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Active Gain Control in Cascades of EDFAs by Pump Compensation

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Abstract— In this paper we analyze active gain control by means of pump compensation in cascades of EDFAs. Based on analytical expressions for the 1dB rise/fall time in case of channels add/drop we derive simple closed form expressions for the conditions on the pump power change at each amplifier. We present numerical simulations of a system comprising 20 WDM channels transmitted through a cascade of 35 EDFAs demonstrating the effectiveness of the gain control.

I. Introduction

Recently there has been growing interest in evaluating the time responses of Erbium-Doper Fiber Amplifiers (EDFA) in case of a channel drop or add in the wavelength division multiplexing (WDM) network scenario [1], [2]. Following the analysis in [2] we first develop simple analytical expressions for the time responses expressed through the figure of merit 1dB time, i.e., time in which the power excursion reaches 1dB [2]. Building on the derivations for the 1dB time, we next focus on analyzing a gain control mechanism based on pump compensation. Pump power is adjusted to compensate the slope of the power excursion at each amplifier. Conditions on the pump power change are derived in a very simple closed form. In order to investigate the effectiveness of the scheme, we present numerical simulations of a system comprising 20 WDM channels passing through a cascade of 35 EDFAs, calculating the resulting power and SNR excursions with and without pump compensation. The results indicate an effective compensation scheme limiting the excursions to within a pre-determined margin.

II. Derivation of the analytical expressions

Define

$$\Delta P_k^{out}(t) = \frac{P_k^{in}(t)e^{G_k(t)}}{P_k^{in}(0)e^{G_k(0)}} = \Delta P_k^{in}(t)e^{G_k(t)-G_k(0)} \quad (1)$$

to be the power excursion of the output power of k-th channel relative to the steady state and due to the step transition of the signal channels at $t = 0^+$, where G_k is the gain given in natural logarithm units. Then

$$\frac{d}{dt}\left(\ln \Delta P_k^{out}(t)\right)\Big|_{t=0+} = \frac{d}{dt}\left(\ln \Delta P_k^{in}(t) + G_k(t)\right)\Big|_{t=0+} \quad (2)$$

represents the slope of the output power excursion in natural logarithm units. Since the interamplifier loss is independent of time, eq.(2) gives the relation between the output power slope of the amplifier and the output power slope of the previous amplifier in the chain:

$$\Delta_k^{(i)} - \Delta_k^{(i-1)} = \frac{d}{dt}G_k^{(i)}\Big|_{t=0+}, \quad \Delta_k^{(0)} = 0 \quad (3)$$

where i designates the i-th amplifier in the chain. This is a difference equation describing the slope evolution along the cascade with initial condition that the slope of the input power at the first amplifier is zero. Assuming steady state before the step power transition, from eq.(8) in [1]:

$$\frac{d}{dt}G_k^{(i)}(t) = \sum_{j=0}^{N} \frac{\Delta P_j^{(i)}}{\tau P_k^{IS}}\left(e^{G_j^{(i)}(0)} - 1\right)$$
$$\Delta P_j^{(i)} = \Delta P_j^{(i-1)} e^{G_j^{(i-1)} - Loss(j)}, \quad \Delta P_j^{(1)} = \Delta P_j \quad (4)$$

where $\Delta P_j^{(i)} \triangleq P_j^{(i)}(0^+) - P_j^{(i)}(0^-)$; τ is the fluorescence time, $\Delta P_j^{(i)}$ is the power change in photons/sec as seen by the i-th amplifier, P_k^{IS} is the intrinsic saturation power in photons/sec, N is the number of signal channels and $Loss(j)$ is the interamplifier loss plus possible notch filter for gain equalization. The summation goes over all the channels- it should be understood that for channels not experiencing step transition $\Delta P_j(i) = 0$. We now approximate the output power excursion by a linear Taylor series expansion conserving only the first two terms

$$\ln \Delta P_k^{out}(t) \doteq \ln \Delta P_k^{out}(0^+) + t\frac{d}{dt}\left(\ln \Delta P_k^{out}(t)\right)\Big|_{t=0+} = t\Delta_k^{(i)} \quad (5)$$

