Finisar

White Paper

Introduction to Optical Amplifiers

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1 Introduction

Optical amplifiers are a key enabling technology for optical communication networks. Together with wavelength-division multiplexing (WDM) technology, which allows the transmission of multiple channels over the same fiber, optical amplifiers have made it possible to transmit many terabits of data over distances from a few hundred kilometers and up to transoceanic distances, providing the data capacity required for current and future communication networks.

The purpose of this paper is to provide an overview of optical amplifiers. For a more detailed discussion on the implementation of optical amplifiers using Erbium doped fiber amplifier (EDFA) technology see Finisar's white paper "Introduction to EDFA technology".

2 What Are Optical Amplifiers?

A basic optical communication link comprises a transmitter and receiver, with an optical fiber cable connecting them. Although signals propagating in optical fiber suffer far less attenuation than in other mediums, such as copper, there is still a limit of about 100 km on the distance the signals can travel before becoming too noisy to be detected.

Before the commercialization of optical amplifiers, it was necessary to electronically regenerate the optical signals every 80-100 km in order to achieve transmission over long distances. This meant receiving the optical signal, cleaning and amplifying it electronically, and then retransmitting it over the next segment of the communication link.

While this can be feasible when transmitting a single low capacity optical channel, it quickly becomes unfeasible when transmitting tens of high capacity WDM channels, resulting in a highly expensive, power-hungry and bulky regenerator station, as shown in Figure 1a. Furthermore, the regeneration hardware depends on the number of channels, as well as the bit-rate, protocol, and modulation format of each individual channel, so that any upgrade to the link would automatically require upgrades to the regenerator stations.

In contrast, an ideal optical amplifier is designed to directly amplifier any input optical signal, without needing to transform it first to an electronic signal. It can amplify all WDM channels together, and is generally transparent to the number of channels, their bit-rate, protocol, and modulation format. Thus, a single optical amplifier can replace all the multiple components required for an electronic regeneration station, as shown in Figure 1b. Furthermore, the transparency of the optical amplifier means that the link can be upgraded without the need to replace the amplifier.

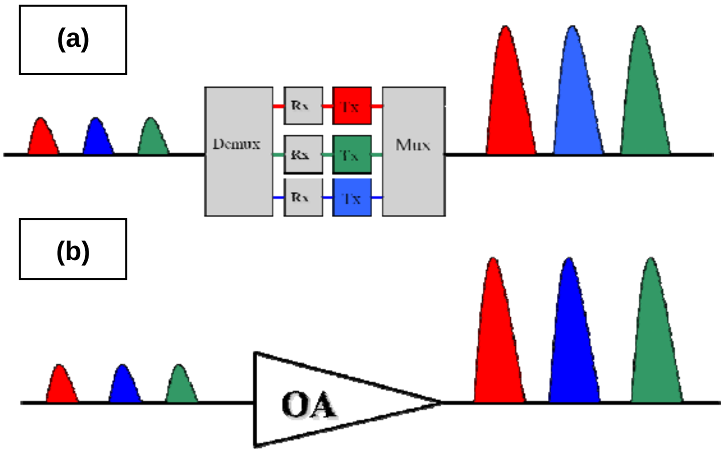

Figure 1: *(a) block diagram of an electronic signal regeneration station, in which channels are separated, detected, amplified and cleaned electronically, retransmitted, and then recombined, versus (b) an optical amplifier where all channels are optically and transparently amplified together.*

3 Properties of Optical Amplifiers

3.1 Gain, Input Power and Output Power

The most basic property of an optical amplifier is its operating gain, which is the amount by which the input optical signal is amplified. The gain is typically measured in dB, and is in the range of 10-30 dB. A gain of 10 dB means the input optical signal is amplified by a factor of 10, while a gain of 30 dB means the input optical signal is amplified by a factor of 1000.

Some amplifiers are designed to operate at a single pre-set gain, while others can support a range of operating gain values, which allows the amplifier to address different applications and functions. Besides gain, an amplifier is also characterized by the range of supported input and output optical powers. In particular, a key specification of the amplifier is the maximum output power which can be supported, also referred to as saturated output power. This parameter is often critical in determining the amplifiers' cost.

