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Theoretical Analysis of Fast Gain-Transient Recovery of EDFAs Adopting a Disturbance Observer with PID Controller in WDM Network

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We have proposed an application of disturbance observer with PID controller to minimize gain-transient time of wavelength-division-multiplexing (WDM) multi channels in optical amplifier in channel add/drop networks. We have dramatically reduced the gain-transient time to less than 3 μsec by applying a disturbance observer with a proportional/integral/ differential (PID) controller to the control of amplifier gain. The theoretical analysis on the 3-level erbium-doped fiber laser and the disturbance observer technique is demonstrated by performing the simulation with co-simulation of the MATLAB^{TM} and a numerical modeling software package such as the Optsim^{TM}.

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I. INTRODUCTION

In wavelength-division-multiplexing (WDM) network with erbium-doped fiber amplifiers (EDFAs), the signal level of each WDM channel fluctuates after EDFA as the number of WDM channels to EDFA changes due to channel add/drops or active rearrangement of WDM networks. To minimize the gain-related errors at the receivers, the signal levels should be kept at the constant values. There are generally two methods for controlling the EDFA gain; an all-optical method and an electrical method. The former uses EDFA output as a feedback signal in an optical feedback control loop [1]. The latter controls the pump laser output electrically according to EDFA output signal level [2]. This is a generally accepted method in industry due to its simple, cheap and robust architecture. However, the main drawback of this scheme is that it generates big dips & spikes in gain in the process of gain recovery or gain flattening. In the previous paper, we proposed a novel technique which minimizes the gain-transient time to less than 3 μsec [3]. In our method, we applied a disturbance observer technique [4,5] with a proportional/integral/differntial (PID) controller to the control of EDFA gain in WDM add/drop networks. To prove the operation and the superiority of the new scheme, we first have made an EDFA gain control module by implemented by MATLAB and a numerical optical communication software package such as the Optsim^{TM} to get more accurate simulation results. In this paper, we provide the theoretical background of the 3-level EDFA rate equations and a disturbance observer technique. To prove the feasibility of the proposed technique in the WDM networks, we apply it to cascaded EDFA networks and show the simulation result.

II. THEORY

To minimize the transient-time, we have derived 3-level EDFA model [6,7]. Fig. 1 represents the 3-level energy model of the erbium-doped fiber amplifier. The erbium-ions at the ground state (level 1 in Fig. 1) are excited into higher energy level (level 3) by the pumping photon (980 nm wavelength), and then, quickly settle down into intermediate level (level 2) nonradiatively. The erbium ions at level 2 stay for around 10 ms and emit photons and come back the original energy level (level 1). In the photon-emission process described above, some of the photons are emitted spontaneously, finally

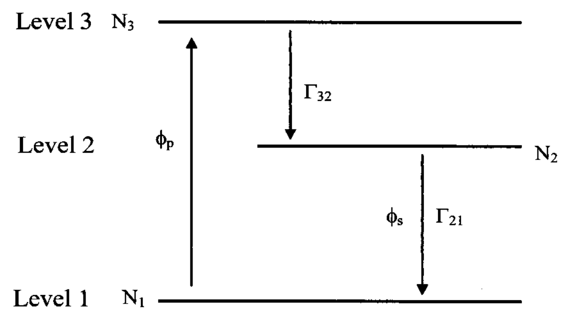


FIG. 1. 3-level energy model of EDFA.

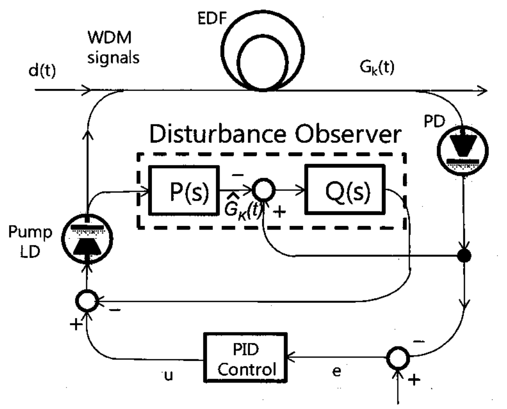


FIG. 2. Disturbance observer with PID controller for EDFA gain control.

becoming a noise source in the EDFA. Others are generated by the stimulated emission due to the signal photon input in the EDFA. The equations for the EDFA plant model are derived in Appendix A.

