First experimental demonstration of all-optical feedforward automatic gain control scheme using a semiconductor optical amplifier

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Abstract: We propose a novel all-optical feedforward automatic gain control (AGC) scheme for multicore erbium-doped fiber amplifiers (EDFAs). In this scheme, a semiconductor optical amplifier (SOA) is used in an AGC circuit. The first experimental demonstration of the dynamic gain control operation is reported. A maximum gain difference of ~ 0.12 dB is successfully obtained using the control scheme. The proposed AGC circuit using an SOA achieves a significantly small response time constant of less than 5 μ s, which is more than 20 times smaller than that of the circuit using an EDFA.

Keywords: automatic gain control, semiconductor optical amplifier, erbium-doped fiber amplifier

Classification: Optical hardware

References

- [1] T. Morioka: “High-capacity transmission using high-density multicore fiber,” OFC (2017) Th1C.3.
- [2] D. Soma, *et al.*: “10.16 Peta-bit/s dense SDM/WDM transmission over low-DMD 6-mode 19-core fibre across C+L band,” ECOC (2017) Th.PDP.A.1 (DOI: [10.1109/ECOC.2017.8346082](https://doi.org/10.1109/ECOC.2017.8346082)).
- [3] G. Rademacher, *et al.*: “159 Tbit/s C+L band transmission over 1045 km 3-mode graded-index few-mode fiber,” OFC (2018) Th4C.4.
- [4] K. Shibahara, *et al.*: “DMD-unmanaged long-haul SDM transmission over 2500-km 12-core $\times$ 3-mode MC-FMF and 6300-km 3-mode FMF employing intermodal interference cancelling technique,” OFC (2018) Th4C.6.
- [5] T. Mizuno, *et al.*: “Long-haul dense space-division multiplexed transmission over low-crosstalk heterogeneous 32-core transmission line using a partial recirculating loop system,” J. Lightwave Technol. **35** (2017) 488 (DOI: [10.1109/JLT.2016.2615070](https://doi.org/10.1109/JLT.2016.2615070)).
- [6] H. Takara, *et al.*: “120.7-Tb/s MCF-ROPA unrepeated transmission of PDM-32QAM channels over 204 km,” J. Lightwave Technol. **33** (2015) 1473 (DOI: [10.1109/JLT.2015.2397009](https://doi.org/10.1109/JLT.2015.2397009)).
- [7] 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. (2016) 76, ME4.2 (DOI: [10.1109/PHOSST.2016.7548735](https://doi.org/10.1109/PHOSST.2016.7548735)).
- [8] K. S. Abedin, *et al.*: “Cladding-pumped erbium-doped multicore fiber amplifier,” Opt. Express **20** (2012) 20191 (DOI: [10.1364/OE.20.020191](https://doi.org/10.1364/OE.20.020191)).
- [9] H. Nakaji and M. Shigematsu: “Wavelength dependence of dynamic gain fluctuation in a high-speed automatic gain controlled erbium-doped fiber amplifier,” IEEE Photonics Technol. Lett. **15** (2003) 203 (DOI: [10.1109/LPT.2002.806849](https://doi.org/10.1109/LPT.2002.806849)).
- [10] C. Tian and S. Kinoshita: “Analysis and control of transient dynamics of EDFA pumped by 1480- and 980-nm lasers,” J. Lightwave Technol. **21** (2003) 1728 (DOI: [10.1109/JLT.2003.815649](https://doi.org/10.1109/JLT.2003.815649)).
- [11] K. Kitamura, *et al.*: “Novel all-optical feedforward automatic gain control scheme for multicore erbium-doped fiber amplifiers,” OECC/ACOFT (2014) TU5C-2.
- [12] K. Kitamura, *et al.*: “All-optical feedforward automatic gain control scheme for pump power shared erbium-doped fiber amplifiers,” IEICE Electron. Express **13** (2016) 20160920 (DOI: [10.1587/elex.13.20160920](https://doi.org/10.1587/elex.13.20160920)).
- [13] Q. Xu and M. Yao: “Theoretical analyses on short-term stability of semiconductor fiber ring lasers,” IEEE J. Quantum Electron. **39** (2003) 1260 (DOI: [10.1109/JQE.2003.817668](https://doi.org/10.1109/JQE.2003.817668)).
- [14] A. E. Siegman: *Lasers* (University Science Books, Mill Valley, 1986) 954.
- [15] C. Qin and D. Yang: “Numerical simulation of ring cavity wavelength-swept laser based on semiconductor optical amplifier,” IEEE J. Quantum Electron. **50** (2014) 831 (DOI: [10.1109/JQE.2014.2347341](https://doi.org/10.1109/JQE.2014.2347341)).

