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L. P. Barry, J. Debeau and R. Boittin (*France Telecom, CNET - LAB/RIO, Route de Trégastel, Lannion, France*)

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Simultaneous in-service fault-locating and EDFA-monitoting supervisory transmission in EDFA-repeatered systems

Y.K. Chen, W.Y. Guo, W.I. Way and S. Chi

Indexing terms: Fibre amplifiers, Fibre lasers, Optical communication

In-service WDM-based supervisory transmission in four/five EDFA-repeater 375km/365km systems is demonstrated. Simultaneous EDFA status-monitoring and fibre fault location are achieved without degrading the 2.5Gbit/s service.

Introduction: The introduction of erbium-doped fibre amplifiers (EDFAs) in a long-distance transmission system requires a practical supervisory method to simultaneously offer in-service monitoring and fault-locating capability. So far, only two methods have been demonstrated [1,2]. However, they require either a costly circulator and an independent supervisory line to activate the second EDFA in each in-line EDFA repeater for optical time domain reflectometry (OTDR) transmission [1] or a sophisticated optical loopback circuit in each repeater and an additional fibre link throughout the whole system for supervision [2]. In this Letter we demonstrate the feasibility of a recently reported method [3], which does not require any independent supervisory lines or additional fibre links. The complete supervision and system performance in the four/five EDFA-repeater 375km/365km systems is investigated.

System design and experiments: The in-service supervisory system based on the principle in [3] is constructed. A 2.5Gbit/s pseudorandom (*PN* $2^{31}-1$) NRZ service signal was emitted from the externally modulated DFB transmitter (1.5347µm) and amplified by a power EDFA (P_{in} = –4dBm, P_{out} = +10dBm). External modulation was used to minimise dispersion limitation. The OTDR probe pulse is combined with the service signal by a WDM multiplexer. A minor-modified HP8146A OTDR, using a suitable 1.551 µm DFB laser source to offer a single-way dynamic range of 32 dB and an event resolution of 1.5km, was used. In all 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) and amplified by the bidirectional protection EDFA to increase the OTDR dynamic range. At the receiving end, the service signal after filtering (1nm FWHM bandwidth) was detected by an optical-preamplifier receiver unit (–42.2dBm sensitivity at bit-error rate, BER, of 10^{-9}) and measured by the BER tester. The receiver unit is composed of an EDF preamplifier (with 29dB gain and 3.7dB noise figure), a 0.2nm filter, a *pin*-FET receiver and a clock recovery circuit.

Each working EDFA(with 8m EDF pumped by a 0.98µm laser diode of about 50mW) was in deep gain compression to provide an output power of +10dBm, and thus made the system tolerant to a limited number of pump degradations. Furthermore, the saturated-EDFA chain results in the gain filtering behaviour necessary to limit the amplified spontaneous emission (ASE) saturation. In contrast, each protection EDFA (with 4.5m EDF pumped by a 0.98µm laser diode of about 15mW; the diode has an output power capability of 60mW for pump protection) was operated in the small-signal gain region to compensate for he interspan loss. All 1.53/1.55µm WDMs have an average insertion loss of ~0.7dB, channel isolation of ~29dB and backreflection of –42dB. This high isolation and low backreflection will not give any mutual crosstalk between transmission and supervision channels.

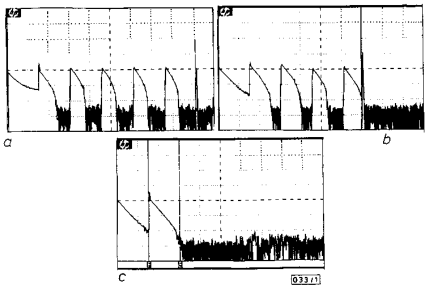

Fig. 1 *OTDR supervision traces of system under normal, fibre-breaking at 278km, and failure of second working EDFA conditions*

Scale: vertical, 5dB/division; horizontal, 40km/division
a Normal: *A* = 2.86227km, *B* = 364.8832km, distance = 362.0210km, loss = 5.072dB
b Fibre-breaking at 278km: *A* = 1.9739km, *B* = 277.9311km, distance = 275.9571km, loss = 11.209dB
c Failure of second working EDFA: *A* = 60.4026km, *B* = 120.7066km, distance = 60.3039km, loss = 3.403dB

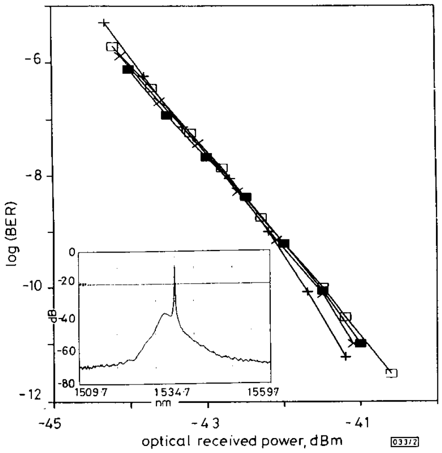

Fig. 2 *Bit error rate at 2.5Gbit/s with OTDR on and off*

Inset: output optical spectrum of service signal after five-in-line EDFA amplification
+ back-to-back
□ 360 km (OTDR off)
■ 360km (OTDR on)
× 375km (OTDR on)

System performance: In the experiments, we tested the in-service supervision performance with four EDFA stages using 75km interspan, and with five EDFA stages using 60.8km interspan.

