All-optical feedforward automatic gain control scheme for pump power shared erbium-doped fiber amplifiers

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Abstract: A novel all-optical feedforward automatic gain control scheme for pump power shared erbium-doped fiber amplifiers has been proposed. Dynamic gain excursion characteristics of the amplifier using the scheme have been experimentally clarified. The maximum absolute value of the gain excursion has been significantly reduced from 7.3 dB without control to 0.47 dB with the control scheme.

Keywords: automatic gain control, EDFA, all optical, feedforward

Classification: Optical systems

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1 Introduction

Optical fiber transmission systems using space-division multiplexing technologies have been intensely studied in recent years in order to realize ultra-high transmission capacities of Peta bps class in future [1, 2, 3]. Multicore fiber transmission is one of the promising technologies for such systems. The multicore-based erbium-doped fiber amplifiers (MC-EDFAs), i.e., multicore EDFA and fiber-bundled EDFA, are crucial devices in multicore fiber transmission systems [1, 2, 3]. All or some of the cores of the MC-EDFA are pumped by a single pump laser diode (LD) module so that the electrical power consumption of the MC-EDFA can be significantly reduced [4]. The MC-EDFA configuration having a pump LD module shared by several cores is called the “pump power shared EDFA (PS-EDFA)” in this paper. This is because a large fraction of the electrical power consumption of the MC-EDFA is due to that of the pump LD module. Although the PS-EDFA can achieve low power consumption, the conventional core-by-core automatic gain control (AGC) scheme cannot be applied to the PS-EDFA. Both feedback and feedforward AGC schemes can be applied to the case of a single core EDFA. The pump light is fed into the erbium-doped fiber (EDF) using a fast optoelectronic circuit in the conventional feedback AGC scheme so that the detected signal gain is kept constant against the change in the number of wavelength-division multiplexing (WDM) signal channels [5]. On the other hand, the control light or pump light is fed into the EDF using a fast optoelectronic circuit in the conventional feedforward AGC scheme [6, 7]. Moreover, there are several studies on the all-optical feedback AGC scheme for the single core EDFA [8, 9]. We propose a novel all-optical feedforward AGC scheme (FF-AGC) for the PS-EDFA and report some experimental results on the dynamic AGC characteristics in this paper. The control light for the FF-AGC is all-optically generated so that the total light power launched into the PS-EDFA is kept constant. For the first time to our knowledge, the signal gain of the PS-EDFA has been successfully controlled to within a sufficiently small gain excursion. Note that some preliminary experimental results on the FF-AGC scheme were reported in [10, 11].
2 System configuration

Fig. 1 shows the schematic configuration of the all-optical FF-AGC scheme for the PS-EDFA. The PS-EDFA has an EDFA gain block (GB) section and an AGC circuit section. The number of cores (N) is set to be 3 for simplicity in the figure, although the values of N reported to date are 7, 12, 19, and so on [1, 2, 3]. The three cores are labeled from C1 to C3. The AGC circuit for each core is set in front of the EDFA GB. Each of the EDFA GB and AGC circuit sections has a pump LD module (LDM), which is denoted as LDM_{GB} and LDM_{AGC}, respectively. The pump light from the LDM_{GB} is divided by an optical divider (Divider_{GB}) and fed into the EDF cores of the MC-EDF module set in the EDFA GB. The MC-EDF module has fan-in and fan-out devices, a wavelength selective coupler for the signal and pump lights (WSC), optical isolators, and other components [1, 2, 3, 4]. On the other hand, the pump light from the LDM_{AGC} is divided by another optical divider (Divider_{AGC}) and fed into the AGC circuits, each of which consists of an optical branch, a fiber ring laser circuit (FRL), and an optical coupler. The FRL has an EDF and an optical band-pass filter (OBPF). The wavelength of the laser oscillation light in the FRL (control light) coincides with the center wavelength of the OBPF and is set near the signal wavelength region. The WDM signal lights for each core are branched and launched into the FRL. An optical coupler combines the control light with the WDM signal lights propagating in the transmission line. The combined lights are launched into the MC-EDF module. Let the powers of the WDM signal lights, control light, and their sum be $P_s$, $P_{cont}$, $P_{tot}$, respectively. The total power $P_{tot}$ is kept constant in the FF-AGC scheme ($P_{tot} = P_s + P_{cont}$) so that the signal gain is kept constant against the change in the number of WDM channels. The AGC circuit section, which has N all-optical AGC circuits driven by a single LDM_{AGC}, can achieve lower power consumption than the conventional AGC circuit section that has N fast and complicated optoelectronic circuits [5, 7].

3 Experiments

The experimental configuration of the all-optical FF-AGC scheme is shown in Fig. 2. Single core fibers and EDFs were used in the experiment for simplicity. The
EDFA GB consisted of two cascaded EDFA GB modules with a gain equalizer (GEQ) set between them. The FRL consists of an EDF module pumped bi-directionally using WSCs, a GEQ set before the EDF module, an optical bandpass filter (OBPF), a variable optical attenuator (VOA\textsubscript{ring}), and an isolator. The EDF module had two pieces of EDF (EDF-1 and -2), which were cascaded with an isolator between them in order to suppress the multi-pass interference noise. The lengths of the first and second stage EDFs were 15.9 and 3.8 m, respectively. The center wavelength of the OBPF was 1561.8 nm, which is a long wavelength edge in the C-band. The wavelength of the pump light was 1.48 µm, and the pump power output from the LDM\textsubscript{AGC} was as low as 55 mW. The power of a typical commercial pump LD module is up to ∼500 mW. Therefore, more than ∼5 or 10 AGC circuits can be pumped by a typical single pump LD module in the FF-AGC scheme.

