Gain flattening in Erbium Doped Fiber Amplifier Based Optical Communication - A Review

N SINDHU and P. K. SHAFEENA

Abstract **- The gain flattening of Erbium-doped fiber amplifiers (EDFA) has been a research issue in recent years, with the development of high capacity wavelength division multiplexing (WDM) optical communication systems. For single channel systems, the gain variation is not a problem. However, as the number of channels increases, the transmission problem arises because a conventional EDFA has intrinsic non-uniform gain. They typically present gain peaking at about 1530 nm and the useful gain bandwidth may be reduced to less than 10 nm. The gain of EDFAs depends on a large number of device parameters such as erbium-ion concentration, amplifier length, core radius and pump power. To increase the gain-bandwidth of an amplified lightwave system several methods can be used, but equalising optical filters operating as spectrally selective loss elements appear to be the best candidates. This paper mainly focuses on different methods used for gain flattening in EDFA.**

Index Terms—Optical amplifiers, EDFA, Optical filter,

I. INTRODUCTION

The increasing demand for new telecommunications services is creating an increase in network capacity requirements. System capacity can be increased by1) deploying new optical fiber, 2) increasing transmission bit rate, 3) multiplexing more channels on to the existing fiber. Deployment of new fiber is time and cost-prohibitive because it involves equipment burial/installation, while increasing transmission bit rate is problematic due to the cost of replacing transmission equipment. Wavelength division multiplexed (WDM) technology employing erbium-doped fiber amplifiers (EDFA's), however, provides an immediate cost effective alternative for increasing network capacity. In a multichannel environment optical amplifiers should provide a flat gain spectrum, independent of input parameters; however, this is not the case with erbium-doped fiber amplifiers. Indeed, the EDFA exhibits a non-uniform and dynamic gain spectrum, so that each channel input (at different wavelengths) to the amplifier experiences a different gain [1].

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When EDFA's are cascaded, this wavelength-dependent gain spectrum produces an accumulated imbalance (between different channels) in both the received power and signal-to-noise ratio (SNR) as signals propagate along the amplifier chain. The accumulated power and SNR imbalance can limit system performance in three different ways. First, the received power imbalance can eventually exceed that allowed by receiver dynamic range. Second, accumulated SNR imbalance can result in the bit error rate (BER), at certain wavelengths, falling below required levels. Third, the minimum received signal power can fall below what is required by receiver sensitivity (for a given bit rate), due to inadequate gain compensation.

The fiber optic communication also have a number of applications in the area of telecommunication. In this paper we are focusing on optical amplifiers which are essential part in fiber optic communications. The optical amplifier of our interest in this paper will be erbium doped fiber amplifier (EDFA) which is widely preferred in the area of fiber optic communication. In this paper an analysis of the performance of optical system consisting of single or a chain of EDFAs (depending upon the system performance) for different data formats are made.

The gain spectrum of EDFA has asymmetrical twin peaks, due to a luminescent spectrum caused by fine structure of the energy levels. The gain spectrum isn't flat, so there is power deviation between amplified signals. In the long haul optical transmission systems, optical signals are transmitted by a multi-amplifier system, so differences between optical signal powers are accumulated. When dividing optical signals for various wavelengths at the receiver, other optical signals affect the signal as noise. If there are differences between optical signals transmitted by amplifiers, optical signals with low signal to noise ratio are more and more deteriorated at WDM as that are transmitted by EDFA. So as the transmission distance becomes more then the number of signal channels decrease. Therefore, it is needed that the gain of EDFA be flat in the range of signals for getting an adequate signal to noise ratio at each wavelength. One of the methods to flatten gain of EDFA is using an optical gain-flattening filter. This is the method to flatten the gain of EDFA by using a filter with reverse loss spectrum against the gain spectrum. This filter is called the optical gain-flattening filter. Section II gives an introduction to optical fiber amplifiers and explains the need for optical amplifiers in fiber optic communication and also this section gives a small introduction to the different classification of optical amplifiers and their typical applications. Section III

explains about EDFA in detail. The principle of operation, working architecture, advantages, applications and problems faced by the use of EDFA will be explained. Section IV focus on the gain flattening and different methods for flatten the gain spectrum. The paper will be concluded in section V.