The schematic diagram of the system is shown in Fig. 2. We consider the random add/drop process as a disturbance ($d(t)$ in Fig. 2), and make the pump laser be prepared to this disturbance ($d(t)$ in Fig. 2) in advance so that the dips & spikes become minimized when the actual control takes place.

In Fig. 2, $Q(s)$ is a filter which makes the characterisitics of transfer function of whole disturbance observer be the same as low-pass filter. $G_k(t)$ is the gain with a disturbance, i.e. the channel variation, $\widehat{G}_k(t)$ is the gain without any disturbance. Eqns. (A.2-A.5) in Appendix describe the functions $P(s)$, $Q(s)$, $G_k(s)$ in eqn.(1).

$$P(s)Q(s) = \frac{\omega_n^2}{s^2 + 2\xi\omega_n s + \omega_n^2}, \quad Q(s) = \frac{\omega_n^2}{\Gamma_{32}B_k}\frac{(s+\Gamma_{32})(s+\Gamma_{21})}{s^2 + 2\xi\omega_n s + \omega_n^2} \tag{1}$$

The disturbance observer obtains the difference between $G_k(t)$ and $\widehat{G}_k(t)$, and the filter $Q(s)$ produces $\hat{d}(t)$ from the difference and $\hat{d}(t)$ information is added to the pump laser driver so that EDFA becomes able to eliminate the effect of disturbance on the gain. PID controller is used together with the disturbance observer to control the gain far more accurately and to speed up the control process. The major gain control due to input channel variations is performed at the disturbance observer first, and the fine tuning of gain control is accomplished at the PID controller. If we perform the gain control with PID controller only under the special situation of large amount of gain change, it takes a lot of time to get the optimum result since PID control process requires a tremendous number of feedback loopings. Since the disturbance observer eliminates most of the gain variation in advance, PID controller just needs to do some kind of final touch-up to get the exact result. $\overline{G_k}(t)$ in Fig. 2 represents the desired gain. A PID controller is described by the following eqn.(2).

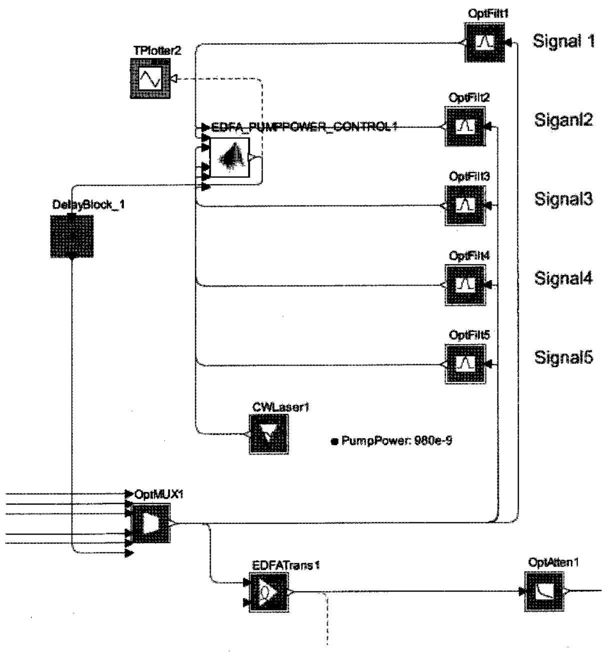


FIG. 3. Simulation layout of the gain control of EDFA in five channel WDM system by the Optsim™ with the Matlab™ cosimulation. One of the five EDFA stages is only present.

$$PID = K_P + K_I/s + K_D s \tag{2}$$

III. SIMULATIONS AND RESULTS

We have proved the operation principle of the proposed system by using well-known commercially available numerical simulator, Optsim™. Fig. 3 is the simulation layout for five channel WDM system with five cascaded system and shows only part of the whole design because of low quality of the graphical image.

