NOVEL STUDIES ON
ERBIUM-DOPED FIBER AMPLIFIER

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CHAPTER 1

INTRODUCTION

1.1 Introduction on Erbium-Doped Fiber Amplifier

It is now widely accepted that optical amplifiers lie at the very heart of the revolution in the field of optical communications and have contributed enormously into the unprecedented expansion in optical communication networks currently observed worldwide. Erbium-doped fiber amplifiers (EDFAs) provide efficient optical amplification around the 1.5μm third telecommunication window. They are transparent to modulation format such as analog/digital or linear/non-linear and can be used as power amplifiers, in-line amplifiers, as well as pre-amplifiers. They show extremely low polarization sensitivity and are fully compatible with the rest of the fiber optic transmission link. They are shown to provide gain in excess of 50 dB and near-quantum-limited noise performance.

Wide-bandwidth, high-power amplifiers are needed in order to increase the amplifier span and optical-link capacity. In composite configurations, EDFAs can provide high gain over bandwidth as wide as 80 nm and output power as high as +37 dBm. However, to exploit the full potential of the EDFA, appropriate gain-flattening and channel-equalization techniques are being employed. Use of wide-bandwidth gain-flattened EDFAs can result in fully transparent, easily upgradeable optical networks through wavelength division multiplexing (WDM) and time division multiplexing (TDM) strategies.
The Periodic Table of Elements (Erbium is located in Lantanide, Group 3)

The Chemical Characteristics of Erbium Ion

Atomic number : 68
Density g/mL : 9.05
Atomic weight u : 167.26
Melting point K : 1795
Bonding radius A : 1.57
Boiling point K : 3136
Atomic radius A : 2.45

(Source: http://www.Resource-World.net)
The basic concept of rare earth doped fibers is simple: by incorporating a laser ion into the core of an optical fiber, one obtains a unique medium that exhibits both a low propagation loss and interesting laser properties. The greater these optical densities, the higher the probability of encounter between an inverted ion and a signal photon, and the higher the optical gain. In an optical fiber, the signal is confined by the fiber core along the entire length of the fiber, which is limited only by the fiber loss. The loss is so small that the interaction length can range anywhere from a few centimeters to several kilometers.

1.2 Thesis Objectives

Below are the objectives of this thesis:

1. To survey the applications of EDFA in fiber communications network,
2. To determine the amplifications concept and system design technology applied in EDFA,
3. To compare the performance of EDFA over other optical amplifiers,

Later chapter will cover the details on what Erbium Doped Fiber Amplifiers (EDFA) is. Information has been gained from various sources such as books, journals, magazines, proceedings, personal interviews and also web-sites. These sorts of information have been collected and compiled in this report to stress on the relevant fields of EDFA.

1.3 History Background of Rare-Earth Doped Fiber Amplifier

The concept of a fiber laser was demonstrated surprisingly early, shortly after the invention of the laser. The first report of a rare earth doped fiber device goes
back to 1963 when Koester and Snitzer, then with the American Optical Company, developed a flash lamp-pumped neodymium-doped fiber amplifier with a net single pass gain as large as 47 dB. This visionary work appeared in the wake of the first reports of laser emission in gases and solids, and it was in fact so revolutionary that its potential was not appreciated for many years.

The potential of single mode rare earth doped fibers was widely recognized for the first time in 1985, following the demonstration of a very low threshold fiber laser by D. N. Payne and co-workers at the University of Southampton. This new development, made possible by the advent of low-loss single-mode fibers fabricated by chemical vapour deposition processes, was spurred by a worldwide interest in high-rate optical transmission systems. These novel systems, targeted to meet the increasing demand for high-speed, high-capacity transmission lines, created a critical need for new active components not available from existing technologies, in particular compact, high-gain and low-noise in-line amplifiers, and stable, narrow-band miniature sources. The device reported by the University of Southampton in 1935 was a laser made of a 2-meter length of neodymium-doped fiber fabricated by an extension of the well-known Modified Chemical Vapour Deposition process.

