

# Design of EDFA Gain Controller based on Disturbance Observer Technique

Seong-Ho Song, Ki-Seob Kim, Seon-Woo Lee, Seop-Hyeong Park

**Abstract**—Based on a theoretical erbium-doped fiber amplifier (EDFA) model, we have proposed an application of disturbance observer (DOB) with proportional/integral/differential (PID) controller to EDFA for minimizing 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 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**—EDFA, Disturbance observer, gain control, WDM.

## I. INTRODUCTION

IN WDM network, the power level of each channel in WDM should be unchanged when channel add/drops or active rearrangements of network occur. 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 are fluctuations of power level in each channel which 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.

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The experimental results of the DOB scheme reduced the gain-transient time to less than 30μs.

## II. DESIGN OF EDFA CONTROL SYSTEM

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

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

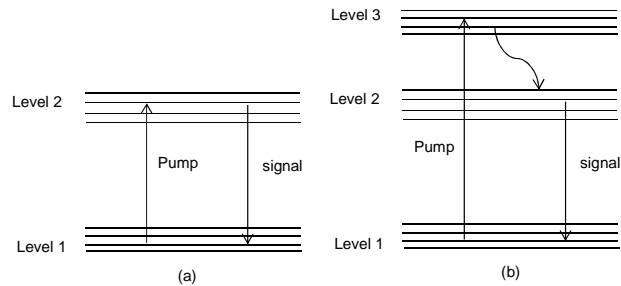
$$\frac{dN_1}{dt} = \Gamma_{21}N_2 - (N_1\sigma_s^a - N_2\sigma_s^e)\phi_s - (N_2\sigma_p^e - N_1\sigma_p^a)\phi_p \quad (2)$$

where  $\phi_s, \phi_p$  are photon flux densities per second of a signal and a pump,  $\sigma_s^e, \sigma_s^a, \sigma_p^e, \sigma_p^a$  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 ( $N = N_1 + N_2 = 1$ ).

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

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

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



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

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

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

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

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).

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

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.

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

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

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

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  $k$ .

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

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

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

$$G_k(t) = B_k r(t) - A_k \quad (12)$$

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

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

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 in advance so that the dips & spikes of other channel's fluctuation become minimized when the actual control takes place.

In Fig.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.

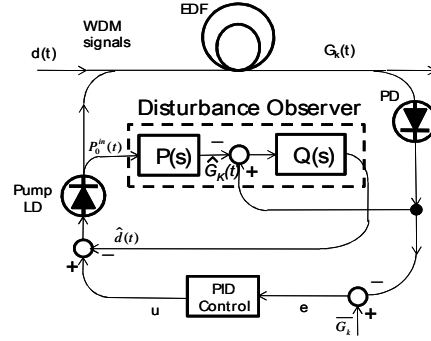


Fig. 2 Disturbance observer with PID controller for EDFA gain control

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

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

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

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).

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

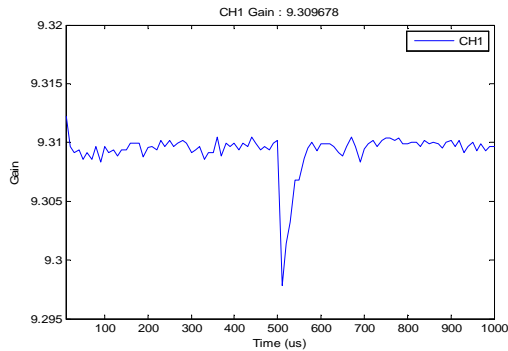
PID controller is used together with the disturbance observer to control the gain far more accurately and to speed up the control process. The major gain control due to input channel variations is performed at the disturbance observer first, and the fine tuning of gain control is accomplished at the PID controller.

### III. EXPERIMENTAL RESULTS

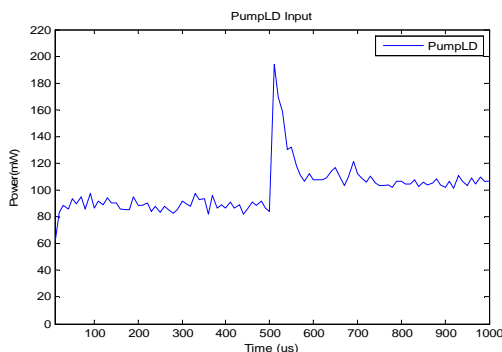
In the experiments, the wavelength of the pump Laser is 980nm and its maximum output power is 200mW. As signals, two channel signals with 1550nm and 1560nm wavelengths are applied to the system.

In the experiments, the desired channel 1 signal gain is set to 9.3068. Fig. 3 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 Fig.3 that the channel 1 signal gain is recovered to the desired one, 9.30 within 80usec.

From (b) of Fig.3, 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.



(a) Gain



(b) Pump power

Fig. 3 Experimental results in case of channel 2 signal addition

Finally, the performance was compared in Fig. 4 between PI control alone (blue line) and PI control with DOB (red line). As shown in Fig. 4, 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 30  $\mu$ sec compared with 80  $\mu$ sec of PI control alone.

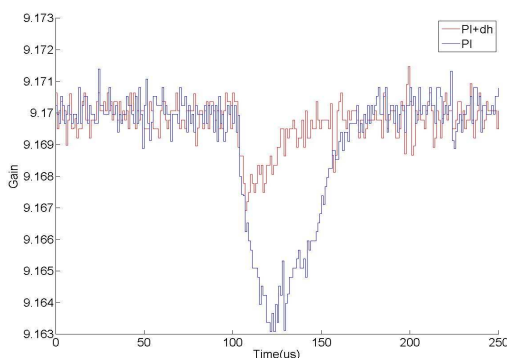


Fig. 5 Performance Comparison between PI and PI+DOB

#### IV. 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 30  $\mu$ sec while the settling time was 80  $\mu$ sec in case of PI control alone. DOB technique seems to be effective in Channel add/drop compensation.

#### ACKNOWLEDGMENT

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