Modeling Gain Dynamics in EDFAs: Space-Resolved Versus Lumped Models

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We present a detailed comparison of dynamic space- and frequency-resolved and lumped erbium-doped fiber amplifier (EDFA) models. The space- and frequency-resolved models are based on an iterative solution of propagation equations for pump, multiple signals, and spectral components of forward and backward propagating amplified spontaneous powers and rate equations for pump, metastable, and ground energy level population densities of erbium ion. In contrast to space-resolved models, the lumped model solves a single ordinary differential equation for time evolution of the length-averaged metastable level population and is therefore substantially less computer time consuming. Both the space, and frequency-resolved and the lumped models give almost identical results when used for an analysis of surviving channel power excursions in concatenated EDFAs fed by multiwavelength signal and add/drop scenarios. For a statistical analysis of output power and signal-to-noise ratio fluctuations in EDFA cascades fed by burst-mode packet traffic, only lumped models can be used.

Keywords  optical communications, optical fiber amplifiers, wavelength division multiplexing

The erbium-doped fiber amplifiers (EDFAs) are essential devices for many optical communication applications, and in the last 12 years much theoretical effort has been devoted to their optimization and analysis. Due to a relatively long lifetime in the \( ^{4}I_{13/2} \) metastable energy level in erbium (10.4 ms; cf. 1 ns for semiconductor amplifiers), transmission of high-bitrate data is undisturbed by signal modulation and EDFA does not cause intersymbol interference in single-channel systems or interchannel cross talk in wavelength-division multiplexed (WDM) systems. For the above reason, steady-state EDFA models have been used in the past for optimization of waveguide parameters of Er\(^{3+}\)-doped fiber (EDF) for small-signal
and large-signal operation of the EDFAs. The most complex steady-state EDFA models are the space- and frequency-resolved ones based on the numerical iterative solution of rate equations for population densities at the $^4I_{11/2}$ pump energy level (or $^4I_{13/2}$ level in case of resonant pumping), $^4I_{13/2}$ metastable level, and $^4I_{15/2}$ ground energy level of Er$^{3+}$ ion and propagation equations for pump, signal, and spectral components of forward and backward propagating amplified spontaneous emission (ASE) powers [1, 2, 3, 4]. In order to limit the number of propagation equations and save some CPU time, ASE spectral components in some space-resolved models were replaced with a signal ASE channel and an equivalent noise bandwidth [5, 6].

Further reduction of computer time has been achieved with lumped EDFA models. They either solve several transcendental equations for individual output signal powers [7] or a single transcendental equation for length-averaged metastable level population [8, 9]. The first lumped models assumed that the amplifier is not self-saturated by its own ASE and were not accurate enough for simulation of small-signal EDFA operation. The effect of ASE was taken into account in later versions of lumped models [10, 11]. Both the space-resolved and lumped models use fundamental fiber and Er$^{3+}$ spectroscopic parameters such as the numerical aperture and core radius of the fiber, erbium atom density, and the absorption and emission cross sections at each wavelength, which are difficult to obtain. Recently, black box EDFA models were proposed [12, 13] for system modeling. The one proposed in [12] is based on gain tilt function and equivalent ASE noise. The disadvantage of this approach is that many additional measurements are required. For the black box model of [13], the gain and noise figure of EDFA can be fully characterized if the small-signal gain and noise figure in the wavelength range of 1530–1565 nm and two sets of gain-saturation and noise figure-saturation characteristics at any two wavelengths are known. The black box models deliver steady-state characteristics of the EDFA only.

