All-optical feedback gain control of remote optically pumped amplifiers

Kokoro Kitamura¹, Kenta Udagawa, and Hiroji Masuda
Interdisciplinary Graduate School of Science and Engineering, Shimane University, 1060 Nishikawatsu, Matsue, Shimane 690–8504, Japan
a) kitamura@ecs.shimane-u.ac.jp

Abstract: A novel all-optical feedback automatic gain control scheme for remote optically pumped amplifiers has been proposed. The static and dynamic gain control characteristics of the remotely pumped erbium-doped fiber amplifier have been experimentally clarified. The maximum gain excursion has been successfully reduced by a factor of ∼10 from 2.1 dB to ∼0.2 dB using the proposed gain control scheme.

Keywords: automatic gain control, ROPA, EDFA, all-optical

Classification: Fiber-Optic Transmission for Communications

References

[1] D. Chang, P. Patki, S. Burtsev, and W. Pelouch, “8 × 120 Gb/s transmission over 80.8 dB/480.4 km unrepeatered span,” OFC/NFOEC 2013, Anaheim, USA, JTh2A.42, Mar. 2013. DOI:10.1364/NFOEC.2013.JTh2A.42
[2] M. X. Ma, H. D. Kidorf, K. Rottwitt, F. W. Kerfoot, and C. R. Davidson, “240-km repeater spacing in a 5280-km WDM system experiment using 8 × 2.5 Gb/s NRZ transmission,” IEEE Photonics Technol. Lett., vol. 10, no. 6, pp. 893–895, Jun. 1998. DOI:10.1109/68.681521
[3] H. Masuda, H. Kawakami, S. Kuwahara, A. Hirano, K. Sato, and Y. Miyamoto, “1.28 Tbit/s (32 × 43 Gbit/s) field trial over 528 km (6 × 88 km) DSF using L-band remotely-pumped EDF/distributed Raman hybrid inline amplifiers,” Electron. Lett., vol. 39, no. 23, pp. 1668, Nov. 2003. DOI:10.1049/el:20031000
[4] H. Masuda, H. Ono, H. Takara, Y. Miyamoto, K. Ichii, K. Takenaga, S. Matsuo, K. Kitamura, Y. Abe, and M. Yamada, “Remotely pumped multicore erbium-doped fiber amplifier system with high pumping efficiency,” 2013 IEEE Photonics Society Summer Topical Meeting on SDM for Optical Comm., Waikoloa, USA, pp. 131–132, WC3.3, Jul. 2013. DOI:10.1109/PHOSST.2013.6614551
[5] H. Takara, T. Mizuno, H. Kawakami, Y. Miyamoto, H. Masuda, K. Kitamura, H. Ono, S. Asakawa, Y. Amma, K. Hirakawa, S. Matsuo, K. Tsujikawa, and M. Yamada, “120.7-Tb/s MCF-ROPA unrepeatered transmission of PDM-32QAM channels over 204 km,” J. Lightwave Technol., vol. 33, no. 7, pp. 1473–1478, Apr. 2015. DOI:10.1109/JLT.2015.2397009
[6] H. Masuda and K. Kitamura, “Distributed optical amplification technologies for multicore fiber transmission,” 2016 IEEE Photonics Society Summer Topical Meeting on SDM for Optical Comm., Newport Beach, USA, pp. 76–77, ME4.2 Jul. 2016. DOI:10.1109/PHOSST.2016.7548735
1 Introduction

