Development of Three-Stage Burst-Mode EDFA with Flat Gain-Spectrum over Full C-Band for Core/Metro Networks

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Abstract *We newly developed a three-stage burst-mode EDFA with flattened gain over full C-band that is tuned for core/metro networks with long spans and broadband signals. The gain-transient suppression and flat gain-spectrum were confirmed and 1,000 km error-free transmission with a commercial optical transponder were demonstrated. ©2023 The Author(s)*

Introduction

For flexible use of limited network and computing resources, network virtualization and network functions virtualization technologies are gaining attention [1-4]. In a virtualized network, it is necessary to establish an operation method that provides optical path groups transporting data with appropriate capacity and time for brief and instant communication service requests. In addition, to improve the robustness of the network, when a communication failure occurs due to a physical disconnection of an optical fiber and multiple optical paths are interrupted, it is necessary to restore the communication of the interrupted optical path with an alternative optical path and to suppress the effect of the broken optical path on the communication quality of the remaining optical path.

To achieve the above-mentioned network, an optical node that can withstand sudden changes in optical input power is required [5]. In particular, an erbium-doped fiber amplifier (EDFA), which is generally used in current optical nodes, can occur gain fluctuations and adversely affects the communication quality when the input power of the optical signal changes rapidly as shown in the right top of Fig.1. To overcome the problem, a flexible optical path network using a burst-mode EDFA (BM-EDFA) has been proposed and demonstrated to realize the gain maintaining as shown at the right bottom of Fig. 1 [6-8]. These BM-EDFA were designed to have a large intrinsic saturation power with a special large-core erbium-doped fiber (EDF) [9] and clamped gain with optical feedback [6-8]. However, the conventional BM-EDFAs are not optimized for core/metro networks with long spans between optical nodes and broadband optical paths, and long-distance and broadband transmission experiments have not been conducted.

In this work, we develop and demonstrate a novel three-stage BM-EDFA that can support long-distance and broadband core/metro networks. The three-stage BM-EDFA has the following two improvements over the conventional BM-EDFA for supporting core/metro networks. First, the optical loss of the wavelength selective switch (WSS), which is essential for optical path switching in core/metro networks, can be supported by introducing the three-stage configuration. Then the gain spectrum in the full C-band can be flattened by

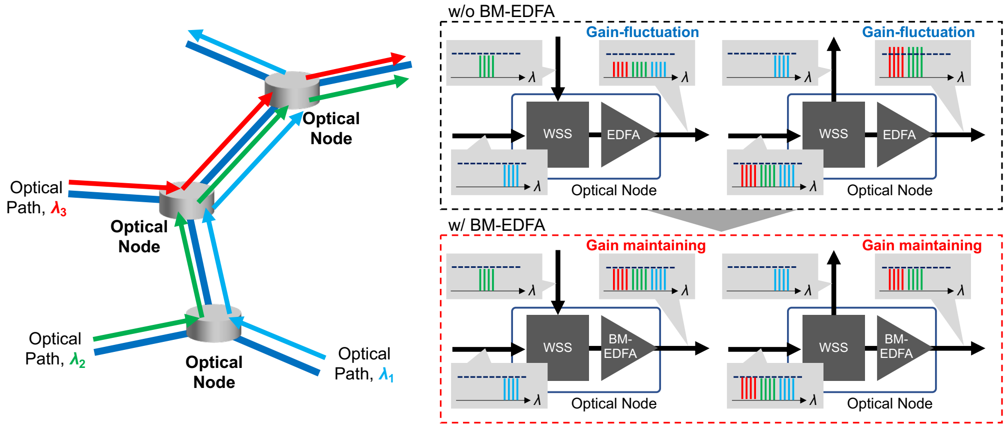

Fig. 1: Conceptual diagram of flexible optical network suppressed the gain-fluctuation by the BM-EDFA.

optimizing the gain flattening filter.

In the experiment, we first confirm the effect of suppressing the gain transient, which is the basic characteristic of the BM-EDFA, and the gain stability in the change of the optical input power due to the dropping of the optical path. At the time, the flatness of the gain-spectrum in our three-stage BM-EDFA was also confirmed. In addition, an experiment using a 1,000 km straight line and a commercial optical transponder shows the possibility of long-distance and broadband transmission with a three-stage BM-EDFA.