TABLE 1. Summary of optical parameters for simulation

Number of EDFA stage	5	Add/drop frequency	0.16 kHz
Number of channels	5	Average loss between stages	15 dB
Input power per channel	-10 dBm	Peak pump power	20 dBm
EDF Length	35 m	Γ_{32}	10^6
Γ_{21}	$1/(10.5\times10^{-2})$	ξ	3
ω_n	1.7×10^6	K_P	1.5809×10^8
K_I	1.5791×10^{12}	K_D	16.1028

EDFA pump-power control-module in the setup was implemented by MATLAB according to three-level EDFA modeling scheme. The major parameter values we have used in the experiment are shown in Table I.

We have performed several experiments by changing the power of laser diodes (LDs). Fig. 4(a) and (b) show the power fluctuations when a channel out of two channels adds and drops when powers of each channel are -15 dBm and 0 dBm, respectively. Fig. 4(c) shows the pump laser's power change due to gain-transient. For low LD-power, the dips and spikes in gain is small and less than 3 μsec gain-transient time has been obtained. For high LD-power case, even if the dips and spikes are much bigger than low LD-power case, the gain of EDFA also has been recovered to its original value within 3 μsec. We have performed various kinds of experiments by not only changing the number of WDM channels to EDFA but also varying the number add/drop channels.

Fig. 5 shows the results when the number of WDM channels and EDFA's stage are five and the number of add/drop channels is one. The peaks and their slow transient in the starting point are only due to the characteristic of the disturbance observer and they do not have any importance in practical applications. The initial power transients settle down within 30 μsec in simulation and are never seen after. The time for gain recovery in this case also is less than 3 μsec. At the last stage, the powers of all the five channels have different values due to the unflattened gain profile of the EDFA. The five channels used in the simulation are selected by their known characteristic values such as absorption and emission coefficient, etc. and hence, the channel spacings are not the same value. For low LD-power case, when four channels out of five are added or dropped, it is observed the amount of gain-transient time was less than 3 μsec. In general, the amount of optical signal power to EDFA in the system is much less than -5 dBm. We just applied 3 mW LD-power to EDFA to verify system peformance and to check its limit. Even under extreme conditions, the system works very well with reasonable gain recovery time.

