NPL REPORT DEM-EM003

Characterisation of a Fibre Optic Raman Amplifier

Pete Tomlins

April 2004

Characterisation of a Fibre Optic Raman Amplifier

Pete Tomlins and Martin Wicks

April 2004

ISSN 1744-0483

National Physical Laboratory
Hampton Road, Teddington, Middlesex,TW11 0LW

Approved on behalf of Managing Director, NPL
by Dr. Stuart Pollitt, Director of Enabling Metrology Division

Executive Summary

This report describes and discusses the characterisation of fibre optic Raman amplifiers (FRA). Techniques developed for erbium doped fibre amplifiers were used to experimentally investigate the noise and gain characteristics of a home built FRA.

Results from this preliminary investigation indicate that the accuracy of gain measurements is affected by the choice of measurement source, either broad or narrow band. This is due to gain saturation and is contrary to previously published results. Analysis of optical noise figure measurements has also shown that gain spectrum structure can lead to high measurement uncertainties when using the interpolation technique. It is also reported that double rayleigh scatter noise was negligable in the FRA under test.

This work is not exhaustive and paves the way for further and more exhaustive investigation. Particular attention should be given to FRA noise figure measurements. In the literature there is currently no comprehensive comparison of optical and electrical measurement techniques that would be especially useful to device and systems manufacturers. Future work should also rigourously examine the origins of gain and noise in a FRA, paying attention to the contribution from multiple non-linear processes.

Contents

1 Introduction

The emergence of laser technology in the 1960's and low loss optical fibres in the 1970's and 80's has formed the basis for the investigation of non-linear fibre optics. The high optical intensity achievable by confinement of a laser beam within the small core of an optical fibre makes them an ideal medium in which to study non-linear optical processes. Much of the effort in this area has been motivated by the optical telecommunications industry where the use of short optical pulses, multiple signal channels and high peak powers is commonplace. Under such conditions non-linear effects can be efficiently generated, according to the properties of the fibre.

Nonlinear effects such as self-phase modulation (SPM), cross-phase modulation (XPM), four-wave mixing (FWM), stimulated Brillouin scattering (SBS) and stimulated Raman scattering (SRS) have been studied extensively in optical fibres [1–6] and more recently in erbium doped fibre amplifiers (EDFAs) [7, 8].

Early work on Raman scattering in optical fibres showed the potential for broadband all optical amplification and measured directly the small signal gain in pure silica core single mode fibre [9]. Although the demonstration of in-fibre Raman amplification predates that of EDFAs [10, 11], it is only recently that Raman amplifiers have attracted renewed attention for expanding the capacity of existing optical fibre links. In order that FRAs can be effectively utilised it is essential that they are accurately characterised. The parameters of merit are the gain and noise figure (NF).

The characterisation of Erbium Doped Fibre Amplifiers is well documented. However, there appears to be relatively little literature available regarding the similar characterisation of Raman amplifiers. Presumably it has been assumed that the techniques employed for EDFAs are applicable to Raman amplifiers, despite the amplification processes being entirely different.

Therefore, this report describes an investigation into the characterisation of fibre optic Raman amplifiers. In order that the characterisation might be comprehensive, the FRA was a 'home-built' device. This was used to measure the gain and NF by a number of techniques, and hence has opened the way for much future research.

The measurement of the amplifier NF and associated assumptions are somewhat more complex than for gain. Therefore the measurement of NF has become the primary focus of this work.

2 Gain

The gain of an amplifier provides a quantitative measure of amplification and a figure of merit for comparison between devices. Gain G is defined as the ratio of the signal input to output power, equation (1), and is hence a relatively straight forward measurement.

$$G = \frac{P_{\text{out}}}{P_{\text{in}}} \tag{1}$$

Accurate gain measurements rely principally on the ability to accurately measure the input and output signal power. This can be done using an Optical Spectrum Analyser (OSA) calibrated for both absolute power and linearity. Gain measurements have been made using both a narrow band tuneable laser and a broadband source of amplified spontaneous emission (ASE). However, in EDFAs care must be taken when comparing results due to the different amplifier saturation conditions. In FRAs equivalent gain measurements have been made by both narrow and broad band techniques [12,13] indicating that saturation conditions were similar. This is probably due to the significantly high pump powers (Watts) used in FRAs.

Gain is typically expressed in logarithmic units G_{dB} and is related to the linear gain by the expression

$$G_{\text{dB}} = 10\log(G). \tag{2}$$

In this investigation FRA gain measurements were made using both the narrow and broadband techniques. However, their equivalence at increasing signal power levels and different pump powers was not investigated.

2.1 Origin of Gain in Raman Amplifiers

FRAs differ somewhat in operation from their doped fibre counterparts. The observed gain does not originate from the stimulated emission of light from an inverted electronic energy level population, but rather from a vibrational interaction between the optical field and the molecular structure of the optical fibre [14].

A strong pump field generates vibrational excited modes within the fibre molecular structure, typically silica ($Si0_2$). The vitreous nature of silica optical fibre allows a continuum of vibrational modes, that in turn causes a broad optical spectrum to be generated. This is known as the spontaneous Raman spectrum and its generation has been discussed in detail in references [15–20].

In Raman amplification a signal light is injected into the fibre. Energy from the pump light is then transferred to the signal light through the fibre excited vibrational modes.

This process is stimulated Raman scattering, and for multiple signal channels the resulting output is known as the Raman gain spectrum, and for pure silica core fibre has the well known form shown in figure 1, first measured by Stolen *et al* [9].

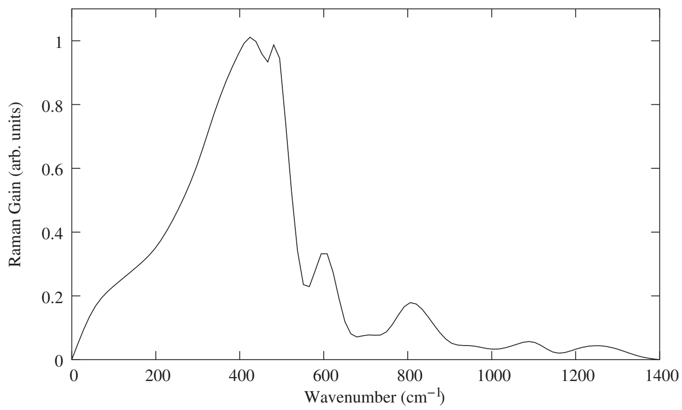

Figure 1:Typical normalised Raman gain spectrum for pure silica core optical fibre.

