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Stimulated Brillouin scattering as the referencing mechanism of an optical fibre intensity sensor

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Abstract

An optical fibre intensity sensor referenced by stimulated Brillouin scattering is presented. The optical sensor uses Fresnel reflection signal at the sensor fibre end and employs an adequate relationship between Brillouin and Rayleigh scattering and Fresnel reflection to have a referenced optical fibre intensity sensor addressed in reflection.

Keywords: Stimulated Brillouin scattering; Optical fibre sensors

1. Introduction

In optical fibre communications the stimulated Brillouin scattering (SBS) is the first nonlinear effect to appear when optical power is raised [1]. In SBS, the pump wave, by electrostriction, creates a travelling sound wave inside the optical fibre. This acoustical wave causes a weak modulation of the refractive index, forming a moving grating. The grating reflects part of the pump wave backwards with a down shift in frequency due to the motion of the grating. Once the threshold of SBS is exceeded, a rapidly increasing percentage of the power launched into the fibre is reflected back towards the transmitter. The threshold for the onset of the SBS can be as low as few milliwatts for some systems, being dependent on the input power and on length of the interaction [2,3].

The nonlinear Brillouin effect can be used for distributed optical fibre sensing [4]. Several authors proposed different configurations to measure strain and/or temperature using the SBS effect [5–7]. A possible solution and proposed by Wait et al. [8] uses Landau Placzek ratio method, which is based on the relationship between the Rayleigh and Brillouin signals.

On the other hand, optical fibre intensity sensors are very attractive since they are conceptually simple. However, to ensure accurate measurements by the optical fibre intensity sensors, the implementation of a reference channel is necessary. Such a channel should provide insensitivity to source intensity fluctuations and to variable optical transmission losses in the fibre link, couplers and connectors, which are often indistinguishable from transducer caused effects [9].

In this work, we use an adequate relationship between Brillouin and Rayleigh scattering and Fresnel reflection to have a referenced optical fibre intensity sensor addressed in reflection. In other words, the Brillouin curve is multiplied by a correction factor in order to have the same slope as the Rayleigh + Fresnel curve. Two optical attenuators were used, one to simulate optical input fluctuations and the other one to introduce loss in sensing zone.

2. Experimental setup

The experimental setup is shown in Fig. 1. A DFB diode laser, with maximum power of 50 mW and central wavelength $\lambda_c = 1554.15$ nm is used. It is followed by an Erbium

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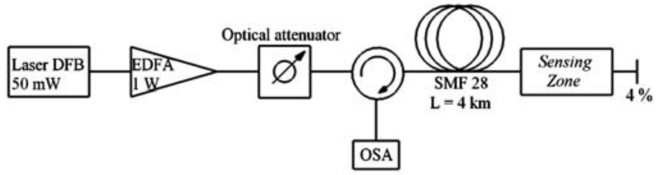

Fig. 1. Experimental setup of the optical fibre intensity sensor referenced by stimulated Brillouin scattering.

Doped Fiber Amplifier (EDFA), IPG laser model EAD-1 K-C3-W, of 1 W of maximum amplification. To simulate optical fluctuations of the optical source, an optical attenuator (Hewlett Packard 8156A) is inserted between the EDFA and the optical circulator. A standard single mode fibre roll, SMF 28, with length $L = 4$ km is used. The far end of the fibre is cleaved inducing the corresponding Fresnel reflection of ≈4%. The Brillouin and the Rayleigh scattering and Fresnel reflection signals are collected by an Optical Spectrum Analyser (OSA) through the optical circulator. The sensing head is implemented by a JDS Fitel VA4 Series optical attenuator, and it is placed at the end of length L, just before the cleaved fibre end, in order not to affect the generation of the stimulated Brillouin scattering. This attenuator emulates the sensing head. In a real application we could have a variety of physical parameters to be measured, as long as the variation of those physical parameters, through their specific sensing heads, could induce variation in terms of optical intensity. For instance, this sensor could be a pressure sensor using a microbending sensing head [10].