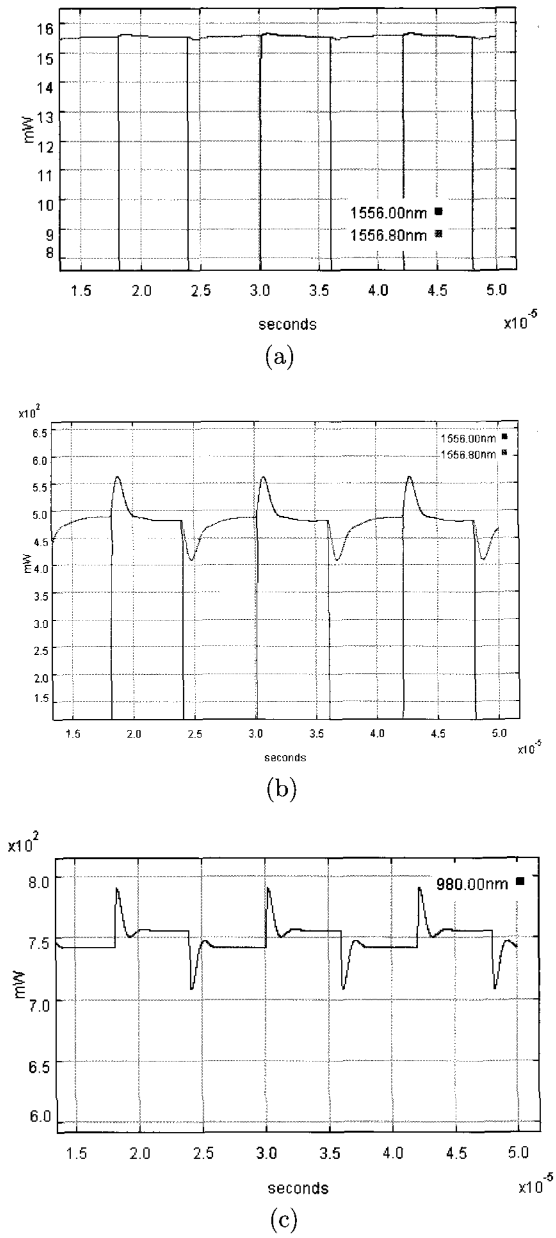
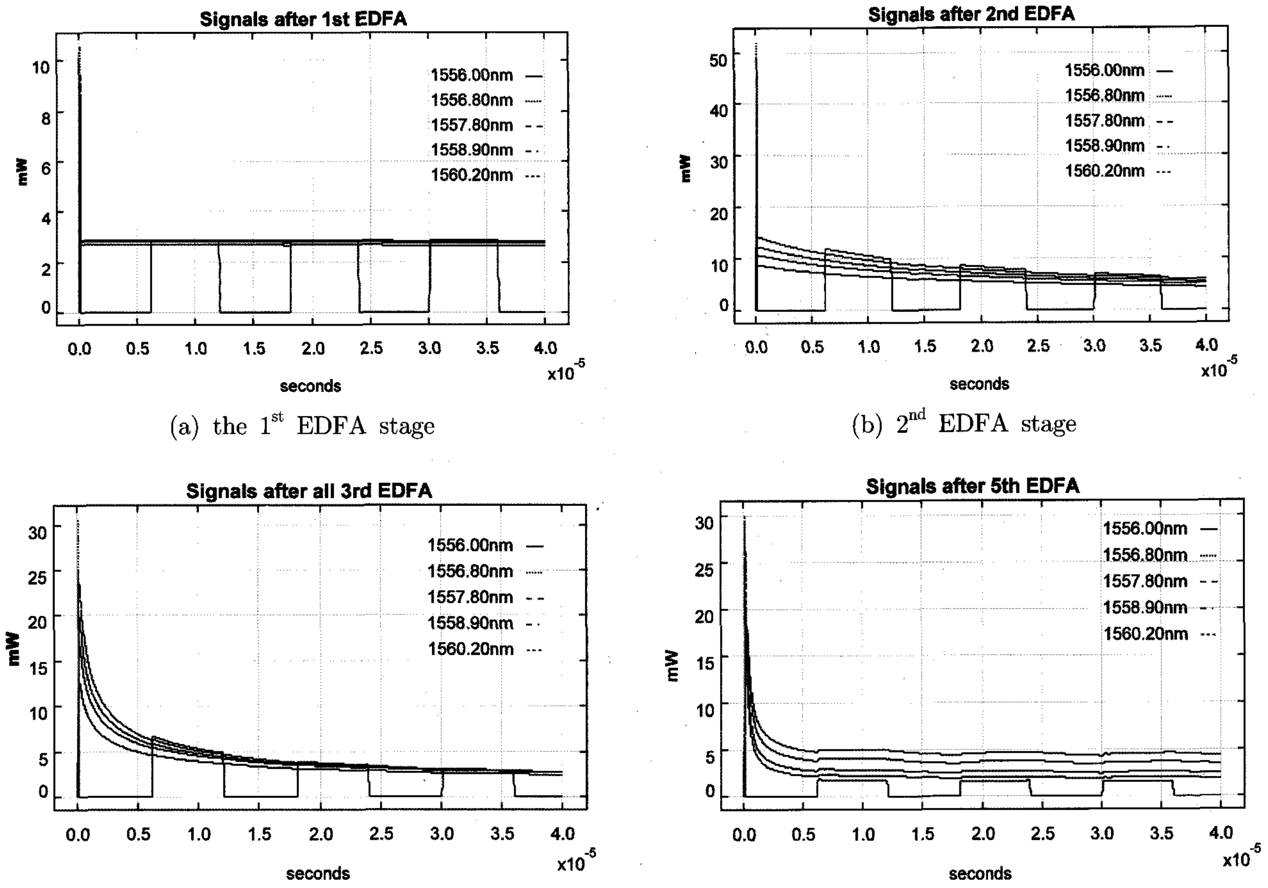


