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**ALL-OPTICAL GAIN SWITCHING OF ERBIUM-DOPED
FIBRE AMPLIFIERS**

by GLENN P. CHENEY B.A.Sc.

**A thesis submitted to
the Faculty of Graduate Studies and Research
in partial fulfillment of
the requirements for the degree of**

Master of Engineering

Department of Electronics

Carleton University

Ottawa, Ontario

December 17, 1992

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**The undersigned recommend to the Faculty of Graduate Studies and
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"ALL-OPTICAL GAIN SWITCHING OF ERBIUM-DOPED FIBRE AMPLIFIERS"

**Submitted by Glenn P. Cheney, B.A.Sc.
in partial fulfilment of the requirements for
the degree of Master of Engineering**

Thesis Supervisor

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December 17, 1992

ABSTRACT

The gain switching characteristics of erbium-doped fibre amplifiers with signal wavelengths in the 1525 nm to 1550 nm range are examined. Short duration, high energy pulses at wavelengths within the signal bandwidth are used to rapidly switch the amplifier gain at the signal wavelength. Experimental results indicate that the switching time is governed by the pulse duration and pulse energy for switching pulses generated by a Q-switched erbium-doped fibre laser. Switch off times on the order of 10 ns were observed. This is many orders of magnitude lower than the fluorescence lifetime of erbium ions in a glass host - which limits the switching speed of amplifiers controlled by pump power modulation alone.

The dynamic range of switching, defined here as the difference in the amplifier gain before and after switching, is determined by the amplifier gain and the peak power of the short duration switching pulse.

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List of Abbreviations

ASE - Amplified Spontaneous Emission
BHS - Buried Heterostructure
CNET - Centre Nationale des Etudes en Telecommunication
EDFA - Erbium-Doped Fibre Amplifier
EDFL - Erbium-Doped Fibre Laser
ESA - Excited State Absorption

CHAPTER 1

INTRODUCTION

1.0 Introduction to Switching Using Erbium-Doped Fibre Amplifiers

The merits of erbium-doped fibre amplifiers (EDFAs) have been established for single mode fibre optic communications networks operating in the 1.55 μm wavelength window. Such merits include high gain, polarization independent operation, wide bandwidth and negligible cross modulation distortion for signal frequencies higher than 10 kHz [1]. Some useful applications are in-line repeaters, power boosting amplifiers and pre-amplifiers to enhance receiver sensitivity.

These amplifiers are optically pumped fibres (single mode at the amplifying wavelength) with a core that is lightly doped with erbium ions (50-800 ppm). The doped silica fibre core is the gain medium. These doped silica fibres combine the properties of a laser material with the advantages of tight optical power confinement and long interaction lengths as provided by the fibre optic structure

To date, several theoretical approaches for the steady state analysis of EDFAs have been reported. These models can be broadly categorized into three groups. Full models of the amplifier steady state gain under both saturation and small-signal response have been published in the literature [2,3]. Pump wavelengths that suffer from excited state absorption (ESA) can be accommodated. These models can be numerically integrated to give complete and accurate results provided that the values for dopant ion density, fluorescence lifetime, effective core area and the atomic absorption and emission cross-sections can be accurately measured. These values are neither easily nor directly measurable using standard laboratory equipment. Accurate information from the fibre manufacturer is required.

The second class of model also requires numerical integration but can handle only those pump wavelengths that are free from excited state absorption (980 nm and 1.48 μm) [4,5,6]. The input parameters are quantities that can be measured directly, namely the gain coefficient, saturation power and absorption coefficient for different lengths of fibre. These models can handle high gain amplifiers where the effects of

self saturation on ASE (Amplified Spontaneous Emission) become significant (gain greater than 20 dB and no restrictions on the input signal power). These models require numerical integration and can be spectrally resolved to provide information about gain versus the wavelength of the amplified signal throughout the amplifier bandwidth.

The third approach is a simplified model which can be solved analytically [7]. This model requires only four input parameters, all of which can be obtained from standard absorption measurements. The results are accurate to within ± 0.5 dB for amplifiers which do not exhibit self saturation from ASE (gain less than 20 dB and input signal power greater than -20 dB). This model handles only the 980 nm and 1480 nm pump wavelengths.

At this point, it should be mentioned that unless great care is taken to minimize back reflections at the 1.53 to 1.55 μm wavelengths in the amplifier's optical circuit then the amplified spontaneous emission power builds up through superradiance¹ and may even begin to lase at high pump powers. In this case, the experimentally determined gain figures will be substantially lower than the values predicted by any of these models. The effects of backreflections can be minimized by using optical isolators fusion spliced to the erbium-doped fibre, or by having low backreflection terminations throughout the optical path at the signal and ASE wavelengths.

¹ In high gain amplifiers, spontaneously emitted photons travelling along the fibre amplifier axis can stimulate the emission of more photons and can lead to substantial output radiation at the amplifier endfaces. This process of mirrorless lasing is known as superradiance. If the amplifying fibre endfaces reflect more than one or two percent of the amplified spontaneous emission optical power back into the gain medium then lasing can occur.

There have been few publications detailing the transient response of EDFAs. A series of articles from the AT&T Bell Laboratories staff [1,8,9] have tackled some of the issues of transient gain saturation and cross-talk in erbium-doped fibre amplifiers. Saturation-induced cross-talk results from a reduction in the amplifier's population inversion due to additional signal channels propagating within the amplification wavelength range. The relatively long fluorescence lifetimes of erbium ions in a glass host (1-10 ms) tend to inhibit rapid changes in the fibre amplifier's population inversion and effectively dampen transient changes in saturation-induced cross-talk. Gain saturation and recovery time constants in the order of 100 to 350 μ s were measured in a two channel experiment with saturating signal powers on the order of -15 dBm [1]. Two models for transient gain saturation were presented. An analytical solution for the time dependence of the amplifier's population inversion at the amplifier input predicts saturation and recovery time constants (for the population inversion at the input only) for a given set of pump, signal and saturating signal powers [8]. A complete solution of the transient response of the pump and signal power at any point along the amplifier's length requires numerical solution of two dimensional coupled differential equations [9]. This is a computationally intensive solution and it requires difficult-to-measure fibre parameters as described above.

Above and beyond the requirements for the transmission of information in telecommunications networks, fibre optics is taking on an expanding role. As the need for high bandwidth switched services increases so will the need for optical switching systems. New switching technologies must be developed to keep up with the high data rates involved in the type of optical transmission services that are predicted for the future. Another potential application of both optical amplification and switching is in sensor based systems such as laser scanning and image analysis, receiver processing for large phased arrays and high precision filtering.

Most of the optical switching technologies explored to date incorporate hybrid opto-electronic circuits to perform switching at a central location. Switching within optical fibre offers at least two advantages over hybrid circuits. The optical signals do

not have to be converted to electronic signals in order to perform the switching operation. All-optical switching can be done at a remote location - an advantage in both communication networks and sensor-based systems.

A paper published by M. Zirngibl at AT&T Bell Laboratories [10] suggests an all-optical feedback scheme that allows remote gain switching in EDFAs. This approach uses a ring lasing technique to achieve a bi-stable switch with an on-off ratio of 26 dB with the signal wavelength tuned to the peak amplifier gain wavelength. Switching can be initiated by fibre laser pulses from a remote location. Switching times on the order of 10 to 50 ms were observed.

Suggested uses of the EDFA as an all-optical switching element in photonic networks have been limited to slow or 'static' switching requirements such as a 1.55 μm filter for signals in a multiplexed 1.3/1.55 μm fibre optic link. This scheme relies on pump power modulation to provide switching or a ring laser topology as described above. High speed switching is not possible using this method due to the long fluorescence lifetimes of the erbium ions in glass.

If optical fibre switching is to be considered as a useful technology for future optical switching applications, then switching times on the order of nanoseconds and minimal switching energy (possibly in the picoJoule range) are criteria that need to be addressed. Analysis of the rate equations governing the gain dynamics of EDFAs (modelled as a three level system) suggests that switch-off times in the nanosecond range and switching energy on the order of tens of nanoJoules are realisable. Switch-on times are governed by the amplifier pumping rate and are on the order of one millisecond.

A rapid increase in the rate of stimulated emission near (but not at) the signal wavelength can reduce the population inversion sufficiently to provide high speed gain suppression in the amplifier. This is essentially an extreme case of cross-talk in which the energy supplied by the switching pulse depletes the 'pumped' or stored energy of the amplifier orders of magnitude more quickly than those mechanisms suggested to date.

The transient behaviour of the amplifier/switch is governed by the peak power

of the switching (saturating) pulse and not exclusively by the the pulse energy. Switch-off times on the order of 10 ns and a dynamic range similar to the net gain of the EDFA are predicted using switching pulses supplied by a Q-switched fibre laser. If sub-nanosecond pulses can be generated (with similar peak powers) as a switching signal then the switch-off times and switching energy could scale down accordingly.

A simplified model is presented for the transient analysis of gain switching in EDFAs along with experimental results using a Q-switched erbium-doped fibre laser as the remote optical switching source.

1.1 Thesis Outline

The second chapter of this thesis is intended to provide the reader with an explanation of the optical gain mechanism in erbium-doped fibre amplifiers. Chapters three and four build upon the theory of optical gain and present models for steady state gain and transient behaviour analysis. These models are applicable to any sample of erbium-doped fibre of arbitrary length. The parameters used in these models may be derived from standard absorption measurements. Chapter six provides an explanation of how the fibre amplifier parameters are measured.

On the basis of these models, predictions are made regarding the erbium-doped fibre sample performance both as a steady state amplifier and in the gain switching mode.

The experimental results are detailed in chapter seven. After steady state gain measurements were made from three samples of erbium-doped fibre, one sample was selected as having the highest steady state gain. This sample was then connectorized and used for the gain switching experiments. Extensive efforts were made to optimize the optical gain of this fibre amplifier.

Comparisons with the theoretical predictions are made and, where possible, the deviations from theory are explained.

In the final chapter, the gain switching experimental results are summarized. Based on these results, the viability of using erbium-doped fibre amplifiers as an all-optical gain switching component in commercial systems is discussed

CHAPTER 2

EXPLANATION OF OPTICAL GAIN IN ERBIUM-DOPED FIBRE

AMPLIFIERS

2.0 Principles of Optical Gain in Erbium-Doped Fibre Amplifiers

Optical gain occurs in the fibre amplifier when stimulated photons promote further stimulated photons in a cascade. The following are necessary criteria, although simplified for the purpose of introduction, for realizing gain in the fibre amplifier. Inverted erbium ion population is required along the length of active fibre. Gain at the signal wavelength can only be sustained over a given section of the active fibre, if the population density of the erbium ions in the excited state level (N_2) exceeds the population density in the ground level, (N_1).

The active ions must be pumped to an energy level which is higher than the excited state level. This is critical to maintaining a population inversion. Without the higher energy pump level, the steady state population densities N_2 and N_1 tend to equalize. This results in a fibre which is effectively transparent to incoming 1.55 μm light.

The total number of participating energy levels in the fibre amplifier dynamics must be greater than two. That is, a model including a ground state, an excited state and a 'pumped' ion energy level is the minimum requirement to describe sustainable optical gain for erbium ions in a silica host. This is known as a three level system and is illustrated schematically in Figure 2.1.

Referring to Figure 2.1, the transition from the upper pump level, $^4I_{11/2}$, to the upper laser level, $^4I_{13/2}$, is non-radiative. The $^4I_{13/2}$ to $^4I_{15/2}$ energy level transition is the most important of the radiative transitions for Er^{3+} ions in a silica host. The fluorescence intensity from this transition, when excited by a suitable pump source, is several orders of magnitude higher than any of the other radiative transitions such as $^4S_{3/2}$ to $^4I_{13/2}$ (near 830 nm) or the $^4I_{11/2}$ to $^4I_{15/2}$ (980 nm).

The diagram of Figure 2.1 assumes a pump wavelength of 980 nm. Pumping at other wavelengths such as 807 nm or 514 nm are also practical alternatives.

However, the efficiency of pumping is impaired due to the phenomenon of excited state absorption (ESA). When the ground state ions are promoted to the energy levels corresponding to these alternative pump wavelengths, only a fraction of the excited state ions undergo non-radiative transitions to the useful $^4I_{13/2}$ level. Other ions return to the ground state via radiative or non-radiative intermediate transitions.

ESA for the 980 nm pump wavelength is negligibly small for erbium-doped fibres with relatively low erbium ion concentrations. As such, erbium-doped fibre amplifiers pumped at 980 nm exhibit the highest pump efficiency for laser diode pumped fibre amplifiers.

If certain assumptions are made, such as the steady state population of level 3 being orders of magnitude lower than level 2, then a two level model may be adequate to describe steady state operation of the amplifier. Four level systems are also possible with other combinations of rare earth ions and host materials. For example, neodymium doped silica is a four level system in which the excited ions exhibit a radiative transition not to the ground state but to an intermediate energy level. In this case the ions then undergo a non-radiative transition from the intermediate energy level back to the ground state.

For a three level fiber amplifier there will be an optimal fibre length that yields a maximum gain. If the fibre is too short, insufficient absorption of the available pump power occurs. If the fibre is too long then net absorption of the stimulated emission of photons occurs.

Figure 2.1. Three- level model for erbium ions in a silica host.

2.1 General Characteristics of Erbium-Doped Fibre Amplifiers

EDFAs are gaining widespread acceptance as in-line repeaters, power boosters and receiver pre-amplifiers in optical fibre communications systems operating in the 1.55 μm window. There are some distinct advantages of these amplifiers over semiconductor laser amplifiers.

EDFAs have inherently high optical power gain. This figure is strongly dependent on the pump and signal wavelengths, the amount of pump power that can be coupled into the fibre and the characteristics of the doped fibre itself. Optical gain of greater than 46 dB has been reported [11] by using combinations of laser diodes at the 1480 nm pump wavelength. The 980 nm pump wavelength is more efficient and gain figures of 33 to 35 dB have been reported using single laser diodes as the pump source [12]. These figures are for the doped fibre itself and do not incorporate the losses associated with coupling single mode light into and out of the doped fibre. The insertion losses which accompany the fused tapered fibre couplers required to combine and separate the pump and signal light at the input and output of the fibre, respectively, must also be considered. By using a combination of careful fibre geometry design and efficient fusion splicing techniques, the fibre to fibre losses can be minimized. Fibre with identical mode field diameters may be fusion spliced with losses of less than 0.2 dB. Splice losses between the CNET erbium-doped fibre and the single mode fibre coupler pigtail was estimated to be 1.5 to 2 dB at the 1.54 μm signal wavelength.

