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Measurement Methods for Stimulated Raman and Brillouin Scattering in Optical Fibres

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Summary

Raman and Brillouin scattering processes can become nonlinear in optical fibres due to the high optical intensity in the core and the long interaction lengths afforded by these waveguides. Stimulated Raman scattering (SRS) and stimulated Brillouin scattering (SBS) occur when the optical power launched into the fibre exceeds a threshold level for each process. Under the conditions of stimulated scattering, optical power is efficiently converted from the input *pump* wave to the scattered *Stokes* wave. The scattered wave is frequency-shifted from the pump and in the case of SBS propagates in the opposite direction.

Raman and Brillouin scattering in optical fibre can be both detrimental and advantageous. The scattering effects are generally undesirable to the optical fibre communications industry as they can limit the maximum launch power and lead to interference between channels in multi-wavelength systems. However, SRS can be used as the basis for optical amplifiers at wavelengths where the ubiquitous erbium-doped fibre amplifiers (EDFAs) are unsuitable. Also, SBS has been successfully used as the basis of an optical fibre sensor to monitor strain distribution along fibres. Similar sensors can also be used to measure temperature in hazardous environments where electrical sensors could present a risk.

This report is the result of a literature survey of experimental methods used to study Raman and Brillouin scattering in optical fibres. The aim of the survey was to identify the most appropriate methods for the development of a traceable measurement infrastructure for SBS and SRS related parameters. Raman and Brillouin scattering are discussed together with definitions of the parameters used to quantify the effects in optical fibre. Measurement methods that have been used to study these parameters are then described and evaluated.

It is concluded that the source dependence of Brillouin scattering makes it difficult for a measurement service provider to satisfy measurement requirements under every possible combination of source and modulation scheme. Customers could, however, provide their own sources and modulators and request a single-point SBS threshold measurement. Under these circumstances, determination of the SBS threshold is reduced to accurate measurements of the absolute optical power entering and leaving the fibre. Alternatively, measurements could be performed using a standard source with calibrated wavelength and spectral width and the source parameters supplied to the customer together with the measured SBS threshold.

Stimulated Raman scattering occurs at significantly higher optical powers than SBS, with threshold powers of the order of watts for SRS compared to milliwatts for SBS. In contrast to SBS, the Raman gain curve is easier to measure in practice than the threshold, simply because the gain can be measured at lower optical powers. The gain curve is also more useful than a single figure for the threshold power since it can be used to calculate Raman amplification in WDM systems. The SRS threshold can be calculated from the peak value of the absolute Raman gain coefficient, making it the most useful Raman parameter to measure.

Contents

1. Introduction

1.1 Raman and Brillouin Scattering

Raman and Brillouin scattering are inelastic processes in which part of the power is lost from an optical wave and absorbed by the transmission medium while the remaining energy is re-emitted as a wave of lower frequency. The processes can be thought of as the conversion of an incident photon into a lower energy scattered photon plus a phonon of vibrational energy. Total energy and momentum before and after scattering must be equal, i.e. the incident photon energy is shared between the phonon and the scattered photon. Since the frequency of an optical wave is proportional to its energy, the photon produced by the scattering event has a lower frequency than the incident photon. This frequency downshifted wave is commonly referred to as the *Stokes wave.*

Spontaneous Raman and Brillouin scattering have been observed and measured in bulk samples of material such as quartz and silica [1, 2, 3]. The intensity of the scattered wave is strongly dependent on the angle of scattering and the optical power density in the material. The growth of the Stokes wave is proportional to the product of the scattering gain coefficient, the intensity of the pump wave and the intensity of any Stokes wave present. In bulk media the Stokes wave quickly disperses as it propagates away from the point of generation. However, single mode optical fibres will support low-loss propagation for waves travelling almost parallel to the fibre axis. Consequently, scattered radiation in either the forward or backward directions relative to the incident wave will be guided within the fibre and will co-propagate with the pump wave over long distances. Under these circumstances, it is possible for the Stokes wave to continue to interact efficiently with the pump wave and exponential growth in the downshifted optical power occurs. For a given length of fibre, gradually increasing the pump power launched into one end will lead to a gradual increase in Stokes power through spontaneous scattering. If the pump power is then increased further, exponential growth in the Stoke power may occur. The input pump power at which the Stokes wave increases rapidly as a function of pump power is termed the stimulated scattering threshold.

A major difference between Brillouin scattering and Raman scattering lies in the type of phonon generated - high-energy optical phonons in SRS and lower-energy acoustical phonons in SBS. The difference in frequency between the pump and Stokes waves is therefore much greater in SRS than in SBS. Typical values of the pump-Stokes frequency difference are 10-GHz (~0.1-nm at 1550-nm) for SBS and 13-THz (~110-nm at 1550-nm) for SRS. Another key distinction between the two effects is that the scattered wave due to SBS travels predominantly *backwards.* The SBS Stokes wave emerges from the input end of the fibre whereas the Stokes wave due to SRS travels forwards with the pump wave.

Both SBS and SRS have so-called *threshold pump powers* above which power transfer to the Stokes wave increases rapidly. In SBS this means that the amount of optical power leaving the far end of the fibre no longer increases linearly with the input power. The maximum launch power becomes clamped and excess power is simply reflected back out of the fibre. For long distance and highly-branched fibre links, it is important that as much power as possible can be launched into the fibre to compensate for attenuation and power splitting. Limits on the maximum launch power due to SBS must therefore be avoided.

The Stokes wave due to Raman scattering can be shifted from the pump wave by typically 10 to 100-nm and continues to propagate forwards along the fibre together with the pump wave. If the pump is actually one channel of a multi-wavelength communication system, then its Stokes wave may overlap with other channels at longer wavelengths - leading to crosstalk and *Raman amplification*. In Raman amplification, the shorter wavelength channel experiences power depletion and acts as a pump for amplification of the longer wavelength channel.

1.2 Metrological Requirements for SRS and SBS in Optical Fibres

Wavelength conversion coupled with loss of optical power to a counter-propagating wave can have serious implications in optical fibre communication systems. For example, the cable television industry uses very highly branched optical networks to divide the signal from a single transmitter and distribute it to as many receivers as possible. High optical powers must be launched into the network to maintain acceptable signal-to-noise ratios at these receivers. Stimulated Brillouin scattering limits the maximum optical power that can be launched into a fibre since any power above the SBS threshold is reflected back out.

In addition to these short-haul networks, the performance of long distance systems using wavelength-division multiplexing (WDM) can be degraded by stimulated scattering. In WDM systems with large numbers of channels, e.g. 32, 64, separated by 100-GHz, the longest wavelength channels may fall within the Raman gain spectrum of the shortest wavelength channel. Also, attention has recently been turned to the possibility of transmission in the 1600-nm to 1625-nm wavelength region, known as the L band. The power in the longer wavelength channel may then be increased through Raman amplification at the expense of loss of power from the shorter wavelength pump channel. This Raman amplification can lead to system impairments through inter-channel crosstalk and power depletion in the pump channels. It is essential that system designers have enough information to predict the onset of these effects and their interaction with the optical signals in the fibre so that systems can be adapted to minimise the detrimental effects.

The process of Raman amplification may however also be used as the basis of optical amplifiers to serve the second optical fibre transmission window at around 1300-nm [4, 35]. Accurate Raman gain spectrum measurements of the fibre used in these devices will be needed in the development of this technology.

2. Brillouin Scattering in Optical Fibre

2.1 Parameter Definitions

2.1.1 Brillouin Gain Coefficient

Stimulated Brillouin scattering (SBS) in single mode optical fibre is characterised by efficient transfer of optical power from a wave propagating in one direction to a wave in the opposite direction. The pump wave generates a refractive index fluctuation within the fibre core through the process of electrostriction. This refractive index fluctuation acts like a Bragg grating travelling forwards at an acoustic velocity. The implication of this is that the backscattered Stokes wave is Doppler shifted to a lower frequency than the forward propagating wave.

The Brillouin frequency shift of the Stokes wave is denoted ν_B and is typically of the order of 10-GHz for an optical fibre. The shift is determined by the velocity of the acoustic grating along the fibre and is therefore dependent on the mechanical properties of the fibre such as the elasto-optic coefficient, applied strain and ambient temperature [5, 6]. The frequency shift has also been demonstrated to be dependent on the dopant concentrations in the core and cladding of the fibre [7, 8]. The gain coefficient of the backscattered wave, $g_B(\nu)$, is commonly approximated by a Lorentzian function of the pump-Stokes frequency separation centred on ν_B and given by:

$$g_B(\nu) = \frac{1}{1+\left[(\nu-\nu_B)/(\Delta\nu_B/2)\right]^2} g_{SBS} \qquad \text{2-1}$$

where

g_{SBS} is the peak value of the Brillouin gain coefficient (m/W)

ν is the frequency shift from the pump frequency (Hz)

$\Delta\nu_B$ is the full width at half maximum of the gain curve (Hz)

The FWHM of the gain curve is typically of the order of tens of MHz (e.g. 35 MHz for fused silica and a pump wave at 1550-nm [9]). The Lorentzian gain curve has been found experimentally to be valid for low input pump powers, i.e. up to the SBS threshold (see section 2.1.2). However, it is known to narrow and evolve into a Gaussian curve as the CW pump power is increased further[10]. To reflect this fact, Bao *et al.* [12] have fitted experimental measurements of the Brillouin gain curve to an equation of the following form:

$$g_B(\nu) = g_{SBS}\left\{C\frac{1}{1+\left[(\nu-\nu_B)/(\Delta\nu_B/2)\right]^2} + (1-C)\exp\left[-\ln(2)\frac{(\nu-\nu_B)^2}{(\Delta\nu_B/2)^2}\right]\right\} \qquad \text{2-2}$$

C is a constant that defines the relative proportions of the Gaussian and Lorentzian contributions to the curve.

The gain curve is also dependent on the temporal width of pump pulses. Until recently, experimental evidence showed only that the Brillouin linewidth increased as the pump pulsewidth was reduced from quasi-cw conditions to pulses approaching the phonon lifetime of ~10-ns [11]. However, experiments using pump pulses shorter than 5-ns have demonstrated narrowing of $\Delta\nu_B$ almost back to the CW value [12].

The peak value of the Brillouin gain coefficient, g_{SBS}, is dependent on the material properties of fibre the spectral width of the pump and any modulation scheme applied. For a pump of spectral width $\Delta\nu_p$ (FWHM), the peak gain coefficient is given by [13, 14]

$$g_{SBS} = \left(\frac{4\pi n^8 p_{12}^2}{c\lambda_p^3 \rho_0 \nu_B \Delta\nu_B} \right) \left(\frac{\Delta\nu_B}{\Delta\nu_B \otimes \Delta\nu_p} \right) \qquad 2\text{-}3$$

where

n is the refractive index of the medium,

p_{12} is the dimensionless longitudinal elasto-optic coefficient,

c is the speed of light in a vacuum (m/s),

ρ_0 is the material density (kg/m^3) and

ν_p is the peak frequency of the pump wave (Hz).

The symbol $\otimes$ represents the convolution of the pump and Brillouin linewidths. For Gaussian profiles, the convolution equates to $\Delta\nu_B \otimes \Delta\nu_P = \left(\Delta\nu_B^2 + \Delta\nu_P^2\right)^{1/2}$, whereas for the more common assumption of Lorentzian profiles, $\Delta\nu_B \otimes \Delta\nu_P = \Delta\nu_P + \Delta\nu_B$.

