Transient gain dynamics in long-haul transmission systems with electronic EDFA gain control

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We report our investigations on the impact of transients stemming from channel reconfiguration or network failure. Erbium-doped fiber amplifier (EDFA) gain dynamics are considered by an average-inversion-level model. The simulation model is also verified by laboratory experiments. In extensive simulations, optimal sets of parameters for an electronic EDFA gain controller have been determined. We show that better results can be obtained if the gain controller is optimized for a chain of EDFAs and not a single amplifier only. Additionally, an efficient simulation methodology to calculate the combined bit error ratio (BER) is presented by coupling simulations of transient phenomena with bit-based simulations incorporating nonlinear fiber effects. © 2007 Optical Society of America

1. Introduction
In future agile transparent optical networks, frequent changes in channel load may be initiated by reconfigurable optical add/drop multiplexers (ROADM). Intended WDM channel switching may lead to total power changes of up to 19 dB (corresponding to a change in channel count from 80 to 1 channels or vice versa). Also in the case of component failures or fiber cuts, a large number of WDM channels may be lost within fractions of milliseconds. In both cases the remaining channels should be maintained within the given bit error ratio (BER) margins. This is why it is mandatory to effectively suppress undesired channel power changes, and why control strategies have been a subject of extensive research in the past.

In this paper we will focus on electronic gain control strategies of the erbium-doped fiber amplifier (EDFA). The paper is organized as follows. In Section 2 we introduce the simulation model, which has been used in our investigations. The numerical model is based on an average-inversion-level model for EDFAs [1,2]. We have verified our simulation model by laboratory experiments, which are presented in Section 3 and which yield excellent agreement with the numerical simulations. In Section 4 we focus on the optimization of the EDFA gain controller. It is shown that the gain control should be optimized for a cascade of amplifiers, and not only a single EDFA, to achieve best results also for long-haul transmission. In Section 5 we show a computationally efficient approach for how to combine simulations of transient effects with simulations of signal distortions on a bit level (e.g., fiber nonlinearities) to calculate a BER of the combined effects. We conclude our results in Section 6.

2. Simulation Model
For all simulations we have used the average-inversion-level model [1,2]. This model describes the gain dynamics of an EDFA by its total number of excited ions employing a simple first-order differential equation (ODE). The incorporation of the amplified spontaneous emission (ASE) is done by an extension according to [3].

The dynamic behavior of the EDFA can be modeled by the following equation [2]:
\[
\dot{r}(t) = -\frac{r(t)}{\tau} + \sum_{k=0}^{N} Q_{k}^{in}(t) \left[ 1 - e^{B_{k}(t) - A_{k}} \right].
\] (1)

In Eq. (1) \(r(t)\) is the total number of excited ions (the reservoir), and \(\tau\) is the fluorescence time (~10 ms). \(Q_{k}^{in}(t)\) denotes the photon fluxes of the signals (or the pump) with wavelengths \(\lambda_{k}\). Please note that in the average-inversion-level model the direction of the photons entering the doped fiber has no effect. The absorption coefficients \(A_{k}\) and the intrinsic saturation powers \(P_{k}^{IS}\) are linked to the parameters used in Eq. (1) as follows:

\[
A_{k} = \alpha_{k} \cdot L,
\] (2)

\[
B_{k} = \frac{h \cdot f}{P_{k}^{IS} \cdot \tau}.
\] (3)

In Eq. (3) \(h\) stands for Planck’s constant and \(f\) for the signal or pump frequency, respectively. The absorption coefficients \(\alpha_{k}\) can be determined by monochromatic measurement of the small signal transmission, and the intrinsic saturation power is defined as the power level where the attenuation is bleached by a factor of \(e\) (=4.34 dB). More details on the experimental determination of both factors are given in Section 3. We have used a fourth-order Runge–Kutta scheme to solve Eq. (1). The initial values are calculated from an iterative root-finding approach [4] with the assumption that the EDFA is in a steady-state condition at \(t=0\). The wavelength-dependent gain \(G_{k}(t)\) of the amplifier can be calculated from

\[
G_{k}(t) = \exp\left[B_{k} \cdot r(t) - A_{k}\right] = \frac{P_{k}^{out}(t)}{P_{k}^{in}(t)}.
\] (4)

So far ASE noise has been neglected. To account for the ASE generated inside the doped fiber, some additional terms have to be added [3]. These terms take into account the ASE fluxes at different wavelength bins.

