Parameters that Affect the Backscattered Signal Power due to Stimulated Brillouin Scattering in Optical Fibres

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Abstract

The main objective of this paper is to analyze by simulation the parameters affecting backscattered signal power in optical fibres. Parameters affecting the backscattered power were investigated and the possibility of using these parameters to model a distributed fibre optic sensor was done. In this research work investigations were carried out using VPI software for simulations. The investigation show that when the pump and stokes (probe) wave counter propagate in the fibre there is transfer of energy between the pump and stokes wave resulting in the pump and stokes waves being depleted and amplified respectively as they travel along the fibre. Thus the Brillouin gain peaks at Brillouin frequency. Further investigations show that the backscattered power was low for input power below 5 d Bm but increased rapidly above it and saturated above input power of 10 dBm for different fibre lengths. The effect of Polarization Mode Dispersion (PMD) on Stimulated Brillouin scattering (SBS) was found to decrease the signal power over time. Further results showed that power reduces with increase in temperature and the frequency shift (Brillouin shift) is directly proportional to temperature and this was used to map out the temperature change along the fibre.

Keywords: Backscattered signal power, The Polarization Mode Dispersion (PMD), Stimulated Brillouin Scattering (SBS).

I. Introduction

With increasing demand for smart structures, the distributed fibre optic sensor provides the basis for a sensing technique capable of detecting strain and temperature and other physical parameters. This sensor solves the challenges experienced when electrical or point sensors are used instead. Its use allows temperature/ strain changes at various points to be monitored at the same point as the power source. This saves time and resources which would otherwise be used in case of monitoring at different points (point sensors). The proposed study will provide information which would help in disaster management which is important in socio-economic development.

Distributed sensing techniques are commonly based on light scattering mechanism occurring inside the fibre. One such mechanism is Stimulated Brillouin Scattering, which is as a result of interaction between acoustic waves, a pump wave and stokes wave. Consequently there is transfer of power between pump and stokes which simultaneously reinforces the acoustic wave. The stokes wave is amplified and the pump wave is depleted as they both travel along the fibre. This is true provided that the frequency shift falls within the Brillouin gain spectrum of the fibre itself which is centered at the Brillouin frequency. At each section along the fibre the Brillouin frequency depends on the temperature and strain thus providing the basis for a sensing technique capable of detecting these two parameters.

II. Theory Of Brillouin Scattering

Brillouin scattering refers to the scattering of a light wave by an acoustic wave [l]. When this process occurs in an optical fibre, the back-scattered light suffers a frequency shift (the Brillouin frequency) which is dependent on the temperature and strain of the fibre. It has been shown that this process can be used as a sensing mechanism for distributed fibre-optic sensors [2]-[4]. Distributed temperature sensors using this sensing medium are very attractive for applications requiring sensing lengths of many kilometers. This is because standard telecommunications-grade optical fibre has a very low loss and inexpensive. The Brillouin interaction results in the generation of scattered light, which experiences a frequency shift through the scattering process. This frequency shift linearly depends on the fibre strain and temperature. As a consequence, the scattered light has a slightly different wavelength than the original light, and the departure from the original wavelength is directly dependent on the strain and temperature of the fibre. A system based on the analysis of the Brillouin scattered light in optical fibres is naturally devoted to perform strain and temperature measurement.

Iii. Coupled Wave Equations

Brillouin scattering process uses the two coupled wave equations describing the incident pulsed and continuous wave(CW) laser intensities (I_p, and I_{cw} respectively) [5]:

$$\frac{d}{dz} I_s = -g I_p I_s - \alpha I_s$$

$$\frac{d}{dz}I_p = -gI_pI_s + \alpha I_p$$

$$g = \frac{\gamma g_o (\Gamma_B /_2)^2}{\Omega_B(T) - \Omega^2 + (\Gamma_B /_2)^2}$$

where z is the distance from the pulsed laser end of the fiber, g_o is the line center gain factor, α is the fiber attenuation coefficient, Γ_B is the Brillouin line width, Ω is the frequency difference between the lasers and $\Omega_B\ (T)$ is the temperature dependent Brillouin frequency shift. The parameter γ is a polarization factor, which accounts for the dependence of gain on the polarizations of the two beams [6].