Compared to conventional lumped erbium-doped fiber amplifiers (EDFAs), remote optically pumped amplifiers (ROPAs) can significantly enhance the transmission distances/capacities in long-haul transmission systems (unrepeatered and repeatered systems) [1, 2, 3, 4, 5, 6, 7]. This is because the ROPAs can achieve higher optical signal-to-noise ratios (OSNRs) of more than ~5 dB over that of the lumped EDFAs. The automatic gain control (AGC) of the ROPA is indispensable in the wavelength routing/switching systems of photonic networks in future [8, 9, 10]. Moreover, realizing core-by-core AGC of a remotely pumped multicore EDFA, which has a shared pump light source for several cores of a multicore EDFA, is a crucial issue in a spatial division multiplexing transmission system [8, 9, 10]. An ROPA consists of a remotely pumped EDFA (RP-EDFA) section and a distributed Raman amplification (DRA) section [6]. Therefore, the gain of each amplifier section must be dynamically kept constant against the change in the number of the wavelength division multiplexing (WDM) signal channels. In this paper, we propose an all-optical feedback AGC (FB-AGC) scheme applicable to both single-core and multicore ROPA transmission systems and report experimental results on the AGC characteristics of ROPA transmission systems for the first time, to our knowledge. Using a novel RP-EDFA module, a dynamic FB-AGC operation with gain excursions of less than ~0.2 dB has been successfully achieved. Note that some preliminary experimental results on the FB-AGC scheme were previously reported in [11, 12].
2 Experimental configuration

The experimental configuration of our proposed all-optical FB-AGC scheme for an ROPA is shown in Fig. 1(a). Here, we assumed a 40-channel WDM system in the experiment. We launched a signal power of 1 mW per channel into the transmission fiber span. The WDM signal lights consisted of a surviving light and four saturation lights. The wavelength of the surviving light was 1550.0 nm, and those of the saturation lights were 1532.7, 1539.0, 1546.9, and 1552.5 nm in the C-band. The saturation lights were periodically added and dropped by an acousto-optic modulator (AOM) to evaluate the dynamic AGC characteristics of the scheme.

The transmission fiber span consisted of a variable optical attenuator (VOA_{span}), two 30-km-long transmission fibers (Fiber-1 and -2), and an RP-EDFA module between the transmission fibers. We used VOA_{span} instead of a transmission fiber for experimental convenience. We varied the loss of VOA_{span} to adjust the loss of the transmission fiber span (L_{span}). Distributed Raman amplification was generated in Fiber-2. We investigated the AGC characteristics of the ROPA system for two typical values of L_{span} of 25.4 and 28.2 dB, corresponding to span lengths of 134 and 149 km, respectively, assuming that the loss coefficient of the transmission fiber at 1550.0 nm is 0.19 dB/km. The gain excursion is expected to be larger with a smaller span loss which corresponds to a shorter span length. Therefore, the case of 25.4-dB span loss is worst for AGC operation. The RP-EDFA module had a fiber-ring-laser circuit, which included an RP-EDF, an isolator, a variable optical attenuator (VOA_{ring}), and two wavelength selective couplers (WSC_F and WSC_R). Both ends of the RP-EDF, whose length was 3.2 m, were fusion-spliced with standard single mode fibers. We adjusted the loss of the VOA_{ring} to obtain a flat gain spectrum of the RP-EDFA module over the C-band. The net flat gain of the RP-EDFA module was $\sim$14 dB. We used the WSC_F and WSC_R to couple and separate, respectively, the WDM signal lights and laser light. WSC_F and WSC_R were dielectric multilayer couplers for the 100- and 200-GHz grid WDM system, respectively. They had 3 ports, referred to herein as the signal, laser, and common port. A pump light from a pump light source (Pump LS) with a wavelength ($\lambda_p$) of 1490 nm (except in the measurement of the static gain characteristics of the RP-EDFA module, which will be described in the next section) was launched into Fiber-2 via a coupler. The power and spectra of the WDM signal lights were measured by a sampling oscilloscope and an optical spectrum analyzer.

