Erbium Doped Fiber Amplifiers - Practical Aspects in DWDM Networks

Introduction

Erbium doped fiber amplifiers (EDFAs) are able to provide optical amplification within the 1550 nm transmission window, thereby allowing all-optical transmission over distances up to many hundreds of kilometers without the need for optical-electrical-optical (OEO) regeneration. Because EDFAs can amplify many dense wavelength division multiplexed (DWDM) signals simultaneously, the network cost savings can be significant. EDFAs are a mature and reliable technology that have been deployed in optical systems for many years.

Figure 1 shows the basic structure of an EDFA, consisting of a length of Erbium doped fiber, a pump laser, wavelength couplers, input and output power detectors, and control electronics.

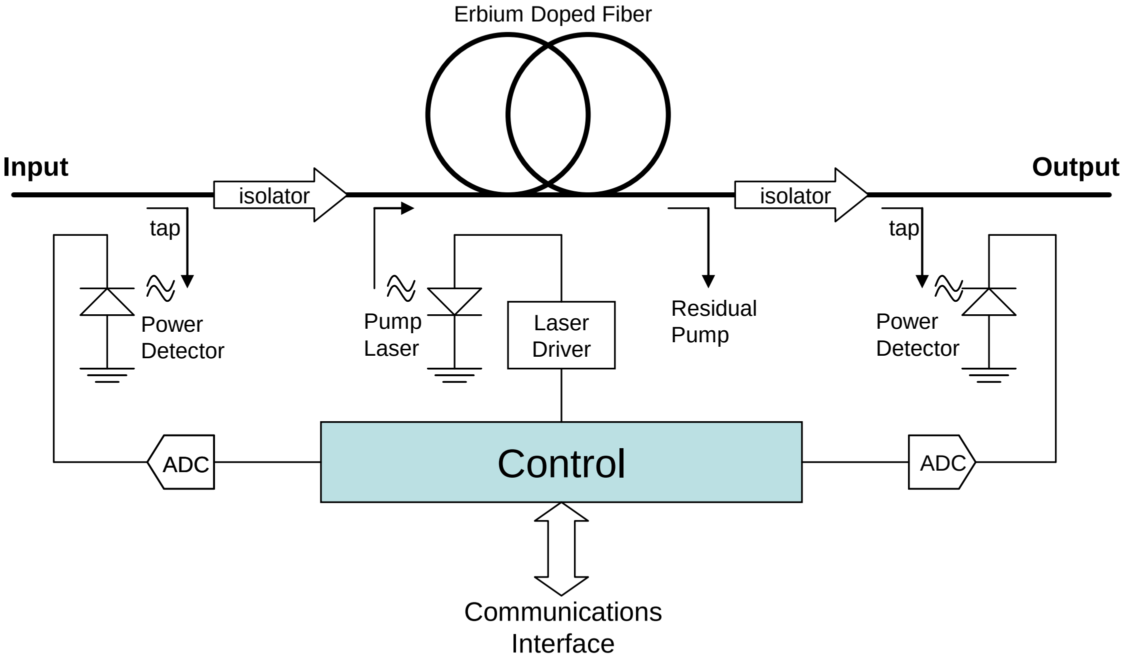

Figure 1 EDFA structure

The pump wavelength, usually at 980 nm or sometimes 1480 nm, is coupled to the Erbium doped fiber at the input, while any residual pump power is removed at the EDFA output by a second coupler. Energy from the pump is absorbed by Erbium ions, causing them to transition to an excited, higher energy state. The signal wavelength then stimulates the excited Erbium ions, causing them to transition back to a lower energy state. The resulting photon energy released from this stimulated emission is at the same wavelength and coherent with the signal, thereby providing optical amplification of the signal.

In addition to stimulated emission, some excited Erbium ions may undergo a spontaneous transition to a lower energy state, where the resulting spontaneously generated photon itself can cause stimulated emission from other Erbium ions. This amplified spontaneous emission (ASE) is a source of optical noise that must be effectively managed and kept within acceptable limits in any network using EDFAs.

EDFAs also usually contain an isolator at the input and output to prevent emissions in the backward direction, and to block any upstream back reflection from entering the amplifier that would otherwise cause additional interference.

