

**The validity of the single mode optical fibre transfer standard for  
the calibration of fibres for high power users**

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**CONTENTS**

**1 SCOPE..... 2**

**2 SUMMARY ..... 2**

**3 INTRODUCTION ..... 3**

**4 BACKGROUND TO THE FAS (FIBRE ATTENUATION STANDARD)... 4**

**5 THE UK NATIONAL REFERENCE FACILITY FOR OPTICAL FIBRE  
SPECTRAL ATTENUATION MEASUREMENTS ..... 5**

**6 BACKGROUND TO SIMULATED BRILLOUIN SCATTERING ..... 6**

    6.1 NON-LINEAR EFFECTS ..... 6

        6.1.1 *Effective Area,  $A_{eff}$* ..... 7

    6.2 STIMULATED BRILLOUIN SCATTERING ..... 8

**7 THE USE OF THE FAS AS A CALIBRATION ARTEFACT FOR A  
SPECTRAL SCAN MEASUREMENT FACILITY AT HIGH POWERS. .... 10**

    7.1 SOURCES OF MEASUREMENT ERROR..... 10

    7.2 MEASUREMENT POWER LEVEL - FIBRE STABILITY EFFECTS ..... 10

    7.3 CALIBRATION POWER LEVEL - SBS EFFECTS..... 11

**8 FURTHER INVESTIGATION OF SBS MEASUREMENTS..... 15**

**9 DISCUSSION OF RESULTS.....**

**10 CONCLUSIONS .....**

**11 REFERENCES..... 22**

## **1 Scope**

This report details the assessment of the potential use of the fibre attenuation transfer standard for the following purposes:

- A calibration artifact for spectral scan benches measuring the attenuation of optical fibre at high powers.
- A calibration artifact for Stimulated Brillouin Scattering power threshold measurements.

## **2 Summary**

The recent commercial development of 1550 nm fibre amplifiers has led to a rapid increase in the optical power utilised in fibre systems. This necessitates the validation of existing test methods and transfer standards used for ensuring traceability of fibre parameter measurements.

The use of the fibre attenuation transfer standard (FAS), developed under a previous NMS Programme, has been demonstrated to be valid for attenuation measurements made with CW input power levels up to 0 dBm.

Preliminary investigations show that the FAS may have the required stability for use as a transfer standard for stimulated Brillouin scattering (SBS) threshold power measurements. However, the philosophy of how to make and demonstrate the accuracy of SBS threshold power measurements requires further investigation before its suitability can be confidently demonstrated to be satisfactory.

In particular, this assessment has identified issues relating to:

- The form of the theoretical model used to calculate SBS thresholds
- The quantification of the parameters used in the model (e.g. effective area)
- The accuracy of the calibration of power meters with angled connectors to enable accurate power measurements
- The standardisation of measurement techniques, including the specification of source linewidth

These issues need to be resolved to ensure accurate measurements which are backed up by a sound theoretical understanding and modelling of the underlying physics of the SBS effect, thus demonstrating their validity. Once this has been achieved, standard test procedures can be refined and tested.

### 3 Introduction

Measurement of the spectral attenuation of a single mode fibre is crucial to the fibre manufacturing, fibre cabling and fibre installation processes. It is the principal mechanism through which product quality is determined. It is used to identify degradation of the performance of installed all-optical telecommunications links.

The increased demand for fibre transmission links to cover longer span lengths at ever higher bit rates requires the use of high optical powers in fibres. This can lead to non-linear interactions between the signal and the transmission medium which impose performance limitations on the system. Consequently, measurement of non-linear fibre behaviour has become an important consideration in implementing both high capacity and long, non-regenerated systems.

The rapid growth of the optical systems has resulted in a highly competitive market. The ability of fibre manufacturers to accurately specify the performance of a fibre or cable is a major factor influencing purchasing decisions of customers. The improvement of this performance specification by reference to a traceable quality standard increases the competitiveness of a supplier. Therefore, fibre and cable manufacturers seek traceability for fibre attenuation measurements in order to demonstrate the validity of performance specifications attached to their product. In fact many national network providers require demonstration of traceability before fibre can be used in their networks.

Traceability for attenuation measurements is obtained through national reference facilities, which are maintained by national standards laboratories or other organisations with responsibility for maintaining and disseminating attenuation measurements for their country.

The accepted method for measuring the attenuation of an optical fibre is the cut-back technique, which has been adopted by standards committees such as the International Telecommunications Union (ITU), as their Reference Test Method. The Alternative Test Method is the OTDR (optical time domain reflectometry) technique. The equivalence of these two techniques has been demonstrated [1] but there are several methods and artefacts suggested for calibrating an OTDR.

The international standardisation bodies have placed considerable emphasis on normalising the methods used to determine fibre attenuation [2,3,4]. A number of national standards laboratories and manufacturers have set up facilities in accordance with these test methods to provide traceable measurements. However, until recently, similar effort has not been applied to the development of transfer standards to transfer the accuracy obtainable in national standards laboratories to the industrial end-user. The last NMS

programme on optical radiation measurements supported work to produce a robust transfer standard for optical fibre attenuation measurements.

In contrast to the fibre attenuation specifications, the traceability for measurements for characterising non-linear effects is only partially developed. This is currently limited to the use of calibrated instrumentation, such as power meters and spectrum analysers and a few guideline annexes to standards documentation. The optical fibre community is now beginning to realise the importance of traceability for these parameters but work is required to validate meaningful and reliable test methods for the specification of fibre non-linear properties.

#### **4 Background to the FAS (fibre attenuation standard)**

In general, transfer standards for fibre attenuation measurements have been based on fibres packaged on standard shipping reels. The measured attenuation of fibre under these circumstances can be highly sensitive to extrinsic factors such as temperature cycling and vibration. Such sensitivity can be increased in a fibre that is not well selected or that is badly wound on a shipping reel.

NPL in conjunction with BICC Cables Ltd developed a 'golden fibre' transfer standard that can be readily packaged and transported world wide with reliability, for use in the calibration of spectral attenuation benches and optical time domain reflectometers.

The fibre is packaged in such a way to protect the fibre from the rigours associated with transit, and so avoid any losses due to macrobending. In addition, the transfer standard was designed to facilitate easy access to both ends of the fibre in order to accommodate the destructive 2 m fibre cut-back performed during the spectral attenuation measurement procedure.

The most significant factor in the design is that the fibre is free from stress along its entire length. This is vital to ensure that environmentally induced changes in attenuation cannot arise from effects such as tight fibre winding or fibre cross-overs. It also results in the fibre exhibiting a very low polarisation mode dispersion.

The fibre attenuation standard underwent a series of design approval tests, including being subjected to harsh environments. The spectral attenuation of the FAS was thus demonstrated to be stable to better than  $\pm 0.03$  dB, this value being the limit of resolution of measurements at the time of testing.

## 5 The UK National Reference Facility for optical fibre spectral attenuation measurements

The UK national reference facility uses the cut-back technique for attenuation measurements, the theory of which is described in the following paragraphs.

The attenuation  $A(\lambda)$ , at wavelength  $\lambda$ , between the two ends of an optical fibre of length  $L$ , is defined as:

$$A(\lambda) = 10 \log [ P_i(\lambda) / P_o(\lambda) ] \text{ dB} \quad \{1\}$$

where:  $P_i(\lambda)$  is the power launched into the fibre  
 $P_o(\lambda)$  is the output power of the fibre, at wavelength  $\lambda$ .