To keep the gain constant at the desired level, a proportional-integral (PI) electronic feedback loop is deployed (Fig. 1). Electrical feedback control provides cost advantages compared to optical approaches, which is important for the component manufacturer and the system vendor. The reason for choosing a PI controller and leaving out a derivative term stems from the fact that the former type is less sensitive to power fluctuations induced by noise or even low-frequency components of the modulation spectrum.

Fig. 1. Setup of electronic feedback gain control, which adjusts the pump power. Total powers are obtained from 5% tap couplers before and after the EDFA.
The total input and output powers of the EDFA are obtained from 5% tap couplers. From these values the control deviation $e(t)$ is calculated, and the pump power is adjusted accordingly:

$$e(t) = 0.05[P_{in,tot}(t)G_{reference} - P_{out,tot}(t)],$$

$$P_{Pump}(t + 1) = P_{Pump}(t) + k_p e(t) + \frac{k_p}{\tau_i} \sum_{\tau=0}^{T_S} e(\tau).$$

In Eq. (6) $k_p$ and $\tau_i$ denote the proportional gain and the integral time, respectively.

In our simulations the effect of spectral hole burning (SHB) has not been considered. The reason has been to keep the investigations simple and not to include second-order effects. In the literature several publications deal with the impact of SHB on long-haul transmission systems (e.g., [5,6]). However, up to this time no closed model for SHB has been presented, and the published models have the drawback that a very small deviation of the parameters may lead to a rather large combined error. For the system designer it may be an option to leave out some parts of the transmission band, which are worst affected by SHB, if the transmission band is not fully occupied.

### 3. Experimental Verification

To verify the numerical simulation model, laboratory experiments have been conducted. In the experiment we cascaded eight EDFAs, which have been operated in constant pump power mode (Fig. 2). After each EDFA we inserted a variable optical attenuator (VOA), which compensates for the amplifier gain so that the input power into each EDFA is identical.

In a first set of monochromatic measurements the absorption coefficients and intrinsic saturation powers of the deployed EDFAs have been measured. The results are given in Table 1.

In the experiment four wavelengths have been used. CW channels have been located at 192.7 THz, 192.3 THz, 192.1 THz, and 192.5 THz. The 192.5 THz channel remained switched on at all times whereas the other channels could be switched on and off with rise and fall times below 1 $\mu$s. To investigate a 3 dB drop in power, the remaining channel has been set at a power level that has been three times as high as the other channels. The total input power into the EDFA has been set to $-3$ dBm. The EDFA operated in the constant pump power regime with a total output power of approximately 13 dBm.

![Fig. 2. Experiment setup.](image)

<table>
<thead>
<tr>
<th>$f$ [THz]</th>
<th>192.1</th>
<th>192.2</th>
<th>192.5</th>
<th>192.7</th>
<th>192.9</th>
<th>193.0</th>
<th>193.1</th>
<th>193.2</th>
<th>193.4</th>
<th>193.5</th>
<th>306.1</th>
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<tbody>
<tr>
<td>$\alpha_b$ [1/m]</td>
<td>0.105</td>
<td>0.105</td>
<td>0.113</td>
<td>0.116</td>
<td>0.117</td>
<td>0.117</td>
<td>0.12</td>
<td>0.123</td>
<td>0.123</td>
<td>0.123</td>
<td>0.3</td>
</tr>
<tr>
<td>$P_{IS}$ [mW]</td>
<td>0.365</td>
<td>0.365</td>
<td>0.350</td>
<td>0.339</td>
<td>0.330</td>
<td>0.322</td>
<td>0.320</td>
<td>0.316</td>
<td>0.31</td>
<td>0.308</td>
<td>0.304</td>
</tr>
</tbody>
</table>
As can be seen from Fig. 3, the experiment and the simulation show excellent agreement. In further investigations a demultiplexer filter has been inserted before the oscilloscope. The transmission spectrum of the filter has been Gaussian-shaped (second-order) with a FWHM bandwidth of 50 GHz. The results are depicted in Fig. 4. Again, a very good agreement between the simulations and the experiments can be observed. Also for the addition of channels, good agreement between simulation and experiment has been shown. For the system designer, however, transients induced by power drops are more important because they may originate from (very fast) network failures.

