Effect of Optical Delay on the Suppression of the Power Transient Excursion in a Combined Gain-Controlled Erbium-Doped Fiber Amplifier

Hee Sang Chung, Sun Hyok Chang, Heuk Park, Hyun Jae Lee, and Moo-Jung Chu

ABSTRACT—This report describes the effect of optical delay on the suppression of the power transient excursion in a combined gain-controlled erbium-doped fiber amplifier with an internal optical feedback loop (OFL). A simple homogeneous model showed that the optical delay caused a phase change in the oscillation of the surviving and laser channels, which resulted in a reduction of the overall power transient excursion. In addition to the reduction, a real system with a 1528.7-nm OFL shifted the oscillation upward or downward according to channel removal or addition, whereas another one with a 1560.9-nm OFL did not. This different transient behavior reflected a control-wavelength dependence on optical automatic gain control, where spectral-hole burning dominated over relaxation oscillation for 1528.7 nm, and vice versa for 1560.9 nm.

Keywords—Optical delay, power transient, gain control, EDFA.

I. Introduction

Optical amplifiers, especially erbium-doped fiber amplifiers (EDFAs) and Raman amplifiers, are key building blocks for wavelength-division multiplexed (WDM) optical transmission systems [1]. One of hot issues in optical amplifiers is power transient control to guarantee high system performance after or even during periodic or sudden changes in the WDM channel counts. Many technologies have been developed to suppress the power transient excursions in EDFAs under dynamic channel addition and removal [2]-[4]. Among them, combined gain control (CGC), i.e., the electronic feed-forward plus optical feedback, is interesting because it reduces the power transient excursion more than other methods [5]-[8]. In CGC, the optical feedback loop can be configured as internal or external. The external loop has the advantage of upgrading the commercial pump-controlled EDFAs, whereas its disadvantage is that it may cause instability in the control laser. A recent report on CGC with an external optical feedback loop (OFL) dealt with instability and offered a solution [7]. On the other hand, the internal OFL has no instability and can reduce the steady-state power offset (SSPO) by adjusting the look-up table for the pump control. In this letter, we investigate the effect of a look-ahead optical delay line inserted in the input section of the CGC EDFA with an internal OFL; we believe this is the first such investigation. First, we present our theoretical investigation to explain the underlying dynamic behavior and then our observation on the effect of the optical delay with a real system.

II. Theory

In our theoretical analysis, we assume a homogeneous broadened gain medium with three levels to simplify the calculations, and we use rate equations (1a)-(1c) and propagation equations (2a)-(2b) [9].

$$\frac{dN_1}{dt} = -R_{13}N_1 + R_{31}N_3 - W_{12}N_1 + W_{21}N_2 + A_{21}N_2 \qquad (1a)$$

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Hee Sang Chung (phone: +82 42 860 6115, email: hschung@etri.re.kr), Sun Hyok Chang (email: shchang@etri.re.kr), Heuk Park (email: parkh@etri.re.kr), Hyun Jae Lee (email: lhj@etri.re.kr), and Moo-Jung Chu (email: mjc@etri.re.kr) are with Network Technology Laboratory, ETRI, Daejeon, Korea.

$$\frac{dN_2}{dt} = W_{12}N_1 - W_{21}N_2 - A_{21}N_2 + A_{32}N_3 \tag{1b}$$

$$\frac{dN_3}{dt} = R_{13}N_1 - R_{31}N_3 - A_{32}N_3 \tag{1c}$$

$$-\frac{\partial P_p(z,t)}{dz} = \sigma_p \Gamma_p (N_3 - N_1) P_p(z,t) \tag{2a}$$

$$\frac{\partial P_s(z,t)}{dz} = \sigma_s \Gamma_s (\eta_s N_2 - N_1) P_s(z,t) + 2\sigma_s \Gamma_s \eta_s N_2 P_o \tag{2b}$$

The symbols represent the following: N_i, the i-th atomic population density; $P_{p,s}$, the pump/signal power; R_{ij}, the pumping rate; W_{ij}, the stimulated absorption/emission rate; A_{ij}, the spontaneous emission rate; $\sigma_{p,s}$, the pump/signal absorption cross section; $\Gamma_{p,s}$, the overlap factor; η_s, the emission-to-absorption ratio; and $P_o = h\nu\Delta\nu$, where h is Planck's constant, ν the frequency, and $\Delta\nu$ the noise bandwidth. The control laser (P_l) has the same equation as (2b) with a boundary condition, $P_l(0, t) = P_l(L, t) \times L_{\text{loop}}$ where L is the doped-fiber length and L_{loop} is the loss of the optical feedback loop. For the feed-forward pump control, time-varying pump powers are used in the calculation. To solve the equations, the steady-state solutions for each fiber segment are used as the initial conditions, and then (1a)-(2b) are integrated iteratively along the doped fiber length and over time. Table 1 lists the EDF parameters used in the calculations.