Broadly speaking, optical amplifiers can be classified as either single channel or multi-channel (WDM). As their name implies single channel amplifiers are designed to amplify only a single optical channel, which can be located anywhere within a specified band, such as the C-band (1528-1564 nm). Single channel amplifiers can usually operate over a wide range of operating gains, and require relatively low levels of output power. The left side of Fig. 2 shows an example spectrum of a single channel amplifier.

In contrast, WDM amplifiers are designed to operate when any number of channels (within a specified band) are input to the amplifier. An important property of WDM amplifiers is the gain flatness, which is the variation of the gain for different channels, as illustrated by the right side of Figure 2. If the gain is not flat, different WDM channels will have different gain, which can accumulate along a chain of amplifiers leading to a large mismatch between channels at the end of the link.

In order to maintain flat gain, most low-end WDM amplifiers only support a single operating gain, or a relatively narrow gain range. WDM amplifiers providing both flat gain and a large operating gain range require a more complex design (see Finisar's white paper "Introduction to EDFA technology" for further details).

In addition to gain flatness, WDM amplifiers are required to provide a large dynamic input power range, to support different input conditions where any number of channels from 1 to 80 may be present. Additionally, in order to support the maximum amount of channels, WDM amplifiers require a relatively high saturated output power, typically in the range 17-23 dBm.

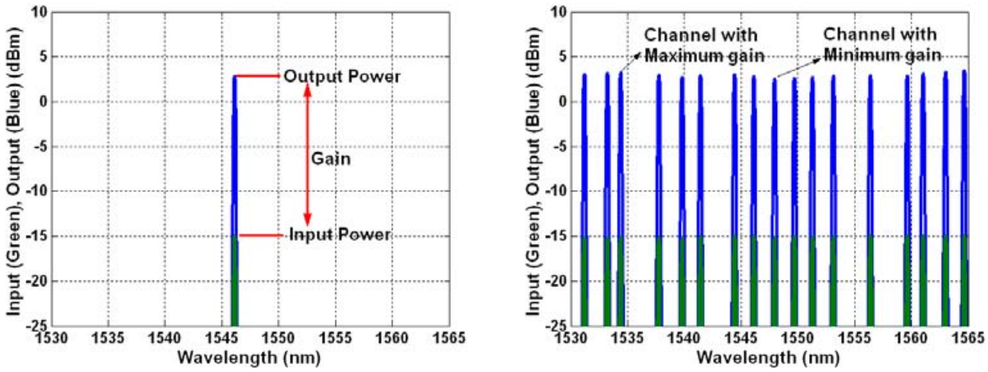

Figure 2: Example i*nput (Green) and output (Blue) spectrums of a single channel amplifier (left) and a WDM multi-channel amplifier (right)*

3.2 Noise

All amplifiers, including optical amplifiers, introduce noise during the amplification process, so that the output signal is always noisier than the input signal. The noise performance of an optical amplifier is characterized by its noise figure (NF), which is defined as the ratio of the signal-to-noise ratio (SNR) at the amplifier output to an ideal SNR at the input. Since there is a one-to-one relationship between the NF of an amplifier and the performance of an optical link, it is essential that the NF should be kept as low as possible. The NF depends on the technology used for the amplifier, as well as the gain, with higher gain amplifier usually having lower NF.

3.3 Dynamic Properties

Another important property of optical amplifiers is their response to dynamic changes in input power. Ideally, the gain of an amplifier should not change at all when the input power changes, however, this is not possible when the amplifier operates at or near the maximum output power. In this case it is essential that the amplifier respond slowly enough so that its gain is determined only by the average input power, and is not affected by fast changes (for example, due to data modulation).

Amplifiers that respond too fast may be noisy, and do not handle multiple channels well. This is because when there are multiple channels the gain of one channel may change according to whether the other channels have a 0 or 1, an affect known as cross-gain modulation. Even if there is a single high power channel near saturation, then distortion could occur since the 0’s will experience different gain than the 1’s.

On the other hand, even if the amplifier has a slow response, it should also be able to handle sudden long term changes in the average input power. Such sudden changes can occur for example due to channel add/drop (especially in dynamically reconfigurable networks) or protection and restoration switching. In such cases the amplifier may experience large temporary gain variations (known as “transients”) that need to be suppressed as much as possible by the amplifier control mechanism. In the absence of suitable transient suppression, the gain transients could accumulate over a chain of amplifier, leading to large power and/or SNR surges at the receiver.

