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Novel in-service supervisory scheme for the amplified WDM link with modified optical time domain reflectometry

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Abstract

We propose a novel optical supervisory system for the wavelength division multiplexing (WDM) transmission link including in-line erbium-doped fiber amplifiers (EDFA). By employing a newly proposed EDFA structure supporting bi-directional transmission at pre-determined wavelength and modified optical time domain reflectometry technique, it was possible to accurately monitor the status of transmission fiber link under in-service condition. A proof of the concept experiment with 8 channel, 320 km WDM transmission in-service state has been successfully carried out giving a clear loss/gain/reflection profile of the link with negligible BER power penalty less than 0.3 dB.

Keywords: Optical time domain reflectometry; Optical fiber measurement; Monitoring; Wavelength division multiplexing

1. Introduction

The introduction of wavelength division multiplexing (WDM) technology and the erbium-doped fiber amplifier (EDFA) has significantly increased both of the capacity and the length of transmission link up to tens of terabit per second over thousands of miles. With this rapid progress, the demand for a supervisory system which can diagnose the status of fiber link, broadband EDFAs and hundreds of WDM signal channels have been also greatly increased. With this traffic size in the fiber, it should be possible to determine the location and origin of the failure quickly for the execution of appropriate treatment if there occurs a fault in the transmission line. However, there has not been much progress in the optical supervisory system in the assessment of the transmission line itself, after the introduction of simple optical supervisory channels (OSC), pilot tones or EDFA gain monitor [1]. While

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the OSC could deliver secondary information on the EDFA status and fiber loss, still the exact location of the fiber break has to be found under out-of-service mode after the break event, by using an optical time domain reflectometer (OTDR). Optical isolators within the EDFA also restrict the assessment range of OTDR within an amplifier span, necessitating excessive personnel dispatch time for repair. To overcome this problem and accomplish higher operating efficiency of the transmission line, several inter-span supervision schemes for the transmission link including cascaded EDFAs have been proposed. Still, those approaches so far have required either a separate EDFA for the amplification of the OTDR pulse or a complex control circuit for the transient control, failing to suppress additional cost and the complexity in the practical implementation [2–5].

In this paper, we propose and experimentally demonstrate a novel inter-span supervisory system for the optically amplified WDM transmission link in service, by applying a traditional OTDR technique. With the minor modification of EDFA structure to support bi-directional transmission at the pre-determined wavelength of probe pulse, the assessment range of conventional OTDR technique has been extended over multiple amplifier spans without the introduction of extra EDFA for probe pulse. We also propose the receiver-end probe pulse injection into the fiber link from the opposite direction of the data signal, to minimize the cross-gain modulation effects in the EDFA [6,7]. The experimental result shows a successful interrogation of the transmission loss/gain/reflection map over 320 km for a 2.5 Gb/s $\times$ 8 channel WDM transmission system, with less than 0.3 dB power penalty.

2. System architecture and analysis

The configuration of the proposed supervisory system for the optically amplified WDM transmission link is shown in Fig. 1. EDFA structures have been modified to support the bi-directional transmission of probe pulse at pre-determined wavelength, with the inclusion of fiber Bragg grating (Fig. 2a). Since the non-reflected lights passing the FBG are removed at the angled fiber end, the modified EDFA still provides optical isolation to the signal waves, minimizing the possible occurrence of unstable lasing phenomena induced by external reflections. Fiber mirrors also have been used to maintain the gain to the same

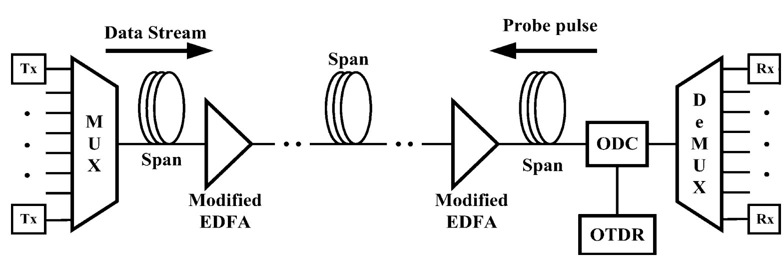


Fig. 1. Configuration of the proposed supervisory system (Tx: transmitter, Rx: receiver, ODC: optical device card, OTDR: optical time domain reflectometer).