The noise figure (F) is defined as the degradation in the signal to noise ratio at the output of the amplifier compared to the input of the amplifier, (usually expressed as a logarithmic ratio). Under conditions of full population inversion, F is nearly quantum limited [13], ($F = 3$ dB is the quantum limit). The noise characteristics of the fibre amplifier determine the limits on receiver sensitivity when the amplifier is used as a pre-amplifier. Spontaneous emission noise establishes a lower limit on the noise power generated by the fibre amplifier.

The insertion loss of a fibre optic amplifier is significantly lower than its

semiconductor based counterpart. When used as an in-line repeater, the single mode fibre to single mode fibre connections and the signal/pump fibre optic coupler losses must be accounted for. The actual insertion loss figure varies inversely with the mode field diameter of the erbium-doped fibre. Erbium-doped fibres have a core diameter that is approximately half that of standard single mode telecommunications fibre and the addition of index-raising co-dopants such as germania and alumina increase the numerical aperture and decrease the mode field diameter. Coupling losses between standard telecommunications fibre and erbium-doped fibre are typically about 2 dB.

The output light from EDFAs is more than 99% unpolarized due to the random orientation of erbium ions in glass. This eliminates the problems of polarization control in the amplifier itself.

The amplifier gain is relatively insensitive to temperature. A variation of 1 dB in gain over the temperature range -40 to +60°C was suggested by E. Desurvire[14].

2.2 Selection of Pump Wavelength

The absorption and fluorescence emission spectra of a representative sample of erbium ions in a silica-based glass host are illustrated in Figure 2.2 [20,21]. To date, practical pump bands have been demonstrated at 514 nm, 528 nm, 807 nm, 980 nm and 1480 nm. The important fluorescence emission band at 1.53 μm is designated as $^4I_{13/2}$ in spectroscopic notation. The superscript 4 refers to the spin multiplicity and the subscript 13/2 denotes the total angular momentum quantum number. The 1 refers to the angular momentum of the outermost electron shell energy level of the erbium atom.

The actual shape of the fluorescence emission spectrum for a given sample of erbium-doped fibre is not a function of the pump wavelength but rather is determined by the presence of co-dopants in the fibre core, the presence of localized strains and defects in the glass host and the degree of population inversion. The fluorescence emission spectra of the sample fibres used for this thesis are shown in section 6.5.

Figure 2.2. Fluorescence Emission Spectrum (top) and absorption spectrum for erbium-doped silica.

2.2.1 Laser Diode Pumping

Due to the commercial availability of laser diodes at this time, useful pumping wavelengths are limited to 807 nm, 980 nm and 1480 nm.

The relative merits and drawbacks for each laser diode pump wavelength are listed in Table 2.1 below.

TABLE 2.1
Comparison of Laser Diode Pump Wavelengths

Wavelength (nm)	Cost and Availability	Relative Pump Efficiency	Laser Diode Reliability
807	Low cost due to sales volume in CD player market	Poorest pump efficiency due to Excited State Absorption	Most reliable due to mature fabrication technology
980	\$5000US in 1991 without fibre pigtail. These devices are available from at least three vendors.	Highest pump efficiency in terms of gain per mW of absorbed pump power. ESA is negligible at this wavelength.	Reliability and the fabrication technology still have room for improvement.
1480	\$10000US with fibre pigtail due to low volume production at the time of writing.	Negligible ESA at this wavelength but pump efficiency is approximately half of the 980 nm figure.	Reliability is similar to that at 980 nm.

The 980 nm laser diode pump wavelength enjoys the advantages of being free from ESA problems and nearly complete population inversion under cw pumping can be achieved.

The 1480 nm wavelength is also free from ESA but complete population inversion is not possible. The pump band and upper lasing energy levels are close enough together that thermal excitation causes some depopulation of the upper laser level. As the pump intensity becomes large, the ratio N_2/N_1 approaches the ratio σ_p/σ_{21} , where σ_p and σ_{21} represent the atomic absorption cross section of the pump wavelength and the stimulated emission cross section (at the signal wavelength), respectively.

The efficiency of the 807 nm band is considerably poorer due to the small ground state absorption cross section and the presence ESA.

2.2.2 Laboratory Laser Pumping

Unfortunately, no laser diodes of suitable wavelength and output power were available to the author. Currently, the high cost and uncertain reliability of 980 nm and 1480 nm diodes are the main factors prohibiting the high volume commercial use of these devices. Gas and solid state lasers provide the following useful pumping wavelengths: 514.5 nm (Argon ion laser), 532 nm (frequency doubled micro-YAG) and the Ti-Sapphire laser (tunable to 980 nm) for laboratory work.

It is worthy of note that 532 nm is an efficient pump wavelength for erbium-doped silica fibres. Pumping at this wavelength was explored experimentally using the micro-YAG laser. This laser is a Q-switched device with a frequency doubling crystal. It produces its maximum equivalent cw output power (6.3 mW) at the fairly low repetition rate of 3.6 kHz. Although this repetition rate is high enough to sustain fluorescence in the erbium-doped fibre, the output power is not large enough to provide any useful gain in the fibres tested to date.

The 514.5 nm pump wavelength suffers from ESA but the Argon ion laser used provides up to 1 Watt of pump power making it a practical alternative and a good

starting point. The Argon ion laser was used in the first "round" of fibre amplifier experiments.

The Titanium-Sapphire laser tuned to 980 nm is the next logical alternative as a pump source and became the workhorse for the majority of the experiments described in this thesis. The Ti-Sapphire laser used was fabricated at the National Research Council's Institute for Information Technology by Dr. Simon Boothroyd. This is an optically pumped crystal laser tunable from 800 nm to nearly 1000 nm by using a birefringent filter placed in the optical path of the laser cavity. The optical pump source is a Coherent Innova 200 Argon ion laser running in multi-line mode. When carefully aligned, the Ti-Sapphire laser produces a circular 2mm (waist diameter) gaussian beam output which can be coupled into single mode fibre. The Ti-Sapphire laser output was tuned from 976 nm to 982 nm during the course of the experiments. The optimum pump wavelength proved to be 978 nm.

2.2.3 Effects of Dopant Ion Concentration in the Active Fibre Core

The relationship between erbium ion concentration in silica-based single mode fibres and optical gain characteristics has been explored in the literature [15]. The results of this work indicate that the optimum erbium ion concentration is less than 100 ppm. The lower erbium ion concentration fibres produce high gain figures with relatively low pumping power. High concentration erbium-doped fibres require high launched pump powers. Under these conditions, lower metastable lifetimes occur as a result of a cooperative upconversion mechanism. The penalty for using lower dopant concentrations is that a longer piece of doped fibre is required to absorb the pump energy.

Three concentrations of erbium-doped silica fibres were used in the fibre amplifier experiments. In each case the fibre core is silica with germania co-doping (germania concentration unknown). The three experimental fibres were:

1. CNET 100ppm erbium ions

2. AT&T ~1000ppm (estimated) erbium ions

3. YORK 300ppm erbium ions

2.2.4 Optimal Fibre Length

As mentioned previously, there is an optimal length of fibre which yields a maximum value for small-signal gain. This optimal length is a function of the input pump power and pump wavelength, the dopant ion concentration, the absorption and emission cross sections of the doped fibre core and geometrical considerations involving the overlap of the dopant ion profile in the fibre core and the pump beam profile. The optimum length of erbium-doped fibre occurs when the output pump power is just enough to create an inverted ion population at the end of the fibre.

If the fundamental mode is assumed to be the only mode propagating at the pump wavelength (as is the case for the 1480 nm pump) then concentrating the dopant ions near the center of the fibre core maximizes the 'overlap coefficient'. At 980 nm pump wavelength, the pump beam wavelength is slightly below the cutoff wavelength of the CNET and AT&T erbium-doped fibres (1.05 μm) and well below that of the YORK fibre (1.275 μm). For the CNET and AT&T fibres, the assumption of singlemode pump beam propagation is reasonable. For the 514 nm pump wavelength, the pump beam propagates through the erbium-doped fibre as a multimode signal. Unfortunately this results in a lower pump efficiency. The doping process produces a higher concentration of erbium-ions at the center of the fiber core. For multimode pump propagation, the intensity of the pump beam at the center of the fibre core is lower than in the single mode case.

The signal is amplified exponentially as it propagates along the length of the fibre, provided the population inversion condition, $P_p/P_{th} > 1$, is satisfied. P_p and P_{th} represent pump power at the input end of the erbium-doped fibre and the threshold pump power, respectively. The pump threshold power is the input pump power level required to produce optical transparency in the erbium-doped fibre, (at the signal wavelength).

Beyond a certain length of fibre, the condition $P_p/P_{in} < 1$ occurs, and the signal power becomes absorbed. The optimal fibre length for a fixed input pump power is given by the condition $P_p(\text{at the axial position } Z=L_{opt}) = P_{th}$.

The threshold pump power is given by the formula in equation 2.1 [1]:

$$P_{th} = \frac{\Gamma_p A_c h \nu_p}{\sigma_p \tau_{21}} \quad (2.1)$$

where, h is Plank's constant, Γ_p represents the fibre amplifier confinement factor at the pump wavelength, σ_p is the atomic absorption cross section of the pump wavelength, A_c is the fibre core area, τ_{21} is the level 2 lifetime of the erbium ions in a silica host, and ν_p is the pump light frequency. An alternative expression for the pump threshold power will be presented in the discussion of section 7.2.2.

The optimal fibre length is identified by solving the differential rate equations which are presented in section 3.2. The geometrical considerations of pump signal profile and dopant ion profile overlap are included implicitly in the measured absorption coefficient used to model each fibre (please see equation 3.1).

Manufacturer's information about the dopant ion concentration profile is not available for any of the three fibre samples used as they are experimental grade fibre samples and are several years old.

For experimental purposes, the optimal fibre length can be fine tuned to a given input pump power by trimming back the fibre length until the output pump power of the doped fibre equals the threshold pump power (approximately 1.2 mW measured at the fibre output for 7.4 m of the CNET 100 ppm fibre pumped at the 978 nm pump wavelength).

Figure 2.3 is derived from the rate equation analysis and it illustrates the dependence of small-signal gain on the fibre length for the CNET 100 ppm Er^{3+}

dopant ion concentration fibre. Three values of launched pump power are indicated and a launched signal power of 10 μW is assumed for the analysis.

In general terms, the optimal fibre length is critically dependent on ρ , the dopant ion density and the amount of pump power launched into the doped fibre.

Figure 2.3. Amplifier gain versus fibre length for the CNLT 100 ppm fibre at 10 uW input signal power.

2.3 Summary

The factors affecting the amount of optical gain that can be realized from erbium-doped fibres are the available pump power, pump wavelength, signal power, signal wavelength and the erbium ion distribution within the fibre core area. The optimal fibre length is selected so that at the output of the erbium-doped fibre, the residual pump power is equal to the threshold power, P_{th} .

CHAPTER 3

STEADY STATE OPERATION OF ERBIUM-DOPED FIBRE AMPLIFIERS

3.0 Analysis in Steady State Operation

Understanding the steady state operation of the erbium-doped fibre amplifier is a critical first step towards being able to predict the switching performance of the amplifier. The steady state gain of the fibre optic amplifier is analogous to the dc operating point of an electronic amplifier. For low optical power inputs, the amplifier operates as a linear device. For a given input pump power, the fibre amplifier exhibits a characteristic output signal saturation power.

Steady state modelling allows one to vary individual fibre amplifier parameters such as input signal power, input pump power and doped fibre length in order to determine an "operating point" which maximizes the signal gain for the minimum pumping power. "Pumping" the fibre amplifier involves supplying an input optical power at an appropriate wavelength that promotes the erbium ions in the ground state (indirectly) to a metastable upper laser level. There is a limit to the degree of population inversion that can be achieved. This limit depends on the pump wavelength used, the pump power available, the presence of ESA and the small but finite steady state populations in the upper pump level (level 3) and ground state. The pumped fibre amplifier stores energy in the form of an inverted population of erbium ions and releases this energy either slowly as a spontaneous emission process or rapidly when stimulated by incident photons at the appropriate wavelength.

In order to achieve gain switching (switching off the gain) in the fibre amplifier this stored energy must be rapidly released by an incident optical switching pulse. Intuitively, the maximum stored energy of the pumped fibre amplifier would be orders of magnitude higher than the energy contained in a single optical switching pulse (see section 4.5 for these calculations). The steady state analysis provides an explanation of how the gain switching mechanism operates.

3.1 General Background Information for Steady State Amplifier Modelling

EDFAs may be modeled as a three level system consisting of a ground level (level 1), an excited state level (level 2) and an upper pump level (level 3), as shown in Figure 2.1. This model is accurate provided several assumptions are made.

Homogeneous broadening of the ions in the upper laser manifold is assumed. That is, each ion in the upper laser manifold is assumed to contribute equally to the stimulated emission process. This simplifies the calculations of erbium-doped fibre amplification of signal wavelengths near 1.53 μm . The light emitted by the fluorescence energy level transition does not have a single frequency, but rather has a frequency distribution best described by the Lorentzian distribution. Generally, active ions in a glass host have wider emission bandwidths than in crystalline host materials. In amorphous materials, the emission peak of each ion will not be at the same frequency. The observed emission spectrum is then the envelope of the sum of the individual emission peaks. When embedded in a glass fibre host, these distinct energy structure levels are broadened into an emission band. Ions within the same emission band are assumed to contribute equally to the emission process.

Using this assumption, the linewidth of the amplified signal is modelled as having a Lorentzian profile. This is desirable from the analytical point of view and is a reasonable approximation when modelling the unsaturated amplifier gain.