The first temporal EDFA models were presented in the early days of EDFA simulation [14, 15]. In connection with the discovery of fast power transients in networks of EDFAs, much attention has been devoted to EDFA dynamics in the last three years. In multiwavelength amplified lightwave networks, the number of transmitted channels may vary due to, e.g., network reconfiguration or failure of a channel. Gain-cross-saturation in fiber amplifiers will induce power transients in the surviving channels, which can cause service impairment not known in electronically switched networks. As fiber amplifiers saturate on a total power basis, channel addition or removal in a multiaccess network will tend to perturb signals at other wavelengths that share all or part of the route. Although this perturbation will generally be small and slow in a single amplifier, it will grow rapidly along a cascade. The resultant effective rise/fall time constants are reduced to the order of microseconds. Recent traffic measurements from working packet networks (including Ethernet local area networks, wide area networks, integrated services digital networks, and variable bit rate videos over asynchronous transfer mode) have shown features of self-similarity: that is, realistic packet network traffic looks the same when measured over time scales ranging from seconds to minutes and hours [16, 17, 18]. It has been concluded that the superposition of many ON/OFF sources or packet-trains with strictly alternating ON- and OFF-periods with infinite variance produces aggregate network traffic that is self-similar. When such packet traffic is directly transmitted in burst-mode on the WDM channels, as in the case of internet protocol (IP) over WDM, long interburst idle intervals may give enough time to fiber amplifiers to reach gains greatly exceeding the average values. This can in turn lead to significant
variation in output power and optical signal-to-noise ratio (OSNR). This effect accumulates along a cascade of fiber amplifiers in the same way as the fast power transients in the circuit-switching scenario. The dynamics of EDFAs and cascades of EDFAs may have an important impact on the performance of WDM systems, and several schemes have been suggested to protect the surviving channels in add/drop scenario or WDM channels with burst-mode packet traffic [19, 20, 21, 22, 23].

With the increased interest in EDFA dynamics, temporal models were necessary to help understand and predict power and signal-to-noise transients in concatenated fiber amplifiers fed by multiwavelength traffic. The first temporal EDFA models [14, 15] were space- and frequency-resolved, and their application for multichannel WDM systems with concatenated EDFAs would demand a lot of CPU time. In [8] the set of rate equations and coupled partial differential equations describing the propagation of pump, signals, and spectral components of ASE was reduced to a single ordinary differential equation for time variation of the length-averaged metastable level population. This model is an extension of the steady-state lumped model of [7]. In the steady-state case, the ordinary differential equation becomes a transcendental equation. Excited state absorption and saturation induced by the amplified spontaneous emission generated inside the amplifier have been neglected. Application of this temporal lumped EDFA model to fast power transient simulation in cascades of EDFAs fed by multiwavelength add/drop and burst-mode packet switched signal has been presented in [8, 9]. We extended the dynamic lumped models [8, 9] by taking into account the effect of ASE, which enables us to calculate the fluctuations of OSNR [23]. Although different types of steady-state EDFA models are now commercially available, dynamic models have not yet been incorporated in these packets. In this paper we compare the limits of applicability of space- and frequency-resolved and lumped dynamic EDFA models for simulation of transient effects in concatenated fiber amplifiers fed by multiwavelength signals.

Numerical Models

Our space- and frequency-resolved dynamic (SFRD) model is based on a three-level approximation of an erbium ion and was described in detail in [24]. Homogeneous broadening of the stark-split energy levels of Er$^{3+}$ is assumed. The time evolution of atomic population densities $n_1$, $n_2$, and $n_3$ at the $^4I_{15/2}$ ground level, $^4I_{13/2}$ metastable level, and $^4I_{11/2}$ pump energy level (when pumped at 980 nm) is given by rate equations. Propagation of pump, multiple signals, and spectral components of both the forward and backward propagating ASE powers is described by a set of coupled nonlinear differential equations. For the numerical solution of the time-dependent rate equations, an assumption is made that the atomic populations remain constant during a time step $\delta t$ of several $\mu s$, and the solution is separated into two steps: a spatial integration with population densities fixed during the time interval $\delta t$, followed by a time integration. Steady state solutions to the rate equations are used as an initial condition for the subsequent time evolution. The backward ASE$^-$ and the counterdirectional pumping scheme introduce a two-boundary-value problem, which leads to the necessity of iterative forward and backward integrations in the fiber. For these integrations the fourth-order Runge–Kutta method has been used. To fulfill the boundary conditions at both ends of the active fiber, 5 to 45 iterations are necessary depending on input signal and pump powers and pump
configuration. For the time integration, closed form solution to propagation equations is used, so that application of Runge–Kutta routine and iterative solution are not necessary.

