EDFA Gain Stabilization via Disturbance Observer Techniques

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ABSTRACT
We propose, for the first time to our knowledge, a novel gain-clamping method for EDFA in WDM Add/Drop networks by introducing a disturbance observer technique. The proposed gain-clamping control input consists of the nominal gain-clamping control such as PI(Proportional and Integral) control and the additional control input for the compensation of the effects caused by channel add/drops. The additional control input is designed using the well-known disturbance observer technique and can be implemented very easily with general electric elements. We proved the superiority of the new technique over the previous methods by showing simulation result of minimized dips and spikes that appear in power profile of EDFA output.

KEY WORDS
Gain-clamping, WDM, Add/Drop, EDFA, cross gain saturation, disturbance observer technique

1 Introduction

For the receiver to detect the signal accurately in WDM network, it is very important to keep the power level of each WDM channel unchanged regardless of active rearrangement of network or WDM channel add/drop, which results in the variation of number of channels in a fiber. The change in signal levels of WDM channels in case of channel add/drop becomes most significant when the WDM signals go through erbium-doped-fiber-amplifier (EDFA). When the number of input channels to EDFA changes, the amplifier gain for each channel also changes due to cross gain saturation effect [1]. Therefore, we need to make the signal levels of WDM channels unchanged when they go through EDFA by making them have the same gain even if the number of channels to EDFA varies.

One of the ways of control EDFA gain is an all-optical method that uses EDFA output as a feedback signal in a feedback control loop[2] . The other one is an electrical scheme that controls pump laser output electrically according to EDFA output signal level [3]. There is a limit for optical scheme to be operated properly, which is that the frequency of channel add/drop should be less than that of relaxation oscillation of EDFA. Therefore, the electrical scheme is preferred in a sense of its simple implementation and lower cost. However, there has been a major drawback in conventional electrical schemes. In conventional schemes, one has to recognize the actual adding or dropping of WDM channels before he or she takes an action to change the gain of EDFA by controlling the power of pump laser. Since the response time of pump laser is relatively slow comparing with add/drop time, the optical output profile of the signal after EDFA shows big dips and spikes, which is very undesirable in terms of system performance. This kind of dips and spikes are added up as the signal travels many EDFAs in a network, which results in a severe signal distortion.

In this paper, we propose a novel gain-clamping technique for EDFA in WDM add/drop network, which overcomes the problem of big dips and spikes in conventional schemes. We apply, for the first time to our knowledge, a disturbance observer technique[4, 5] to the control of EDFA gain in WDM add/drop networks. We consider the random add/drop process as a disturbance, and make the pump laser be prepared to this disturbance in advance so that the dips and spikes become minimized when the actual control happens.

2 Gain Control of EDFA

In order to design a gain controller for EDFA, we need to have a mathematical model for EDFA. In this paper, two-level model for EDFA is used [6]. The total number of exicited Er^{3+} ions, $r(t)$, called as reservoir can be usually defined by

$$r(t) \;==\; \rho \int_0^L N_2(z,t)dz \tag{1}$$

where all the parameters are same as defined in [6]. Then, the EDFA model can be simply described by the following equation[6, 7, 8].

$$\begin{aligned} \dot{r}(t) &= -\frac{r(t)}{\tau} + (1 - e^{G_o(t)})P_0^{in}(t) \\ &\quad + \sum_{k=1}^{N} P_k^{in}[1 - e^{G_k(t)}] \\ G_k(t) &= \frac{\Gamma_k \sigma_k^T r(t)}{A} - \rho \Gamma_k \sigma_k^a L \\ &= B_k r(t) - A_k \end{aligned} \tag{2}$$