For a uniform fibre, the attenuation coefficient per unit length of the fibre is defined as:

$$a(\lambda) = A(\lambda) / L \text{ dB/km} \quad \{2\}$$

where:  $L$  is the length of the fibre in km

In practice, it is difficult to directly measure the power launched into an optical fibre, therefore the cut-back technique is employed to measure the attenuation. The output power  $P_o(\lambda)$  of the fibre is recorded as a function of wavelength. Then the fibre is cut to a very short length  $X$ , without disturbing the launch conditions. The attenuation of this short length of fibre is assumed to be negligible and therefore the output power of this short length is equivalent to the power launched into the fibre,  $P_i(\lambda)$  and this is also recorded as a function of wavelength. The attenuation is calculated using equation {1}. The attenuation coefficient is calculated using a slightly modified form of equation {2} as follows:

$$a(\lambda) = A(\lambda) / [ L-X ] \text{ dB/km} \quad \{3\}$$

The measurement equipment is shown as a schematic diagram in figure 1.

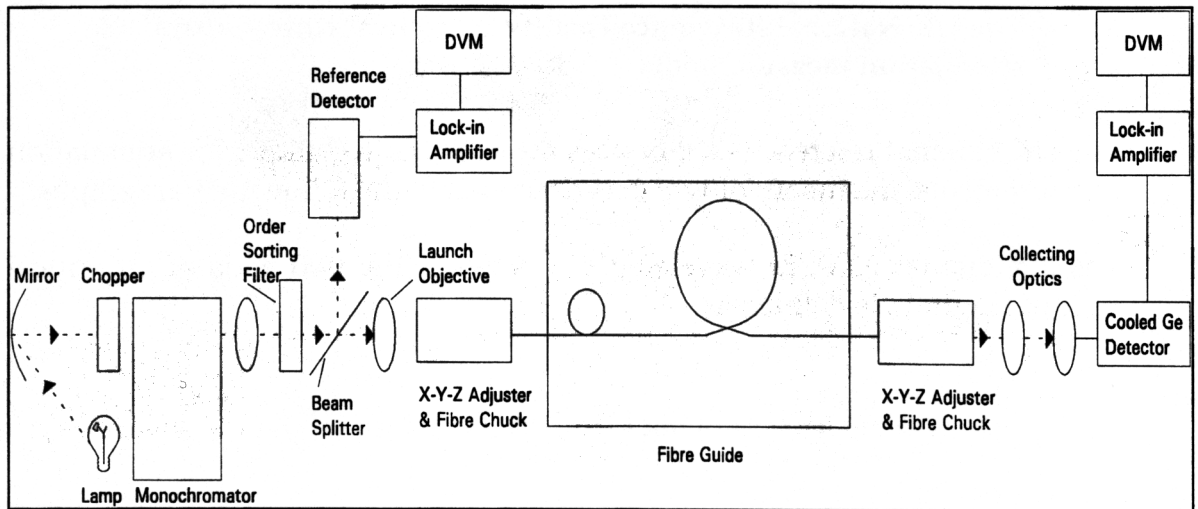


**Figure 1: Schematic diagram of the UK National reference facility for optical fibre spectral attenuation measurements**

In practice, the source used is a tungsten halogen lamp, modulated by a mechanical chopper and the measurement wavelength is selected by a single grating monochromator. The transmitted power is measured using a cooled germanium photodiode with synchronous signal processing. The ends of the fibre are checked with an interferometer to ensure that the perpendicularity of the end faces to the optical axis of the fibre is within  $0.5^\circ$ . A single loop of 6 cm diameter is placed in the fibre under test at the launch end to act as a mode filter thus ensuring single mode operation of the fibre in the 1300 nm transmission window. The fibre between the launch and collecting ends is placed in a guide to ensure that bends of radius less than 14 cm are not formed, which may cause additional bend-induced attenuation.

## 6 Background to Simulated Brillouin Scattering

### 6.1 Non-linear effects

Non-linear effects in optical fibres can be divided into two categories: Scattering effects such as stimulated Brillouin Scattering (SBS) and Stimulated Raman Scattering (SRS), and non-scattering effects related to the intensity dependence of the refractive index such as the Kerr effect self-phase modulation, cross-phase modulation, modulation instability, soliton formation and four wave mixing. The magnitude of these effects is a function of both the fibre characteristics and system dependent parameters.

Important fibre parameters to be considered include the effective area ( $A_{\text{eff}}$ ), the non-linear refractive index ( $n_2$ ), dispersion characteristics and longitudinal fibre uniformity. The quantities  $A_{\text{eff}}$  and  $n_2$  are interrelated when considering

non-linear effects and so a non-linear coefficient is defined as  $A_{\text{eff}} / n_2$ . This coefficient plays an important role in evaluating the system performance degradation due to non-linearities in high power density systems.

Important system parameters to be considered include the number and spacing of channels in a multiple channel system, overall non-regenerated system length, signal intensity and source linewidth and repetition rate.

The result of the non-scattering effects is usually to cause some form of pulse reshaping or noise on a modulated system. Attenuation measurements made using the Reference Test Method are made with CW (as opposed to pulsed) sources and so these effects are not considered to affect the accuracy of such measurements. When considering the two scattering effects detailed above, SBS is the most likely effect to be of concern when making attenuation measurements as SRS typically occurs at power levels an order of magnitude higher than SBS.

#### 6.1.1 Effective Area, $A_{\text{eff}}$

Effective area,  $A_{\text{eff}}$  is defined as follows:

$$A_{\text{eff}} = \frac{2\pi \left[ \int_0^{\infty} I(r) r dr \right]^2}{\int_0^{\infty} I(r)^2 r dr}$$

Where:

$I(r)$  is the field intensity distribution of the fundamental mode at radius  $r$

The integration of {4} is carried out over the entire cross-sectional area of the fibre. Using the Gaussian approximation such that:

$$I(r) = \exp(-2r^2 / w^2)$$

where  $2w$  is the mode field diameter (MFD), then {4} can be analytically integrated to give:

$$A_{\text{eff}} = \pi w^2$$

The Gaussian approximation is valid for step index fibres close to the  $LP_{11}$  cut-off wavelength but not at much longer wavelengths (e.g 1550 nm). The approximation is also not a true representation of depressed-cladding and dispersion shifted fibre, thus limiting the accuracy of the calculation of  $A_{\text{eff}}$  using {6} to approximately 10%.

Y Namihira [5] has postulated a more general but empirical form of equation {3}, such that:

$$A_{eff} = k \pi w^2 \quad \{ 7 \}$$

where  $k$  is a correction factor.

The MFD of a fibre was measured using the variable aperture technique. The near-field pattern was calculated using an inverse Hankel transformation of the far-field pattern.  $A_{eff}$  was then derived from the NFP using equation {4} directly. The value of  $k$  is then determined by the ratio of the values of  $A_{eff}$  obtained by this method and from equation {6}. The value of  $k$  will be dependent on the fibre parameters and wavelength. Values of  $k$  are reported in the literature [6,7] but there is still further research being performed to refine this database.

