

Injection locking applied to distributed Brillouin sensing

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Abstract—Stimulated Brillouin Scattering (SBS) can be applied in truly distributed long distance sensing with great accuracy and resolution. SBS requires pump and probe signals which are precisely separated by a frequency in the 10GHz range and tunable in at least 1MHz steps. This precise signal generation poses one of the major challenges. A high spatial resolution will require shorter interaction lengths, leading to stricter component specifications, ultimately driving up system cost. In conventional systems an amplitude modulator with extinction ratio of better than 30dB is required for high spatial resolution. These amplitude modulators are expensive since telecommunication standards only require an extinction ratio of better than 20dB. Various configurations have been proposed to overcome this problem including electrical synchronisation of two lasers and phase modulation of a single laser. In this work injection locking of two lasers is used to generate the appropriate Brillouin sensing signals. Theoretical and experimental investigation show we can use any commercially available phase modulator.

Index Terms—Stimulated Brillouin Scattering, Injection Locking

I. INTRODUCTION

Brillouin Scattering is one of the major limitations on power that can be transmitted over an optical fibre. Once a certain power threshold, the Brillouin threshold, is reached light is backscattered through Bragg diffraction. The origin of this Bragg grating is an acoustically induced modulation of the refractive index. The backscattered light is at a lower frequency due to a Doppler shift between the forward propagating light and the acoustic wave. A backward propagating wave stimulates the acoustic wave and gives rise to Stimulated Brillouin Scattering (SBS).

Although the threshold for Brillouin scattering can be as low as 1mW for a continuous wave or wide pulses ($> 1\mu s$), it can be suppressed using various techniques[1]

- Broadening the source spectral width through phase modulation. This is done by modulating the constant wave source before information is encoded onto it.
- Modulating pseudo-random binary data on the channel roughly doubles the threshold.
- Differences along the length of the fibre can also increase the threshold significantly. Changing the core radius or nonuniform doping along the length of the fibre. In one experiment the threshold was increased to 30mW.

- When the state of polarisation in the source is completely random the threshold increases with 50%.

This non-linear effect can also be utilised for several applications:

- Selective sideband amplification (recovering signals from WDM systems and phase-to-amplitude conversion [2]).
- Narrow bandwidth Brillouin lasers. [1]
- Distributed strain and temperature measurements. [3]

Distributed temperature sensing has been accomplished by using Landau-Placzek ratio[4] and SBS. SBS offers great spatial resolution. Various experiments have achieved a spatial resolution of 1cm[3], [5], with an upper limit in the $100\mu m$ range[3].

II. THEORY

SBS interaction requires light signals from both directions in the fibre under test. These signal frequencies must differ by the Brillouin shift, ν_B , which is in the 10GHz range in standard single mode fibre. We call the source with the higher frequency the pump and the lower frequency source, the probe. When scattering occurs the pump creates a Stokes wave opposite in direction and downshifted in frequency. The Stokes wave adds to the probe and result in amplification of the probe as it travels through the fibre. The power transfer from the pump to the probe is described by the following coupled equations.

$$\frac{dI_p}{dz} = -g_B I_p I_s - \alpha I_p \quad (1)$$

$$\frac{dI_s}{dz} = -g_B I_p I_s + \alpha I_s \quad (2)$$

where I_p is the pump intensity and I_s the Stokes (or probe) intensity. α is the standard attenuation constant and g_B is the Brillouin gain coefficient.

Figure 1 shows pump and Stokes intensities for a 5km fibre. This figure clearly shows the exponential power transfer from the pump to the probe, which is one of the characteristics of the scattering effects.

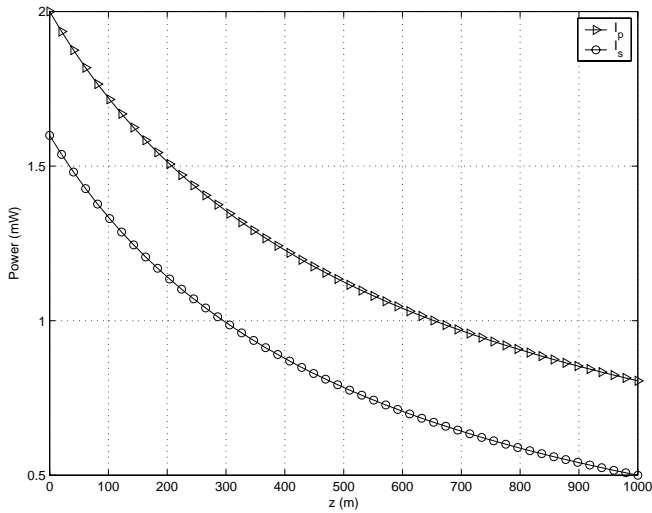


Fig. 1. Signal Intensities with Brillouin interaction

The probe's frequency is swept so that the difference between the pump and probe is in the vicinity of ν_B . This sweep will provide us with the Brillouin gain spectrum, which has a Lorentzian form.[1]