2.1.2 SBS Threshold

A number of definitions of the threshold pump power for SBS in optical fibres can be found in the literature. The SBS threshold has been variously defined as:

1) the input optical power at which the emerging backscattered power equals the input power [9, 15].

2) the input optical power at which the emerging backscattered and transmitted powers are equal [16, 27].

3) the input pump power at which the backscattered power begins to increase rapidly or, equivalently, the pump wave begins to be depleted [17, 18].

4) the input power at which the backscattered power at the fibre input is equal to 1% of the input pump power at this point [19, 23].

The first definition seems impractical, since it implies a point at which optical power backscattered out of the fibre begins to exceed the power launched into the fibre. However, this definition is based on the assumption that the backscattered wave builds up due to amplification of spontaneous noise in the fibre. In practice, the measured SBS threshold is often quoted using definition 2 or 3. It is then usually compared with theoretical figures calculated using equation 2-4 below, which is actually derived for definition 1.

In analytical treatments of SBS, it is normally assumed that the pump power is significantly higher than the Stokes power and is not appreciably depleted by the scattering process. The optical power in the pump wave is assumed to decrease along the fibre, but only due to the usual linear attenuation found in single mode fibres. Using this undepleted pump approximation and taking definition 1 for the SBS threshold, P_{th} for a fibre of length L can be estimated from [9]:

$$P_{th} \cong 21\frac{K_{SBS}A_{eff}}{g_{SBS}L_{eff}}.$$

The term K_{SBS} is a polarisation factor and L_{eff} is the effective length of the fibre, given by:

$$L_{eff} = \frac{1}{\alpha}\left[1-\exp(-\alpha L)\right],$$

where α is the attenuation of the fibre in neper/km. The attenuation coefficient is assumed to be identical for the pump and Stokes waves since they are so closely spaced in frequency. Equation 2-4 also assumes that the Brillouin gain coefficient curve is Lorentzian - an assumption which appears to be valid in the small signal regime.

The value of the polarisation factor, K_{SBS}, depends on the polarisation of the pump and Stokes waves and takes values between 1 and 2. K_{SBS} is minimised for pump and probe pulses that are co-polarised along the entire length of the fibre. For completely scrambled polarisation, a value of 1.5 has been quoted [20], and a value of 2 has been given for conventional fibres [21].

Although equation 2-4 is widely used in the literature, the results of a recent COST intercomparison lead to a recommendation to the ITU that the threshold equation be adapted to [22]:

$$P_{th} \cong 19\frac{K_{SBS}A_{eff}}{g_{SBS}L_{eff}}$$

Bayvel *et al.* [23] pointed out that definition 1 corresponds to the input power at which the backreflected Stokes intensity equals approximately 10% of the input intensity at the near end of the fibre. These authors chose to use definition 4 for the SBS threshold, which they equated to a threshold power given by equation 2-6 with the factor of 19 replaced with 18. It is important to note that both definitions 1 and 4 have an advantage over 2 (and 3 if pump depletion is the indicator) for experimental determination of the SBS threshold. If the SBS threshold is defined only in terms of the input and backscattered power, then only two absolute power measurements need to be made, rather than three when the transmitted power is measured.

2.2 Measurement Techniques

2.2.1 Brillouin Gain Coefficient

The Brillouin gain coefficient consists of three key parameters - the frequency shift, ν_B (~10-GHz), the linewidth, $\Delta\nu_B$ (~40-MHz) and the peak gain, g_{SBS} ($\sim 5\times10^{-11}$-m/W). Measurement of the frequency shift is becoming increasingly important as a technique for studying distributed temperature and strain along fibres [6]. The linewidth and peak gain of the Brillouin spectrum play crucial roles in determining the SBS threshold under arbitrary pump spectra and are therefore important metrological issues for telecommunications applications. Although some measurement techniques have been used to measure both ν_B and $\Delta\nu_B$ simultaneously, many lack the spectral resolution of a few MHz required for the Brillouin linewidth. Three methods for measuring the Brillouin gain coefficient in optical fibres are outlined below and their relative merits discussed within the context of accurate characterisation of Brillouin scattering in optical fibre.

2.2.1.1 Fabry-Perot Interferometer

The general experimental system for measuring the backscattered Stokes signal optically with a Fabry-Perot device is shown in Figure 1. Detectors 1 and 2 are included to monitor the launch and backscattered powers respectively and an optical isolator is used to prevent scattered light from re-entering and de-stabilising the source.

The earliest experimental investigations of SBS in optical fibre made use of a Fabry-Perot etalon to analyse the backscattered wave and deduce the Brillouin frequency shift [24]. The resolving power of the etalon was not sufficient to actually measure the shape of the gain curve, only to indicate a value of the frequency shift of 32.2-GHz for a pump wavelength of 535.5-nm. More recently, a Fabry-Perot interferometer with 9.7-GHz free spectral range and a finesse of 195 has been used for similar measurements of the Brillouin frequency shift [25]. The minimum resolved bandwidth of this device, $\Delta\nu_{FP}$, was ~50-MHz - slightly larger than the anticipated $\Delta\nu_B$ value of 40-MHz. The transmission frequency of the Fabry-Perot, ν_{FP}, was scanned until a maximum signal was found to pass through the device at $\nu_{FP} = \nu_B$. The peak power transmitted through the Fabry-Perot was assumed to be equal to the backscattered power, since $\Delta\nu_{FP} > \Delta\nu_{BS}$.

Brillouin gain curve measurements have been successfully performed using a "supercavity" Fabry-Perot interferometer with 6-GHz FSR and finesse in excess of 10^4 [10]. The minimum resolved bandwidth of this device was approximately 0.6-MHz - sufficient to measure the width of the Brillouin spectrum and study narrowing and shape changes as the cw pump power was increased from 5.8-mW to 66-mW for a 500-m length of conventional fibre.

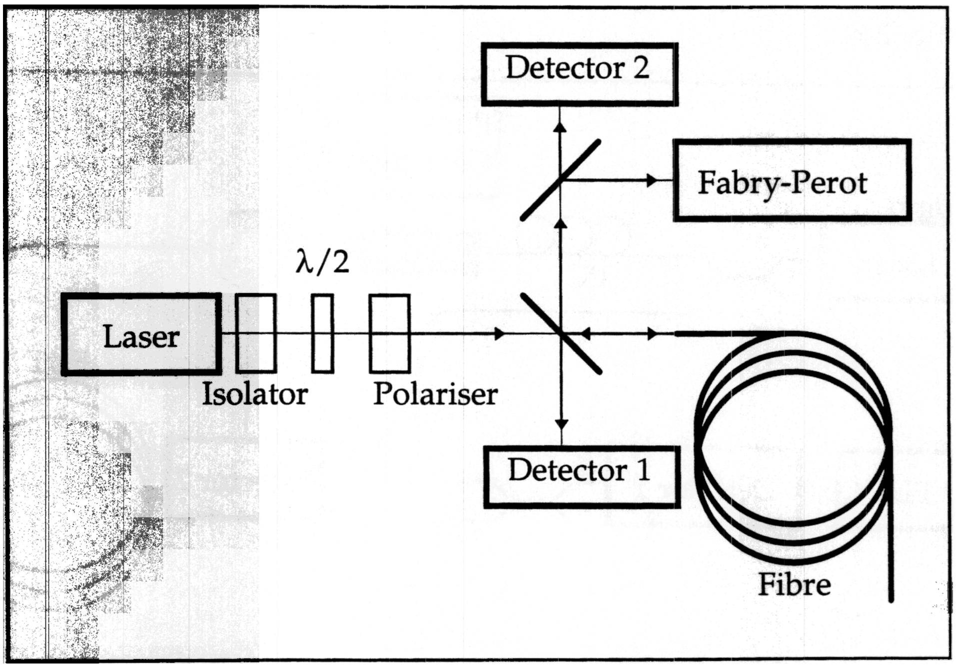

Figure 1. Experimental system for measuring the backscattered Brillouin spectrum from an optical fibre (after [10]).

Advantages of this method:

- Relatively simple construction and operation.

Disadvantages:

- Resolution of a few MHz is a demanding specification for a Fabry-Perot interferometer.

2.2.1.2 Pump-Probe Techniques

Pump-probe techniques refer here to those methods whereby the gain of a CW probe signal due to Brillouin amplification is measured as counterpropagating pump pulses are launched into the fibre. These methods may used for distributed measurements of the Brillouin frequency shift if the pump pulses are narrowed until the interaction length between the pump and probe waves is of the order of a few metres [11]. For longer pulses, the interaction may exceed the fibre length and an average value of the Brillouin gain can be measured.

A pump-probe technique was recently used to study the variation in the width of the Brillouin gain spectrum as the pump pulse width was varied between 1-ns and 100-

- allows distributed measurement, authors achieved resolution of 500-mm.

Disadvantages:

- direct detection of fluctuations on top of the co-propagating CW probe signal rather than looking at a backscattered signal.

- time domain measurements require a fast digitising scope (authors used 4-gigasample/s).

An interesting variation on the pump-probe Brillouin gain method has been proposed by Thevenaz, Nicklès *et al.* [6, 7, 26] A single 150mW, 1.32-μm Nd:YAG (typical $\Delta\nu_P \approx$ 20-kHz [29]) laser source is used to derive both the pump and probe pulses. The system used is shown schematically in Figure 3 below.

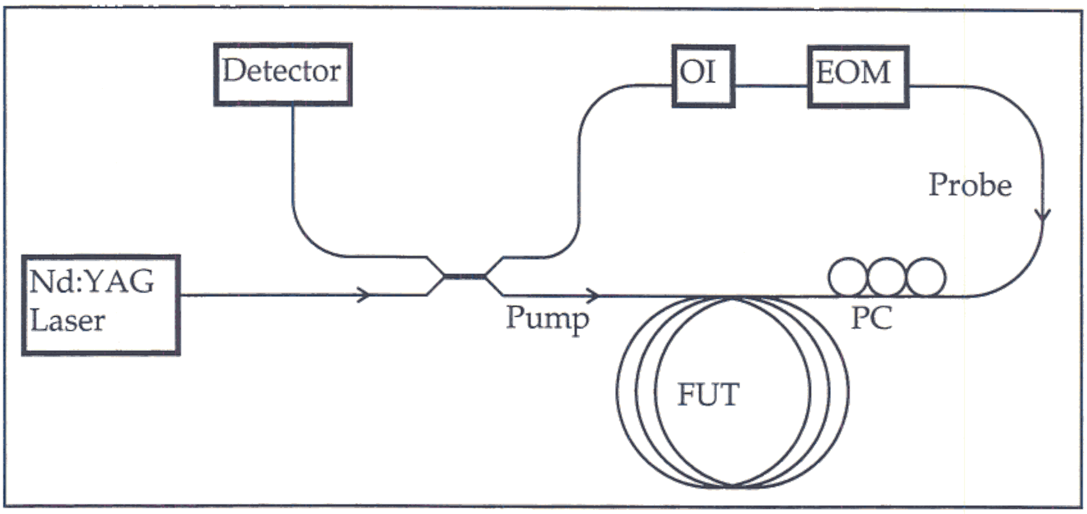

Figure 3. Experimental system used by Thevenaz et al. to measure Brillouin gain spectra in optical fibre (after ref. 7)

A wide band lithium niobate optical intensity modulator is used to generate and tune sidebands of the pump wave so that the lower frequency sideband falls within the Brillouin gain band of the carrier signal. The upper sideband may be suppressed using a narrow-band filter if necessary - leaving the main pump signal and the counterpropagating lower sideband. The sideband is amplified through Brillouin amplification within the fibre and the Brillouin gain spectrum can be calculated from the measured gain as the frequency of the modulator is swept. If the pump can be assumed to lose negligible power during the interaction with the probe, then analysis of the measured gain is simplified by the undepleted pump approximation. Assuming that the intensity of the pump wave is not significantly reduced along the test fibre, the Brillouin gain coefficient, $g_B(\nu)$, at frequency difference ν can be found from [7]

$$I(L,\nu) = 2I(0,\nu)\cosh\left(g_B(\nu) I_P L_{eff}\right) \qquad 2\text{-}7$$

where

differences (GHz) and spectral widths (MHz) found in optical fibre Brillouin scattering. A typical experimental arrangement for heterodyne analysis of backscattered light is shown in Figure 4.