## 6.2 Stimulated Brillouin Scattering

Stimulated Brillouin scattering (SBS) in optical fibres is characterised by an energy transfer from an input (pump) wave to a backward travelling frequency downshifted (Stokes) wave [8,9]. This occurs because the pump light generates an acoustic wave through the process of electrostriction. This acoustic wave causes a periodic modulation of the refractive index of the fibre, creating a Bragg grating from which photons can be scattered. Energy and momentum must be conserved in this process and thus counter-propagating photons are preferentially amplified. The frequency of these amplified photons is less than the pump wave due to the Doppler shift associated with the grating moving at an acoustic velocity. Therefore, if a wave with the appropriate Brillouin frequency shift is propagating counter to the pump wave, it will be amplified.

In general the SBS threshold power,  $P_{th}$ , is expressed as:

$$P_{th} = 21 \frac{K A_{eff}}{g L_{eff}} \frac{\Delta\nu_p + \Delta\nu_B}{\Delta\nu_R} \quad \{ 8 \}$$

where:

$g$  denotes the Brillouin gain coefficient

$A_{eff}$  is the effective area

$K$  is a constant ( $1 \leq K \leq 2$ ), determined by the degree of freedom of the polarisation state.

A Lorentzian pump and Brillouin linewidth is assumed.

$\Delta\nu_B$  and  $\Delta\nu_p$  represent the Brillouin bandwidth and the pump bandwidth respectively.

$L_{eff}$  is the effective length, defined as

$$L_{eff} = \frac{1 - \exp(-\alpha L)}{\alpha} \quad \{ 9 \}$$

where  $\alpha$  is the attenuation coefficient and  $L$  is the fibre length

The SBS threshold depends on the bandwidth of the pump light. When  $\Delta\nu_p / \Delta\nu_B \ll 1$ , then  $P_{th}$  attains its minimum value and equation {8} becomes:

$$P_{th} = 21 \frac{K A_{eff}}{g L_{eff}} \quad \{ 10 \}$$

## 7 The use of the FAS as a calibration artefact for a spectral scan measurement facility at high powers.

### 7.1 Sources of measurement error

The main sources of error to be considered in the measurement of attenuation by a spectral scan system are:

- temperature
- humidity
- source drift
- polarisation dependence
- linearity of detection system
- wavelength
- measurement power level

The first six items have been investigated previously and are detailed in a previous report submitted to NMSPU [10]. The final item - the measurement power level - introduces two main effects to be considered when measuring the attenuation of a fibre. The first is the effect on the stability of the fibre due to the power dissipation in the fibre and the second is to ensure that the fibre is not being operated in the non-linear regime.

### 7.2 Measurement power level - fibre stability effects

The power dissipation in a fibre due to high optical power levels may lead to localised heating. This may cause a change in refractive index and in the stress in the fibre due to the difference in the thermal expansion coefficients of the core and cladding. These changes would change the attenuation of the fibre.

The stability of a 10 km Fibre Attenuation Standard was investigated using the experimental set-up shown in figure 2.

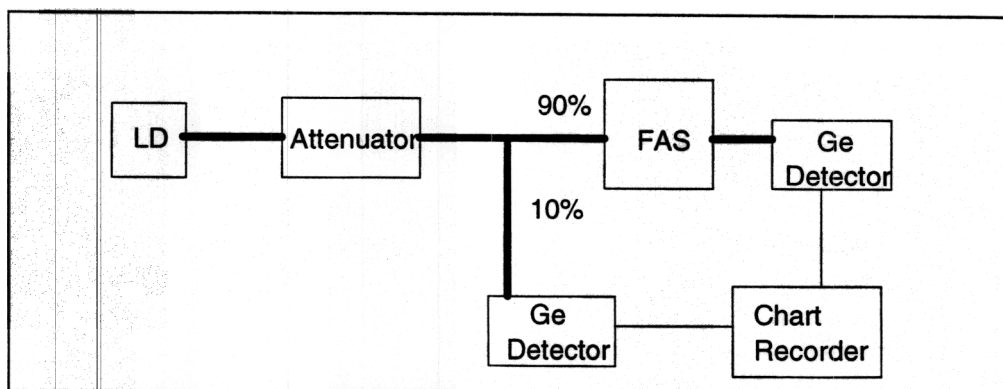


Figure 2: Schematic diagram of FAS stability measurement set-up

A 1300 nm source was launched into the fibre via a 90:10 coupler. The 10% arm was used to monitor the source power and so act as a reference channel to normalise out any source power changes. The transmitted power was monitored for one hour with the cooled germanium detector. This test was performed using launch powers of -30 dBm and 0 dBm.

The transmitted power was measured to be stable to  $\pm 0.04$  dB for both launch powers. This is comparable with the stability of the coupler and so it was concluded that, for input powers up to 0 dBm there is no effect on the transmission properties of the fibre due to the increased power dissipation in the fibre.

### 7.3 Calibration power level - SBS effects

It is important that attenuation measurements of the fibre transfer standard are made at a power level below the on-set of any non-linear effects. The most likely effect to occur is stimulated Brillouin scattering. Therefore the SBS threshold power was measured for a matched cladding fibre packaged in a FAS and compared with lengths of similar fibre of varying lengths when wound on a shipping spool.

The transmitted and backscattered powers of the fibres were measured as a function of input power using the equipment shown schematically in figure 3.

