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EDFA Gain Control using Disturbance Observer Technique

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Abstract

Based on a theoretical erbium-doped fiber amplifier (EDFA) model, we have proposed a systematic design method for EDFA gain control. In the design, a disturbance observer(DOB) technique is adopted for minimizing gain-transient time of wavelength-division-multiplexing (WDM) multi channels in optical amplifier in channel add/drop networks. We have reduced the gain-transient time to less than 30μsec by applying DOB with PID controller to the control of amplifier gain. The proposed DOB-based gain control algorithm for EDFA was implemented as a digital control system using TI's DSP(TMS320C28346) chip and experimental results of the system verify the excellent performance of the proposed gain control methodology.

Keywords: *Erbium-Doped Fiber Amplifier, Gain Control, Disturbance Observer, Digital Control System, Channel Add/Drop*

1. Introduction

In a WDM network, the output power level of each channel should be maintained even when channel add/drops occur in a WDM network. Keeping the signal powers to a constant value is more important when the signals are amplified through EDFAs. At the EDFA, the change of the number of signals causes the change of the amplifier gain of each signal due to the cross gain saturation effect [1]. Therefore, there exist fluctuations of power level in each channel and they results in the gain-related error at the receivers. To avoid this effect, several methods have been developed. One of them uses EDFA output as a feedback signal in an optical feedback control loop [2], The all-optical scheme has a drawback; the frequency of channel add/drop should be less than that of the relaxation oscillation frequency of EDFA, which is several hundred Hz. On the other hand, the mostly used one is an electrical scheme which controls the pump laser output electrically according to EDFA output signal level [3]. This is a generally accepted method in industry due to its simple, cheap and robust architecture. In the previous paper [4, 5], we propose a novel technique which minimizes the gain-transient time effectively. In our method, we applied a disturbance observer (DOB) technique [6-8] with a proportional /integral/differential (PID) controller to the control of EDFA gain in WDM add/drop networks. In this paper, the theoretical design of the gain-clamping system for EDFA based on a mathematical model is proposed and the experimental results to prove feasibility of that scheme is also shown.

2. EDFA Model

To design EDFA gain controller to minimize the gain transient-time, we used two level model of EDFA [9]. The diagram of energy level of EDFA is shown in Figure 1.

The equations for two-level process are explained in this paper. The number of ions at each state in Figure 1(a) is described by eqn. (1).

$$\frac{dN_2}{dt} = -\Gamma_{21}N_2 + (N_1\sigma_s^a - N_2\sigma_s^e)\phi_s - (N_2\sigma_p^e - N_1\sigma_p^a)\phi_p \tag{1}$$

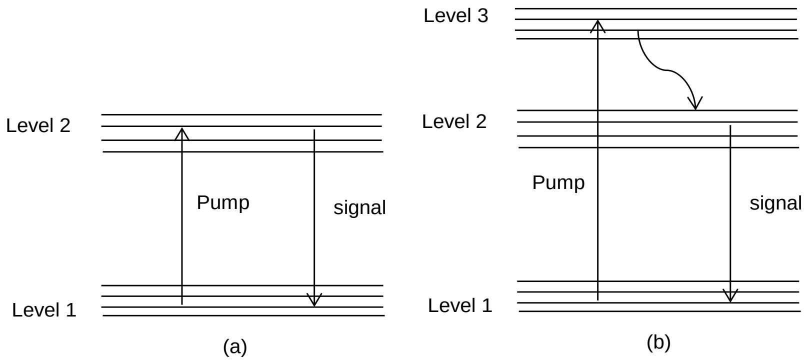
$$\frac{dN_1}{dt} = \Gamma_{21}N_2 - (N_1\sigma_s^a - N_2\sigma_s^e)\phi_s - (N_2\sigma_p^e - N_1\sigma_p^a)\phi_p \tag{2}$$

where ϕ_s, ϕ_p are photon flux densities per second of a signal and a pump, $\sigma^e{}_s$, $\sigma^a{}_s$, $\sigma^e{}_p$, $\sigma^a{}_p$ are absorption and emission cross section of a signal and a pump ($\sigma^T=\sigma^e+\sigma^a$). N_1, N_2 are the number of erbium-ions at each level ($N=N_1+N_2=1$).

$$\frac{dP_s}{dt} = \rho\Gamma_s\left(\sigma_s^T N_2 - \sigma_s^a\right)P_s \tag{3}$$

$$\frac{dP_p}{dt} = \rho\Gamma_p\left(\sigma_p^T N_2 - \sigma_p^a\right)P_p \tag{4}$$

$P_{s,p}$ is the power of the signal and the pump, ρ is an erbium density, and Γs,p is the geometric correction factor for the overlap between the power and the erbium-ions.