The exact shape of the gain spectrum is dependent upon the fibre core dopants and quantities and the related spontaneous spectrum has been used to investigate dopant profiles across the core diameter [21]. An exact functional form for the gain spectrum is not known, and the models available are somewhat limited [22, 23], however these do yield some physical insight. A more recent investigation has attempted to model the gain spectrum using a simplified molecular dynamics approach [14], which shows much promise for future development. Such an approach may be of benefit to manufacturers since it is sensitive to dopant molecules.

From figure 1 it is clear that the Raman gain spectrum contains significant structure. Recent developments in Raman amplifier technology have been directed at generating flat gain profiles. This has been achieved by using multiple pump lasers [24] to produce a number of overlapping gain spectra.

3 Noise

Amplifier noise is a critical parameter that limits system performance and leads to a decrease in receiver sensitivity. The noise generated in an optical amplifier is parameterised by the noise figure (NF), defined as the additional input noise required to obtain the measured amplifier noise at the output. This can be written in terms of the signal to noise ratios at the input ($\mathrm{SNR_{in}}$) and output ($\mathrm{SNR_{out}}$) measured with an ideal detector as the optical bandwidth is reduced infinitesimally [25, 26] so that the contribution from mixing between ASE and itself is negligable.

$$\mathrm{NF} = \lim_{B_0 \to 0} \frac{\mathrm{SNR_{in}}}{\mathrm{SNR_{out}}} \tag{3}$$

3.1 Origin of Noise in Raman Amplifiers

In FRAs spontaneous Raman scattering generates a broad spectrum of light. Some of this light is generated at the signal frequency, but is not signal, and therefore it acts as ASE noise in the detected output. Optical noise can also be present from residual pump light at the signal wavelength. This can be reduced significantly by using a couter-propagating pump configuration, however due to Rayleigh backscattering some pump light may be found at the signal output. By using a bandpass filter residual pump noise can be removed and hence ignored. Therefore the primary noise sources are ASE and amplified shot (quantum) noise caused by fundamental optical field (zero-point) fluctations.

Optical amplifiers are frequently referred to as having quantum limited noise performance. In order that the Heisenberg uncertainty principle is not violated it has been shown [27] that an optical amplifer must at least generate an ASE noise power P_q, i.e. the quantum limit. Such quantum limited noise originates from optical fluctuations of the vacuum state.

$$P_\mathrm{q} = \frac{1}{2}(G-1)h\nu B_0 \tag{4}$$

It is therefore evident that any optical source must also generate similar quantum limited, or shot noise $P_\mathrm{shot} = 1/2h\nu B_0$. B_0 is the optical bandwidth of the detector, h is Planck's constant and ν is the optical signal frequency.

In a practical amplifier the total ASE noise power P_ASE can be written as the sum of the quantum limited noise and any additional noise P_add.

$$P_\mathrm{ASE} = P_\mathrm{N} + P_\mathrm{add} \tag{5}$$

Therefore, the total noise power P_T at the output of a high gain ($G \gg 1$) optical amplifier is the sum of the amplifier ASE and amplified source noise power.

$$P_{\mathrm{T}} = P_{\mathrm{ASE}} + GP_{\mathrm{shot}} \approx Gh\nu B_0 + P_{\mathrm{add}} \tag{6}$$

Assuming that the amplifier input power is given by P_{in}, then the input SNR is

$$\mathrm{SNR}_{\mathrm{in}} = \frac{P_{\mathrm{in}}}{P_{\mathrm{shot}}} = \frac{2P_{\mathrm{in}}}{h\nu B_0} \tag{7}$$

and the output SNR:

$$\mathrm{SNR}_{\mathrm{out}} = \frac{GP_{\mathrm{in}}}{P_{\mathrm{T}}} = \frac{GP_{\mathrm{in}}}{Gh\nu B_0 + P_{\mathrm{add}}} \tag{8}$$

Substituting equations (7) and (8) into equation (3);

$$\mathrm{NF} = \frac{2(Gh\nu B_0 + P_{\mathrm{add}})}{Gh\nu B_0}. \tag{9}$$

In the quantum limited case where $P_{\mathrm{add}} = 0$ it is clear that $\mathrm{NF} = 2$, and hence the quantum limit of 3 dB for high gain optical amplifiers.

In Raman amplifiers there is one further contribution to the noise. This is double rayleigh scatter (DRS). DRS is caused by the Rayleigh scattered light undergoing a secondary Rayleigh scatter in the direction of the propagating signal. It has been recently investigated and measured by both electrical [28] and optical techniques [29]. It can be an important contribution to the overall noise figure due to the high powers and long lengths of optical fibre used in FRAs.

3.2 Noise Figure Measurement Techniques

A number of well established techniques exist for measuring the NF in EDFAs. These are listed below:

- Spectral Interpolation [30]
- Polarisation Extinction [31]
- Time Domain Extinction [32]
- Relative Intensity Noise (RIN) Subtraction [33]

The top three of these are optical techniques, whereas the RIN subtraction method is performed in the electrical domain. Optical and electrical techniques for noise figure measurement in EDFAs have been compared previously by Nishi *et al* [34], however there has been no such comparison for Raman amplifiers. A brief summary of each technique is given in the following sub-sections.

Spectral Interpolation

This method is relatively simple to carry out and requires the least equipment. Indeed some optical spectrum analysers are pre-loaded with software to carry out the analysis of measured data. The European standard for the measurement of noise figure in optical amplifiers [35] specifies the measurement configuration shown in figure 2.

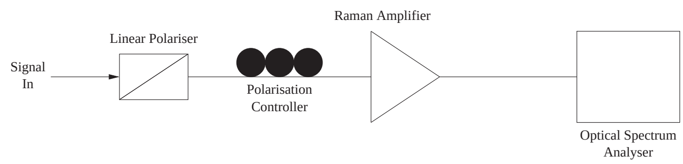

Figure 2:Experimental arrangement for measuring noise figure by spectral interpolation, [35].