3. Experimental results

Fig. 2 presents the spectral response of the implemented setup for two distinct cases. One for low loss in the sensing head, where the Rayleigh + Fresnel peak is at its maximum, and the other case for high loss in the sensing head where the contribution of the Fresnel reflection is not present. The Brillouin peak power is downshifted from the pumping wave of approximately 11.7 GHz [11].

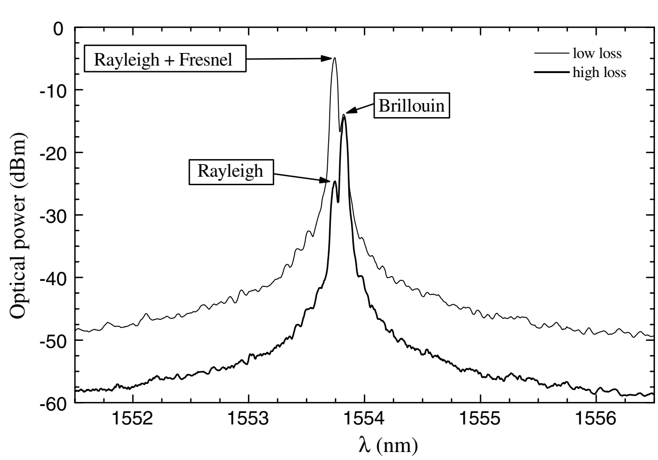

Fig. 2. Spectral response of the implemented setup for two distinct cases: low loss and high loss.

When there was no Fresnel reflection, the power associated to the Rayleigh + Fresnel peak that reaches the OSA is reduced, but the power of the Brillouin peak remains the same for the two situations. This is because the Brillouin signal depends only on the input power and on the interaction length of the optical fibre and since the sensing head is located at the end of the interaction length, it will not affect the Brillouin signal. Therefore, in principle, we can have an intensity sensor referenced by the Brillouin signal. From the graphic, the possible dynamic range of this intensity sensor is 19.75 dB, and it is measured between the maximum and the minimum of the Rayleigh + Fresnel peak as showed in Fig. 2. The lower limit of the dynamic range is due to the Rayleigh scattering, while the upper limit can be raised by increasing the reflection of the fibre end, which can be accomplished by silvering the fibre end.

In order to demonstrate the possibility of this sensor to be referenced, optical loss was applied just right after the optical source to simulate optical source fluctuations. Figs. 3 and 4 illustrate the linear and normalized response (S_{out}) of the optical power of both Rayleigh + Fresnel and Brillouin, as function of the optical input attenuation, respectively.

On the other hand, Fig. 5 presents the subtraction of $P_{Brillouin}$ from $P_{Rayleigh+Fresnel}$ expressed in dBs as function of the sensing head loss, for different optical input losses (0, 0.5 and 1 dB respectively). As it can be seen, the sensor is not referenced and this is due to different slopes of the curves of Fig. 4.

Analytically, we can say that the linear equations of Brillouin and Rayleigh + Fresnel can be written as

$$\begin{aligned} s_{R+F} &= -m_{R+F} \cdot \alpha_{R+F} \\ s_B &= -m_B \cdot \alpha_B \end{aligned} \tag{1}$$

where s_i represents the linear optical power, m_i, indicates the slope and α_i is the sensing head loss, with $i = R + F$, B.

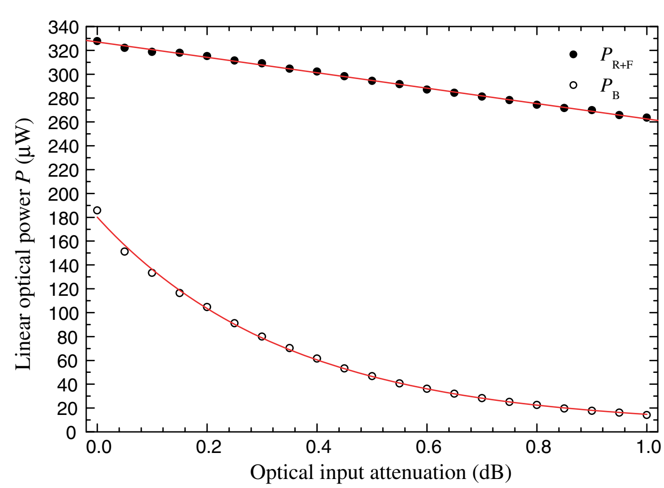

Fig. 3. Linear response of Rayleigh + Fresnel and Brillouin optical power versus optical input attenuation.

