

# Stability of a 500 km Erbium-Doped Fiber Amplifier Cascade

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**Abstract**—The stability of a cascade system of erbium-doped fiber amplifiers, due to pump and signal power variations, has been examined by use of a very accurate model. Even with an automatic gain control loop included, a fallout of a pump laser in the first in-line amplifier is shown to produce a more than seven times as high increase of the bit error rate than for the fallout of other amplifier pumps. The fallout of the forward pump is found to be the far most critical. The stability to simultaneous changes in pump and signal power is examined and can be increased remarkably by insertion of an additional amplifier.

## INTRODUCTION

THE erbium-doped fiber amplifier (EDFA) has emerged as a key element for long distance optical communication systems because of high-gain, low-noise, low-coupling losses [1] and polarization insensitivity. As the comprehensive examination of the EDFA latest has produced a design proposal for the optimum Er-doped fiber [2], [3], the next step in the increase of the distance between transmitter and detector is to cascade couple EDFA's to a long-haul multirepeater optical amplifier system. However, in such a system, difficulties arise as the amplified spontaneous emission (ASE) accumulates. This will result in amplifier saturation and in a high ASE power at the detector [4]. Although the Er-doped fiber itself is polarization insensitive, variations in the input signal power, i.e., caused by polarization sensitive couplers, or variations in the launched pump power, caused by temperature variations or laser degradation, will have a significant influence on the detected signal after amplification in the cascade [5]. Therefore, some type of automatic gain control (AGC) loops have to be incorporated to ensure the system reliability [5]. In this letter, the stability of an EDFA cascade with respect to signal and pump power variations, is investigated at a 520 km long transmission line. This length covers the longest span between two Atlantic islands (Iceland and the Faroe islands) in a line from the US to Europe. Two different control systems are examined, a pump-to-pump and a signal-to-pump regulation scheme, respectively. The influence of pump laser degradation upon the bit error rate (BER) shows large dissimilarity for the two systems and it is clarified how requisite a control system is.

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## CASCADE SETUP

Models for a system of EDFA's have been presented [4], [6]. Compared with these, our accurate model does not only take into account the forward traveling ASE from the neighboring amplifiers (as in [4]), but also the backward traveling ASE at the determination of the properties of each amplifier as well as the overall system performance. Furthermore, also the self saturation of each amplifier caused by the ASE produced within the amplifier itself, is included in this model. That part which concerns each single amplifier without the ASE influence from the neighboring EDFA's, has earlier been reported and verified [7]. In addition, the model takes into account both insertion loss and isolation for a number of isolators as well as the insertion loss for each WDM coupler between the amplifiers.

Each amplifier consists of a length of erbium-doped fiber with a dopant concentration of  $5 \cdot 10^{24} \text{ m}^{-3}$  at a confinement of 0.8, a core diameter of  $2.4 \mu\text{m}$  and a refractive index difference of 0.03. These data are chosen as realistic values in agreement with the optimum design proposal [2]. Each erbium-doped fiber is pumped with both forward and backward traveling pump power at  $1.48 \mu\text{m}$  (realistic values of 25 mW for each in-line amplifier pump laser and 45 mW for each booster pump laser have been chosen [8]) to ensure system reliability and to allow for a local control loop between the pump sources. An isolator is placed on the output end of each EDFA to minimize the backward traveling ASE. An insertion loss of 1 dB and an isolation of 40 dB is used for these isolators and in addition a 1 dB insertion loss is assumed for each of the couplers. The input power of the booster is 0 dBm and, to limit the buildup of ASE, the input power for the in-line amplifiers, is higher than  $-16.5 \text{ dBm}$  [8]. The bit rate is 2.5 Gb/s.

As seen on Fig. 1, which illustrates the system setup, the detector is located after a transmission distance of 520 km, where at the signal level is lowered to  $-25 \text{ dBm}$ . It is assumed that the average zero dispersion wavelength of the transmission fiber is identical with the signal wavelength at  $1.55 \mu\text{m}$  and that the average loss of the fiber, including splicing and connecting, is  $0.225 \text{ dB/km}$ . To reduce the ASE power and to separate the signal light from eventually remaining pump light, a filter is placed on the output end of the transmission line.