$$g_B(\nu) = \frac{g_{B0}}{1 + \frac{4(\nu - \nu_B)^2}{\Delta\nu_B^2}}$$

with g_{B0} , the Brillouin gain coefficient and $\Delta\nu$, the Brillouin spectral width. The centre of this gain peak will reveal the exact value of ν_B , a frequency which is jointly dependent on temperature and strain.

To restrict Brillouin interaction to a single position along the fibre, the goal of distributed measurement, there are two methods. Initially the pump or probe was pulsed and the position along the fibre could be determined through time of flight. The drawback of such a method is spatial resolution, if the length of the pulse shortens below the time needed to excite an acoustical wave ($\sim 10ns$) the measurement deteriorates. A spatial resolution of about 1m was achieved using this method. Another technique[3] propose the use of correlation between the pump and probe. The two sources are modulated so that their phases has a high correlation at a certain point along the fibre, limiting Brillouin interaction to this point of high correlation.

Since the Brillouin gain bandwidth, $\Delta\nu$, is very narrow ($\sim 35MHz$), the two laser frequencies need to be controlled with great precision. To measure a $1^\circ C$ change in temperature at least 1MHz frequency accuracy is required. These precise requirements is almost impossible with electrical synchronisation of two separate lasers.

Generating the proper probe signal is one of the major challenges of distributed Brillouin sensing.

Earlier techniques used an amplitude modulator to generate the required probe signal from the pump source. The biggest drawback is that the setup requires an amplitude modulator

with extinction ratio better than 30dB, a rare and thus expensive device. Amplitude modulators with extinction ratios of 20dB is more common because of telecommunication demands.

Other techniques developed to improve the stability problem uses a single laser modulated with a phase modulator. Very accurate shifts can be accomplished if modulated using a microwave oscillator. If the pump is phase modulated with the Brillouin frequency with $\beta \approx 2.4$ we completely suppress the carrier frequency. This leaves us with an upper and a lower sideband spaced perfectly for Brillouin interaction with the original pump.

It is important to note that the the lower sideband of this phase modulated signal will also undergo Brillouin scattering and thus amplify the pump. The pump is amplified by the anti-Stokes and the probe is amplified by the pump. Over a long distance the probe will undergo large amplification due to signal power from the pump and the anti-Stokes wave. Over a short interaction length this is a problem: The nett effect of the anti-Stokes decreasing and the Stokes increasing gives us a constant total probe wave.

To illustrate this we modify equations 1 and 2 to add the anti-Stokes wave. This gives the following set of differential equations

$$\frac{dI_p}{dz} = -g_B I_p I_s - \alpha I_p + g_B I_p I_a \quad (3)$$

$$\frac{dI_s}{dz} = -g_B I_p I_s + \alpha I_s \quad (4)$$

$$\frac{dI_a}{dz} = g_B I_p I_a + \alpha I_a \quad (5)$$

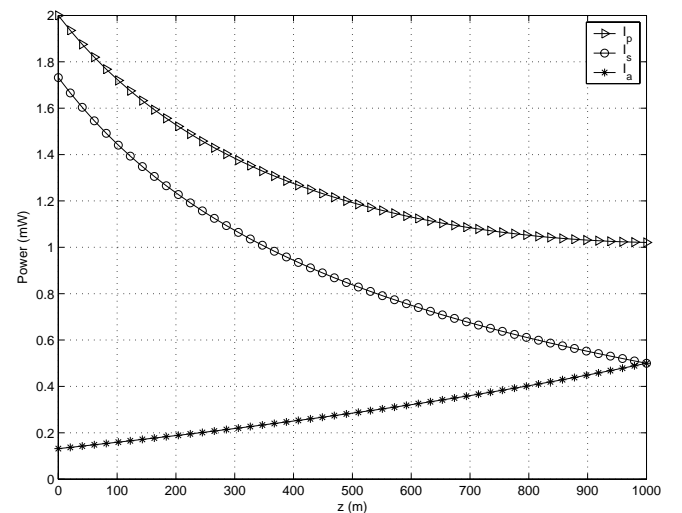


Fig. 2. Signal intensities with Brillouin interaction

One of the created sidebands is thus amplified to produce the second signal. Several methods have been suggested to improve the extinction ratio between the pump and the probe. We will apply injection locking to generate the appropriate signals.