The noise figure is measured by obtaining OSA traces of the signal (bypassing the amplifier) and the amplified signal. A line is then interpolated beneath the signal in each case and the power integrated to obtain both the signal and total spontaneous emission powers, P_{SSE} and P_{SE} respectively. The noise figure is then calculated using equation (10).

$$\mathrm{NF} = \frac{1}{G} + \frac{2P_{\mathrm{ASE}}}{Gh\nu B_0} \tag{10}$$

In this expression G is the amplifier gain at the signal frequency ν, h is Planck's constant and B_0 is the optical bandwidth of the OSA in Hz. The amplified spontaneous emission (ASE) power, P_{ASE}, of a polarised input signal is calculated from the measured source spontaneous emission and total spontaneous emission, P_{SSE} and P_{SE} respectively.

$$P_{\mathrm{ASE}} = P_{\mathrm{SE}} - P_{\mathrm{SSE}}G \tag{11}$$

Polarisation Extinction

Polarisation extinction depends on the fact that ASE produced by the amplifier is randomly polarised. A polarised signal can therefore be filtered from the ASE measurement by measuring an orthogonal polarisation state. If the ASE is truly randomly polarised then the measured ASE power will be half of the total. A simple experimental arrangement for making this measurement is shown in figure 3.

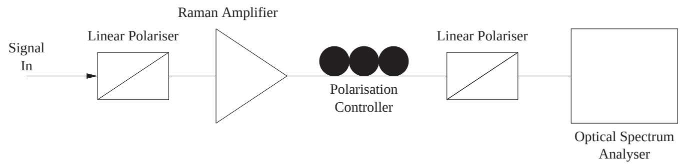

Figure 3: Experimental arrangement for the measurement of amplifier noise figure using the polarisation extinction method, [25]

The NF is determined using equation (10).

Time Domain Extinction

The time domain extinction method was first proposed by Baney *et al* [32] to measure the noise figure in Erbium Doped Fibre Amplifiers (EDFAs). The method uses a modulated signal and a time gated receiver to measure ASE noise directly. The delay of the gated receiver is varied so that the amplifier output can be measured when the signal is either 'on' or 'off'. A modulation frequency is chosen such that the amplifier gain is not modulated, i.e. in an EDFA the modulation must be faster than the erbium excited state lifetime (≈10 ms).

Since the operation of FRAs is fundamentally different to that of EDFAs, this technique cannot be used to measure their NF. However, a modified version of the time domain extinction method has been demonstrated for making direct optical measurements of DRS [29].

3.3 Relative Intensity Noise Subtraction

The noise figure of an optical amplifier can be measured in the electrical domain. It is useful for measuring the total amplifier noise, and can also provide extra information about the origin of noise, such as multi-path interference (MPI). However, electrical domain measurements can be difficult to make and it is essential that the detector and RF amplifier used have excellent noise performance and wide dynamic range.

The principle of electrical measurement is fairly straight forwards. An optical signal is modulated at some frequency in the RF spectrum that is used as an absolute reference. The modulated signal is amplified by the optical amplifier and detected by a photodetector. The signal from the photodetector is fed into an Electrical Spectrum Analyser (ESA).

Any low frequency noise, such as multi-path interference (MPI), signal-spontaneous or spontaneous-spontaneous beat noise appears on the ESA as a sideband at a shifted frequency. Each noise power component is calculated by in a similar way to the interpolation technique described above. The electrical technique is advantageous since it provides a direct measurement of the NF, separating out each component as different RF frequencies.

European standard EN 61290-3-2 [36] describes a procedure and experimental arrangement for the measurement of noise figure by the RIN subtraction technique. A similar configuration is shown in figure 4.

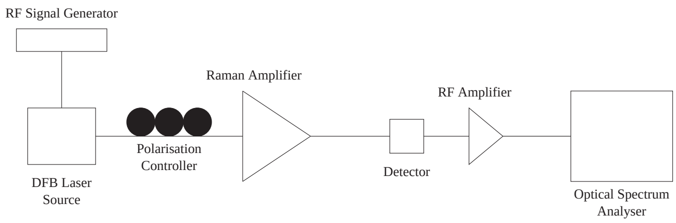

Figure 4: Experimental arrangement for the measurement of noise figure in an optical amplifier using the electrical method

4 Raman Amplifier Design

The Raman amplifier developed for characterisation in this project follows a simple counter-propagating pump design, based on that found in reference [12]. A schematic of the amplifier used in the experiments described here is shown in figure 5.

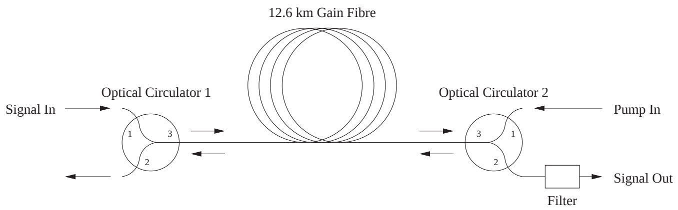

Figure 5:The Raman amplifier constructed for the experiments reported on here.

A Raman laser pump source was chosen, with a nominal wavelength of 1480 nm, maximum power of 4 Watts and linewidth of approximately 10 nm. A broad pump linewidth is preferable to minimise the effect of stimulated Brillouin scattering, and therefore maximise the pump power coupled into the 12.6 km of SMF-28^{TM} gain fibre. The choice of gain fibre was made since it reflects the fibre that already exists in many networks that could potentially be expanded by incorporating Raman amplification. The long wavelength pass filter was inserted on the output stage of the amplifier to further reduce the presence of any residue backscattered pump at the output.

Insertion losses for each component used in the amplifier setup are tabulated in table 1. The losses are given for the signal wavelength of 1585 nm.

Component	Loss (dB)
Circulator 1 (Ports 1-3)	1.14
Circulator 1 (Ports 3-2)	1.30
Circulator 2 (Ports 1-3)	1.12
Circulator 2 (Ports 3-2)	0.79
Gain Fibre (12.6 km)	2.74
Filter	0.58

Table 1:Component insertion loss at signal wavelength of 1585 nm

The amplifier spontaneous Raman spectrum, i.e. its ASE output, is shown in figure 6. This was measured using a calibrated OSA at 0.5 nm intervals.

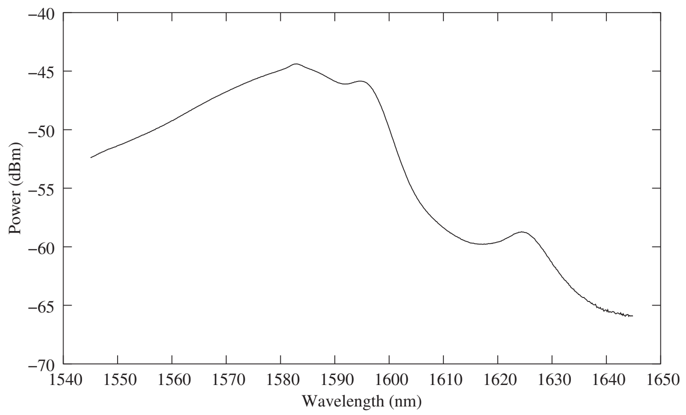

Figure 6:Measurements of the Raman amplifier ASE spectrum using a 1480 nm, 2 Watt pump.