(a) two-level model (b) three-level model

Figure 1. Two Level Model of EDFA

By using eqn (3-4), and relations $\sigma^T=\sigma^e+\sigma^a$, $N=N_1+N_2=1$, eqn. (1) is changed into the following equation.

$$\frac{dN_2}{dt} = -\frac{N_2}{\tau} - \frac{1}{\rho A}\frac{\partial P_p}{\partial z} - \frac{1}{\rho A}\frac{\partial P_s}{\partial z} \tag{5}$$

If there are N channels, eqn. (5) can be changed into eqn. (6).

$$\frac{dN_2}{dt} = -\frac{N_2}{\tau} - \frac{1}{\rho A}\sum_{k=0}^{N}\frac{\partial P_k}{\partial z} \tag{6}$$

where k = 0 means the pump, and $\tau = 1/\Gamma_{21}$. We use a reservoir *r(t)* that represents the number of excited erbium-ions (level 2).

$$r(t) \equiv \rho A \int_0^L N_2(z,t)dz \tag{7}$$

where L is the length of the erbium-doped fiber and A is the cross-section area of erbium-doped fiber core. By integrating eqn.(6) according to the whole length of EDF, we can obtain the following equation.

$$\rho A \int_0^L \frac{dN_2}{dt} dz = -\frac{1}{\tau} \rho A \int_0^L N_2 dz - \sum_{k=0}^{N} \int \frac{\partial P_k}{\partial z} dz \tag{8}$$

By using definition (7), eqn. (8) is rearranged into eqn. (9).

$$\frac{dr(t)}{dt} = -\frac{r(t)}{\tau} + \left(1 - e^{G_0(t)}\right) P_0^{in}(t) + \sum_{k=1}^{N} \left(1 - e^{G_k(t)}\right) P_k^{in}(t) \tag{9}$$

where $G_0(t) = \ln(P_0^{out}/P_0^{in})$, $G_k(t) = \ln(P_k^{out}/P_k^{in})$.

In eqn. (3), changing s into k for k-th channel, dividing by P_k and integrating through the length of EDF, we can obtain the gain equation of channel k.

$$\ln P_k^{out} - \ln P_k^{in} = \frac{\Gamma_k \sigma_k^T r(t)}{A} - \rho \Gamma_k \sigma_k^a L \tag{10}$$

By the following definitions, the eqn. (10) is changed into eqn. (12).

$$G_k(t) = \ln \frac{P_k^{out}}{P_k^{in}}, \quad B_k = \frac{\Gamma_k \sigma_k^T}{A}, \quad A_k = \rho \Gamma_k \sigma_k^a L \tag{11}$$

$$G_k(t) = B_k r(t) - A_k \tag{12}$$

The d(t) is defined by Eq. (13).

$$d(t) = -e^{G_0(t)} P_0^{in}(t) + \sum_{k=1}^{N} \left(1 - e^{G_k(t)}\right) P_k^{in}(t) \tag{13}$$

The schematic diagram of the system is shown in Figure 2. We consider the random add/drop process as a disturbance ($d(t)$ in Figure 2), and make the pump laser be prepared to this disturbance in advance so that the dips & spikes of other channel's fluctuation become minimized when the actual control takes place.

3. Design of EDFA Control System

Figure 2 describes the configuration of an EDFA control system. In Figure 2, transfer function $P(s)$ represents nominal EDFA plant model with no disturbance and $Q(s)$ is a filter which makes the characteristics 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, $\hat{G}_k(t)$ is the gain without any disturbance. Eq. (14)-(16) describe the functions P(s), Q(s), $G_k(s)$. In this paper, we do not explain the parameters of the equations and do not derive the equations because these are well-known in the EDFA and the control theory.

