Stimulated Brillouin scattering gain profile characterization by interaction between two narrow-linewidth optical sources

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Abstract: We report on results from the characterization of Stimulated Brillouin Scattering (SBS) spectra for standard single-mode fiber produced by the interaction between two counter-propagating tunable laser sources (TLS) using one as the probe signal to measure and the other as the pump, sweeping a wide span around the signal. Assuming TLS linewidth negligible against SBS gain bandwidth, we measure SBS spectrum for a wide range of pump and probe signal power levels and study the evolution of relevant SBS parameters such as linewidth and gain profile. High signal to noise ratio measurements allows analyzing the evolution of the SBS gain profile from Lorentzian to Gaussian as predicted by current theory of SBS and the use of SBS response for filtering applications.

OCIS codes: (060.4370) Nonlinear optics, fiber; (290.5900) Scattering, stimulated Brillouin

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1. Introduction

Stimulated Brillouin Scattering (SBS) is the dominant nonlinear effect in optical lightwave systems for narrow linewidth optical sources and has been extensively studied in optical fiber

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communications in recent years [1-3]. SBS can limit the performance of optical communication systems due to the reflection of part of the power propagating along a fiber into a backward Stokes wave shifted in frequency.

Despite SBS may be a drawback for optical communications systems [4], it is also being used in some applications such as optical sensing [5] or optical filtering [6]. In this paper, we will focus on the analysis of the spectrum given by SBS when using a light source narrower than the SBS linewidth as a pump to amplify a narrow-linewidth counter-propagating signal.

The gain spectrum of the SBS in optical fibers is supposed to have a Lorentzian shape [7]. Nevertheless, recent works, using the noise source model by Boyd [8] have theoretically deduced a more complicated spectral shape of the backscattered Stokes light produced by the SBS [1]. The cited spectral shape is a Lorentzian in the low gain limit and becomes Gaussian in the high gain limit. This is an important result for applications of SBS such as optical filtering and to our knowledge, there is no experimental verification of this theoretical prediction, since measurements with high signal to noise ratio are required for good differentiation between Lorentzian and Gaussian profiles and the transition between them. In this paper, different measurements of the shape of the spectrum of the SBS effect are performed involving different optical power levels of the stimulating signal, considering that the pump and probe signals have much narrower linewidth than the measured effect.

2. Experimental setup

We use the setup shown in Fig. 1. A Tunable Laser Source (TLS) is amplified and injected into a spool of about 2 km of single-mode optical fiber. Another TLS, tuned at a fixed wavelength, is used as the Signal Under Test (SUT). The scanning TLS scans the wavelengths around the SUT, in such a way that the SBS is produced only when the two wavelengths are within the interaction range of the SBS. The signal produced by the SBS is analyzed by an InGaAs detector and acquired and processed by a PC. We can assume that the linewidths of both TLSs used can be neglected, as they are below 100 kHz from specifications, compared with the bandwidth of the SBS, which ranges typically from 10 to 30 MHz in literature. With this assumption we can consider the SUT as a spectral line for the measurements.

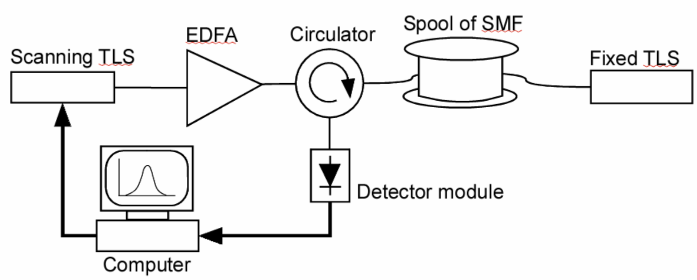

Fig. 1. Experimental setup to perform SBS spectrum measurements. A narrow linewidth TLS is used as the scanning probe.