We will compare the results of the SFRD EDFA model with simulations performed with the dynamic lumped model (DL1) of [9], which neglects the generation of ASE within the amplifier, and with a more accurate dynamic lumped model (DL2) of [23]. Both lumped models are based on a two-level Er³⁺ atomic approximation, homogeneous line broadening and absence of excited-state absorption. All emission and absorption cross sections included in the SFRD and DL2 models are spectrally resolved. The spectral region from 1450 to 1650 nm has been resolved in \( M \) bins of constant width \( \Delta \lambda \). Let \( \mathcal{A} \) denote the set of all ASE bins, and \( S \) denote the set of bins on which the WDM signals and the pump fall (the bin width is small enough such that at most one signal per bin is present, located at its center). The DL1 model solves a first-order differential equation ((eq. 5) of [9])

\[
\frac{d}{dt} r(t) = \frac{-r(t)}{\tau} + \sum_{i \in \mathcal{A}} Q_{i}^{\text{in}}(t)[1 - G_{i}(r(t))],
\]

where

- \( \tau \) is the spontaneous lifetime of the metastable level;
- \( Q_{i}^{\text{in}} \) is the pump \( (i = 0) \) and signals \( (i = 1, \ldots, N) \) photon flux [ph/s] entering doped fiber at wavelength \( \lambda_{i} \) corresponding to wavelength bin \( i \); 
- \( G_{i}(r(t)) = \exp(B_{i}r(t) - A_{i}) \) is the gain at \( \lambda_{i} \) of EDFA, where \( A_{i}, B_{i} \) are nondimensional coefficients, dependent on frequency \( v_{i} \) through the erbium ions absorption and emission cross sections:

\[
A_{i} \triangleq \alpha_{i} \ell, \quad B_{i} \triangleq (g_{i} + \alpha_{i})/(\rho A_{\text{eff}}),
\]

\( \rho \) being the erbium concentration \([\text{m}^{-3}]\), \( A_{\text{eff}} \) the effective area of the doped part of fiber \([\text{m}^2]\), \( \ell \) the length of the doped fiber \([\text{m}]\), \( \alpha_{i} \triangleq \rho \Gamma_{i} \sigma_{i}^{a} \) and \( g_{i} \triangleq \rho \Gamma_{i} \sigma_{i}^{e} \) the absorption and emission constants, \( \Gamma_{i} \) the confinement factor at \( \lambda_{i} \) calculated by the overlap integral between the radial distribution of the \( LP_{01} \) mode intensity and the erbium ions doping distribution and \( \sigma_{i}^{a} \) and \( \sigma_{i}^{e} \) \([\text{m}^2]\) the absorption and emission cross sections at \( \lambda_{i} \), respectively.

In contrast to the DL1 model, in the DL2 model, the amplified spontaneous emission is taken into account in accordance with [25]. We arrive at a first-order ordinary differential equation describing the dynamic time behavior of \( r(t) \):

\[
\frac{d}{dt} r(t) = \frac{-r(t)}{\tau} + \sum_{i \in \mathcal{A}} Q_{i}^{\text{in}}(t)[1 - G_{i}(r(t))] - \sum_{i \in \mathcal{A}} 4n_{\text{sp}}^{i}(r(t))[G_{i}(r(t)) - 1] \Delta v_{i}.
\]

- \( Q_{i}^{\text{in}}(t) \) is now the signal or pump \( (i \in \mathcal{S}) \) or external ASE photon flux \( (i \in \mathcal{A}) \) entering doped fiber at wavelength \( \lambda_{i} \) corresponding to wavelength bin \( i \).
Signal fluxes are distinguished from ASE fluxes even when occupying the same wavelength bin, in order to be able to evaluate the OSNR at the doped fiber output:

\[ n_{sp}^i (r(t)) = \frac{g_r(r(t))}{(g_i + \alpha_r) r(t) - \alpha_i A_{eq}} \]  

is the spontaneous emission factor, and the summation in which it appears in eq. (2) represents the ASE-generated inside doped fiber, the factor 4 representing two polarization components for both forward and backward ASE; \( \Delta v_i \) is the frequency width [Hz] of wavelength bin \( i \).