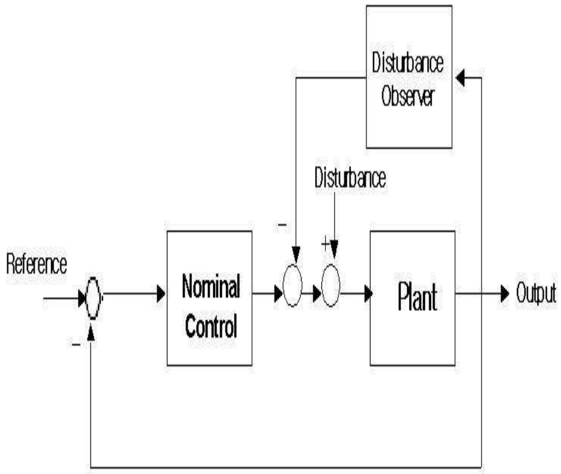

Figure 1. Block Diagram of Control System

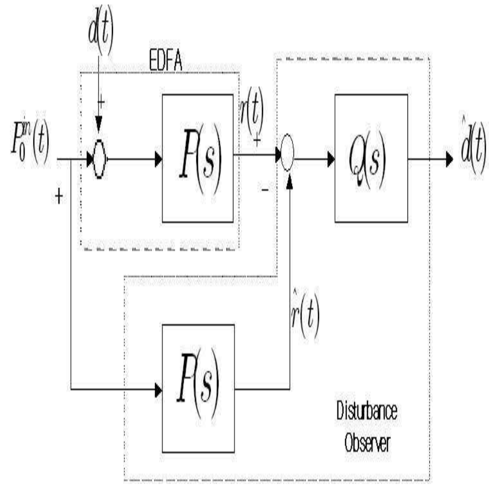

Figure 2. Block Diagram of Disturbance Observer

where G_k, P_o^{in} and P_k^{in} are repectively the gain of channel k, the power of pump input, and the signal power of channel k, and other constant parameters are related to EDFA's own properties. From (2), note that if we can keep the reservoir r constant, then the gain of each channel can be kept constant. However, it is not easy to regulate $r(t)$ because of signal power decay as well as channel add/drops. In the field of control engineering, disturbance observers have been widely used to compensate for uncertain external inputs and shown good performance. If we consider these signal power decay and channel add/drops as external disturbance, then disturbance observer techniques can be adopted to EDFA gain control problems.

Figure 1 is the block diagram of the control system which we propose. As shown in Figure 1, the nominal control is to control the system when there exist no disturbances. The disturbance observer block generates the estimation of disturbances and this estimted output is subtracted from the control input in order to cancel the effects of disturbances on the EDFA plant.

2.1 Design of a Disturbance Observer

In the EDFA model described by (2), the term $-e^{G_0(t)}P_0^{in}(t) + \sum_{k=1}^{N} P_k^{in}[1 - e^{G_k(t)}]$ can be considered as disturbances. If the value of this term is changed, then disturbance observer would estimate it. Define a disturbance by

$$d(t) = -e^{G_0(t)}P_0^{in}(t) + \sum_{k=1}^{N} P_k^{in}[1 - e^{G_k(t)}]. \quad (3)$$

Now, we design an estimator for the function d using the well-known disturbance observer technique [4].

Figure 2 describes the structure of a disturbance observer. The estimator is designed to perform as if it is a low-pass filter so that the transfer function from the unknown function $d(t)$ to the estimator output $\hat{d}(t)$ satisfies the following equation.

$$G_D(s) \triangleq \frac{\pounds[\hat{d}(t)]}{\pounds[d(t)]} = \frac{K}{s+K}, \;\; K > 0 \quad (4)$$

where $\pounds[(\cdot)]$ means the Laplace transform of $(\cdot)$. Actually, the frequency of the change of the EDFA gains due to channel add/drops is relatively lower than actual signal frequencies and so, it is reasonable for a disturbance observer to have a form of low-pass filter. If we choose large observer gain K, the estimation performance is improved. In Fig. 2, the block marked by a transfer function $P(s)$ represents nominal EDFA plant model with no disturbances. Thus, from (2) and (3), $P(s)$ can be written by

$$P(s) \triangleq \frac{\pounds[\hat{r}(t)]}{\pounds[P_0^{in}(t)]} = \frac{1}{s + 1/\tau} \quad (5)$$

where $\hat{r}$ means the reservoir predicted if there exist no disturbances. Then, the variable $r(t) - \hat{r}(t)$ implies the reservoir difference caused by disturbances such as channel add/drops. So, we can use this variable as a disturbance estimate, but the estimation bandwidth which is determined by $\frac{1}{\tau}$ is so small that there must exist estimation errors and time delays. In terms of these reasons, the block marked by $Q(s)$ is added to enhance the performance of a disturbance observer. The transfer function of $Q(s)$ should be designed to satisfy $G_D(s)$. So, $Q(S)$ is obtained mathematically from (4) and (5) as follows.

$$Q(s) \triangleq \frac{\pounds[\hat{d}(t)]}{\pounds[r(t) - \hat{r}(t)]} = \frac{G_D(s)}{P(s)} = \frac{K(s+1/\tau)}{s+K} \quad (6)$$

Using the $P(s)$ and $Q(s)$ designed, the relationship between the disturbance $d(t)$ and its estimate $\hat{d}(t)$ can be described by the equation (4). The blocks $P(s)$ and $Q(s)$ are kinds of filters and easily implemented using OP amps and passive elements. The performance of the proposed disturbance observer will be shown in the computer simulation section.

2.2 Design of a Gain Controller

As described in Figure 1, a gain control input can be designed using the disturbance estimate and the nominal control input. Since the EDFA system is actually stable, the nominal control is not essential. In general, the nominal control input would be utilized in order to get better performance and can be designed for the EDFA system as follows.

$$u_c(t) = -K_c\{r(t) - \bar{r}\} + \frac{1}{\tau}r(t) \quad (7)$$

In (7), the control parameter K_c improves the time-constant of the EDFA system and $\bar{r}$ is a desired reservoir value for desired gain. Then, the total actual pump input $P_0^{in}(t)$ is given by

$$P_0^{in}(t) = u_c(t) - \hat{d}(t). \quad (8)$$

If this control input is applied to the EDFA system with the assumption $\hat{d}(t) = d(t)$, closed-loop system satisfies the following equation.

$$\dot{r}(t) = -K_c\{r(t) - \bar{r}\} \quad (9)$$

Thus, it follows that

$$r(t) = r(0)e^{-K_c t} + \bar{r}(1 - e^{-K_c t}). \quad (10)$$

As $t \rightarrow \infty$, the reservoir $r(t) \rightarrow \bar{r}$. If K_c is large enough, $r(t)$ converges very fast to $\bar{r}$ even when channel add/drops exist and the gains have little fluctuations. In (8), we need to measure the value of the reservoir r. It can be indirectly obtained from the gain of any one channel using the gain equation in (2). In the next section, the advantage and superior performance of the proposed gain controller will be shown through computer simulations.