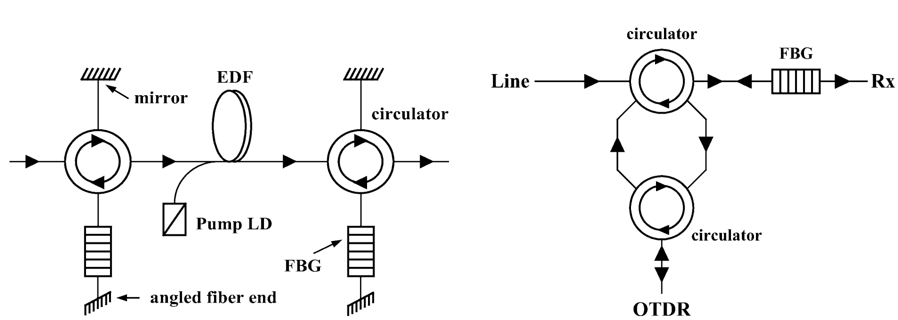


Fig. 2. Configuration of the (a) modified EDFA, (b) optical device card (ODC).

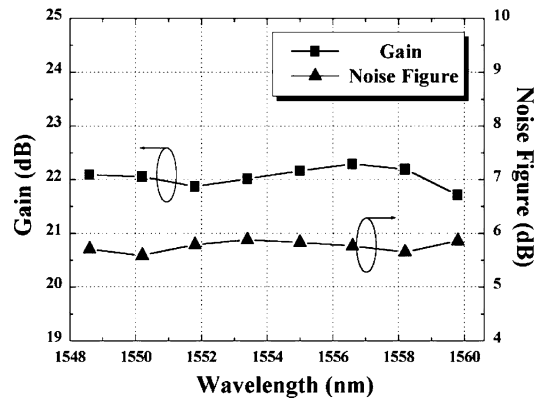


Fig. 3. Measured gain and noise figure of the modified EDFA.

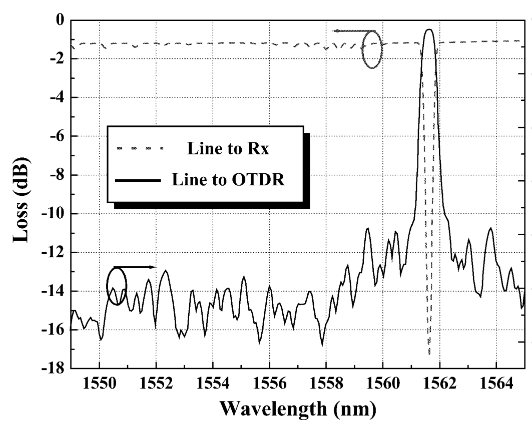
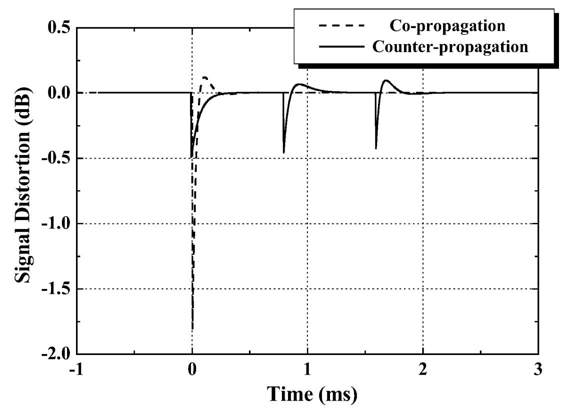


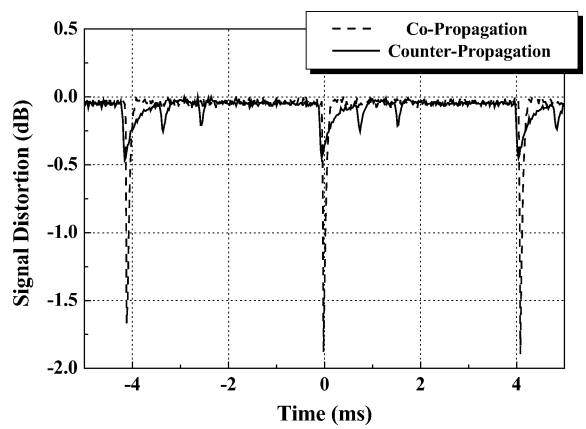
Fig. 4. Transmission profile of the optical device card (ODC).