The numerical solution to the time dependent eqs. (1, 2) is separated into two steps: first, the steady state value of \( r \) is determined for continuous wave (CW) input signals, followed by a time evolution of \( r(t) \) with add/drop or burst-mode WDM traffic at the input to doped fiber, \( Q^i_{in} \), \( i \in S \). To obtain a steady-state value of \( r \), a transcendental equation derived from eqs. (1, 2) by setting \( dr(t)/dt = 0 \) is solved numerically.

Both the SFRD and the DL2 models give the spectrally resolved ASE power at the output of the EDFA. The noise performance of the EDFA is characterized by the noise figure \( F \), defined as a ratio between optical signal-to-noise ratio (OSNR) at the input and OSNR at the output of the amplifier. For the case of a coherent signal at the EDFA input and an optical band pass filter with a transmission characteristic \( H(\nu) \) in front of the photodetector, the EDFA noise figure at signal frequency \( \nu_i \) is given by

\[
F = \frac{1}{G} \left[ 1 + \frac{\int_0^\infty P_{\text{ASE}+}(\ell, \nu) H(\nu) d\nu}{\nu_i GP_{\text{ASE}}} + \frac{P_{\text{ASE}+}(\ell, \nu)}{\nu_i GP_{\text{ASE}+}} \right]
\]  

where \( P_{\text{ASE}+}(\ell, \nu) \) is the spectral power [W] of the forward propagating ASE at the end of the Er\(^{3+}\)-doped fiber contained in one bin \( \Delta \lambda \), \( P_{\text{ASE}}^{in} \) is the signal power at the input of doped fiber. The first and the second terms in eq. (3) represent the signal and the ASE shot noise, the third and the fourth terms, the signal-ASE and the ASE–ASE beat noise, respectively. The predetector filter is assumed to have a Gaussian shape with a 3 dB bandwidth of 1 nm. The OSNR at the output of the amplifier is also calculated.

**Simulation Results**

We consider a typical Lucent Technologies erbium-doped fiber (EDF) pumped at either 980 or 1480 nm. As already mentioned, the steady-state solutions to the rate equations (eq. (1) of [24]) or to eqs. (1, 2) are used as an initial condition for the subsequent time evolution. Therefore, we will first compare the steady state characteristics obtained by the SFRD and the DL1, DL2 models. Figure 1 shows the gain and noise figures at signal wavelength \( \lambda_s = 1550 \text{ nm} \) as a function of input signal power, \( P_{\text{in}}^{in} \), for \( \ell = 30 \text{ m} \) of EDF pumped by \( P_p = 30 \text{ mW} \) at \( \lambda_p = 980 \text{ nm} \). Codirectional and counterdirectional pump configurations have been considered for the SFRD model. As expected, the small signal gain (\( P_{\text{in}}^{in} < -30 \text{ dBm} \)) of the codirectionally pumped EDF is slightly higher (0.1 dB) than that of the counterdirectionally pumped one. The reason is the stronger saturation of the counterdirectionally
pumped amplifier by the ASE peak around 1530 nm. The codirectional pump configuration gives a lower noise figure than the counterdirectional configuration, independent of input signal power. As the dynamic lumped model DL2 calculates the overall ASE power developed within the amplifier and divides it equally into the forward (ASE+) and backward (ASE−) components, the small signal gain calculated by the DL2 model is 1.5 dB higher than that obtained by the SFRD model. The noise figure calculated by the DL2 model is 0.2 dB higher than that of the counterdirectionally pumped EDFA and 1.5 dB lower than that of the codirectionally pumped EDFA at $P_{\text{in}} < -30$ dBm. The DL1 model does not take into account the generation of ASE power within the amplifier. Therefore, the small signal gain is not saturated by the ASE and, at $P_{\text{in}} = -50$ dBm, it is 18 dB higher than the gain calculated by the SFRD model. At $P_{\text{in}} = -10$ dBm the difference in gain calculated by the SFRD, DL1, and DL2 models is less than 0.5 dB. Spectral distribution of the ASE+ power density at the output port of the EDFA calculated by the SFRD model for the co- and counter-directional pump configuration and by the DL2 model for $P_{\text{in}} = -40$ and 0 dBm are shown in Figures 2a, 2b, respectively. The complete simulation of the 13 points of the gain/input signal power characteristic shown in Figure 1 requires 5 minutes with the SFRD model and only three s with the DL1 or DL2 models on Pentium III 667 MHz PC.

