In-Service Supervisory EDFA-Repeated Wavelength Division Multiplexing Transmission System

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***Abstract*—An in-service supervisory wavelength division multiplexing (WDM) transmission system is demonstrated for the first time. Simultaneous fault location and EDFA status-monitoring are achieved without degrading the 2.5 Gb/s service in a five-EDFA, 365-km, four-WDM-channel system.**

I. INTRODUCTION

THE wavelength division multiplex (WDM) technique combined with erbium-doped fiber amplifiers (EDFA's) is very useful for increasing the capacity of long-distance optical communication systems. With the ever-growing development in EDFA-repeated WDM systems, it is important to use a practical supervisory method that facilitates in-service monitoring and fault-locating capability. Three methods for in-service monitoring and fault-locating have been demonstrated for single-channel systems [1]–[4], but demonstration for multichannel systems has not yet been reported. In this letter, an in-service supervisory EDFA-repeated four-channel transmission system, based on a recently reported WDMed supervision technique [3], [4] and the use of strongly inverted EDFA's [5], is constructed and investigated. To our knowledge, this is the first demonstration of a supervisory and an in-service supervised WDM transmission system. Simultaneous fiber fault location and EDFA status monitoring and diversity protection can be achieved without degrading the 2.5-Gb/s service in a five-EDFA, 365-km, four-WDM-channel system.

II. SYSTEM CONFIGURATION AND DESIGN CONSIDERATIONS

The supervisory WDM transmission system configuration, shown in Fig. 1, consists of an optical time domain reflectometer (OTDR), a booster amplifier (TOA), five 1.53/1.55-μm WDMed in-line EDFA-repeater pairs, and four optical-preamplifier (ROA) receiver units. Four DFB-laser service signals at 1549, 1551, 1553, and 1555 nm were delivered to the 4 × 1 optical coupler at -6 dBm per channel. A 2.5-Gb/s pseudorandom $2^{31}-1$ NRZ signal was used to modulate a chirp-adjustable $\mathrm{Ti:LiNbO_3}$ Mach–Zehnder external modulator for the channel at 1551 nm. The other three DFB lasers were running CW. An EDFA booster amplifier was employed after the coupler in order to compensate the insertion loss of the 4 × 1 optical coupler and to maintain sufficient optical signal power to the transmission line. The booster amplifier is a 980-nm single-pumped EDFA yielding +12 dBm total output power.

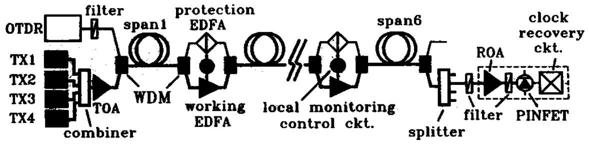

Fig. 1. In-service supervisory WDM system. TOA: booster EDFA, ROA: optical preamplifier.

The probe signal of a minor-modified HP8146A OTDR (with a suitable 1535 nm DFB laser diode) is combined with four service signals by a WDM multiplexer. For a pulse width of 12 μs, the OTDR offers a single-way dynamic range of 21 dB with an event resolution of 1.2 km. In all WDMed in-line repeater stages, the forward OTDR probe signal and backscattered Rayleigh signal are passed around the "unidirectional" *working* EDFA ("unidirectional" because of one included optical isolator at the output port) and amplified by the bidirectional *protection* EDFA to increase the OTDR dynamic range. The pump laser of a *protection EDFA* is used under normal conditions, and is used to replace the failed pump laser in a *working* amplifier under failure conditions. A local monitoring control circuit is used to activate two mechanical optical switches so that the original failure *working* pump laser can be replaced. All 1.53/1.55 μm WDM's have an averaged channel isolation of ~29 dB and back-reflection of -42 dB. The high isolation and low back-reflection features of WDM prevented any mutual crosstalk between transmission and supervision channels.

The operation conditions of *working* and *protection* EDFA's are different and must be carefully designed. Unlike single-channel systems that favor saturated operation, multiwavelength silica-based EDFA cascades offer small interchannel power spread when operated with minimal saturation at very strong inversion levels [5]. Therefore, the operation of each working EDFA was in strong inversion instead of deep saturation. The alumino-germano-silicate EDF in each EDFA, whether the *working* or *protection* EDFA, had a NA of 0.20, and a peak absorption at 1532 nm of 5.6 dB/m. The EDF length (8 m pumped by a 980-nmW laser diode of 50 mW) was the same for all *working* EDFA's. The average total output power of each working amplifier was about +11 dBm. On the other