4. Optimization of Controller Parameters

In further investigations the automatic gain control (AGC) has been analyzed. The goal is to determine how AGC parameters for a long EDFA cascade (which is the common case in long-haul transmission systems) can be optimized.

In a first step, the transient behavior of cascaded single- and cascaded double-stage EDFAs has been compared. The single-stage amplifier operated with a gain of 26 dB and a total output power of 21 dBm. The gain of the first stage of the double-stage amplifier has been set at \(G=15\,\text{dB}\). The midstage device exhibited an attenuation of 10 dB, and the second stage operated with a gain of \(G=21\,\text{dB}\). As an example, the results for a 3 dB drop in power with a fall time of 5 ms are depicted in Fig. 5. For the double-stage E DFA the same controller parameters have been chosen as for the single-stage amplifier \((k_p=60, \tau_i=4.5\,\text{ms})\). As can be seen from Fig. 5 the maximal overshoots for both devices are approximately the same. The double-stage amplifier shows slightly increased overshoots. The reason may be that both stages used the same controller parameters, which have been optimized for the single-stage EDFA. Both EDFAs reached a 0.2 dB margin around the desired gain within below 0.7 ms after 20 cascaded EDFAs. Therefore, to speed up simulation, in the following all results are given for single-stage EDFAs only.
To guarantee the desired service level (or BER margins) it is essential that the individual channel powers remain more or less fixed at the desired power level. That is why the EDFAs need an AGC in WDM operation. As already mentioned, in this paper an electrical feedback loop (Section 2) is deployed to control the pump power. In extensive simulations the controller parameters have been analyzed for different scenarios relevant for practical applications.

As an example for a network failure, the results for a 3 dB power drop within 5 μs are depicted in Fig. 6. Such a fast power drop may be seen as the worst-case scenario when a fusion splice is breaking [8]. Our investigations show that the optimal choice of controller parameters differs for single EDFAs and EDFA cascades. We assumed the controller parameters to be the same for all EDFAs deployed in the network. In
automatically switched optical networks the origin of different WDM signals may not be the same. That is why in optical networks it makes no sense to optimize the controller parameters for a certain position along the transmission link, as it is possible for point-to-point routes. For a single EDFA a high proportional gain factor may be chosen, which can suppress transient induced power excursions efficiently. A high proportional gain factor, however, may induce unwanted oscillations due to an insufficient phase margin of the controller, which may become detrimental in long EDFA cascades. From Fig. 6 it can be concluded that for the regarded system a proportional gain factor $k_p < 60$ and an integrator constant of $\tau > 1$ ms lead to a good performance.

5. Combination of Transient and Bit-Based Simulations

At this point an efficient simulation methodology shall be presented based on the previous investigations, combining the results of the transient simulations with bit-based simulations taking into account the nonlinear fiber effects by solving the nonlinear Schrödinger equation (NSE) [9,10]. Conventional simulations solving the NSE with the split-step Fourier (SSF) method operate on a time scale of only a few nanoseconds (equivalent to several hundred bit intervals). Transient events, however, occur on a time scale of microseconds to several milliseconds. Due to the prohibitively long simulation time and the high computational effort, it is not desirable to conduct SSF simulations for transient events over a couple of milliseconds.

As a computationally more efficient approach we propose the following procedure. Our idea is to conduct a simulation of the transients in a first step. This simulation may also incorporate the nonlinear effect of (time averaged) stimulated Raman scattering (SRS), which will lead to a spectral tilt of the WDM channels when the number of channels changes. In a second step, based on the results of the transient simulation, a few time instances are selected for which a bit-based simulation is started (Fig. 7). As an example the maximal overshoot, the maximal undershoot, and the steady-state may be selected. At these time instances the spectral characteristics of the signal and noise are exported to the bit simulation. In the bit simulations these values are imported at all positions where an EDFA is located. The bit-based simulation may assume the amplifier characteristics to remain constant (both in time and spectrum) because during the simulation time interval of only a few nanoseconds the average power spectral characteristics do not change. Additionally, it is possible to manually set the decision threshold of the receiver. In our simulation we assumed that the decision threshold is fixed and has been optimized for the steady-state case before the transient event.