Operating Modes and Transient Control

Commercial EDFAs are usually capable of operating in one of three modes – 1) constant gain, 2) constant power, and 3) constant pump.

When in constant pump mode the drive current to the pump is kept constant, resulting in a constant pump power. In this mode the gain of the EDFA is a function of pump current and input signal power, as shown in Figure 2. As the input signal power is increased the average number of excited Erbium ions is depleted, leading to reduced, saturated gain of the amplifier.

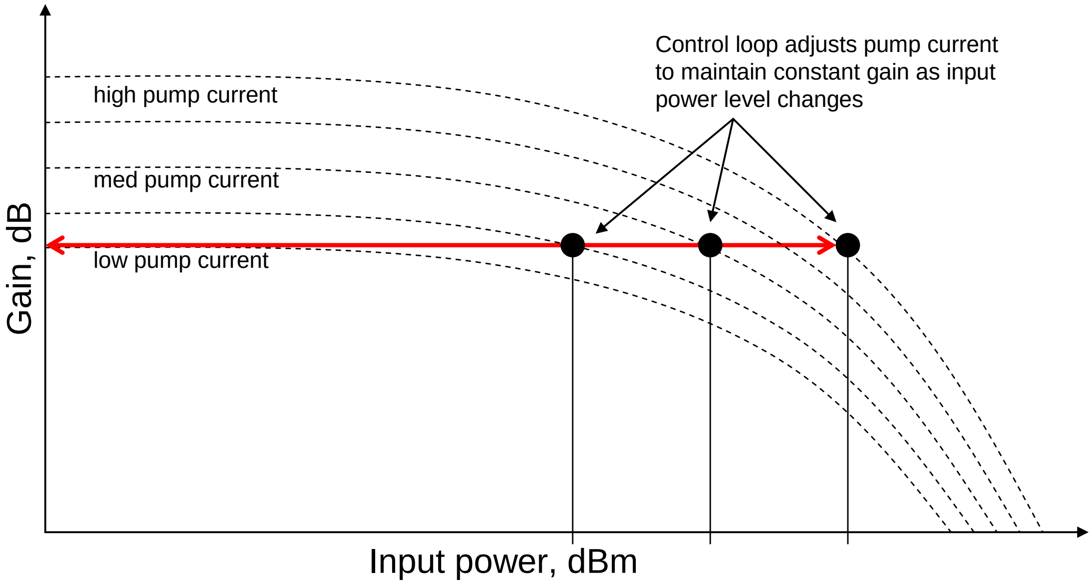

Figure 2 EDFA gain versus input signal power for different pump currents

When in constant gain mode, the control electronics dynamically adjust the pump current such that the gain of the EDFA is maintained at a constant setpoint, as shown in Figure 2. The speed of this control loop is usually very fast with a response time in the range 50 to 500 μs. Hence, if there is a sudden change in the input signal power level, the gain control loop offers fast transient control that maintains the gain at a constant setpoint. This fast transient response is especially important in DWDM networks because the input power level to EDFAs varies due to the adding and removing of wavelengths, or during certain fault conditions.

When in constant gain mode, the gain is maintained according to the *total* power read by the input and output power detectors, as these detectors are usually only able to measure total integrated power for all wavelengths.

In constant power mode, the control loop maintains the total output power at a constant target. Hence, as the input power level changes, the pump current is adjusted to keep the output power at a constant level.

For DWDM systems it is usually a requirement to add and/or remove wavelengths without effecting power levels of other wavelengths. For this reason EDFAs are usually not operated in constant power mode because the desired total power target would have to constantly be adjusted as wavelengths are added and removed. Moreover, any fault condition that causes the power level on some wavelengths to suddenly change would affect the power level of other wavelengths because the EDFA controls the *total* output power to a given target. For this reason, DWDM networks usually operate EDFAs in constant gain mode.

Gain Flattened EDFAs

The intrinsic spectral gain profile of Erbium doped fiber is not flat, as shown in Figure 3.

