Introduction to EDFA Technology

June 2009

1 Introduction

Shortly after their commercialization in the early 1990’s, Erbium Doped Fiber Amplifiers (EDFAs) became a key enabling technology for optical communication networks, and have since comprised the vast majority of all optical amplifiers deployed in the field.

The purpose of this paper is to provide an introduction to EDFA technology. The paper begins with the basics of the technology, and then goes on to discuss some of its more advanced aspects, such as transient suppression, wide band variable gain operation, and double stage designs with mid-stage access. For a general introduction to optical amplifiers, please see Finisar’s white paper “Introduction to Optical Amplifiers”.

2 EDFA Basics

2.1 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 or 1480nm) 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.](image-url)
2.2 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.

![Diagram of a typical single stage EDFA](image)

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.

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. 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. The control unit also provides external communication, for example via an RS232 interface.

![Use of a Gain Flattened Filter (GFF) to achieve a flat gain spectrum](image)

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.
2.3 EDFA Control

An EDFA is typically operated in one of two operating modes: Automatic Gain Control (AGC), or Automatic Power Control (APC). In the AGC mode the amplifier gain is kept constant, whereas in APC mode the amplifier output power is kept constant. While APC mode is used in some single channel applications, AGC mode is far more common, and is almost always used in multi-channel WDM applications. Figure 4 shows a schematic diagram of AGC in an EDFA. Information from the input and output detectors is used to calculate the actual gain, which is then compared to the required gain. Based on this comparison the pump current is then adjusted to change the actual gain towards the required gain. This is a classical feedback control loop which can be implemented using analogue or digital circuitry. The response time of the control loop is dictated by the response of the EDF to changes in the pump power, which may be quite long (1ms and longer) due to the long lifetime of the Erbium ions’ quasi-stable state.

If there are sudden changes in input power, for example due to channel add/drop in reconfigurable WDM systems, then during the time it takes for the feedback loop to respond, large gain transients of up to a few dB can develop. Advanced EDFA designs include additional circuitry to suppress such transients, which will be discussed in the next section.

![Figure 4: Schematic diagram of Automatic Gain Control (AGC) in an EDFA. The control loop consists of a Feed Back (FB) loop for maintaining stable gain, as well as a Feed-Forward (FF) loop for fast transient suppression.](image)

3 Advanced EDFA Designs

In this section we discuss some of the more advanced aspects of EDFA design. We begin by considering fast transient suppression, then go on to discuss WDM Variable Gain EDFA’s, and conclude with double stage EDFA’s with mid-stage access.
3.1 Fast transient suppression

As noted previously, the AGC Feed-Back loop of an EDFA has an inherently slow response time, of the order of 1ms or more. Thus, to suppress gain transients that could develop during this slow response time due to sharp changes in input power, it is necessary also to use a feed-forward control loop. As the input to this control loop is only the signal from the input detector, it immediately detects a change in input power, and adjusts the pump power accordingly even before the transient begins to develop. This adjustment is performed using an approximate pre-defined relationship between the pump current and input power for a given required gain. Thus, the feed-forward control supplies a rapid, relatively coarse initial response, while the feed-back control provides a slower and finer response. The combination of well designed feed-back and feed-forward control loops can provide stable gain under all conditions, with a maximum overshoot of up to 1dB during 100μs, even in the case of a sharp increase or decrease of input power, as shown in Figure 5.

![Figure 5: Output power of a single channel (blue curves) in response to a change in the total input power (magenta curves). The maximum transient deviation of the output signal is <1dB, while the setting time before stable operating is resumed is <100μs. Left – Transient response in the case of a sharp decrease in input power (e.g. channel drop). Right - Transient response in the case of a sharp increase in input power (e.g. channel add).](image)

3.2 Variable Gain EDFA

In order to support different span lengths between amplifiers in a transmission link (typically in the range 60-120 km), as well as to provide for aging of the link (which may lead to increased link loss over time), it is desirable for an amplifier to support as large as possible dynamic gain range, i.e. to allow the gain to be dynamically configured over a wide range. For a single channel amplifier this is can easily be achieved, and most single stage amplifiers support a large dynamic gain range. For WDM multi-channel amplifiers the situation is much more complicated due to the need to maintain a flat gain for all gain values. Thus, most low-end WDM amplifiers are designed as fixed gain amplifiers, i.e. they provide flat gain for only a given pre-designed gain value. To support different gain values, system designers may either use a number of fixed gain amplifiers with different pre-set gain values, or place a Variable Optical Attenuator (VOA) before the fixed gain amplifier. The former solution requires different part numbers for the various amplifiers, and therefore complicates operational issues such as inventory control and sparing, while the latter solution leads to a large deterioration in OSNR, and therefore is not suitable for links longer than 200-300 km. These drawbacks can be addressed with a variable gain WDM amplifier.