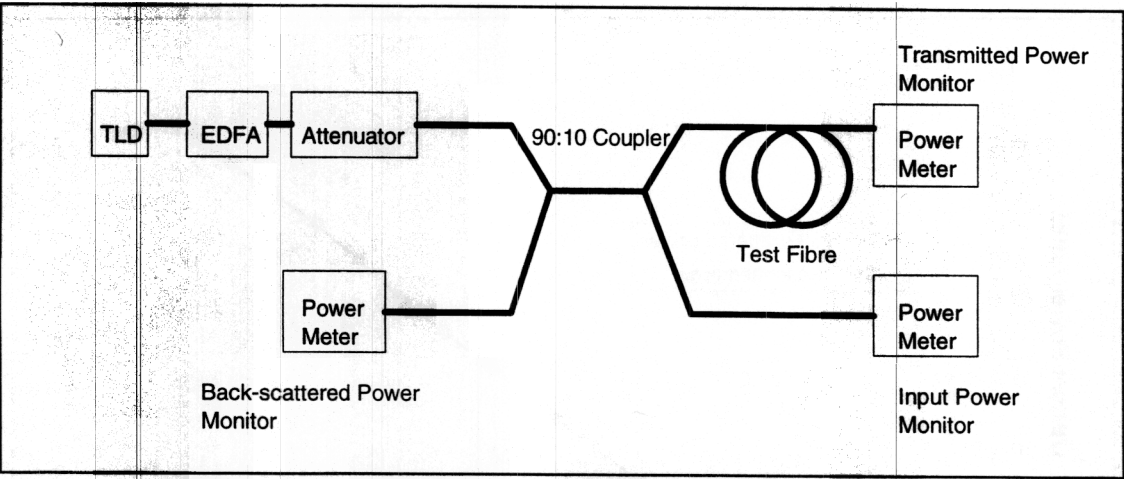
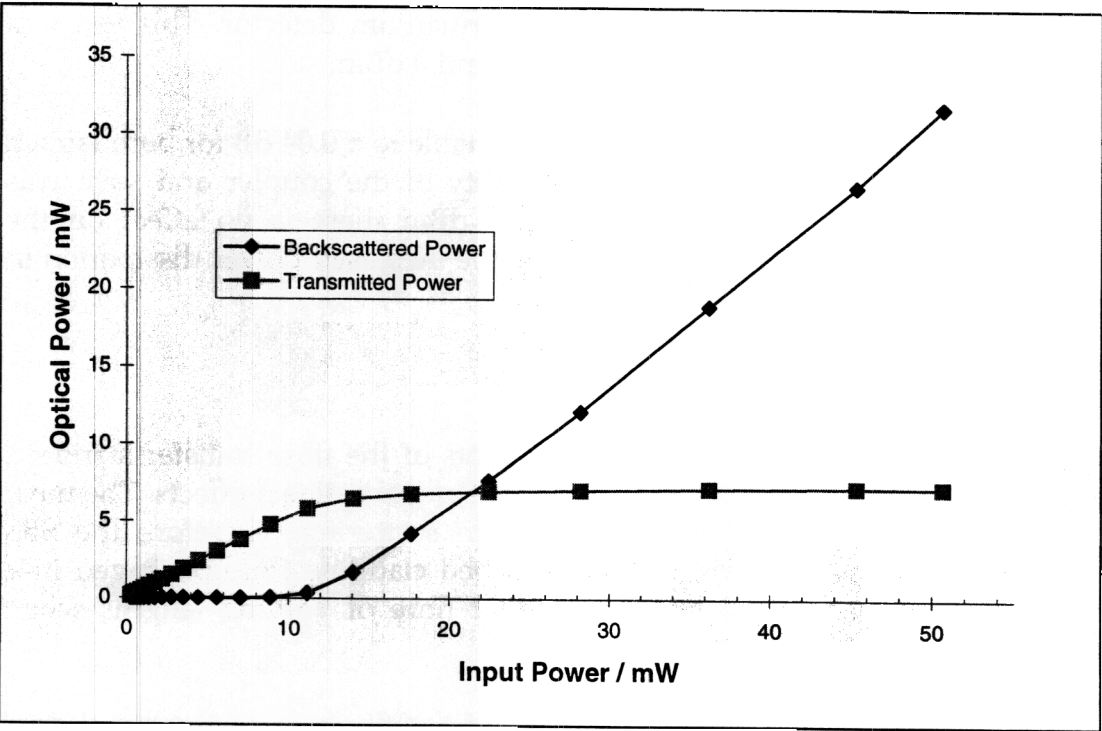


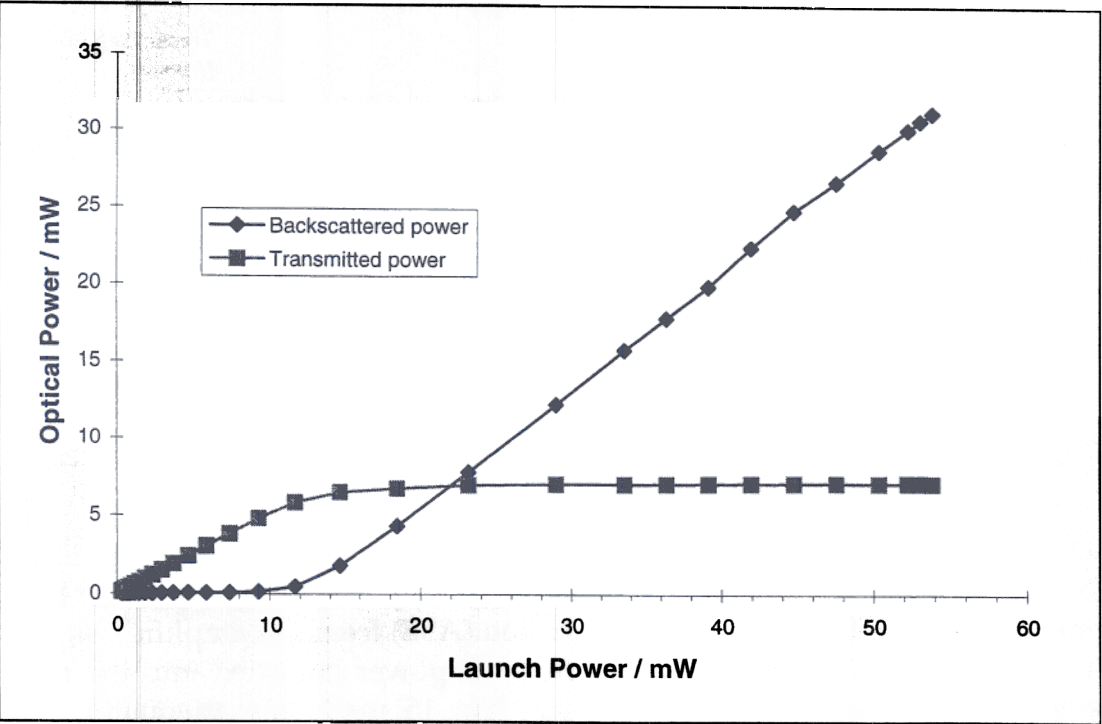
Figure 3: Schematic diagram of SBS measurement system

The source comprised of a tuneable 1550 laser coupled to a fibre amplifier. The optical output of the amplifier was filtered by a 3 nm bandpass filter to remove the amplified spontaneous emission (ASE) from the amplified signal. The optical attenuator was used to vary the power launched into the fibre under test. For launch powers greater than 15 mW, this attenuator was removed and the power varied by adjusting the gain of the amplifier. The 90:10 coupler was characterised for the loss across each branch and the power meter readings were corrected accordingly. The SBS threshold is defined as the input power which produces a back-scattered Stokes power that is equal to the input power.

Graphs 1 and 2 show two independent measurements of a 10 km FAS, manufactured using Optical Fibre matched cladding fibre.



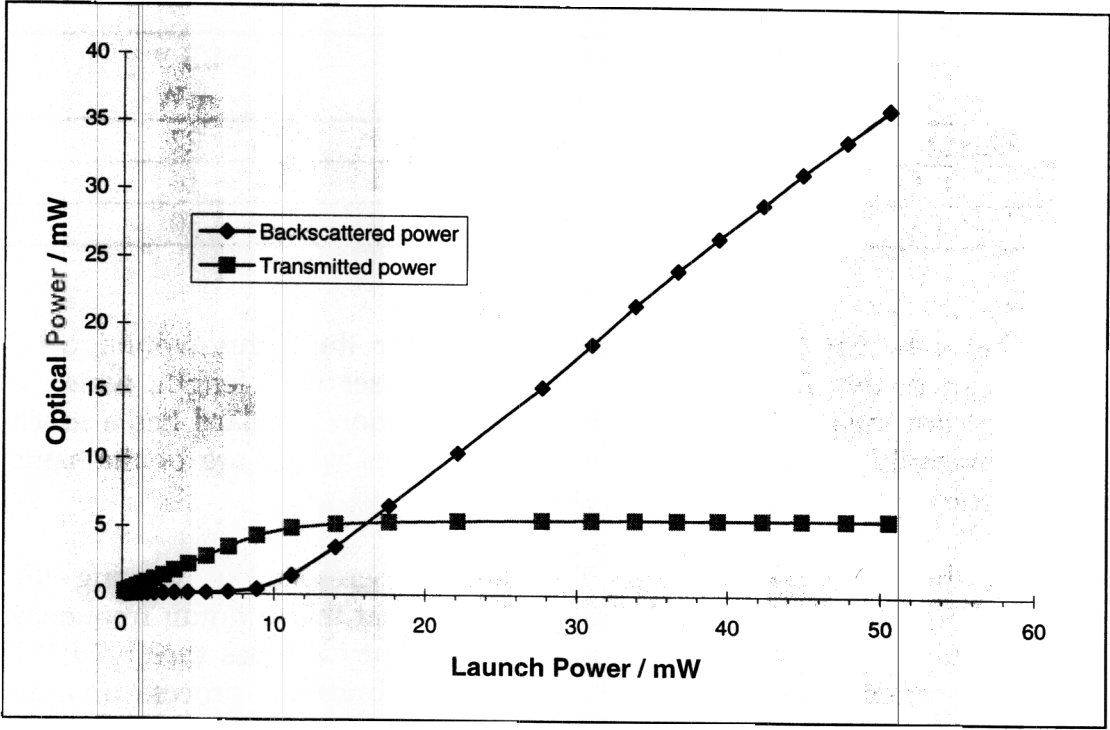
Graph 1: SBS Threshold Power Characteristic of 10 km FAS - Run 1