The impact of pump power and gain fibre length on gain and noise figure has been investigated but requires more comprehensive research. Therefore these results have been witheld from publication at this point.

5 Gain Measurements

Simple on-off gain measurements were made using both a narrow band tunable laser and broadband ASE source. An OSA was used to measure the gain directly. The tuneable laser input power was maintained at 1 mW, whilst the total output power of the ASE source was nominally 50 mW. The amplifier pump power was set at 2 Watts, measured with a high power thermopile detector with 10% uncertainty. For comparison the measured gain figures for both methods are plotted in figure 7.

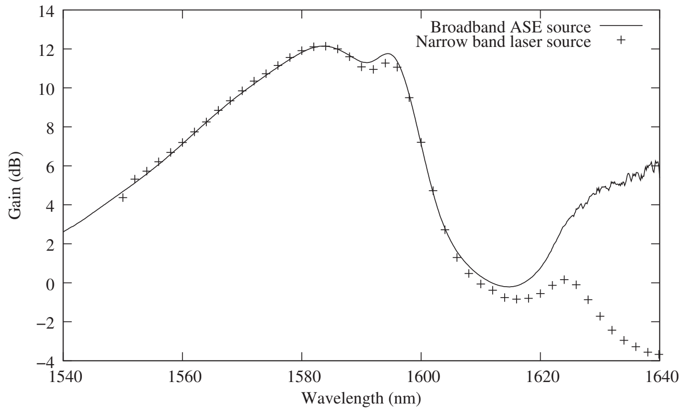

Figure 7:Comparison between broad and narrow band gain measurements.

These measurements indicate good agreement for wavelengths shorter than 1580 nm. However, for longer wavelengths (above the gain peak) the gain measured by the narrow band technique are lower. At this time it is unclear whether this discrepancy is due to gain saturation effects or simply experimental uncertainty. Lewis [12] suggests that accurate gain measurements are possible using a broadband source when low signal powers are used, i.e. ASE from a laser diode. The results of this investigation demonstrate the need for a comprehensive study into the relationship between saturation effects and gain measurement accuracy in FRAs.

6 Noise Figure Measurements

This section contains a more detailed account of our measurements of the noise figure for our amplifier. It contains a comparison of results using four different techniques. All measurements were carried out using the amplifier shown in figure 5, using a 1480 nm wavelength pump source operating at 2 Watts. The signal wavelength was 1585.125 nm from a tunable external cavity (EC) laser source.

6.1 Noise Figure by Spectral Interpolation & Polarisation Extinction

Noise figure measurements of the Raman amplifier shown in figure 5, were made by both spectral interpolation and polarisation extinction techniques. The results were analysed by hand rather than using software processing available on commercial instruments. These two techniques are directly comparable since they measure the same quantities, assuming that signal spontaneous beat noise is the dominant noise source.

Spectral Interpolation

We measured the noise figure using the arrangement shown in figure 2, modified by placing an optical attenuator between the filter and OSA. This was done to keep the OSA within its linear range and avoid damaging the detector, the attenuation was then added to the output trace before analysis. Traces were then taken of the signal bypassing the amplifier setup, directly into the OSA, and then of the amplified signal through the Raman amplifier, figure 8.

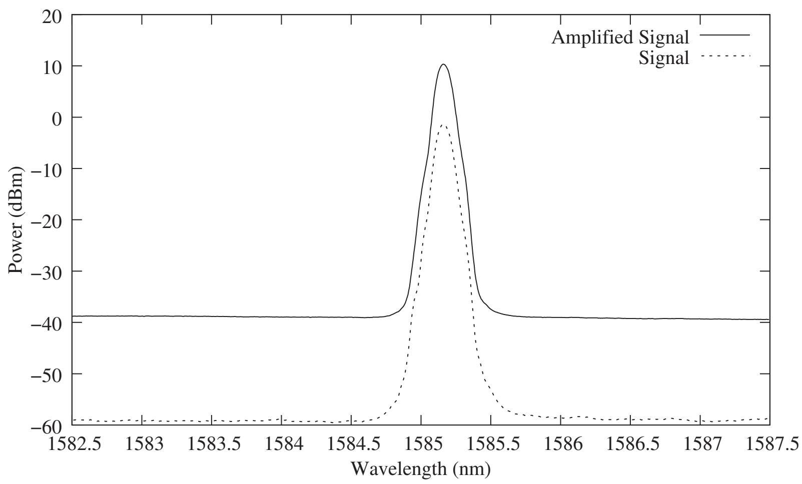

Figure 8:The OSA traces for the signal only, and amplified signal

In order to calculate the source and amplifier noise contributions, the peak is removed from each trace. This procedure is not trivial, since the Raman gain spectrum contains significant structure. The interpolation or curve fitting technique used is therefore critical. As a result of this study, it has been shown [37] that depending on the position along the gain spectrum and the interpolation or curve fit order, the NF uncertainty may be affected by as much as 1.6 dB. It was found that 1st, 2nd and 3rd order polynomial curve fits give repeatable results and introduce the least uncertainty, around 0.3 dB. It was also shown that for polynomial fits the signal peak should be removed over a 1-2 nm span. Here a 2 nm peak removal width was chosen and a 3rd order polynomial fit. An example of these results is shown in figure 9. When making these measurements it was essential that the OSA sensitivity was sufficiently high to enable measurement of the source and amplifier noise floors. A sensitivity that is too low gives an artificially high noise power and therefore a high noise figure.

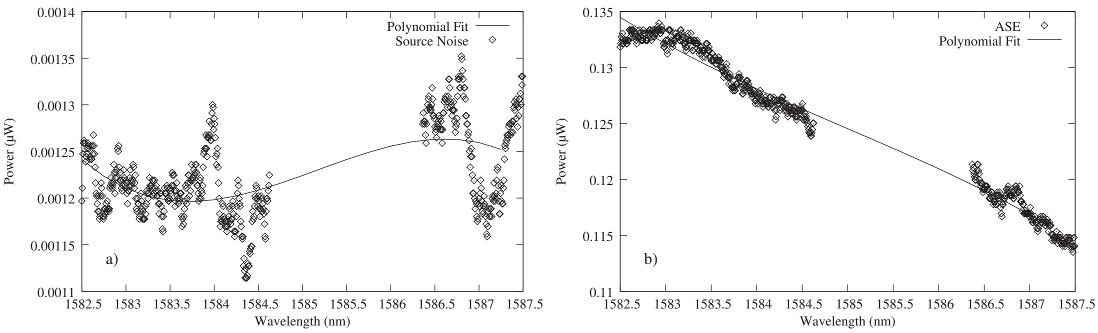

Figure 9:3^{rd} order polynomial trendlines fitted to a) the source noise, b) the amplified noise.