No single subject has received more attention than erbium-doped fiber amplifiers (EDFAs). This amplifier, which operates in the important third communication window around 1.55 μm, exhibits a high gain, a low pump power requirement, a high saturation power, and a low noise and low inter-channel cross talk. These properties, which stem to a large extent from the long lifetime of the metastable level of erbium in silica, make EDFAs well suited for in-line optical
amplification. Preamplifiers and repeaters have been developed that exhibit excellent characteristics for both local area network and long-haul communication systems. Special fibers incorporating very low dopant concentrations have been designed for use as distributed amplifiers, in which the signal is continuously regenerated over lengths of several kilometers, an approach beneficial for some transmission systems. EDFAs now offer such a promising alternative to electronic regenerators and semiconductor amplifiers that they have emerged as the solution of choice for the next generation of several types of communication systems.

The excellent performance of EDFAs and their relevance to the communication industry are reflected in the early incorporation of EDFAs in several experimental communication systems. Some of the most striking examples include propagation of soliton pulses over distances exceeding 10,000 kilometers, amplification of up to 100 channels with a common EDFA (which is made possible by the low cross-talk of EDFAs) and transoceanic fiber communication systems using hundreds of EDFAs as repeaters.

1.4 Rare-Earth Doped Fiber Amplifier

Fiber amplifiers boost optical signal strength internally, without first converting the signal into electrical form, unlike other optical amplifiers (e.g. regenerative repeaters). They work on the stimulated emission principle that is basic to the laser (explained further in Chapter 2), and are essentially special-purpose lasers designed to amplify signals from an external source rather than to generate their own light. They amplify a weak signal beam that enters one side, to produce a stronger
signal emerging from the other side.

Semiconductor lasers are only one of several types of lasers. All work by amplifying stimulated emission, but they do so in different ways. One important family consists of glasses or crystals doped with small quantities of elements that can be excited by light from an external source, then stimulated to emit light at a longer wavelength. (Laser specialists often call these “solid-state” lasers, but in the laser world solid-state are not synonymous with semiconductor.) Traditionally, the laser material was made in a rod shape, but it can also be made in the form of a fiber, with the core doped with the light-amplifying impurity. This doped fiber can serve either as a laser or as an amplifier.

Two basic types of optical amplifiers have been developed. Optical fibers doped with elements that amplify light at certain wavelengths have become the most reliable amplifier in system application. The operating wavelength depends largely on the dopant. Semiconductor optical amplifiers are essentially semiconductor lasers with their ends coated to suppress reflections back into the chip so they can amplify light passing through them. A critical concern for the practical use of optical amplifiers is their operating wavelength, which determines their compatibility with existing atoms and how well they fit into new systems. Most interest has centered on the two windows where silica fibers have their lowest attenuation: 1300 and 1550 nm. Most efficient systems operate at 1300 nm, but the best optical amplifiers operate at 1550 nm.

A relatively new class of fiber amplifiers makes use of rare-earth ions as a gain
medium. These ions are doped inside the fiber core during the manufacturing process and pumped optically to provide the gain. Although doped fiber amplifiers were studied as early as 1964, their use became practical only in 1988, after the techniques for fabrication and characterization of low-loss doped optical fibers were perfected. The amplifier characteristics such as operating wavelength and the bandwidth are determined by the doped rather than by the silica fiber, which plays the role of a host medium. Many different rare-earth ions, such as erbium, holomium, neodymium, samarium, thulium, and ytterbium, can be used to realize fiber amplifiers operating at different wavelengths covering visible to infrared region. Erbium-doped fiber amplifiers (EDFAs) have attracted the most attention among them simply because they operate near 1.55 \( \mu \)m, the wavelength region in which the fiber loss is minimum. EDFAs with high gain and low noise were demonstrated in 1987. Their development has revolutionized the field of fiber optic communications. Many laboratory experiments have shown their potential applications in actual light wave systems. EDFAs are expected to play an important role in the design of fiber optic communication Systems.

