Novel In-Service Supervisory System Using OTDR for Long-Haul WDM Transmission Link Including Cascaded In-Line EDFAs

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***Abstract*—In this letter, we propose and demonstrate a novel optical supervisory system for long-haul wavelength-division-multiplexing (WDM) transmission link including cascaded erbium-doped fiber amplifiers (EDFAs). By employing a modified optical time domain reflectometry technique with a wavelength selective bidirectional EDFA, it was possible to monitor the status of the WDM transmission link and EDFA at in-service states with negligible power penalty. Proof of the concept with a 2.5 Gb/s $\times$ eight-channel WDM transmission system [single-mode fiber, 320 km] shows clear trace of the transmission line loss/gain/reflection map with minimal signal power penalty of 0.3 dB.**

***Index Terms*—Monitoring, optical fiber measurements, optical time-domain reflectometry, wavelength-division multiplexing.**

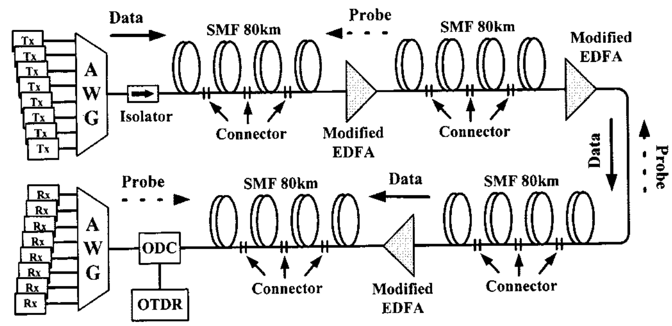

Fig. 1. The experimental configuration of proposed supervisory system and transmission link.

I. Introduction

WITH THE RAPID advance of wavelength-division-multiplexing (WDM) technology and introduction of wideband optical amplifiers, both the capacity and the length of optical transmission link have been greatly increased to terabit per second over thousands of miles. While this obvious trend has been calling for the development of better supervisory system to monitor the status of hundreds of WDM channels and wideband erbium-doped fiber amplifiers (EDFAs)—with all their health depend up on to a string of fiber—there has not been much progress after the introduction of simple optical supervisory channels (OSC), for which its functionality being seriously limited in the assessment of the transmission line itself. While the OSC could deliver secondary information on the EDFA status and fiber loss, the exact location of the fiber break has to be found after the break event, by using an optical time domain reflectometer (OTDR) with its assessment commonly restricted to an amplifier span. This in turn requires excessive personnel dispatch time, and also means the failure of preventive mode operations of the supervisory system. In this sense, in-service transmission link monitoring system, integrated with the EDFA status monitor in optical domain at least over the optical multiplexing layer, will be an attractive/compelling option as the number of channels inside a fiber, and its capacity/transmission distance further increases. While many different approaches for the supervision of an amplified transmission link have been proposed in this reason, they still required either a separate EDFA for the OTDR pulse or complex transient control circuits, failing to minimize extra cost and system complexity [2]–[4].

In this letter, we propose and successfully demonstrate a novel in-service supervisory system using traditional Rayleigh scattering-based OTDR for optically amplified WDM transmission link. With the modification of an EDFA structure to support bidirectional transmission only at the OTDR pulse wavelength, and the receiver-end injection of the probe signal, the proposed system does not require additional EDFA for amplification of probe pulse or suffer from cross-gain modulation (XGM) effects from the in-line EDFAs in the long-haul transmission link. The experimental result shows a successful interrogation of the transmission loss/gain/refection map over 320 km for a 2.5 Gb/s $\times$ 8 channel WDM transmission system, with less than 0.3-dB power penalty.

II. System Architrcture

The configuration of the proposed supervisory system and transmission link is illustrated in Fig. 1. The structure of the EDFA was modified to support the bidirectional transmission of probe pulse, as shown in Fig. 2(a). Fig. 2(b) shows the configuration of an optical device card (ODC) introduced to add the probe pulse into the fiber link and drop the backscattered light. By matching the reflection peak of fiber Bragg grating (FBG) to the wavelength OTDR probe pulse, the modified EDFA supports bidirectional transmission of the probe pulse

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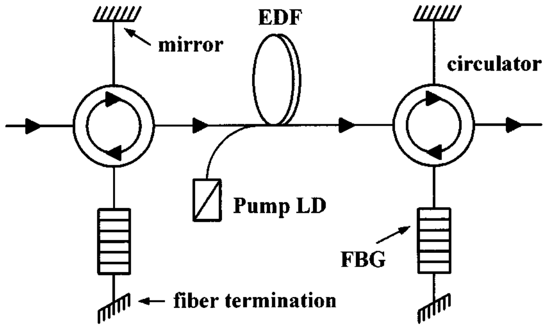
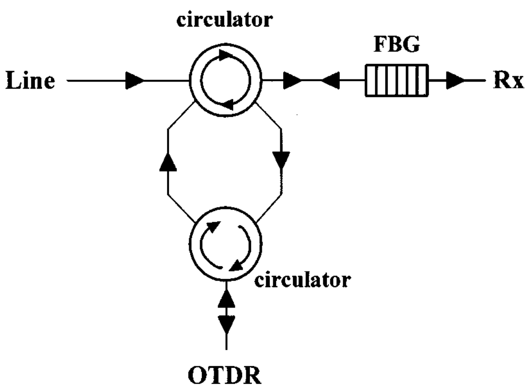


(a)



(b)

Fig. 2. Configuration of (a) the modified in-line EDFA and (b) the optical device card (FBG).