Excited state absorption (ESA) from the upper pump level (level 3) is neglected. ESA from level 3 may occur if the population of level 3 becomes significant. Under conditions of strong pump excitation, the pump rate from the ground state may exceed the rate of decay from level 3 to level 2. The incident pump photon energy at 980 nm matches the energy required to promote an ion in level 3 to the higher $^4F_{7/2}$ energy level. However, for steady state operation, the population of the upper pump level (N_3) is negligible and from a statistical point of view all of the active ions are assumed to be in either the ground state (level 1) or the excited state level (level 2). Ions pumped to level 3 have a very short lifetime as they undergo a rapid non-radiative transition to the lower energy excited state level (level 2). ESA

from the pump level is then neglected on the basis of the level 3 population being a very small fraction of the total ion distribution.

Under steady state conditions, the level 2 and level 1 populations stabilize and the three level system may be represented with reasonable accuracy by a simplified two level model. This model makes two assumptions. As described above, the steady state population of the upper pump level (level 3) is negligibly small. This assumption is reasonable as the lifetime of the ions in the upper pump level (10^{-4} s) is several orders of magnitude smaller than the level two fluorescence lifetime (10^{-2} s).

Excited state absorption from the upper laser level to a higher energy level is assumed to be absent. This premise is valid if the 980 nm or 1480 nm pump bands are used.

3.2 Models for Steady State Operation

Two models were used to investigate the amplifier steady state performance. An analytical model proposed by Saleh et al. [7] provides a solution to the rate equations of a two level system for an arbitrary number of pump and signal beams in a fibre amplifier.

The second model proposed by Giles and Desurvire [4] caters to high gain amplification and the condition of self-saturation. These equations are more complex than the analytical model equations and must be solved by using a numerical integration technique.

These models were selected because the parameters involved may be measured directly in the laboratory using straight forward absorption and gain measurements. The complex parameters of absorption and emission cross-sections, fluorescence lifetime and the active area are included indirectly in these measurements. For example, the absorption coefficient at the signal wavelength α , is related to the absorption cross section by

$$\alpha_s = \rho \Gamma_s \sigma_s^a \quad (3.1)$$

, where ρ is the dopant ion density, Γ_s is the overlap coefficient of the signal beam and the dopant ion profile and σ_a is the atomic absorption cross section.

3.2.1 The Analytical Model

This model was proposed by A.A.M. Saleh and colleagues at AT&T Bell Laboratories. Although the derivation is omitted here, it may be found in reference [7]. Equations 3.2 through 3.9 provide sufficient information to characterize the gain and saturation properties of an amplifier of any length provided that ESA is absent and gain saturation due to amplified spontaneous emission noise can be neglected. The parameters of Table 3.1 are obtained by measurements of a sample of the erbium-doped fibre under investigation.

The gain versus input pump and signal power figures calculated using this method agree to within 1 dB of the experimental results provided that the amplifier is not operating in a regime which produces self-saturation due to ASE.

For amplifiers with gain less than 20 dB and with careful attention paid to minimization of back-reflections in the amplifier's optical path this solution provides reasonably accurate results. The analytical model was used to investigate the sensitivity of the amplifier gain to the parameters of fibre length, input pump power and input signal power. The maximum experimental signal gains of the erbium-doped fibre samples tested were in the range of 10 to 14 dB. The condition for a low gain amplifier is valid. However, considerable effort was required to minimize the backreflections in the amplifier's optical signal path. Minimizing backreflections from the erbium-doped fibre end faces reduces the amount of stored amplifier energy wasted in amplifying the spontaneous emission noise.

The equations for the analytical model are listed below along with a description of the parameters in Table 3.1. These equations may be adapted to any number of signal or pump beams in the fibre amplifier. For the models described in this section, k represents either the signal or the pump beam. The absorption coefficient, α , at any pump or signal wavelength, k , is given by,

$$\alpha_k = \rho \Gamma_k \sigma_k^a \quad (3.2)$$

Where ρ = dopant ion density, Γ = the confinement factor of the pump or signal beam and σ^a = the atomic absorption cross section.

$$P_k^{IS} = \frac{A_{core}}{\Gamma_k (\sigma_k^e + \sigma_k^a) \tau_{21}} \quad (3.3)$$

The intrinsic saturation power, P^{IS} at any wavelength k , represents the input power required to bleach the absorption by a factor of e and is expressed in photon flux units (power in Watts divided by the photon energy). A_{core} is the core area of the doped fibre, σ^e is the atomic emission cross section and τ_{21} represents the fluorescence decay lifetime from level 2 to level 1.

The rate equations for a simplified two-level system may be integrated to obtain an expression for the amplifier output power for a given signal or pump wavelength.

$$P_k^{out} = P_k^{inp} \exp(-\alpha_k L) \exp\left(\frac{(P_k^{inp} - P_k^{out})}{P_k^{IS}}\right) \quad (3.4)$$

The total input and output powers are given by the sum of all individual beam powers.

$$P^{inp} = \sum_j P_j^{inp} \quad (3.5)$$

$$P^{out} = \sum_j P_j^{out} \quad (3.6)$$

The total output power may be expressed as a single equation summed over the k signal and pump beams.

$$P^{\text{out}} = \sum_k A_k \exp(-B_k P^{\text{out}}) \quad (3.7)$$

Where:

$$A_k = P_k^{\text{exp}} \exp(-\alpha_k L) \exp\left(\frac{P_k^{\text{exp}}}{P_k^{\text{sat}}}\right) \quad (3.8)$$

$$B_k = \frac{1}{P_k^{\text{sat}}} \quad (3.9)$$

Once the input powers are established, A_k and B_k become constants under steady state conditions. The transcendental equation (3.7) may then be solved for P^{out} , the total output power. The result may then be used to find the output power at either the signal or pump wavelength (equation 3.4). In accordance with the assumption that self saturation due to ASE can be ignored, the contribution of ASE output power to P^{out} is neglected. This assumption would lead to a theoretical value of amplifier gain being higher than the experimentally determined values.

For the purpose of this thesis, these analytic expressions provide a reasonable estimate of the gain and absorption of light passing through the fibre amplifier when pumped at the 980 nm wavelength.

Table 3.1 - Analytical Model Fibre Parameters

Fibre Parameter Description	symbol used in Model
Absorption coefficient at the signal wavelength (m^{-1})	α_s
Absorption coefficient at the pump wavelength (m^{-1})	α_p
Intrinsic saturation power at the signal wavelength (Watts/ $h\nu_s$)	P^{is}
Intrinsic saturation power at the pump wavelength (Watts/ $h\nu_p$)	P^{is}_i
Fibre Length (m)	L
Input Signal Power (Watts/ $h\nu_s$)	P
Input Pump Power (Watts/ $h\nu_p$)	P_i

3.2.2 The Numerical Model

A numerical model is more flexible than the one proposed by Saleh as it does not impose the limitations of a maximum amplifier gain. Although the solution is more complex, the results provide a good check on those obtained using the analytical approach. The models of Giles and Desurvire [4] and Giles, Burrus, et. al. [5] are presented in this section in a form which accommodates steady state operation of the amplifier. This model is modified in Chapter 4 to provide an insight into the transient performance of the erbium-doped fibre amplifier.

The rate equations for the numerical model are presented below followed by a description of the model parameters in Table 3.2. Either forward or backward propagating optical signal powers along the axial direction, z , of the erbium-doped fibre are accounted for by this model. The rate of change of pump or signal power with respect to axial position along the fibre is given by equation 3.10. Please note that the unit of optical power used in these equations is the Watt.

$$\begin{aligned} \frac{dP_k}{dz} = & (\alpha_k + g_k) \frac{n_2}{n_t} P_k \\ & + 2g_k \frac{n_2}{n_t} h\nu_r \Delta\nu_r \\ & - (\alpha_k + l_k) P_k \end{aligned} \quad (3.10)$$

Where:

$$\frac{n_2}{n_t} = \frac{\sum_r \frac{P_r \alpha_r}{h\nu_r \zeta}}{1 + \sum_r \frac{P_r (\alpha_r + g_r)}{h\nu_r \zeta}} \quad (3.11)$$

In the equations above, g_k is the gain coefficient (dB m) of either the signal and ASE beams in the fibre. The absorption coefficient for the signal, pump or ASE beam, α_k

is expressed in units of dB/m. The background loss coefficient at either the signal, ASE or pump wavelengths, l_b is expressed in units of dB/m. The fibre saturation parameter, ζ , is the ratio of linear ion density to the lifetime of ions in the excited state, τ_{21} . ζ is related to the fibre intrinsic saturation power at the pump wavelength, P_p^{in} , by the expression $\zeta = \alpha_p P_p^{in}$.

Table 3.2 - Numerical Model Fibre Parameters

Fibre Parameter Description	symbol used in Model
Absorption coefficient at the signal wavelength (dB/m)	α
Absorption coefficient at the pump wavelength (dB/m)	α_p
Fibre saturation parameter ($m^{-1}s^{-1}$)	η
Level 2 ion erbium population (m^{-3})	n_2
Total erbium ion population (m^{-3})	n_t
Fibre background loss coefficient (dB/m)	l_b
Beam frequency (Hz) ($\Delta\nu$ indicates the frequency band)	ν_k
Fibre gain coefficient (dB/m, where k is one of signal pump or ASE wavelengths)	g_k
Fibre length (m)	l
Input signal power (Watts)	P
Input pump power (Watts)	P_p

The equations simplify significantly when the 980 nm pump wavelength is used as $g_{k=980nm} = 0$. The second term in equation 3.10 ($+ 2g_k...$) is contribution of spontaneous emission of two photons from the local n_2 population as they are amplified along the gain medium. The two photons represent the two polarization states of the lowest order optical mode. The ASE frequency bandwidth, $\Delta\nu_k$, was determined by resolving the ASE spectral width into an 5nm intervals

This second term may be omitted for low gain amplifiers, (< 20 dB). Note that the fibre gain coefficient, g_k , represents the net gain per metre of the erbium-doped

fibre when the ion population is fully inverted by strong input pumping power.

3.3 Effects of Excited State Absorption

The effects of ESA have been ignored in the two models discussed above. When pumping at wavelengths other than 980 nm or 1480 nm this effect needs to be modelled. As some of the early amplifier work was done with the Argon ion laser as the pump source (514 nm) the expected and observed effects of ESA on the signal gain are mentioned here.

The presence of ESA has the undesirable effect of absorbing a portion of the useful pump power without populating the upper level of the 1535 nm laser transition (level 2). As part of the three level model for erbium ions, absorption of a pump photon by the ground state absorption band excites an erbium ion to the upper pump level from which it quickly relaxes through multi-phonon emission to the excited state. Absorption of another pump photon may then promote the erbium ion in the excited state to a higher energy level if the energy gap matches the energy of the pump photon. At a pump wavelength of 514 nm the effects of ESA are evident. The 514 nm input pump power required to bleach the erbium-doped fibre to transparency is approximately an order of magnitude higher than required at the 980 nm pump wavelength. The ESA atomic cross-section is approximately equal to the absorption cross-section at the 514 nm wavelength [5] assuming conditions of nearly complete population inversion.

The effects of ESA can be observed by measuring the fluorescence lifetime of the erbium-doped fibres when pumping at an input power just high enough to achieve population inversion. When ESA occurs, non-radiative energy transfer takes place between neighbouring excited ions in the metastable $^4I_{13/2}$ level (see Figure 2.1). The acceptor ions undergo a co-operative upconversion mechanism making non-radiative energy level transitions at a higher energy level. The donor ions return to the ground state. The fluorescence decay curve exhibits a rapid initial decay rate in response to this process which considerably shortens the $1/e$ lifetime. Level 2 lifetime measurements performed on the CNET 100ppm fibre pumped at 514 nm indicate a $1/e$

lifetime of 1.7ms. This is well below the nominal value of $\tau=10$ ms. The same test performed using a 980 nm pump source yielded a τ lifetime of 4.4 ms.

Accurate modelling of the effects of ESA on the signal gain of the amplifier requires a model that incorporates σ_{1SA} , the atomic cross-sectional area of excited state absorption, and explicitly uses the measured value of fluorescence lifetime.

3.4 Steady State Signal Gain versus Launched Pump Power

Both the analytical and numerical models above were solved using the parameters for the 7.4m CNET 100ppm erbium-doped fibre sample. The results are plotted and the experimentally measured points are superimposed on these curves in the experimental results section 7.2.4, Figure 7.6.

3.5 Amplifier Gain Slope

The amplifier gain slope is a figure of merit indicating the maximum value of gain (dB) vs. pump power absorbed by the fibre amplifier (mW). Curves for this figure of merit were obtained by running the analytical model simulation for the three erbium-doped fibre samples. The simulation results are shown in Figure 3.1. The best values for gain slope were predicted for the CNET and the AT&T fibre samples with a maximum gain slope of 1.6 dB/mW. It is worthy of note to compare this to figures of 4.9 dB/mW (NTT fibre @ 980 nm [12]) and 6.3 dB/mW (Sumitomo fibre @ 1480 nm [16]).

Figure 3.1. Gain slope efficiency of three erbium doped fibres versus pump power absorbed along the fibre length.

3.6 Predicting Amplifier Saturation Performance

Erbium-doped fibre amplifiers exhibit a characteristic output saturation power. At this output power level the small-signal gain has been reduced by 3 dB from its maximum value given a particular fibre length and input pump power.

The fibre amplifier effectively operates as a three level atomic system providing that excited state absorption (ESA) can be neglected. Well below saturation, the population inversion is maintained by the pump beam which indirectly populates level 2. The rate, W_p , at which the active ions can be promoted from the ground state (level 1) to the pump energy level (level 3) is slower than the relaxation rate (W_{12}) from level 3 to the upper lasing level (level 2). This ensures that the population of level 3 remains negligibly small.

There is no upper limit to the fibre amplifier output signal intensity provided that the population inversion can be restored by exciting level 3 followed by relaxation to level 2 as quickly as it is depleted by the rate of stimulated emission (W_{21}). However, in a practical three level system the analytical and numerical models indicate that steady state gain is a decreasing function of the fibre core photon flux. As the pump power increases so does the stimulated emission (and absorption) rate. A large stimulated emission rate tends to equalize the ion populations in levels 1 and 2. Note that as the stimulated emission and absorption rates increase with the higher incident pump power, the relaxation rate, W_{12} , stays constant. W_{12} is governed by the lifetime of ions in the level 3 state (on the order of 10^{-5} s).