## AUTOMATIC GAIN CONTROL

To reduce the system sensitivity upon pump laser degradation, an AGC-loop is assumed for each of the amplifiers in

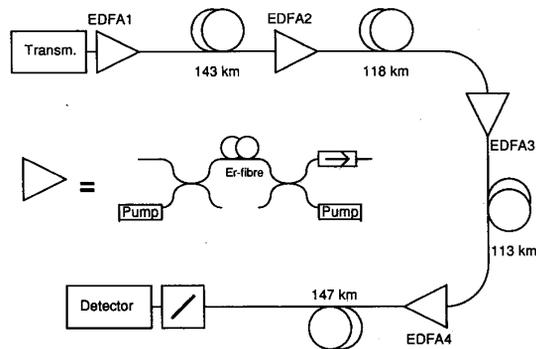


Fig. 1. Transmission line setup.

the cascade. Both launched pump and output signal power are measured for each EDFA. If a change in the launched power from one of the pump lasers is monitored, the other pump laser will be adjusted accordingly so the signal output power is kept constant. However, if a change in output signal power is caused by a changed input signal power and no variations are monitored in the launched pump power, no regulation will occur. As a relative measure of the pump laser fallout, the pump laser performance is defined as the fraction between the launched pump power from the laser and the amount of launched pump power that originally was designed for the laser (25 mW for an in-line EDFA and 45 mW for the booster). Therefore, a pump-laser performance among 0 and 1 corresponds to variations in the launched pump power between 0 and 45 mW for the booster and variations between 0 and 25 mW for the in-line amplifier pumps. Fig. 2 illustrates how critical the overall system BER is to the fallout of the forward pumping laser. The BER is shown versus variations in the laser performance among 0 and 1 when only one laser performance is changed at the time.

The EDFA's in the system are seen to have much different influence on the BER. The booster (EDFA1) and the last in-line amplifier (EDFA4) causes only minor changes while the system acts with even a large BER increase for pump power changes to the first in-line amplifier (EDFA2). These differences are indirectly caused by the unfavorable ASE buildup in the system.

The ASE generation in the amplifier is strongly dependent upon the inversion in the signal input end of the active fiber. As the inversion in this end decreases simultaneously with the shifting to backward pumping, the ASE will increase, but as the ASE mainly buildup around the emission peak at 1.53  $\mu\text{m}$ , only minor changes will be observed within the optical detector bandwidth at 1.55  $\mu\text{m}$ . The latter can be seen from Fig. 2, as for the last EDFA in the cascade a constant output power corresponds to a constant signal power at the detector. The negligible changes in the BER therefore reflect the direct influence of the increased ASE. When the pump degradation occurs for one of the other in-line amplifiers, the larger amount of ASE will furthermore increase the saturation of the successive amplifiers. This reveals in gain reduction and thereby in a gradual lowering of the input signal power for the following amplifiers in the cascade. However, for a

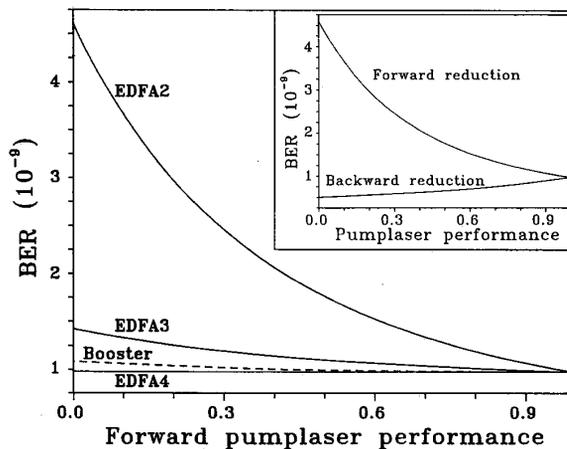


Fig. 2. BER versus the forward pump laser performance. The performance for each laser is defined as the ratio between pump power and the original designed pump power. Insert: BER versus pump laser performance for pump lasers in EDFA2.