FIG. 4. Power fluctuations of two WDM channels due to channel add/drops (a) when the power of laser diode is -15 dBm, and (b) when the power of laser diode is -5 dBm in single EDFA stage. (c) Fast recovery of pump power to the steady state whenever the channel add/drop occurs.



(a) the 1st EDFA stage

(b) 2nd EDFA stage

(c) 3rd EDFA stage

(d) 5th EDFA stage

FIG. 5. Power fluctuations of WDM channels due to channel add/drops when the powers of laser diodes are 0.3 mW.

IV. CONCLUSION

In this paper, we have introduced the application of disturbance observer to minimize the gain-transient time of EDFA in WDM add/drop networks. We have applied a disturbance observer to detect and compensate the gain variation due to channel add/drops. While the major compensation of gain is performed by the disturbance observer, the fine control process for exact gain recovery is done by PID controller. The proposed gain control algorithm for EDFA was implemented by MATLAB and the performance has been verified by single and cascaded EDFA WDM network system. Simulation results show that the technique decreases the amount of gain-transient time to less than 3 μsec in most of the cases.

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APPENDIX A

The equations for the photon-emission process in EDFA are as follows

$$\frac{dN_3}{dt} = -\Gamma_{32}N_3 - (N_3\sigma_p^e - N_1\sigma_p^a)\phi_p$$
$$\frac{\partial P_p}{\partial z} = \rho\Gamma_p\left[\sigma_p^T N_3 + \sigma_p^a N_2 - \sigma_p^a\right]P_p$$
$$\frac{dN_2}{dt} = -\Gamma_{21}N_2 + (N_1\sigma_s^a - N_2\sigma_s^e)\phi_s + \Gamma_{32}N_3$$
$$\frac{\partial P_s}{\partial z} = \rho\Gamma_s\left[\sigma_s^T N_2 + \sigma_s^a N_3 - \sigma_s^a\right]P_p$$
$$\frac{dN_1}{dt} = \Gamma_{21}N_2 - (N_1\sigma_s^a - N_2\sigma_s^e)\phi_s + (N_3\sigma_p^e - N_1\sigma_p^a)\phi_p \quad (A.1)$$

where ϕ_s, ϕ_p are photon flux densities per second of a signal and a pump, σ_s^e, σ_s^a, σ_p^e, σ_p^a are absorption and emission coefficients of a signal and a pump. N_1, N_2, N_3 are the number of erbium-ions at each level and the sum of them is generally normalized to 1. $P_{s,p}$ is the power of the signal and the pump, ρ is an erbium density, and $\Gamma s,p$ is the geometric correction factor for the overlap between the power and the erbium-ions. Γ_{ij} is the spontaneous transition rate of the ion from level i to level j and has the following values in EDFA.

$$\Gamma_{32} = \frac{1}{\tau_{23}} \approx \frac{1}{1\mu s} = 10^6, \quad \Gamma_{21} = \frac{1}{\tau_{21}} \approx \frac{1}{10ms} = 10^2 \quad (A.2)$$

We use a reservoir $r(t)$ that represents the number of excited erbium-ions (level 2) defined by the eqn. (A.3).