II. OPTICAL AMPLIFIERS

The transmission of signal in optical fiber is affected by two fundamental limitations i.e. attenuation and dispersion. Here dispersion is as a result of signal components at different wavelength travelling at different speeds inside the optical fiber. Attenuation is as a result of the partial transparency of the glass materials constituting the optical fiber which will result in gradual reduction of amplitude of the signal propagated and hence the gain. Both attenuation and dispersion results in the reduction of precision associated with the signal transmission through optical fiber. In the case of single mode fibers the effect of dispersion is neglected but the problem associated with attenuation is a very serious issue. Transmission of signal in optical fibers mostly takes place around 1310nm and 1550 nm. The typical attenuation of silica fiber is in the order of 0.2dB/km at 1550nm. Hence after a distance of approximately 100km, the signal attenuation will be nearly 20dB which will result in considerable loss of signal.

The optical amplifiers play a key role in limiting the attenuation of optical communication network. Optical amplifiers compensate for propagation losses in long distance links and branching losses in access networks, at the same time avoiding costly two-way conversions between optical and electrical signals. By optical amplification the network performance is increased and also optical amplification results in lowering the number of repeaters and thereby simplifying the network. Optical amplifiers amplify the signals and thereby increases the SNR of the signals and also it brings the BER rate below 10^{-9} which is the desired rate in optical communication.

A. WORKING PRINCIPLE

The main working principle of Optical amplifiers are explained below. To achieve optical amplification the population of the upper energy level has to be greater than that of lower energy level ($N_2 > N_1$ where N_2, N_1 are the population densities of upper and lower state respectively), this condition is known as population inversion and is achieved by exciting electron into higher energy level by external source called pumping. Here one photon enters in the amplifier, An atom is stimulated in order to decay to the fundamental state, emitting a photon identical to the one which gave rise to it; This process is repeated and the signal gets amplified (gain). Stimulated emission occur when an incident photon with energy E= hc/λ interact with electron in the upper energy state causing it return to lower state with creation of second photon, where h is plancks constant, c is the velocity of light and λ is the wavelength of light.

B. CLASSIFICATION OF OPTICAL AMPLIFIERS

Optical amplifiers are basically classified into three based on their typical application in optical communication, they are as follows:
   a.   Semiconductor Optical amplifiers(SOA)

SOAs uses the principle of stimulated emission to amplify the optical signals. Output-level control that accepts a wide range of input power and delivers constant output power is essential for in-line optical amplifiers, optical burst and packet systems and in all optical regeneration and reshaping (2R). Semiconductor optical amplifiers SOA's can meet this demand. The reason for this is because SOA has short carrier lifetime of about several tenths to several hundreds of picoseconds compared to several hundred microseconds to several milliseconds in other optical amplifiers. Hence SOAs are generally used as pre amplifiers which is located before the receiver.

   b.   Rare earth doped optical amplifiers

Erbium doped fiber amplifiers (EDFA), Thulium doped fiber amplifiers etc comes under this classification. These types of optical amplifiers are widely used as power amplifiers which are located at the transmitter in optical communication systems. It targets the compensation of the loss of the modulation devices and the lack of power in lasers. The detailed working of these types of amplifiers will be explained in the following sections.
   c.   Raman optical amplifiers
   d.

Raman scattering occurs in any silica glass which means if we inject an optical beam (pump) in an optical fiber , then a signal passing through that fiber will be amplified if its frequency is around the shifted frequency of the pump. This is called Stock shift, which is a round 13 GHz (equivalent to about 100 nm) from the pump propagating beam frequency assuming that its wavelength is 1450 nm. That means the signal will be amplified if its wavelength is 1550 nm. Raman amplifiers are based on this phenomenon. The exciting property of RAs is reduction for chromatic dispersion and loss . This can be done by increasing the pump power. But if the number of cascaded amplifiers increases, then gain fluctuation might occur. One way to deal with this situation is to optimize the multi span amplifiers jointly rather than individually. Raman amplifiers are used as line amplifiers in optical applications which should provide high gain, high output power and low noise. The effect of Raman amplifiers is similar to the cascade of a pre amplifier and a power amplifier.