level both for forward and backward transmission, at the OTDR probing wavelength. Figure 3 shows the measured multi-channel gain and noise figure of the implemented EDFA with modified structure, using 8 WDM signal wavelengths (−20 dB m/channel, from 1548.6 to 1559.8 nm with 1.6 nm spacing). The measured average gain of the EDFA was 22 dB and the gain flatness between the WDM channels was maintained under 0.5 dB. The external noise figure was measured to be less than 6.0 dB, enough for the practical application to the long-haul WDM transmission link. The backward gain/noise figure of the EDFA at 1561.4 nm, the pre-determined wavelength for OTDR probing at the out-of-signal band, was 22 and 5.8 dB, respectively. For the probe pulse source in OTDR, we have used a narrow linewidth DFB laser instead of the commonly used high-power Fabry–Perot laser, to match the narrow reflection bandwidth of FBGs in the system. Figure 2b shows the configuration of optical device card (ODC) in the receiver side, which was used to add/remove the probe pulse from the fiber link. Also shown in Fig. 4 is the reflection/transmission profiles of the ODC, showing the back-scattered light of OTDR probe pulse to ‘Receiver’ and ‘OTDR’ port. The measured crosstalk of ODC was 18 dB from the OTDR to WDM data transmission band and 40 dB from the WDM data to the OTDR port, respectively, providing enough suppression of the system penalty.

While this introduction of the newly proposed EDFA supporting bi-directional transmission of probe pulse and the ODC made the inter-amplifier span diagnosis of WDM link using OTDR technique feasible, it was observed that the introduction of the probe pulse degrades the transmitted data signal through the gain transient and cross-gain modulation process in the in-line EDFA [7]. This implies that the transmission system had to be out-of-service during the monitoring process in this configuration, failing to provide flexibility and high efficiency of system operation [1]. An even more serious prob-



(a)



(b)

Fig. 5. The signal distortion due to cross-gain modulation: (a) simulation, (b) experiment.

lem occurs when there exist several in-line EDFAs in the system, since this distortion of data stream by gain transient effect accumulates as it passes through the EDFA, limiting the OTDR supervisory measurement system range within few EDFA spans. Rather than introducing an additional amplifier unit or active feedback element as suggested in former studies [2–5], we overcame this problem by launching the probe pulse at receiver-end in the counter-direction of the data signal transmission. Figure 5a shows the signal distortion trace obtained with numerical calculation using average inversion analysis [6,7], by the cross-gain modulation effect from three in-line EDFAs. Span length of 80 km, 8 WDM signal of -20 dB m/channel at in-line EDFA input and OTDR pulse of 13 dBm peak power and 10 μs width were used in calculation. Figure 5b is the experimentally obtained result, showing good agreement with as the numerical result. When the probe pulse propagates in the same direction the data signal, the effects of gain variation by cross-gain modulation between the probe pulse and the data signal at each in-line EDFAs are accumulated at the same position in the data stream repeatedly, resulting severe reduction of transmitted signal power level and large power penalty to BER. In contrast, when the OTDR probe pulse was injected from the receiver-end in the reverse direction, the signal distortion from each in-line EDFA has been distributed to different time marks in the data stream, not generating the accumulation of undesirable transient response. As a result, the transient level has been deeply suppressed (from 2 to 0.5 dB), enabling the in-service monitoring over many EDFA span in WDM transmission system. It is also worth noting that the remaining transient level will be further suppressed as the number of WDM channels increases, since the relative power between the probe and total signal power will decrease, making the cross-gain modulation effects smaller.