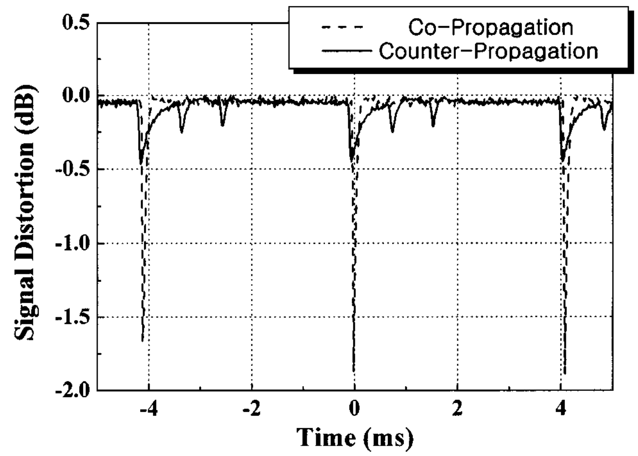


Fig. 3. Signal transient trace from the XGM effects in the link [signal-probe co-propagation (dashed line); signal-probe counterpropagation (solid line)].

while providing isolation to the signal waves. To balance the gain mismatch between forward and backward transmission at the probing wavelength, a gold-coated fiber mirror was introduced with a four-port circulator. While this adaptation enables bidirectional transmission and amplification of the probe pulse for the supervision of long-haul WDM link, still the problem of signal distortion from the XGM in the EDFA exists in executing supervision under in-service condition [5]. An even more serious problem occurs when there exists 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 adding in additional amplifier unit or active feedback element [2]–[4] to the in-line EDFAs in the system, we easily overcome this problem by launching the probe pulse from the receiver end in reverse direction to the transmitted data signal. In this scheme, the data signal distortion does not experience multiple gain modulations from the interactions with probe pulse within in-line EDFAs, but distributed over different time marks while its maximum distortion value being suppressed to that of single EDFA stage. Fig. 3 shows the experimental observation of the data signal distortion trace with respect to the relative direction of probe pulse injection. Distribution of the data distortion in the time domain with 0.8-ms spacing (twice the propagation time of 80-km fiber span) is evident as shown in Fig. 3 with the counterinjection of the probe pulse. Also can be found is a deep suppression of the transient level (from 2 to 0.5 dB), which allows the supervisory system measurement range to extend over much larger number of EDFA spans. It is also worth to mention that the level of the remaining transient will be also further suppressed as the number of WDM channels increases, since the relative power level between the probe and total signal power will decrease in that case. The degradation of the received SNR of OTDR signal by noise addition through the increment of WDM channels was almost negligible due to the high isolation (>30 dB) and narrow optical bandwidth (<0.4 nm) of the FBG in ODC. By applying formerly suggested noise analysis for the OTDR in optically amplified transmission system, the limit of monitoring range and cascaded EDFA was calculated [7]. With OTDR probe pulse of 10-μs duration and 13-dBm peak power, the proposed scheme could be applied to the WDM transmission link over a thousand kilometers including tens of in-line EDFAs with 80-km spacing.

III. Experiment and Discussion

The experimental setup was built based on the target system configuration, shown in Fig. 1. Eight channels of WDM signal externally modulated at 2.5 Gb/s with $2^{23}-1$ pseudorandom nonreturn-to-zero (NRZ) bit sequence have been launched into the transmission link composed of four single-mode fiber (SMF) spans with each length of 80 km. An optical isolator was inserted after the arrayed-waveguide grating (AWG) to prevent possible reflections from the out of fiber link under monitoring. Each span was made up of four 20-km SMF spools concatenated by optical connectors, which were intentionally placed to be seen as detectable reflection events in the OTDR trace. Three modified in-line EDFAs were inserted between each span for the regeneration of both data signals and counterpropagation OTDR pulse. The wavelengths of the WDM signal were from 1548.2 to 1559.4 nm with channel spacing of 1.6 nm. The wavelength of the OTDR pulse was selected as 1561.4 nm, right next to the data signal wavelength band. A commercial OTDR (HP6058A) was modified to include DFB laser sources and circulator, respectively, instead of a Fabry–Pérot laser and 3-dB coupler. The ODC was inserted at the end of transmission link to add/drop the OTDR probe pulse. Fig. 4 shows the optical spectrum of the WDM signal at the receiver end before the data signal demultiplexer, after transmitted through three in-line EDFA and ODC. Dropping of