III. ERBIUM DOPED FIBER AMPLIFIER (EDFA)

A) Physical Principle of EDF Amplification

At the heart of EDFA technology is the Erbium Doped Fiber (EDF), which is a conventional Silica fiber doped with Erbium. When the Erbium is illuminated with light energy at a suitable wavelength (either 980nm or1480nm) it is excited to a long lifetime intermediate state (see Figure 1), following which it decays back to the ground state by emitting light within the 1525-1565 nm band. If light energy already exist within the 1525-1565nm band, for example due to a signal channel passing through the EDF, then this stimulates the decay process (so called stimulated emission), resulting in additional light energy. Thus, if a pump wavelength and a signal wavelength are simultaneously propagating through an EDF, energy transfer will occur via the Erbium from the

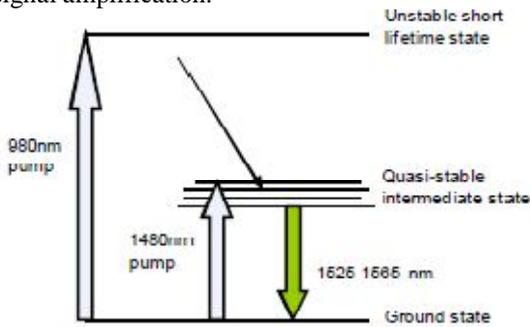pump wavelength to the signal wavelength, resulting in signal amplification.

Figure 1: The energy levels of the Erbium with the EDF.

The Erbium can be either pumped by 980nm light, in which case it pass through an unstable short lifetime state before rapidly decaying to a quasi-stable state, or by 1480nm light in which case it is directly excited to the quasi-stable state. Once in the quasi-stable state, it decays to the ground state by emitting light in the 1525-1565nm band. This decay process can be stimulated by pre-existing light, thus resulting in amplification.

B) Basic EDFA Design

In its most basic form the EDFA consist of a length of EDF (typically 10-30m), a pump laser, and a component (often referred to as a WDM) for combining the signal and pump wavelength so that they can propagate simultaneously through the EDF. In principle EDFA's can be designed such that pump energy propagates in the same direction as the signal (forward pumping), the opposite direction to the signal(backward pumping), or both direction together. The pump energy may either by 980nm pump energy,1480nm pump energy, or a combination of both. Practically, the most common EDFA configuration is the forward pumping configuration using 980nm pump energy, as shown in Figure 2. This configuration makes the most efficient use of cost effective, reliable and low power consumption 980nm semiconductor pump laser diodes, thus providing the best overall design with respect to performance and cost trade-offs. Besides the three basic components described above, Figure 2 also shows additional optical and electronic components used in a basic single stage EDFA. The signal enters the amplifier through the input port, and then passes through a tap which is used to divert a small percentage of the signal power (typically 1-2%) to an input detector.
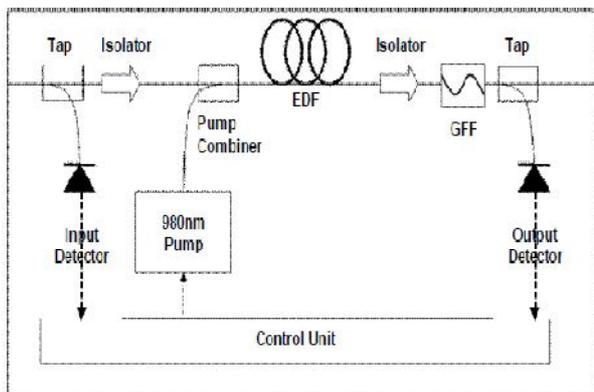

Figure 2: Diagram of a typical single stage EDFA, showing the three basic components (EDF, pump and WDM combiner), as well as additional optical and electronic components used to optimize performance and control the amplifier.