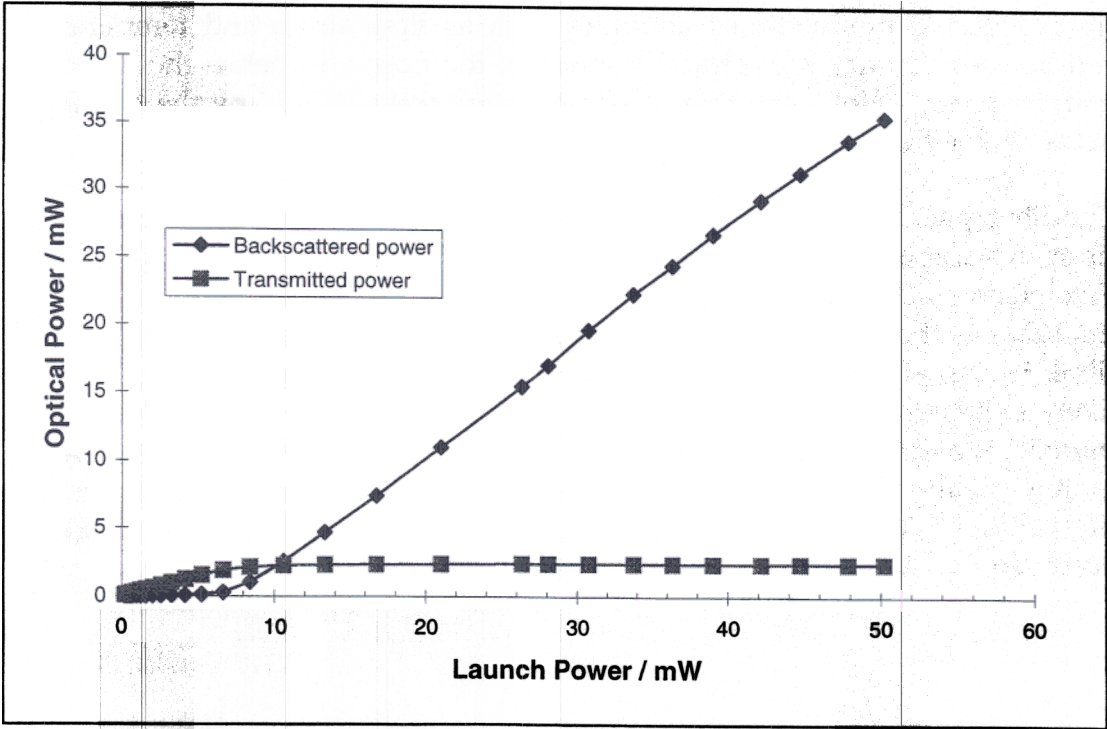
Graph 2: SBS Threshold Power Characteristic for 10 km FAS - Run 2

The measurements gave the SBS threshold as 21.7 mW and 22.0 mW respectively, showing good agreement between the runs.

Graphs 3 and 4 show the SBS characteristic curves for 12 km and 25 km lengths of Optical Fibre matched cladding fibre of the type used in the FAS.



Graph 3: SBS Threshold Power Characteristic for 12 km OF matched clad fibre



Graph 4: SBS Threshold Power Characteristic for 25 km OF Matched-clad Fibre

The results for these fibres are summarised in Table 1.

**Table 1: Summary of SBS Threshold Powers**

| Fibre:    | Length<br>km | SBS $P_{th}$<br>mW |
|-----------|--------------|--------------------|
| FAS SM010 | 10           | 22                 |
| OF1       | 12           | 16                 |
| OF2       | 25           | 10                 |

It can be seen that the SBS threshold power for the fibres wound on a shipping spool two fibres (OF1 and OF2) decreases with length, which is expected from theory. However, the fibre attenuation standard has a much higher threshold power than the other two fibres which are of the same manufacture and have similar mfd values.

The SBS threshold power of a fibre can be increased by varying the waveguide or material properties of the fibre so that the Brillouin frequency changes before the Stokes light at a given frequency reaches threshold[11]. The fibre properties can be varied during the fabrication process or after (external modulation) fabrication. In general, modifying the fibre parameters such as the core radius, dopant concentration or draw induced residual strain will have the advantage of giving the fibre an inherent property but the disadvantage of significantly degrading the transmission properties of the fibre. External modulation techniques such as fibre strain and temperature can be used to vary the refractive index of the fibre and hence the Brillouin gain frequency. However, these techniques are often limited by the restricted access to the fibre in a system.

The fibre packaged in the FAS is under virtually zero tension where as the fibre on a shipping spool is wound at a tension in the region of 60 - 100 grams. The tension induced strain in the fibre in the shipping spool would be greater than that of the FAS, leading to a bigger change in the refractive index of the fibre. However, the percentage *variation* of strain along the length of fibre is likely to be greater in the FAS compared to the shipping reel fibre due to the uniform winding tension in the latter case. It is postulated that this may cause more variation in the refractive index and hence the Brillouin frequency of the fibre in the FAS, leading to the increased Brillouin threshold power that is observed.

## 8 Further investigation of SBS measurements

Due to the proven stable nature of the FAS, it was considered that the FAS may have potential to be used as a transfer standard for SBS threshold power measurements. Therefore, in order to determine the problems that might be encountered in measuring SBS, a preliminary investigation of the measurement of SBS threshold powers of several fibre types was investigated using the measurement procedure detailed in the annex of the ITU recommendation G652 [6].