Erbium-doped fiber amplifiers are amplifiers with cores doped with elements that can amplify light at certain wavelengths. The wavelength depends primarily on the dopant, the secondarily on the fiber depends on the fiber composition. The best-developed fiber amplifiers are types doped with the rare earth erbium, which has good gain between 1520 and 1560 nm. Another type of doped fiber, praseodymium doped fibers are the best amplifiers so far available in the 1300 nm window, but their performance is not as good as that of erbium-doped fiber.
Details depend on the type of fiber amplifier. Standard erbium-doped fiber amplifiers are pumped by semiconductor lasers that emit light at 980 or 1480 nm and amplify light between about 1520 and 1560 nm wavelength. Ytterbium can be added to the fiber to absorb light at a broad range of other wavelengths, including the 1064 nm output of neodymium-YAG lasers; the ytterbium can transfer the energy it absorbs to the erbium atoms, exciting them so the fiber amplifier can be pumped with other wavelengths. Praseodymium-doped fibers can amplify light at 1280 to 1330 nm when pumped with a laser at 1017 nm.

The performance of a fiber amplifier depends on the fiber material as well as on the dopant, because the host material affects the energy level structure of the dopant. As a result, the degree of amplification at different wavelengths can differ greatly among materials. One big advantage of erbium is that it works fine when doped into the silica glass used in standard optical fibers. Unfortunately, praseodymium does not since it works best in fluoride glasses. This means that it cannot be spliced to silica fibers and would require special endorsers in harsh environments. Erbium-doped fiber amplifiers are very good, but they are not perfect. They generate small amounts of noise by a process called amplified spontaneous emission. Some of the dopant atoms do not wait but instead spontaneously emit light in the 1550 nm range. Some of that spontaneous emission travels along the fiber and is amplified or is simply transmitted along the communication fiber to the next amplifier, which amplifies it. Most spontaneous emission is at other wavelengths, but some is at the signal wavelength. Good digital receivers can discriminate against this noise.
2.1 Basic Amplification Concept of Erbium-Doped Fiber Amplifier

Figure 2.1 shows the basic operation of one type of fiber amplifier, the erbium doped fiber amplifier (often called an EDFA) at 1550 nm. Light from an external diode laser emitting at 980 or 1480 nm excites erbium atoms in the fiber. Those specific wavelengths are needed to excite the erbium; other wavelengths do not transfer their energy to the erbium atoms. When a weak signal at 1550 nm enters the fiber, those light waves can stimulate the erbium atom to release their stored energy as additional 1550 nm light waves. The process continues as the signal makes a single pass through the fiber, building a stronger and stronger signal. Typical gains are 20 to 40 decibels, a factor of 100 to 10,000. Output powers can exceed 100 mW. These and other properties make the erbium doped fiber amplifier nearly ideal as an optical amplifier.

Fiber amplifiers work better than semiconductor laser amplifiers and have many characteristics that make them very attractive for use in fiber-optic systems. As single-mode fibers, they are easy to connect to other single-mode fibers with minimal loss. They have very low signal distortion; the pulses that come out are quite similar to those that go in. Noise and cross talk are also low, and fiber amplifiers are not sensitive to polarization of the input light. They respond very rapidly to input changes. Signals can pass through hundreds of them in series-separated by tens of kilometers.
of fiber-and still be recognizable at the end.