The signal then passes through an isolator, before being combined with pump energy emitted by the 980nm pump laser diode. The combined signal and pump energy propagate along the EDF, where signal amplification occurs, and then the amplified signal exits the EDF and passes through a second isolator. The purpose of the two isolators, which allow light to pass only in a single direction, is to ensure that lasing cannot take place within the EDF. Furthermore, the output isolator also acts as a filter for 980nm light propagating in the forward direction, thus stopping the 980nm light from exiting the amplifier output port. In a multi-channel WDM amplifier, a Gain Flattening Filter (GFF) is usually placed following the output isolator in order to flatten the gain spectrum, as shown in Figure 3. The attenuation spectrum of the GFF is designed to match the Gain spectrum of the EDF (operating at a given fixed gain), such that the combination of the two produces a flat gain. Following the GFF the signal passes through an output tap used to divert a small percentage of the output power (typically 1-2%) to the output detector. The output and input detectors are used to monitor the input and output power respectively, and thus provide feed-back to the control unit, which controls the amplifier by setting the pump laser current, and thus the amount of pump power injected into the EDF.
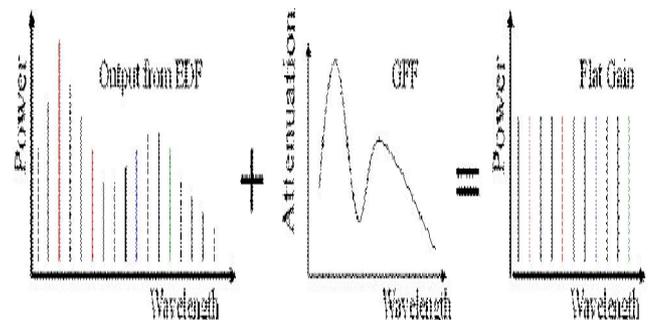

Figure 3: Use of a Gain Flattened Filter (GFF) to achieve a flat gain spectrum. The attenuation spectrum of the filter matches the gain spectrum at the output of the EDF, such that the combination of the two provides a flat gain spectrum.

IV. GAIN FLATTENING IN EDFA

Erbium doped fiber amplifiers have had a major impact in the field of light wave communications. Optical amplifiers have contributed to the growth of a fifth generation of optical communication systems. But as the demands on the networks increased techniques like Dense Wavelength Division Multiplexing (DWDM) were developed. The performance of DWDM in ultra-long haul networks improved because of the fact that amplifiers were available that could amplify the wavelengths used in the network without requiring any conversion of the optical signal to the electrical signal. The importance of EDFA's is due to their compatibility with the

fiber network, low insertion loss, polarization insensitivity, high gain levels and near quantum limited noise performance. In DWDM transmission systems and their related optical networks, one of the key technological issues is the achievement of broad and flat gain bandwidth for Erbium Doped Fiber Amplifiers (EDFA's). Gain differences occur between optical channels having large wavelength spacing (e.g. $\Delta\lambda > 1nm$). In long amplifier chains, even small spectral gain variations (e.g. $\Delta G < 0.75$ dB) can result in large differences in the received signal power, causing unacceptably large BER discrepancies between received signals. For some optical channels, complete power extinction can occur at the system output, due to insufficient gain compensation along the amplifier chain. Additionally, the ASE generated in the region of highest gain (i.e., near $\lambda = 1530$ nm) in un equalized EDFAs causes homogenous gain saturation, which affects WDM channels at longer wavelengths.

Uniformity of gain involves two aspects, namely gain equalization and gain flattening. Gain equalization means achieving identical gains for a discrete number (two or three) of optical channels. Gain flattening means achieving a spectrally uniform gain bandwidth. Gain equalization can be achieved with requiring gain flattening. For example, given an EDFA of length L, the pump power can be chosen such that the gains at two different wavelengths become exactly equal due to signal re-absorption at short wavelengths. This method though useful does not work under saturated operating conditions. Later methods to flatten the gain using hosts such as fluoro zirconate glass were investigated. It was found that the gain spectrum for these fibers though more uniform did not provide high pump efficiency. Therefore, these methods were not investigated any further.
Standard EDFA gain flattening techniques were based on six different principles: (1) Gain clamping with enhanced inhomogeneous saturation, (2) Use of passive internal/external filters, (3) Use of external active filters, (4) Cascading EDFAs with different gain spectra, (5) spatial hole burning in twin core fibers and (6) Adjustment of input signal powers [1] . Among these techniques, the only dynamic technique was the one using AOTF's as transmission filters. With the increase in network traffic, the number of WDM channels increased and so the demands on the amplifiers used in the network also increased. EDFAs were now required to provide a flat gain over a broad range of wavelengths and also cater to changes in the optical power levels due to add and drop of channels along the link. This called for dynamic gain flattening techniques like the one using AOTF's but this method had its own drawbacks like a high insertion loss and the requirement of a high RF power for the acoustic wave.