At the onset of saturation the relaxation rate, W_{12} , is equivalent to the pump rate, W_p , creating a bottleneck in the three level system. Strong signal inputs to the amplifier deplete the upper lasing level population and the gain then is reduced as saturation occurs.

Beyond the saturation threshold, the population in level 3 becomes significant as the populations in level 3 and the ground state begin to equalize. This allows excited state absorption to occur from level 3 if there is an allowable higher energy level transition available [18]. Pump photons which closely match the energy gap

between the upper pump level and an allowable electron orbit may undergo an up-conversion process. The up-converted ions may then decay to the ground state energy level by a path other than the desired laser transition. This has been observed experimentally as samples of the highly doped AT&T fibre when pumped strongly at 978 nm exhibit a green fluorescence (approx. 532 nm).

Gain saturation is the basis for distortion in the fibre amplifier. While operating below the saturation power threshold, fibre amplifiers are very linear devices. In order to reduce the influence of amplifier distortion, being able to calculate the pump power required to saturate the amplifier is a valuable asset.

Equation 3.12 expresses the amplifier input pump saturation power in terms of the relaxation rate W_{32} and the atomic absorption cross section at the pump wavelength, σ_p [18].

$$P_{inp, sat} = \frac{W_{32} h\nu_p A_{core}}{\sigma_p} \quad (3.12)$$

This expression defines the bottleneck point where the pump rate, W_p and the relaxation rate, W_{32} , are equal. As the pump power increases beyond this point, stronger signal intensities actually decrease the population inversion which limits the gain.

An alternate expression based on the analytical model of Saleh [7], is written in terms of the output signal saturation power and is presented in equation 3.13. In this expression, the signal saturation power is defined as the output signal saturation power for which the signal gain drops by a factor of $1/e$ (4.3 dB). This gives the expected amplifier output power as a function of input signal and pump powers.

$$P_s^{sat} = P_s^{input} + P_s^{IS} + P_{p, noise}^{out} \left[1 - \exp\left(-\frac{P_s^{IS}}{P_p^{IS}}\right) \right] \quad (3.13)$$

Where P_s^{input} represents the launched input signal power and $P_{p, noise}^{out}$ is the output

pump power in the absence of any signal beam.

The effects of gain saturation as predicted by analytical modelling are shown in Figure 3.2 for one 7.4 m length sample of CNET 100 ppm erbium-doped fibre at a signal wavelength of 1543 nm. The effects of increasing signal input power on the amplifier gain are evident.

Figure 3.2. Amplifier gain versus input signal power for the CNFT 100 ppm fibre. Signal wavelength is 15.33 nm

3.7 Applying Steady State Modelling to Optimize Switching Performance

The models of Saleh [7] and Giles [4,5] may be used to investigate the steady state performance of EDFAs. Using these models as a design tool, the range of amplifier operating parameters can be selected to maximize the dynamic range of the switch.

Using this information, input pump and signal powers of 15 mW and 10 μ W, respectively, were selected as operating conditions for the experimental analysis of our 7.4 m CNET 100 ppm fibre sample. These values provide the best compromise of signal gain, efficient pumping and useful dynamic switching range.

3.8 EDFA Static Switching Performance

The static switching performance establishes an upper bound on the dynamic range of switching for a particular EDFA. In this mode of operation, the pump power is simply modulated on-off. The theoretical dynamic range available from the CNET 100 ppm fibre is shown in Figure 3.3. Experimentally, a dynamic range of 32 dB was measured using 7.4 m of this fibre and a signal wavelength of 1543 nm. The turn-off time of this switch is similar to the lifetime of the ions in the upper laser manifold. This time decreases with increasing pump power as higher rates of stimulated emission depopulate the upper laser level more rapidly. A turn-off time of 4 ms (90% - 10%) at output pump powers of 350 μ W to 1 mW was measured. Turn-on times are directly related to the pumping rate and were observed to be on the order of 5-10 ms (10-90%).

3.9 Summary

This chapter presented the tools for analysing EDFAs operating in steady state with small signal power inputs. The fibre amplifier performance is highly linear until the photon core flux increases to the onset of saturation. Beyond this point, stronger signal powers deplete the population inversion and reduce the amplifier gain. The theory predicts that the maximum gain reduction achievable by using strong saturating signal power inputs is on the order of the net gain of the fibre amplifier.

Chapter 4 presents an initial attempt at modelling the saturation transient behaviour of EDFAs with high peak power signal inputs. The transient analysis is an extension of the rate equation theory to incorporate the time varying signal powers and population inversion.

Table 2: Operating System, the NLP framework, and the proposed NLP framework. **Model**

CHAPTER 4

TRANSIENT ANALYSIS AND GAIN SATURATION

4.0 Amplifier Model for Transient Analysis

The amplifier model for transient analysis is based on the three atomic level system using the $^4I_{15/2}$ and $^4I_{13/2}$ levels of the erbium atom. The difference between the transient analysis and static analysis models is that the rate equations must be solved simultaneously in both time (Δt) and axial position along the amplifying fibre (Δz).

A full three level model for the transient analysis is preferred. In steady state analysis, the lifetime of the erbium ions in the upper pump level (level 3) is several orders of magnitude smaller than the fluorescence lifetime. However, the level 3 lifetime contribution to the recovery transient response (turn on time) should not be ignored since it is on the order of one hundred microseconds. Yet, with the amplifier highly inverted, the upper pump level population is a very small proportion of the total erbium ion density and only weakly influences the saturation transient response (turn off time of the amplifier).

The equations for the transient model are presented as equations 4.1 through 4.7. The model is a series of seven equations that need to be resolved in both time and axial position along the fibre's length. To clarify the notation, equation 4.1 indicates the relationship between the fractional erbium ion densities.

$$N_1(z, t) + N_2(z, t) + N_3(z, t) = 1, \quad (4.1)$$

where $N_1(z, t)$, $N_2(z, t)$ and $N_3(z, t)$ are fractional erbium ion densities of the ground state, the upper laser manifold and the upper pump level, respectively. The time dependent fractional population inversion is given by equations 4.2, 4.3 and 4.4

$$\begin{aligned}
\frac{dN_2}{dt} = & \frac{N_2}{\tau} \\
& - \frac{\alpha_p}{\rho A} (N_1 - N_3) \frac{P_p}{h\nu_p} \\
& + \frac{1}{\rho A} N_2 \left(\alpha_{sig} \frac{P_{sig}}{h\nu_{sig}} + \alpha_{sa} \frac{P_{sa}}{h\nu_{sa}} \right) \\
& - \frac{1}{\rho A} N_1 \left(\alpha_{sig} \frac{P_{sig}}{h\nu_{sig}} + \alpha_{sa} \frac{P_{sa}}{h\nu_{sa}} \right)
\end{aligned} \tag{4.2}$$

$$\begin{aligned}
\frac{dN_1}{dt} = & - \frac{N_2}{\tau} \\
& + \frac{N_3}{\tau_{32}} \\
& - \frac{1}{\rho A} N_2 \left(\alpha_{sig} \frac{P_{sig}}{h\nu_{sig}} + \alpha_{sa} \frac{P_{sa}}{h\nu_{sa}} \right) \\
& + \frac{1}{\rho A} N_1 \left(\alpha_{sig} \frac{P_{sig}}{h\nu_{sig}} + \alpha_{sa} \frac{P_{sa}}{h\nu_{sa}} \right)
\end{aligned} \tag{4.3}$$

$$\begin{aligned}
\frac{dN_3}{dt} = & - \frac{N_3}{\tau_{32}} \\
& + \frac{\alpha_p}{\rho A} (N_1 - N_3) \frac{P_p}{h\nu_p}
\end{aligned} \tag{4.4}$$

For the equations above, A is the effective core area, τ_2 and τ_3 are the lifetimes of level 2 and 3 ions, respectively, ρ is the total dopant ion density and h represents Planck's constant. The absorption coefficients α_p , α_{sig} and α_{sa} represent pump, signal and saturating (switching) beams, respectively. The input powers are denoted by P_p , P_{sig} and P_{sa} and their corresponding frequencies by ν_p , ν_{sig} and ν_{sa} . Four terms in equations 4.2 and 4.3 can be identified. The first term on the right of the equals sign is the fluorescence decay rate, followed by the pumping rate (level 1 to level 3), the

rate of stimulated emission and the rate of stimulated absorption at the signal wavelength.

The signal, saturating pulse and pump power rates of change along the fibre axial coordinate, z , are given by equations 4.5 to 4.7.

$$\frac{dP_{sig}}{dz} = g_{sig} N_2 P_{sig} - \alpha_{sig} N_1 P_{sig} \quad (4.5)$$

$$\frac{dP_{sat}}{dz} = g_{sat} N_2 P_{sat} - \alpha_{sat} N_1 P_{sat} \quad (4.6)$$

$$\frac{dP_p}{dz} = (N_3 - N_1) \alpha_p P_p \quad (4.7)$$

Here g_{sig} and g_{sat} represent the gain coefficients [4.5] at the signal and saturating pulse wavelengths, respectively. The gain coefficient as used here corresponds to the maximum net gain per metre available from a fully inverted section of a particular doped fibre sample. The absorption and gain coefficients are scaled by $\ln(10)/10$ to achieve per metre (and not dB per metre) values.

The following assumptions and simplifications have been made in the equations above. The effects of Amplified Spontaneous Emission (ASE) have been ignored in equations 4.5 to 4.7. This is valid for low gain amplifiers ($G < 20$ dB) as the amplifier will not self-saturate under these conditions provided that suitable precautions have been taken to minimize backreflections in the amplifying fibre. A fluorescence lifetime of 10ms (nominal value for erbium ions in glass) was used to

calculate the fluorescence decay rate in equations 4.2 to 4.4. Measured values of the level 2 lifetime ranged from 4 ns to 9 ns depending on pumping power and fibre type. The assumptions that the switching pulse is rectangular in shape and has duration greater than or equal to its transit time through the fibre simplify these calculations. However, the second assumption limits the validity of the model to situations where the length of erbium-doped fibre is less than 2 metres (for 10 ns switching pulses). The switching pulse experiences gain along the fibre's length. This assumption is reasonable given that the total energy of the switching pulse is two to three orders of magnitude below the total stored energy in the amplifier.

To solve the set of equations 4.2 through 4.7 requires a simultaneous solution in both time and space. Initial (steady state) conditions at time $t=0$ at each point along the fibre (25 to 40 position intervals were used) are established prior to the arrival of the switching pulse. The solution can be found by iteratively solving equations 4.5 to 4.7 followed by 4.2 through 4.4 using the forward Euler method to advance the result over a small time increment ($\Delta t = 1$ ns was used here). The solution was verified in steady state by using a graphical and analytical [8] technique to plot N_2 vs the fibre axial coordinate, z , for several values of saturating pulse power/energy. Each curve obtained in this way was then integrated over the fibre length to find a single point on the plot of saturation power versus gain.

A final comment on equations 4.1 through 4.7 provides an insight into the main thrust of this thesis. When the switching pulse peak power becomes very large ($P_{sat} \gg$ the intrinsic saturation power of the fibre) then the stimulated emission rate becomes the dominant term in the rate equation. From equations 4.2 to 4.4, the stimulated emission rate exceeds the stimulated absorption rate by the ratio N_2/N_1 under these conditions. For a fibre amplifier that is initially highly inverted, ($N_2 \gg N_1$), the switching pulse tends to equalize the level 2 and level 1 population densities. Under these conditions the amplifier gain can be reduced to or below transparency depending on the ratio between the stimulated emission and stimulated absorption cross-sections at the signal wavelength.

4.1 Transient Gain Saturation in EDFAs

One of the advantages of erbium-doped fibre amplifiers over their semiconductor counterparts is their relative immunity to saturation-induced cross-talk. Saturation-induced cross-talk occurs in multi-channel fibre amplifiers when large signal inputs cause a reduction in the population inversion ($N_2 - N_1$). The sudden reduction in population inversion causes the average gain to decay according to a saturation time constant [8]. The saturation time constant depends on the relative pump power and the saturating signal power. When the large signal pulse is removed, the population inversion recovers according to a recovery time constant (see Figure 4.1).

Work performed at AT&T Bell Laboratories suggests saturation and recovery time constant in the range 110 μ s to 340 μ s [1] (10% to 90% levels). These relatively long time constants tend to damp any rapid changes in the amplifier's population inversion. The saturation and recovery time constants are about two orders of magnitude shorter than the fluorescence lifetime of erbium ions in silica. The time constants decrease with increasing pump power. In a two-channel amplification experiment, the effects of saturation-induced cross-talk were found to vanish for signal frequencies above 5 kHz [1]. However, these results were obtained with input saturating powers (the probe signal) of approximately 35 μ W and duration of 2 ms.

For the gain switching experiments performed for this thesis, the probe signal had a duration on the order of 10 ns and a peak power as high as several Watts. This is a different regime of operation and it essentially constitutes an extreme case of cross-talk.

Figure 4.1. A qualitative illustration of the saturation and recovery time constants of the inverted ion population.

4.2 Transient Analysis With Switching Pulses

The transient analysis model of section 4.1 was used to investigate the influence of the switching pulse characteristics on the dynamic range and turn-off time of the fibre amplifier in the gain switching mode. The analysis here is limited to gain switching triggered by a single high energy, short duration pulse such as the output of an erbium-doped Q-switched fibre laser. This analysis serves only as a guide to understanding the amplifier dynamics in the gain switching mode of operation.

The switching dynamic range of the fibre amplifier is defined here as the difference in signal gain before and immediately after the switching pulse has passed through the erbium-doped fibre. This gain difference is determined by the steady state operating conditions of the fibre amplifier, the switching pulse peak power and the absorption and gain coefficients at the switching pulse wavelength. In the following analysis the pump power was applied continuously for the duration of the switching pulse. This should make little difference as the pumping rate is orders of magnitude less than the stimulated emission rate during the switching process.

The three level model for the rate equations as described in section 4.1, is used to predict the theoretical limits of the switching dynamic range. Simulation results for the 7.4 m CNET 100 ppm fibre, with a launched pump power of 25 mW, are shown in Figure 4.2. The characteristics of dynamic range versus fibre length are intuitively correct, the maximum gain switching effect occurs at the peak signal gain.