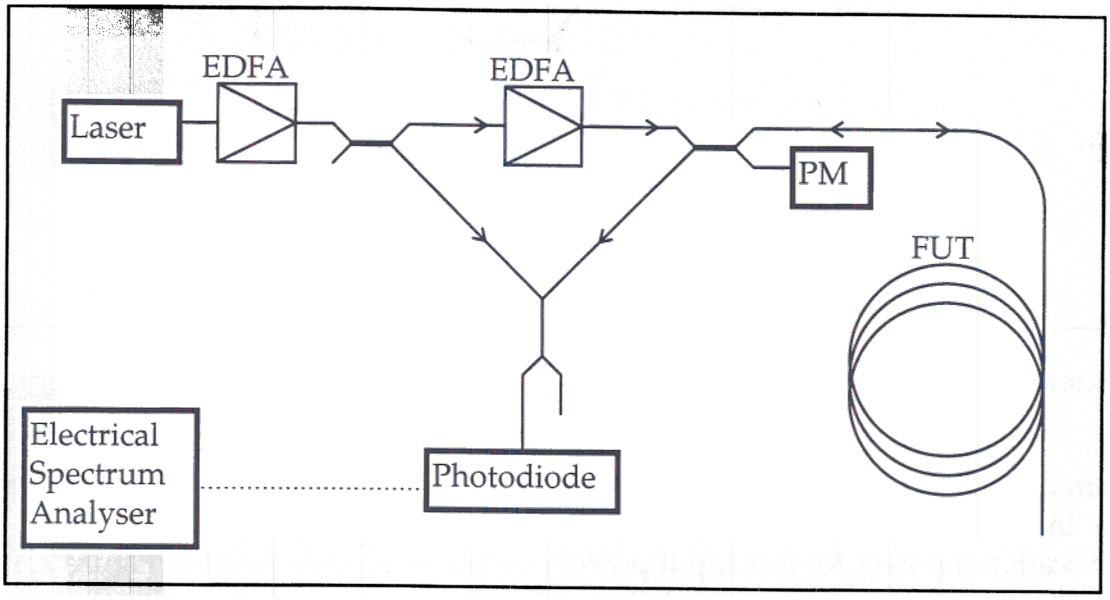

Figure 4. Typical arrangement for spectral analysis of the backscattered wave due to Brillouin scattering (after ref. 15)

The source laser must have a spectral linewidth less than the Brillouin gain linewidth. External cavity, DFB LD and Nd:YAG lasers are commonly used for this purpose. The power spectrum of the beat signal between the local oscillator and the backscattered signal is measured without tuning the wavelength of the source laser. Since it is only the relative frequency of the pump and Stokes waves that is being measured, this technique is more immune to source frequency drift than Fabry-Perot and pump-probe methods.

2.2.2 SBS Threshold

The SBS threshold of optical fibre can be calculated from the gain spectrum but is usually measured directly using an experimental system similar to that shown in Figure 5. The optical power launched into the fibre must be variable over a range that includes the SBS threshold, which is typically between 10 and 20-mW but depends on the length of the fibre and the spectral width of the source. In Figure 5, the output from a tuneable laser diode is amplified with an optical amplifier and controlled with a variable attenuator to give a range of launch powers between 0-mW and 50-mW. Optical power meters are used to measure the input, transmitted and backscattered powers as the input power is varied. From the optical power measurements, the SBS threshold can easily be determined using any of the definitions outlined in section 2.1.2.

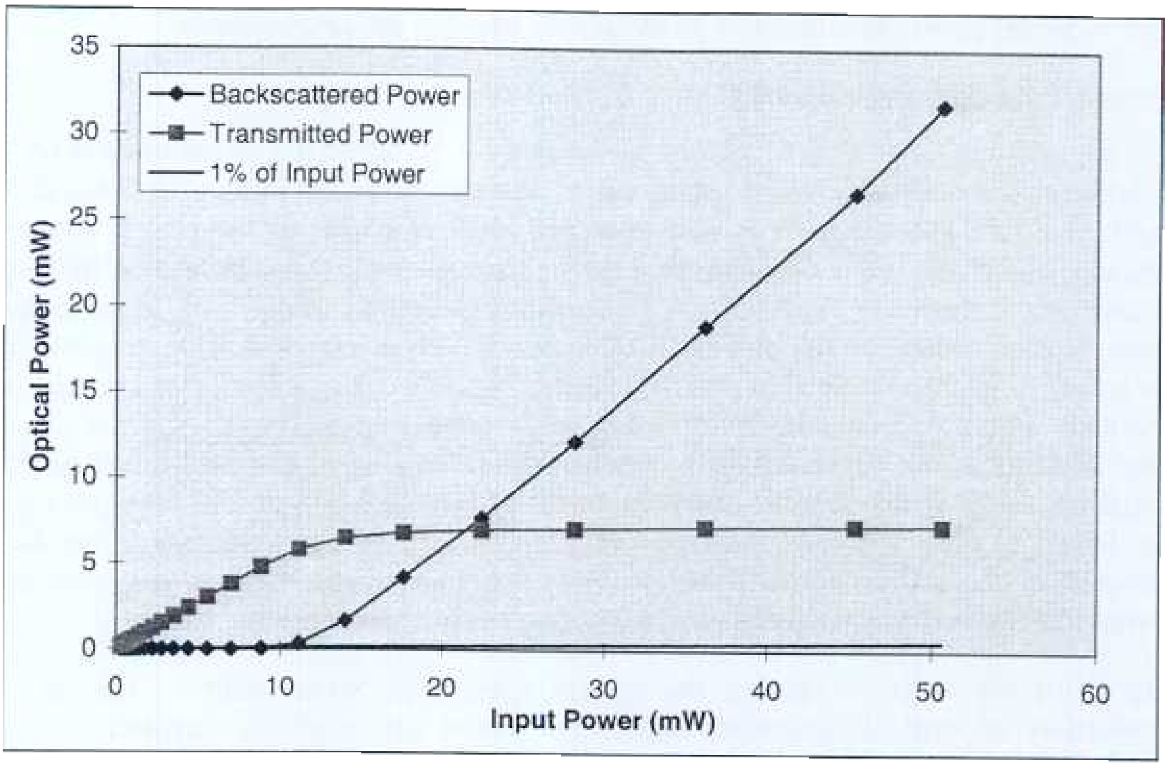

Figure 6. *Backscattered and transmitted powers vs. launch power measured for a 10-km length of matched-cladding fibre [27].*

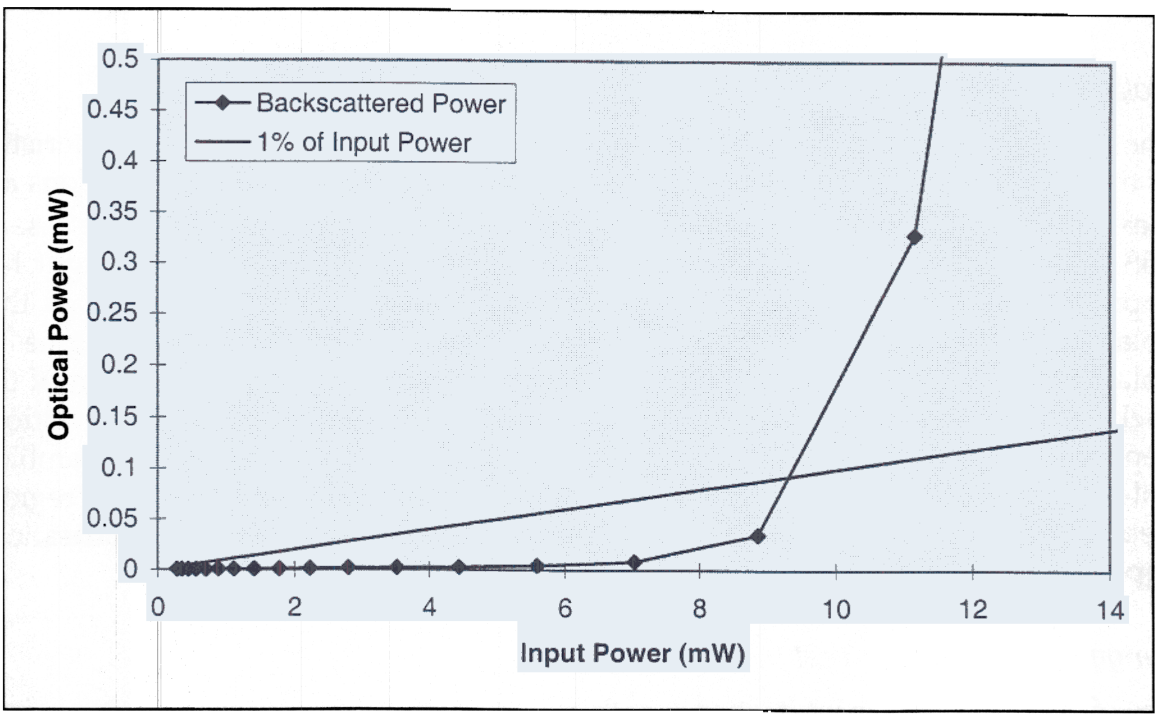

Figure 7. *Backscattered power measured as a function of input launch power for a 10-km length of matched-cladding fibre.*

length of fibre required to reach the asymptotic threshold increases for lower loss fibres. Figure 8 illustrates this behaviour. The SBS threshold was calculated for a fibre with $A_{eff} = 50\mu m^2$, $g_{SBS} = 4.6\times10^{-11} m/W$, $K_{SBS} = 2$, $\Delta\nu_B = 40-$MHz, $\Delta\nu_P = 100-$KHz and the fibre attenuation values of 0.2-dB/km and 0.4-dB/km. For a narrow linewidth cw pump with completely scrambled polarisation the asymptotic length is predicted to be approximately 100-km for a fibre with 0.2-dB/km loss. The threshold power was calculated to be 47.9-mW for a 1-km length and 2.1mW for 100-km. For a typical supplied length of 20-km of 0.2-dB/km fibre, the SBS threshold will be approximately 3.5-mW if the pump linewidth is significantly narrower than the Brillouin linewidth.