Making the transition from natural to decimal logarithms, the 1dB rise or fall time is thus given by

$$t_{1dB}^{(i)} = ln10/(10\Delta_k^{(i)}). \quad (6)$$

The knowledge of the slope evolution along the cascade and the associated 1dB times could be put into practical use in designing a gain control mechanism by switching the pump. In this scenario, the power transition is detected, and following a certain delay, the pump power is adjusted. Knowledge of the fastest 1dB rise/fall time allows us to guarantee 1dB power excursions to within tolerable limits - the pump must be switched within this time period. The amount of pump power change should be such that it provides an effective gain control - knowledge of the slope could be employed to *design a pump compensation scheme that exactly counters the slope by inducing an additional slope with the opposite sign.* Hence

$$\sum_{j=1}^{N} \frac{\Delta P_j^{(i)}}{P_k^{IS}}\left(e^{G_j^{(i)}(0)} - 1\right) + \frac{\Delta P_0^{(i)}}{P_k^{IS}}\left(e^{G_0^{(i)}(0)} - 1\right) \doteq 0 \quad (7)$$

where the first factor is the component of the slope due to the power change in the signal channels and the second factor represents the slope component induced by the pump power change. The pump change $\Delta P_0^{(i)}$, given in units of photons/sec, necessary to compensate the slope at the i-th amplifier is given by:

$$\Delta P_0^{(i)} \doteq -\frac{1}{e^{G_0^{(i)}(0)}-1}\sum_{j=1}^{N}\Delta P_j^{(i)}\left(e^{G_j^{(i)}(0)}-1\right) \qquad (8)$$

Some comments are in order for the $\doteq$ sign in eq.(8): if the pump change occurs at $t = 0^+$, eq.(8) gives an exact result. In reality, the pump power transition will occur after some time necessary to detect the change in input power and to align the pump power. If this time is sufficiently small, that is, if we are still in the linear region of the power excursion (eq.(5)), it follows that the slope induced at $t = t_1 > 0^+$ is approximately equal to the slope at $t = 0$. However, the slope at $t = t_1 > 0^+$ is slightly smaller than the slope at $t = 0^+$, easily deduced from the convexity of the power excursion curve. Hence, the pump power induced slope will be slightly stronger than the signal power induced slope and will gradually drive the power excursion back to the zero level.

III. Numerical simulations

In order to check the validity of the derived expressions, we perform numerical simulations. Following the analysis in [6], the system under consideration comprises 20 WDM channels, spaced uniformly between 1542 and 1551.5 nm with 0.5 nm spacing, each channel having -10 dBm input power. Such traffic was fed into a cascade of 35 EDFAs (the spectral parameters of the EDFAs were taken from [3]). The amplifier length was 14.7 m and the pump power was 18.4 dBm giving roughly 10 dB gain to exactly balance the interamplifier loss. To assure gain equalization, a notch filter with filter depth of 1.4 dB, central wavelength of 1546 nm and bandwidth of 2.5 nm was placed periodically after every 4 amplifiers [6], [7] and a filter was placed after every EDFA to block the harmful ASE below 1540 nm [6]. An optical filter of width 0.125 nm was assumed at the detector. The optical signal-to-noise (SNR) ratio at the output of the first, tenth, twentieth and the 35th EDFA for the steady-state case are plotted in Fig. 1a) indicating fairly flat SNR over the channels (represented with circles). The corresponding output powers are plotted in Fig. 1b) from where it is evident that channel at 1546nm has one of the highest output power. Calculations of the transients were based on the model introduced in [1] into which ASE was included as outlined in [5] and [4], with the transients being described with the following ordinary differential equation (ODE)

$$\tau\frac{d}{dt}P_k^{IS}G_K(t) + P_k^{IS}G_k(t) + P_k^{IS}A_k = \qquad (9)$$
$$= \quad -\sum_{j=1}^{N}P_j^{in}(t)\left\{e^{[(P_k^{IS}G_k(t)+A_{kj})/P_j^{IS}]}-1\right\} - P_k^{ASE}(t)$$

where N is the number of WDM channels (including the pump), τ is the fluorescence time of the amplifier, P_k^{IS} are the intrinsic signal saturation powers in photon fluxes, G_k is the gain (given as $ln(P_{out}/P_{in})$) in channel k, $A_k = \alpha_k L$