IV. Parameters Affecting Backscattered Signal Power.

Methodology

In designing of the optical sensor two optical fibres were used as shown in Figure 1. The first fibre was used as a reference and its temperature kept constant. The temperature of the second fibre was varied as the frequency difference between the probe and the pump was swept in the spectral of the Brillouin frequency (10.5-11.0 GHz) so that the frequency response of the fibre was determined by use of the optical analyzers. The magnitude of the temperature of the second fibre was varied as the frequency difference between the probe and the pump was swept in the spectral of the Brillouin frequency (10.5-11.0 GHz) so that the frequency response of the fibre was determined by use of the optical analyzers**.** The interaction between pump and probe was recorded at every location along the fibre. The frequency difference between the two lasers was set at 10.5-11.0Hz, which corresponds to Brillouin frequency of the optical fibres, and the CW probe would experience gain varying along the fibre. The gain as a function of position along the fibre was thus determined by the time dependence of the detected light. By measuring the time dependent CW signal over a wide range of frequency differences between pump and probe, the Brillouin frequency at each fibre location was determined. This allowed mapping temperature distribution along the entire fibre length. Using the time-of-flight of the returning backscattered light and the velocity of light, then the location of the amplified pulse is obtained.

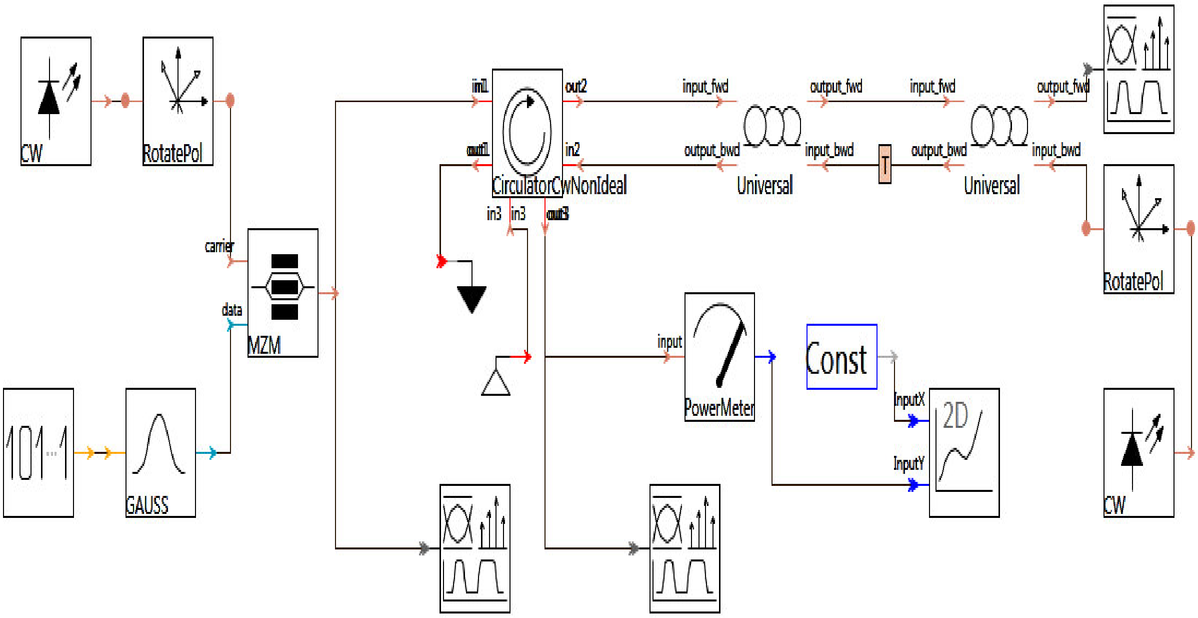
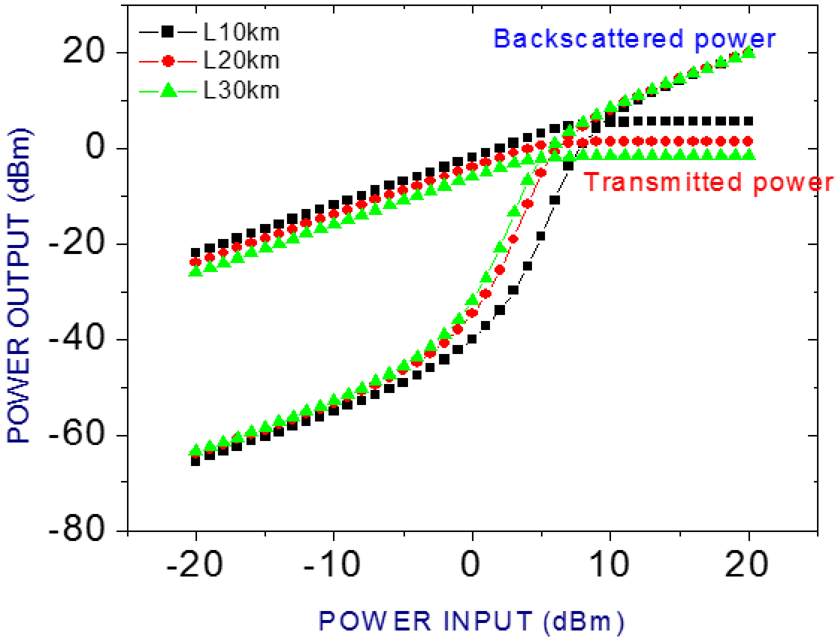