The experimental results for switching pulse energy versus dynamic switching range (measured as the reduction in amplifier gain immediately after switching compared to just before the arrival of the switching pulse), are not shown on Figure 4.2 but are deferred to Chapter 7. As a prelude to the experimental results, gain reductions similar to those shown in Figure 4.2 were realised with pulse energies that were an order of magnitude lower than predicted.

Figure 4.2 Predictions of gain switching dynamic range versus fibre length. CNET 100 ppm fibre, signal power = 10 mW.

On the basis of this discrepancy, it is evident that too many assumptions have been made regarding the characteristics of the switching pulse and the interaction of the switching pulse energy and the stored energy in the fibre amplifier. The pulse itself was assumed for simplicity to have a uniform distribution of optical power versus time. In fact, the pulse shape may appear more like a Gaussian distribution as it enters the fibre amplifier. Further, the pulse may become distorted as it travels through the amplifying medium.

The results of the switching dynamic range simulations are strongly influenced by the values used for atomic emission and absorption cross sections. Although the cross sections do not appear explicitly in equations (4.1) to (4.7) they are calculated indirectly by knowing the dopant ion density, the absorption coefficient and the erbium-doped core area. These values are determined by absorption measurements at the signal and pump wavelengths but were estimated for the switching pulse wavelength.

The interaction between the pulse energy and the stored energy in the amplifier requires further study. In the equations of (4.1) to (4.7) the switching pulses were expressed in terms of peak powers rather than pulse energies. This is an adequate representation for pulses that have a time duration in excess of the travel time through the amplifying fibre. However, it does not appear to be an accurate model for Q-switched pulses travelling through several metres of erbium-doped fibre. For example, in an amplifying fibre 10 metres in length and a switching pulse that has a duration on the order of 10 ns, the length of the pulse in the fibre is only one fifth of the doped fibre length (2 metres for a 10 ns pulse). To accommodate this situation, the model should be re-written to represent the fact that the switching pulse energy is applied to only one fifth of the total energy stored in the fibre. The switching pulse is amplified as it travels down the fibre and in so doing it rapidly consumes the population inversion as it travels down the fibre length. The result is a reduced population inversion profile along the length of the erbium-doped fibre. In the solution of the rate equations, boundary conditions would have to be applied to the leading and

trailing edges of the pulse. The boundary conditions could then be adjusted with each time step of the simulation. Testing of this new concept requires a fairly complex model and was not attempted here (but it is recommended for further study by other interested parties).

Alternatively, if the erbium-doped fibre was short enough ions in the 7.4 m fibre was short enough to allow the switching pulse energy to influence all of the erbium ions at some snapshot in time, then the analysis technique developed here would yield more realistic results. In an attempt to test this hypothesis, a sample of laser grade erbium-doped fibre of length 48.4 cm (the AT&T sample) and erbium ion concentration of 800 to 1000ppm was evaluated for steady state gain properties and had a signal gain within 0.75 dB of the 7.4 m CNET 100ppm fibre at a signal wavelength of 1543 nm and input pumping powers of 15 to 25 mW. This suggests that under conditions of strong pumping total stored energy in both fibre samples is similar. The measured absorption and gain coefficient parameters for the laser grade fibre are tabulated in section 6.4 and are used in the analysis below.

4.3 Modelling of Gain Switching Using Short Fibre Amplifiers

The switching pulse peak power strongly influences the dynamic range of switching. For equal energy pulses of varying peak power and pulse duration the strongest gain switching effect is predicted for pulses of the highest peak power and the shortest duration (see Figure 4.3).

The predicted transient gain response of the fibre amplifier to a single 10 ns duration pulse of varying peak power is shown in Figure 4.4. The analysis indicates that in order to achieve a useful switching dynamic range, of perhaps half of the amplifier net gain, requires a pulse energy of 80-100 nJ. This energy level corresponds to peak powers of 8 to 10 W. In the experimental work, (to be discussed below), a maximum pulse energy of 75 nJ per 10 ns pulse was coupled from the Q-switched erbium-doped fibre laser to the input of the erbium-doped fibre. A pulse repetition rate of 1 kHz was used.

The turn-on time of the amplifier after the gain switching has occurred is determined by the pumping rate and the lifetime of the erbium ions in the upper laser level (level 2). Using the three level model in the absence of the saturating pulse power and cw pumping, the recovery time (time to recover to within 90% of the pre-switching signal gain) varies between 1 ms and 10 ms depending on the value of input pump power selected (see Figure 4.5). The recovery time is also strongly influenced by the fluorescence lifetime of the erbium ions in the upper laser level. Note the difference in Figure 4.6 between the curve assuming the measured fluorescence lifetime of 4.4 ms and the three curves which use the nominal lifetime of 10 ms.

Figure 13: Gain reduction versus pulse duration. Modulation frequency = 2.50W, 42mJ per cycle = 1.6W

Figure 4.4. Transient response of amplifier gain using a 10 ns pulse width. Pump power = 25mW, signal = 100W

Fig. 4.5. CNET fibre amplifier recovery time, $P_{\text{signal}} = 10\text{mW}$

Fig. 4.6. Recovery time versus pump power and ion lifetime, CNET 100ppm fibre.

4.4 Total Stored Energy In The Fibre Amplifier

One interpretation of the pulse energy required to perform gain reduction in the fibre amplifier is the total stored energy in the active fibre due to the inverted erbium ion population. The switching pulse must reduce the population inversion to a level below which the incremental signal power dP/dz becomes negative. Using equation (3.10), setting $dP/dz = 0$ and neglecting the ASE term yields an expression for the this population inversion ratio $n_2/n_1 \leq (\alpha_{sp} + l_{sp})/(\alpha_{sp} + g_{sp})$. Note that this is not necessarily the point where $N_2 = N_1$.

The total energy stored in the active fibre can be deduced from measured parameters. The fibre saturation parameter [4] of a given sample is the ratio of the linear ion density to the fluorescence lifetime of the erbium ions in the sample and is given in units of $m^{-1}s^{-1}$.

$$\eta = \frac{A\rho}{\tau} \quad (4.8)$$

This parameter may be found experimentally by measuring the unbleached absorption coefficient at the pump wavelength and the input power required to increase the transmission of signals at this wavelength by a factor of 1/e (4.3 dB). This value gives the intrinsic saturation power at the pump wavelength. The fibre saturation power may then be determined by,

$$\eta = \frac{P_P^{IS} \alpha_F}{h\nu_P} \quad (4.9)$$

Using the measured fluorescence lifetime of 4.4 ms and estimating that the active core area is equal to the geometrical core area (assumes a uniform dopant density across the fibre diameter) the total number of active ions per unit volume can

be calculated. This figure is then multiplied by the fractional population inversion N_2 (calculated from the absorbed pump power) and the active volume of the fibre to determine the total number of inverted ions. Multiplying by the energy per ion undergoing the $^4I_{15/2}$ to $^4I_{13/2}$ transition yields the total stored energy.

For the 7.4 m length of CNET 100ppm fibre, calculations indicate that 10.5 μ J of stored energy when pumping at 15 mW input pump power. This energy content is well in excess of the 40 to 200 nJ, (see Figure 4.3), that was estimated earlier for the switching pulse energy requirements. The question remains, how can a switching pulse that has two orders of magnitude less energy than the stored (potential) energy of the amplifier achieve significant gain switching in the EDFA? There are two points to consider. The switching pulse experiences gain along the amplifying fibre length and so is capable of initiating more stimulated emission transitions in the amplifier than might be expected of a single input pulse of known energy. The results of amplifier modelling suggest that only a fraction of the population inversion needs to be negated to cause several dB change in small signal gain.

4.5 Summary

The time varying rate equations of (4.1) to (4.7) were intended as a first attempt at modelling the gain switching mechanism using Q-switched pulses. Although these equations do provide for amplification of the switching pulse, the experimental results to be presented in Chapter 7 suggest that the model does not sufficiently describe the switching dynamics. It appears that the pulse peak power, rather than its energy content, is the dominant factor for gain reduction. The Q-switched pulses may be completely contained within amplifying fibres greater than two metres in length. This feature needs to be modelled more accurately by stepping the pulse through the fibre length and allowing for the ion population inversion changes at each step. This type of modelling approach is recommended for further study.

It is useful to note that by removing the time dependence of equations (4.1) to (4.7), the rate equations will collapse back to the steady state models.

CHAPTER 5

GAIN-SWITCHED EDFA PERFORMANCE PREDICTIONS

5.0 Gain-Switched EDFA Performance Predictions Using Steady State and Transient Analysis

The purpose of this chapter is to summarize the results of the amplifier modelling efforts as they apply to the 7.4 m CNET 100 ppm erbium-doped fibre. The analysis predicts the steady state 'operating point' of the amplifier, the degree of gain switching (dynamic range) that is achievable using the switching pulse powers available and provides an estimate of the turn on/off times of the amplifier in switching mode.

5.1 Steady State Operation

The analytical and numerical models of section 3.1.2 indicate that when using signal powers on the order of 10 μ W there is little improvement in the amplifier steady state gain when using more than 15 mW input pump power. At this pump power level approximately 10-11 dB gain is anticipated when using the 7.4 m length of CNET 100 ppm erbium-doped fibre.

Two signal laser diode wavelengths were available. A 1527 nm BHS laser diode (multiple transverse mode) and a 1543 nm DFB laser diode (courtesy of H. Kim at Bell Northern Research). The analytical model of section 3.2.1 was used to predict the gain at both of these wavelengths. The 1543 nm diode gain predictions were 3.5 dB higher than the 1527 nm gain figures.

The steady state analysis also allows one to determine the optimum doped fibre length for situations where the maximum amount of pumping power available is well defined, (e.g. laser diode pumping) and arbitrary lengths of doped fibre are available. Figure 2.3 illustrates the characteristic curve of amplifier gain versus the doped fibre length for three values of input pump power. For the CNET 100 ppm fibre, the analytical model predicts an optimal length of 17 m with an input pump power of 15 mW.

5.2 Transient Operation

The analytical model for steady state analysis may be used to determine the upper bound on the pre-switching signal gain. However, it is necessary to use a numerical solution to solve for the amplifier transient response at selected time intervals after the switching pulse enters the doped fibre. It was explained in section 4.3, that the transient analysis model in its present form is of limited value for predictions of switching dynamic range versus switching pulse energy/power. The results of the transient analysis for the 7.4 m CNET 100 ppm fibre are summarized in the paragraph below.

The dynamic range versus fibre length plot of Figure 4.2 suggests that a 2 μ J pulse is required to produce a 3.5 dB gain switching effect. The amplifier turn off time is estimated to be similar to the switching pulse width (10 ns). The recovery (turn-on) time is directly related to the input pump power (see Figure 4.5) and is judged to be in the 1.5 to 10 ms range for 10 to 25 mW pumping powers. An obvious drawback to this approach for amplifier gain switching is that the turn-on time of the amplifier is relatively slow.

CHAPTER 6

CHARACTERIZATION OF ERBIUM-DOPED FIBRES

6.0 Explanation of Fibre Parameters

The rate equations for a three-level fibre amplifier require knowledge of several optical and atomic parameters. These data are the erbium ion density, the excited state spontaneous lifetime, the active area of the fibre core, the atomic absorption and emission cross-sectional areas and the confinement (overlap) factor. The cross sectional areas and the confinement factors must be determined for each pump and signal wavelength involved. The absorption and emission cross-sections are derived from quantum-mechanical principles and cannot be measured directly in the laboratory. These values are calculated from the integrated fluorescence emission and absorption measurements which have been calibrated using the Ladenburg-Euchbauer equation [4]. Measurement of all of these parameters described above is time consuming and often inaccurate. In cases where information from the fibre manufacturer is not available, then determination of the fibre amplifier parameters becomes difficult.

Instead, the models used to describe the fibre amplifiers used in the experiments in this thesis are based on parameters that are easily measured using monochromatic absorption data, fibre length and oscilloscope or optical spectrum analyser based gain measurements. Both analytical [7] and numerical [4,5] models were used to characterize the fibre amplifiers.

The analytical and numerical model parameters are listed in Table 3.1 and Table 3.2 in section 3.2.

6.1 Absorption Coefficient Measurements

The absorption coefficients may be measured by plotting the transmission characteristics of the doped fibre at both the pump and signal wavelengths. The transmission characteristic curves illustrate the ratio of output power to the launched input power (expressed in dB) versus the launched input pump power (expressed in dBm). The unbleached region of operation (the region where input powers are

sufficiently low that the transmission curve is flat) is used to determine the absorption coefficient, α . The absorption coefficient values for three fibre samples are presented in Table 6.1.

Alternatively, fibre cutback measurements may be made to determine the attenuation versus fibre length characteristics. Care must be taken when using this approach to ensure that the input power is sufficiently low that absorption bleaching of the fibre does not occur.

Accurate measurements of fibre length are required in order to determine the absorption coefficients using either method.

Plotting the transmission characteristics proved to be a more practical approach as these curves were also required to obtain the intrinsic saturation powers for both the pump and signal wavelengths. The signal and pump wavelength absorption coefficients were measured using the experimental setups shown in Figures 6.7 and 6.8 respectively. The single mode fibre was used as a dummy fibre to provide an estimate of the launched optical power for each setting of the attenuator. The estimate of launched power into the erbium-doped fibre had to be corrected to account for the mismatch in core sizes between the variable attenuator pigtail and the erbium-doped fibre.

The measured transmission versus input signal power characteristics at the signal wavelength of 1543 nm are illustrated in Figures 6.1, 6.2 and 6.3 for three erbium-doped fibre samples. The same characteristics are shown in Figures 6.4, 6.5 and 6.6 for the 978 nm pump wavelength.

Figure 6.1. Absorption bleaching in the CNFT 100ppm fibre sample at 1543 nm

Figure 6.2 Absorption bleaching in the AT&T fibre sample at 1543 nm.

Figure 6.3. Absorption bleaching at 1543 nm in YORR 300 ppm erbium-doped fibre.

Figure 6.4. Absorption bleaching at 978 nm in CNFT 100 ppm erbium-doped fibre.

Figure 6.5 Pump wavelength 1978 nm) absorption bleaching in AT&T Terbium-doped fibre

Figure 6.6. Absorption bleaching at 978 nm in YORR 300 ppm erbium-doped fibre.