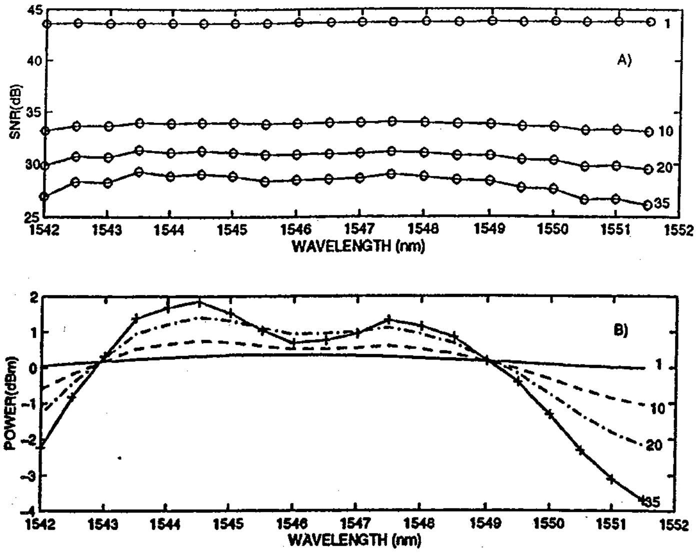

Fig. 1. Simulation of a cascade of 35 amplifiers with 20 WDM channels: a) optical SNR at the output of the first, tenth, twentieth and the 35th amplifier; b) power at the output of the first, tenth, twentieth and the 35th amplifier.

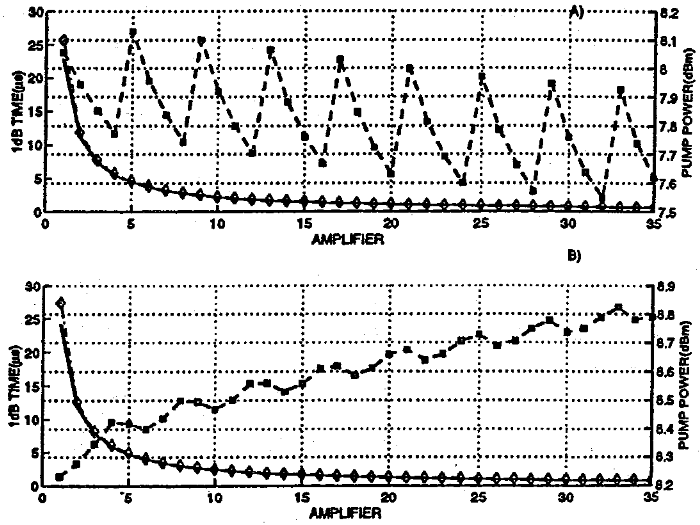

Fig. 2. 1dB times and pump compensation powers for 19 channel drop: a) surviving channel at 1542 nm; b) surviving channel at 1546 nm. Full line - analytically calculated 1dB times; broken line with diamonds - numerically calculated times; broken line with boxes - pump power.