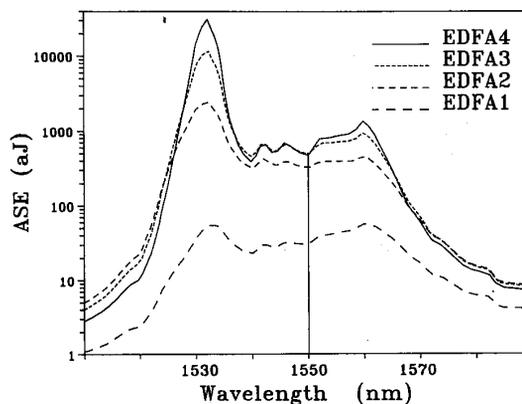


Fig. 3. ASE in aJ versus the wavelength in nanometers, on the output end of each amplifier. The vertical line corresponds to the signal wavelength.

booster amplifier, the highly suppressed ASE will not influence on the other amplifiers after the reduction in the passive fiber between the booster and EDFA2.

For the first in-line amplifier (EDFA2), variations in the overall system BER is shown in the upper right corner of Fig. 2, for variations in respectively the forward and the backward pump laser performance among 0 and 1. A reduction in the backward pumping, and thereby an increase in forward pumping power, produces a higher inversion in the signal input end of the fiber, yielding ASE reduction. In this case the successive amplifiers will be less saturated and thereby produce a higher gain. In all, higher signal power and less ASE reach the detector, yielding a minor BER decrease.

The gradual ASE buildup in the cascade system is illustrated in Fig. 3 where the ASE spectrum on the output end of each amplifier is shown. As mentioned above, and as seen from the figure, the ASE does mainly buildup at the emission peak at 1.53  $\mu\text{m}$ . The 3-dB bandwidth narrows from 8.5 nm after the booster and 6.0 nm after the first in-line amplifier

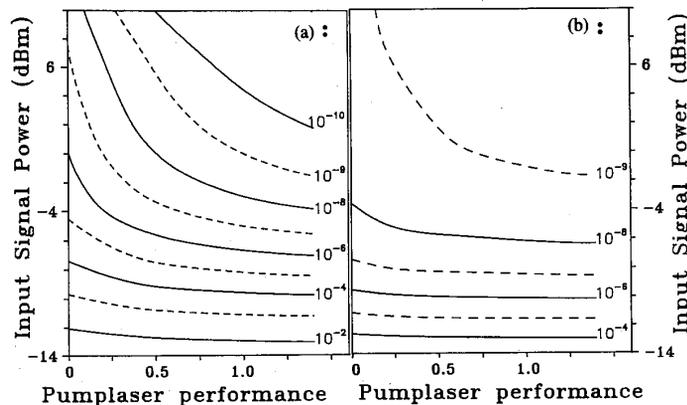


Fig. 4. (a) Input signal power in dBm versus the forward pump laser performance for EDFA2 for a system with four amplifiers. The BER is represented as contour-lines. (b) As in (a) when a total of five amplifiers are used in the system.

(EDFA2) to 3.5 nm after EDFA4. An increase of 11 dB is observed between the second and the fourth amplifier at 1.53  $\mu\text{m}$ , while only 2 dB ASE increase is observed at 1.55  $\mu\text{m}$ .

#### SIMULTANEOUS CHANGES IN PUMP AND SIGNAL POWER

For some system applications (i.e., submarine systems) it might be inconvenient to have an electric AGC-loop located at the in-line amplifier. Instead, gain degradation caused by pump power changes can be compensated by simultaneous variations of the overall system signal input power. The cascade system sensitivity to such changes is illustrated in Fig. 4(a). Fixed values of the BER among  $10^{-11}$  and  $10^{-2}$  are shown as contour-lines for variations in the signal input power between  $-14$  dBm and  $+10$  dBm together with variations in the pump laser performance among 0 and 1.2.

The worst case is considered which, as shown above, arise with changes in the forward pumping laser in the first in-line amplifier (EDFA2). For a launched pump power decrease of 50% it is possible to reestablish the BER at the detector, by increasing the overall input signal power by 5.5 dB. However, when the pump laser almost is turned off (performance  $\approx 0$ ), it will not be possible to regulate the BER alone by the input signal. For a fixed signal level at 0 dBm, the BER is  $10^{-6}$  (compared to approximately  $5 \cdot 10^{-9}$  by use of the AGC-loop), when the laser performance is zero.