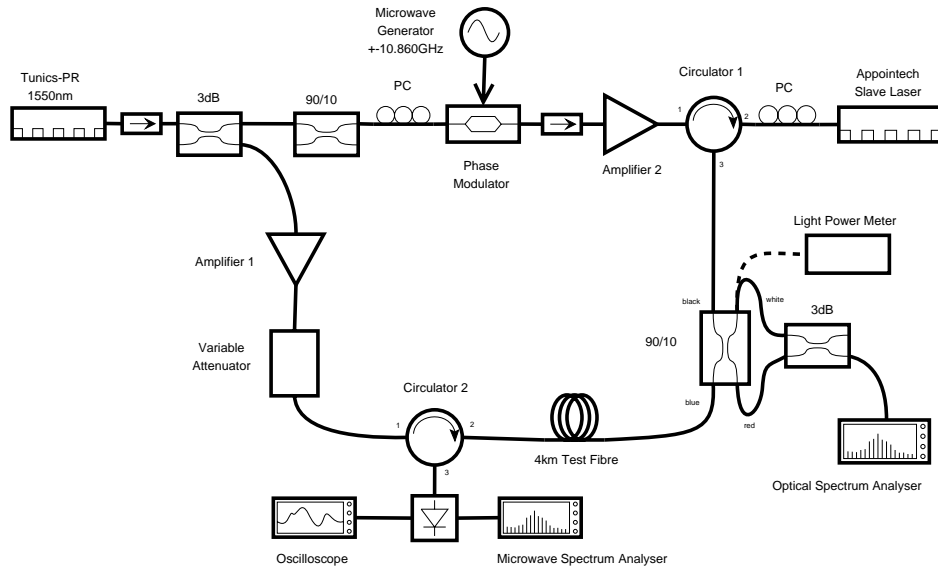


Fig. 4. Brillouin sensing using injection locking

III. INJECTION LOCKING

Injection locking occurs when light from a light source (master) is injected into another free running laser (slave). If the slave frequency and the injected frequency are close ($< 1GHz$) to one another and their polarisation states match the slave will lock on to the injected master frequency. To protect the master from any disturbances an optical isolator is placed in front of the master. See figure 3 for an illustration of the master and slave outputs.

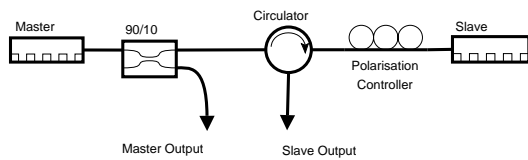


Fig. 3. Injection locking generates Brillouin sensing signals

Interesting modulation schemes can be accomplished using injection locking. Amplitude-, phase- and sideband modulation can be accomplished through simple setups [6]. The sideband modulation which uses a phase modulator is of particular interest in a Brillouin sensing application. It allows us to lock a second laser onto a sideband shifted by the Brillouin shift. The laser can then be easily modulated and has a spectrum that resembles the pump source.

To achieve sideband modulation a phase modulator is placed between the coupler and circulator. The phase modulator creates two sidebands and if the slave laser frequency is tuned close to one of these sidebands it will lock onto it. See the experimental results section for a complete setup.

IV. EXPERIMENTAL RESULTS

The experimental setup in figure 4 was used. The Tunics-PR laser signal was split into two and used for the injection

locking master and the pump for Brillouin interaction respectively. The microwave generator is adjustable in small steps to allow us to sweep the region close to the Brillouin shift. The modulated signal is amplified and fed into the slave laser through a polarisation controller.