is the product of the absorption constant α_k and the length of the amplifier L and $A_{kj} = P_k^{IS}A_k - P_j^{IS}A_j$. $P_k^{ASE}(t)$ is the amplifier spontaneous emission noise in photon fluxes calculated as follows [5], [4]:

$$P_k^{ASE} = 4\int(e^{G_k(\nu)}-1)\frac{\sigma^e(\nu)}{\sigma^T(\nu)}\frac{G_k(\nu)+A_k(\nu)}{G_k(\nu)}d\nu \qquad (10)$$

where $\sigma^e(\nu)$ is the emission cross-section, $\sigma^a(\nu)$ is the absorption cross-section and $\sigma^T(\nu) = \sigma^a(\nu)+\sigma^e(\nu)$, all at frequency ν. The ODE was solved in $0.1\mu s$ time increments. First, 19 out of the possible 20 channels were dropped (the surviving channel was the first channel at 1542 nm), the 1dB times, the pump values for compensation and the power and

SNR excursions were calculated, and then, after 400 μs, the channels were added back and the calculations repeated. Fig. 2a) summarizes the 1dB times calculated analytically using (eq.(5)) (full line), the 1dB times calculated numerically by solving the ODE (broken line with diamonds) and the pump power for compensation calculated using eq.(8) (broken line with boxes). Note the excellent agreement between the analytical and numerical 1dB times. Also note the sawtooth character of the pump curve, a clear consequence of the notch filters being inserted after every 4 EDFAs. In order to investigate the spectral behavior of the 1dB times and the pump power, the same simulation was performed with the channel at 1546 nm being the surviving channel and the results in terms of 1dB times and pump power for compensation are shown in Fig. 2b). Comparing Fig. 2a) with Fig. 2b) it is evident that the transients are faster (the 1dB times shorter) when observing the channel at 1542 nm. In this scenario, dropping all 19 channels and observing the channel at $\lambda = 1542$ nm would result in the fastest transients, this being the reason for which it was chosen for study. Comparing the pump powers, few diferences can be observed. First, the discrepancy between the maximums and minimums of the sawtooth curve are smaller for the channel at 1546 m, a fact easily ascribed to the notch filter being situated exactly at 1546 nm. Since that channel does not experience drop, it does not appear in eq.(8) and hence the influence of the notch filter on the pump curve is less profound. Second, observing the channel at 1542 nm the pump power decreases along the cascade because the net power drop increases along the cascade (the strong channels in Fig. 1b) are all being dropped). When observing the channel at 1546 nm the pump power increases along the cascade, a consequence of the fact that one of the strong channels in Fig. 1b) (the observing channel at 1546 nm) is not being dropped and hence, the net power drop decreases along the cascade. The power and optical SNR excursions for the case when observing the channel at 1542nm and dropping the other 19 channels are depicted in Fig. 3a) and b) respectively representing the output of the first, tenth, twentieth and the 35th EDFA. Note the sizable excursion, reaching up to 18dB for the case of the output power.

Having calculated the pump values for compensation and the 1dB times, a second run was performed with pump compensation. The initial pump values were 18.4 dBm, but after 0.6 μs (the fastest 1dB time in the cascade) the pumps were switched to the newly calculated values. The resulting power and optical SNR excursions are depicted in Fig. 3c) and d) respectively. Initially the excursion goes as in the uncompensated case, but when the pump is switched a negative slope is induced which starts driving the excursion back to the zero level as expected. This is more pronounced further along the cascade as .6 μs is closer to the limit of the linear regime. Hence, the slope induced by the pump change is stronger than the original slope and the rate with which the excursion decays is faster. For the amplifiers closer to the beginning of the cascade, .6 μs is well within the linear regime and hence the additional slope is much closer to the originally induced slope - the rate of decay towards the zero level is much slower. Note that the largest power change occurs at the output of the 35th amplifier and is approximately .9 dB, in good agreement with

