CHAPTER I:

INTRODUCTION

1.1 BRIEF HISTORY OF FIBER AMPLIFIERS

Erbium-doped fiber amplifiers (EDFAs) are an enabling technology for Wavelength Division Multiplexing (WDM) optical networks. Their ability to simultaneously amplify multiple wavelengths provides significant performance and cost advantages over electronic regeneration. EDFAs are used in networks to boost transmitted power (booster amplifier), amplify signals in transit to compensate for losses sustained in the fiber (in-line amplifier), or amplify signals before a receiver (preamplifier).

Investigation into optical fiber amplification first began in the mid-1960s with the oscillation of rare-earth glass laser [1-3]. Later research into optical fiber amplifiers has centered on fiber doped with rare earth ions such as neodymium or erbium. Since the later 1980s, the rare earth ions doped fiber amplifiers have received considerable attention [4-6].

Optically pumped amplifier devices must be driven by another optical source that excites the active dopant ion from one of its absorption bands. Signal gains of greater than 30 dB has been achieved by pumping an erbium-doped fiber (EDF) at 660-nm [7]. Using a Ti^{3+}: Sapphire laser emitting at 820 nm, the gain was pushed to 37.5 dB [8]. In addition, 46.5 dB has been demonstrated for an amplifier driven near

1480 nm by four InGaAsP diodes [9]. Pumping the amplifier at 660 nm and 880 nm suffers from the problem of *excited state absorption* (ESA) [7,10-11] that lowers the overall efficiency of a device and increases heat in the gain medium [12]. The lowest ESA can be obtained from 980 nm pumping [12-13]. Pump wavelength in the 980 nm and 1480 nm wavelength absorption band are most commonly used today. Choosing a pump wavelength around 1480 nm is a good compromise between having a strong ground-state absorption in order to excite the erbium ions, and a weak gain coefficient to minimize pump stimulated emission. However, it suffers a $\geq$ 1-dB noise figure penalty over what can be obtained pumping at 980 nm [10,14]. One advantage of 980 nm pumping is that the effective gain coefficient at the pump wavelength is practically zero and pump stimulated emission does not occur.

A glass fiber amplifier, rather than a bulk glass device would seem to be the natural choice for the amplification medium to be used in fiber optic communication due to its physical compatibility with standard telecommunications fiber. In a single transverse mode fiber, there is good overlap between the pump and guiding waves. Since glass fiber cores can be made with only a few microns in diameter, the pump intensity in a fiber may well be around 100 times larger than those in a bulk device. The lasing threshold can be expected to decrease by the same factor. The high surface area-to-volume ratio, inherent of optical fiber geometry, leads to good heat dissipation. These factors explain the CW operation of fiber lasers at low pumping power levels, whereas bulk lasers with glass hosts usually only operate as a pulsed laser, and often require a supply of considerable pumping power to obtain lasing.

Due to the cylindrical geometry of fiber amplifiers, they can be coupled to standard telecommunication fiber systems with high efficiency. Another advantage of fiber geometry is that the pump spot size and the device length are now independent parameters. If the ions are reduced, the lasing efficiency can be maintained simply by increasing the fiber length by the same factor. Furthermore, the advantage of fiber directional coupler allows beam splitting to be realized in fiber form. This is very attractive since diffraction losses associated with bulk optics and micro-optics can be avoided.

The output spectral characteristic of rare-earth ion amplifiers are influenced by molecular environment in which the rare-earth ions lie. Therefore, the output spectrum can be varied by adjusting the composition of the host material and a broad fluorescence spectrum is observed when the host material is glass.

1.2 PRINCIPLES OF AMPLIFICATION MECHANISM

Similar to the laser system, an EDFA exploits the phenomenon of light amplification by stimulated emission of radiation as predicted by Albert Einstein in 1917 [15]. Einstein suggested that if a photon interacts with an excited electron, and if that photon's energy equals the difference in energy between the electron's excited state and its ground state, then the electron will relax into its ground state and emit a new photon with the same wavelength and direction as the original photon. The original photon will continue on its path undisturbed, accompanied by a clone of itself.

