Measurement of the Temperature Coefficient for the Brillouin Frequency Shift in an Optical Fiber

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Abstract

The temperature dependence of the Brillouin frequency shift in an optical fiber is used as a way to implement fiber optic distributed temperature sensors. This work presents a simple experimental setup to characterize this linear relation. The measured temperature coefficient for the Brillouin frequency shift was 1,54 Mhz/^{o}C, which agrees with literature measurements for single mode silica fibers. (FAPESP 00/09731-8)

Introduction

The stimulated Brillouin scattering, SBS, has been studied as a powerful tool to the development of fiber optic distributed sensors since 1990 [1]. This nonlinear optical effect has intrinsic characteristics that make possible the measurement of the temperature and the strain profiles distributed over the sensor fiber length. In fact, SBS distributed sensors demonstrated measurements resolutions as good as 20$\mu\varepsilon$ and 2^{o}C, with a 5m spatial resolution over a 22Km sensor fiber length [2]. As result, SBS distributed sensors are ideal candidates to implement structure health monitoring systems to large structures as bridges, pipelines, dams, etc.

One of the steps needed to develop Brillouin distributed sensors is the characterization of the thermal and mechanical dependences of the SBS. This communication presents a simple experimental setup to measure the Brillouin frequency shift as a function of temperature. However the same method could also be exploited to measure the strain dependence of the Brillouin effect.

Brief Theory

The stimulated Brillouin scattering can be described as a parametric interaction between two counter propagating optical fields, and an acoustic field. Through the electrostriction effect, the two optical fields interact causing the appearance of an acoustic field in the optical fiber. This traveling acoustic wave spatially modulates the refraction index along the optical fields propagation direction, this modulation induces the coupling between the two optical fields. As a major consequence, it is observed the amplification of one of the optical field in detrimental to the depletion of the other [3,4].

The two optical fields are detuned in frequency, what is a direct consequence of the momentum and energy conservation laws. The higher energy field is called as the pump field and the lower one as the Stokes filed. In a quantum mechanical description, the annihilation of a pump photon creates a Stokes photon and an acoustic phonon (if no energy is absorbed by the medium).

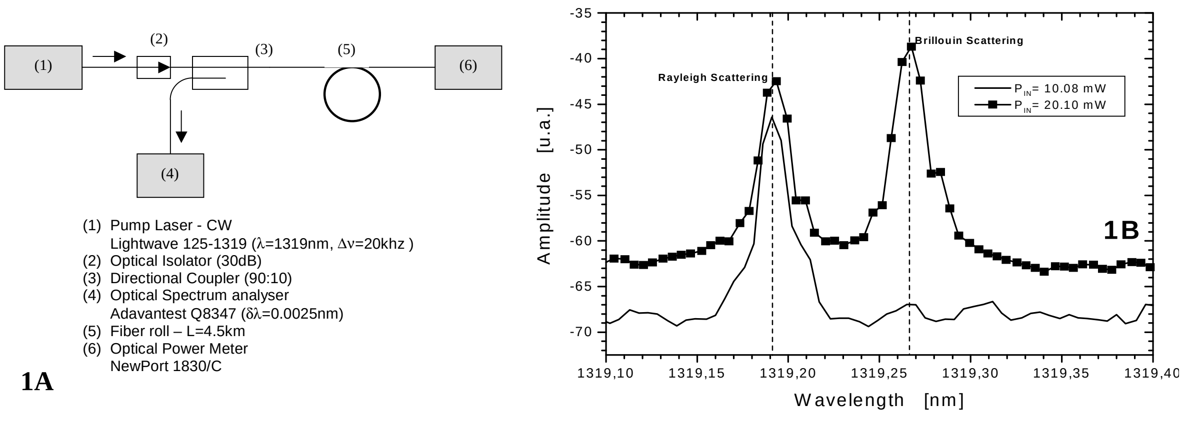

Fig. 1: (a) Simple setup to observe the SBS, and (b) optical spectrum of the spontaneous Brillouin scattering [5].