The loss spectra of WSC_F and WSC_R are shown in Fig. 1(b)–(d) and (e)–(g), respectively. Fig. 1(b) and (e) shows the spectrum of WSC_F and WSC_R, respectively, between the common and signal ports. The losses of WSC_F and WSC_R for the WDM signal lights were less than 0.5 dB. The low losses for the WDM signal lights are required to achieve high OSNRs. The loss of WSC_R for the pump light was also less than 0.5 dB. The low loss for the pump light is required to achieve a high pumping efficiency. The pump power penalty to employ the FB-AGC scheme was equal to the pump loss of the WSC_R. Fig. 1(c) and (f) show the detailed loss characteristics of the rejection band of WSC_F and WSC_R, respectively. The losses of WSC_F and WSC_R within a 1-dB bandwidth of WSC_F for the laser light transmission were more than 11 and 22 dB, respectively. High attenuation at the
laser light wavelength ($\lambda_1$) is necessary for WSCR to avoid degradation of the signal light propagating in Fiber-2 owing to nonlinear effects caused by co-propagating laser light at high power. Fig. 1(d) and (g) shows the loss spectra of WSCF and WSCR, respectively, between the common and laser ports. $\lambda_1$ was within the pass band of WSCF, which was narrower than that of WSCR. The center wavelength and 1-dB bandwidth of the pass band of WSCF were 1559.3 and 0.5 nm, respectively.

### 3 Experimental results

First, we measured the OSNRs of the systems with and without the ROPA scheme. We used an input signal power of 0 dBm launched into the transmission fiber span and a noise bandwidth of 0.1 nm. For an $L_{\text{span}}$ value of 25.4 dB, the OSNRs without ($\text{OSNR}_{w/o}$) and with ($\text{OSNR}_w$) the ROPA scheme ranged from 26.3 to 27.6 dB and 31.0 to 32.8 dB, respectively. The ONSR improvements ($\Delta\text{OSNR}$) ranged from 4.7 to 5.1 dB. Here, $\Delta\text{OSNR}$ was defined as the difference between $\text{OSNR}_w$ and $\text{OSNR}_{w/o}$. On the other hand, for an $L_{\text{span}}$ value of 28.2 dB, the $\Delta\text{OSNR}$ values ranged from 4.7 to 5.3 dB. The data indicate that $\Delta\text{OSNR}$ values of $\sim$5 dB were achieved across the C-band by employing the ROPA scheme for both cases of $L_{\text{span}}$.  

Fig. 1. (a) Experimental configuration of all-optical FB-AGC scheme for an ROPA. Loss spectra of (b)–(d) WSCF and (e)–(g) WSCR.
Next, we investigated the static gain characteristics of the RP-EDFA module for two values of the wavelength of the surviving light ($\lambda_{\text{suv}}$). Fig. 2(a) and (b) show the dependences of the gain on the total input signal power ($P_{\text{sin}}$) at typical pump powers ($P_{\text{p}}$) from 131 to 170 mW for $\lambda_{\text{suv}}$ of 1550.0 and 1531.0 nm, respectively. $P_{\text{sin}}$ and $P_{\text{p}}$ were the powers launched into the RP-EDFA module in this measurement. $P_{\text{sin}}$ was the sum of the power of the surviving light ($P_{\text{suv}}$) and that of the saturation light ($P_{\text{sat}}$). $P_{\text{suv}}$ was kept at 0.039 mW while $P_{\text{sin}}$ was adjusted by varying $P_{\text{sat}}$. For experimental convenience, we used $\lambda_{\text{p}}$ of 1.48 µm in this measurement. In Fig. 2(a), the maximum static gain ($G_{s,\text{max}}$) was $\sim$13.5 dB at $P_{\text{sin}}$ of 0.039 mW for all values of $P_{\text{p}}$. The gains decreased with increasing $P_{\text{sin}}$ and increased with $P_{\text{p}}$. The minimum static gain ($G_{s,\text{min}}$), which depended on $P_{\text{p}}$, ranged from $\sim$13.2 to $\sim$13.3 dB at $P_{\text{sin}}$ of 1.51 mW. The gain difference ($\Delta G_{s}$), the difference between $G_{s,\text{max}}$ and $G_{s,\text{min}}$, ranged from 0.2 to 0.3 dB for the tested pump powers $P_{\text{p}}$ with $\lambda_{\text{suv}}$ of 1550.0 nm. On the other hand, $G_{s,\text{max}}$ was $\sim$14.4 dB, and $G_{s,\text{min}}$ was in the range from $\sim$13.8 to $\sim$13.9 dB with $\lambda_{\text{suv}}$ of 1531.0 nm, as shown in Fig. 2(b). $\Delta G_{s}$ ranged from 0.5 to 0.6 dB. The data indicate that the average value of $\Delta G_{s}$ at 1531.0 nm (0.55 dB) was $\sim$2 times larger than that at 1550.0 nm (0.25 dB). It is considered that $\Delta G_{s}$ was large at near the gain peak wavelength ($\sim$1532 nm) due to the spectral hole burning effect [11].