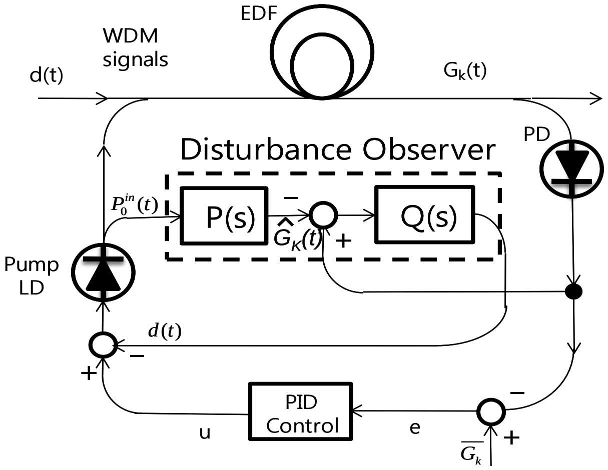


Figure 2. Disturbance Observer with PID Controller for EDFA Gain Control

$$P(s) \equiv \frac{G_k(s)}{\{P_0^{in}(s) + d(s)\}} = \frac{B_k}{s + 1/\tau} \tag{14}$$

$$Q(s) = \frac{\omega_n^2 (s + 1/\tau)}{B_k (s^2 + 2\zeta\omega_n s + \omega_n^2)} \tag{15}$$

$$G_k(s) = \frac{B_k (P_0^{in}(s) + d(s))}{s + 1/\tau} \tag{16}$$

The disturbance observer obtains the difference between $G_k(t)$ and $\hat{G}_k(t)$, 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. The equation for the PID controller is described in eqn. (17).

$$C(s) = K_p + \frac{K_I}{s} + K_d s \tag{17}$$

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.

In order to show the superior performance of the proposed DOB-based gain control method, the EDFA control system is digitally implemented using TMS320C28346 DSP Chip and through hardware experiments, its performance is verified. Figure 3 represents the implementation of the EDFA control system.

The EDFA control system consists of DSP main board and Driver board depicted in Figure 4. DSP main board is to implement the control algorithm using TMS320C28346 DSP Chip with 300Mhz clock and 32 bit floating point processing unit. Driver board is to generate the current of pump laser according to the calculated control value and provide the input and output signal power data for the calculation of the EDFA channel gain data. Because of the computation of the control algorithm, the sampling period is 10usec.