### 8.1 SBS Threshold Power

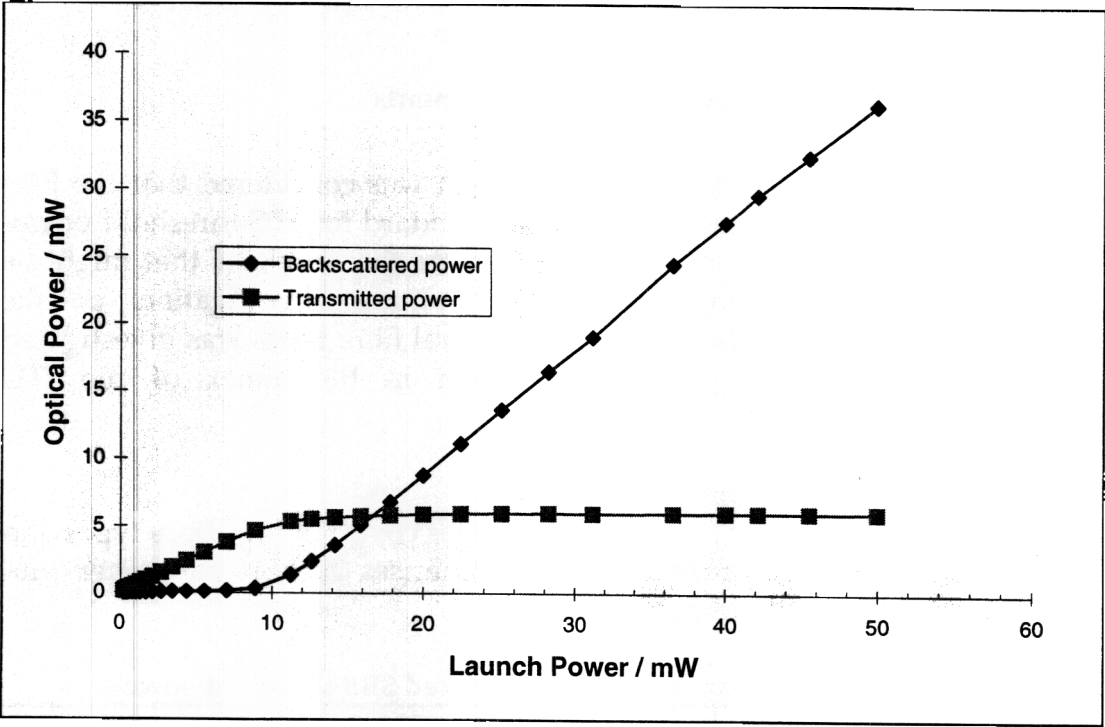
The SBS threshold power of seven fibre samples covering four fibre types and including a FAS were measured. Table 2 summarises the fibre parameters and the measured SBS threshold powers.

**Table 2: Summary of fibre parameters and measured SBS threshold powers**

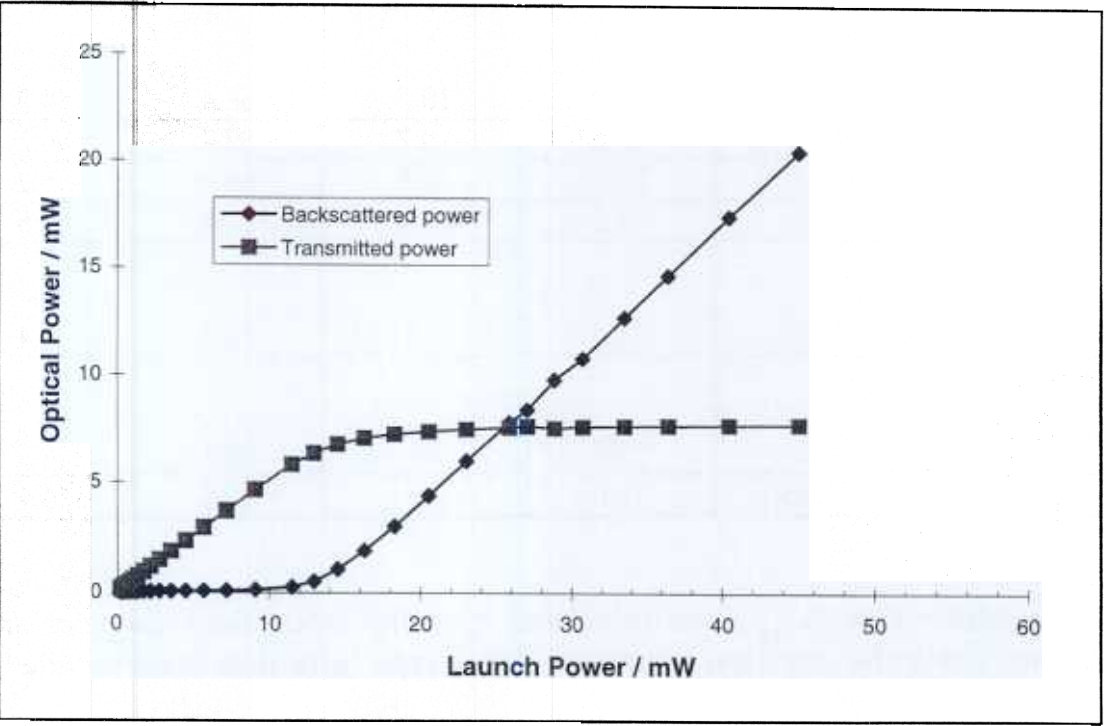
| Fibre                          | Measured<br>SBS $P_{th}$<br>mW | Length<br>km | mfd<br>(@ 1550 nm)<br>$\mu\text{m}$ | $A_{eff}$<br>$\mu\text{m}^2$ | $L_{eff}$<br>km |
|--------------------------------|--------------------------------|--------------|-------------------------------------|------------------------------|-----------------|
| <b>Matched<br/>Clad:</b>       |                                |              |                                     |                              |                 |
| FAS - OF                       | 22                             | 10.0         | 10.7                                | 87.4                         | 4.5             |
| OF1                            | 16                             | 12.0         | 10.7                                | 87.4                         | 4.7             |
| OF2                            | 10                             | 25.2         | 10.6                                | 85.7                         | 5.2             |
| LYC1                           | 16                             | 12.5         | 10.5                                | 84.2                         | 4.8             |
| <b>Depressed<br/>Clad:</b>     |                                |              |                                     |                              |                 |
| LYC2                           | 25                             | 11.5         | 9.6                                 | 70.3                         | 4.4             |
| <b>Dispersion<br/>Shifted:</b> |                                |              |                                     |                              |                 |
| LYC3                           | 20                             | 13.5         | 8.6                                 | 55.1                         | 4.5             |
| SUM1                           | 12.5                           | 12.0         | 7.5                                 | 42.0                         | 4.4             |

The effective area,  $A_{eff}$ , was calculated from the mode field diameter at 1550 nm using the empirical formula and fibre type correction factor detailed in the ITU measurement procedure.