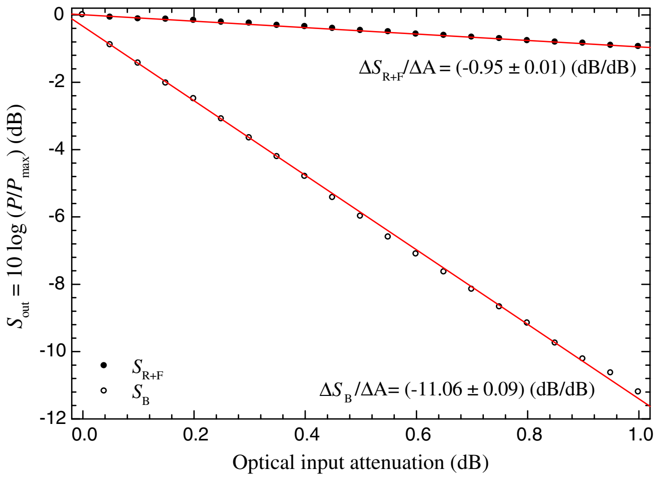

Fig. 4. Normalized logarithmic response of Rayleigh + Fresnel and Brillouin optical power versus optical input attenuation.

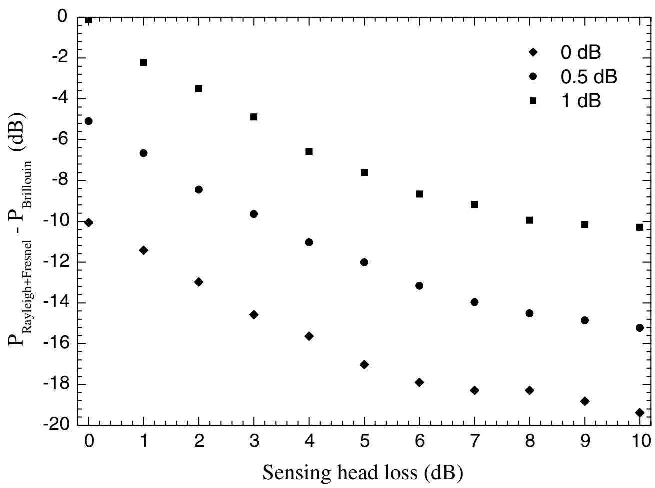

Fig. 5. $P_{\text{Rayleigh+Fresnel}} - P_{\text{Brillouin}}$ versus sensing head loss.

In a logarithmic form:

$$
\begin{aligned}
S_{\mathrm{R+F}}\ (\mathrm{dB}) &= 10\log(s_{\mathrm{R+F}}) = -\beta_{\mathrm{R+F}} \cdot \alpha_{(R+F)_{\mathrm{dB}}} \\
S_{\mathrm{B}}\ (\mathrm{dB}) &= 10\log(s_{\mathrm{B}}) = -\beta_{\mathrm{B}} \cdot \alpha_{(B)_{\mathrm{dB}}}
\end{aligned} \tag{2}
$$

where S_i represents the optical power in dB.

In order to have a referenced sensor and since we are subtracting the $P_{\text{Brillouin}}$ from $P_{\text{Rayleigh+Fresnel}}$ (in logarithmic scale, corresponding to the ratio of these two optical powers in a linear scale), ideally, we would need to have the Rayleigh + Fresnel and Brillouin versus optical input attenuation with same slopes. To achieve an equivalent result, one of the curves can be multiplied by a correction factor in order to have a similar slope with respect to the other curve.