The simple experimental setup presented in figure 1a could be used to observe the spectral characteristics of the scattered light due to the spontaneous Brillouin effect in optical fibers. Figure 1b shows the returning spectra for pump powers equal and higher than the Brillouin threshold (*~10mW* for a *4,5km* long optical fiber). The spectral shift between the pump and the Stokes components is the Brillouin frequency shift, f_{DB}, and was measured as *12,756GHz* (*0.074nm@1,32μm*). Theory predicts that

$$f_{DB} = \frac{nv_A}{c}(f_P + f_S) \tag{1}$$

where f_P an f_S are respectively the pump and Stokes power, n is the fiber's core refraction index and v_A is the core fiber speed of sound [3,4]. Using f_{DB} we could estimate v_A as *5,76km/s* which is in good agreement to literature values (*~5,97km/s* for single mode silica fibers) [3,4].

Although both the refraction index and the sound speed depend on local temperature and local mechanical deformation, the second one is more sensitive to these parameters than the first. This occurs because of the explicit relationship between density and sound velocity.

The measurements of the temperature coefficient for the Brillouin frequency shift showed that f_{DB} linearly depends on temperature, so that

$$f_{DB}(T) = f_{DB}(T_{ref}) + C_T(T - T_{ref}) \tag{2}$$

where T_{ref} is a reference temperature and C_T is the temperature coefficient of the Brillouin frequency shift (*~1,3MHz/°C*) [2].

In a stimulated situation, where two counter-propagating lasers are used to generate the interacting pump and Stokes optical beams, it is observed a simultaneous amplification of the Stokes beam and a depletion of the pump beam when the frequency difference between the two fields are close to f_{DB}. For dynamic situations, where the transients are longer than 16ns, a system of two coupled nonlinear partial differential equations describes the spatial and temporal behavior of the two optical fields,

$$\frac{\partial I_S}{\partial z} - \frac{n}{c}\frac{\partial I_S}{\partial t} = -g_b I_P I_S + \alpha I_S \qquad \frac{\partial I_P}{\partial z} + \frac{n}{c}\frac{\partial I_P}{\partial t} = -g_b I_S I_P - \alpha I_P \tag{3}$$

where, I_P and I_S are respectively the pump and Stokes intensities, g_b is the Brillouin gain, α is the optical absorption coefficient and c is the speed of light [3]. A classical theoretical approach permits to demonstrate that the Brillouin gain, g_b, can be well described as lorentzian distribution,

$$g_b = \left(\frac{\Delta f_{g_b}}{2}\right)^2 \frac{1}{[(f_P - f_S) - f_{DB}]^2 + \left(\frac{\Delta f_{g_b}}{2}\right)^2} g_b^{max} \tag{4}$$

where Δf_{gb} (*~60MHz*) is the Brillouin gain width and g_b^{max}(*~5x10⁻¹¹m/W*) is the modulus of the maximum Brillouin gain [3,4].

Using a tunable laser as a pump, or a Stokes field source, it is possible to observe the amplification spectrum of the Stokes field as consequence of the g_b dependence with f_{DB}. Then, having two identical fibers subjected to different known temperatures, and measuring the spectrum profile of the Stokes field amplification in both fibers (simultaneously), one can observe that the maximum points are not the same (just because of the temperature dependence of f_{DB}). As conclusion, varying the temperature step between the two fibers and measuring the difference between the two maximum points, makes possible the determination of C_T in the equation (2).