Three-stage burst-mode EDFA with flat gain-spectrum over the full C-band

Figure 2 shows the configuration and exterior appearance of the developed three-stage BM-EDFA. As shown in Fig. 2(a), the system consists of three BM-EDFAs, and all stages are optical automatic gain control (AGC). Additional switching elements can be arranged between Stage1 and Stage2, and additional optical losses of less than 12 dB can be permitted. Thus, it is possible to arrange elements with relatively large optical loss, such as WSS, which are essential for optical path switching on core/metro networks. Then, a gain flattening filter (GFF) is arranged between Stage2 and Stage3. This GFF can flatten the overall gain of three BM-EDFAs in the full C-band. The overall gain spectrum in the full C-band of the three BM-EDFA units was measured when the input power was -13dBm,

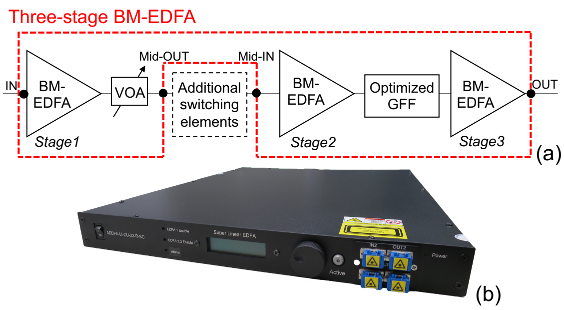

Fig. 2: (a) Configuration and (b) exterior appearance of the developed three-stage BM-EDFA.

and the GFF was designed to cancel the gain spectrum profile. As a result, the overall gain would be 27 dB over the full C-band at -13 dBm input level with the designed GFF profile. Moreover, we use a longer EDF in Stage1 and Stage3 to reduce the overall gain peak at a shorter wavelength of the conventional BM-EDFA. Thus, all optical signals in C-band can be amplified with the good gain condition.

Experiment

Figure 3 shows the experimental setup with the 1,000 km straight line and commercial optical transponder (Fujitsu, 1Finity T-600). In the setup, first, lights from 112 wavelength laser diodes (LD) are consolidated into odd and even channels by the wavelength division multiplexing (WDM) couplers and are modulated to 32 Gbaud quadrature phase shift keying (QPSK) signals with the IQ-modulator and the arbitrary wave generator (AWG). When the optical transponder is the signal under test, WSS1 selects an optical signal from the transmitter in the 1Finity T-600 instead of the corresponding dummy channel. Then, after transmitting the 1,000 km straight line consisting of 10 × 100.4 km standard single mode fibers (SMF-28), 10 × EDFA modules (the normal EDFAs, the conventional BM-EDFAs or our BM-EDFAs) and 10 × WSS modules, the optical signals are received or measured by 1Finity T-600 or optical spectrum analyzer (OSA).

We first measure the effect of the gain transient suppression in the developed three-stage BM-EDFA. During the measurement, a tunable laser (Agilent 81682) was used instead of the above light source. An optical packet of 800 ns in length was generated by an acoustic-optical modulator. Then, the optical packet amplified by our three-stage BM-EDFA was detected by the lightwave communications analyzer (HP 83475B). Figure 4 shows the input and output optical packets. The top of the output optical packet maintained the flat top. The gain transient was less than 0.1 dB/μm. Thus, the results showed

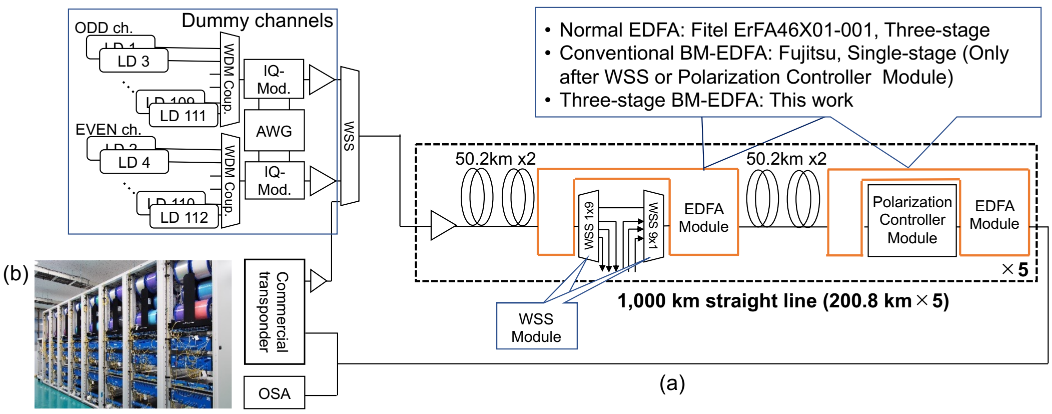

Fig. 3: (a) Experimental setup, (b) the exterior appearance of the 1,000 km straight line.

that our three-stage BM-EDFA suppress the gain transient correctly.

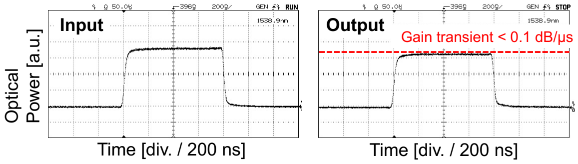

Fig. 4: Gain transient suppression effect in our three-stage BM-EDFA.