Next, let us compare the results of add/drop simulation obtained with SFRD, DL1, and DL2 models. We will consider a cascade of six identical EDFAs ($\ell = 30$ m, $P_p = 30$ mW, $\lambda_p = 980$ nm, $\lambda_s = 1550$ nm); □: SFRD model, codirectional pump; ○: SFRD model, counterdirectional pump; ◆: DL1 model; ●: DL2 model.

Figure 1. Gain and noise figure as a function of input signal power ($\ell = 30$ m, $P_p = 30$ mW, $\lambda_p = 980$ nm, $\lambda_s = 1550$ nm); □: SFRD model, codirectional pump; ○: SFRD model, counterdirectional pump; ◆: DL1 model; ●: DL2 model.
Figure 3 shows the power variation at the output of EDFA no. 1 and no. 6 as a function of time for the surviving channel at $\lambda_s = 1547$ nm when 6 out of 8 WDM channels are switched off at $t = 0.125$ ms and are on again at $t = 0.625$ nm. Surviving channel power fluctuations at the output of EDFA no. 1 obtained with all three models are almost the same (the steady-state power increase $\Delta P = 1.9$ mW, the rise-time $\tau_r = 280$ $\mu$s, the fall-time $\tau_f = 210$ $\mu$s). After EDFA no. 3 and the successive amplifiers, an initial power overshoot/undershoot develops after channels are switched off/on. The speed of the power transient increases along the cascade, 90% of the steady-state power increase is reached after 45 $\mu$s at the output of EDFA no. 6, independent of the model used. Forward propagating ASE is amplified when traveling along the cascade, part of the excited $\text{Er}^{3+}$ ions is wasted, and the gain of successive amplifiers is reduced. Therefore, the DL1 model which disregards the generation of ASE power gives the highest surviving channel power excursion at the output of EDFA no. 6, $\Delta P = 5.5$ mW while the DL2 model, which in comparison with the SFRD model overestimates the ASE$^+$ power, exhibits the lowest surviving

Figure 2. Spectral distribution of ASE$^+$ power density at the output of EDFA ($\ell = 30$ m, $P_p = 30$ mW, $\lambda_p = 980$ nm, $\lambda_s = 1550$ nm): (a) $P_{in} = -40$ dBm; (b) $P_{in} = 0$ dBm.
channel power overshoot and steady-state power increase, $\Delta P = 3.3\, \text{mW}$. Simulation results obtained with the SFRD and the DL2 models are in qualitative agreement with our experimental results [24] shown in Figure 4. In the experimental setup, six Corning FGM-S-035 EDFAs were concatenated with five 20 dB fiber attenuators. The six dropped/added channels were represented by one channel at 1551.1 nm with power at the input of EDFA no. 1 of $P_{1551.1}^{in} = -12.2\, \text{dBm}$, the two surviving channels were replaced by a c.w. signal at 1556.3 nm with input power of $P_{1556.3}^{in} = -17\, \text{dBm}$. The add/drop modulation frequency was 500 Hz.

Simulation results of time evolution of the length-averaged metastable level population, $r(t)$, of the EDFA no. 6 corresponding to removal/addition of six out of eight WDM channels are shown in Figure 5. It is seen that the DL1 model gives the highest population inversion with the largest $r(t)$ swings.

When channels are dropped at $t = 0.125\, \text{ms}$, the surviving channel power starts to increase, which results in the improvement of the OSNR. Due to the concurrent increase in ASE, the surviving channel OSNR fluctuations are lower than those of the output power. Fluctuations of the OSNR at the output of EDFA no. 6

Figure 3. Power variation at $\lambda_s = 1547\, \text{nm}$ as a function of time at the output of EDFA no. 1 and no. 6 when six out of eight channels are dropped/added.

Figure 4. Power variation at $\lambda_s = 1556.3\, \text{nm}$ as a function of time at the output of EDFA no. 1 and no. 6, when six out of eight channels are dropped/added (experiment).
corresponding to removal/addition of six out of eight WDM channels are displayed in Figure 6. As the DL2 model slightly overestimates the forward propagating ASE, the steady-state OSNR increase is 0.3 dB lower compared with the SFRD model.

