Modeling of Optical Fibre Temperature Sensor Based on Stimulated Brillouin Scattering

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Abstract: Distributed fibre optic sensing presents unique features that have no match in conventional sensing techniques. The ability to measure temperatures and strain at thousands of points along a single fibre is particularly interesting for the monitoring of elongated structures such as pipelines, flow lines, oil wells and landslides. This paper presents the analysis by simulation of stimulated Brillouin scattering (SBS) in optical fibres. The behavior of stimulated Brillouin scattering in optical fibres are studied through the backscatter signals. The results show that the backscattered power is low for input power below 5 dBm but increased rapidly above it and saturated above input power of 10 dBm for different fibre lengths. The analysis of parameters affecting backscattered signal power is presented. The simulation of distributed fibre optic sensor (DFOS) is carried out with the aim of temperature sensing.

Key Words: Backscattered signal power, Distributed fibre optic sensors (DFOS), Optical fibre, Stimulated Brillouin Scattering (SBS)

I. INTRODUCTION

Distributed fibre optic sensing has been one of the vital fibre optic technologies developed for sensor applications. Distributed sensing using stimulated Brillouin scattering, is highly preferable due to its capability of extracting information such as temperature and strain continuously along the sensing fibre [1]. Optical fibre, being a physical medium, may be subjected to perturbation of any kind, which will experience geometrical and optical changes, depending upon the nature and magnitude of perturbation. In this case, temperature variation can be detected by optical fibre over long distances [2, 3]. Whenever there is a change in temperature or strain, the refractive index of silica (material of optical fibre) changes in response to such variations. Stimulated Brillouin scattering (SBS), which is observed at high guided light intensity, will also be affected by the change in refractive index. This change is realized through the Brillouin shift, by measuring the change in Brillouin shift the distribution of temperature over long distances can be obtained, hence distributed fibre sensors.

This paper focuses on simulations using VPI for distributed Brillouin fibre optic sensor. It is organized as follows: - A brief introduction on stimulated Brillouin scattering, parameters affecting backscattered signal power methodology, Experimental results and discussions.

II. THEORY OF BRILLOUIN SCATTERING

Brillouin scattering refers to the scattering of a light wave by an acoustic wave [1]. 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 (Ip, and Icw respectively) [5]:

\[ \frac{d}{dz} I_p = -g I_cw I_p - \alpha I_p \]

\[ \frac{d}{dz} I_cw = -g I_cw I_p + \alpha I_cw \]

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

where z is the distance from the pulsed laser end of the fiber, \( g_o \) is the line center gain factor, \( \alpha \) is the fiber attenuation coefficient, \( \Gamma_B \) is the Brillouin linewidth, \( \Omega \) is the frequency.
difference between the lasers and $\Omega_2(T)$ is the temperature dependent Brillouin frequency shift. The parameter $\gamma$ is a polarization factor, which accounts for the dependence of gain on the polarizations of the two beams [6].

IV. PARAMETERS AFFECTING BACKSCATTERTED SIGNAL POWER.
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 SBS sensors
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 length 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 Show 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,

\[ \nu_B = 2n_{eff} \frac{v_A}{\lambda P} \]  (3)

The relation between Brillouin frequency shift, \( \nu_B \) and temperature/strain is given by [11]:

\[ \nu_B(\Delta T, \Delta \varepsilon) = \nu_{BO} + C_r \Delta T + C_e \Delta \varepsilon \]  (4)

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

\[ \nu_B(\Delta T) = \nu_{BO} + C_r \Delta T \]  (5)

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

\[ n_{eff} = \frac{(\nu_{BO} + C_r \Delta T)\lambda_P}{2v_A} \]  (6)

where \( \nu_{BO} \) represents the Brillouin frequency of the unperturbed fibre, that is for a fixed temperature, \( \Delta T \) is the change in temperature and \( C_r \) 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 \( \nu_B \) 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