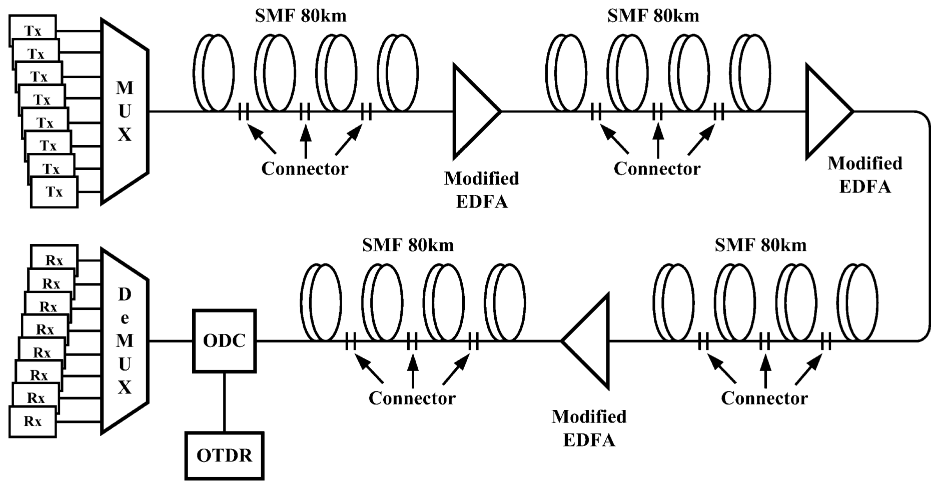


Fig. 6. The experimental configuration of proposed supervisory system.

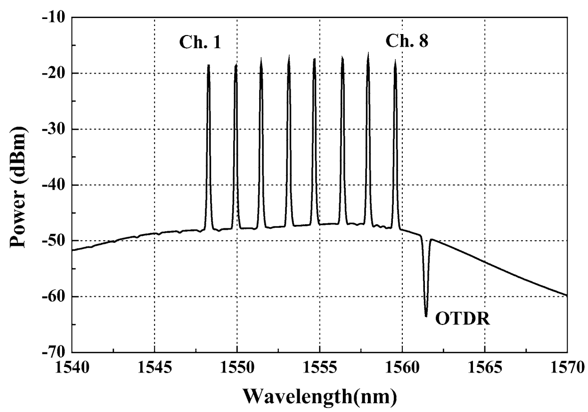
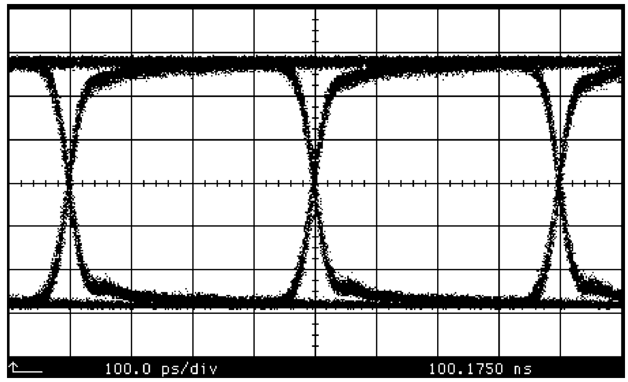


Fig. 7. Optical spectrum after propagating the transmission link.

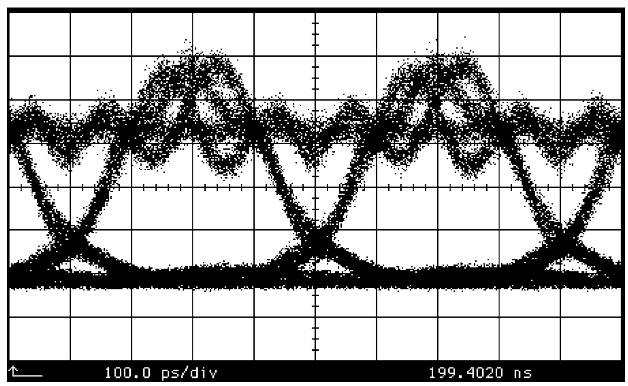
3. Experiment and discussion

Figure 6 shows the experimental setup of the proposed supervisory scheme. Eight channels of WDM signals externally modulated with $2^{23} - 1$ pseudo-random none-return-to-zero (NRZ) bit sequence at 2.5 Gb/s have been transmitted into the fiber link, which is made up of four 80 km standard single mode fiber (SMF) spans. Each amplifier span was composed of four 20 km SMF spools, which were concatenated by optical connector used as detectable events in the trace result of OTDR. Three in-line EDFAs with modified structure were inserted between each span for the regeneration of both data signals and counter-propagating OTDR probe pulse. To avoid interference between the OTDR probe pulse and the data signal, a commercial OTDR (HP6058A) was modified to use DFB laser (1561.4 nm) as the optical source instead of the existing Fabry–Perot laser, right above the data signal wavelength band (1548.2 to 1559.4 nm with channel spacing of 1.6 nm). The ODC was spliced at the end of transmission link to carry out the bypass of data signals and the add/drop of OTDR pulses. The probe pulse peak power was set at of 13 dB m with 10 µs pulse width, and the pulse has been launched into the fiber link at every 4 ms repetitively over 3 min.