Finally, we evaluated the dynamic characteristics of the FB-AGC scheme of the ROPA. $P_{\text{sin}}$ launched into the transmission fiber span was 16.0 dBm in this experiment. For simplicity, $P_{\text{suv}}$ launched into the RP-EDFA module was set at $-17.7$ dBm in both cases of $L_{\text{span}}$. $P_{\text{p}}$ launched into the transmission fiber were 315 and 170 mW for the cases of $L_{\text{span}}$ of 25.4 and 28.2 dB, respectively. Raman gains in the DRA section were 4.3 and 2.3 dB, respectively. Fig. 3(a) shows the transient gain excursions of the surviving light with and without the FB-AGC scheme at $L_{\text{span}}$ of 25.4 dB. To evaluate the AGC characteristics of the ROPA system, the gain was measured at the end of Fiber-2. The saturation lights were dropped at the times ($t$) of 1.3 and 6.3 ms, and added at 3.8 ms. The gain difference as a function of $t$, $\Delta G_{d}(t)$, is defined as the gain at $t$ minus the gain in the steady state for the case of adding. Without the FB-AGC scheme $\Delta G_{d}$ ($t$) increased (decreased) when the saturation lights were dropped (added) owing to the gain saturation effect of the ROPA. The maximum value of $\Delta G_{d}$ ($t$) ($\Delta G_{d,\text{max}}$) was 2.1 dB. On the other hand,
with the FB-AGC scheme, the gain excursion was significantly suppressed. Fig. 3(b) shows the transient gain excursion with the FB-AGC scheme in the short time range for the case of dropping. Oscillation in the gain excursion was observed when the saturation lights were dropped. It is considered that the gain-excursion oscillation was caused by the relaxation oscillation of the laser light in the fiber-ring-laser circuit in the RP-EDFA module. $\Delta G_{d,max}$ was 0.20 dB with the FB-AGC scheme, $\sim$10 times smaller than that without the scheme.

On the other hand, $\Delta G_{d,max}$ without and with the FB-AGC scheme at $L_{span}$ of 28.2 dB were 1.7 and 0.14 dB, respectively, which was $\sim$12 times smaller than that without the scheme. $\Delta G_{d,max}$ was decreased with increasing $L_{span}$ of 2.8 dB (28.2–25.4 dB), because the signal power launched into the RP-EDFA module was decreased by 2.8 dB.

![Fig. 3](image-url)

Fig. 3. (a) Transient gain excursions of the ROPA with and without the FB-AGC scheme. (b) Oscillation in the gain excursion with the FB-AGC scheme.

### 4 Conclusion

We have proposed a novel all-optical feedback AGC scheme for ROPAs. We experimentally clarified the static and dynamic gain control characteristics of the RP-EDFA. The OSNR improvements of $\sim$5 dB were achieved across the C-band by employing the ROPA scheme. The maximum gain excursion was significantly reduced from 2.1 dB without AGC to $\sim$0.2 dB with the all-optical feedback AGC scheme for the worst case of 25.4-dB span loss.

### Acknowledgments

This work was supported in part by JSPS KAKENHI Grant Number JP16K06355.