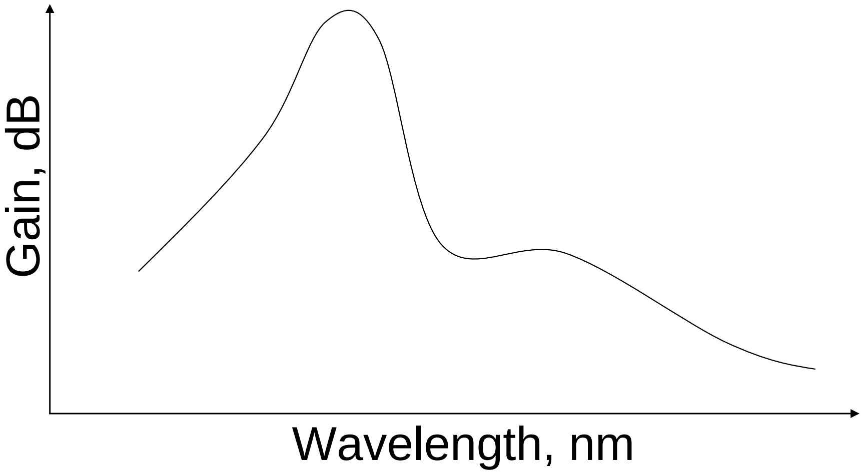

Figure 3 Intrinsic spectral gain profile for an EDFA

For the gain profile shown in Figure 3 it is possible to maintain the gain of a single wavelength at a desired setpoint. When multiple wavelengths are present the gain control loop would maintain the average gain, based on total input and output power readings, to a desired setpoint. However, the gain of individual wavelengths would differ, with some wavelengths having a gain higher than the setpoint, and some lower than the setpoint.

A non-flat spectral gain profile is undesirable in DWDM networks, especially when cascading EDFAs, as it complicates power management and leads to significant variability in performance and power levels among DWDM signals.

To address the issues with non-flat gain, a gain flattening filter (GFF) can be introduced to equalize the non-flat gain characteristic of Erbium doped fiber. Such filters have a loss characteristic that is inverted with respect to the intrinsic gain profile of the Erbium doped fiber, such that the cascaded response is spectrally flat, as shown in Figure 4.

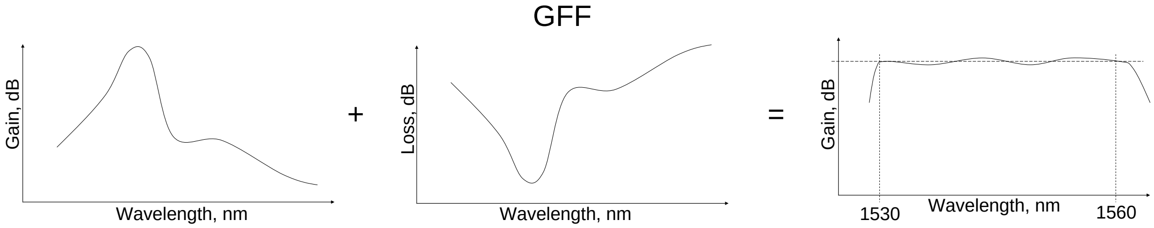

Figure 4 Gain flattening filter to achieve flat gain across the C band

Gain flattened EDFAs with a typical flatness of ±0.5 dB across the C band are commercially available. Because the gain is the same for all wavelengths, a gain control loop that operates on total input and output power readings is able to maintain the gain of each wavelength at a constant and common setpoint, independent of the number of wavelengths present and/or the spectral distribution of power at the EDFA input.

Design Flat Gain and Dynamic Gain Tilt

A gain flattened EDFA is able to achieve essentially flat gain for all wavelengths across the C band. However, for a basic single-stage device this flat gain is achieved at one gain setting only, called the design flat gain (DFG), determined at design time for the EDFA. If the gain target is set to something other than the DFG, the resulting spectral gain will no longer be flat due to the gain properties of Erbium doped fiber. Typical DFGs for a single-stage EDFA are in the range 10 to 30 dB, depending on the application.

A fundamental property of EDFAs is the dynamic gain tilt (DGT) characteristic, which determines how the spectral gain at one wavelength changes with respect to another, as shown in Figure 5. For example, if the gain at 1530 nm were to increase by, say, 1 dB, then Figure 5 indicates that the gain at 1560 nm would correspondingly increase by 0.5 dB. Hence, as the EDFA is operated away from its DFG, the resulting spectral gain profile increasingly tilts.