Figure 7 shows the optical spectrum of WDM signals after the transmisson over 320 km SMF link with three in-line EDFAs and ODC. It is possible to see that the probing light at the wavelength of 1561.4 nm is clearly dropped into the OTDR at ODC. The flatness over WDM signal channels was maintained below 2.0 dB after the whole link. Figure 8a shows the eye diagram of data signal modulated at 2.5 Gb/s before the transmission at transmitter. Figure 8b shows the obtained eye after the 320 km SMF link (Fig. 6), exhibiting 2 typical



(a)



(b)

Fig. 8. Eye diagram of data signal: (a) before transmission, (b) after transmitted over 320 km normal dispersion single mode fiber.

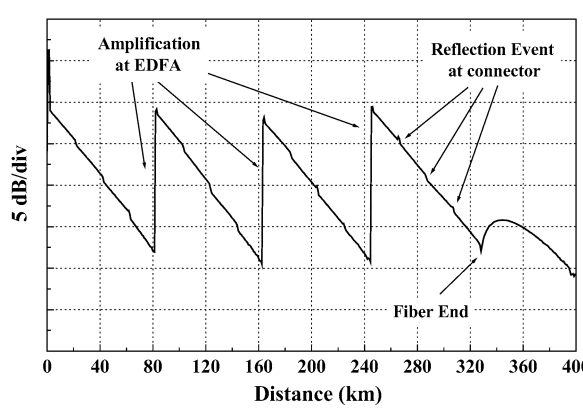


Fig. 9. The OTDR trace showing gain/loss/reflection profile.

distortion pattern from the dispersion. There was no noticeable change in the eye at the receiver end, irrespective of the supervisory system activation status. Figure 9 shows the OTDR trace result of the WDM transmission link in service. As can be seen from the figure, it was possible to monitor the gain values of EDFA at every 80 km span, as well as the reflection/loss events by connector pairs at every 20 km. We attribute the curved trace after the fiber end as the ghost signal due to the higher order multiple reflection term within the link [8]. Figure 10 shows the results of BER measurement with/without the supervisory system in operation. Even already negligible (less than 0.3 dB), the penalty even will be lower for larger channel count WDM systems or distributed amplification systems, implying the potential application of this technique over even longer WDM transmission systems.

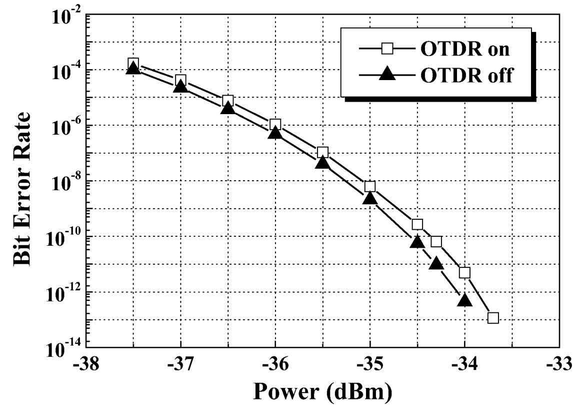


Fig. 10. BER measurement result with OTDR on and off.

4. Conclusion

In this paper, a novel in-service supervisory system using OTDR for WDM transmission link including cascaded in-line EDFAs has been proposed and experimentally demonstrated. The proposed scheme, which requires only minor modification of in-line EDFA, can simultaneously monitor the status of a long-haul WDM transmission link and the characteristics of an EDFA under in-service conditions with negligible power penalty. Successful application of the supervisory system has been demonstrated with 8×2.5 Gb/s, 320 km transmission line in service, with 0.3 dB of power penalty.

Acknowledgments

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