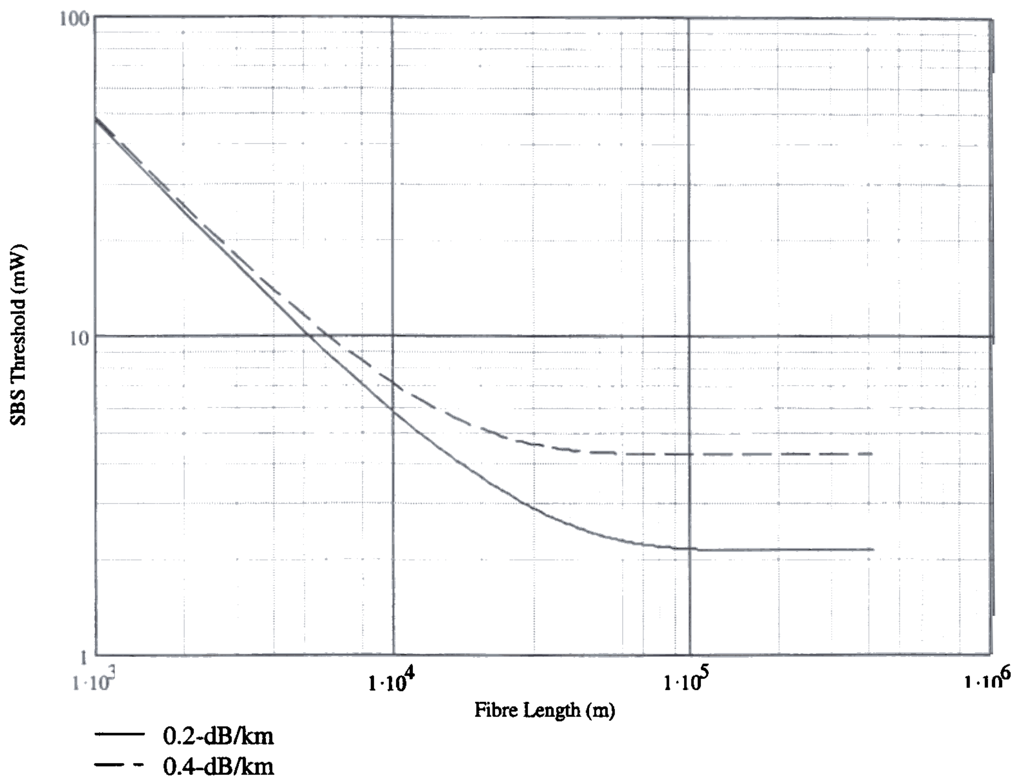

Figure 8. Calculated SBS threshold vs. fibre length for fibres with differing attenuation coefficient.

Variations in Dopant Concentration

The addition of dopants such as germania and fluorine to the basic fused silica material of an optical fibre changes the Brillouin shift, ν_B, i.e. the Stokes frequency at which maximum gain occurs. If the dopant concentration fluctuates along the length of the fibre, then the build-up of any single Stokes frequency component is less efficient than for the peak of the fixed gain spectrum. The SBS threshold is essentially determined by the growth of the Stokes frequency with the highest gain and therefore varying the Brillouin shift increases the SBS threshold. Theoretical investigations have shown that the change in SBS threshold induced by varying the frequency shift along a fibre depends on the shape of the longitudinal Brillouin shift distribution and not simply the maximum variation in ν_B [15]. The results also showed that variations near the pump end of the fibre could have a more significant effect than those at the far end. This would lead to a measured SBS threshold that depends on the direction of the pump wave.

Brillouin Gain Linewidth Dependence on Pump Characteristics

The spectral width and form of the Brillouin gain curve, $\Delta\nu_B$, is not constant but is dependent on the power in the pump wave and also the pump pulse width. To be able to calculate the SBS threshold under for any pump signal, it is theoretically necessary to fully characterise the dependence of the Brillouin linewidth on both the pump pulsewidth and power. However, linewidth narrowing due to increased pump power tends to become significant only above threshold. Also, measurements are likely to be performed using cw pump to reduce uncertainties on the measured optical powers. It is therefore likely that for cw measurements at powers up to and not greatly exceeding the SBS threshold, $\Delta\nu_B$ can be assumed to be constant.

Use of Angled Fibre Connectors

The use of angled connectors in high-power optical fibre systems can increase the uncertainty of absolute power measurements made with commercial power meters. Angled fibre connectors are used to reduce high power back-reflections and prevent laser sources from becoming destabilised. There is no guarantee that the optical detector in a commercial fibre-optic power meter will be fully excited by the spatial power distribution leaving an angled endface. The uncertainty on absolute optical fibre power attainable at NPL for FC/APC connectorised fibres is ±0.5% at -10dBm. It is estimated that a commercial optical fibre power meter may increase this uncertainty to ±2% when angled connectors are used [27]. Optical fibre power meter sensor heads have been developed at NPL that position the fibre endface directly in front of a bare photodiode chip, rather than imaging through lenses and then the chip window. It is anticipated that such detectors will be less sensitive to the use of angled fibre connectors and hence these detectors may be used in preference to commercial power meters. Such detectors may give low uncertainty at low (<0-dBm) optical powers but can exhibit a nonlinear response at higher powers. The development of high-accuracy optical fibre power measurements is an active area of research at NPL. One possibility is to use detectors based on an integrating sphere, which can attenuate the optical power into the linear region of the detector response.

Definition of the SBS Threshold

Clarification is required as to the operational definition of the SBS threshold. The ITU recommendation for SBS threshold measurement seems to use the input pump power at which the fibre-transmitted output power equals the emerging backscattered power [21]. This corresponds to definition 2 of section 2.1.2 above. However, the equation stated in the same document for calculating the threshold power is from Smith's [9] definition of P_{SBS} and corresponds to definition 1 in section 2.1.2. Typically, experimental data is presented in the literature that shows the transmitted and backscattered optical powers from the test fibre. The theoretical threshold value is then calculated from equation 2-4 and compared with the measured data. The calculated threshold typically coincides with the region where

2.3 Special Considerations in Brillouin Scattering Measurements

Source Linewidth Dependence

For a given fibre, the SBS threshold as defined by equation 2-4 is dependent on the relative spectral widths of the pump signal and the Brillouin linewidth through the peak Brillouin gain, g_{SBS}. **It is vital that the spectral width of the pump source is known, or at the very least known to be significantly less than the Brillouin linewidth. Otherwise the measured threshold power is essentially meaningless.** This requires either the use of a calibrated source with known spectral characteristics or a facility to accurately characterise arbitrary sources. It is also important that any intensity, phase or frequency modulation subsequently applied to the source is taken into account in the spectral width measurement. To exceed the SBS threshold, the source spectral width should be of the order of tens of MHz or less, depending on the length of fibre and the source power. Equation 2-4 assumes that the pump has a Lorentzian spectral power distribution. A facility to measure the source spectrum in detail may be necessary to confirm the validity of this assumption.

The difficulty with measuring the optical spectra of MHz width is the lack of resolution of optical spectrum analysers, which are typically limited to GHz resolution. Heterodyne detection can be used to bring the spectral width to within the range of electrical spectrum analysers but providing a suitable local oscillator can present difficulties at arbitrary pump wavelengths. Delayed self-heterodyne detection is one method of solving this problem [28]. The technique has been used to provide 50-kHz resolution at a pump wavelength of 840-nm and to measure the 20-kHz linewidth of a cw Nd:YAG laser at 1300-nm [29].

Relative Source-Stokes Wave Polarisation

The polarisation of the pump wave and the polarisation-maintaining characteristics of the fibre also affect the threshold through the constant, K_{SBS}. SBS interactions are maximised for pump and Stokes waves with parallel polarisation [20]. In the case of SBS built up from noise in the fibre, below threshold the backscattered light has approximately half as much power polarised perpendicular to the pump as that polarised parallel. Once the SBS threshold has been exceeded the degree of polarisation of the backscattered light increases to 100% and the polarisation of the backscattered wave completely matches the pump. To avoid polarisation-dependence in SBS measurements, the pump polarisation should be scrambled unless it can be maintained in a known state along the interaction region. Depolarised measurements will have the additional benefit of reducing polarisation-dependent losses in power splitters and circulators.

Length of Fibre Under Test

The effective nonlinear interaction length of optical fibre is not linearly proportional to the actual fibre length but is given by the effective length formula (equation 2-5). The SBS threshold is therefore dependent on the length of fibre used and the attenuation coefficient. Equation 2-4 predicts that the SBS threshold initially falls with increasing fibre length but then tends asymptotically to a uniform value. The

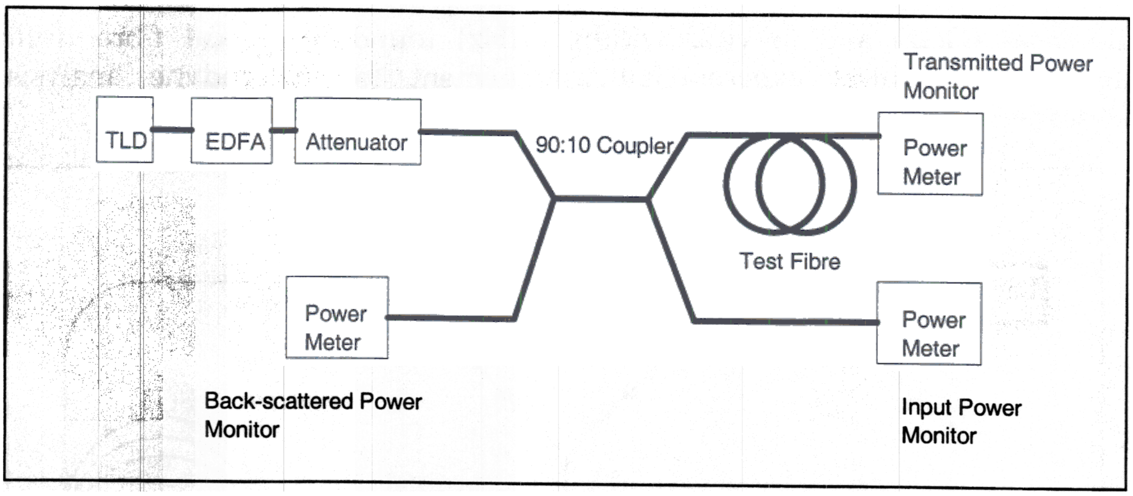

Figure 5. Experimental system used at NPL to study stimulated Brillouin scattering in optical fibre [27].

Examples of optical power measurements made previously at NPL to investigate SBS in a 10-km length of matched-cladding fibre are shown in Figure 6. The backscattered power for low input powers is shown in more detail in Figure 7. It can be seen that for input powers below ~20-mW, the backscattered optical power initially increases linearly with launch power due to Fresnel reflection from the far end. However, as the launch power approaches the SBS threshold, the backscattered power increases rapidly and the input pump power becomes depleted. Beyond the threshold, the transmitted optical power is clamped and excess input power is transferred to the backscattered wave. The SBS threshold can be estimated from this experimental data using any of the definitions of section 2.1.2. Using definition 2, the SBS threshold is approximately 22-mW whereas definition 4 gives a significantly lower value of around 9.2-mW.

$I(L,\nu)$ is the measured probe intensity at frequency ν after Brillouin gain over a length L of fibre,

$I(0,\nu)$ is the intensity of the probe signal before amplification and

I_P is the intensity of the pump wave.

Note that the intensity values in equation 2-7 must be calculated from optical power measurements taken at each end of the fibre under test and divided by A_{eff}. The power measurements can be made by using optical couplers to branch-off part of the optical power entering and leaving each end of the fibre to optical power meters. The measured values must be corrected from relative to absolute powers to calculate the Brillouin gain coefficient. This can be done by breaking the fibre at the input and output ends of the gain section and comparing the actual absolute power with that measured in the corresponding branch.