The set-up also includes an optical amplifier to achieve the relative high pump powers studied by Yeniay et al. [1]. The main difference with the experimental set-up of [1] is that in our set-up the stimulated Brillouin amplification of an external signal is measured, instead of the signal generated by spontaneous Brillouin emission. The Erbium Doped Fiber Amplifier used for the measurements provides a maximum output power of 20.5 dBm and has been used at fixed output power mode for several output power values from 7 dBm to 20.5 dBm. The scanning TLS provides an output power of 2 dBm at the set of wavelengths under study and the fixed probe signal TLS provides a maximum output power of 6 dBm. In order to achieve good resolution for the measurements, the scanning TLS is set to make a continuous sweep at 500 pm/s and, after a relatively narrow bandwidth detector (~10MHz), signal is acquired by a fast data acquisition card (DAQ) obtaining an effective sampling step of around 300 kHz.

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Precise characterization of the SBS gain profile is difficult due to all non linear responses of the set-up and the SBS itself which saturates at high pumping optical powers. In fact, pump depletion occurring close after the pump reaches the Brillouin threshold level avoids from checking the analytical solutions of the SBS gain profile found by Yeniay et al. and is the reason attributed by the cited authors to explain divergences between the experimental results and the theoretical predictions. In this paper our goal is to provide high signal to noise ratio SBS gain profiles in the linear regime, in order to check the SBS gain profile and to explore the applications of SBS for filtering applications.

SBS gain spectrum is described, in the low gain limit [1], by a Lorentzian shape [7]:

$$g_B(\delta\nu') = g_0 \frac{(\Delta\nu_B/2)^2}{(\delta\nu)^2 + (\Delta\nu_B/2)^2} \tag{1}$$

with $\delta\nu' = \nu - \nu_p - \nu_D$, where ν_p is the pump frequency, ν_D is the Doppler frequency shift and $\Delta\nu_B$ is the bandwidth (FWHM) of the Brillouin gain spectrum and g_0 is the peak gain.

The backscattered Stokes field detected by our set-up ($P_{det}(\nu_s,\nu_p,\nu_D$) depends on the relative frequencies of the pump, signal and Doppler shift. In the linear regime and considering that the optical spectrum of the pump signal is around two orders of magnitude narrower than the expected bandwidth of the SBS effect, the detected backscattered Stokes signal can be described by:

$$P_{\det}(\nu_p,\nu_s,\nu_D) = \int g_B(\nu - \nu_p - \nu_D) P_s(\nu) d\nu \tag{2}$$

That is, the convolution of the Brillouin gain profile and the optical signal to be measured, shifted in frequency by the Doppler shift:

$$P_{\det}(\nu_p,\nu_s,\nu_D) = \{g_B * P_s\}(\nu_p + \nu_D) \tag{3}$$

In our set-up, P_s has an optical spectra nearly two orders of magnitude narrower than $\Delta\nu_B$, so that it can be approximated to a delta function $P_0 \cdot \delta(\nu - \nu_s)$ and consequently:

$$P_{\det}(\nu_p,\nu_s,\nu_D) = P_0 g_B(\nu_s - \nu_p - \nu_D) \tag{4}$$

As ν_D is a constant value, varying the wavelength difference between the pump and the signal it is possible to obtain a direct measurement of the Brillouin gain profile as $g_B(\delta\nu')$ where $\delta\nu' = \nu_s - \nu_p - \nu_D$..

3. Results and discussion

Pump depletion, and consequently gain saturation, is observed after reaching Brillouin threshold. The observed Brillouin spectrum is then much more complicated and the analytical solution obtained by Yeniay el al. under un-depleted conditions is no longer valid. This situation produces a deformation of the detected gain profile, because outside the linear regime, the convolution between the Brillouin gain profile and the sample signal no longer fulfills the convolution properties. More precisely the homogeneity condition: $(a \cdot f) * g = a \cdot (f * g)$, where a is an scalar and f and g are the convoluted functions, is not verified. Ideally, measurements using a very low signal level or using fibers with very low losses would reproduce the required conditions. Alternatively precise correction over the output power spectrum must be made in order to get valid information of the convolution between the SBS spectrum and the measured signal spectrum.