If the EDFA is operated away from its DFG, the gain seen by a given wavelength becomes dependent on the input spectral profile, or loading condition, due to DGT. The loading dependent gain for each wavelength occurs because the EDFA gain control operates on total input and output power readings. Hence, as the input loading conditions change, the gain control loop causes the EDFA spectral gain profile to tilt such that the gain target, based on total input and output power, is maintained. Excessive gain tilt is usually undesirable in DWDM systems because it complicates power management and can lead to significant wavelength power perturbations in fault scenarios where the input spectral profile suddenly changes.

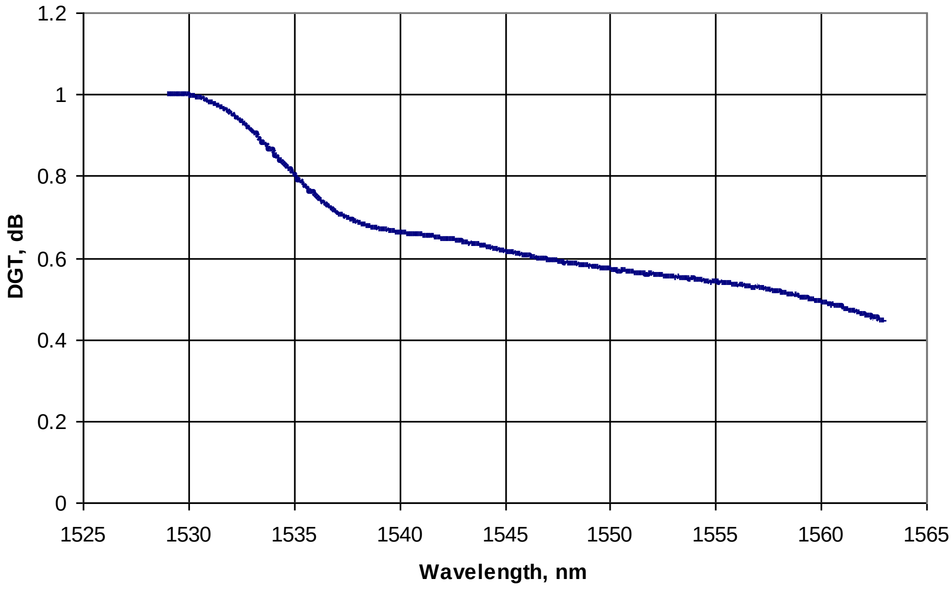

Figure 5 Dynamic gain tilt for an EDFA

Variable Flat Gain EDFAs

As mentioned in the previous section, it is usually desirable to operate EDFAs at their DFG. However, it is also often desired to adjust the gain of deployed EDFAs. To provide an EDFA with adjustable gain that is kept spectrally flat, a VOA can be introduced, often between two single stage EDFAs, as shown in Figure 6.

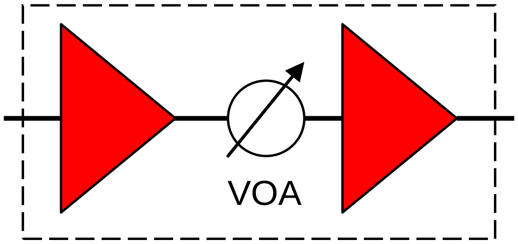

Figure 6 Dual-stage EDFA to provide variable flat gain

Dual stage EDFAs provide the advantage of variable flat gain and mid-stage access for insertion of components such as a dispersion compensation module (DCM) and/or an optical add/drop multiplexer (OADM). However, they tend to cost more, consume more power, and have a net noise figure that degrades as the mid-stage loss is increased.

EDFA Noise Figure

As with electrical amplifiers, EDFAs introduce unwanted noise, due to ASE. Upon photodetection at the receiver the ASE and signal beat together, leading to signal-spontaneous beat noise, which is often the limiting noise source in an optically amplified network. In addition, the ASE beats with itself, producing spontaneous-spontaneous beat noise.