Figure 6.7. Measurement of signal absorption at 1543nm in erbium-doped fibre.

Figure 6.8. Measurement of pump absorption at 978nm in erbium-doped fibre.

6.2 Intrinsic Saturation Power Measurements

The intrinsic saturation power represents the launched input optical power required to bleach the absorption of the doped fibre sample by 1 e (4.3 dB). This point is indicated on the transmission curve for both pump and signal wavelengths as the input power corresponding to a 4.3 dB increase in transmission above the horizontal (unbleached) portion of the curve. Physically, the intrinsic saturation power is a threshold value that indicates the 'knee' of the transmission curve.

The fibre saturation parameter, η , is closely related to the intrinsic saturation power at the pump wavelength and can be derived as shown previously in equation (4.9). In this form, the saturation power is equivalent to the ratio of the linear ion density to the fluorescence lifetime of the erbium ions in the upper laser level. Knowledge of the intrinsic saturation power allows one to perform the calculations requiring dopant ion density and fluorescence lifetime without actually measuring these values. The measured values for the pump and signal wavelengths P_{sp}^p and P_{sp}^s were obtained using the experimental configurations of Figure 6.7 and 6.8 and the results are shown in Table 6.1.

6.3 Gain Coefficient Measurements

Sufficient input pump power to produce the maximum population inversion in the sample of erbium-doped fibre facilitates the calculation of the gain coefficient, g . The ratio of maximum net gain to the active fibre length is equal to the gain coefficient. This value is expressed in nepers (per metre units) as opposed to dB per metre units. The measured values were obtained from the experimental setup shown in Figure 6.9 and are shown in Table 6.1.

Tables 6.1 and 6.2 show the measured fibre parameters and the manufacturer supplied (or calculated) data for the three fibre samples tested.

Figure 6.9. Measurement of erbium-doped fibre gain coefficients.

TABLE 6.1 - Measured Parameters for Three Samples of Erbium-Doped Fibre

Parameter	CNET 100ppm fibre	AT&T laser grade fibre	YORK 300ppm fibre
L	7.4m	484mm	1.96m
α_c (m^{-1})	0.61	10.35	2.72
α_p (m^{-1})	0.72	8.38	2.88
P_{in}^h (photon flux units power in W/hv)	3.9×10^{15}	3.7×10^{15}	4.5×10^{15}
P_{sp}^h (W/hv)	5.75×10^{15}	7.7×10^{15}	5.8×10^{15}
η ($m^{-1}s^{-1}$)	4.14×10^{17}	6.4×10^{15}	1.67×10^{15}
$g(1543nm)$ (m^{-1})	0.39	4.28	0.48

TABLE 6.2 Basic Fibre Parameters - Manufacturer Supplied Data and Calculated Values.

Parameter	CNET 100ppm	AT&T	YORK 300ppm
Cutoff Wavelength	1.05 μ m	-	1.25 μ m
Core Diameter	5.4 μ m	4.4 μ m	4.4 μ m
Numerical Aperture	0.15 (calc)	0.16	0.21
Mode Field Diameter (1543/978 nm)	8.5/5.7 μ m (calc)	-	-

6.4 Amplifier Noise - Amplified Spontaneous Emission

The effects of Amplified Spontaneous Emission (ASE) on the signal to noise performance of EDFAs pumped by laser diodes have been reported in the literature [14]. Spontaneous emission sets a lower limit on the noise generated by the fibre amplifier. The aggregate noise power detected at the output of the EDFA consists of four components. In addition to shot noise of the signal and the ASE, the mixing of ASE and the signal fields at the detector creates two additional noise products, spontaneous-spontaneous and signal-spontaneous beat noise. In most applications it is possible to operate with the signal output powers much greater than the output ASE power. Under these conditions the signal-spontaneous beat noise is the limiting mechanism for determining the noise figure of the amplifier. Figure 6.10 shows the amplified signal and ASE spectrum for the 7.4m CNET 100 ppm fibre amplifier with a 1543 nm DFB laser diode signal source, (the amplifier output pump power was 1.7 mW).

However, care must be taken to avoid backreflections in the amplifier optical signal path. Backreflections from unterminated fibre end faces or from components with inadequate backreflection performance can cause the ASE power to build up rapidly through two or more passes along the amplifying medium. This effect is illustrated in the optical spectrum analyser plots in Figures 6.11 and 6.12 for varying levels of amplifier output pump power. In this case, no attempt was made to provide low backreflection terminations on either end of the erbium-doped fibre so that the effects of increasing the input pump power could be observed. The data was measured with no signal power applied (the pump wavelength was 978 nm). Note that with increasing pump power the ASE spectral width narrows, indicating the onset of lasing in the amplifier.

Figure 6.10. Amplified signal output at 1543 nm.

Figure 6.11. Evolution of forwards propagating amplified spontaneous emission using the CNET 100 ppm fibre

Figure 6.12. Evolution of backwards propagating amplified spontaneous emission using 7.4 m of CNET 100 ppm fibre

By tuning the pump wavelength away from the optimum 978 nm to 979 nm, the spectral characteristics of the ASE power can be modified due to reduced pumping efficiency. Figure 6.13 illustrates the wavelength dependence of the ASE spectrum for a constant 20 mW input pump power for the 1.96 m YORK erbium-doped fibre sample. Once again, the erbium-doped fibre end faces were not terminated. The erbium-doped fibre was butt coupled to the 980:1550 nm coupler output using precision mechanical stages.

The next section discusses some of the effects of backreflections from various sources in the optical signal path and presents recommendations for "cleaning" the amplifier's signal path in order to minimize the ASE output power.

Figure 6.13. Evolution of ASE spectrum with pump wavelength using the YORK 300 ppm fibre.

6.4.1 Backreflections and Amplified Spontaneous Emission

The combined effects of increasing the input pump powers many times above the threshold level, P_{th} , and backreflections in the signal path result in a rapid build up of forward and backward propagating ASE. Even a small amount of backreflection from the fibre end faces or from the fibre couplers at either end of the amplifier may result in ASE noise powers in excess of 100 μ W. Under these conditions, the amplifier exhibits superradiance and in extreme cases becomes an oscillator (a laser). If this occurs then gain saturation at the signal wavelength may occur sooner than expected. When using signal laser diodes with intensity peaks of 1525 nm and 1543 nm, the onset of lasing at the erbium ion characteristic emission peak at 1536 nm becomes a strong contender for the inverted ions in level 2.

By paying careful attention to some techniques for reducing backreflections in the optical signal path, (1543 nm), the amount of ASE power at the amplifier output can be dramatically reduced. The following techniques proved to be the most useful (see Figures 6.9 and 7.1):

1. Low backreflection (-60 dB) Angled Physical Contact (APC) connectors were fusion spliced to the erbium-doped fibre and the 980/1550 nm coupler. This is a low loss, repeatable method of aligning the erbium-doped fibre and virtually eliminates the reflection of backward propagating ASE at this particular interface. A repeatable coupling loss of 0.2 to 0.3 dB was achieved. However, the fusion splice between the APC connector pigtail (9 μ m core telecommunications grade fibre) and the erbium-doped fibre (5.4 μ m core) resulted in an estimated 1.5 to 2.0 dB loss. The loss figure is difficult to determine accurately without doing destructive cutback measurements on the erbium-doped fibre. Ideally, several sets of cutback measurements and fusion splices would be required in order to estimate the splice loss more accurately. This connection method is more robust in the lab environment, it is repeatable and provides lower backreflection than the butt coupled alignment method used previously.

The optical signal path extends back through the 980/1550 nm coupler, through

the 3 dB coupler, if used, to the optical isolator. Low backreflection (-45 dB typical) FC/ super-PC connectors were selected for use between the 3 dB and the 980/1550 nm coupler. These connectors are much less expensive than the APC connectors while still providing adequate backreflection performance for this interface.

2. Optical isolators may be used in series with the erbium-doped fibre. While this component does nothing to suppress the backreflections at their sources, it does effectively reduce the ASE build up by preventing the backward propagation of signals in the erbium fibre. This technique is useful but has its drawbacks. Optical isolators are expensive components, ranging in price from \$2000 to over \$4000 US each for connectorized and pigtailed devices. One such device was already in place to isolate the DFB laser diode from backreflections in the rest of the optical circuit. The isolator used for most of these experiments had a measured forward attenuation of 1.5 to 2 dB.

3. The quality of the fibre optic components used played a significant role in the reduction of the total ASE power. A higher quality optical isolator (made by E-Tek) eventually replaced the original (Optics For Research) device. The E-Tek component permitted lower reflections in both signal arms than the Optics For Research device. This feature resulted in a remarkable reduction in ASE power. Figure 6.14 illustrates the importance of placing the optical isolator so as to minimize backreflections in the signal path.

The use of low backreflection, fused tapered couplers would also be useful to reduce the total ASE power. This idea was not put into practice.

4. The end facet of the erbium-doped fibre was polished to a 7 degree angle [18] to minimize the amount of power that would be reflected back into the fibre core from the glass-air interface. The polished angle was achieved by inserting a cleaved fibre into a glass ferrule and polishing the protruding fibre face to the required angle.

6.5 Summary

The measurements discussed in this chapter were used to optimize the design of the EDFA prior to performing the final gain switching experiments. The absorption

measurements and the manufacturer supplied data were used in the modelling phase to maximize the amplifier gain. ASE characteristics were taken into account to generate an amplifier design with minimum output noise. "Cleaning" the amplifier of backreflections allows a maximum amount of population inversion to be directed towards signal amplification rather than ASE.

The CNET 100 ppm erbium-doped fibre was selected as the best of the fibre samples to be connectorized and used in the gain switching experiments

2 OF 2

PM-1 3 1/2" x 4" PHOTOGRAPHIC MICROCOPY TARGET
NBS 1010a ANSI/ISO #2 EQUIVALENT

Figure 6-14. Forward ASE power versus output pump power under 5 experimental configurations

CHAPTER 7

EXPERIMENTAL RESULTS

7.0 Introduction

The experimental results detailed in this chapter are organized to indicate a progression towards an optimized design for a gain switched erbium-doped fibre amplifier (EDFA). The final design was realized by using the materials available within the Masters thesis time frame, the budget restrictions and the "windows" of availability of the laboratory equipment at the Autonomous Systems Laboratory. The components involved and the experimental configuration used were selected to give the best gain switching behaviour.

This section highlights the experimental results for the EDFA steady state operation and the gain switching transient response.

7.1 Experimental Improvements

The final gain switching experimental configuration (see Figure 7.1) required a substantial amount of optical and electronic hardware. Five lasers, (two Argon Ion pump sources, the Ti-Sapphire laser, the Q-switched erbium-doped fibre laser and the 1.54 μm laser diode signal source) were required to operate in unison to obtain the gain switching measurements of this chapter. Achieving stable and reliable operation of all of the lasers over a period of several hours became a major obstacle to overcome from the practical standpoint. In particular, achieving stability of the 10 W Argon Ion laser for pumping the Ti-Sapphire and the stable operation of the Ti-Sapphire laser tuned to 978 nm (near the limits of its tuning range) were time consuming and tedious operations. If any experiments are to be repeated in the future, the author's first recommendation would be to invest in a laser diode pumping source at either 980 nm or 1480 nm. At the time these experiments were performed, the cost of these devices was prohibitively expensive and the device reliability was questionable.

Figure 7.1. The gain switching experiment - final setup.

The tasks listed in the sections below were crucial to achieving optimal performance of the gain-switching EDFA.

7.1.1 Cleaning the Amplifier of Reflections

This operation is described in detail in section 6.6.1. Backreflections were minimized at each interconnection point and the fibre-air interfaces. This resulted in an order of magnitude reduction in the ASE output power. In addition, an improvement in the steady state gain of 2-3 dB was realized. The APC connectors used between the erbium-doped fibre and the 980:1550 nm coupler enhanced the repeatability of measurements. The APC coupler pigtails were fusion spliced to the CNET 100 ppm erbium-doped fibre sample. One drawback with this experimental setup is that using fusion spliced connections did not facilitate the interchange of erbium-doped fibre samples.

7.1.2 Detector Design

A substantial effort was required to develop detection circuitry that could cope with the requirements for high transimpedance gain, wide bandwidth (150 MHz or greater) and high stability, low noise operation. The simultaneous requirements for high gain and wide bandwidth conflict with each other as do the aspirations for wide bandwidth and low noise operation.

Two approaches for the detector design were pursued. The first design used a high gain transimpedance amplifier (14 K Ω) followed by a wide bandwidth differential amplifier (10 dB gain). This combination had sufficient gain and a bandwidth of 90 to 100 MHz. The problem with this design was the noisy output background signal. The transimpedance amplifier is susceptible to feedback through the power supply and ground traces. Use of a solid ground plane and inductive and capacitive filtering partially solved this problem.

The second approach used a small area photodiode detector with a 50 Ω termination. This detector design is in use at the National Research Council for high speed pulse detection but it is not a very sensitive device. The voltage generated

across the $50\ \Omega$ termination required two cascaded rf amplifier stages to provide sufficient gain for an observable trace on the oscilloscope.

7.1.3 Selection of the Laser Diode Signal Source

The 1543 nm distributed feedback laser diode was selected as the signal source for the gain switching experiments. This operating wavelength is located in the middle of the gain bandwidth of the CNET fibre amplifier. An increase of several dB in the amplifier small-signal gain would be realized by operating at a signal wavelength of 1533 nm. However, the Q-switched pulses were tuned to this 1533 nm wavelength in order to maximize the gain switching effect. If the signal and Q-switched pulses were too closely spaced in wavelength then filtering the two signals at the amplifier output would not have been possible using the experimental setup of Figure 7.1.

The other candidate laser diode was a 1525 nm to 1527 nm multimode buried heterostructure (BHS) device. The peak of the laser diode spectrum varied between 1523 nm and 1529 nm depending on the ambient temperature and the test equipment used. The steady state gain for this device was 3 dB to 4 dB lower than for the DFB laser diode (see Figure 7.3). The amplified signal from the BHS device is located a nominal 5 nm from the switching pulse wavelength which complicates the problem of filtering the amplifier output signal.