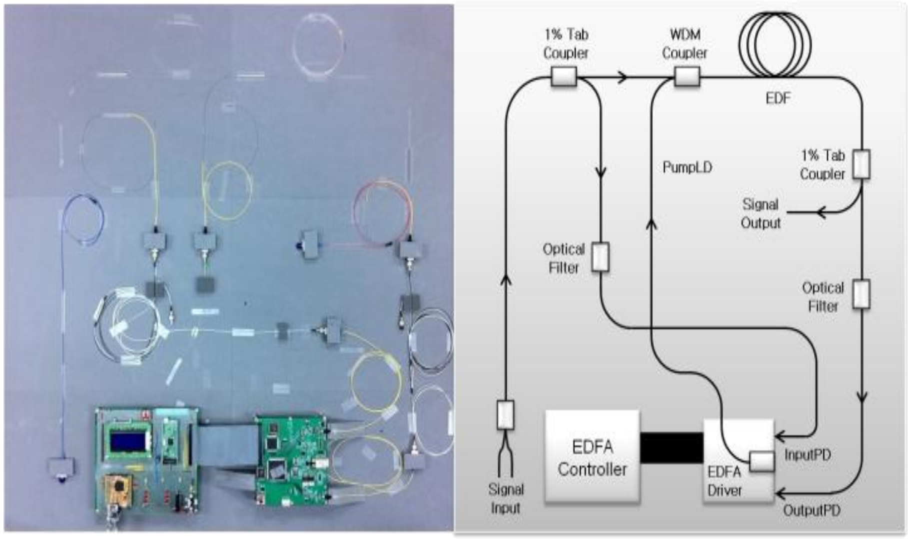


Figure 3. EDFA Control System

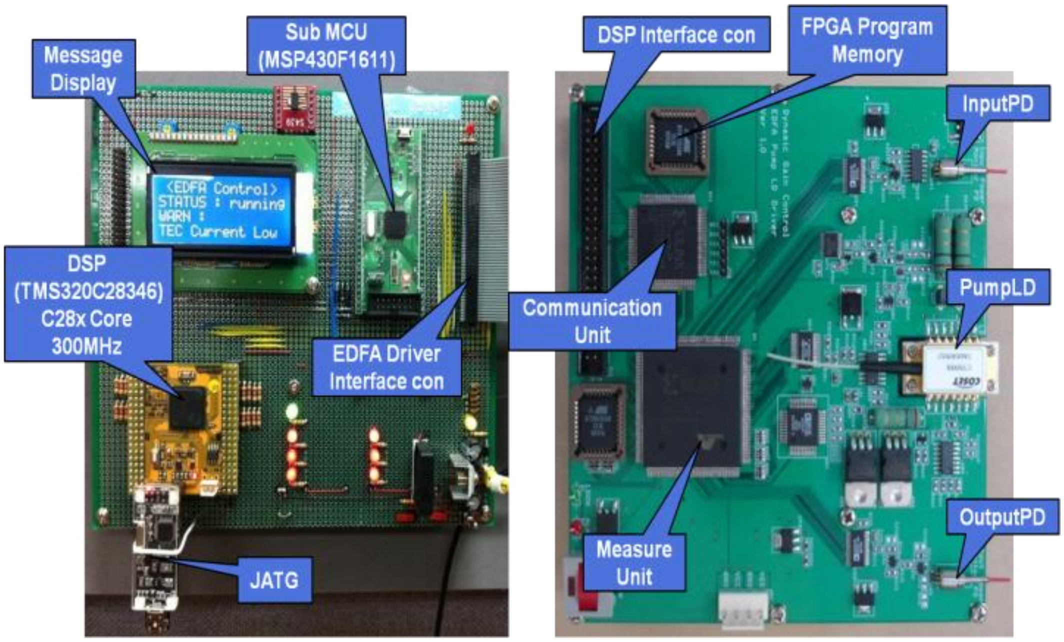


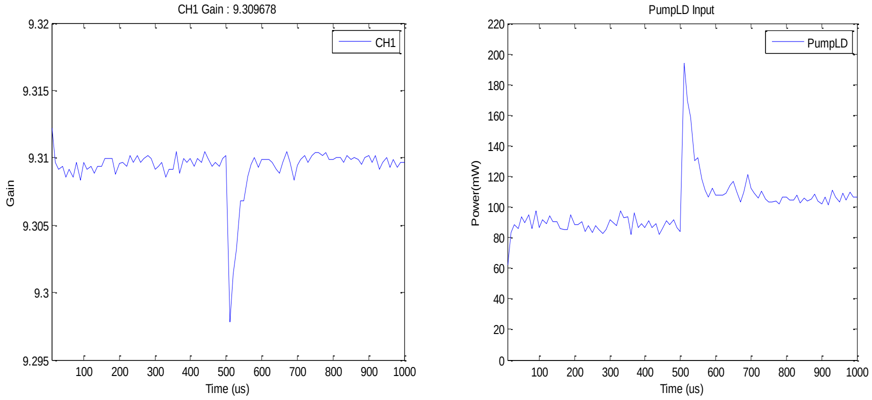
Figure 4. Main DSP Board and EDFA Driver Board

4. Experimental Results

In the experiments, the wavelength of the pump Laser is 980nm and its maximum output power is 200mW. As signals, two channel signals with 1550nm and 1560nm wavelengths are applied to the system. In the experiments, the desired channel 1 signal gain is set to 9.3068.