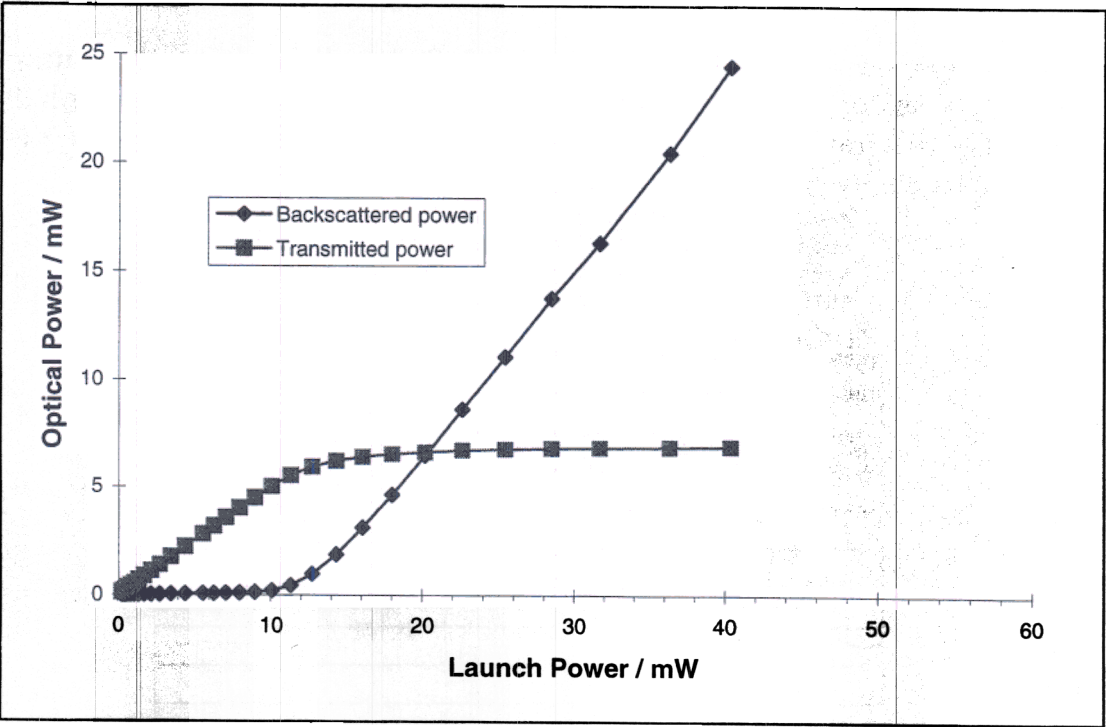
Graphs 5 to 8 show the SBS characteristics for the four fibres not previously shown in Section 7: matched cladding LYC1, depressed cladding LYC2, dispersion shifted LYC3 and SUM1.



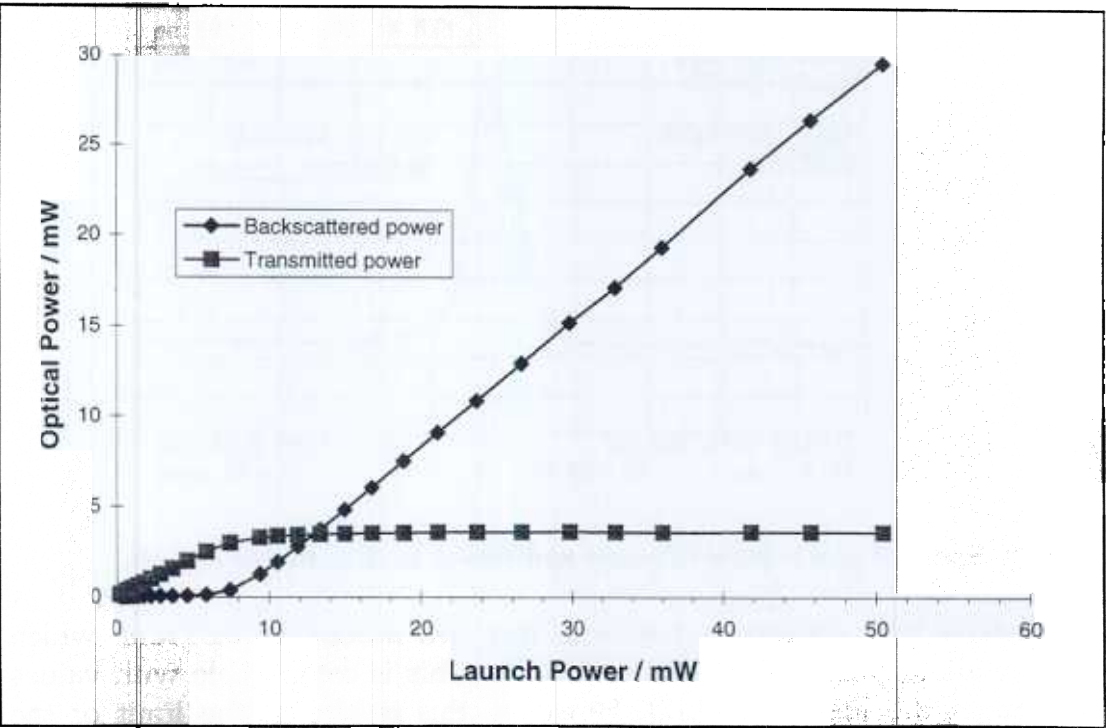
Graph 5: SBS Threshold Power Characteristic For LYC1 - 12 km Matched Clad Fibre



Graph 6: SBS Threshold Power Characteristic For Fibre LYC2 - 11 km Depressed Clad



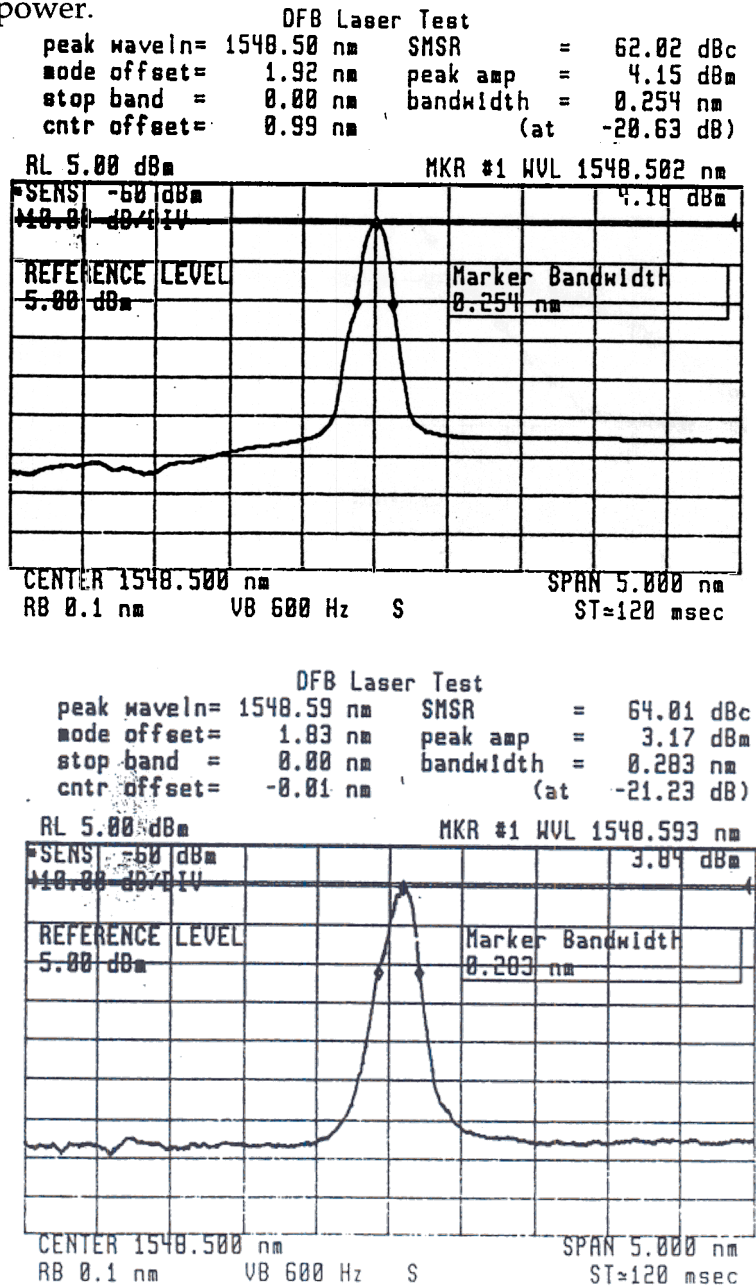
**Graph 7: SBS Threshold Power Characteristic for Fibre LYC3 - 13 km Dispersion shifted**



**Graph 8: SBS Threshold Power Characteristic For Fibre SUM1 - 12 km Dispersion shifted**

8.2 Frequency shift

The frequency shift of the back-scattered Stokes light from the pump frequency was investigated using an optical spectrum analyser. Graph 9 shows the spectral power distribution plots of the pump laser and the back-scattered power.