For distributed measurements, only a single end of the fibre is accessed and pulsed pump and probe signals are used to scan the interaction region along the fibre. The counterpropagating probe pulses are produced by Fresnel reflection from the far end of the fibre. The pump and probe signals are generated with a variable time delay by applying a dc pulse and small ac signal respectively to the biased modulator. An advantage of pulsed measurements - even when distributed data is not required - is that the interaction between the pump and probe pulses is spatially limited. It is therefore easier to ensure that the undepleted pump approximation used in the derivation of equation 1 remains valid.

Advantages of this method:

- Requires only a single source
- Resolution of gain spectrum measurement is of the order of hundreds of kHz
- High accuracy distributed strain measurements possible with access to only one end of the fibre

Disadvantages:

- Very wide bandwidth modulator required
- High-power cw laser required
- High (~4.7-dB) insertion loss into EOM

2.2.1.3 Self-Heterodyne Technique

If the Stokes wave generated through the Brillouin scattering process can be heterodyned with the pump wave or a similar frequency wave, then electrical spectral analysis can be used rather than optical. This has the immediate advantage of higher spectral resolution than optical spectral analysis for the frequency ns [12]. The experimental system used is schematically illustrated in Figure 2. Two narrow-linewidth CW 1320-nm Nd:YAG lasers were used as the pump and probe sources with the pump signal pulsed using an electro-optic modulator driven by a pulse generator. The frequency separation between the two lasers was variable and controllable to within 1-Hz using heterodyne detection and a phase-locked loop. The pump and probe signals were launched into opposite ends of the fibre and the power in the forward-propagating probe signal measured leaving the pump input end of the fibre.

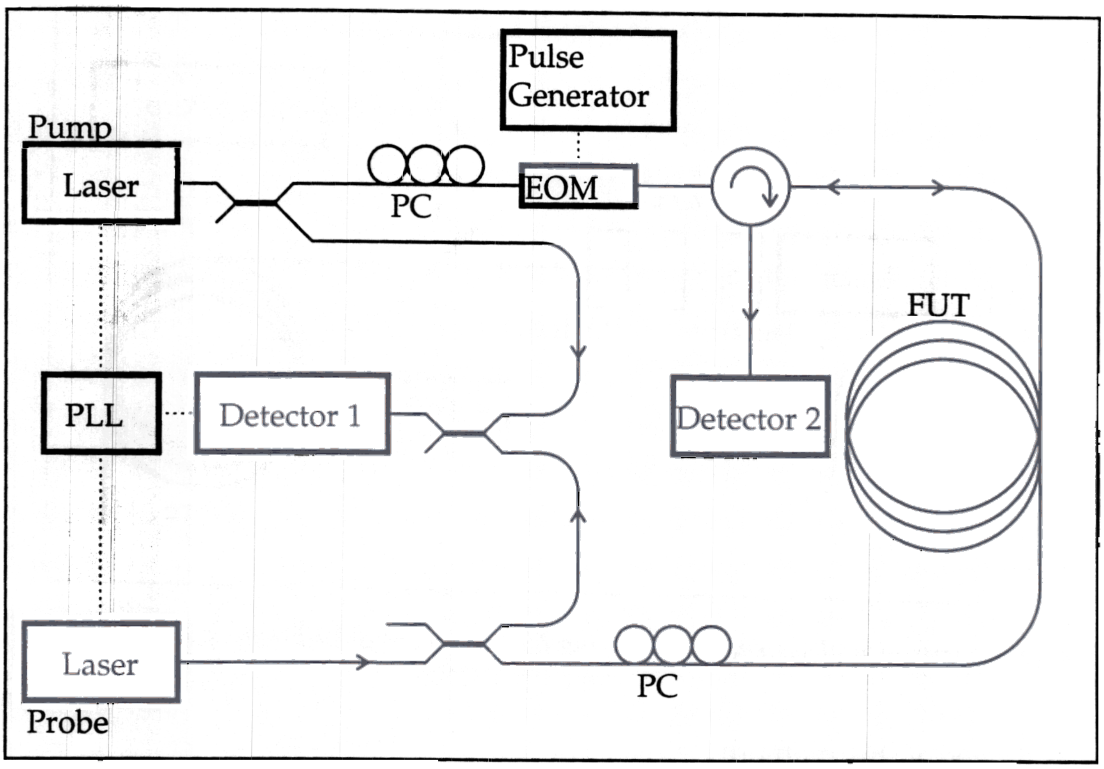

Figure 2. *Pump-probe arrangement for measuring Brillouin gain coefficient (after [12]).*

With no pump wave present the probe signal is expected to suffer a uniform loss due to Rayleigh scattering and absorption. The output from detector 2 is therefore constant. When a pump pulse is launched into the fibre, it propagates in the opposite direction to the probe wave and amplifies it through the process of spontaneous Brillouin amplification. The gain of the process varies along the fibre as the Brillouin shift $\Delta\nu_B$ changes along the length due to the mechanical conditions such as temperature and strain. The time-varying probe signal at detector 2 can then be analysed to build up a map of the Brillouin gain at frequency shift $\nu_{probe} - \nu_{pump}$ occurring along the fibre. By tuning this frequency shift and repeating the measurements, the Brillouin gain curve may be mapped along the fibre with resolution determined by the pump pulse width.

Advantages of this method:

- gain spectrum may be scanned with resolution limited by the characteristics of the phase-locked loop i.e. its resolution and bandwidth.

the backscattered power begins to increase rapidly and this is taken to show agreement between theory and experiment.

Operational definitions exist in which the threshold is defined at the input power at which the backscattered Stokes power equals a smaller percentage of the input power than at the threshold value given by equation 2-4. These definitions apparently give improved measurement repeatability and one has been recommended to the ITU as an amendment to the SBS reference test method.

2.4 Conclusions

The Brillouin gain curve has been found in the literature to be dependent on source power and pulsewidth. Had this not been the case, the Brillouin gain curve would be the most useful SBS measurement since Brillouin gain and the SBS threshold can be calculated from $g_B(\nu)$ for any source spectrum. However, measuring the gain coefficient is complicated and does not actually avoid the problem of source dependence.

The SBS threshold can be calculated from the measured Brillouin gain curve but this has also been found to depend on the source characteristics. Specifically, the Lorentzian line shape of the spontaneous Brillouin scattering gain curve evolves into a Gaussian shape as the pump power is increased up to the SBS threshold. The width of the gain curve also decreases as the input pump power is increased. If the pump wave is pulsed rather than cw, then the linewidth is also dependent on the pulse duration - assuming a maximum value for pulses approximately 10-ns wide. Therefore, although the Brillouin gain coefficient could be offered as a measurement service, its usefulness may be restricted to cases where the signal in the fibre closely resembles the measurement conditions.

It is essential to know the spectral width of the source used to measure the SBS threshold. For sources with $\Delta\nu_P << \Delta\nu_B$, the precise spectral width is less important and the SBS threshold is effectively independent of $\Delta\nu_P$. However, as the source spectrum approaches the Brillouin linewidth, the gain coefficient is reduced and the measured threshold increases. The question arises of at what source spectral width should P_{SBS} be quoted. The asymptotic value for narrow pump spectra seems the obvious choice since this is independent of the shape of the source spectrum and should correspond to the theoretical value given by equation 2-4.

The operational definition of the SBS threshold needs clarification. A number of definitions have been used in the literature and it has been illustrated that large discrepancies can occur as a result. This is an area that must be resolved, although it is essentially a data analysis issue and could be resolved by providing multiple SBS threshold values from the same measured data.

2.5 Recommendations

SBS measurements should be restricted primarily to SBS threshold with a cw source of known linewidth. Either a calibrated source should be used or a facility provided

3. Raman Scattering in Optical Fibre

3.1 Parameter Definitions

3.1.1 Raman Gain Coefficient

Stimulated Raman scattering (SRS) is similar to SBS in that it is an inelastic process in which energy is transferred to the medium and a lower frequency Stokes wave is generated. Unlike SBS, however, the lower frequency Stokes wave can propagate in the forward as well as the backward direction. Also, because the interaction generates optical rather than acoustical phonons, the energy difference between the pump and Stokes wave is significantly larger than in SBS. This translates into a much greater frequency shift - of the order of 10-THz compared to 10-GHz in stimulated Brillouin scattering.

The Raman gain coefficient, $g_R(\nu)$, is significantly smaller than the Brillouin gain coefficient and has been measured to be of the order of 3×10^{-14} m/W for standard single mode fibre pumped at 1550-nm [30]. The gain spectrum of the amorphous glassy materials used to produce optical fibre also has a much broader spectrum than that of SBS. The gain curve typically extends over a range of up to 40-THz in bulk samples of fused quartz and in silica fibres. The Raman gain spectrum consists of a main peak with a number of smaller peaks in the tails. An example of a typical Raman gain curve for fused silica is shown in Figure 9.

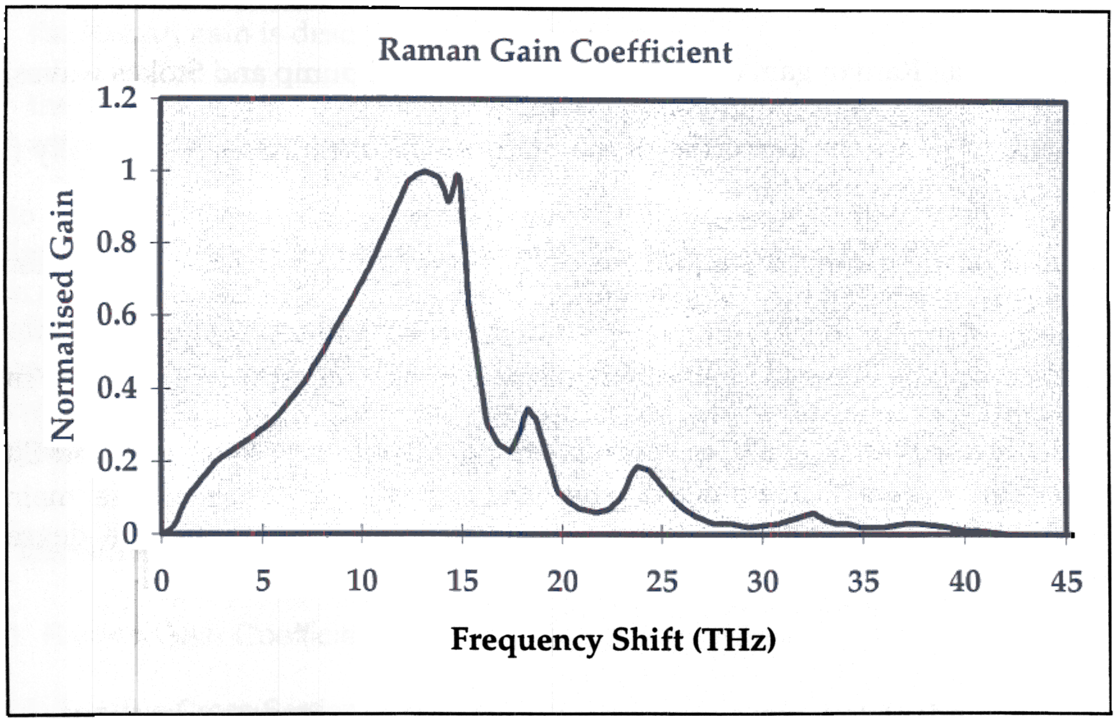

Figure 9. *Typical Raman gain spectrum. Data supplied by J. R. Taylor, Femtosecond Optics Group, Dept. of Physics, Imperial College, London.*