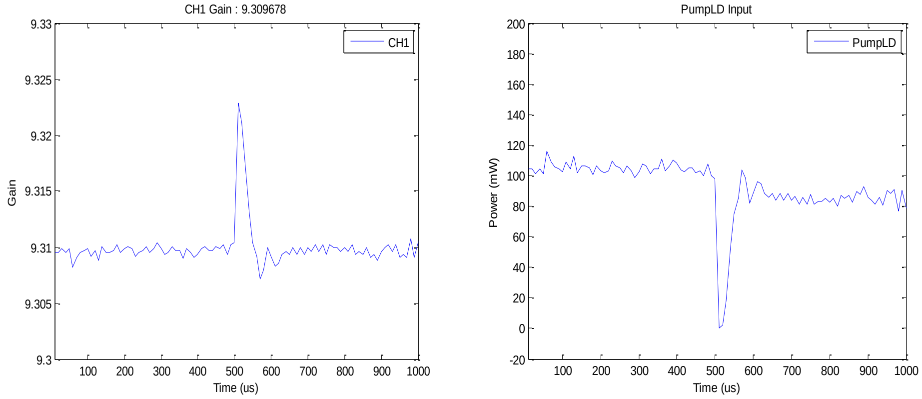
Figure 5 shows the graphs of the gain of channel 1 signal with 0.25mW signal power and the pump power when channel 2 signal is added. Note from (a) of Figure 5 that the channel 1 signal gain is recovered to the desired one, 9.30 within 80usec. From (b) of Figure 5, it can be noticed that the steady state pump power is increased in order to recover the reduced gain to the desired one. Pump power is 90mW before the channel 2 signal with 0.25mW signal power is added. After channel 2 signal is added, the pump power is abruptly increased to about 200mW in order to recover the reduced channel gain as soon as possible. The steady state pump power is increased to 110mW to compensate the effect of the channel 2 addition.

Figure 6 shows the graphs of the gain of channel 1 signal and the pump power when channel 2 signal is subtracted. Note from (a) of Figure 6 that the channel 1 signal gain is recovered to the desired one, 9.30 within 90usec. From (b) of Figure 6, the steady state pump power is about 110mW when channel 1 and channel 2 signal are applied to the EDFA system. Since the channel 2 signal is abruptly subtracted, the channel 1 signal gain is also increased instantly. To compensate this, pump power should be reduced. The steady state pump power is 90mW which is the same as in Figure 5 before the channel 2 signal is added. After channel 2 signal is subtracted, the pump power is abruptly decreased to about 5mW in order to recover the increased channel gain as soon as possible.



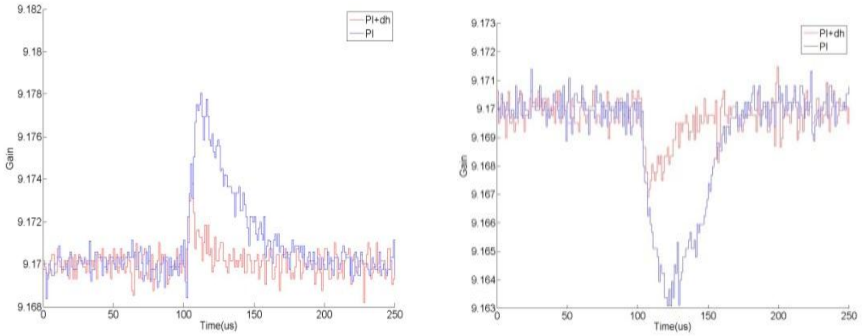
(a) Gain (b) Pump power

Figure 5. Experimental Results in Case of Channel 2 Signal Addition



(a) Gain (b) Pump power

Figure 6. Experimental Results in Case of Channel 2 Signal Subtraction



(a) Channel Drop (b) Channel Add

Figure 7. Performance Comparison between PI and PI+DOB

Finally, the performance was compared in Figure 7 between PI control alone(blue line) and PI control with DOB (red line). As shown in Figure 7, the performance of PI control with DOB is much better than PI control alone. This is because the channel add/drop signal is estimated and fed forward as soon as channel add/drop occurs. The gain fluctuation is compensated very fast and the settling time was reduced to about 30usec compared with 80usec of PI control alone.

5. Conclusion

In this paper, we showed a technique to minimize gain-transient time of WDM signals in EDFA in channel add/drop networks. The proposed gain controller is composed of a disturbance observer and a PI controller. 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 PI controller. The proposed gain control algorithm for EDFA was digitally implemented by TMS320C 28346 DSP and the performance has been verified by experiments. Experimental results show that the PI control with DOB decreases the amount of gain-transient time up to less than 30μsec while the settling time was 80μsec in case of PI control alone. DOB technique seems to be effective in Channel add/drop compensation.

Acknowledgements

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