With this in mind, we can obtain two different spectral shapes for SBS and consequently two different full-width at half-maximum (FWHM) values: the first one calculated directly affected by gain saturation, and the other calculated from the normalized response, guaranteeing linearity by applying a conversion function to the measured power values so that

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they correspond with those of the input signal. SBS linewidth dependence with the pump power is shown in Fig. 2. When saturation is present (up from 10 dBm), if FWHM is measured directly, it broadens as the pump power increases (as reported in [2]), whereas for the linearized signal, SBS linewidth decreases..

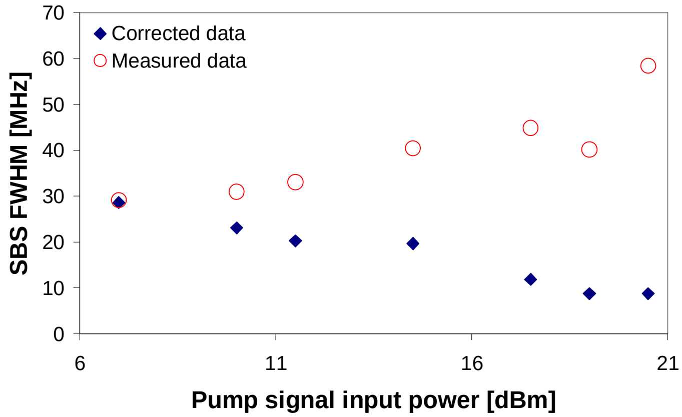

Fig. 2. Evolution of the SBS filter bandwidth againts pump signal power measured directly and after normalization.

Previous studies of the Brillouin Scattering [1] show that the shape of the SBS spectrum varies depending on the gain. Theoretically, it has a Lorentzian shape in the low gain region and a gaussian shape in the high gain limit. This Gaussian functional form in the SBS gain profile could not be proved experimentally at high powers in [1]. This is due to the fact that the spectrum actually reflected by SBS, without linearizing the response, and for the higher optical pumps, is different than the actual spectrum of g_B. Therefore, the shape measured when using high pump power is not gaussian (Fig. 3a) and its FWHM linewidth is different from that obtained with a linearized response. In Fig. 3b the normalized SBS power response using our set-up is shown, and under linear behaviour the shape is confirmed to be gaussian. Lorentzian shape for low powers remains very similar as gain saturation is almost negligible.

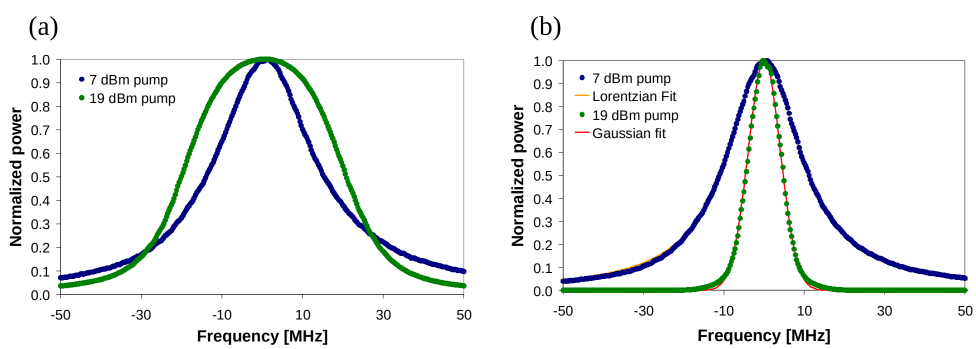

Fig. 3. SBS response for low (7dBm) and high (19dBm) pump powers measured with 0 dBm SUT power. (a) Direct measurements (b) Measurements after linearization and fitting for 7 dBm pump power to a lorentzian function and for 19 dBm to gaussian function.