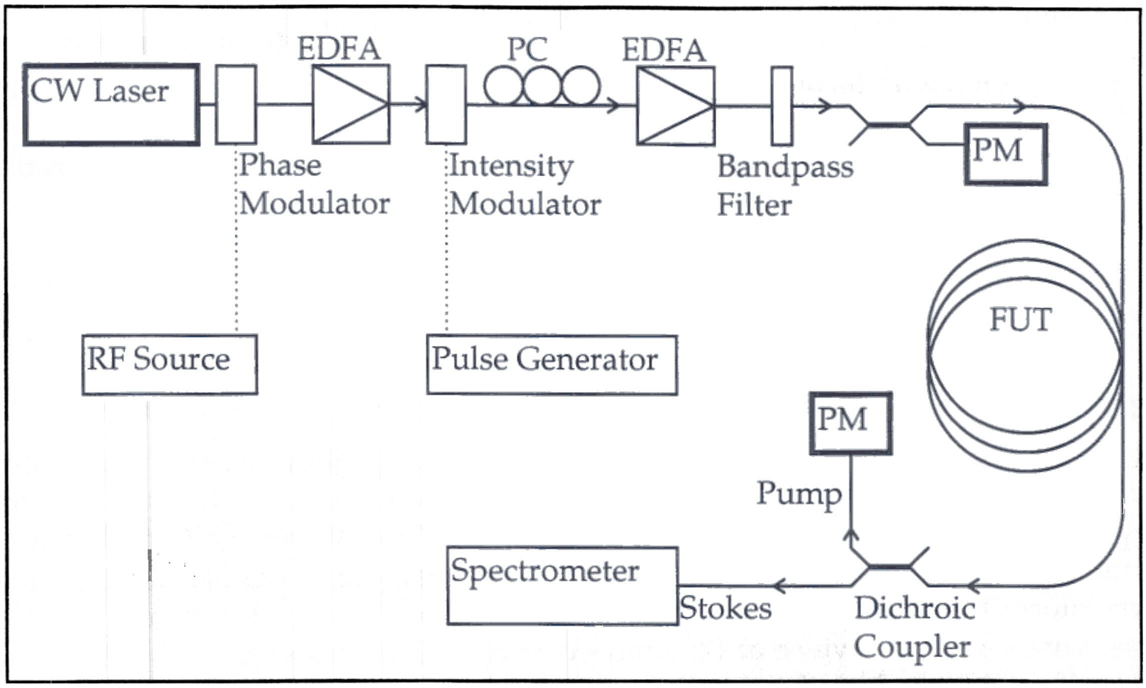

Figure 10. Experimental pulse-scan apparatus as used by Mahgerefteh et al. [30].

The average power in the pump pulses was set to 120-mW for all pulses by operating the optical amplifier at saturation. The peak power was also kept constant at 3.94-W by maintaining a fixed pulse duty cycle together with the constant average power. Stimulated Brillouin scattering was suppressed using a lithium niobate phase modulator operating at between 2 and 3-GHz.

The average Stokes power emerging from the fibre at frequency ν was measured as a function of pulse duration. A parameterised curve was then fitted to the results by using the gain coefficient, $g_R(\nu)$, and group velocity mismatch as the free parameters. The peak gain coefficient, g_{SBS}, calculated by this method agreed well with the results of other gain measurements performed on the same fibre. Typical experimental values for g_{SRS} determined by this method were around 3×10^{-4}-m/W with the absolute uncertainty calculated to be ±5%. The main limitation of this method is that the forward-scattered signal must be separated from the pump wave at the fibre output. For Stokes wave components with 3-THz of the pump wave, it was necessary to use a tuneable band-pass filter before the spectrometer to maximise sensitivity. Otherwise the accuracy of the Raman gain measurement deteriorates rapidly near the pump wavelength. Even with the band-pass filter, the authors were unable to measure the gain coefficient within 1-THz of the pump signal.

Advantages of this method:

- Absolute value of the gain coefficient can be measured without the need for calibration with a known reference
- Single source required
- Pump and probe signals are automatically co-polarised

becomes comparable to the ASE of the Raman amplifier. The amplifier ASE is therefore measured separately with no input signal and is subtracted from the aggregate signal to give the gain curve for the ASE from the semiconductor optical amplifier. An example of a relative gain spectrum measured with a tuneable laser and ASE source is shown in Figure 12.

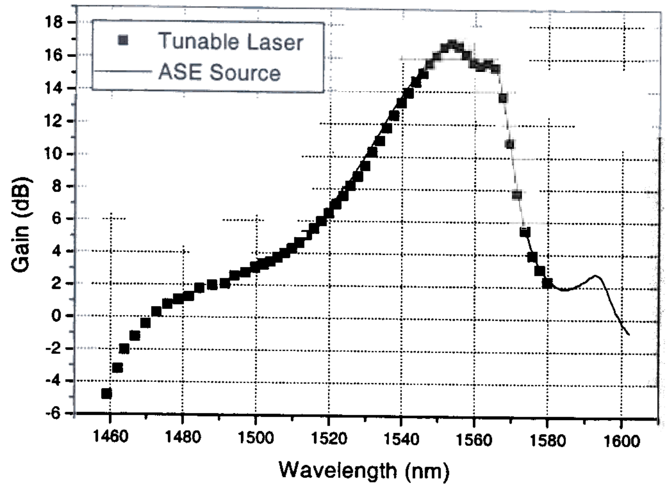

Figure 12. Measured Raman amplifier gain spectrum supplied by J. R. Taylor at Imperial College, London.

The gain curve in Figure 12 does not account for losses within the amplifier due to linear attenuation. These are measured using the tuneable laser and ASE source independently and at low enough power levels to avoid nonlinear effects. Once the spectral loss characteristics of the amplifier are known, the true gain of the amplifier can be calculated by subtracting the spectral loss curve from the spectral gain curve. The actual gain of the Raman amplifier is then related to the Raman gain coefficient through equation 3-4, in that:

$$\text{true gain}(\nu) = \frac{P_S(L,\nu)}{P_S(0,\nu)} = \exp\left\{\frac{g_R(\nu)}{K_{SRS}}\frac{P_P(0)}{A_{eff}}L_{eff} - \alpha_S L\right\}. \qquad 3\text{-}6$$

Equation 3-6 assumes the undepleted pump approximation and is therefore only strictly valid for small signal gain. To calculate the Raman gain coefficient from this expression, it is necessary to know the effective area of the fibre, A_{eff}, the optical pump power entering the gain fibre, $P_P(0)$, the true gain and the relative polarisation of the pump and Stokes wave. Examples of the relevant fibre parameters with uncertainties as supplied by Imperial College are shown in Table 1. Additional errors in the measurement procedure include variable reconnection losses in the FC/PC fibre connectors used at the input and output to the gain fibre. The resulting value for the Raman gain coefficient at a Stokes shift of 95-nm from the 1455-nm pump wavelength is 4.17×10^{-14} - m / W ±10%.

3. Raman Scattering in Optical Fibre

3.1 Parameter Definitions

3.1.1 Raman Gain Coefficient

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The Raman gain coefficient, $g_R(\nu)$, is significantly smaller than the Brillouin gain coefficient and has been measured to be of the order of 3×10^{-14} m/W for standard single mode fibre pumped at 1550-nm [30]. The gain spectrum of the amorphous glassy materials used to produce optical fibre also has a much broader spectrum than that of SBS. The gain curve typically extends over a range of up to 40-THz in bulk samples of fused quartz and in silica fibres. The Raman gain spectrum consists of a main peak with a number of smaller peaks in the tails. An example of a typical Raman gain curve for fused silica is shown in Figure 9.

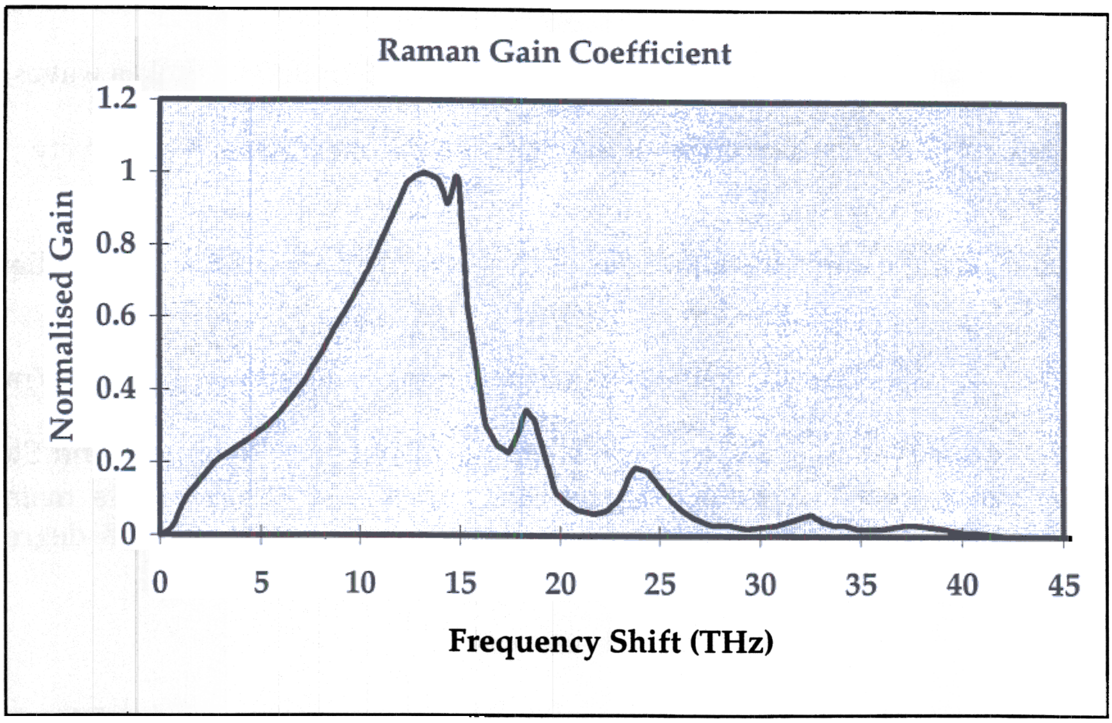

Figure 9. Typical Raman gain spectrum. Data supplied by J. R. Taylor, Femtosecond Optics Group, Dept. of Physics, Imperial College, London.

No functional form for the Raman gain curve has been suggested in the literature. For the purposes of calculating SRS thresholds, it is the main peak that contributes almost exclusively to the growth of the Stokes wave. The gain curve is usually assumed to consist of a single Lorentzian peak [9]. Calculations of SRS therefore make use of the peak value of the spontaneous Raman gain spectrum, g_{SRS}, taking this as the gain coefficient for SRS. However, for applications such as fibre Raman amplifiers and to calculate crosstalk in long-haul WDM communication systems, the actual shape of the Raman gain curve is important. The Raman gain coefficient is known to be inversely proportional to the pump wavelength and is dependent on the composition of the core material - varying significantly with the dopants used [31].