The BER sensitivity to pump laser degradation can however be reduced remarkably by insertion of additional in-line amplifiers in the system. This is valid both for this regulation scheme as well as for the AGC scheme. Assuming unchanged overall system signal input and output powers as well as unchanged transmission length, the extra EDFA allows for shorter amplifier spacing resulting in a higher average signal input power from the EDFA with saturation and a more insensitive response to pump power changes as a consequence. Fig. 4(b) shows the input signal power versus forward pump-laser performance for EDFA2, when a total of five amplifiers is used in the transmission link. A minor decrease in BER from  $1 \cdot 10^{-9}$  to  $0.8 \cdot 10^{-9}$  is obtained as a result of the more suppressed ASE for increased signal input

power at the in-line EDFA's. As expected, a much less dependence upon pump laser variations is observed. A change of 50% in pump power to EDFA2 will only need a change of 2.5 dB in the signal input power.

#### CONCLUSION

The stability of a cascade of erbium-doped fiber amplifiers has been examined. The most critical EDFA with respect to pump reduction, is the first in-line amplifier. When a pump in this amplifier is totally turned off, it will influence on the BER seven times as much as if the pump reduction occurs for another amplifier in the considered system. Furthermore, the reduction of the forward pump is generally much more critical than in the backward. For input power stabilized systems, the demand for power extension ratio can be remarkably reduced by insertion of additional amplifiers. For the considered system it is possible to maintain unchanged BER to a 50% pump power deterioration, by simultaneous adjustment of the signal input power by 5.5 dB. A single additional amplifier in the cascade will reduce this requirement by 3 dB.

#### ACKNOWLEDGMENT

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# SNR Analysis of Crosstalk and Filtering Effects in an Amplified Multichannel Direct-Detection Dense-WDM System

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**Abstract**—An SNR analysis is presented for multichannel dense-WDM networks using optical amplifiers and optical filters. By using Lorentzian approximations for the amplified spontaneous emission and the optical and electrical bandwidths, simple expressions are derived for the relevant noise sources and crosstalk and filtering effects. Guidelines are stated for choosing appropriate optical filter widths and channel spacings to reduce power penalties. For any experimental system, easily measurable quantities can be inserted into the analytical solutions to obtain close approximations for minimizing SNR degradation due to filtering and crosstalk.

## INTRODUCTION

DENSE-wavelength-division-multiplexed (WDM) multichannel systems have the potential to provide enormous aggregate communications capacity [1]. These networks may require optical filters, such as Fabry-Perots (FP) to demultiplex the channels, and optical amplifiers, such as erbium-doped fiber amplifiers [2] to compensate for splitting or transmission losses [3]. Although these amplifiers provide gain, they also introduce amplified-spontaneous-emission (ASE) noise which beats with itself and all the channels passing through the filter [5], [6]. In this letter, relevant noise and signal-degradation sources are identified when utilizing a Fabry-Perot filter demultiplexer in an optically amplified multichannel or multitone system. Using realistic Lorentzian approximations for the optical and electrical filters, simple expressions which contain easily measurable parameters are derived for both the signal-to-noise ratio (SNR) and power penalty. Given a single channel, the optical filter must be

amply wide to transmit the selected signal but sufficiently narrow to limit the ASE-related noise. In the case of many channels, the power penalty due to crosstalk from rejected channels decreases rapidly as the channel spacing increases and is weakly related to the ASE beating with these channels. The model neglects pattern dependencies of an actual transmitted signal but does provide workable expressions which give close approximations to real system performance.

## SYSTEM MODEL

The system modeled is shown in Fig. 1 and includes  $N$  amplitude-shift-keyed (ASK) channels [or tones in the case of frequency-shift-keying (FSK)] spaced  $f_d$  apart. The selected channel, with power  $P_S$  and a 3-dB bandwidth  $f_S$ , is flanked on one side of the spectrum by many rejected channels of power  $P_R$  and width  $f_R$ . These signals pass through an optical amplifier of gain  $G$  and spontaneous emission factor  $N_{sp}$ . The output from the amplifier passes through the Lorentzian-shaped FP filter of width  $f_{FP}$ , which is centered on the center frequency of the selected channel ( $f_o$ ), and subsequently impinges on a detector of electrical bandwidth  $B_e$ . The magnitude of the signal- and noise-induced photocurrents is determined by calculating the filter-transmitted power of the ASE and the selected and rejected channels and then appropriately multiplying and convolving them with the aid of Fourier transforms.

The functional form for the optical channels is approximated to be Lorentzian in order to derive a closed-form solution [7]. The selected-channel power,  $S$ , which has been transmitted through the filter is

$$S = \frac{(cP_S G f_{FP})}{(f_{FP} + f_S)} \quad (1)$$

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