For the gain switching experiment, the signal laser diode was sinusoidally modulated at 150 MHz. The $50\ \Omega$ output of the Wavetek model 3510 rf generator was coupled using coaxial cabling to a PCB mounted SMA connector on the laser diode driver circuit board. Particular attention was paid to minimizing the trace lengths of the $50\ \Omega$ resistive-capacitive coupling to the laser diode. Surface mount passive components were used to minimize the connection lengths and rf chokes were employed to isolate the rf and dc ground paths. These circuit design procedures assured a minimum of parasitic reactance associated with the laser diode modulation.

7.1.4 Test Instruments

The Anritsu Optical Spectrum Analyzer performed a dual role in the gain switching experiments. Steady state gain measurements were made by comparing the peak power of the amplified signal to the input signal connected to the spectrum analyzer using a short section of standard single mode fibre (undoped). During the gain switching experiments, the spectrum analyzer's monochromator output was used to filter the amplified signal from the Q-switched pulse. Multimode fibre connected the monochromator output port to the small area Ge photodiode. It was necessary to compensate for the 10 dB (optical power) insertion loss of the monochromator by using cascaded rf amplifier modules (Minicircuits models ZFL500LN and ZFL1000H). This amplified signal was then displayed on a Tektronix 7854 oscilloscope using a 7B87 time base.

All of the optical power measurements were made using a Newport model 835 power meter with a model 818IR detector. This is a Germanium photodiode detector with electronic wavelength calibration.

7.1.5 Calibration of Optical Power in the Fibre Amplifier

Calibration of the launched input pump power based on the output pump power is a non-trivial task. The relationship between the launched power and the output power in an erbium-doped fibre is not only an exponential absorption function, $\exp[-\alpha L]$, but also is influenced by photobleaching, mode field diameter mismatches between the source fibre and the erbium-doped fibre and the launching conditions. The calibration curve of Appendix A is based on empirical measurements of output pump power (corrected for ASE) compared to the power launched into a 1.5 m single mode fibre patchcord. The loss of the fusion splice to the erbium-doped fibre at the pump wavelength was also incorporated into the final estimate of launched power.

Calibration of the launched signal power is based on the same type of empirical measurements as the pump power estimates. The results were not plotted as a calibration curve because most of the experimental work involved only two or three

discrete signal powers.

The mode field diameter values at the signal wavelength are poorly matched. The calculated values at 1543 nm are 8.5 μm for the CNET erbium-doped fibre versus 9.76 μm for the single mode fibre coupler. At the pump wavelength, the calculated mode field diameters for the erbium-doped fibre and the single mode fibre are 5.7 μm and 6.3 μm respectively.

Cutback measurements of some unused sections of the CNET erbium-doped fibre verified the coupling losses at the signal wavelength. The estimates of the overall coupling loss (connector and fusion splice) at the signal wavelength are 1.5 dB to 2 dB.

7.1.6 Stability of the Pump Source

One of the most frustrating aspects of the experimental work was in achieving a stable and consistent pump power delivery into the erbium-doped fibre. Replacement of the Argon Ion laser tube and modifications to the Titanium-Sapphire laser improved this situation. These modifications involved redesign of the mirror and crystal mounts as well as rebuilding the laser on the optical table instead of on a thin base-plate. This work improved the robustness of the laser in the presence of mechanical vibration and thermal variations.

Coupling of the free-space pump beam into single mode fibre was greatly improved by using an Optics For Research Selfoc lens assembly. A coupling efficiency of 60% to 70% was realized but adjustments were time consuming and tedious. The Selfoc lens design was optimized for 1.06 μm operation but worked well at 978 nm.

7.2 Experimental Results - Steady State Gain

This section presents the results of the steady state gain experiments that were performed in the months prior to the final gain-switching experiment. Ultimately, the purpose of these experiments was to identify the most suitable of the candidate erbium-doped fibre samples to use for gain switching measurements. The CNET 100ppm erbium-doped fibre emerged as the best sample to use.

7.2.1 Comparison of Three Erbium-Doped Fibre Samples

In the early stages of experimental gain testing, three erbium-doped fibre samples were tested. The CNET fibre (100 ppm), the YORK fibre (300 ppm) and the AT&T (high dopant concentration ~1000 ppm - laser grade) fibre samples were evaluated for signal gain using 30 μ W input signal power from the 1543 nm LD and the pump wavelength tuned to $\sim$ 78 nm. Figure 7.2 shows the test results plotted as signal gain against the pump power measured at the output of the erbium-doped fibre. Plotting the results this way simplifies the experimental procedure but the results are useful for comparative purposes only. A correction to the horizontal axis has been done to account for ASE power (maximum 1 mW at the gain peak) and the amplified signal power (100 μ W-250 μ W) to get an accurate estimate of the true output pump power.

The erbium fibres were butt-coupled to the input fibre arm of the 980:1550 nm coupler using precision mechanical stages and the alignment was fine tuned until the output power was a maximum for each fibre sample. The fibre to fibre coupling losses are estimated to be within 0.5 dB of each other using this approach.

Although the AT&T fibre yields the highest overall gain, a relatively high pump power was required. In the 1 mW to 5 mW output pump power range the CNET fibre outperformed the AT&T sample indicating a more efficient gain slope. This was predicted from theory in section 3.1.5 - Figure 3.1. The signal gain for the YORK fibre was consistently lower than the other samples. For the YORK fibre, the manufacturer specified the cutoff wavelength as 1275 nm. This cutoff wavelength ensures that the 978 nm pump beam propagates as multimode energy thus reducing the effective overlap coefficient between the pump beam and the erbium ion dopant profile. This accounts for the lower gain figures of the YORK fibre.

The influence of the signal source laser diode wavelength is illustrated in Figure 7.3. Both the 1543 nm DFB laser diode and the 1525 nm (nominal peak power) buried heterostructure (BHS) laser diode were used as signal sources. The tests were performed with an input signal power of 25 μ W in each case. It is interesting to note that while the gain of the CNET fibre amplifier is higher at the

1543 nm wavelength than the 1525 nm wavelength, the situation is reversed for the AT&T fibre.

Figure 7.2. Signal gain versus pumping power (measured at the fibre output end). Pump wavelength is 978 nm.

Figure 7.3. Signal gain versus pumping power and the signal wavelength.

7.2.2 Gain versus Pump Power - CNET Sample

The gain versus pump power characteristics were measured using the experimental configuration of Figure 7.1 but with the fibre laser switched off. The measured gain versus the launched (input) pump power characteristics for the CNET fibre are shown in Figure 7.4 for three values of launched signal power. The maximum launched signal power was limited to 37 μW due the result of the aggregate insertion and coupling losses in the optical signal path from the laser diode pigtail to the erbium-doped fibre input. The gain was measured using the full complement of couplers, attenuator and isolator so as to be representative of the amplifier performance for the upcoming gain switching experiment. The gain figures for input signal powers lower than 1 μW are not plotted as they are almost indistinguishable from the 1.6 μW values.

The signal gain was measured using two methods. The first approach was to use 100 kHz sinusoidal modulation of the laser diode current. With a 1 m (dummy) piece of single mode fibre inserted in place of the erbium-doped fibre, the amplitude of the detected output signal was measured on the oscilloscope. This approach has the advantage of being able to see the amplified signal quality and the effects of ASE. The disadvantage of this method is the inability to measure the output signals over a wide dynamic range.

A second method was made possible when an optical spectrum analyzer became available. The spectrum analyzer peak search feature was used to determine the ratio of the amplified gain peak to the peak of the power spectrum when the undoped fibre was substituted for the erbium-doped fibre and the pump power was turned off. This latter method proved to be more practical for making measurements. In order to plot the horizontal axis as launched pump power, a conversion from amplifier output pump power to input pump power had to be performed. The calibration curve for this conversion was determined empirically and is presented in Appendix A.

Figure 7.4 Gain versus launched pump power. Experimental measurements for the CNFT fibre

Note the effect of increasing the signal power to 37 μ W. The amplifier shows strong evidence of saturation at lower input signal powers than the models of chapter 3 predicted. In addition, the analytical model proposed by Saleh [7] suggests that the input pump threshold power, P_p^{th} , defined as the pump power required to achieve transparency in the fibre, is independent of the launched signal power level. This threshold pump power is given by the equation below.

$$P_p^{th} = \alpha_s L P_s^{IS} / [1 - \exp(\alpha_s P_s^{IS} / P_p^{IS} - \alpha_p) L] \quad (7.1)$$

This equation predicts a value of 2.53 mW for the CNET 100 ppm fibre (7.4 m). This value is in reasonable agreement with the measurements at the 1.6 μ W signal power but does not accurately represent the situation where input signal powers in excess of about 10 μ W are used.

7.2.3 Gain versus Signal Power - CNET Sample

Figure 7.5 illustrates the effects of increasing the input signal power on the CNET fibre amplifier. Three families of input pump power are used ranging from 1.7 times to approximately 4 times greater than the threshold pump power (as defined in the previous section). The measurements for Figure 7.5 were performed in the same way as the gain versus signal power measurements using a section of dummy fibre and the optical spectrum analyser (see Figures 6.8 and 6.9).

Increasing the pump power above 17 mW made no appreciable difference to the measured value of signal gain. The optical spectrum analyser input is rated at a maximum of 10 mW cw and it was desirable not to approach this limit.

The amplifier's output signal saturation power, P_s^{sat} , is defined as the output signal power for which the gain drops by 4.3 dB (1/e) from its peak value at a given pump power. This power may be estimated from the analytical model for P_{out} (see section 3.2.1).

Figure 5. Signal power versus signal gain. Experimental values for the CNFT fibre.

$$P_s^{sat} = P_p^{out} [1 - \exp(-P_s^{in}/P_p^{in})] \quad (7.2)$$

Where P_p^{out} represents the true output pump power (no signal power applied at the input). For a launched pump power of 17 mW the true output pump power was 3.1 mW. The parameters for the CNET 100ppm fibre indicate that the output saturation power using equation (7.2) is 1.5 mW. Extrapolating the experimental points for the 17 mW pump power curve of Figure 7.5 suggests that the -4.3 dB point occurs at a launched signal power of approximately 100 μ W. This input signal power experiences a 10 dB gain to yield an output saturation power of 1 mW.

The output saturation power of the amplifier is an indicator of the level 3 ($^4I_{11/2}$) fluorescence lifetime of the erbium ions [17]. The longer the lifetime of the ions in this level, the smaller the maximum signal output powers become. The theory and experimental figures are in the right ballpark but show a discrepancy of about 35%.

7.2.4 Comparison of Theory and Experiment

In the previous section, the experimental results of the amplifier performance in both saturated and unsaturated regimes of operation were presented. The results were qualitatively checked against two values calculated using the analytical model, P_p^{th} and P_s^{sat} . Using the analytical model, equations (3.1) to (3.9), provides results which are within about 35% of the experimental figures. The analytical solution breaks down when the amplifier is operating with input signal powers greater than 10 μ W (nearing the saturation regime). Under these conditions, a more complex numerical solution, equations (3.10) to (3.11), to the rate equations is required.

Figure 7.6 suggests that the analytical solution, rather than the numerical approach, is more closely matched to the experimental points for an input signal power of 10 μ W. In Figure 7.7, the signal gain versus the fibre output pump power experimental and theoretical points (analytical solution) are plotted for all three fibre

samples. Agreement with theory at this signal power level (30 μW) is considerably poorer than in Figure 7.6. Note the unexpected shape of the CNFT fibre curve which illustrates a premature "flattening" of the gain curve. This indicates that some mechanism for producing self-saturation of the amplifier is occurring - possibly ASE. These measurements were performed prior to the replacement of the Optics for Research isolator with the E-tek isolator. This may account for self-saturation occurring at a lower pump power than anticipated.

The best agreement with theory occurs with input signal powers less than 15 μW .

Figure 7.6. Analytical and numerical solutions versus experimental results for 100W launched signal power.

Figure 3.7. Experiment versus theory - signal gain versus output pump power. $P_{sig} = 30 \text{ uW}$.

7.2.5 Comparison of Pumping at 980 nm versus 514 nm

The initial experimental work for the erbium-doped fibre amplifier involved pumping the CNET 100ppm fibre sample directly with the Argon Ion laser (514 nm line). A maximum gain of 11 dB was achieved with an input pumping power of about 160 mW. Figure 7.8 shows a comparison of the gain versus output pump power characteristics for the same (CNET 100) fibre sample pumped at 514 nm and at 978 nm. A direct comparison between the two curves is not straightforward. The signal wavelength used for the 514 nm pumping experiment (performed nearly a year earlier) was 1553 nm. After extensive use, the performance of this laser diode deteriorated and was replaced with the 1543 nm device which was used for the 978 nm pumping experiments.

The effects of Excited State Absorption (ESA) at the 514 nm pump wavelength cause a reduction in the gain slope efficiency. The launched pump power required to produce a 10 dB gain using 514 nm (140 mW) is an order of magnitude higher than that needed at 978 nm. Note also that the output pump power required to produce transparency in the fibre is 800 μ W for the 514 nm pumping compared to 200 μ W for the 978 nm pump wavelength.

The cutoff wavelength of the CNET 100 ppm fibre is 1.04 μ m, well above the 514 nm pump wavelength. This results in multimode pump propagation through the erbium-doped fibre.

Figure 7-8. Comparison of signal gain versus pump wavelength. (Experimental values).

7.3 Experimental Results - Gain Switching

This section highlights the results for EDFA gain switching experiments performed using a Q-switched erbium-doped fibre laser as the source of switching pulses. The Q-switched fibre laser was developed by Dr. Piotr Myslinski at the National Research Council of Canada. The erbium-doped fibre amplifier is based on a 7.4 metre length of silica/germania co-dopant single mode fibre with approximately 100 ppm erbium ion doping (made by CNET, Lannion, France). The pumping source is a Titanium-Sapphire laser tuned to 978 nm. The signal source is a DFB laser diode operating at the 1.54 μm wavelength (see Figure 7.1). The amplifier parameters of signal wavelength, pump wavelength and fibre type were selected as the best available combination for achieving optimal steady state gain with a minimum of pump power.

The experimental configuration was optimized to reduce backreflections in the optical signal path. The purpose of this was to achieve the most efficient steady state gain operation prior to the introduction of the gain switching pulses.