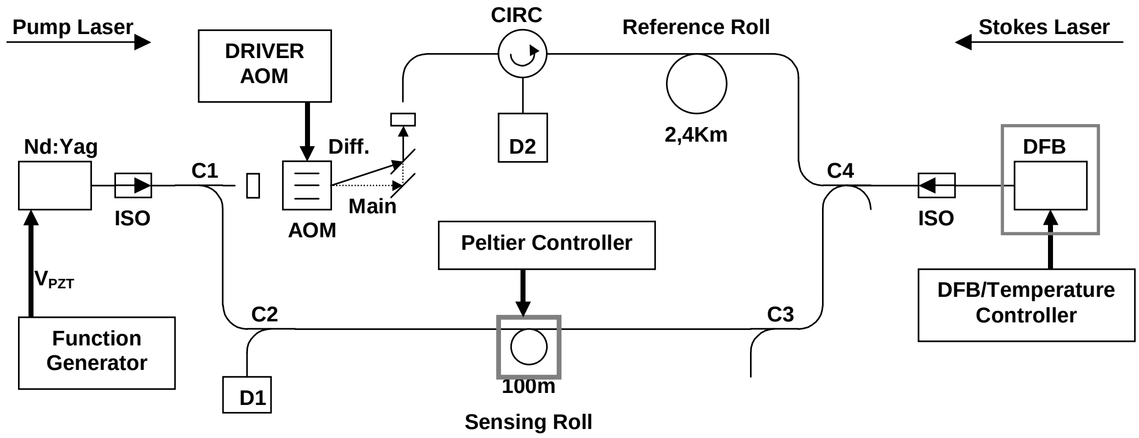

Fig. 2: Experimental setup

Experimental Setup

The experimental setup is shown in figure 2. The pump laser is a tunable NPOR Nd:Yag laser (Ligthwave 125-1319-150 – NPOR stands for Non Planar Optical Ring) and the Stokes laser is an DFB diode laser (Newport LD-1310-21B) mounted in a temperature stabilized mount. The optical isolators are used to prevent reverberation inside the lasers cavities. Both lasers operate in the *1319nm* region.

The sensing roll is temperature stabilized using a thermoelectric cooler. The reference roll is subjected to the laboratory temperature, which was measured during all the experiment and showed itself constant around 21^oC. Both fiber rolls are sections from the same fiber cable, so the fiber's properties are the same in both rolls. However, some differences were expected as consequence of the rolling process strain for which the sensing fiber was subjected.

The reference roll was *2.4km* long and the sensing roll length was *100m*. As was pointed before, the idea is to do a scan in the optical frequency difference between pump and Stokes laser sources. The DFB laser frequency was constant during the measurements. The pump laser frequency was tuned using a triangular voltage signal applied to a PZT which deforms the laser NPOR cavity, undergoing an optical frequency variation linearly proportional to the applied voltage signal. An optical circulator was used to observe the Stokes amplification in the reference roll through D2. The directional coupler C2 was used to observe the Stokes amplification in the sensing roll through D1. Common optical power detectors were used in the measurements.

An acoustic optical modulator (Intraaction 40N) was used to intentionally up shift the pump laser frequency being coupled to the reference roll (coupling the AOM diffracted beam). As we will see in the results section, this was done as a way to have a frequency reference (the AOM frequency shift is very stable, and equal to *40MHz*) when measuring the relation between the pump laser frequency changes with the applied voltage to its PZT.

Results and Discussions

This discussion starts showing how it was measured the tuning coefficient for the pump laser. Looking for equation (1) is easy to see that the maximum Brillouin gain occurs when $(f_P - f_S) - f_{DB}(T) = 0$. For the reference fiber roll there are two different situations,

$$f_P^A = f_{DB}(T_{REF}) + f_S \text{ and } f_P^B = f_{DB}(T_{REF}) + f_S + \delta f_{AOM} \tag{5}$$

where T_{REF} is the temperature of the reference fiber and δf_{AOM} is the frequency shift induced in the pump beam by the AOM. Similarly, for the sensing fiber roll,

$$f_P^S = f_{DB}(T_{SENS}) + f_S \tag{6}$$

where T_{SENS} is the temperature of the sensing fiber. The pump laser frequency has a linear dependence with the applied voltage to the PZT, which is attached to the Nd:Yag NPOR cavity, so that,

$$f_P(V_{PZT}) = f_{P0} + C_P V_{PZT} \tag{7}$$

Using (5) and (7) it is possible to show that,

$$\delta f_{AOM} = C_P\left(V_{PZT}^B - V_{PZT}^A\right) \tag{8}$$

where V_{PZT}^A and V_{PZT}^B satisfy (5). In other words they are the correspondent voltages for the maximums of the Stokes power amplification spectrum in the reference fiber. To determine this peak position, a modified Lorentz distribution was used to fit the acquired spectrums,

$$L(x) \sim h_0 + a_0 \frac{d^2}{\left[p(x-x_0) + m(x-x_0)^2 + n(x-x_0)^3\right]^2 + d^2} \tag{9}$$

Figure 3a presents the amplified Stokes power as function of the tuning voltage applied to the pump laser with and without the use of the AOM to shift the frequency of the pump beam inserted in the reference roll. The applied PZT voltage was a triangular wave with *100Hz* and *10V* of amplitude. The sensing roll temperature was $23,55^oC$ and the reference temperature was 21^oC. The presence of the *40MHz* frequency shift dislocates the reference roll peak position to a positive direction by an amount equal to 8,31V. This measurement allowed the estimation of the tuning coefficient, C_P, as *4,81MHz/V*.