The amount of ASE noise, *Nsp*, generated by an EDFA is a function of its gain and noise factor, *F*, according to

$$N_{sp} = k\left(FG-1\right) \approx kFG \qquad (1)$$

where *k* is a constant, *G* is the linear power gain, and *F* is the EDFA noise factor, where the noise factor and noise figure for the EDFA are related by *NF*=10log(*F*).

The NF for an EDFA usually has some spectral dependence, and can vary with input power level. However, these dependencies are usually small in practical EDFA designs, leading to cumulative variation in the NF of no more than a few tenths of a dB. Well designed, single-stage commercial EDFAs have a typical NF of ~5 dB.

For dual-stage EDFAs the NF is a function of the mid-stage loss. For example, the NF for a dual-stage EDFA, made from two single-stage EDFAs each having a NF of 5 dB and 15 dB gain, is shown in Figure 7.

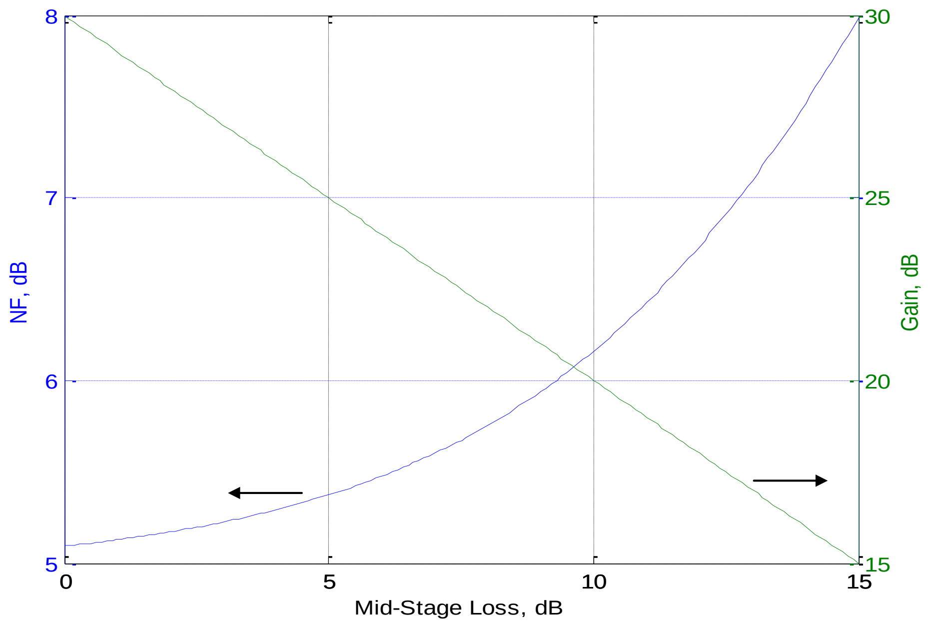

Figure 7 Net noise figure and gain for a dual-stage EDFA versus mid-stage loss

As the mid-stage loss in dB approaches the gain in dB of the first EDFA stage, the overall EDFA NF begins to degrade rapidly. Hence, the NF degradation of a dual-stage EDFA can be minimized by keeping the mid-stage loss reasonably lower than the gain of the first EDFA stage.

The NF performance shown in Figure 7 assumes each EDFA stage is maintained at its DFG. In some cases, however, it is possible to increase the gain of the first stage while decreasing the gain of the second stage to provide an improved NF for a given mid-stage loss. With that approach the individual gain spectrum for each EDFA stage is allowed to tilt, such that the combined gain spectrum remains flat.

EDFA Power Rating

The output power rating for an EDFA is the maximum total output power the EDFA can deliver without exceeding its maximum pump current. This value is typically in the range +14 dBm to +20 dBm, but may be as high as ~+27 dBm for very high power devices. A higher output power rating is achieved by incorporating higher power pumps and/or multiple pumps in the EDFA design. Higher power EDFAs tend to cost more and consume more power.

It is important to ensure that a DWDM system does not demand more power than the EDFA is rated for, as the EDFA would saturate under such conditions and automatically lower its gain such that the total output power does not exceed its power rating. For this reason it is important to design a DWDM system such that it can operate under fully loaded conditions without saturating EDFAs. For example, if an EDFA is rated for, say, +16 dBm, then the power target for each individual wavelength in a 40 channel system should not exceed 0 dBm at the EDFA output, as under full loading the total output power would increase to 0+10log(40)=+16 dBm, i.e., the maximum power the EDFA is able to output.