Next, we verify the spectrum characteristics over the full C-band in the developed three-stage BM-EDFA. During the measurement, all 112 wavelength LDs are used for the probe light. Then, the probe light was amplified by our three-stage BM-EDFA and detected by the OSA. In addition, for verifying the effect of the suppression for the sadden gain change due to dropping the wavelength paths, half of the wavelength channels were dropped according to the following conditions by the WSS. Condition 1: half of the shorter wavelength side, Condition 2: half of the longer wavelength side, Condition 3: four fifths of the wavelength channels were evenly dropped, Condition 4: wavelength channels were not dropped. Figure 5 shows the optical spectrum of the amplified probe light over the full C-band. According to Fig. 5, you can see that although the gain of the normal EDFA was excessively enhanced in all conditions, the conventional BM-EDFA and our three-stage BM-EDFA suppressed the excessive gain enhancement. In addition, the gain spectrum of our three-stage BM-EDFA was flat because of the optimized GFF and EDF.

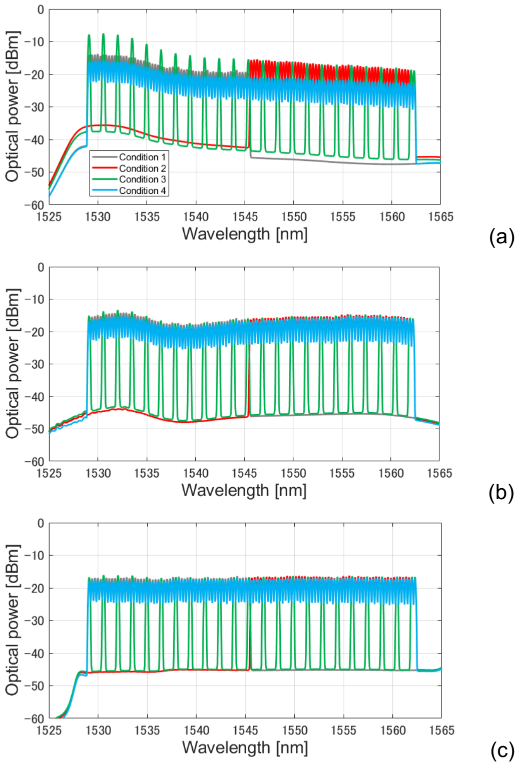

Fig. 5: Optical spectrum of the amplified probe light when dropping half of the wavelength paths, (a) normal EDFA, (b) conventional BM-EDFA, (c) our three-stage BM-EDFA.

Finally, we performed the transmission experiment with the 1Finity optical transponder. The transmission and reception of 1Finity were performed under three conditions, the shorter and longer side (1530.58 nm, 1560.96 nm) and the center (1545.67 nm) of the C-band with the dual-polarization 16-value quadrature amplitude modulation. Figure 6 shows the transmitted optical spectrum from 1Finity and the dummy channels. In the transmitter, the pre-emphasis which enhances the shorter wavelength side and tilts the transmission spectrum, was performed to compensate for the wavelength-dependent loss of SMF until the first WSS module. Table 1 summarizes the received optical power, the optical signal-noise-ratio (OSNR), the pre-forward error correction bit error rate (pre-FEC BER), and the FEC BER obtained by the 1Finity receiver. Since the FEC BERs at all wavelength conditions were 0, we can say that 1,000 km transmission with our three-stage BM-EDFA was achieved.

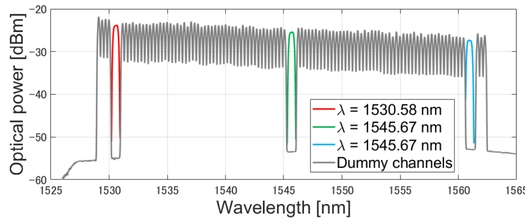

Fig. 6: Spectrum of the optical signal of 1Finity and dummy channels.

Tab. 1: Results of 1,000 km transmission obtained by 1Finity.

	1530.58 nm	1545.67 nm	1560.96 nm
Received optical power [dBm]	1.8	-0.2	-2.7
OSNR [dB]	20.0	21.0	20.0
Pre-FEC BER	0.014670	0.013387	0.014851
FEC BER	0	0	0

Conclusions

We developed and demonstrated the three-stage burst-mode EDFA with flat gain characteristics over the full C-band for the core/metro networks. In the experiment, the suppression of the gain-transient and 1,000 km error-free transmission with a commercial optical transponder was confirmed. In future work, we will demonstrate the error-free transmission when switching the wavelength paths.

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