Figure 2.1 Amplification concept of an erbium-doped fiber amplifier

Erbium-fiber amplifiers are insensitive to signal speed and format, so they can be used with many different transmitters. They also have gain over a broad range of wavelengths, from 1530 to ~ 570 nm, so they can amplify signals from two or more sources at different wavelengths in that band-without causing overlap or cross talk. One limitation is that the gain is not uniform over the entire range, so the relative strengths of signals at different wavelengths can change after passing through a series of erbium-fiber amplifiers.
Figure 2.2 Basic configuration of an EDFA

Figure 2.2 shows the simplest block diagram of an EDFA. The erbium-doped fiber is a silica based fiber waveguide with a high concentration of erbium atoms. The presence of the erbium provides for ionic transitions leading to photon emission in the 1530-to-1570-nanometer wavelength range. Pump lasers at one or more of the absorption wavelengths (typically 1480 nm or 980 nm) provide the excitation for the emission process. The fiber length is typically around 70 meters and amplifier small-signal gains of 35 dB are common. Figure 2.2 also shows the pump laser in the counter-propagating configuration, in which the pump energy travels in the direction opposite to the signal. Amplifiers can be pumped in the co-propagating direction by placing the WDM on the input side. Many amplifiers have both co-propagating and counter-propagating pumps for redundancy.
Without an input signal, the EDFA is a source of spontaneously emitted photons. The wavelength spectrum of this spontaneous emission process is determined by the statistical distribution of the energy bands in the erbium atoms. Spontaneous emission photons are of random phase, random direction, and random states of polarization. As these spontaneous photons travel along the fiber, they can replicate through the process of stimulated emission. This process creates a second photon of the same wavelength, phase, polarization, and direction as the first. The total output spectrum originating from spontaneous emission photons of the EDFA is called the amplified spontaneous emission (ASE), which will be discussed, in later Chapter 3. With a laser signal applied at the amplifier input, many of the would-be spontaneous emission photons from both the forward and reverse directions in the fiber are stimulated by photons from the laser. This not only provides the required amplification, but also reduces the ASE.

The parametric nature of the amplification provides nonlinear gain characteristics. EDFAs are generally operated in the compression region. This is highly desirable for long haul communications link because the amplifiers provide leveling of the signal. An additional feature of EDFAs is their long time constants for the absorption and emission processes. These are typically from 100 to 500 microseconds. Since the lasers are modulated with 2.5Gbits/second data or higher, there is virtually no distortion of the information being transmitted. This attribute also proves highly desirable in Wavelength Division Multiplexing (WDM) system because it eliminates the possibility of cross-modulation products in the amplifier, which would be devastating to the system integrity.
2.2 **Principle of Light Amplification in Erbium Doped Fiber**

The principle of amplification in EDFA is by the light amplification by stimulated emission of radiation. The amplifying medium is the erbium ions that dope the core of the fiber. The notable feature of an EDFA is its ability to amplify an optical signal by as much as 30 dB by the incorporation of a short length of a short length of single-mode erbium-doped fiber. The signal amplification is a passive process with the exception of the pump laser and auxiliary monitor and control electronics.

The amplification process is based on the principle of ion stimulation of the erbium-doped fiber by the pump laser. The pump laser provides constant optical energy at a fixed wavelength to excite the erbium ions in the doped fiber to a higher energy state. A portion of this energy is then transferred to the weak incoming optical signal as the erbium photons return to their lower energy state. The direction and phase of the energy emitted from the excited erbium ions corresponds to that of the incoming optical signal, so the weak optical signal is amplified or biased along its direction of travel. The EDFA can only operate if the wavelength band of the incoming signal is at a different wavelength band from that of the pump laser. A partial 3-level energy diagram for this three-level atom is shown in Figure 2.3. The atomic population is normally in the ground state.
Figure 2.3: The erbium ion as a three level atom.