A variable gain EDFA is typically designed to have flat gain at the top of the required gain range, using an appropriate GFF, while a VOA is used to attenuate all the channels uniformly in order to achieve a range of gain values. If the VOA is placed at the amplifier input, then a large deterioration in NF will occur. On the other hand, if the VOA is placed at the amplifier output then high pump power will be required, thus increasing the cost of the amplifier. Therefore it is necessary to place the VOA between two amplification sub-stages, as shown in Figure 6. The two gain stages are typically pumped by a single pump where the pump power is split between the stages, and the control loop controls the gain of the entire amplifier (both gain sub-stages and VOA).
By carefully designing the EDF length and designated pump power for each sub-stage, it is possible to achieve very good NF performance over a range of gain values, with only a moderate increase in total pump power compared to a fixed gain EDFA. The typical NF performance of a variable gain EDFA is also shown in Figure 6 as compared to a comparable fixed gain EDFA with a VOA placed beforehand. As can be seen, the NF increases only slightly at the low gain range, representing a significant performance advantage compared to the alternative fixed gain EDFA with a VOA placed before.

![Figure 6: Left: Basic design of a WDM Variable Gain EDFA, where the VOA is placed between two gain sub-stages in order to improve NF. Right: Resulting improvement of NF compared to the case of a fixed gain EDFA with a VOA placed before. As can be seen, the variable gain EDFA provides much better NF performance over the entire gain range.](image)

### 3.3 Dual Stage EDFA with Mid-stage Access

Besides optical amplifiers, modern optical networks also require other components to be place along the link, such as Dispersion Compensating Modules (DCM’s) used to correct signal distortion due to Chromatic Dispersion of the transmission fiber. Since the attenuation of DCM’s can be quite large, in the range of 5-10 dB, additional amplification is needed to accommodate them. In order to minimize the OSNR and cost impact of this addition amplification, it is beneficial to place the DCF between two amplifiers.

Dual stage amplifiers are basically two amplifiers in one package, where there is access for an optical component such as a DCM to be placed between them, as is illustrated in Figure 7. Most often the first amplifier (the pre-amplifier) is variable gain, and the second amplifier (the booster) is fixed gain, such that the amplifier as a whole provides variable gain operation. The control of both amplifiers is combined – in other words the user sets the required net gain of the entire combination (including the DCF), and the control units sets the gain of each of the two amplifier in order to achieve the net gain.

The amplifiers are designed a-priori to take into account the DCM loss. For example, the dynamic range of the input detectors of both amplifiers is set accordingly, and the optical performance, such as NF, is specified already taking the DCM loss into account. Since the DCM is often implemented using special Dispersion Compensating Fiber (DCF), there can be a large optical delay between the first and the second stage of the amplifier. For this reason transient suppression of each amplifier needs to be performed separately, and consequently each amplifier has its own pump and own local control mechanism (in addition to the overall control used to set the net gain).

![Figure 7: The basic scheme for a dual stage EDFA with mid stage access. The two amplifiers are packaged in the same module and are controlled together with the mid-stage device (e.g. DCM) as a single unit. Additionally, each amplifier also has its own local control loops.](image)
4 Conclusion

Of the various technologies available for optical amplifiers, EDFA technology is by far the most advanced, and consequently the vast majority of optical amplifiers deployed to date are based on this technology.

Today it is possible to build broadband WDM EDFA’s which provide flat gain over a large dynamic gain range, low noise, high saturation output power, and stable operation with excellent transient suppression. These features are provided in small modules measuring <100x100 mm, and with power consumption of just a few Watts. This combination of good reliable performance, together with relatively low cost, allows EDFAs to address most application and functions in modern optical networks.

For more information please contact sales@finisar.com.