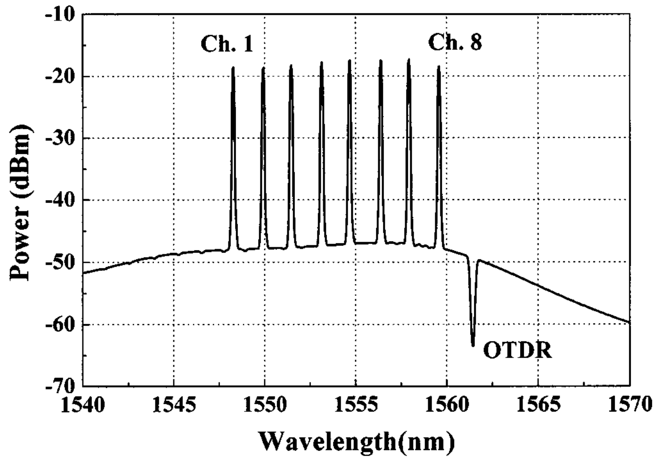


Fig. 4. Optical spectrum at the receiver end, after the ODC (RBW = 0.2 nm).

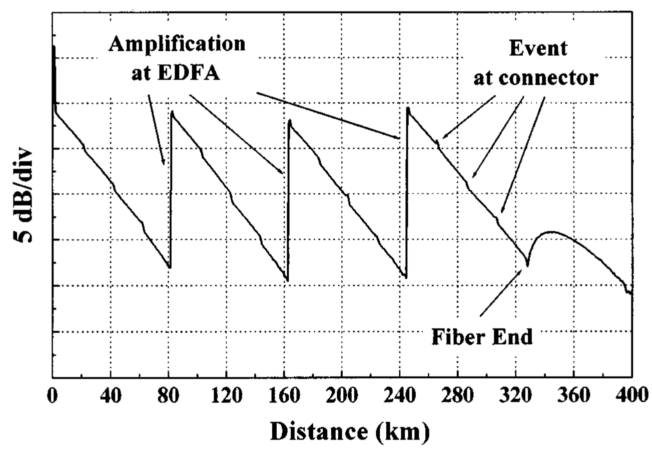


Fig. 5. Measured loss/gain/reflection map of the transmission link and EDFA.

the probe signal at the wavelength of 1561.4 nm is clear. Fig. 5 shows the OTDR trace result of the WDM transmission system in service state. The probe pulsewidth was set at 10 μs with 13-dBm peak power, and launched into the fiber at every 4 ms repetitively over 3 min. As can be seen from the figure, it was possible to monitor the gain values of EDFA at every 80-km span, and to observe the reflection events from connector pairs at every 20-km fiber spools. We attribute the curved trace after 320-km transmission fiber end as the ghost signal due to the multipath Rayleigh-scattered light, amplified by bidirectional in-line EDFAs within the link [6]. Fig. 6 shows the bit-error rate (BER) measurement result of received data stream with/without the supervisory system in operation. It was not possible to observe any fluctuation in the eye diagram of the transmitted data by the gain transient effects during measurement. Even already negligible (less than 0.3 dB), the penalty will be much smaller for larger channel count WDM systems or distributed amplification systems, implying the potential application of this technique over even longer WDM transmission systems.

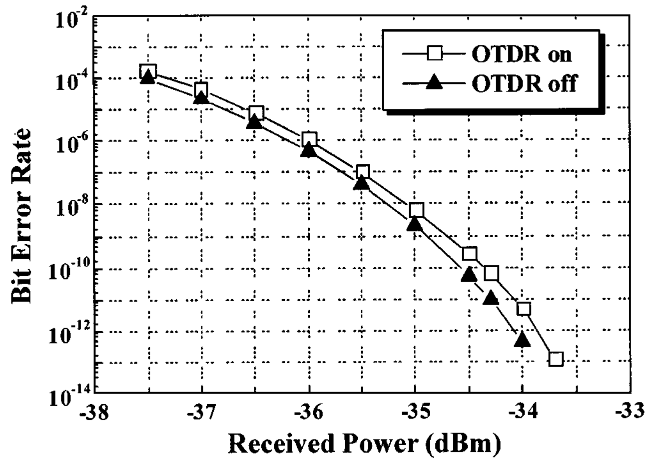


Fig. 6. BER curve of the transmission system with and without the supervisory system in operation.

IV. Conclusion

In this letter, a novel in-service supervisory system using OTDR for WDM transmission link including in-line EDFAs has been proposed. The proposed scheme can simultaneously monitor the status of long-haul WDM transmission link and operation characteristics of EDFAs under in-service condition, with negligible power penalty. Successful application of the test system has been demonstrated with a 8×2.5 Gb/s, 320 km systems in service, with less than 0.3 dB of power penalty.

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