1 Introduction

Space-division multiplexing (SDM) technologies have been intensely studied in order to realize ultra-high transmission capacities in future optical fiber communication systems [1, 2, 3, 4, 5, 6, 7, 8]. Multicore fiber transmission is one of the promising technologies, and multicore erbium-doped fiber amplifiers (MC-EDFAs) are crucial devices in such systems [1, 5, 6, 7, 8]. Automatic gain control (AGC) schemes for the MC-EDFAs are indispensable in SDM networks, as is the case in the single-core networks [9, 10]. Although the MC-EDFAs that share the pump power (PS-EDFAs) realize efficient power consumption, conventional core-by-core AGC schemes cannot be applied to them [8]. We propose an all-optical feedforward AGC (FF-AGC) scheme, which is applicable to the MC-EDFAs, including PS-EDFAs [11, 12]. In our proposed FF-AGC scheme, the total input light power launched into the gain block (GB) is maintained at a constant level by the AGC circuit against the change in the wavelength division multiplexing (WDM) signal channels in such a manner that the gain of the GB is kept constant. The AGC circuit consists of a fiber ring laser (FRL). By using the AGC circuit, in which an EDFA was used as a laser gain medium, the characteristics of the all-optical FF-AGC was experimentally clarified [11, 12]. In this paper, a novel all-optical FF-AGC scheme, which employs a semiconductor optical amplifier (SOA) as a gain medium in the AGC circuit, is proposed, and the results of the first experimental demonstration of the scheme are reported. By using the SOA, the response time constant of the

proposed AGC circuit is significantly reduced, more than 20 times, compared to that of the AGC circuit with an EDFA.

2 Experimental setup

Fig. 1 shows the experimental configuration of our proposed all-optical FF-AGC scheme using an SOA. Single-core fibers and components were used in the experiment for convenience. We assumed a 16-channel WDM system in the C-band. The signal light power launched into the AGC circuit was set at -16.0 dBm per channel. The WDM signal lights consisted of a surviving channel and two saturation lights. The wavelength of the surviving channel light was 1549.9 nm and those of the saturation lights were 1546.9 and 1552.5 nm. The saturation lights were periodically added and dropped by using an acousto-optic modulator (AOM) to simulate the change in the WDM channels. The modulation frequency of the AOM was 200 Hz.

The AGC circuit consisted of an optical branch (BR_{line}), a variable optical attenuator (VOA_{sig}), an FRL, and an optical coupler (CP_{line}). A part of the signal light was branched from a transmission line by BR_{line} and launched into the FRL through VOA_{sig} . The control light generated in the FRL was combined with the signal light propagating in the transmission line by CP_{line} . The branching ratio of BR_{line} was 90:10. CP_{line} was a wavelength-selective coupler for the signal and control lights. The FRL consisted of an SOA, two isolators, an optical band-pass filter (OBPF), a variable optical attenuator (VOA_{ring}), a branch (BR_{ring}), and a coupler (CP_{ring}). The isolators were installed in the front and rear of the SOA to avoid unintended oscillations due to residual reflections. The wavelength of the control light was 1560.6 nm, which coincided with the center wavelength of the OBPF. The branching ratio of BR_{ring} was 80:20. CP_{ring} was a wavelength-selective coupler for the signal and control lights. The gain of the SOA was adjusted by the attenuation of VOA_{ring} . The attenuations of VOA_{ring} and VOA_{sig} were adjusted to satisfy the AGC condition, which is described later. At the rear of the AGC circuit, a monitoring port (BR_{mon}) was set, and the output light power was measured by an optical power meter (PM).

The signal and control light outputs from the AGC circuit was launched into the EDFA GB. The GB consisted of two cascaded EDFA GB modules with a gain equalizer set between them. The optical waveforms of the surviving channel light

Fig. 1. Experimental configuration of the all-optical FF-AGC scheme using an SOA.

output from the GB were measured via an OBPF using an oscilloscope with an optical-to-electrical converter.