3 Simulations

Through the simulations, the performance of the proposed gain-clamping method is compared with that of the conventional PI control method which is widely used for the set-point tracking problems.

In the simulations, we consider the EDFA with two channel siganl inputs with wavelength 1552.4 nm and 1557.9 nm and pumping input with wavelength 980 nm.

Actually, in this case, three-level model is the exact model for the EDFA and two-level model (2) is the approximation of three-level model. The control input (8) is designed based on two-level model (2) and the simulation is carried out for three-level EDFA model.

The parameters used for the simulations are summarized as follows.

L	:	32 m
τ	:	10.5 msec
A_0, A_1, A_2	:	8.995,5.075,4.375
B_0, B_1, B_2	:	4.6099 $\times e^{-16}$, 6.4998 $\times e^{-16}$, 5.9624 $\times e^{-16}$
P_1^{in}, P_2^{in}	:	-2 dbm, -2 dbm
K_c, K	:	8000, 20000

We assume that the channel add/drop happens every 0.005 second. The PI control is chosen as follows.

$$P_0^{in}(t) = -2*K_c\{r(t)-\bar{r}\}-4K_c^2\int_0^t\{r(\tau)-\bar{r}\}d\tau \quad (11)$$

The time constant of the closed-loop system with PI control is almost same as the proposed control. So, the comparison of the performance between PI control and the proposed control is acceptable.

In all the figures, the dotted line represents the result of PI control and the solid line means that of the proposed control. Figure 3 shows the graphs of the gains of channel 1 and channel 2. The proposed control method compensates for the effects of channel add/drops much faster and keeps the gains constant. It regulates the gain fluctuation more effectively than the conventional PI control. As seen in Figure 4, the signal variations due to channel add/drops were detected as soon as the channel add/drop happened. Actually, if the observer gain is chosen large enough, the estimation error can be made arbitrarily small. Figure 5 shows the graphs of the control inputs. The control input generated by the proposed method was changed effectively based on the channel add/drops.

4 Conclusion

In this paper, a novel gain-clamping control method was proposed. In order to compensate for the effects of channel add/drops, the well-known disturbance observer technique was employed. Using this disturbance observer, the signal variations due to channel add/drop can be estimated as fast as possible and the estimated value was subtracted from the input to cancel the effects due to channel add/drops. We have proved the performance of this algorithm by showing simulated results of minimized dips and spikes of optical output signal of EDFA.

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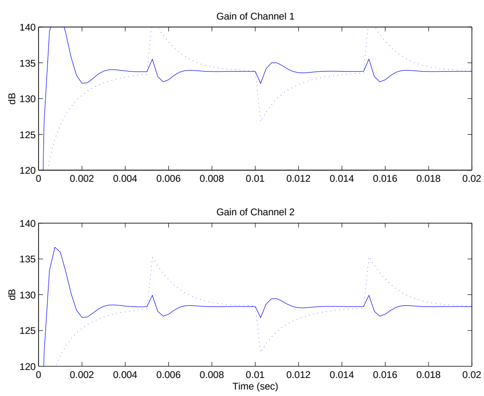

Figure 3. Gains of Channel 1 & Channel 2

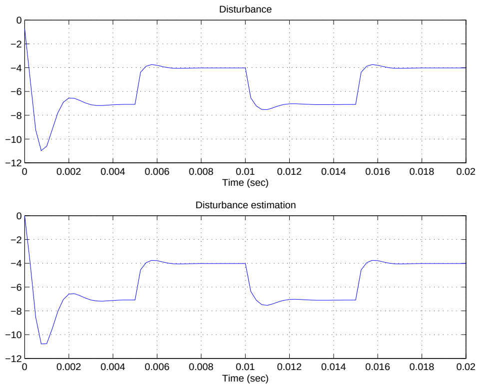

Figure 4. Disturbance & Estimation

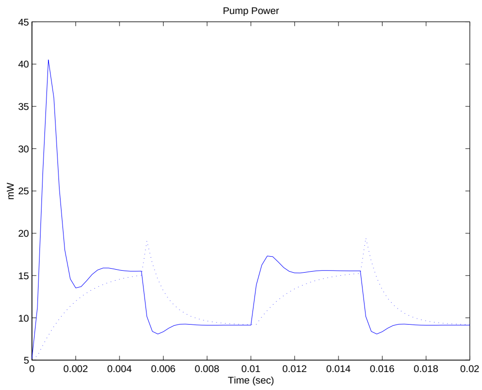

Figure 5. Control Inputs

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