Table 1. EDF parameters.

λ (nm)	980	1529	1545	1550
σ ($\times 10^{-25}$ m)	1.41	3.96	2.15	1.86
η	0	0.95	1.31	1.45
fluorescence lifetime (ms)	10 (meta-stable), 0.01 (upper)			
Er^{3+} concentration (m^{-1})	8.1×10^{-24}			
Core diameter (μm)	2.94			

First, the CGC EDFA model comprises a 980-nm forward pumped erbium-doped fiber (EDF, 15 m) and an OFL with both a band-pass filter (λ_{laser}=1529 nm, $\Delta\nu$=12.5 GHz) and an optical attenuator. Figure 1 shows the schematic diagram. The input signals consist of a surviving channel, –18 dBm at 1545 nm, and an on-off channel at 1550 nm that simulates the addition or removal of 39 out of 40 channels. The clamped gain for the surviving channel is 20 dB. To investigate the effect of the optical delay, we compare two types of CGC EDFA. One has no optical delay but 2 μs of pump settling time and another has 5 μs of effective optical delay considering 7 μs of optical delay and 2 μs of pump settling time. The chosen optical delay was close to the optimum for the overall transient suppression.

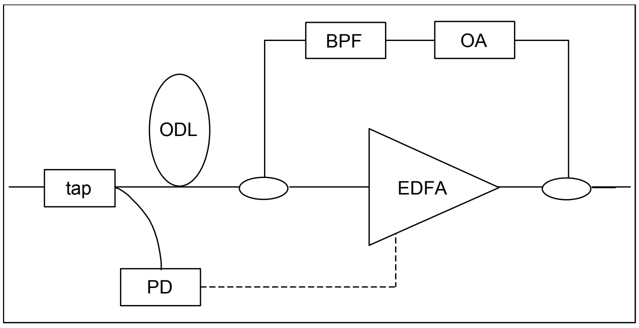

Fig. 1. Schematic diagram of the CGC EDFA. PD: photo-diode, ODL: optical delay line, OA: optical attenuator, BPF: band-pass filter.

Figure 2 shows the calculated power transients of the surviving channel for the CGC EDFA with or without the optical delay. Note that all the pairs of traces in Figs. 2 to 5 have intentional offsets for comparison. Although the steady-state powers coincide, the peak-to-peak power variation is reduced from 1.2 to 0.8 dB. See the phase of the oscillation for the optical delay case; it begins with the opposite phase to the normal CGC, which is the result of the pump set prior to the arrival of the abrupt signal due to the optical delay. Additionally, Fig. 3 shows the power transients of the control laser channel corresponding to those in Fig. 2. The reversal of the phases at the beginning of the oscillations for the channel removal or addition is also shown. In the CGC without the optical delay, the laser overshoots just after the channel removal and then oscillates toward the steady state. Conversely, the laser oscillation begins with the undershoot on the channel addition. On the other hand, due to the optical delay, the preset pump eliminated the first overshoot and undershoot for the channel removal and addition, respectively.

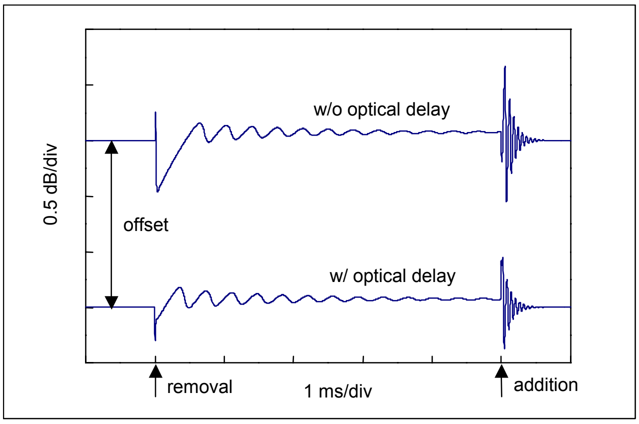

Fig. 2. Calculated power transients of the surviving channel in the CGC EDFA with and without optical delay.