The above simulation of channel removal/addition in a cascade of six EDFA s with eight WDM channels has been performed over five periods of square wave modulation, which represents integration over 1,000 time steps. The simulation performed with the SFRD model takes seven minutes of CPU time on a Pentium III 667 MHz PC, while it lasts only three seconds when DL1 or DL2 models are used. The disadvantage of the DL2 model is that, compared with the SFRD model, it overestimates the ASE power, which results in lower surviving channel power and OSNR fluctuations. The DL1 model cannot be used for evaluation of OSNR fluctuations because it does not take the generation of ASE power into account. The advantage of both the DL1 and DL2 models with respect to the SFRD model is more than two orders of magnitude shorter run time.

Dynamic EDFA models were also used for a theoretical analysis of output power and OSNR fluctuations in cascades of EDFA s caused by the variability of

![Figure 5](image_url)  
**Figure 5.** Time evolution of the length-averaged metastable level population of EDFA no. 6 when six out of eight WDM channels are dropped/added.

![Figure 6](image_url)  
**Figure 6.** OSNR variation at $\lambda_s = 1547$ nm as a function of time at the output of EDFA no. 6 when six out of eight channels are dropped/added.
burst-mode packet-switched traffic transmitted over WDM channels. It has been shown that the high variability of ON/OFF times in packetized links may lead to self-similarity in the aggregate traffic [16, 17, 18]. When no signal is transmitted on long inter-burst idle intervals, fiber amplifiers may have enough time for substantial swings in gain [27, 28]. In the following, we will demonstrate an application of the SFRD and DL2 models for an analysis of transmission of burst-mode, 10 Mb/s local area network (LAN) traffic on three WDM channels over a cascade of five EDFAs (\( \ell = 27 \) m, \( P_p = 36 \) mW, \( \lambda_p = 1480 \) nm) concatenated with four 20 dB attenuators that represent the loss of transmission fibers. The three WDM channels were placed at 1549, 1551, and 1553 nm with input power/channel to the first EDFA of \( P_{in}^{1} = -14.8 \) dBm/channel. Continuous wave signal at 1556 nm with input power of \( P_{in}^{2} = -17 \) dBm to the first EDFA was used to monitor EDFA gain fluctuations. The ON/OFF sources simulating the time-slotted burst-mode WDM traffic were generated for each WDM channel using a random number \( U \) uniformly distributed on [0, 1] interval with a truncated Pareto distribution via

\[
T_{ON} = T_{slot} \left[ \frac{1}{U^{1/a_{ON}}} \right], \quad T_{OFF} = T_{slot} \left[ \frac{1}{U^{1/a_{OFF}}} \right],
\]