Figure 1. Simulation of parameters affecting backscattered signal in optical fibre.

Results and Discussions

The results were obtained by use of virtual photonic imaging software (VPI) and optisystem software..



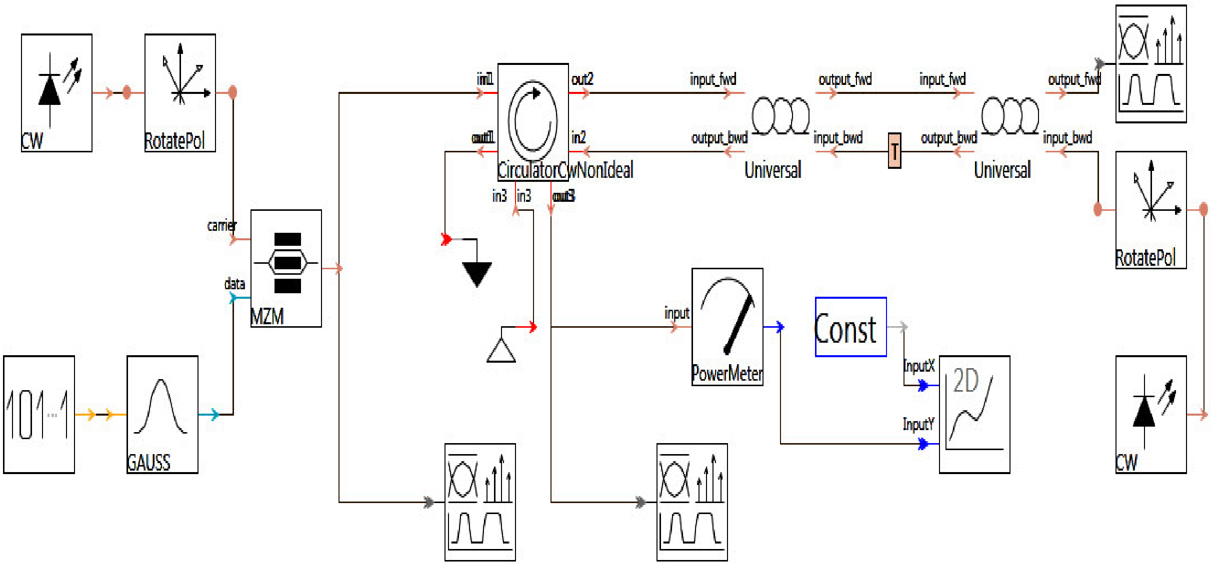


Figure 2 Reflected (stokes) power and transmitted power measured as a function of the input power.

Figure 2 shows that at low input powers the backscattered power is low but increases rapidly at an input of about 5 dBm, while the transmitted power increases linearly and reaches saturation level for input power in excess of 10 dBm. At low input powers the backscattering is dominated by simple Brillouin and Rayleigh scattering which are linear and differ from each other by Brillouin shift. But as the power is increased Brillouin scattered light is increasingly amplified by stimulation process. At a power input of 5 dBm, that is stimulated Brillouin scattering threshold, the amount of backscattered light increases rapidly with .increasing input power until it constitute input light [8]. At the same time, the transmitted power at the fibre output saturates at a level that barely increases with increased input power, it becomes independent of input power.

Figure 3 shows that output power varies with time for various lengths due to interaction of pump wave with CW probe waves as they counter propagate along the fibre. This is due to interaction of pump wave with CW probe waves as they counter propagate along the fibre. Hence optical power is transferred from the pump to probe and amplification of probe wave at points where the frequency difference between them is equal to the Brillouin frequency. SBS occurs when pump and probe overlap, resulting in an amplification of the probe wave provided the difference between the two frequencies lies within the Brillouin gain spectrum at the overlapping position in the fibre [9],[10]. Power gain reduces with length due to power losses along the fibre.

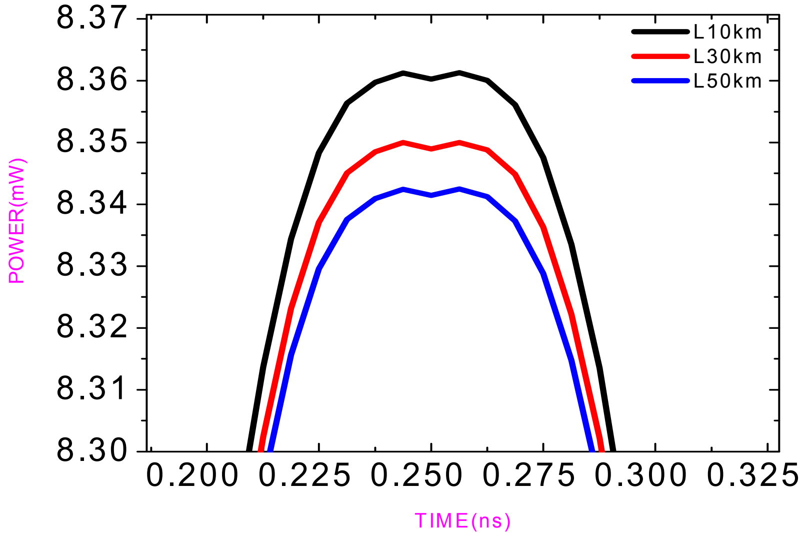


Figure 3 Shows Brillouin gain spectrum for various Fibre lengths.