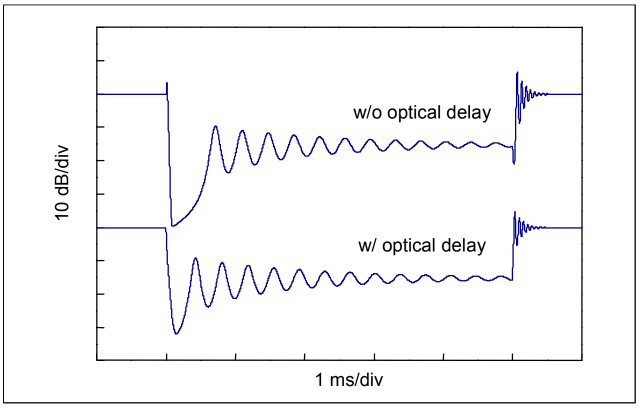

Fig. 3. Calculated power transients of the laser channel in the CGC EDFA with and without optical delay.

III. Experiment

Next, we observed the gain dynamics in the CGC EDFA whose configuration was the same as that used in the above calculation. For the control laser in the OFL, wavelengths of 1528.7 or 1560.9 nm were used and compared. The total input signal power was –1 dBm for the fully loaded channels and –17 dBm for the one remaining channel. The maximum output power was 16 dBm for 150 mW of a 980-nm pump. To implement a look-ahead optical delay in the real system, a single-mode fiber (SMF) of 1.4 km was inserted between the tap for monitoring the input signals and EDFA (Fig. 1). It was close to the optimum length for the overall transient suppression. The SMF delayed the input channels 7 μs while the pump power had been preset according to a look-up table. Without the SMF, the pump was settled within 2 μs after the channel removal or addition.

Figure 4 shows the measured power transients of the surviving channel for the CGC EDFA including the 1528.7-nm OFL with and without the optical delay. The peak-to-peak power variation was reduced from 0.8 to 0.5 dB. The phase change of the oscillation for the optical delay is apparent as expected in the above simulation. In addition, the measured oscillation behaved differently from the calculated one; the oscillation was done mainly above the steady-state power for the channel removal, and vice versa for the addition. In other words, the oscillation was shifted upward and downward for the channel removal and addition, respectively. As a result, the reduction of the power variation mainly came from the suppressed undershoot on the addition of the channel. This could be understood by the suppressed spectral-hole burning (SHB) effect at the control laser channel, which was not seen in Fig. 2 since we had ignored the inhomogeneous broadening of Er^{3+} ions. The control laser at a wavelength of about 1530 nm in the optical automatic gain control (OAGC) causes the SHB, which leads to the SSPO on the removal of the channel [10]. However, the SSPO was forced into reduction in our CGC EDFA by a lowered pump power: the look-up table for the pump had been written to minimize the SSPO. Nonetheless, the oscillation was not fully shifted downward, which represented an up-shift. At the same time, a downshifted oscillation occurred on the channel addition because the pump was lower than that in the pure OAGC. On the other hand, the relaxation oscillation (RO) dominated over the SHB in a laser oscillation of about 1560 nm. Thus, we may expect no shift of the oscillation for the 1560.9-nm OFL. Figure 5 shows the power transients for the 1560.9-nm OFL. It also shows a reduction of the power variation from 0.8 to 0.3 dB, but as expected, no shift of the oscillation was observed.

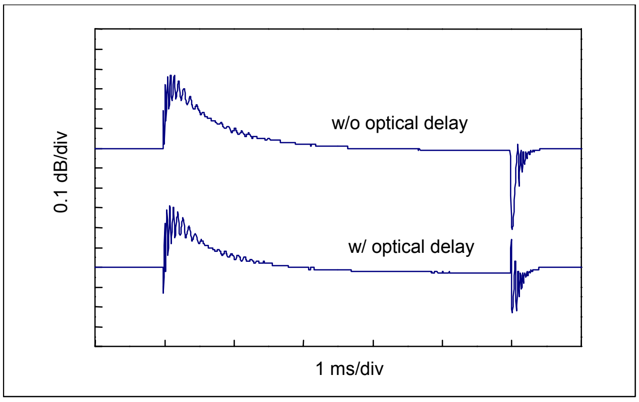

Fig. 4. Measured power transients of the surviving channel in the CGC EDFA including the 1528.7-nm OFL with and without optical delay.