Laser Safety and Automatic Shutdown

Requirements relating to accessible optical power levels in optical networks are governed by the IEC-60825-2 safety standard. These requirements are given in the context of a *hazard level*, which specifies the maximum allowable optical power that can be made accessible in a given environment.

For DWDM networks operating in the C band, the hazard level is classified as 1M if the accessible power level does not exceed +21.3 dBm, referenced to a connector output. According to the IEC-60825 standard, optical networks cannot exceed hazard level 1M. This implies that the use of EDFAs with an output power rating greater than ~+20 dBm must include an automatic shutdown or power reduction mechanism to reduce the accessible power to hazard level 1M during a fault, such as a connector pull or fiber break. For EDFAs with an output power rating no greater than ~+20 dBm, such automatic power reduction mechanisms are not required.

In addition to safety considerations, there are other scenarios that mandate automatic shutdown of an EDFA. One scenario is during an input loss-of-signal (LOS) when operating the EDFA in constant power mode. If the EDFA did not shutdown in response to the input LOS, the pump would rail in an attempt to maintain the output power target. In such a railed state the gain of the EDFA could become very high, for which the sudden reappearance of an input signal could produce a very large output power transient. In some cases the transient could potentially damage downstream devices, such as receiver photodetectors.

An EDFA operating in constant gain mode would generally not be susceptible to the fault scenario described above when there is an input LOS condition. Its exact behavior would depend on details of how the gain control loop is implemented and how the input and output power detectors are calibrated, but generally the gain would be maintained close to the desired setpoint. However, it still may be desired to disable the EDFA during an input LOS condition. For example, the EDFA may be part of a protected line system, where a break in the preceding fiber needs to be reliably detected by a line protection module a few hops away that switches on total optical power. If the EDFA did not shutdown, the cumulative ASE at the line protection module could potentially be sufficiently high to fail the desired protection switch.

Cascaded EDFAs and Optical Signal-to-Noise Ratio

Among the most important parameters in an optically amplified system is the optical signal-to-noise ratio (OSNR), given by the ratio of signal power to ASE power in a specified bandwidth, usually taken as 0.1 nm. If the overall OSNR is not maintained above a certain value, the resulting BER will degrade below an acceptable level, usually taken as 1E-12 or 1E-15.

The OSNR requirement depends strongly on parameters such as the modulation format, bit rate, and accumulation of other impairments, such as fiber dispersion. For a 10 Gbps system the minimum required OSNR is typically ~20 dB, whereas for a 2.5 Gbps system it is ~16 dB. With forward error correction (FEC), the required OSNR can be further reduced by up to a few dB, depending on the FEC coding gain.

ASE is added by each EDFA the signal traverses, degrading the overall OSNR. Although an EDFA's NF influences the OSNR, the most significant parameter is the wavelength power at the EDFA input. If there are *N* EDFAs in a line system, the overall system OSNR can be calculated from

$$\frac{1}{OSNR_{sys}} = \sum_{n=1}^{N} \frac{1}{OSNR_n} \qquad (2)$$

where $OSNR_n$ is the OSNR contribution of the n^{th} EDFA. Note that the OSNR values in (2) are in linear units, which relate to the OSNR in dB according to $OSNR_{dB}=10\log(OSNR_{lin})$.

The OSNR contribution of a given EDFA can be calculated from

$$OSNR_{dB} = p_{in} + 58 - NF \qquad (3)$$

where p_{in} is the signal power level in dBm of a single wavelength, referenced to the EDFA input, and *NF* is the noise figure for the EDFA. Note that the OSNR given by (3) is independent of the EDFA gain.

From (2) and (3) it can be seen that the EDFA signal input power level is the main parameter that dictates the overall OSNR. For EDFAs with high input power, the respective contribution to (2) will be small compared to EDFAs with low input power. Hence, EDFAs with low input power levels, e.g., those with preceding high loss spans, will tend to dominate the overall OSNR.

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