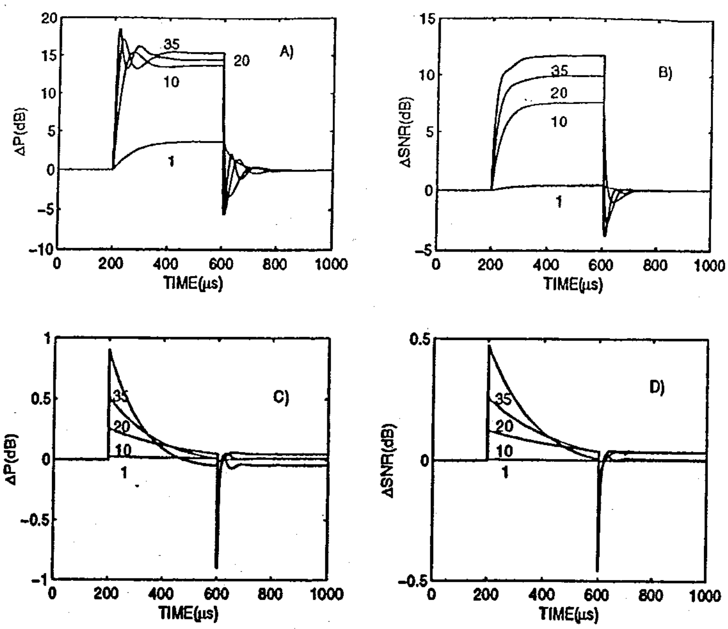

Fig. 3. Simulation of dropping and then adding back 19 channels in a cascade of 35 amplifiers (surviving channel at 1542nm): a) power excursion of the surviving channel; b) SNR excursion; c) power excursion with pump compensation; d) SNR excursion with pump compensation. Curves apply to the first, tenth, twentieth and the 35th amplifier.

the analytical results that indicate .64 μs 1dB rise time for the 35th amplifier. It should be emphasized that the compensation scheme is based solely on the knowledge of the steady state gain conditions and the power dropped providing for a straightforward implementation. Also, by using "look-ahead delay" the switching time could be made shorter than .6 μs limiting the power excursions to levels well below 1dB.

In conclusion: we have derived conditions for the pump in a closed analytical form based on compensating the slope. Numerical simulations indicate that this is a very effective method for gain control.

References

[1] Y. Sun, G. Luo, J. L. Zyskind, A. A. M. Saleh, A. K. Srivastava and J. W. Sulhoff, "Model for Gain Dynamics in Erbium-Doped Fibre Amplifiers," *Electron. Lett.*, Vol. 32, No. 16, pp. 1490-1491, Aug. 1996.

[2] Y. Sun, A. K. Srivastava, J. L. Zyskind, J. W. Sulhoff, C. Wolf and R. W. Tkach, "Fast Power Transients in WDM Optical Networks with Cascaded EDFAs," *Electron. Lett.*, Vol. 33, No. 4, pp. 313-314, Feb. 1997.

[3] E. Desurvire, *Erbium-doped fiber amplifiers*, New York, Wiley, 1994.

[4] T. Georges and E. Delevaque, "Analytic Modeling of High-Gain Erbium-Doped Fiber Amplifiers," *Optics letters*, Vol. 17, No. 16, pp. 1113-1115, Aug. 1992.

[5] A. Bononi, L. Barbieri and L. A. Rusch, "Using Spice to Simulate Gain Dynamics in Doped-Fiber Amplifier Chains," to be presented at *Proc. OFC'98*.

[6] W. Zeiler, F. Di Pasquale, P. Bayvel and J. E. Midwinter, "Modeling of Four-Wave Mixing and Gain Peaking in Amplified WDM Optical Communication Systems and Networks," *IEEE/OSA J. Lightwave Technol.*, Vol. 14, No. 9, pp. 1933-1942, Sept. 1996.

[7] A. E. Willner and S. Hwang, "Transmission of Many WDM Channels Through a Cascade of EDFA's in Long-Distance Links and Ring Networks," *IEEE/OSA J. Lightwave Technol.*, Vol. 13, No. 5, pp. 802-816, May 1995.

[8] Y. Sun, J. L. Zyskind and A. K. Srivastava, "Average Inversion Levels, Modeling, and Physics of Erbium-Doped Fiber Amplifiers," to appear in *IEEE J. Selec. Areas Quantum Electr.*