3 Experimental results

First, we studied the static characteristics of the AGC circuit. The total power of the signal lights launched into the AGC circuit (P_{sin}) was manually varied. Fig. 2 shows light power with different values launched into the GB ($P_{\text{sig}}, P_{\text{cont}}, P_{\text{tot}}$) as functions of P_{sin} . The values of the signal light power (P_{sig}) and total input light power (P_{tot}) were measured, and the value of the control light power (P_{cont}) was calculated as P_{tot} minus P_{sig} . P_{sig} increased with P_{sin} linearly. The difference between P_{sig} and P_{sin} corresponded to the sum of the losses of BR_{line} and CP_{line} for the signal light. The AGC circuit compensated the increasing P_{sig} by decreasing P_{cont} . Therefore, P_{cont} decreased with increasing P_{sin} , and P_{tot} was kept constant. This AGC condition was obtained by adjusting the gain of SOA and the attenuation of VOA_{sig} [11, 12]. The average and variation of P_{tot} were 0.48 mW and 0.01 mW, respectively. The blue dashed line in Fig. 2 shows the average level of P_{tot} .

Fig. 2. Static characteristics of the AGC circuit.

Next, we evaluated the dynamic characteristics of the proposed AGC scheme. The saturation lights were added and dropped using the AOM, and the temporal gain variation of the surviving light was measured. Fig. 3 shows the transient gain excursion characteristics of the GB with and without the AGC scheme. The gain difference ($\Delta G(t)$) as a function of time (t) is defined as the gain at t ($G(t)$) minus the gain in the steady state for the case of adding (G_0), where G_0 was 18.0 dB. The saturation lights were added at 1.0 and 6.0 ms, and dropped at 3.5 ms. Without the AGC scheme, $\Delta G(t)$ decreased and increased when the saturation lights were added and dropped, respectively, owing to the gain saturation effect of the GB. The maximum absolute value of $\Delta G(t)$ (ΔG_{max}) was 6.9 dB without the AGC scheme. However, the gain difference was suppressed significantly by employing the AGC scheme. ΔG_{max} was ~ 0.12 dB with the AGC scheme. It can be recognized that there are spike-like gain differences at the time of adding and dropping. The response times required to obtain the $\Delta G(t)$ of less than 0.05 dB were ~ 0.07 and ~ 0.05 ms at adding and dropping, respectively.

Finally, we investigated the response characteristics of the AGC circuit. The gain control characteristics in the FF-AGC scheme depend on the response

Fig. 3. Transient gain excursion of the GB with and without the AGC scheme.

characteristics of the AGC circuit. Figs. 4(a) and (b) show the transient total output light power from the AGC circuit ($P_{\text{out}}(t)$) at adding and dropping, respectively. $P_{\text{out}}(t)$ in the both figures are normalized by the steady state values. The transient responses of $P_{\text{out}}(t)$ corresponds to those of the output light power from the FRL, because the signal lights modulated by the AOM are considered as step-like pulses. It is shown that there are no oscillation pattern in the waveforms of $P_{\text{out}}(t)$. The cavity length of the FRL (L) was ~ 34 m in the experiment, and the photon lifetime is estimated to be ~ 37 ns using the cavity loss of ~ 20 dB. Because the carrier lifetime of the SOA (~ 1 ns typically) was shorter than the photon lifetime of ~ 37 ns, there were no relaxation oscillations in the FRL [13, 14]. The response times of the AGC circuit can be represented by the decay time constants (times to be $1/e$) of $P_{\text{out}}(t)$. They were ~ 3.5 and ~ 4.8 μs at adding and dropping, respectively. The round-trip time of the FRL is estimated to be ~ 0.17 μs , using L of ~ 34 m. Therefore, the response time of ~ 3.5 (~ 4.8) μs corresponds to a traveling time for a circulation of ~ 21 (~ 28) loops. From these results, it is found that the FRL reached the steady states in several tens of circulation (more than ~ 21) of the FRL loop [15]. On the other hand, in the case of the AGC circuit using an EDFA, relaxation oscillations were found in the total output light power $P_{\text{out}}(t)$ [12], where the decay time constant in the envelope of the oscillations was ~ 130 μs . Therefore, the response time constant was decreased by more than 20 times by using the AGC circuit with the SOA (from ~ 130 μs to less than 5 μs).

Fig. 4. Transient total output light power from the AGC circuit at (a) adding and (b) dropping.

4 Conclusion

We have proposed a novel all-optical FF-AGC scheme using an SOA as a gain medium in the AGC circuit and experimentally clarified the static and dynamic characteristics of the scheme. The maximum gain difference was reduced from 6.9 dB (without AGC) to ~ 0.12 dB (with AGC) by employing our proposed AGC scheme. A response time constant of less than 5 μ s of the AGC circuit was achieved by using an SOA. The response time constant was significantly reduced by more than 20 times as compared to that of the AGC circuits using an EDFA (~ 130 μ s).

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