A pump laser, typically a semiconductor laser emitting at either 980 or 1480 nm, excites electrons in erbium atoms to a higher energy level. The 1480-nm laser excites electrons directly to a metastable level, where they reside for a period known as the spontaneous lifetime, before relaxing into the ground state. The spontaneous lifetime at the metastable level is relatively long, about 10 ms. The 980-nm laser, on the other hand, stimulates the electrons into an even higher energy level, where they remain for only a few microsecond before falling into the metastable level. The erbium atoms in EDFAs reside in a glass host, an amorphous material that preserves most of the dynamics of the erbium energy states while also spreading out the energy levels.

Amplification occurs when a signal photon enters the EDFA and stimulates an erbium electron occupying the metastable energy level. The excited electron falls back into its ground state and emits a photon with the same wavelength and direction as the signal photon. In this way, one photon becomes two. Subsequently, each of those two photons stimulates excited electrons downstream, resulting in four photons, and so forth. In this way, the EDFA amplifies the incoming signal. Key to the process is that photons with optimal wavelengths for single mode glass optical fibers have an energy that happens to equal the difference in energy between two states of an erbium atom.

1.3 RECENT DEVELOPMENT IN ERBIUM-DOPED FIBER AMPLIFIERS WITH OPTICAL FEEDBACK

The development of optical-fiber amplifiers for use in WDM systems has resulted in more stringent design requirements for amplifiers and their components. For example, the development of multi-channel WDM systems is driving the need for optical amplifiers that can automatically control the signal gain during channel adding/dropping [16-18]. This is critical due to the wavelength dependent gain of an EDFA when channels are added or dropped for network configuration. One effective approach for achieving this is to induce lasing at a particular wavelength in an EDFA system so that a constant average population inversion can be maintained regardless of the input signal levels [19-21]. As a result, the signals gain can be "clamped" within a wide range of input signal power. Such system is normally treated as a gain clamped amplifier [21-22], or a gain control amplifier [23-24]. One advantage to this approach is that it can easily be implemented with two fiber Bragg gratings [23]. Other gain control techniques include: i). dynamically control of pump power [25], and ii). compensating light injection [26].

The first EDFA with optical feedback was demonstrated in 1991 [27] in ring configuration. It was used to remotely control optical gain switching in DEFA through on and off switching of the ring lasing. In 1993 [23], a linear configuration based on two fiber Bragg grating was presented and comparison with the theory had been done. A more detailed study was done in 1995 [20] where the effects of lasing wavelength, cavity loss and the critical input power were demonstrated. An intensive study had been done from 1997 to 1999. A comprehensive theoretical analysis had been carried out [16, 20, 28-29]. In [16], gain dynamics gain control EDFA had been analyzed theoretically. In particularly, the transient power excursions and relaxation oscillations experienced by surviving channels when the number of channels passing through an EDFA changes, had been studied [17]. Experimental studies had been demonstrated to study the output power stabilization [30]. And relaxation oscillations and spectral hole burning [31]. Different gain-controlled EDFA schemes based on fiber Bragg grating [32] and Faraday rotator mirrors [33] had also been proposed. Performance improvement in terms of noise figure had been achieved by employing preamplifier fiber [34] and midway filter [35].

To our knowledge, the first EDFA with optical regenerative-feedback was presented in 1999 [22]. Without the bandpass filter, circulation of the injected signal and amplified spontaneous emission caused the system differs from the conventional EDFA system with optical feedback in terms of amplification bandwidth and flatness.

1.4 OUTLINE OF THIS THESIS

In this study, a *feedback-loop* is introduced to the EDFA system to establish a laser oscillation in a ring cavity. However, the ring configuration has several drawbacks: the optical couplers on the input and output of the amplifier increase the noise figure and reduce the output power. Additionally, the minimum gain is limited by the loss through the ring. The thesis studies in detailed the effects of employing different feedback schemes in terms of feedback directions and the case with/without the existence of wavelength selective element. In particular, the system with regenerative-feedback has been studied in detailed. Depending on feedback scheme, effects such as suppression of backward amplified spontaneous emission (ASE) by the oscillating laser, laser-induced saturation, gain-clamping, improvement of dynamic range, etc., have been observed.