$$r_2(t) \equiv \rho A\int_0^L N_2(z,t)dz, \quad r_3(t) \equiv \rho A\int_0^L N_3(z,t)dz \quad (A.3)$$

where L is the length of the erbium-doped fiber and A is the cross-section area of erbium-doped fiber core. By using eqns. (A.1-A.3), the following eqn. (A.4) for reservoir r_2, r_3 are obtained.

$$\frac{dr_2}{dt} = -\Gamma_{21}r_2 + \Gamma_{32}r_3 + \sum_{k=1}^{N}\left(1 - e^{G_k(t)}\right)P_k^{in}(t)$$
$$\frac{dr_3}{dt} = -\Gamma_{32}r_3 + \left(1 - e^{G_p(t)}\right)P_p^{in}(t) \quad (A.4)$$

where $e^{G_k(t)} = P_k^{out}(t)/P_k^{in}(t)$, $P_k^{in,out}(t)$ is the input and output power of the k-th channel in the EDF. Finally, the gain G is derived in eq. (A.6) by modifying the eqn.(A.1) with the relations of eq. (A.5)

$$\phi_p = \Gamma_p P_p/A, \quad \phi_s = \Gamma_s P_s/A \quad (A.5)$$
$$G_k(t) \approx B_k r_2 - A_k \quad (A.6)$$

where $A_k = \rho\Gamma_s\sigma_s^a L$, $B_k = \Gamma_s\sigma_s^T/A$.

By eqns. (A.4), (A.6), the final rate eqns. (A.7, A.8) for reservoirs are obtained.

$$\frac{\dot{G}_k}{B_k} = -\Gamma_{21}\frac{G_k}{B_k} + \Gamma_{32}r_3 + \sum_{k=1}^{N}\left(1 - e^{G_k}\right)P_k^{in} - \Gamma_{21}\frac{A_k}{B_k}$$
$$\dot{r}_3 = -\Gamma_{32}r_3 + P_p^{in} - P_p^{out} \quad (A.7)$$

$$X \equiv \begin{pmatrix} r_3 \\ \frac{G_k}{B_k} \end{pmatrix},$$
$$\dot{X} \equiv \begin{pmatrix} \dot{r}_3 \\ \frac{\dot{G}_k}{B_k} \end{pmatrix} = AX + BP_p^{in} - BP_p^{out} + \bar{B}\left(\sum_{k=1}^{N}\left(1 - e^{G_k}\right)P_k^{in} - \Gamma_{21}\frac{A_k}{B_k}\right),$$
$$G_k = C_k X$$
$$A = \begin{pmatrix} -\Gamma_{32} & 0 \\ \Gamma_{32} & -\Gamma_{21} \end{pmatrix}, \quad B = \begin{pmatrix} 1 \\ 0 \end{pmatrix}, \quad \bar{B} = \begin{pmatrix} 0 \\ 1 \end{pmatrix}, \quad C_k = \begin{pmatrix} 0 & B_k \end{pmatrix} \quad (A.8)$$

The $d(t)$ is defined by Eq. (A.9).

$$d(t) = -BP_p^{out} + \bar{B}\left(\sum_{k=1}^{N}\left(1 - e^{G_k}\right)P_k^{in} - \Gamma_{21}\frac{A_k}{B_k}\right) \quad (A.9)$$

The disturbance $d(t)$ goes to zero when steady-state, and the transfer function P(s) represents the nominal EDFA plant model with no disturbance.

$$s\hat{X} = A\hat{X} + BP_p^{in}(s) \rightarrow \hat{X} = (sI - A)^{-1}BP_p^{in}(s)$$
$$\hat{G}_k = C_k\hat{X} = C_k(sI - A)^{-1}BP_p^{in}(s) \quad (A.10)$$

$$P(s) = \frac{\hat{G}_k}{P_p^{in}} = C_k(sI - A)^{-1}B = \frac{\Gamma_{32}B_k}{(S + \Gamma_{32})(S + \Gamma_{21})} \quad (A.11)$$