3.4 The Ideal Optical Amplifier

To summarize, the ideal optical amplifier should support multi-channel operation over as wide as possible a wavelength band, provide flat gain over a large dynamic gain range, have a high saturated output power, low noise, and effective transient suppression. These properties should be achieved while maintaining low power consumption, small size, and low cost. As described in more detail in Finisar’s white paper “Introduction to EDFA technology”, modern EDFA technology has advanced to the point where many of these features can be provided simultaneously.

4 Functions of Optical Amplifiers

Broadly speaking, optical amplifiers may be used within an optical network as boosters, line amplifiers, or pre-amplifiers, as shown in Figure 3, with each one of these functions requiring slightly different specifications.

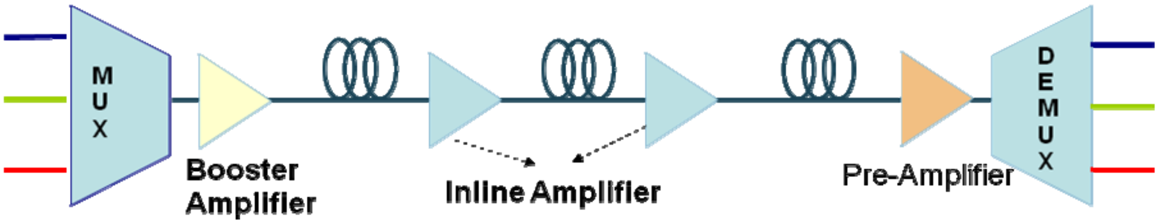

Figure 3: *A simple WDM optical network, where a number of transmitted channels are combined using a WDM multiplexer (MUX), amplified using a booster amplifier before being launched into the transmission fiber, re-amplified every 80-120 km's using in-line amplifiers, and finally pre-amplified before being demultiplexed and received*

A booster amplifier is used to amplify the signal channels exiting the transmitter to the level required for launching into the fiber link. In most applications this level is in the range of 0-5 dBm per channel, however, it can be higher for more demanding applications. A booster is not always required in single channel links, but is essential in a WDM link where the multiplexer attenuates the signal channels. A booster amplifier typically has low gain (in the range of 5-15 dB) and high output power, typically about 20dBm for a 40 channel WDM system. The NF of a booster amplifier is not usually a critical parameter.

At the other end of a link a pre-amplifier may be required to amplify the optical signal to the level where it can be detected over and above the thermal noise of the receiver. A pre-amplifier should provide high gain, often in the range of 30 dB, and have a low NF in the range of 4-5.5 dB, in order to assure error-free detection of the signal channels. The output power of the pre-amplifier need not be very high.

For links up to about 150 km, a booster and/or pre-amplifier are usually sufficient to ensure error-free transmission. However, for links above 150 km the performance deteriorates to such an extent that the signal becomes undetectable. To avoid this, in-line amplifiers are placed every 80-100 km to ensure that the optical signal level remains above the noise floor. In-line amplifiers typically require moderate gain in the range of 15-25 dB, and NF in the range of 5-7 dB. Output power requirements are similar to those of booster amplifiers.

While in the early days of optical amplifiers different amplifier models had to be specifically tailored for each of the above functions, today the technology has advanced so that a single well designed amplifier model can perform many of the functions for typical applications. However, there still remain challenging applications which require specially designed amplifiers, such as very high output power boosters, or ultra-low noise pre-amplifiers.

5 Main Amplifier Technologies in Use Today

The main optical amplifier technologies in use today are EDFAs, Raman amplification, and semiconductor optical amplifiers (SOAs). EDFAs by far outnumber amplifiers based on the other two technologies, and are discussed extensively in the paper titled “Introduction to EDFA technology”. Here we briefly discuss Raman amplification and SOAs, and note some special applications where they may provide advantages over EDFA technology.

5.1 Raman Amplification

In a Raman amplifier, the signal is amplified due to stimulated Raman scattering (SRS). Raman scattering is a process in which light is scattered by molecules from a lower wavelength to a higher wavelength. When sufficiently high pump power is present at a lower wavelength, stimulated scattering can occur in which a signal with a higher wavelength is amplified by Raman scattering from the pump light. SRS is a nonlinear interaction between the signal (higher wavelength; e.g. 1550 nm) and the pump (lower wavelength; e.g. 1450 nm) and can take place within any optical fiber. In most fibers however the efficiency of the SRS process is low, meaning that high pump power (typically over 1 W) is required to obtain useful signal gain. Thus, in most cases Raman amplifiers cannot compete effectively with EDFAs.

