0}}{A}L_{eff}\right] \qquad (3)$$

where γ is the transfer function gain of the experimental set-up (detector sensitivity, optical losses, etc.). However in that case, an accurate determination of g_B requires a precise estimation of γ parameter, which is difficult to evaluate.

To separate Stokes and anti-Stokes parts of the spectrum, we propose to add an acousto-optic frequency shifter in one arm of the heterodyne detection as shown in Figure 1. Since coherent detection is polarization dependant, a polarization scrambler is inserted in the LO path. Using a polarization controller in pump path, we have verified the pump polarisation doesn't affect measurement.

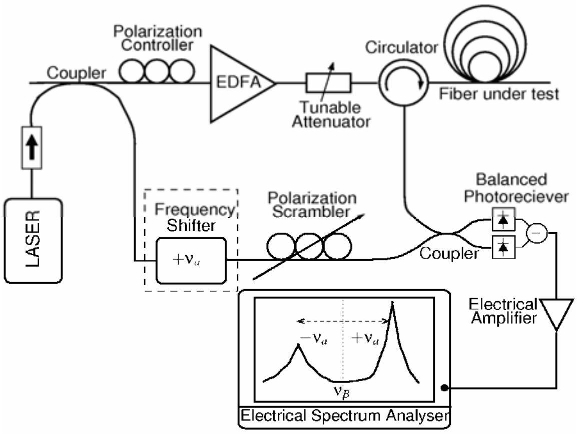

Figure 1: Experimental set-up for self-referenced Brillouin gain coefficient measurement (ν_B is the Brillouin frequency and ν_a the modulation frequency of the acousto-optic frequency shifter)

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As the frequency shift is $\nu_a = 111\text{MHz}$, Stokes and anti-Stokes spectra are separated in the electrical spectrum by an amount of $2 \cdot \nu_a = 222\text{MHz}$. Since Brillouin linewidth is about $\Delta\nu_B = 40\text{MHZ}$, we can consider them fully separated. So, it is possible to simultaneously evaluate the maxima of the Stokes and anti-Stokes power spectral densities. Unlike the previously evocated case leading to (3), we use the ratio between these 2 values:

$$\frac{PSD_{elec}(\nu_B + \nu_a)}{PSD_{elec}(\nu_B - \nu_a)} = \frac{N_s(\nu_0 - \nu_B)}{N_{As}(\nu_0 + \nu_B)} \approx \exp\left(\frac{1}{2} g_B \frac{P_{p0}}{A} L\right) \quad (4)$$

which is independent of the experimental set-up transfer function gain γ (parameter sensitive to the external conditions). It provides our method with a high degree of precision and a high reliability in g_B determination.

Experimental verification of the theory

To validate the proposed method, we used the previously exposed experimental set-up to determine the Brillouin gain coefficient at 1560 nm of a Corning SMF-28 fiber as accurately as possible. We used a 65m-long fiber span to perform that experiment.

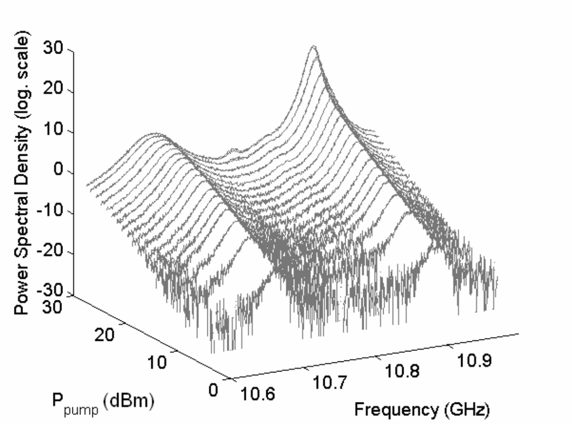

Figure 2: Measured electrical power spectral density of a SMF-28 (L=65m), for several pump powers. Stokes spectrum is the right part and anti-Stokes the left one.

As expected, the Stokes and anti-Stokes spectra appear separated by an amount of 222MHz in Figure 2. In addition, the measurements confirm the evolution of Stokes and anti-Stokes spectra as a function of pump power described in equations (2).

Deduction of the SMF-28 Brillouin gain coefficient

From curves of Figure 2, we extract the maximum values of Stokes and anti-Stokes PSDs using a peak detection method (here we used the theoretical equations (2) to fit measurements assuming $g(\nu)$ has a Lorentzian shape) to determine the ratio of these 2 PSDs at the Brillouin frequency shift. From measurements, we plot in Figure 3 the quantity:

$$Y = 2\frac{A}{L}\ln\left(\frac{PSD_{elec}(\nu_B + \nu_a)}{PSD_{elec}(\nu_B - \nu_a)}\right) \quad (5)$$

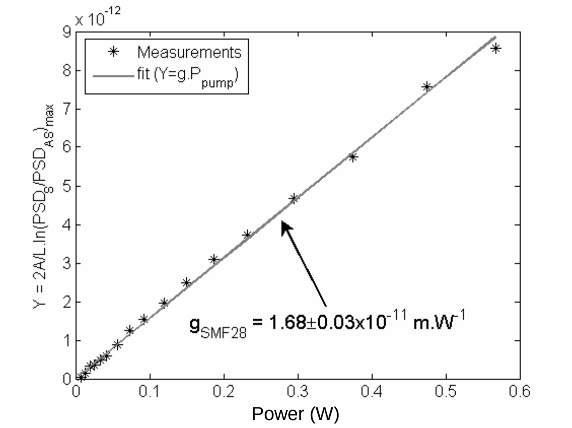

Figure 3: Y as a function of pump power. The slope gives directly g_B coefficient.

as a function of pump power. Y is clearly proportional to pump power via the Brillouin gain coefficient as predicted by relationship (4).

So for the Brillouin gain coefficient of SMF-28 fiber, we found a value of $g_B = 1.68 \times 10^{-11}\text{m.W}^{-1}$. Assuming we knew perfectly the fiber length (65m) and $A = 87\mu\text{m}^2$ (from [2]), the accuracy on that value is about 2%. Quite different results can be found in literature, from $g_B = 1.3 \times 10^{-11}\text{m.W}^{-1}$ [5] to $g_B = 2.6 \times 10^{-11}\text{m.W}^{-1}$ [6,7] measured using different techniques such as pump/probe methods or Brillouin linewidth evolution with pump power.

In addition to be self-referenced, and unlike previous methods, our technique requires only 2 PSDs measurements with different pump powers. Pump power ratios can be measured very simply with a coupler and an optical power meter placed between the attenuator and the circulator.

Conclusions

We proposed a new self-referenced single-end method to measure Brillouin gain coefficient g_B in optical fibers. In a Corning SMF-28 fiber, we evaluated this coefficient to be $g_B = 1.68 \times 10^{-11}\text{m.W}^{-1}$ with an uncertainty of 2%. The technique can be extended (with some precautions) to any type of single-mode fiber using a short span, typically small enough to neglect the fiber attenuation and the pump depletion (less than 1km).

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