The source spontaneous emission (P_{SSE}) and amplifier spontaneous emission (P_{SE}) are calculated from the interpolated OSA spectra by integrating across the OSA resolution centred at the signal wavelength. The optical bandwidth B_0 is calculated from the calibrated OSA resolution.

Measured values for each of the parameters defined for equation (10) are given in table 2. The noise powers were obtained by spectral interpolation.

Description	Parameter	Value
Gain	G	12.05 (11.68 dB)
Noise due to source	P_{SSE}	1.23 nW
Noise due to amplifier	P_{SE}	0.124 μW
ASE power	P_{ASE}	0.106 μW
Centre frequency	ν	1891277 GHz
Optical bandwidth	B_0	11.65340 GHz
Noise figure	NF	9.98 (9.95 dB)

Table 2:Measured parameters for calculation of noise figure by spectral interpolation

These values do not seem unreasonable when compared to the similar results of Lewis [12]. The noise figure is a little high, although this can be explained by the amplifier design. The main contributors are most likely the high pump power and relatively low input signal power, back-scattered long wavelength ASE from the pump laser, the use of relatively low non-linearity fibre and perhaps reflections from splices and connectors. However, quick analysis of the amplifier construction with an OTDR revealed that there were no significant reflections from splices or connectors. For the purposes of this investigation the amplifier design has not been optimised. A study into the effect of fibre type and overall amplifier design on the noise and gain performance should be considered as an important next step in future research.

Polarisation Extinction

For comparison, noise figure measurements were also made using the polarisation extinction method. The experimental arrangement of figure 3 was used. Below we show the output trace of the amplified signal, figure 10.

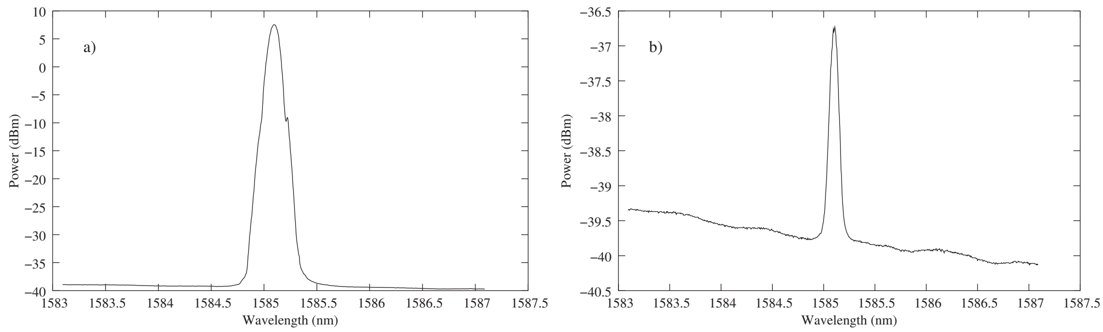

Figure 10: Raman amplifier output, a) amplified signal with no polarisation extinction, b) Maximum polarisation extinction

It is clear from the traces that the polarising beam splitters used have an extinction ratio of around 44 dB. In the case of this experiment, the signal to noise ratio of the amplifier output was 47 dB, and therefore it was not possible for the signal to be entirely nulled. Complete removal of the residual signal peak was carried out by spectral interpolation as in the previous section. Table 3 shows the results from these measurements.

Description	Parameter	Value
Gain	G	15.24 (11.83 dB)
Noise due to source	P_{SSE}	0.199 nW
Noise due to amplifier	P_{SE}	0.108 μW
Total ASE power	P_{ASE}	0.105 μW
Centre frequency	ν	1891277 GHz
Optical bandwidth	B_0	11.65340 GHz
Noise figure	NF	9.47 (9.76 dB)

Table 3:Measured parameters for calculation of noise figure by polarisation extinction

The noise figure results obtained by polarisation extinction and spectral interpolation show good agreement. The lower noise figure yielded from polarisation extinction is due to the use of equation 11 for the power of the ASE in equation 10. Equation 11 effectively applies the amplifier gain to the measured source noise, and then subtracts this figure from the measured noise at the amplifier output. However, the polarisation extinction carries out this procedure optically, by excluding the polarised source 'signal' and 'noise' from being measured by the OSA. Therefore, for polarisation extinction measurements, equation 10 can be modified to, equation 12.

$$\mathrm{NF_{PN}} = \frac{1}{G} + \frac{P_{\mathrm{SE}}}{Gh\nu B_0} \qquad (12)$$

The subscript *PN* stands for *Polarisation Nulling.* Having made this correction, the noise figure is calculated as

$$\mathrm{NF_{PN}} = 9.89 \text{ dB}$$

It can be seen that this modification has gone some way to improving the agreement between results for the two measurement techniques. Some of the remaining discrepancy may be attributable to the polynomial interpolation of noise data. There is certainly agreement within any sensible estimate of uncertainty.

7 Noise Contribution From Double Rayleigh Scatter

Rayleigh scatter is a well known and understood effect in fibre and bulk optics. It describes the scattering of light from inhomogeneities in the host medium. The scattering of light by this mechanism, in the opposite direction to that of propagation is known as Rayleigh backscatter. In high gain systems involving long lengths of fibre the number of backscattered photons can become sufficiently high such that a significant number of these photons are backscattered once again in the direction of signal propagation. This phenomenon is known as Double Rayleigh Scatter, DRS. Raman amplifier systems would seem to offer an ideal situation in which DRS could occur.

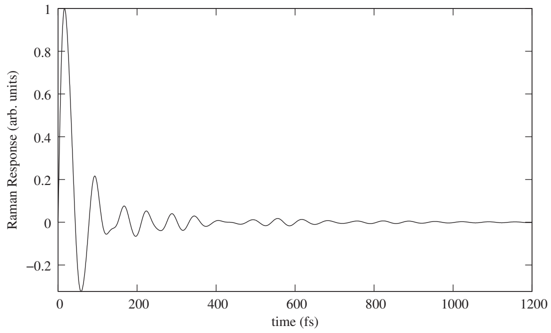

Figure 11:The Raman response function for pure silica core fibre, [19].