where \( a_{OFF} \) and \( a_{ON} \) are parameters regulating the burstiness of the traffic, and \( \lfloor x \rfloor \) is the floor function. The ON intervals represent the presence of packets, the OFF intervals represent idle periods. Time slot length of \( T_{slot} = 57.6 \) \( \mu s \), corresponding to 65 bytes packets of 10 Mb/s IP, was selected to simulate the traffic. The monitoring channel power was sampled at 100 points per \( T_{slot} \). The resultant time step was \( \delta t = 0.576 \) \( \mu s \), and \( a_{OFF} = a_{ON} = 1.2 \) were chosen for the ON and OFF periods for each WDM signal, leading to infinite variance for these time periods. Optical noise with Poisson distribution and amplitude equal to ASE power has been added to an instantaneous value of the monitoring channel power. Figures 7a, 7b show a short time segment of 30 ms of the monitoring channel power evolution at the output of EDFA no. 1 and no. 5 obtained by the SFRD model. This simulation represents integration over more than 52,000 time steps and takes 124 minutes of CPU time on a Pentium III 667 MHz PC. We can compare the simulation results with experimental ones [26]. In our experimental setup, electrical signals at 10 Mb/s from three Ethernet Hubs carrying the traffic of the COPL LAN were converted to optical signals in three Ethernet transmitters. At least three personal computers were connected to each Hub. The traffic was generated by copying long data files between personal computers and servers, playing video files stored in another computer, and transferring files with ftp. Optical signals from three Fujitsu DFB lasers tuned to 1549.1, 1551.1, and 1552.9 nm were combined in 3 dB directional couplers with a continuous wave monitoring channel power at \( \lambda_{cw} = 1556.3 \) nm and fed to the input port of EDFA no. 1. An optical band pass filter was used to select the 1556.3 nm wavelength power from the output spectrum of an EDFA. PIN FET photodetector and a data acquisition card were used to process the time variable monitoring the channel signal. In order to acquire fast power transients after amplifier no. 5 caused by the CW channel power over- and undershoots, sampling rate of 1 MHz has been selected. Two-second-long samples of the CW channel power have been recorded and stored in a PC. Figure 8 shows a zoomed interval from 105 to 145 ms of the monitoring channel power recorded at the output of EDFA no. 1. The insertion loss of the OBPF was subtracted. We have reached a qualitative agreement between the simulation and experimental results.
Due to the random nature of the input traffic in individual WDM channels, output power and OSNR fluctuations caused by gain-cross saturation must be evaluated statistically. The range of output power and OSNR fluctuations was divided into 100 bins of equal width and the occurrence of $P_{\text{out}}(t)$, $\text{OSNR}(t)$ within each bin counted, normalized, and divided by the bin width to obtain a probability density function (PDF). In order to get statistically significant results and to catch the influence of the heavy tails of the interpacket distribution, the simulation should be performed over more than 10 million time steps. Such as analysis, when performed with the SFRD model, would take more than 1050 hours. Therefore, the DL2 model must be used. Figure 9 shows the PDF of monitoring channel power at the output port of EDFA no. 1 and no. 5. The simulation has been performed with the DL2 model over 6s of bursty traffic and took 125 minutes.

Figure 7. Time evolution of monitoring channel power, SFRD model: (a) at the output of EDFA no. 1; (b) at the output of EDFA no. 5.
Conclusion

We have compared space- and frequency-resolved EDFA dynamic models with two lumped dynamic models. A cascade of six identical 20 dB gain EDFAs fed by a multiwavelength signal consisting of eight channels ranging from 1547 to 1554 nm with 1 nm spacing concatenated with five transmission fibers of span loss of 20 dB has been simulated. We have shown that both the SFRD model and the DL2 model can be used for the analysis of channel addition/removal in cascades of fiber amplifiers. In comparison with the SFRD model and codirectional pump configuration, the DL2 model slightly overestimates the ASE\(^+\) and gives smaller swings in surviving channel power and OSNR. Simulation results obtained with the SFRD and the DL2 models are in qualitative agreement with our experimental results [26]. The DL1 model which disregards the generation of ASE power and its propagation along the EDFA cascade cannot be used for an analysis of OSNR time evolution. Although the SFRD model requires 500 times more computer time than the DL2

Figure 8. Time evolution of monitoring channel power at the output of EDFA no. 1 (experiment).

Figure 9. Probability density function of the monitoring channel power at the output of EDFA no. 1 and no. 5, DL2 model.
model, the add/drop analysis of an eight channel WDM signal transmitted through a cascade of six EDFAs takes only seven minutes of CPU time on a Pentium III 667 MHz PC.

Results of the theoretical analysis of transmission of burst-mode, 10 Mb/s LAN traffic on three WDM channels over a cascade of five EDFAs have been presented. A continuous-wave signal was used to monitor EDFA gain fluctuations. The independent ON/OFF sources simulating the time-slotted burst-mode WDM traffic were generated for each WDM channel using a random number $U$ uniformly distributed on a $(0, 1)$ interval with a truncated Pareto distribution. Application of the SFRD model for the statistical evaluation of output power and OSNR fluctuations is impractical. In order to get statistically significant results and to catch the effect of the heavy tails of the interpacket distribution, such a simulation should be performed over more than 10 million time steps, which would require more than 1,000 h of computer time. Therefore, the DL2 model must be used. Simulation results obtained with the DL2 model are in reasonable qualitative agreement with experimental results.

References


Biographies

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