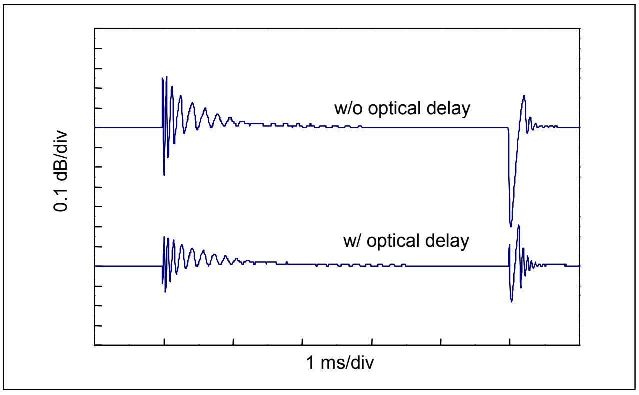

Fig. 5. Measured power transients of the surviving channel in the CGC EDFA including the 1560.9-nm OFL with and without optical delay.

IV. Summary

In summary, we investigated the power transient behavior in the CGC EDFA with and without the optical delay line under dynamic channel addition and removal. The theoretical investigation assuming a homogeneous EDF model revealed that the optical delay reduces peak-to-peak power variation through phase changes in the oscillations of the surviving and laser channels. We also found that CGC with an optical delay line of 1.4 km suppressed the peak-to-peak power variation from 0.8 to 0.5 (0.3) dB for the 1528.7-nm (1560.9-nm) OFL. In addition, the1528.7-nm OFL shifted the oscillation upward or downward for the channel removal or addition, whereas the 1560.9-nm OFL did not. The different transient behavior due to the inhomogeneity of Er^{3+} ions, which was not considered in the simulation, reflected the control-wavelength dependence on the optical feedback, i.e., the SHB dominated over the RO for the 1528.7-nm OFL, and vice versa for the 1560.9-nm OFL.

References

[1] S.K. Kim, S.H. Chang, J.S. Han, and M.-J. Chu, "Design of Hybrid Optical Amplifiers for High Capacity Optical Transmission," *ETRI J.*, vol. 24, no. 2, Apr. 2002, pp. 81-96.

[2] A.K. Srivastava, Y. Sun, J.L. Zyskind, J.W. Sulhoff, C. Wolf, and R.W. Tkach, "Fast Gain Control in an Erbium-Doped Fiber Amplifier," *Proc. OAA*'96, 1996, p. 24.

[3] J.L. Zyskind, A.K. Srivastava, Y. Sun, J.C. Ellson, G.W. Newsome, R.W. Tkach, A.R. Chraplyvy, J.W. Sulhoff, T.A. Strasser, J.R. Pedrazzain, and C. Wolf, "Fast Link Control Protection for Surviving Channels in Multiwavelength Optical Networks," *Proc. ECOC*'96, 1996, vol. 5, pp. 49-52.

[4] M. Zirngible, "Gain Control in Erbium-Doped Fiber Amplifiers by an All-Optical Feedback Loop," *IEE Electron. Lett.*, vol. 27, no. 7, Mar. 1991, pp. 560-561.

[5] M. Fukutoku and M. Jinno, "Pump Power Reduction of Optical Feedback Controlled EDFA Using Electrical Feedforward Control," *Proc. OAA*'98, 1998, p. 32.

[6] H.S. Chung, H.H. Lee, J.C. Lee, M.J. Chu, and J.H. Lee, "Reduction of Relaxation Oscillations in Optical Automatic Gain Clamped EDFA Using Fast Electronic Feedforward," *IEE Electron. Lett.*, vol. 38, no. 5, Feb. 2002, pp. 215-217.

[7] S. Sergeyev, E. Vanin, and S. Popov, "Suppression of Dynamic Instabilities in Erbium-Doped Fiber Amplifiers with a Combined Gain Control System," *Opt. Lett.*, vol. 27, no. 13, July 2002, pp. 1117-1119.

[8] S. Sergeyev, E. Vanin, and G. Jacobsen, "Theoretical Model of Instability-Free Operation for Erbium-Doped Fiber Amplifier with a Combined Gain Control System," *Proc. OFC*'03, 2003, p. 19.

[9] E. Desurvire, *Erbium-Doped Fiber Amplifiers*, John Wiley & Sons, Inc., New York, 1994.

[10] G. Luo, J.L. Zyskind, J.A. Nagel, and Mohamed A. Ali, "Experimental and Theoretical Analysis of Relaxation-Oscillations and Spectral Hole Burning Effects in All-Optical Gain-Clamped EDFA's for WDM Networks," *J. Lightwave Technol.*, vol. 16, no. 4, Apr. 1998, pp. 527-533.