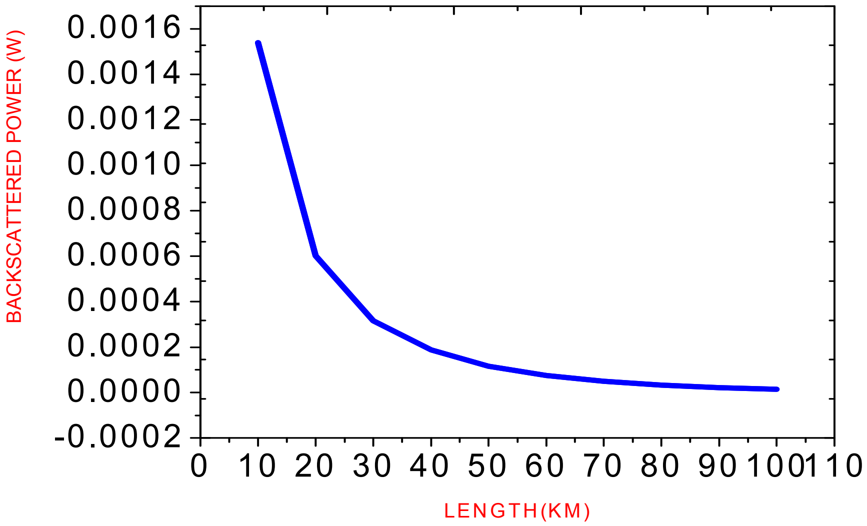


Figure 4 Variation of backscattered power with length

From the graph shown in Figure 4, the optical power propagating in a fibre decays exponentially with length. This is due to material absorption and scattering losses. Scattering can couple energy from guided to radiation modes, causing loss of energy from the fibre. Rayleigh scattering is as a result of elastic collisions between light waves and silica molecules in the core of the fibre causing attenuation. Rayleigh scattering losses occurs in short fibres due to small-scale index fluctuations producing attenuation. Irregularities in core diameter and geometry or changes in fibre axis direction also cause scattering [11].

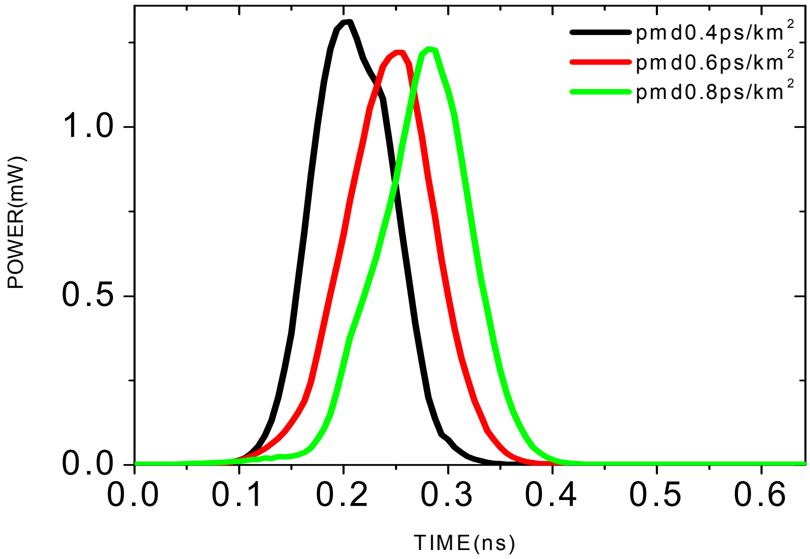


Figure 5. The signal power change with time for three fibres of different PMD coefficient

Figure 5 shows that increase in PMD decreases output power over time. The interaction between the probe and pump ensures energy transfer from the pump to the signal and hence gain. However, with the introduction of PMD to the signal, this interaction is impaired. PMD causes rotation of propagation axis which limits the probe-pump interaction and the eventual power exchange. This limitation of power transferred to the signal reduces the Brillouin gain