7.3.1 Wavelength Dependence of the Switching Pulses

The wavelength of the erbium-doped fibre laser (EDFL) is tuneable over a 60 nm range. When operated in cw mode, this device acted as a tuneable signal source for investigating the amplifier gain spectrum and the preferred wavelength for the switching pulses. The EDFL was operated with an external diffraction grating to provide a tuneable, Q-switched range of 1518 to 1568 nm. The wavelength dependence of the amplifier gain was measured using a launched pump power (978 nm) of 20 mW and two signal power levels of 20 μW and 90 μW (launched into the erbium-doped fibre amplifier). Figure 7.9 shows the wavelength dependence of the amplifier gain. Gain saturation is occurring at the higher signal power as is evidenced by the flattening of the gain spectrum. The preferred wavelength for signal amplification occurs in the 1532 nm to 1534 nm range for this fibre.

The measured wavelength dependence of gain suppression using cw power from the fibre laser is shown in Figure 7.10. A cw probe signal of 200 μW power

was launched into the erbium-doped fibre and the wavelength was tuned from 1527 nm to 1565 nm. These results indicate that the preferred wavelength for the switching signal also occurs in the 1532 -1534 nm range.

Figure 7.9. Amplifier signal gain versus wavelength for the CNET fibre amplifier. Pump power = 20mW.

Figure 7.10 Amplifier gain reduction versus wavelength for CNET 100 ppm fibre. $P_{pump} = 20$ mW

7.3.2 The Gain Switching Experimental Results

Using the experimental setup of Figure 7.1 the EDFL was operated in Q-switched mode with a repetition rate of 1 kHz. The DFB laser diode was modulated with a sinusoidal input at 150MHz using the Wavetek model 3510 radio frequency signal generator. The figures shown on the following pages illustrate the effects of the switching signal on the amplified 1543 nm signal output. The maximum switching pulse energy delivered to the erbium-doped fibre input was 75nJ with a nominal 10 ns FWHM (full width half maximum).

Figures 7.11(a) through (d) show the effect of varying the switching pulse energy on the gain compression in the CNET 100 ppm fibre amplifier. For these four cases, the input pump power was fixed to 25 mW and the 1543 nm signal power was 15 μ W. The peak power per 10 ns pulse was successively reduced from the maximum of 7.5 W (75 nJ). Figure 7.11(a) shows the gain compression effect (3.8 dB) using 10 ns duration, 75 nJ switching pulses applied to the input of the EDFA. If the switching pulse energy is reduced to 20 nJ, then the gain compression effect is reduced to 1.7 dB as illustrated in Figure 7.11(c). Reducing the signal power to 1 μ W and increasing the pump power to 30 mW resulted the maximum gain compression effect of 4.3 dB using a 75 nJ pulse.

Spectral plots of the fibre laser operating in cw mode and an oscilloscope photograph of the Q-switched pulse are shown in Appendix B. The Q-switched pulse was detected at the output of the erbium-doped fibre laser by using a thick glass plate to deliver the Fresnel reflection (4%) to a high speed (small detector area) photodiode. The detected pulse shape is a slightly asymmetrical, single pulse (no sidelobes) with a polarity that appears as an inverted trace on the oscilloscope.

The experimental trends of gain compression versus switching pulse energy are shown in Figure 7.12.

Figure 7.11(a)
Gain compression vs. switching pulse energy.
75nJ switching pulse, (7.5W peak power)
 $P_p = 25\text{mW}$, $P_s = 15\text{uW}$

Figure 7.11(b)
Gain compression vs. switching pulse energy.
38nJ switching pulse, (3.8W peak power)
 $P_p = 25\text{mW}$, $P_s = 15\text{uW}$

Figure 7.11(c)
Gain compression vs. switching pulse energy.
20nJ switching pulse, (2W peak power)
 $P_p = 25\text{mW}$, $P_s = 15\text{uW}$

Figure 7.11(d)
Gain compression vs. switching pulse energy.
10nJ switching pulse, (1W peak power)
 $P_p = 25\text{mW}$, $P_s = 15\text{uW}$

Figure 7.12. Gain compression versus pulse energy - CNET fibre results with $P_{\text{pump}} = 25\text{mW}$, $P_{\text{sig}} = 10\text{uW}$.

The input pump power to the erbium-doped fibre establishes the degree of population inversion prior to the switching pulse arrival. The higher the pumping power, the higher the population inversion along the active fibre and the greater the potential dynamic range. Figures 7.13(a) through (c) show the effects of decreasing the input pump power to the amplifier. At 25 mW pump power, a gain compression of 4.3 dB was realized. By reducing the pump power to 10 mW, the gain compression dropped to 1.4 dB without changing the switching pulse energy. It should be noted that at this pumping rate the amplifier does not have time to fully recover between switching pulses (time between switching pulses is 1 ms here). The estimated 10% to 90% recovery times for six different launched pump powers are plotted in Figure 7.14. The rate equation theory suggests that the time to achieve population re-inversion is directly related to the pump rate (as an exponential term in the solution to the differential equations).

The turn-off transient response is illustrated in Figures 7.15(a) through (d) for Q-switched pulses of 10 ns duration. Figure 7.15(a) shows the transient "switching off" with the fibre amplifier operating near maximum steady state gain and the 75 nJ switching pulses tuned to 1533 nm. As the switching pulse wavelength is detuned from the optimal 1533 nm to 1527 nm, (Figure 7.15(b)) the gain switching dynamic range is reduced. Figures 7.15(c) and (d) illustrate the change in transient response incurred by reducing the switching pulse energy and lowering the pump power respectively. Note that the turn-off times do not appear to differ significantly in Figures 7.15(a) through (d).

A ringing effect is evident in Figure 7.15 as the amplifier gain is being switched. This attribute is coincident with the arrival of the Q-switched pulse. The large switching transient as seen on the oscilloscope may be due in part to spectral leakage from the 1.533 μm switching pulse into the output light spectrum (centered at 1543 nm) that is coupled into multimode fibre at the spectrum analyser's output.

Figure 7.13(a)
Gain compression vs. pumping power,
75nJ pulse energy, $P_s = 1.5\mu\text{W}$, $P_p = 25\text{mW}$

Figure 7.13(b)
Gain compression vs. pumping power,
75nJ pulse energy, $P_s = 1.5\mu\text{W}$, $P_p = 15\text{mW}$

Figure 7.13(c)
Gain compression vs. pumping power,
75nJ pulse energy, $P_s = 1.5\mu\text{W}$, $P_p = 10\text{mW}$

Figure 7.14. Recovery time versus launched pump power for CNET 100ppm fibre.

Figure 7.15(a)
Transient response during gain switching.
Switching pulse energy = 75 nJ, P_p = 25 mW
 P_s = 15 μ W

Figure 7.15(b)
Transient response during gain switching.
Switching pulse wavelength detuned to 1527 nm
pulse energy = 75 nJ, P_p = 25 mW, P_s = 15 μ W

Figure 7.15(c)
Transient response during gain switching.
Switching pulse energy = 20 nJ, P_p = 25 mW
 P_s = 15 μ W

Figure 7.15(d)
Transient response during gain switching.
Switching pulse energy = 75 nJ, P_p = 10 mW
 P_s = 15 μ W

A more precise wavelength selective fibre optic filter inserted between the monochromator output and the PIN detector module would help to negate this ringing effect. This spectral leakage argument does not fully explain why the ringing continues for 300-400 ns after the pulse has traversed the fibre. The transit time of the switching pulse through the active fibre is only 37 ns indicating that the transient effects are much longer lived than the pulse lifetime. One alternative explanation is that a small fraction of the switching pulse is reflected back through the erbium-doped fibre. Backreflections of the switching pulse in excess of -50 dB may be sufficient to cause signal gain modulation (at 1543 nm) in the amplifier.

CHAPTER 8

SUMMARY AND CONCLUSIONS

8.0 Summary

The experimental results obtained using 7.4 m of 100ppm CNET fibre may be summarized as follows: a gain compression of 4.3 dB of an amplified 1543 nm signal was achieved using a single 75nJ switching pulse (7.5W peak power, 10 ns duration) launched into an erbium-doped fibre amplifier. The amplifier operated with an input pump power of 25 mW at 978 nm and an input 1543 nm signal power of 1.5 μ W. The gain switching (turn-off) time was difficult to measure precisely due to the transient ringing effect that the Q-switching pulse created on the detected signal power at or near the 1543 nm signal wavelength. Figures B2 and B3 illustrate this ringing effect. From Figure 7.15, the gain switching of the 1543 nm signal occurs within 50 ns, however, the ringing effect persists for up to 600 μ s when the maximum switching pulse energy is used (Figure 7.15(a)). This ringing attribute was not predicted prior to performing the experiment. The unexpected transient behaviour is most likely due to a combination of the following events: (a) spectral leakage of the shorter wavelength Q-switched pulse into the detected signal, (b) backreflection of the switching pulse at the output end of the EDFA and (c) the possibility that by rapidly increasing the rate of stimulated emission (with the switching pulse) in the fibre amplifier that other signals within the amplifier bandwidth (1525 nm to 1560 nm) experience cross-talk effects that are not present when normal cw signal powers are used in the amplifier.

Theory predicted that the recovery time of the amplifier was directly related to the input pump power and to the measured level two lifetime of the erbium ions. In the experiment, we did not observe full recovery to the pre-switching amplifier gain within the 1 ms switching pulse interval. However, measurements of the estimated 10% to 90% recovery times as plotted in Figure 7.15 suggest that little improvement is achieved for launched pump powers in excess of 30 mW.

The models used herein to describe the behaviour of short duration high peak power switching pulses travelling through the fibre amplifier are based on the theory developed in the literature to describe the transient gain saturation effects on co-

propagating cw signals or long (millisecond) duration probing pulses. This theory does not adequately describe the situation where 10 ns duration (FWHM) pulses are travelling through erbium-doped fibres that are much longer than the section of fibre occupied by the pulse itself (approximately 2 m). In the case of a 7.4m fibre, the switching pulse, which is amplified as it travels along the erbium-doped fibre's length, 'works' only on a fraction of the fibre length at any particular window in time (1ns windows were used in the analysis above). Using this picture of the amplifier dynamics, the saturating pulse is only gain switching a fraction of the stored energy in the fibre amplifier over the duration of any time window. With fewer ions to depopulate from the upper laser level, the switching pulse is more effective at gain compression on this fibre segment than on the entire fibre length. An alternative representation of the amplifier dynamics is to consider a 'condensed' version of the fibre amplifier with an equivalent number of active erbium ions (giving approximately the same steady state gain) located in a piece of doped fibre that is short enough to allow the switching pulse to occupy at least the full fibre length. A 48cm length of laser grade erbium fibre produced steady state gain figures that were within 1 dB of the values measured for the 7.4 m CNET fibre. The absorption and saturation parameters for the shorter fibre were used to model the gain switching dynamic range. The results of this simulation were in good agreement with the experimental points for the 7.4m CNET fibre amplifier. These results are not conclusive as it was not possible to test the 48 cm fibre for gain switching properties.

8.1 Conclusions and Recommendations for Further Work

The work presented above serves only as an introduction to a novel use of erbium-doped fibre amplifiers that may already be installed and operating as a power booster in a communications network. The results obtained here suggest that if shorter duration pulses (less than 1 ns) with high peak power (10 W or greater) can be generated in a cost effective manner then high speed, remote, all-optical gain switching can be performed within the erbium-doped fibre.

Several issues remain to be resolved. The fibre amplifier steady state gain (14

dB maximum) was much lower than the figures in the 25 to 40 dB range that have been reported to date in the literature. This was despite extensive efforts to optimize the experimental setup. The erbium-doped fibres used in this experiment were samples of early efforts from fibre drawing facilities. This issue was partially resolved by Dr. Piotr Myslinski at the National Research Council when a 30 m length of erbium-doped fibre from the National Optics Institute (Quebec) was substituted in the experimental setup of Figure 7.1. A new 980:1550 nm coupler was purchased and the results were presented by Dr. Piotr Myslinski at the Montebello Conference on Photonic Networks [19]. Further results soon to be published in "Optics Communications", describe a steady state gain of 26 dB at 1540 nm with 30 mW launched pump power was realized. The gain switching dynamic range was greater than 25 dB and the switching off times for Q-switched pulse widths of 240 ns, 90 ns and 50 ns were 200 ns, 50 ns and 30 ns respectively. The ringing effect was still present however.

The reason for the transient ringing during and after gain switching is yet to be fully explained. This is a phenomenon which would prevent the practical application of the gain switched amplifier until it can be resolved.

An improved model for the gain switching transient analysis, as described in the discussion section, is needed before gain switching features could be incorporated into an erbium-doped fibre amplifier on a practical level.

High peak power, Q-switched pulses distributed over significant lengths of undoped single mode fibre may suffer from pulse scattering problems. Losing the integrity of the switching pulses generated at a remote site is a practical problem that would degrade the amplifier's switching performance.

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APPENDIX A

PUMP POWER CALIBRATION CURVE

The curve below represents an empirical relationship between the 980 nm optical power measured at the output of the erbium-doped fibre and the corresponding power launched into the fibre. These measurements correspond to the CNET 100ppm erbium-doped fibre sample. Measurement of the output pump power greatly simplifies the experimental process.

Appendix Figure A1. Calibration curve for launched pump power versus output pump power - CNET 100ppm fibre.

APPENDIX B

Q-SWITCHED PULSE CHARACTERISTICS

Figure B1 illustrates the temporal characteristics of the Q-Switched pulse at the output of the erbium-doped fibre laser. The optical pulse detected is the reflection from a thick glass plate which was positioned at a 45 degree angle to the direction of beam travel. Note the narrow pulse width.

Figures B2 and B3 illustrate the "ringing effect" that the Q-Switched pulse produces on the gain switched output of the erbium-doped fibre amplifier.

APPENDIX B

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Figures B2 and B3 illustrate the "ringing effect" that the Q-Switched pulse produces on the gain switched output of the erbium-doped fibre amplifier.

Figure B1. Oscilloscope trace of the Q-switched pulse.

Figure B2. Oscilloscope trace of the gain switching transient "ringing" effect.

Figure B3. Ringing effect on a shorter time base.

Figure B4. Spectral characteristics of the Q-switched fibre laser output - tuned from 1517 nm to 1530 nm.

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