As an example a 107 Gbit/s regional system has been investigated. The system setup is depicted in Fig. 8. We assumed a 40 channel system with $\Delta f = 100$ GHz. For higher spectral efficiency duobinary modulation has been used [11]. The span length has been set to 50 km. The dispersion map employed a precompensation of $-160$ ps/nm and an inline undercompensation of 22 ps/nm/span. The dispersion has...
been perfectly compensated by the post dispersion compensation fiber (post-DCF) at the receiver. We have chosen a conservative optical signal-to-noise ratio (OSNR) value of 38 dB at the transmitter and assumed the noise figure (NF) of the EDFAs to be NF = 5.5 dB. The launch power into the transmission fiber was 3 dBm/ch.

In a first set of simulations the AGC has been turned off (constant pump power regime). The results are depicted in Fig. 9. It is clearly visible that for a 10 dB drop in power the transmission is feasible over a maximum of only two spans. In the case of a 6 dB power drop a transmission distance of four spans is achievable, and a 3 dB power dropping ratio enables transmissions over eight spans to remain below the forward error correction (FEC) limit. For all BER curves the worst-case channel has been plotted. It can be concluded that for a reconfigurable (and failure safe) transmission system AGC is mandatory.

Up to this point the transient impairments, which are introduced by SRS, have not been addressed. SRS causes energy transfer between signal channels in the transmission fiber, which results in a tilt of the channel power distribution. If the system operates in the desired steady-state condition, the SRS tilt is usually compensated by filter components with inverse characteristics or dynamic gain tilt in EDFAs. However, any change of the number of active channels is a potential source of Raman tilt changes leading to transients. The impairments are worst for a group of channels activated or deactivated at the edges of the used wavelength spectrum with a single edge channel surviving. The transition time of the SRS transients equals the transition time of the switching event (which can be very fast in the case of failure). In the literature several studies suggest different concepts of how to compensate for SRS-induced transients (e.g., [12,13]). In this paper we consider the SRS-induced impairments as an additional effect, which is not compensated. We show that in the investigated regional
transmission system SRS-induced transient effects lead to an additional penalty, which may be tolerated if the transmission distance is limited to only a few spans.

The results for the simulation incorporating both transient effects (SRS and EDFA transients) with active AGC are shown in Fig. 10. Because the investigated transmission system is OSNR-limited, the transient-induced undershoot is the limiting factor in this case (compare Fig. 7). When only EDFA transients are taken into account and SRS is neglected (Fig. 10, black squares), the BER is increasing only slightly. For the simulations incorporating SRS impairments it has been assumed that the spectrum is flat, if it is fully loaded (by appropriate filtering). For the 10 dB power drop it has been assumed that 36 channels at the blue side of the spectrum are dropped due to a component failure within 160 μs. The remaining four channels at the red side of the transmission spectrum now lack the “pumping” from the higher frequency channels, and the channel power decreases. Additionally, the AGC of the EDFA introduces an undershoot in the transition period before the steady-state is reached again. For the regarded transmission system the achievable reach is reduced to eight spans, if an FEC limit of BER < 10⁻³ is assumed, which is acceptable for a regional system (Fig. 10, blue triangles).

6. Conclusion

We have investigated the transient behavior in long-haul and regional transmission systems originating from desired switching of WDM channels or unintentional network failure. An average inversion level model, which has been verified in laboratory experiments, has been employed to simulate EDFA transients. Numerical simulations showed that the automatic gain controller parameters should be optimized for a cascade of EDFAs instead of single amplifiers. We presented a computationally efficient approach of how to combine transient and bit pattern simulations. The impact of EDFA and SRS transients has been investigated for a 107 Gbit/s regional transmission system, showing that electronic AGC enables transient proof transmission over eight spans.

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References