By absorbing a pump photon, electrons are elevated to a higher energy state. They decay quickly from this state to a third metastable state. This state is termed metastable because the atom will remain in this state for 10msec (a long time) before spontaneously decaying to the ground state, emitting a photon in the process. This atom, however, while in the metastable excited state, can be stimulated to emit its energy by another stimulating photon flux. As this process continues to occur, an incident beam is amplified with propagation through the erbium-doped fiber core.
2.3 System Design

The development of erbium-doped fiber amplifier (EDFA) technology has greatly changed the design methodology of fiber optic system designers. Traditional fiber optic systems used regenerative repeaters to boost the signals, as shown in Figure 2.5. When the length of the link exceeded the practical single-span passive limit, these regenerative repeaters detected the signal and retransmitted it with a laser, restoring the signal level as well as the signal fidelity. Although these regenerative repeater systems work well, they were very expensive, and once installed, the capacity of the link was fixed.
Figure 2.5: Light wave system with regenerative repeaters. Gain is provided by the electronics and each regenerative repeater is matched to the data rate of the system.

With the development of EDFAs, the link losses could be overcome by amplification as shown in Figure 2.6. Unlike the regenerative repeater systems, these ‘transparent’ amplified systems are independent of the digital bit rate. This feature allows an upgrade path to higher bit rates as solution to other limiting factors such as chromatic and polarization mode dispersion become available. EDFAs are also able to amplify multiple signals in a wavelength-division multiplexed...
Erbium Doped Fiber Amplifier

![Diagram of Light wave system with erbium-doped fiber amplifiers (EDFAs). The amplifiers boost the signal independent of the data rate and allow multiple wavelengths.](image)

Figure 2.6: Light wave system with erbium-doped fiber amplifiers (EDFAs). The amplifiers boost the signal independent of the data rate and allow multiple wavelengths.

Many point-to-point terrestrial links are being upgraded from regenerative repeaters to amplified links because of the high cost each. Many point-to-point terrestrial links are being upgraded from regenerative repeaters to amplified links because of the high cost of laying more fibers in the ground. In many cases, adding sections of dispersion-compensating fiber with each amplifier can allow upgrades in bit rate as well as the possibility of WDM. Amplified systems will soon use WDM not only for increased capacity, but also as a means for information routing, eliminating the need for expensive high-speed demultiplexing and re-multiplexing at each optical node.

To date, the major emphasis of EDFAs has been in the high-capacity portions of the network, but as the cost of EDFAs comes down, they will also be deployed in the subscriber loop. Here the emphasis will be on WDM to allow single users high-
speed access to the network. Thus, the EDFA is rapidly becoming the workhorse of the system of fibers that spans our globe.

2.4 Devices and Configurations for Fiber Amplifiers (Erbium-doped fiber amplifier)

2.4.1 Basic concept

An understanding of the operation and limitations of fiber amplifiers requires the knowledge of a diverse range of technologies. An important constituent of an overall view of this subject is the physical structure of fiber amplifiers. Doped-fiber technology, whereas in this case, erbium-doped fiber amplifier technology has made use of an impressive range of fiber-based components. These include directional couplers, fiber Febry-Perot and other resonators, fiber Bragg reflectors, and all-fiber modulators. This chapter aims to give an overview of some of the most important components and their influence on the fiber amplifier performance. All the fiber-based components discussed are made of silicate glass and operate with a single transverse mode.

At a simple level, a fiber amplifier consists of a section of doped-fiber of predetermined length and V value, which contains a suitable density of the required ion. Pump and signal waves are launched into the fiber at either the same end (co-directional pumping, Figure 2(a)) or at opposite ends (contra-directional pumping, Figure 2(b)), and the amplified signal emerges at the opposite and from which it was launched.
A number of practical issues associated with the device configurations must be addressed to ensure best performance. A dichroic beam-splitter in the form of a fiber directional coupler is required to launch both the incident pump and signal into the fiber and/or to separate the amplified signal from the unconverted pump light. The pump source is usually in the form of semi-conductor diode laser from which a beam of light that does not always exhibit circular symmetry must be efficiently launched into a circular fiber end. Fiber amplifiers may be located at the transmitter, at the receiver, or at one or more locations between the transmitter and the receiver.