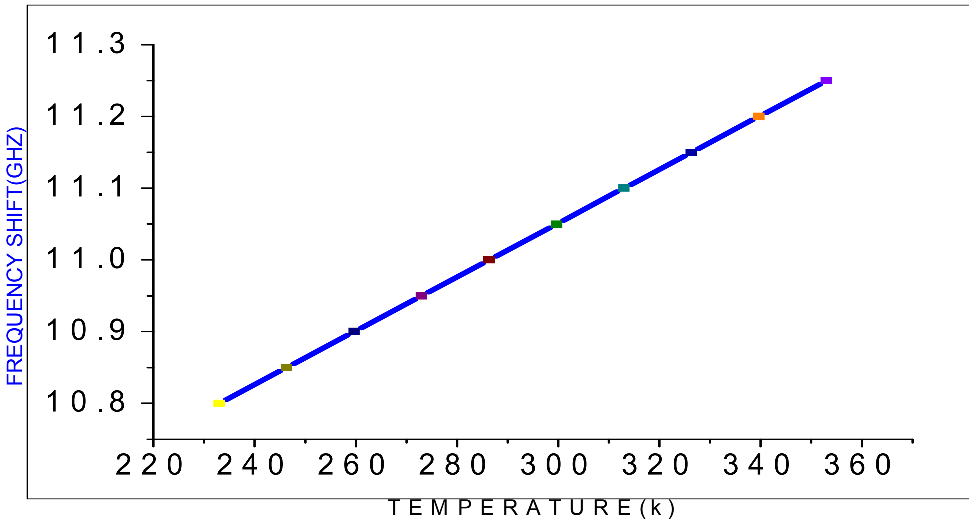


Figure 6 Shows increase in temperature with frequency shift.

Figure 6 shows that Frequency shift is linearly dependent on the change of temperature in the fibre. From the equation below, Frequency shift,

$$v_B = 2n_{eff}\frac{v_A}{\lambda p}\text{……………......…………..}(3)$$

The relation between Brillouin frequency shift, v_B and temperature/strain is given by [11]:

$$v_B(\Delta \mathrm{T}, \Delta\varepsilon) = v_{BO} + C_{\mathrm{T}}\Delta \mathrm{T} + C_{\varepsilon}\Delta\varepsilon\text{.......}(4)$$

Taking strain to be constant, equation (4) becomes:

$$v_B(\Delta \mathrm{T}) = v_{BO} + C_{\mathrm{T}}\Delta \mathrm{T}\text{..........}(5)$$

Combining equations (3) and (5), gives:

$$n_{eff} = \frac{(\nu_{BO} + C_T \Delta T)\lambda_P}{2\nu_A} \ldots\ldots\ldots\ldots\ldots\ldots\ldots(6)$$

where ν_{BO} represents the Brillouin frequency of the unperturbed fibre, that is for a fixed temperature, ΔT is the change in temperature and C_T is the shift/temperature coefficient. Therefore, Equation (6) shows that refractive index is directly proportional to temperature. Thus an increase in temperature of the fibre increases its refractive index and thus increases Brillouin frequency shift and vice versa.

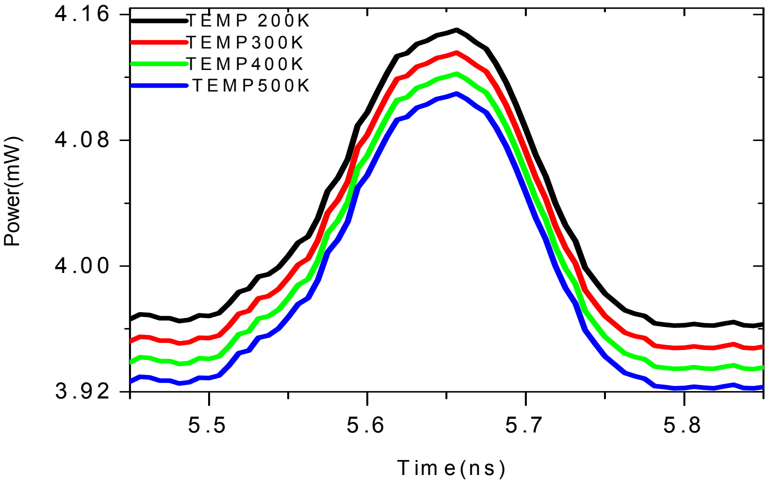


Figure 7 illustration points of power peaks as temperature changes

Figure 7 shows that power reduces with increase in temperature. The Brillouin gain spectrum peaks at the Brillouin frequency shift ν_B and the peak value is given by the Brillouin gain coefficient.