The operation of a Raman amplifier is significantly different to that of an EDFA, depending on the vibrational modes of the host medium for amplification. The vibrational response of molecules within the glass indicates a half-life of the order 100 femtoseconds, figure 11. This fast decay of the vibrational modes suggests that a modulation of the order 10 THz would be required to observe Raman ASE directly in the optical domain. However, the time-domain extinction method can still be useful for looking at noise due to Double Rayleigh Scatter (DRS) in Raman amplifiers [12]. The long length of fibre used for signal amplification means that the round trip time of DRS light is of the order micro-seconds, i.e. (126 μs for 12.6 km amplifying fibre). Therefore the DRS noise can be detected by looking for some trace of a signal when the actual signal is in its ‘off’ state.

7.1 Optical Measurement of DRS

Our method for looking for evidence of DRS is based upon that of Lewis [29]. However, we chose to look for the scattered light in the time domain using an oscilloscope. The experimental arrangement is shown in figure 12.

In this configuration the signal generator drives the acousto-optic modulator at a frequency to generate optical pulses having a temporal length longer than the time of flight of a photon passing twice the length of the fibre. This way the fibre is ‘filled’ with light. When the modulator switches the optical signal off the oscilloscope should display any light that is delayed in arriving at the detector due to DRS.

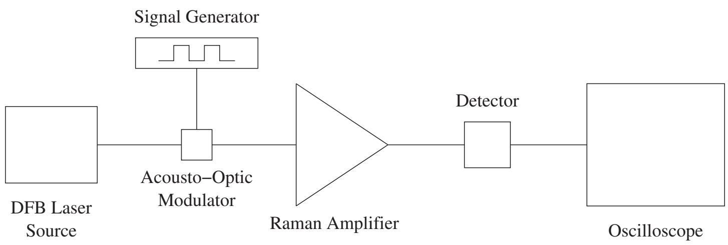

Figure 12:NPL system for observing Double Rayleigh Scatter in a Raman amplifier

This measurement system is limited by two major factors. The first of these is the difficulty with coupling enough of the signal power back into the fibre from the free-space modulator. This leads to a second problem of finding a detector with sufficient dynamic range to observe the DRS, or an electrical amplifier with sufficiently low noise to avoid swamping the DRS signal. The method of Lewis, whereby a time gated receiver is used to look at the signal during its off state could be beneficial, however, this requires a second modulator that would further reduce the optical power at the detector.

Due to the presence of such experimental difficulties, a simple model was developed to calculate the expected DRS power at the detector. Previous models for DRS have been developed by Fludger [28] and Parolari [38]. The model developed here is based on the OTDR backscatter calculations of Danielson [39]. In this simple model it is assumed that the fibre attenuation is due entirely to Rayleigh scattering, and therefore the optical signal is attenuated exponentially along the fibre length, equation (13),

$$P(\ell) = \exp(-\alpha\ell) \tag{13}$$

where $P_(\ell)$ is the optical signal power along the length of the fibre ℓ. Now, if we consider the Rayleigh backscatter at infinitesimal length steps ($d\ell$), we can determine the corresponding backscattered power, $dP_{BS}(\ell)$. Integrating over the whole fibre we find, equation (14).

$$P_{BS}(\ell) = \alpha\Gamma \int_0^L P(\ell)d\ell \tag{14}$$

α is the fibre attenuation and Γ is the fibre capture fraction. The attenuation per metre in linear form, is determined as $\alpha = 1 - 10^{\alpha_{dB}/10}$. Where α_{dB} is the attenuation in decibels per metre. The capture fraction is found from the numerical apperture θ_{NA} as $\tan^2(\theta_{NA})$.

From the previous equations, it then follows that at each infinitesimal length step there will be some double scattering. This analysis leads to equation (15) for the double-backscattered power, $P_{DRS}(\ell)$.

$$P_{DRS}(\ell) = \alpha\Gamma \int_0^L P_{BS}(\ell)d\ell \tag{15}$$

Substituting into (15) for $P_{BS}(\ell)$ leads to the simple result for the double Rayleigh scattering power as a function of fibre length, equation (16).

$$P_{DRS}(\ell) = -\alpha\Gamma^2[\exp(-\alpha\ell) - 1]\ell \qquad (16)$$

For 12.6 km of standard single mode fibre, with an input signal of 2 mW and wavelength of 1585 nm, we obtain the plot shown in figure 13.

Clearly, when the transmission fibre is lossy the contribution due to double Rayleigh scattering is negligible. However, within a Raman amplifier there is gain within the active fibre. By assuming an exponential Raman gain along the fibre length the DRS power can be estimated, figure 14. Here the internal gain of the amplifier is chosen to be 20 dB, this is similar to that of our amplifier under test.

The simulation indicates that the DRS noise is still very small, approximately -50 dBm compared with -80 dBm for lossy fibre. This result is highly dependent on the ability to couple high enough power into the amplifier from the modulator, i.e. the simulation assumes 2 mW. Practically this is not trivial. Another option might be to use electro-optic intensity modulators to switch off the signal beam. In this case the modulator must have an extinction ratio of better than 80 dB. In the following section we compare electrical measurements of the double Rayleigh scatter noise with the theoretical results of the current section.

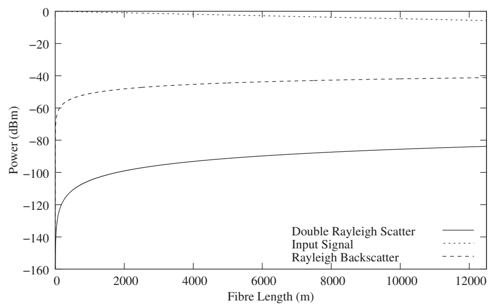

Figure 13:Simulation of Double Rayleigh Scattering in 12.6 km of single mode fibre

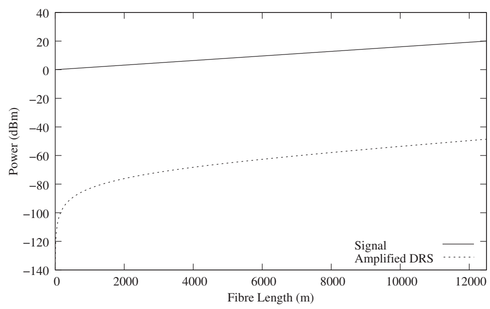

Figure 14: Simulation of Double Rayleigh Scattering in a Raman amplifier, having 12.6 km single mode gain fibre.

8 Conclusions

In the study reported on here, an all optical fibre Raman amplifier was successfully built and characterised. Although the basic characterisation is at first reasonably simple, there are a number of aspects that require further investigation.