On the other hand, Raman amplification provides two unique advantages over other amplification technologies. The first is that the amplification wavelength band of the Raman amplifier can be tailored by changing the pump wavelengths, and thus amplification can be achieved at wavelengths not supported by competing technologies. A second, more important, advantage is that amplification can be achieved within the transmission fiber itself, enabling what is known as distributed Raman amplification (DRA).

In this process high pump power is launched into the transmission fiber (usually from the output end of the fiber) in order to provide amplification for the signal as it travels along the fiber. Since gain occurs along the transmission fiber, DRA prevents the signal from being attenuated to very low powers, as shown in Figure 4, improving the SNR of the signal.

Raman amplifiers are most often used together with EDFAs to provide ultra-low NF combined amplifiers, which are useful in applications such as long links with no inline amplifiers, ultra-long links spanning thousands of kilometers, or very high bit-rate (40/100 Gb/s) links. For more details about DRA and its applications, see Finisar’s white paper “Applications for Distributed Raman Amplification”.

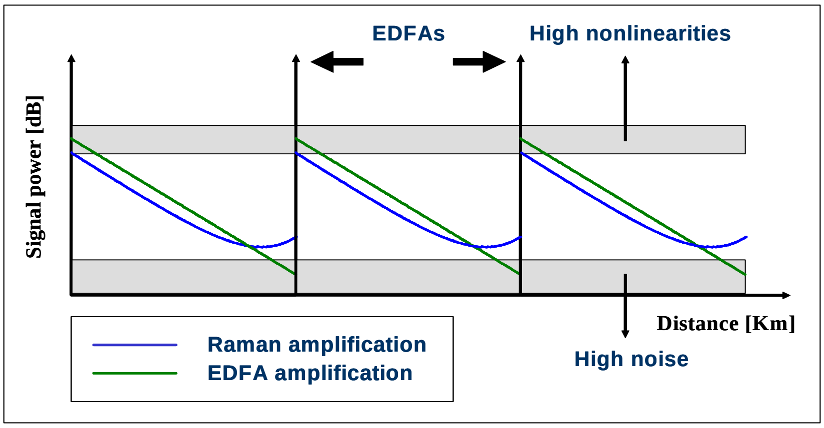

Figure 4: *The difference between DRA, and “discrete” or “lumped” amplifiers such as EDFAs. In discrete amplifiers the amplification takes place at a single point at the end of the link. In DRA the amplification takes place along the transmission fiber, avoiding low power at the end of the link, and/or allowing lower power to be launched at the beginning of the link.*

5.2 Semiconductor Optical Amplifiers (SOAs)

SOAs are amplifiers which use a semiconductor to provide the gain medium. They operate in a similar manner to standard semiconductor lasers (without optical feedback which causes lasing), and are packaged in small semiconductor “butterfly” packages. Unlike other optical amplifiers SOAs are pumped electronically (i.e. directly via an applied current), and a separate pump laser is not required.

Despite their small size and potentially low cost due to mass production, SOAs suffer from a number of drawbacks which make them unsuitable for most applications. In particular, they provide relatively low gain (<15 dB), have a low saturated output power (<13 dBm), and relatively high NF. Furthermore, the fast response time of SOAs means that when operating near the saturation level they suffer from signal distortion for single channel operation, and noise due to cross-gain modulation for multi-channel WDM operation. These drawbacks make the SOAs largely unsuitable for multichannel WDM applications. However, they can suit some applications such as single channel booster amplifiers which don't require high gain or high output power.

6 Conclusion

Optical amplifiers perform a critical function in modern optical networks, enabling the transmission of many terabits of data over long distances of up to thousands of kilometers.

In this paper we have discussed the need for optical amplifiers in optical networks, their important properties and functions, and the various technologies used to implement optical amplifiers.

For a dedicated discussion of EDFA technology, see Finisar's white paper "Introduction to EDFA technology".

For more details regarding Raman amplification, see Finisar's white paper "Applications for Distributed Raman Amplification".

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