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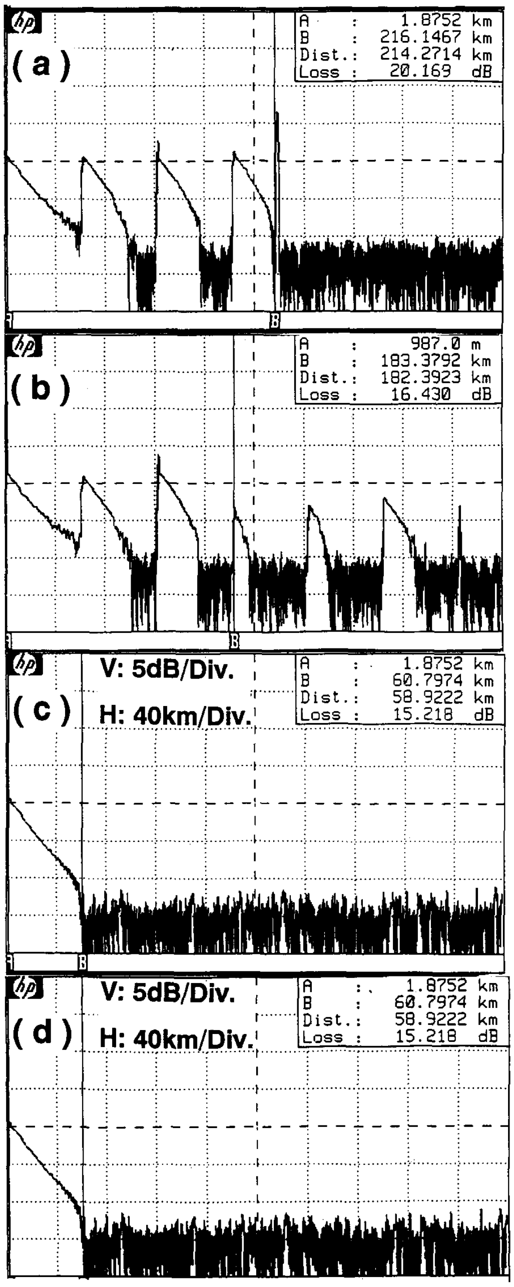


Fig. 2. (a) Normal system using a bandpass filter in the first, third, and fifth *protection* EDFA's to reduce the accumulated forward and backward ASE noise, (b) fault condition with a fiber-breaking at 216 km, and (c) fault condition with a fiber-bending at 183.4 km, and (d) fault condition with pump failure of the first working EDFA.

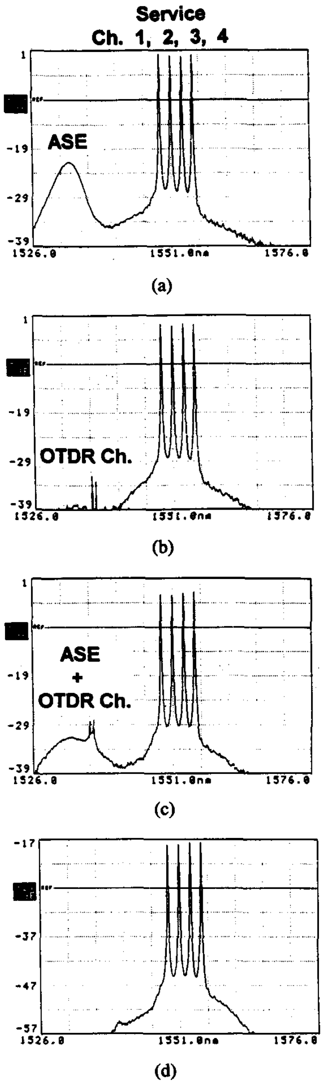
hand, each *protection* EDFA (with 4 m EDF pumped by a 980-nm laser diode of 20 mW; the diode has an output capability of 60 mW for pump protection) was operated in small-signal region to reduce the detrimental transient gain compression effect [6] on the OTDR probe pulses. Furthermore, the high isolation of WDM demultiplexer in each in-line repeater stage contributes to suppress the buildup and accumulation of ASE noise at 1.53 μm in the *working* amplifier and at 1.55 μm in the *protection* amplifier. All *protection* EDFA's gain were designed to just compensate for the interspan loss. The conventional single-mode fiber was used for the transmission fiber in the experiment. The averaged 60.8-km interspan loss was about 19.5 dB, which includes the losses of a WDM multiplexer (0.7 dB), conventional single-mode fiber span (0.21 dB/km), a WDM demultiplexer (0.7 dB), fiber connections (2 dB), and an optical bandpass filter (3.2 dB) before the *protection* amplifier. At the receiving end, the demultiplexed service signal after splitting and filtering (1 nm FWHM bandwidth) was detected by an optical-preamplifier receiver unit (−43.2 dBm sensitivity at a bit-error-rate (BER) of 10^{-9}), and measured by the BER test. The receiver unit is composed of a 980-nm pumped EDF preamplifier, a 0.2-nm filter, a PINFET detector, and a clock recovery circuit.