Optical gain measurements were performed using both a narrow band and broadband source. The results here suggest that saturation effects *are* important in FRAs as in EDFAs. Elsewhere it has been implied that these measurement approaches are equivalent in FRAs [12, 13] for small signals and therefore the relationship between broad and narrow band measurements and the resulting gain uncertainty merits much further invesitgation. It remains to be seen whether there are any significant advantages to one method over the other. Saturation characteristics of Raman amplifiers has been previously investigated [40], however the effect of saturation on accurate gain and NF measurements in FRAs is yet to receive comprehensive research. A comparison of gain measurements should be made by optical and electrical measurement methods including a rigourous assessment of uncertainties. Related to the amplifier gain is the Raman gain coefficient. This study has not focussed on this parameter, however it is often used to in the characterisation of optical fibres that might be used for Raman amplification. This parameter is dependent on the finite pump linewidth, and therefore in future studies should be taken into consideration.

A number of difficulties with NF characterisation of FRAs have been identified by this investigation. Optical techniques have been primarily studied here, of these the direct interpolation method yielded a higher NF than the polarisation nulling technique. However the results can be seen to agree to well within the uncertainty conribution from interpolation only [14]. It was shown that high order interpolation techniques, such as cubic spline fits, can introduce significant uncertainty into the optical measurement. It was also concluded that 1st, 2nd and 3rd order polynomial curve fits give the best measurement repeatability, however the measured NF uncertainty can differ significantly depending upon the signal location on the gain spectrum. The results of this study indicate that the NF standard deviation can vary between 0.01 dB to 0.12 dB with signal wavelength.

The polarisation extinction method also requires further investigation, since it assumes that the ASE is randomly polarised. Previous experiments on spontaneous Raman scattering in bulk silica [41] indicate that this may not be an accurate description. It also remains to be seen if any more useful information can be obtained from electrical NF measurements. Although the work of Fludger *et al* [28] has shown that electrical measurements can be used to measure multi-path interference in FRAs it is concluded here that for a Raman amplifier consisting of standard optical fibres, DRS and MPI are negligable contributions. However, further experimental investigation into the effect of fibre type and length, pump characteristics and configuration on the NF and DRS contribution are required in order to validate this claim. For example, it is expected that DRS may become significant for dispersion compensating optical fibres. In high DRS systems it may also be useful to determine the effect of DRS on the bit error rate (BER), and hence establish acceptable DRS levels. Following this the management of DRS in amplifier design could have far reaching implications for network and component design.

In an attempt to achieve a flat gain spectrum over a broad wavelengh band researchers have used mainly two approaches. The first most common is to use multiple pump lasers separated in centre wavelength. This configuration produces overlapping Raman gain spectra, and hence a nominally flat gain response. In another approach the pump laser spectrum is broadened first by using a highly non-linear optical fibre before the amplifying fibre. In both approaches it would be useful to compare the gain and noise performance, as no such study is yet to be found in the literature, as this may prove critical to system design.

The gain and NF measurements made here are directly comparable with those for other discrete optical amplifiers such as EDFAs. However, one of the attractive features of Raman amplifiers is that any existing fibre optic link can be turned into a Raman amplifier by installing a pump laser and circulators, providing that other in-line components can withstand the high pump power. In such a 'distributed' amplifier, the traditional gain and NF definitions are perhaps not a fair indication of the amplifier performance. Therefore, it is concluded that these definitions should be revised for distributed FRAs in such a way that they represent a fair comparison with the gain and NF of discrete amplifiers inserted into an equivalent link.

In a further study a FRA should be designed to have similar gain and NF characteristics in an EDFA. The BER due to each amplifier should then be compared with a network analyser. Such an experiment may indicate the usefulness of using just the gain and NF as figures of merit by which to characterise FRAs.

Therefore in summary, in this investigation a FRA was successfully built and characterised, with the outcome of proposals for much needed further research in this area.

9 Acknowledgement

This document has been produced for the Department of Trade and Industry's National Measurement System Directorate (NMSD) under contract number GBBK/C/011/00005.

Post publication note:
Since this work has been completed a new gain and noise figure measurement technique has emerged in the literature [42]. It is an optical method that uses a broadband source and transmission filter and has been applied only to EDFAs thus far. In any further investigations this new technique should be used to measure the NF in a FRA and compared to other established methods.

Bibliography

[1] G. P. Agrawal, *Nonlinear Fiber Optics.* New York: Academic Press, 2nd ed., 1995.

[2] K. J. Blow and D. Wood, "Theoretical description of transient raman scattering in optical fibers," *IEEE J. Quantum Electronics*, vol. 25, pp. 2665–2673, 1989.

[3] A. Boskovic, S. V. Chernikov, J. R. Taylor, L. Gruner-Nielsen, and O. A. Levring, "Direct continuoue-wave measurement of n_2 in various types of telecommunication fiber at 1.55 μm," *Opt. Lett.*, vol. 21, pp. 1966–1968, 1996.

[4] K. O. Hill, D. C. Johnson, B. S. Kawasaki, and R. I. MacDonald, "cw three-wave mixing in single-mode optical fibers," *J. Appl. Phys.*, vol. 49, pp. 5098–5106, 1978.

[5] S. C. Pinault and M. J. Potasek, "Frequency broadening by self-phase modulation in optical fibers," *J. Opt. Soc. Am. B*, vol. 2, pp. 1318–1319, 1985.

[6] R. Billington, "A report on four-wave mixing in optical fibre and its metrological applications," NPL Report COEM 24, National Physical Laboratory, Teddington, UK, 1999.

[7] R. Billington, "Requirements for the characterisation of non-linear effects in optical fibre amplifiers," NPL Report COEM 41, National Physical Laboratory, Teddington, UK, 2000.

[8] P. Tomlins, "Investigation of nonlinear effects in long fibre amplifiers," NPL Report CETM 53, National Physical Laboratory, Teddington, UK, 2003.

[9] R. H. Stolen and E. P. Ippen, "Raman gain in glass optical wave-guides," *Appl. Phys. Lett.*, vol. 22, pp. 276–278, 1973.

[10] R. J. Mears, I. M. Jauncey, L. Reekie, and D. N. Payne, "High-gain rare-earth doped fiber amplifiers at 1.54 μm," in *Proc. OFC*, vol. IOOC87, p. W12, 1987.

[11] E. Desurvire, J. R. Simpson, and P. C. Becker, "High-gain erbium-doped travelling-wave fiber amplifier," *Opt. Lett.*, vol. 11, pp. 888–890, 1987.