Probe spectrum without injection locking

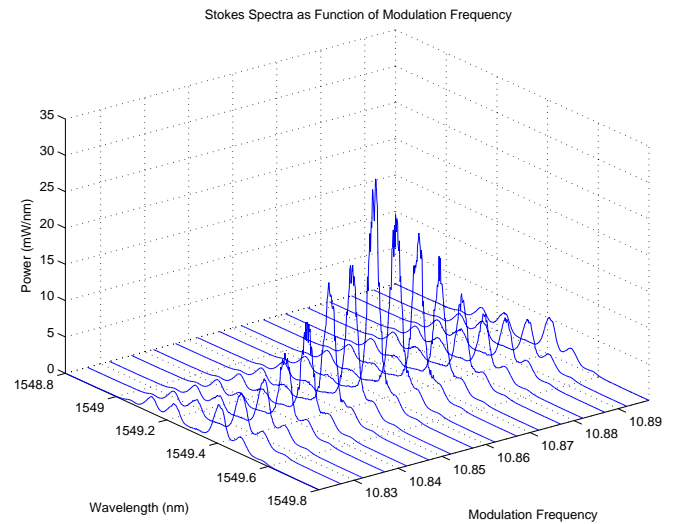


Fig. 5. Probe spectrum for a range of Modulation frequencies

Figure 5 contains data from the Optical Spectrum Analyser (OSA) for a range of modulation frequencies. For this figure the OSA was connected to port 3 of circulator 2 (setup in figure 4) and the signal after phase modulation was used as the probe signal. The modulation generator's frequency was varied between 10.822 and 10.897GHz in steps of 5MHz. The pump signal was measured as it exited circulator 2 (port 2) with the light power meter (6.7mW). Note that

the first upper sideband is amplified and the first lower sideband attenuated near the Brillouin shift. The reason for the amplification is power transfer from the pump to the upper sideband.

As the modulation frequency changes and moves closer to the exact Brillouin shift value, we see that the first lower sideband loses power. This power is transferred from the lower sideband to the pump in the same way that power is transferred from the pump to the upper sideband. Using injection locking eliminates the lower sideband as is shown below.

Probe and pump spectrum with injection locking

The OSA from our experimental setup is connected to show the pump and probe power spectra simultaneously. To avoid pump power depletion the modulation frequency was set well outside the Brillouin shift. Figure 6 shows the spectrum clearly. We can see here that the lower sideband is completely eliminated, which will avoid pump amplification.

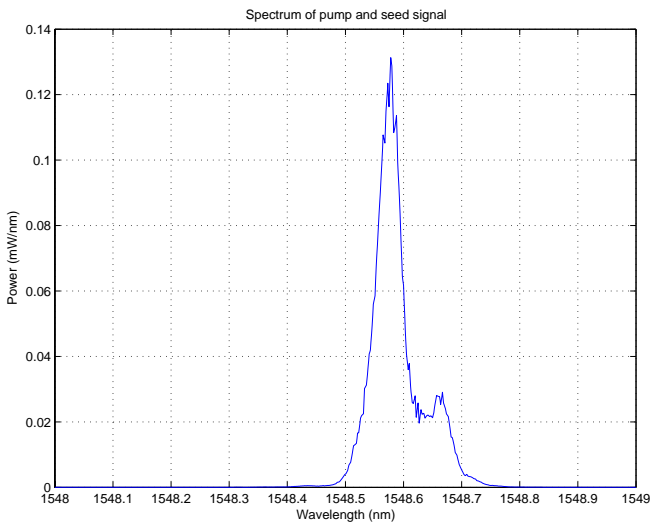


Fig. 6. Probe and pump spectrum

Noise

The signal to noise ratio (SNR) was calculated using V_{avg} and V_{rms} measurements from the oscilloscope and the formula:

$$SNR = 20 \times \log_{10} \left(\frac{V_{avg}}{V_{rms}} \right) \quad (6)$$

These measurements were repeated for several pump power attenuations. Higher pump powers generate more noise when the modulation frequency is farther from the Brillouin shift. The behaviour of the SNR is not fully understood at present.

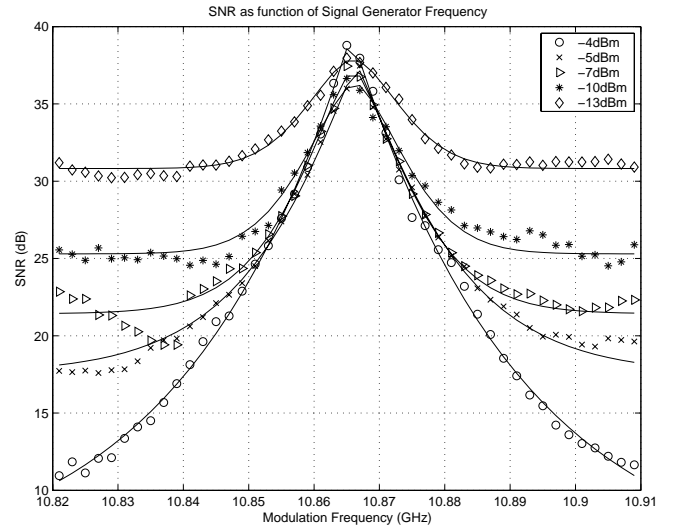


Fig. 7. Signal to noise vs modulation frequency

V. CONCLUSION

Experimental work show that injection locking can generate proper Brillouin sensing signals using commercially available phase modulators. Proper control of the slave laser is required to ensure that it stays locked while sweeping over the Brillouin frequencies.

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