The loss of the VOA\textsubscript{ring} was adjusted to obtain a flat gain spectrum of the EDF module over the C-band. The WDM signal lights were launched into the FRL through a branch (BR\textsubscript{sig}) and a coupler (CPL\textsubscript{sig}). The control light was branched by an optical branch (BR\textsubscript{cont}) and combined with the WDM signal lights by an optical coupler (CPL\textsubscript{cont}). The branching ratios of BR\textsubscript{sig} and CPL\textsubscript{cont} were 1:20 and 1:1, respectively. Two VOAs (VOA\textsubscript{sig} and VOA\textsubscript{cont}) were set in the front and rear sides of the FRL. Losses of the VOAs were adjusted to achieve the FF-AGC condition.

We assumed a 40-channel WDM system in which the signal power per channel launched into the transmission fiber was 1 mW/ch. The span loss was assumed to be ∼16 dB. A VOA (VOA\textsubscript{span}) was employed instead of the transmission fiber for experimental convenience. The WDM signal lights consisted of a surviving channel light and four saturation lights. The wavelength of the surviving channel light was 1550.0 nm and those of the saturation lights were 1532.7, 1539.0, 1546.9, and 1552.5 nm. The saturation lights were periodically added and dropped by an acousto-optic modulator (AOM). The optical waveform of the surviving channel light output from the EDFA GB was measured via an OBPF using an optical-to-electrical converter and an oscilloscope. In the optically amplified transmission system using the FF-AGC scheme, the control light must be rejected at the rear of the EDFA GB using an optical filter to reduce the degradation of the WDM signal due to the fiber nonlinear effects caused by the high-power control light.
First, we evaluated the static characteristics of the FF-AGC scheme. The total power of the WDM signal lights launched into the AGC circuit \( P_s^* \) was manually changed. Fig. 3 shows the light power launched into the EDFA GB \( P_{s}, P_{\text{cont}}, P_{\text{tot}} \) as a function of \( P_s^* \). \( P_s \) increased with \( P_s^* \) linearly. \( P_{\text{cont}} \) decreased with increasing \( P_s^* \). \( P_{\text{tot}} \), which was the sum of \( P_s \) and \( P_{\text{cont}} \), was almost constant. The average and variation of \( P_{\text{tot}} \) were 0.40 mW and 0.02 mW, respectively.

Next, we evaluated the dynamic characteristics of the FF-AGC scheme. Fig. 4 shows the transient gain excursion characteristics of the surviving channel light with and without the FF-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 \( G_0 \), where \( G_0 \) was 18.9 dB. The saturation lights were dropped at 0.8 and 5.8 ms, and added at 3.3 ms. \( \Delta G(t) \) increased (decreased) when the saturation lights were dropped (added) owing to the gain saturation effect of the EDFA GB without the FF-AGC scheme. The maximum absolute value of \( \Delta G(t) \) \( \Delta G_{\text{max}} \) was 7.3 dB without the FF-AGC scheme. On the other hand, the gain difference was suppressed significantly by employing the FF-AGC scheme. Oscillations in the gain excursion were observed when the saturation lights were dropped and added. These oscillations were caused by the relaxation oscillations in the FRL in the AGC circuit. The absolute value of the gain difference \( \Delta G(t) \) in the case of dropping was larger than that in the case of adding.

Finally, we investigated the dependence of the gain excursion on the loop length of the FRL \( L \). Additional fibers were installed between the VOA\(_{\text{ring}}\) and
We measured oscillation waveforms by the oscilloscope in four cases: at $L$ of 68 m (without the additional fiber), and 98, 128, and 1068 m (with the additional fibers). The cavity loss was kept constant by adjusting $\text{VOAring}$ in each case. Fig. 5(a) shows the transient gain excursions at the four lengths $L$ in the case of dropping. The amplitudes and frequencies of the oscillations depend on $L$. The oscillation frequency is denoted by $f_{\text{osc}}$. The overshoot and undershoot of the gain excursion are denoted by $\Delta G_{\text{over}}$ and $\Delta G_{\text{under}}$, respectively. Fig. 5(b) shows $f_{\text{osc}}$, $\Delta G_{\text{over}}$, and $\Delta G_{\text{under}}$ as functions of $L^{-1/2}$. $f_{\text{osc}}$ is proportional to $L^{-1/2}$. This length dependence is the same as that of the relaxation oscillation in a laser [12]. Moreover, $\Delta G_{\text{over}}$ and $\Delta G_{\text{under}}$ decreased with $L$. The minimum values of $\Delta G_{\text{over}}$ and $\Delta G_{\text{under}}$ were obtained with the shortest $L$ ($L = 68$), with values of 0.45 and 0.47 dB, respectively. Therefore, $\Delta G_{\text{max}}$ with the FF-AGC scheme was 0.47 dB, which is $\sim$16 times smaller than $\Delta G_{\text{max}}$ without the AGC scheme of 7.3 dB.

![Fig. 5.](image)

4 Conclusion

We have proposed a novel all-optical feedforward AGC scheme for the pump power shared EDFA and experimentally clarified the dynamic gain control characteristics of the EDFA. A low pump power of 55 mW required for the all-optical AGC circuit was achieved. The maximum gain excursion was significantly reduced from 7.3 dB without AGC to 0.47 dB with the fast feedforward AGC scheme.

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