Conclusion

Distributed fibre optic sensor based on SBS is an attractive tool for a number of applications as outlined earlier. This work presents the effect of various parameters that are involved in the stimulated Brillouin scattering (SBS) process and how these parameters influence the design and effectiveness of fibre optic sensor were investigated. It shows that SBS process in single mode fibres, through amplification of probe wave when the frequency difference between probe and pump is equal to Brillouin frequency. The Brillouin gain of the optical fibre used is about 9.615 x10^{-4} W _ 9.655x10^{-4} W for a fibre length of 25 km. It was observed that there is minimum power (threshold power) below which SBS is affected by other nonlinearities. For a fibre length of 25 km, the Brillouin power threshold is equal to 5 dBm. Below this, Rayleigh scattering comes into effect and results in fluctuations of Brillouin gain. So the power threshold obtained showed the minimum input power for SBS as 5dBm. Further investigations showed that the backscattered power decreased with increase in length of single mode fibre, while polarization affected Brillouin gain spectrum. Polarization mode dispersion in combination with SBS was found to decrease the signal power over time. This is due to differential group dispersion impairing the interaction between the pump and probe wave. The results also showed the backscattered power reduces with increase in temperature and the frequency shift is directly proportional to the temperature along the fibre. The above parameters were used to model a sensor based on stimulated Brillouin scattering.

REFERENCES

[1] Gholamzadeh, B., & Nabovati, H. (2008). Fibre optic sensors. *World Academy of Science, Engineering and Technology*, *42*(3), 335-340.

[2] Bao, X., & Chen, L. (2011). Recent progress in optical fibre sensors based on Brillouin scattering at university of Ottawa. *Photonic Sensors*, *1*(2), 102-117.

[3] Horiguchi, T., Shimizu, K., Kurashima, T., Tateda, M., & Koyamada, Y. (1995). Development of a distributed sensing technique using Brillouin scattering. *Lightwave Technology, Journal of*, *13*(7), 1296-1302.

[4] Fellay, A. (2003). Extreme temperature sensing using Brillouin scattering in optical fibres. *École Polytechnique Fédérale de Lausanne-Thèse*, (2728), 105-106.

[5] Bernini, R., Minardo, A., & Zeni, L. (2002). A reconstruction technique for stimulated Brillouin scattering

fibre-optic sensors for simultaneous measurement of temperature and strain. In *Sensors, 2002. Proceedings of IEEE* (Vol. 2, pp. 1006-1011). IEEE.
[6] Azizan, S., Shahimin, M. M., & Murad, S. A. Z. (2011, December). Simulation of distributed fibre optic sensor for temperature and stress sensing. In *Humanities, Science and Engineering (CHUSER), 2011 IEEE Colloquium on* (pp. 449-453). IEEE
[7] http://www.intechopen.com/books/fibre-optic-sensors.
[8] F. Yu and S. Yin, *Fibre optic sensors*. Marcel-Dekker, (2002).
[9]Galindez, C. A., Madruga, F. J., Ullan, A., & Lopez-Higuera, J. M. (2009).Technique to develop active devicesby modifying Brillouin gain spectrum. *Electronics letters*, *45*(12), 637-638.
[10] Dick, B., Gierulski, A., Marowsky, G., & Reider, G. A. (1985). Determination of the nonlinear optical susceptibility χ (2) of surface layers by sum and difference frequency generation in reflection and transmission. *Applied Physics B*, *38*(2), 107-116.
[11] Zeni, L. (2009). Optical fibre distributed sensors: a tool for in-sit structural and environmental monitoring. In *Italian Workshop on Landslides*.