3.1.2 SRS Threshold

Under stimulated Raman scattering, the intensities of the pump and forward-propagating Stokes waves along the fibre are related by the coupled intensity equations [13]:

$$\frac{dI_S(z)}{dz} = \frac{g_{SRS}}{K_{SRS}} I_P(z) I_S(z) - \alpha_S I_S(z), \qquad \text{3-1a}$$

$$\frac{dI_P(z)}{dz} = -\frac{\omega_P}{\omega_S}\frac{g_{SRS}}{K_{SRS}} I_P(z) I_S(z) - \alpha_P I_P(z). \qquad \text{3-1b}$$

Where:

g_{SRS} is the peak Raman gain coefficient for co-polarised pump and Stokes waves,

$I_P(z)$ and $I_S(z)$ are the intensities of the pump and Stokes waves respectively (Wm^{-2}) at distance z along the fibre,

ω_P and ω_S are the angular frequencies of the pump and Stokes waves in radians/s and

α_P and α_S are the linear fibre attenuation coefficients at ω_P and ω_S (in neper/m).

K_{SRS} is a factor that depends on the relative polarisations of the pump and Stokes waves. Raman gain is maximised when the pump and Stokes waves maintain identical polarisation along the fibre. For conventional fibres, there is a degree of polarisation scrambling and a value of $K_{SRS} = 2$ has been suggested [32].

Making the undepleted pump approximation, the equation for intensity of the pump wave along the fibre reduces to:

$$\frac{dI_P(z)}{dz} = -\alpha_P I_P(z), \qquad \text{3-2}$$

Parameter	Value Used	Estimated Error
Fibre Length	9000-m	±1%
Fibre Loss at 1455-nm	0.3-dB/km	±5%
Fibre Effective Area	50.3-μm^2	±5%
Amplifier Loss at 1550-nm	4.6-dB	±4%
Amplifier Gain at 1550-nm	16.4-dB	±3%
Pump Power	870-mW	±8%

Table 1.Typical Raman amplifier parameters and estimated errors.

Advantages of this method:

- Use of cw signals makes accurate power measurements easier
- Counterpropagating pump and probe improves SNR and permits gain measurements at the pump wavelength
- Polarisation sensitivity avoided by using depolarised source and counterpropagating pump and probe signals

Disadvantages:

- Accuracy on ASE measurements is questionable if the gain measurement of the amplifier without the signal is performed under saturation

3.2.2 SRS Threshold

The forward threshold power at 1550-nm for SRS in a 10-km length of typical single mode fibre with $A_{eff} = 50\times10^{-12} - m^2$, $g_{SRS} = 4.17\times10^{-14}\text{-}m/W$, 0.2-dB/km attenuation and $K_{SRS} = 2$ is given by equation 3-5 to be 4.79-W. This is prohibitively high for direct experimental confirmation at 1550-nm. The definition of P_{th} for SRS requires that the input pump, output pump and output Stokes powers are measured simultaneously. The output from the fibre in the forward direction must therefore be split into pump and Stokes components separated by approximately 12-THz (~100-nm at 1550-nm). A basic experimental system for measuring the SRS threshold in an optical fibre is shown in Figure 13.

Precautions need to be taken to avoid the maximum cw launch power from being limited by SBS. The threshold power for SBS is typically a few tens of milliwatts when a narrow-linewidth (< 100-MHz) cw laser diode is used. However, this can be increased by using a source with a broader spectrum or by using a phase modulator to spectrally broaden the pump signal.

Disadvantages:

- High power levels required to reach SRS threshold
- Pulsed power measurements required, although pulses are comparatively long
- Accuracy decreases close to the pump wavelength since this method relies on discrimination between forward scattering pump and Stokes waves

3.2.1.3 Raman Amplification Method

The method currently employed at Imperial College, London, to measure the Raman gain coefficient in optical fibres is a cw Raman amplification technique. The basic experimental arrangement is shown in Figure 11. Pump and probe waves counterpropagate within the gain fibre and are separated at each end using optical circulators OC1 and OC2. The pump wave consists of the output from a fibre-Raman laser with 1-nm bandwidth at 1455-nm - corresponding to a spectral width of ~150-GHz. The SBS threshold for the fibre with this pump source is approximately 20-W, which easily exceeds the 870-mW typically coupled into the fibre. The counterpropagating configuration tends to average out high frequency power fluctuations in the pump and also reduces the requirement for optical selectivity at the spectrum analyser.

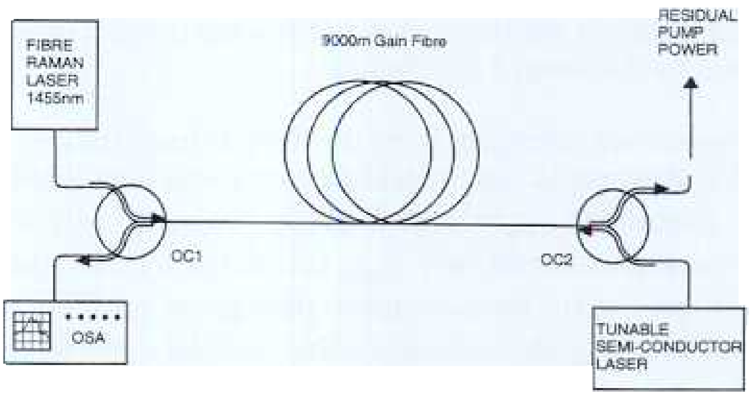

Figure 11 *Raman gain measurement apparatus as used by Imperial College, London. Diagram supplied by J. R. Taylor at IC.*

To measure a broad range of the Raman amplifier gain spectrum, both a tuneable semiconductor laser (1459-1580-nm with 700-kHz linewidth) and broadband ASE from a semiconductor laser amplifier are combined to constitute the probe signal.

Relative spectral gain measurements between 1459-nm and 1580-nm are made by tuning the laser source and measuring the optical powers entering and leaving the gain fibre with an optical spectrum analyser. This is a variant of the classic pump-probe arrangement for measuring Raman gain as used by other authors [35, 1]. For measurements outside the range of the laser source, the ASE source is used. However, the broad emission spectrum of this source saturates the Raman amplifier unless the input power is reduced to very low levels. The amplified source then powers of tens of Watts were necessary. The basic experimental procedure was to excite the fibre with the pump wave and disperse the output with a prism. The relative intensities of the frequency components in the Stokes wave were then measured. This gave the relative spontaneous Raman scattering cross section of the fibre as a function of Stokes wavelength but was not tied to an absolute value. Absolute values for the cross section were deduced by using the same experimental system to measure scattered intensity from a sample of Benzene - for which the absolute scattering cross section was known. The absolute Raman scattering cross section for the fibre was then deduced and used to calculate the gain coefficient, $g_R(\nu)$, as a function of the Stokes wavelength.

A similar method was used by Galeneer *et al.* [2] to investigate the peak Raman cross sections of the compounds found in doped fibre cores: GeO_2, B_2O_3 and P_2O_5 relative to the scattering cross section for silica, SiO_2. It was found that silica had the smallest scattering cross section of all of these materials.

Advantages of this method:

- Simple arrangement

Disadvantages:

- Pulsed method introduces difficulties in determining peak pulse powers

  Requires calibration to an absolute reference

- Not at a convenient communications wavelength

3.2.1.2 Pulse-Scan Technique

Mahgerefteh *et al.* recently demonstrated a novel technique for Raman gain measurement in optical fibre using a single pulsed source near 1550-nm [30, 34]. Unlike the relative cross section method, stimulated rather than spontaneous Raman scattering is measured. Absolute values of the gain coefficient can also be found without the need to calibrate the system against a known reference. The technique uses a cw pump laser and a $LiNbO_3$ modulator to generate square-shaped pulses of between 1-ns and 100-ns duration. These pulses generate Stokes waves within the fibre that co-propagate with the pump pulse but at a different group velocity as determined by the chromatic dispersion of the fibre. The group velocity mismatch causes the pump and Stokes pulses to walk-off with respect to each other and the SRS interaction length is consequently limited. The length of the interaction region can be controlled by varying the pulse widths.

that can accurately determine customer source linewidths with resolution of approximately 100-kHz. Delayed self-heterodyne detection using a 10-km fibre delay line can measure spectral linewidths greater than approximately 2-kHz. If customers supply their own sources and/or modulators and do not require a linewidth measurement then the service can be reduced to accurate measurement of absolute optical powers and calculation of the SBS threshold. Optical power sensor heads may need to be constructed to give improved accuracy over commercial power meters when angled fibre connectors are used.

The production of an SBS fibre standard, similar to the fibre attenuation standard (FAS) is another possibility. The attenuation standards produced by NPL are wound under very low tension and are highly stable under shipping. The standard could be supplied with a specified SBS threshold using a standard source - the details of which would also need to be supplied to the customer.

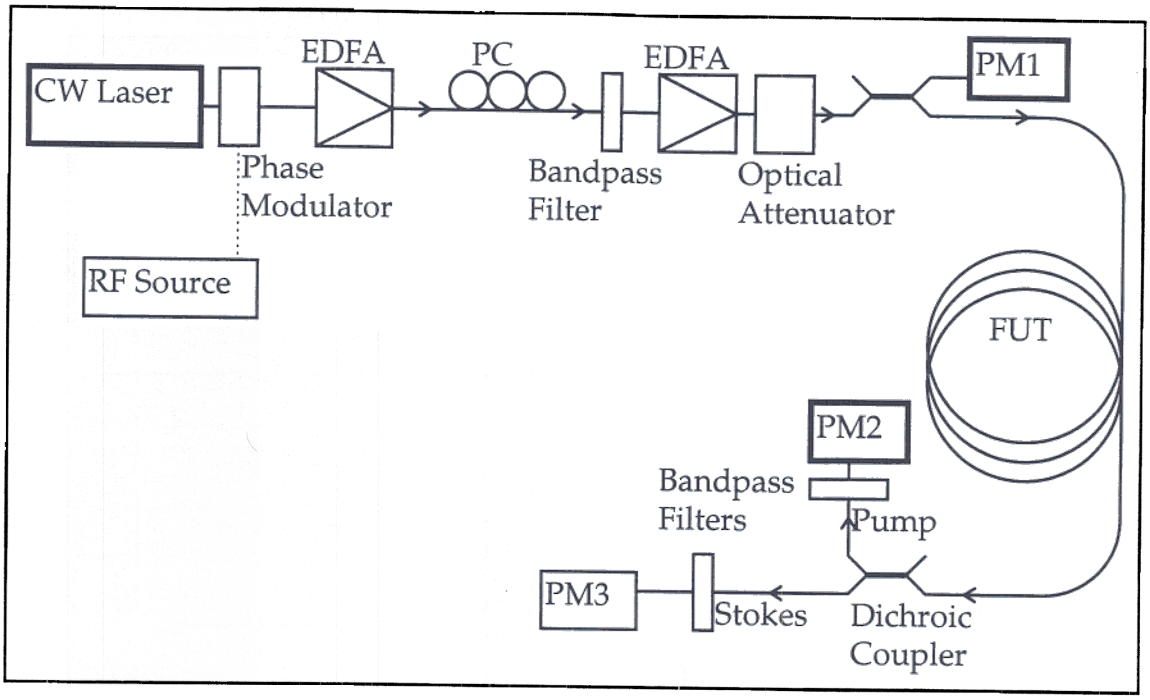

Figure 13. Basic experimental system for measuring the forward SRS threshold.