Graph 9 : Spectral power plots of pump and Stokes back-scattered signals

The wavelength difference between the two traces is 0.09 nm, which corresponds to a frequency shift of 12 GHz. This is comparable with values reported in the literature [8,12]. However, this is also at the limit of the resolution of the spectrum analyser.

## 9 Discussion of results

Table 3 summarises the measured SBS threshold power and the theoretical value calculated from the formula and Brillouin gain coefficient reported in the annex of the measurement procedure.

**Table 3: Summary of Measured and Calculated SBS Threshold Powers For Different Fibres:**

| Fibre                      | SBS $P_{th}$   |                           |                               |
|----------------------------|----------------|---------------------------|-------------------------------|
|                            | Measured<br>mW | Calculated<br>(ITU)<br>mW | Calculated<br>(Agrawal)<br>mW |
| <b>Matched Clad:</b>       |                |                           |                               |
| FAS - OF1                  | 22             | 2.1                       | 8.4                           |
| OF1                        | 16             | 2.0                       | 7.8                           |
| OF2                        | 10             | 1.8                       | 6.9                           |
| LYC1                       | 16             | 1.9                       | 7.3                           |
| <b>Depressed Clad:</b>     |                |                           |                               |
| LYC2                       | 25             | 1.8                       | 6.9                           |
| <b>Dispersion Shifted:</b> |                |                           |                               |
| LYC3                       | 20             | 1.3                       | 5.1                           |
| SUM1                       | 13             | 1.0                       | 4.0                           |

### 9.1 Theoretical Results

It can be seen that measured and calculated SBS values are considerably different. In the case of the ITU calculations there is an order of magnitude difference from the measured values. This formula includes an unsubstantiated value for the Brillouin gain coefficient. Due to the lack of information it is difficult to assess where this formula is in error but the Brillouin gain coefficient is most likely to be the largest contribution to the discrepancy.

There are a number of factors which affect the accuracy with which the Agrawal model can estimate the SBS parameters of a fibre. In particular, the SBS threshold power is dependent on the pump linewidth,  $\Delta\nu_p$  being much narrower than the Brillouin gain spectrum,  $\Delta\nu_B$ . Thus the SBS threshold power will be increased by a factor of  $\Delta\nu_p / \Delta\nu_B$  for  $\Delta\nu_p \gg \Delta\nu_B$ . In the case of this experiment the assessment of the linewidths was limited by the resolution of the OSA, but it would appear that the pump and Brillouin linewidths were of a comparable value, which would increase the calculated threshold power by a factor of 2. This would bring the general trend of the measured results in line with the calculated values.

However, there are a number of factors which would act to reduce the calculated threshold power. The frequency shift of the Stokes wave depends on the scattering angle by the relation  $\sin(\theta/2)$ . The model only considers the Stokes intensity in the backward ( $\theta=\pi$ ) direction but in fact there would be a significant contribution in other directions that could be back-scattered by the fibre which would decrease the threshold power. Also, the model is derived assuming a Lorentzian profile to the Brillouin gain spectra. However, recent work [13] has shown that for modern telecoms fibres this assumption may not be valid. A more realistic profile would lead to a reduction in the multiplicative factor of 21 to 19 and thus reduce the theoretical SBS threshold power by 10%.

There are two further parameters in the model which cause uncertainty in the calculated values. Firstly there is a factor of  $K$  which relates to the polarisation behaviour of the pump and Stokes waves and hence the strength of interaction between them. The possible range is ( $1 < K < 2$ ), leading to a possible error of 50 %. This is a complex subject and there appears to be little information reported in the literature as to how to determine the exact value of  $K$ . The second parameter is  $A_{\text{eff}}$ , which for the purposes of this work was calculated using the empirical relationship between it and  $mfd$  with the Namihiro correction factor for fibre design type. However, this is still an active research area to accurately determine  $A_{\text{eff}}$ . The uncertainty in this parameter could lead to a 10% error in the calculated threshold power.

## 9.2 Measured Results

There are a number of critical factors which affect the accuracy of the measured threshold powers. Firstly the power meters should be calibrated for absolute response and linearity of response to ensure accurate power readings. In this experiment all the power meters were calibrated to an accuracy of  $\pm 1$  % and used within their linear range. However, due to the high optical power levels an angled connector was used on the power meter sensor interface which degraded this absolute power calibration to an estimated  $\pm 5$  %. It is essential to ensure that low loss and low return loss connections are used in the experimental system. This was achieved by utilising fusion splices and angled FC connectors wherever possible.

The ITU test method has some omissions in the test procedure. It does not include an optical isolator before the input to the splitter. It was evident that there were some reflections in the system as when the attenuator was removed for the higher power measurements, the transmitted power would drop in the region of 0.5-1% compared to the input and backscatter arms. The attenuator used is currently the best available in terms of reflection properties but that at low attenuator settings this reflection can increase and it is thought that this was responsible for the effect observed. This will be worse with poorer specification attenuators. To achieve the highest level of accuracy, an optical isolator should be included in the test system and a full assessment of the reflection characteristics of the system performed.

## 10 Conclusions

The single mode, matched-cladding fibre attenuation standard has been demonstrated to be a suitable transfer standard for the calibration of attenuation measurement equipment with an input power of up to 0 dBm. Above this power level, non-linear effects may significantly affect the accuracy of the calibration of the FAS.

Three main measurement issues have been identified as limiting factors in the accuracy of SBS measurements. These are:

- The requirement for having a source of known linewidth, to ensure that this is less than the Brillouin frequency of the fibre or matches the actual conditions under which the fibre will be utilised.
- The need for a power meter that can be accurately calibrated when using angled connectors.
- The requirement for optical isolators to remove reflections within the measurement set-up.

In addition to the above areas, further work is required on the temperature dependence of the SBS threshold power before it is possible to accurately assess the potential of the FAS as an SBS power threshold transfer standard. However, the work presented in this report suggests that the FAS may have the stability required for this purpose.

Three main areas require further research to enable accurate calculation of Brillouin thresholds. These are:

- The correction of the model to include the forward scattering contribution to the SBS signal
- The accurate determination of  $A_{\text{eff}}$  and further work into the investigation of the accuracy of empirical form of its calculation
- Further investigation into the value of  $K$ , the polarisation dependent constant

In order to be a reliable and accurate standard test procedure, the appendix in the ITU Recommended test method needs further refinement, to include the points detailed above.

An intercomparison of SBS threshold measurements is currently underway between COST241 participants. Preliminary results indicate that the agreement between participants is at best 20%, indicating a need to address these areas if improved accuracy is to be achieved.

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