The peak position of the Stokes amplification spectrum is related to Brillouin shift, f_{DB}, and has a temperature dependence given by (2), which used with (6) and (7) makes possible to show that,

$$\Delta f_{DB} = f_{DB}(T_{SENS}) - f_{DB}(T_{REF}) \propto C_T(T_{SENS} - T_{REF}) = C_P\left(V_{PZT}^S - V_{PZT}^{A/B}\right) \tag{10}$$

it must be observed that the constant terms where removed without any debt to linear relation presented.

Figure 3b shows presents the relation between the measured voltage distance between V_{PZT}^{S} e V_{PZT}^{B} and the temperature difference between the reference and sensing fibers. These points were taken shifting the frequency of the pump beam using the AOM just as described before. The measured data shows the expected linear relation of (10). The measured temperature coefficient for the Brillouin frequency shift, C_T, was *1,54MHz/°C*, in good agreement with literature measurements around *1,3MHz/°C* for singlemode silica fibers [2].

As a last observation, the intermittent line in figure 3b shows the position of the fitted curve for the non-shifted pump beam case. At *21°C* the fiber rolls are with the same temperature, in theory the peaks positions had to be the same (because f_{DB} is the same in both fibers), however, a difference of *37,9MHz* (*~7,88V*) was observed. This large difference was primarily caused as consequence of the induced strain when rolling the sensing fiber. In fact, the same experimental procedure can be also used to measure the strain coefficient for the Brillouin frequency shift. In this case, a known strain must be applied to the sensing fiber while the reference fiber is maintained undisturbed.

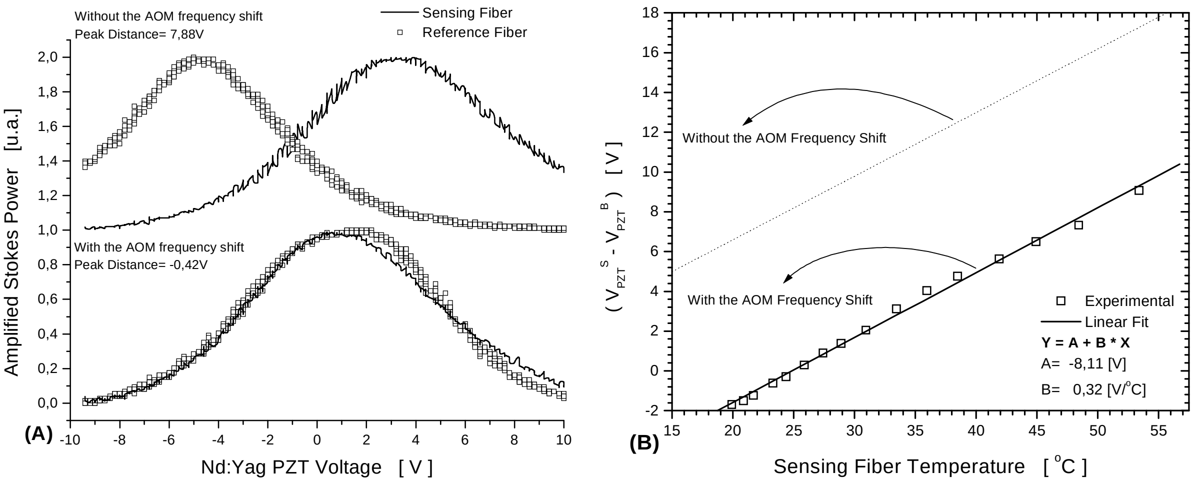

Figura 3: Experimental Results.

Conclusions

The linear relation between the Brillouin frequency shift and the fiber temperature was measured using a simple experimental setup. The measured temperature coefficient of *1,54MHz/°C* is in agreement with the literature results for singlemode silica fibers. Future work will deal with the determination of the strain coefficient for Brillouin frequency shift, and to study how temperature induces a variation in the Brillouin gain (which defines the maximum power of the amplified Stokes power spectrum). The presented results are part of the authors' research efforts to develop a distributed temperature/strain sensor using the SBS in optical fibers.

References

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