III. SYSTEM PERFORMANCE AND DISCUSSIONS

Fig. 2(a) shows the observed real-time OTDR trace of the in-service transmission system under normal condition. Note that the Fresnel reflection spike at 365 km coincides with the total link length of the system. The distorted bending OTDR trace at the rear part of each interspan does not affect any reflective fault location of each interspan as illustrated in Fig. 2(b); a fiber break at 216 km was observed and located. Furthermore, Fig. 2(c) shows the OTDR trace of the system when a non-reflective fault (e.g., a 5-dB loss resulting from fiber bending) occurred at 183.4 km. This position is right after the third in-line repeater output port. Fig. 2(d) shows the real-time OTDR trace of the system under pump failure condition of the first *working* EDFA. The sharp drop at the position of the corresponding failed *working* EDFA's was due to the strong absorption in the unpumped *protection* EDFA when the failed *working* pump laser was switched by the local monitoring control circuit to the *protection* pump laser.

Fig. 3(a)–(d) shows the evolution of output signal spectrum through the system link of the booster, the first, fifth in-line repeater, and the last demultiplexer, respectively. The spectra at 1.53 μm band in Fig. 3(b)–(c) consists of the instantaneous spectrum of OTDR probe pulses and the accumulated ASE of the corresponding amplifier stage. In Fig. 3(d), the spectra at 1.53 μm band was rejected by the demultiplexer in the demultiplexed signal spectrum. Furthermore, the optical signal-to-noise ratio after six EDFA's (a booster and five in-line EDFA's) amplification was about 28 dB for each channel. Fig. 4 shows the BER performance with OTDR operation on and off. Negligible degradation (0.02 dB) of system performance due to the OTDR supervision was found. The dispersion penalty introduced by the five-repeater 365 km WDM transmission was about 0.1 dB at BER of 10^{-10}.

From a cost-saving point of view, a common optical preamplifier could have been used before the 1×4 splitter instead of four separate optical preamplifiers. However, a receiver sensitivity degradation of about 2 dB will be incurred. Furthermore, the supervisory system can detect the failure of a



(a)

(b)

(c)

(d)

Fig. 3. Output spectrum of (a) booster amplifier, (b) the first repeater, (c) the fifth repeater, and (d) the last demultiplexer.

working EDFA, and can also discriminate the failure of a *protection* EDFA. When a sharp drop (due to absorption) at the location of any in-line EDFA's on the OTDR trace is found, it may indicate that the corresponding *protection* pump laser has failed, providing the service channels maintain normal operations. This *protection* EDFA failure can be discriminated by the OA&M operating system at the central office.

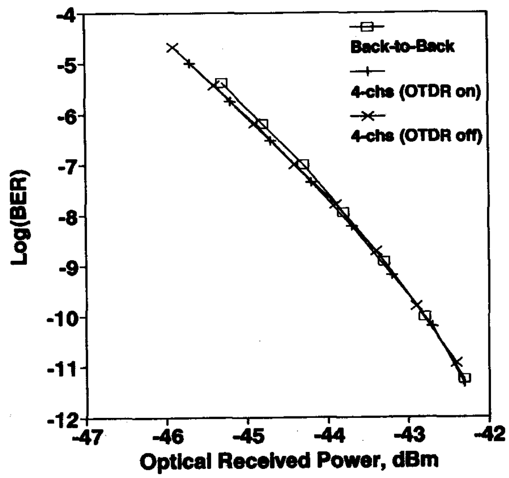


Fig. 4. System bit-error-rate at 2.5 Gb/s with OTDR on and off.

IV. CONCLUSION

In conclusion, we have demonstrated, for the first time, an in-service supervisory WDM transmission system based on WDMed in-line EDFA-repeater pairs and strongly inverted EDFA's. Simultaneous EDFA status-monitoring and diversity-protection, and fiber fault location have been achieved without degrading the 2.5 Gb/s channel service in a five EDFA-repeater 365 km four-WDM-channel transmission system. The system demonstrated that the supervisory technique can be practically applied to long-distance terrestrial WDM transmission systems.

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