Next chapter in this thesis describes basic principles of erbium-doped fiber amplifiers. The physical properties of the earth-doped optical fiber will be discussed thoroughly. In the description of the energy levels, energy transfer process together with the rate equations is presented. Various pump bands and effects of different pump band are then introduced. With the optical feedback, gain-clamping effect is established. Therefore, principles of gain-clamping is addressed. Simulation work using commercial available software: OptiAmplifier 3.0 is then carried out in comparing wth the experimental data. Different concentration quenching effects are compared in order to choose the best assumption that agrees with the experimental data.

Chapter 3 presents the basic experimental setup used for the course of study. All the components had been well characterized. Back reflection of the components and the splicing points will be shown. Based on this simple configuration, different pumping schemes, namely co-pumping and counter-pumping, were investigated and compared. Based on this comparison, the co-pumping had been chosen for the whole course of study due to the high noise figure manifested by the counter-pumping scheme. Final part of this chapter explains and compares different measurement methods, namely *Interpolation Method* and *Time-Domain Extinction Method.* It was found that discrepancy in data between both measurement methods arose from the way in determining the level of ASE.

Chapter 4 starts to study the erbium-doped fiber amplifier with counter-feedback where the input signal and oscillating laser propagates in the opposite direction. The original idea of this scheme is to eliminate the oscillating laser at the EDFA output [36]. However, the laser still existed at the output port due to the back reflection originated from the passive components in the cavity. Performance of the systems with and without the wavelength selective element was compared. Discrepancy of the data arose from the fact that the ASE was allowed to oscillate in the scheme without wavelength selective element whereas in the scheme with wavelength selective element, only the selected mode was allowed to circulate. Effect of the lasing wavelength was also studied over the entire amplification bandwidth. It was found that the choice of the lasing wavelength does not only affect the gain distribution but also affects the achievable gain value.

In Chapter 5, co-feedback scheme is demonstrated. The input signal and the oscillating laser propagate in the same direction in this scheme. The wavelength selective element was used for the whole experiment. Performance of the system was studied and compared with that of counter-feedback. Although there was a laser existing at the amplifier output port in the co-feedback scheme, noise figure was significantly improved. Backward ASE suppression by the oscillating laser in the cavity was found to be the mechanism in achieving such an improvement. Besides the variation of the lasing wavelength, effects of the cavity loss and the effects of the input signal on the oscillating laser were also investigated.

Without the wavelength selective element, the system becomes a regenerative-feedback amplifier. This scheme will be treated in Chapter 6. The regenerative amplifier systems differ from the gain-clamped amplifier systems in the sense that the input signal experiences regenerative-feedback and thus regenerative amplification through circulation in the cavity. This type of amplifier can be operated either below or above the lasing threshold [37-39]. To our knowledge, the first regenerative erbium-doped fibre amplifier had been demonstrated in 1999 [22]. In that study, it has been reported that the superiority of the system over conventional single-pass configuration is the high gain performance in the near-resonance regime for small input signals. Since the injected signal experiences regenerative-feedback, it experiences phase changes in each round-trip oscillation and results in inaccuracy in the measurement using *time-domain extinction method.* Results are compared with those obtained from the *interpolation method.* Injection locking phenomenon is investigated when the injected signal is high enough and/or close enough to the oscillation wavelength. Based on the data obtained, the potential application as a frequency stabilized laser source was proposed. The system under second external injection was also studied. We proved that gain enhancement and noise improvement under this condition was due to the effectiveness of backward ASE suppression instead of attributing the second injection as a secondary pump source as claimed in Ref. [40]. Without the optical isolator in the cavity, the system becomes a bidirectional-feedback regenerative amplifier and the studies are presented at the end of the chapter.

The thesis ends with the conclusions of the study and some suggestions for future woks.

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