As mentioned before, these spectral shapes should remain the same for any power level of the TLS used as SUT, so if we use very low input powers so that depletion of the pump does not occur, same shapes as those in Fig. 3b should be observed, but with a poor signal-to-noise ratio. Measurement with high pump power and low SUT power were carried out resulting in Fig. 4

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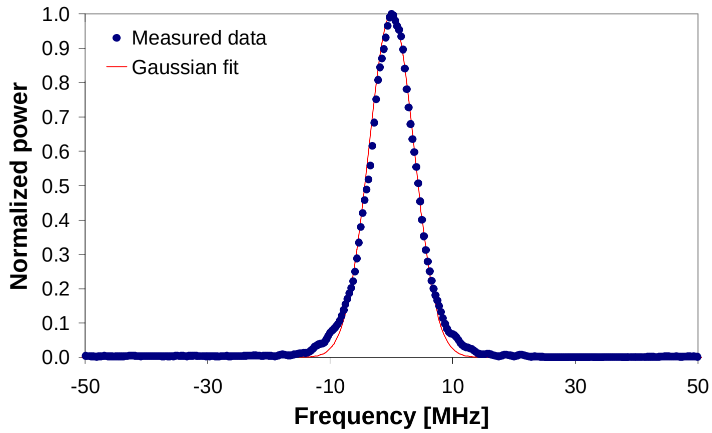

Fig. 4. Measured power response without linearization for 19 dBm pump power with very low SUT power (-45dBm) and fitting curve to a gaussian function.

Good accordance with the theoretical results proposed in [1] is achieved. Nevertheless, in the intermediate gain region, the SBS spectral shape does not fit well none of these proposed functions, as shown in Fig. 5. An evolution in the spectral shape can be noticed: as pump signal power increases, the decay in the flanks becomes sharper, reaching the gaussian decay rate for high pump power values.

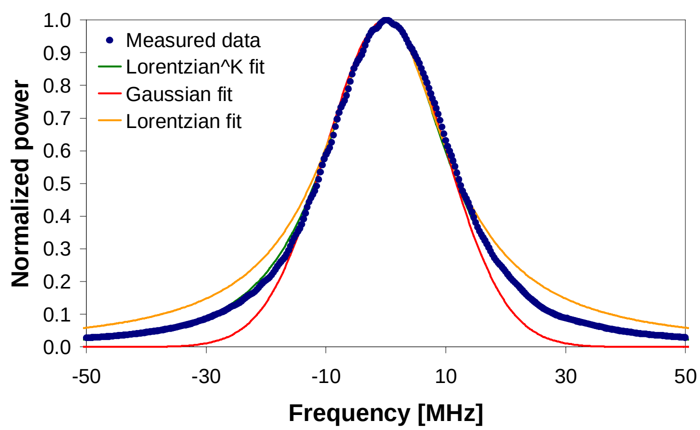

Fig. 5. Fitting for normalized SBS power response with signal probe input power 11.5 dBm fitting with k=1.6

We propose a mathemathical model to describe this evolution with good results. We will apply a fitting of the normalized SBS spectrum to a lorentzian function to the power of a variable value *k*. Results are shown in Fig. 6. When *k* equals 1 we have a regular lorentzian function, whereas for high *k* values, the shape tends to a gaussian function. We express lorentzian and gaussian functions in terms of linewidth and normalize so that the center value is always 1. Both expressions and their relation are summarized in the next equation.

$$\lim_{k\to\infty}\left[\left(\frac{\Delta\nu_B}{2\sqrt{2^{1/k}-1}}\right)^2 \Big/ \left\{\left(\frac{\Delta\nu_B}{2\sqrt{2^{1/k}-1}}\right)^2+(\nu-\nu_0)^2\right\}\right]^k = \exp\left[-(\nu-\nu_0)^2 \Big/ 2\left(\frac{\Delta\nu_B}{2\sqrt{2\ln 2}}\right)^2\right] \quad (5)$$

where $\Delta\nu_B$ is the Brillouin linewidth, ν_0 is the central optical frequency of the input signal and k is the exponent value in our model. The left side of the equation stands for the lorentzian function to the power of k and the right side, for the gaussian function, both with $\Delta\nu_B$ MHz linewidth. For high values of k (over 10), shape is considered gaussian with good accuracy.