However, fiber lasers (another fiber-based optical source) differ from fiber amplifiers in two important aspects, which can be seen by inspecting Figure 2.5. First,
each fiber end must be coupled to a component that provides reflection at the signal wavelength, and second, in all except when there is no signal being injected into the laser cavity. The signal grows from the amplified spontaneous emission (ASE), and the laser output power is directly proportional to the excess pump power above threshold. In the laser shown in Figure 2.5, a pair of mirrors mounted directly against the fiber ends provides resonant enhancement. End-mounted mirrors are particularly important in fiber lasers. In addition, there are a number of problems associated with end-mounted mirrors, and one particularly attractive alternative is the loop reflector.

The fiber laser shown in Figure 2.5 is suitable for demonstration of continuous wave operation in situations that do not require fine spectral control. The fiber laser consists of a large number of closely spaced longitudinal modes. Several methods, based on grating reflectors, have been used for line-narrowed and wavelength-tunable operation.

![Figure 2.5: Schematic diagram of a fiber laser](image)

Figure 2.5: Schematic diagram of a fiber laser
2.4.2 Locations for a Fiber Amplifier (EDFA) in Optical Communication Link

Rare earth doped fiber amplifiers are of considerable importance for telecommunications in both trunk and local networks. For details of how they operate and how they are used in communications systems, see chapter 5 on Applications of EDFA. The attention of this chapter is to consider one specific aspect of fiber amplifiers and that concerns their physical configurations. Besides, this chapter describes the various locations of a fiber amplifier, some of the constraints on the fiber waveguiding properties, the limitations imposed by coupling pump light into a single-mode fiber, and the possibilities that are available as a result of fused fiber coupler technology.

There are four ways in which a fiber amplifier can be incorporated into a telecommunications system. Optical amplifiers for telecommunications have traditionally been thought as falling into three categories according to where they are positioned in the fiber communications system. These categories are the power amplifier, which is located immediately after the transmitter; the in-line amplifier (also known as the optical repeater), which is at one or more predetermined locations between the transmitter and the receiver; and the preamplifier, which is located immediately prior to the receiver (refer to Figure 2.6(a-c)). In categorizing the fiber amplifier in these three ways, the EDFAs are essentially treated as a 'lumped' component, similar to a semiconductor amplifier. However, an important feature of fiber amplifiers is that there is a considerable control over both the dopant density in the fiber and the length of the fiber chosen to make the active section of fiber. Figure 2.6(d) shows the fourth configuration of fiber amplifier in which the dopant is
distributed over all, or a substantial portion of, the communications link, with a density that is two or more orders of magnitude lower than in the other three categories. Such a system is known as a 'long span' or 'distributed' fiber amplifier.

All the configurations shown in Figure 2.6 are being pumped in the same direction as the launched signal. Now, the discussion goes to the circumstances in which co-directional and contra-directional pumping configurations are appropriate. When operating a power amplifier, in nearly all situations it is necessary to use co-directional pumping. The two reasons for doing so are first, to avoid any unconverted pump light from being coupled into the transmitter laser, and second, to take advantage of the higher signal-to-noise ratio that results when pumping is co-directional.

The in-line amplifier, illustrated in Figure 2.6(b), is also shown as being co-directionally pumped. The usual argument for co-directional pumping is that noise build up is lower. Occasionally, other considerations are more important and contra-directional pumping is used instead. Optical pre-amplifiers are usually co-directionally pumped as shown in Figure 2.6(c). Co-directional pumping generates less noise but has the disadvantage that without the use of a filter and that the associated insertion loss, unconverted pump light can be coupled into the detector. In the majority of situations, a few decibels of additional loss is considered to be less serious than a lower signal-to-noise ratio, and definitely, co-directional pumping is used.

The long-span fiber amplifier as shown in Figure 2.6(d), is unlike the other three configurations in that in many situations it is operated with substantial pump
depletion. Long-span amplifiers have also been configured as an amplifying bus network in which the distributed gain compensates for the discrete losses of a series arrangement of directional couplers.

![Diagram of EDFA-based system configurations](image)

Figure 2.6: EDFA-based system configurations