This section describes about the different methods used to flatten the gain spectrum of EDFA.

A.   OPTICAL GAIN FLATTENING FILTERS

In general, the gain profile of an EDFA can be flattened by modifying the material composition in the erbium-doped fiber (EDF) [2], or by using optical filters to compensate for the variations in the gain spectrum [3]–[8]. Various kinds of optical filters have been demonstrated for this application, including long-period fiber gratings [3], [4], fiber Bragg gratings [5], fiber acousto optic tunable filters [6], [7], Mach–Zehnder filters [8], and a split-beam Fourier filter [9]. As the method of flattening a gain spectrum of EDFA, methods using optical gain-flattening filter with reverse loss spectrum against gain spectrum are common. The principles of optical gain-flattening filter are shown in Figure . It is shown that EDFA has gain dependence on wavelength before flattening. After flattening of gain by using the optical gain-flattening filter, it is shown that dependence of EDFA on wavelength is flattened and deviation of signal power is improved. In Figure 2 sample configuration of EDFA with optical gain-flattening filter is shown. Normally optical gain-flattening filter is used in series with EDFA as shown in Figure:4, where the filter is inserted in the middle stage of EDFA between two erbium doped fibers (EDFs).
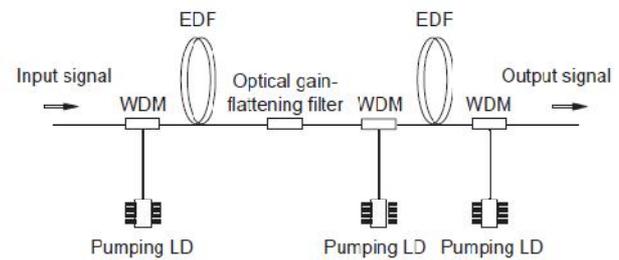

Figure :4 – gain flattening filter.

Commonly used Optical filters for gain flattening are etalon filter a dielectric filter and a long period fiber Bragg grating filter a Mach-Zehnder type filter and the split-beam Fourier filter. The above-mentioned intrinsic EDFA gain-wavelength characteristics have asymmetrical twin peaks and the loss-wavelength characteristics of the optical gain-flattening filter to compensate the EDFA gain wavelength characteristics have counterbalanced characteristics.

The EDFA gain-wavelength characteristics depend on power characteristics of pumping lasers, the concentration of erbium ion in EDF, the kind of co-doped ion and its volume, and the length of EDF as well.

The gain-flattening filter requires flexibility of design for various kinds of EDFA gain-wavelength characteristics to minimize errors between the target and design. Moreover it is required to have low polarization dependence loss (PDL) and capability of producing highly reproducible spectral profiles.

B.   GAIN FLATTENING BY USING DUAL CORE FIBER

Many of the techniques involve the use of expensive components and complicated design. The use of twin-core fiber is also an obvious choice in which both cores are identically doped with erbium. This technique has been suggested in 1993 by Laming *et al[10].* and it involves the concatenation of a length of single core EDF with a length of twin-core EDF. The purpose of the twin-core EDF here is to introduce spatial hole burning which decreases the excessive gain at certain wavelength. Wu and Chu has also suggested the use of twin-core EDF for gain flattening by launching pump power into both cores. The ratio of these powers has to

be predetermined. This technique is not practical as it is difficult to have simultaneous access of the two input cores.

The EDFA with flat gain over a wide wavelength range can simply be constructed by means of a length of dual-core fiber[11]. This fiber consists of two closely-spaced cores, one of which is doped with erbium and the other is nondoped. This amplifier has a gain variation less than 0.7 dB over the wavelength range 1525 to 1555 nm. Furthermore, the amplifier noise floor is very low, approaching 4 dB.
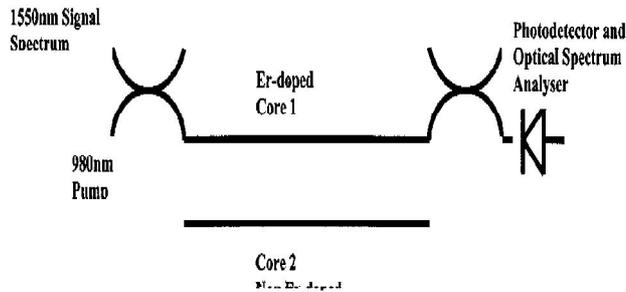

Figure :5 -Structure of dual core gain-flattened EDFA.