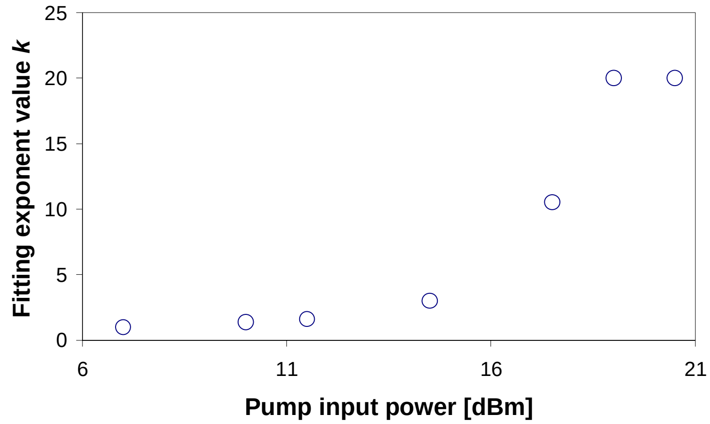

Fig. 6. Values for k obtained from fitting to Eq. 5.

According to these results, the shape of the function $g_B(\nu\text{-}\nu_p\text{-}\nu_B)$ and, accordingly, the quality of the SBS as a filtering effect, is highly dependent on the optical power of the pumping probe. It happens in such a way that if the obtained response is linearized to get rid of the non-linear gain of the SBS effect at high optical powers, a filter with a bandwidth as narrow as 8.7 MHz and with Gaussian profile can be obtained. This Gaussian shape allows a rejection ratio of ±30 MHz at -40dB, as can be seen in Fig. 7 where measurements were performed with 19 dBm pump optical power. Notwithstanding, if the filtering effect of the SBS is used without linearizing its response, the shape and linewidth of the filter is not defined, as it depends of the actual optical power involved in the experiment.

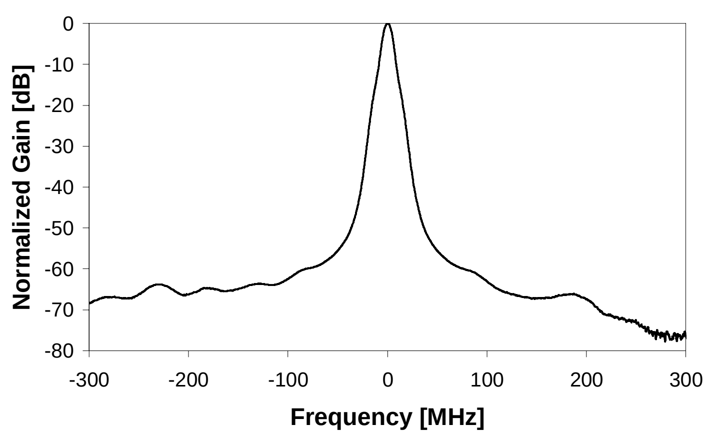

Fig. 7. Representation of the normalized gain of the SBS spectrum for a pump power of 19 dBm. Secondary modes appear below -60 dBm [9]

4. Conclussions

Characterization of the SBS spectrum has been performed. Evaluation of bandwidth and shape has been done over a wide range of pump power levels, obtaining a model to describe the transition of the SBS spectral shape from the low gain region to the high gain limits where saturation has a great influence over the process.

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