3.3 Special Considerations in Raman Scattering Measurements

Most of the special considerations for SRS measurements are the same as for SBS. The use of high optical powers means that sources must be protected with optical isolators to avoid destabilising lasers. Angled fibre connectors should also be used for the same reason and these introduce the same problem with calibrated absolute power measurement as was discussed in section 2.3. Polarisation sensitivity of the measured gain coefficient is also a problem and is best avoided by the use of a randomly polarised source. Length-scaling of the SRS threshold follows a similar pattern to that for SBS, as can be appreciated from the similarity between equation 2-4 and 3-5. The SRS thresholds for fibres with $A_{eff} = 50\mu m^2$, $g_{SRS} = 4.17 \times 10^{-14} m/W$, $K_{SBS} = 2$ and the attenuation values of 0.2-dB/km and 0.4-dB/km are plotted in Figure 14 as a function of fibre length. It can be seen that the threshold power falls significantly for longer fibres, although it always remains approximately three orders of magnitude higher than the SBS threshold for a narrow linewidth pump.

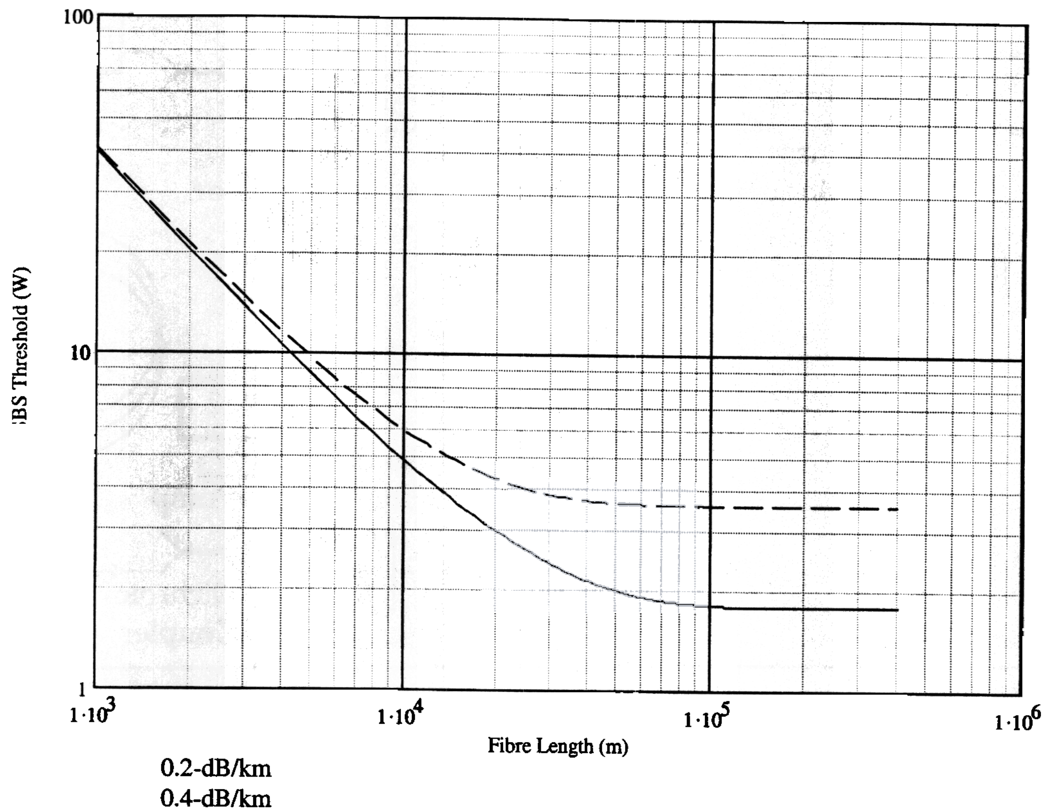

Figure 14. Calculated SRS threshold vs. fibre length for fibres with differing attenuation coefficient.

Suppression of SBS

SRS threshold measurement requires a significant increase in the SBS threshold. A pump linewidth of 40-GHz is required is required to raise the SBS threshold for a 10-km length of the fibre described above to ~5-W. SBS suppression can be achieved by using phase-modulation of the pump signal [14, 30] or generation of a beat signal between two closely-spaced sources [36]. Using 1π-PSK modulation with a pseudorandom binary bit sequence at bit-rate B has been predicted to increase the SBS threshold linearly with B such that:

$$P_{PSK} \approx P_{CW} \frac{B + \Delta\nu_l}{} \qquad 3\text{-}7$$

Cotter [36] showed that SBS could be significantly suppressed in an ASK communications channel using by duplicating the data onto two closely-spaced optical carrier frequencies. The same principle applied to a cw pump wave was predicted to raise the SBS threshold of a silica fibre to 15-W if two cw sources spaced by 1-GHz are used. This method of SBS suppression is however included in a US patent assigned to British Telecommunications [37, 38].

SBS suppression has also been achieved by applying variable strain to the optical fibre in order to smear the aggregate gain coefficient over a wider frequency range[5]. For pump spectra much narrower than the normal Brillouin gain linewidth, the peak gain coefficient becomes inversely proportional to the $\Delta\nu_B$ through equation 2-3. Broadening the Brillouin linewidth from 50-MHz to 406-MHz was found to increase the SBS threshold from approximately 7-dBm to more than 14-dBm, which was the highest optical power used in the experiment. Assuming that the SBS threshold increases linearly with the Brillouin linewidth, the strain applied in this experiment was expected to raise the threshold power by 9-dB. This increase would still be insufficient to permit SRS threshold measurements, which typically require launch powers in excess of 30-dBm.

Variations in Dopant Concentration

The intensity of Raman scattering is proportional to the Raman cross section of the scatterers, which varies from one substance to another. Of particular interest in optical fibres are the relative scattering cross sections of germania and silica. Experiments have shown that germania is a much stronger Raman scatterer than silica and therefore highly-doped silica fibres are expected to have a reduced SRS threshold [2]. A high germania concentration in the fibre core also restricts the mode field and gives a smaller effective area. However, doping also increases the linear loss of the fibre, reducing the effective nonlinear interaction length, L_{eff}. All of these effects increase the rate at which the pump wave is depleted along the fibre - either through increased nonlinear activity or higher linear losses. The dependence of the SRS threshold on the core-cladding index difference is complicated as it will depend on the relative doping dependence of the linear loss, the effective area and the Raman gain coefficient.

As in SBS, the stokes wave in SRS builds up from amplification of noise at the peak frequency of the Raman gain curve. Anything that causes the peak frequency to fluctuate along the interaction length of the fibre would therefore be expected to slow the accumulation of Stokes radiation and increase the SRS threshold. However, the frequency shift of the Raman gain peak in germano-silicate fibre varies only slightly with germanium concentration [39]. Furthermore, the peak is less well defined than that of the SBS gain curve and single mode fibres exhibit only minimal longitudinal dopant variations, so this effect is expected to be negligible.

3.4 Conclusions

Both the pulse-scan and the cw amplification methods have been successfully used for measurements at 1550-nm - the region where Raman gain will affect ITU WDM systems and the L band. The uncertainties achieved with these methods have been quoted as 5% and 10% respectively [30, 40]. However, the pulse-scan technique loses accuracy for Stokes shifts less than a few terrahertz owing to the resolution of the spectrometer and the co-propagating pump and Stokes waves.

Measuring an amplified signal counterpropagating with respect to the pump wave helps to improve signal to noise. The largest individual source of uncertainty in the cw amplification method used at Imperial College was the 8% uncertainty on the 870-mW absolute pump power given by the thermal power meter used. Accurate optical fibre power measurements at power levels up to 1-W are an active area of research at NPL and we believe that this figure can be improved upon - potentially to as low as 1.5%.

In general, continuous wave methods are preferred over pulses since the optical power can be measured more accurately. The challenge with using cw methods at telecommunications wavelengths is the provision of sufficient optical power to exceed the SRS threshold. Measurements could theoretically be performed at any wavelength since the gain coefficient can be scaled for another pump wavelength. High power sources, such as Nd:YAG lasers are available for visible wavelengths. However, difficulties arises in calculating the effective length and effective area at arbitrary wavelengths. The effective length depends on the linear attenuation coefficient, which will not normally be specified for wavelengths shorter than ~1300-nm. The effective area of the fibre becomes difficult to measure below the cut-off wavelength (typically ~1200-nm), where the fibre becomes multimoded.

Raising the SBS threshold sufficiently to exceed the SRS threshold is a significant challenge unless a relatively broadband source is used. The amplified output from a fibre Raman laser, as used at Imperial College, has sufficient spectral width to eliminate SBS as a concern.

3.5 Recommendations

The SRS measurement services should be based upon measurement of the gain coefficient. This can be used to calculate the single-valued SRS threshold as well as giving more detailed information on the Raman gain profile that would be relevant to WDM systems and Raman amplifiers. We prefer the use of cw methods as these facilitate more accurate optical power measurement than pulses and therefore intend to follow the method used by Imperial College, i.e. the cw Raman amplification technique. This technique does not offer the same potential for distributed measurements as the pulse-scan technique. However, it does permit evaluation of the Raman gain curve at frequencies close to the pump, which is important for determining Raman amplification of channels in a DWDM system.

4. Appendix A - The Effective Area Parameter, A_{eff}

All nonlinear effects are dependent upon the intensity of the electromagnetic field in the medium. However, it is the total optical power entering and leaving the fibre that is usually measured. Some method is required for converting between the two when comparing theoretical and experimental results. The measured optical power leaving a fibre is simply the integral of the intensity distribution over the fibre cross section. Assuming a uniform intensity distribution, I, over a core of area A_{core}, the intensity could be calculated from the measured power, P_{meas}, using:

$$I = \frac{P_{meas}}{A_{core}} \qquad 4\text{-}1$$

However, the field in a single mode fibre is not evenly distributed or even fully contained within the core. It is larger at the fibre axis than near the core-cladding interface and extends into the cladding to a degree depending on the actual refractive index profile. Calculating a uniform intensity in the core using equation 4-1 will underestimate the value on the axis of the fibre and overestimate the value near the core-cladding interface.

The effective area parameter has been defined for the purposes of calculating nonlinear effects. It is a single value, based on the modal field distribution, and can be used in equation 4-1 instead of A_{core} to calculate a value for the optical intensity. The effective area is defined as:

$$A_{eff} = \frac{2\pi\left(\int_0^\infty |E(r)|^2 r dr\right)^2}{\int_0^\infty |E(r)|^4 r dr} \qquad 4\text{-}2$$

where $E(r)$ is the amplitude of the field of the fundamental mode at radius r from the axis of the fibre. In conventional step-index fibres, the mode field is well-approximated by a Gaussian function of radius w at the $1/e$ amplitude points. In this case, the effective area can be shown simply to be

$$A_{eff} = \pi w^2(\lambda) \qquad 4\text{-}3$$

where $2w(\lambda)$ is the mode field diameter (MFD) of the fibre at wavelength λ. Mode field diameter is a well-established parameter with recognised measurement procedures. However, for fibres that do not have simple step-index geometry such as dispersion-shifted and dispersion-flattened fibres, the mode field cannot be approximated by a Gaussian function and alternative methods are required to calculate the effective area. This can be done either by measuring the field distribution and using equation 4-2 or by including a fibre-dependent correction factor into equation 4-3 and using the fibre MFD value [41].

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