The structure of the amplifier is shown in Fig. . It consists of three components: 1) the input fiber coupler which combines the 1550 nm signal and the 980 nm pump power into one of the cores of the fiber; 2) the dual core fiber; and 3) the output fiber coupler which separates the amplified 1550 nm signal from the residual pump power. It is noted that only the erbium-doped core is used for connection to the two couplers. The other core (undoped core) is not used. In our experiment, an optical spectrum analyzer is connected to the output port of the second coupler for wavelength characterization of the amplifier. The input signal is continues wave at different wavelengths.

The principle of operation of this amplifier is that the coupling efficiency from core 1 to core 2 is maximum at the wavelength where the gain is maximum, i.e., at 1533 nm. In this case, the excessive signal is coupled to core 2 which is not used. On the other hand, the coupling efficiency from core 2 to core 1 at this wavelength is minimum, so that this excessive signal that has been coupled to core 2 would not return to core 1.

The reason for the nonreciprocity of the coupling efficiency is because one core is doped with erbium while the other core is nondoped. The doped core is an amplifying medium whereas the nondoped core is a passive medium

C. GAIN FLATTENING BY USING COMPOSITE AMPLIFIERS

Zervas et. al[12] proposed in their paper, a composite amplifier design where a commercially available fiber isolator is incorporated into the erbium doped segment of the EDFA. The active length now comprises of two erbium doped fiber lengths with the isolator spliced in between. The amplifier is pumped in the forward direction i.e. the pump and signal co-propagate. It was found that without the isolator, the backward ASE grows to a high value towards the input end of the amplifier, becomes comparable with the pump power and, therefore, significantly depletes the population inversion of the gain medium. In fact, at the input

end of the EDFA, the pump power is primarily used to amplify the backward traveling ASE, which considerably exceeds the signal. This causes an increase in the noise figure and also introduces non-uniformity in the gain spectrum. If the isolator was used, then the isolator cuts down the backward travelling ASE. This causes a reduction in the pump depletion at the input due to the ASE and therefore an increased gain and improved noise figure. Also, the uniformity in the gain is increased as the ASE effect is reduced.
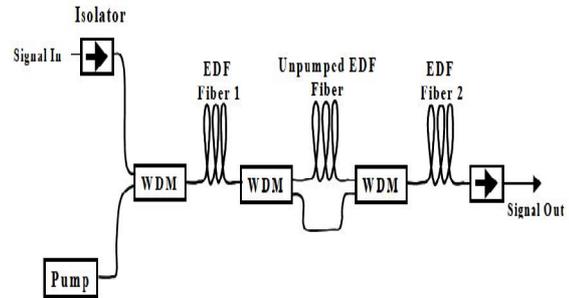

Figure :6 -A new design of a gain-flattened amplifier using an unpumped erbium doped fiber as a gain-flattening filter

It is well known that an erbium-doped fiber has a strong absorption in the wavelength range 1500 – 1600 nm, which is wavelength dependent. In this design we use this very fact to our advantage.

In this composite amplifier, the conventional amplifier is divided into three stages. The first stage consists of a standard forward pumped EDFA configuration. At the output of this amplifier, a WDM coupler removes the residual pump power and the signal is input to a length of unpumped erbium-doped fiber. This is now input to another conventional amplifier where it is amplified by the remaining pump power. The issues in this design are (1) Length of the fiber used in the unpumped section and (2) The length of the EDF fibers used in the two conventional amplifier sections. The other factors that can be investigated are the improvement in the dynamic range provided by this composite amplifier in terms of the input signal power and the pump power variations.

V. CONCLUSION

This paper investigates different methods for gain flattening in erbium doped amplifier. The gain of EDFAs depends on a large number of device parameters such as erbium-ion concentration, amplifier length, core radius and pump power. So by changing any one of these parameters we can make a flat gain spectrum.

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