[12] S. A. Lewis, *Raman Amplifiers for Telecommunications.* PhD thesis, Imperial College London, 2000.

[13] T. Miyamoto, T. Tsuzaki, M. Kakui, and K. Nakai, "Investigation of accurate measurement of raman gain coefficient," SEI Technical Review 53, Sumitomo Electric Industries, Ltd, 2002.

[14] P. Tomlins, "The development of a new model for the raman gain spectrum in silica optical fibres," NPL Report DEM-EM002, National Physical Laboratory, Teddington, UK, 2004.

[15] R. Bell and D. C. Hibbins-Butler, "Raman scattering by normal modes in vitreous silica, germania and beryllium fluoride," *J. Phys. C: Solid State Phys.*, vol. 9, pp. 2955–2959, 1976.

[16] R. J. Bell, N. F. Bird, and P. Dean, "Spectra of glasses: The effect of disorder upon frequency spectra," *J. Phys. C: Solid State Phys.*, vol. 7, pp. 2457–2466, 1974.

[17] R. Shuker and R. W. Gammon, "Raman-scattering selection-rule breaking and the density of states in amorphous materials," *Phys. Rev. Lett.*, vol. 25, pp. 222–225, July 1970.

[18] R. H. Stolen, C. Lee, and R. K. Jain, "Development of the stimulated raman spectrum in single-mode silica fibers," *J. Opt. Soc. Am. B*, vol. 1, pp. 652–657, 1984.

[19] R. H. Stolen, J. P. Gordon, W. Tomlinson, and H. A. Haus, "Raman response function of solica-core fibers," *J. Opt. Soc. Am. B*, vol. 6, pp. 1159–1166, June 1989.

[20] P. Umari and A. Pasquarello, "First-principles analysis of the raman spectrum of vitreous silica: comparison with the vibrational density of states," *J. Phys.: Condens. Matter*, vol. 15, pp. S1547–S1552, 2003.

[21] J. M. Benson and C. J. Chunnilall, "Relative dopant profiling of silica optical fibres," *Glass Technol.*, vol. 34, pp. 78–79, 1993.

[22] G. E. Walrafen and P. N. Krishnan, "Model analysis of the raman spectrum from fused silica optical fibers," *Appl. Opt.*, vol. 21, pp. 359–360, February 1982.

[23] D. Hollenbeck and C. D. Cantrell, "Multiple-vibrational-mode model for fiber-optic raman gain spectrum and response function," *J. Opt. Soc. Am. B*, vol. 19, pp. 2886–2892, December 2002.

[24] J. Hu and B. S. M. abd Curtis R. Menyuk, "Flat-gain fiber raman amplifiers using equally spaced pumps," *J. Lightwave Technol.*, vol. 22, pp. 1519–1522, June 2004.

[25] D. Derickson, *Fiber Optic Test and Measurement.* Upper Saddle River, New Jersey: Prentice Hall, 1998.

[26] S. Poole, "Noise figure measurement in optical fibre amplifiers," in *SOFM*, pp. 1–6, NIST, 1994.

[27] H. Heffner, "The fundamental noise limit of linear amplifiers," in *Proc. of the IRE*, pp. 1604–1608, 1962.

[28] C. R. S. Fludger and R. J. Mears, "Electrical measurement of multipath interference in distributed raman amplifiers," *J. Lightwave Technol.*, vol. 19, pp. 536–545, April 2001.

[29] S. A. E. Lewis, S. V. Chernikov, and J. R. Taylor, "Characterization of double rayleigh scatter noise in raman amplifiers," *IEEE Phot. Technol. Lett.*, vol. 12, pp. 528–530, May 2000.

[30] J. F. Marcerou, H. Fevrier, J. Hervo, and J. Auge, "Noise characteristics of the edfa in gain saturation regimes," in *Optical Amplifiers and Their Applications. Technical Digest Series*, vol. 13, pp. 162–165, Optical Society of America, 1991.

[31] J. Aspell, J. F. Federici, B. M. Nyman, D. L. Wilson, and D. S. Shenk, "Accurate noise figure measurement of erbium-doped fiber amplifiers in saturation conditions," in *Optical Fiber Communications, 15th Conference, OSA Technical Digest Series*, vol. 5, pp. 189–190, IEEE, 1992.

[32] D. M. Baney and J. Dupre, "Pulsed-source technique for optical amplifier noise figure measurement," in *18th European Conference on Optical Communication*, vol. 1, (Berlin), pp. 189–192, Swiss Electrotech. Assoc., September 1992.

[33] T. Mukai and Y. Yamamoto, "Noise in an algaas semiconductor laser amplifier," *IEEE J. Quantum Electronics*, vol. 18, pp. 564–574, April 1982.

[34] S. Nishi and M. Saruwatari, "Comparison of noise figure measurement methods for erbium doped fibre amplifiers," in *19th European Conference on Optical Communication*, vol. 2, pp. 177–180, Swiss Electrotech. Assoc., September 1993.

[35] BSI, "Test methods for noise figure parameters - optical spectrum analyser method." British Standards Institute, 2003.

[36] BSI, "Test methods for noise figure parameters - electrical spectrum analyser method." British Standards Institute, 2003.

[37] P. Tomlins, "Analysis of noise figure measurements in lumped raman amplifiers." To be published, 2004.

[38] P. Parolari, L. Marazzi, L. Bernardini, and M. Martinelli, "Double rayleigh scattering noise in lumped and distributed raman amplifiers," *J. Lightwave Technol.*, vol. 21, pp. 2224–2228, October 2003.

[39] B. Danielson, "Backscatter signiture simulations," NBS Technical Note 1050, National Bureau of Standards, Boulder, Colorado 80303, December 1981.

[40] S. A. E. Lewis, S. V. Chernikov, and J. R. Taylor, "Gain saturation in silica-fibre raman amplifier," *IEEE Phot. Technol. Lett.*, vol. 35, no. 11, p. XXX, 1999.

[41] F. L. Galeener, A. J. Leadbetter, and M. W. Stringfellow, "Comparison of the neutron, raman, and infrared vibrational spectra of vitreous $si0_2$, $ge0_2$, and bef_2," *Physical Review B*, vol. 27, pp. 1052–1078, January 1983.

[42] S. Gupta and L. Qian, "Measuring gain and noise figure of erbium-doped fiber amplifiers using a broad-band source and a transmission filter," *IEEE Phot. Technol. Lett.*, vol. 16, pp. 2030–2032, September 2004.