Knowing that S_{out} is a function of the losses

$$
\begin{aligned}
&\alpha_{(\mathrm{R+F})_{\mathrm{dB}}} = -\frac{S_{\mathrm{R+F}}}{\beta_{\mathrm{R+F}}} \quad \text{and} \quad \alpha_{(\mathrm{B})_{\mathrm{dB}}} = -\frac{S_{\mathrm{B}}}{\beta_{\mathrm{B}}} \\
&S_{\mathrm{out}}\ (\mathrm{dB}) = S_{\mathrm{R+F}} - \frac{\beta_{\mathrm{R+F}}}{\beta_{\mathrm{B}}} S_{\mathrm{B}}
\end{aligned} \tag{3}
$$

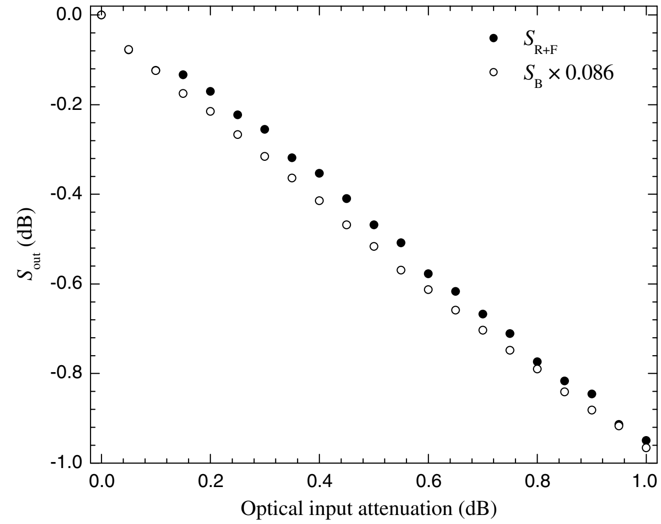

Fig. 6. Normalized logarithmic response of Rayleigh + Fresnel and Brillouin optical power versus optical input attenuation after the Brillouin result is multiplied by a correction factor.

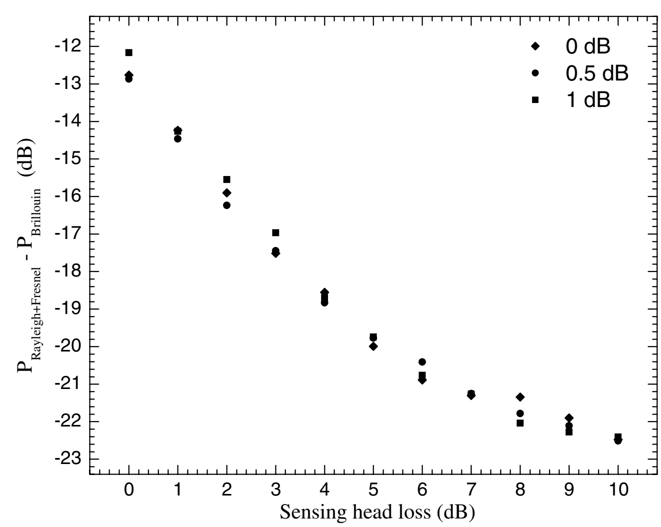

Fig. 7. $P_{\text{Rayleigh+Fresnel}} - P_{\text{Brillouin}}$ versus sensing head loss after the Brillouin result is multiplied by a correction factor.

Fig. 6 shows that outcome after multiplying the Brillouin result by a correction factor, in this case $\beta_{\text{Rayleigh+Fresnel}}/\beta_{\text{Brillouin}} = 0.086$, making the Brillouin curve approximately parallel to the Rayleigh + Fresnel curve. The next step was to verify that the sensor was indeed referenced. Fig. 7 shows that result, where the sensor behaviour as function of the sensing head loss is once again analyzed for different optical input attenuations.

As it can be seen in Fig. 7, the sensor is indeed referenced in intensity, presenting a similar behaviour when optical input fluctuations are induced. The referentiation maximum error is ≈4% and the sensor has an average sensitivity of -1.88 ± 0.09 dB/dB.

4. Conclusion

An optical fibre intensity sensor referenced by the Brillouin effect was presented. The sensing configuration uses sufficient optical power and fibre length to generate the Brillouin effect. Employing an adequate relationship between Brillouin and Rayleigh scattering and Fresnel reflection, it is possible to have a sensor addressed in reflection and referenced in intensity. The sensor presents an average sensitivity of -1.88 ± 0.09 dB/dB.

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