Conventional singlemode fibre (SMF) with a loss of 0.21dB/km and an average dispersion of 17ps/km/nm was used as the transmission medium. The average interspan loss is about 18.8 dB and 16dB for the 75km and 60.8km cases, respectively. For the 60.8km interspan case, the observed real-time OTDR traces under normal, fibre break at 278km, and failure of the second working EDFA conditions are shown in Fig. 1*a*, *b* and *c*. Note that the distorted bending OTDR trace at the rear part of each interspan resulted from the transient gain compression effect [4] in each protection EDFA; nevertheless, this phenomenon does not affect the reflective fault location as illustrated in Fig. 1*b*. The pump laser of a protection EDFA is used under normal conditions, and is switched by a local monitoring control circuit to replace the failed pump laser in a working amplifier under failure conditions. Therefore, the sharp drop at 121km in Fig. 1*c* is due to the strong absorption in the unpumped protection EDFA after the failed working pump laser was replaced by the protection pump laser. The supervision performance for the 75km interspan case is similar to that in Fig. 1. Therefore, the above results show the simultaneous supervision capability of fibre fault location and EDFA status monitoring and diversity protection. Fig. 2 shows the BER performance of the system with OTDR operation on and off. Negligible degradation (0.08dB) was observed for both 60.8 km and 75km interspan cases. The power penalty between back-to-back and after transmission (for both 365km and 375km cases) was ~0.2dB at a BER of 10^{-10}. This penalty was caused by a dispersion penalty. The output optical spectrum of the service signal after five-in-line EDFA amplification was also shown in the inset in Fig. 2.

Conclusion: An in-service WDM-based supervisory transmission in EDFA-repeatered systems has been demonstrated. Simultaneous EDFA status-monitoring and fibre fault location were achieved without degrading the 2.5Gbit/s service. This practical and simple supervisory technique can be used in long-distance EDFA-repeatered transmission systems.

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Y.K. Chen and W.Y. Guo (*Telecommunication Laboratories, Ministry of Transportation and Communications, Taiwan, Republic of China*)

W.I. Way and S. Chi (*Institute of Electro-optical Engineering and Center for Telecommunications Research, National Chiao-Tung University, Taiwan, Republic of China*)

Y.K. Chen is also with the Institute of Electro-optical Engineering, National Chiao-Yung University

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Voltage-controlled distributed Bragg reflectors for modulation and integrated power monitoring of vertical-cavity surface-emitting lasers

A. Khan, K. Woodbridge, A. Marinopoulou,
C. Roberts and G. Parry

Indexing terms: Distributed Bragg reflector lasers, Vertical cavity surface emitting lasers

The authors demonstrate a voltage-controlled distributed Bragg reflector with a very high off-state reflectivity and low-voltage operation suitable for use within a vertical-cavity surface-emitting laser. The unbiased peak reflectivity approaches 99.8% at 980nm, which may be modulated through the quantum-confined Stark effect by 1%. The mirror allows measurement of photocurrent to monitor VCSEL output power.

Because of their ultrashort cavities, singlemode operation, low threshold currents/voltages and high photon densities, vertical-cavity surface-emitting lasers (VCSELs) will be important for high-speed modulation and telecommunications applications [1].

At present high-speed amplitude modulation is brought about through direct modulation of the injected current. However, this relies on injection of electrons and holes into the active region of the device, currently limiting the device speed to approximately 20 GHz [1]. More importantly, rapid modulation of the carrier injection level results in frequency chirp of the laser output.

Recently Avrutin *et al.* [2] have shown theoretically that modulation of the photon lifetime within a VCSEL results in a structure with improved high-frequency response. Such modulation may be brought about through the modulation of the reflectivity of one of the VCSEL distributed Bragg reflectors (DBRs). We have subsequently shown that reduced chirp is feasible using such a system [3]. Such a variable DBR would, however, require a peak reflectivity of not less than 99%, for a low VCSEL threshold current, and the modulation must rely on effects that are intrinsically faster than carrier injection mechanisms.

Blum *et al.* [4] have previously demonstrated a variable DBR which has all of the high index quarter-wave (λ/4) layers replaced by λ/4 (optical thickness) sections of quantum wells (QWs). Unfortunately this DBR suffers from a high voltage operation (thick intrinsic layer), a high intrinsic chirp and a low peak reflectivity. We must, however, note that this structure was designed for external modulation.

Here we demonstrate a variable DBR with a high peak reflectivity and a 1% reflection change for a applied bias of 5V. Note that because the variable DBR forms one of the reflectors of the VCSEL only a very small reflection change (~0.5%) is enough, theoretically, to modulate the output appreciably (~8dB [3]). The optical field within a VCSEL, at threshold, decays exponentially into the DBRs such that the deeper sections of the DBR experience a lower optical field intensity and photon density than the preceding layers. If we replace a single high index λ/4 layer, within a given period of the DBR, with a λ/4 (optical thickness) layer of QWs the overall reflection spectrum of the DBR will be perturbed by the absorption spectrum of the QWs. Importantly, the position within the DBR of the QWs will dictate the decrease in reflectivity brought about by the introduced absorption. In the case of a GaAs/AlAs DBR designed for 980nm emission we need to place the QWs into the fifth period of the DBR to maintain a peak, off-state, reflectivity of 99.8%.

The structure of the voltage-controlled DBR we have designed is shown in Fig. 1. In this case we have used a 3λ/4-thick layer of QWs to increase the absorption length (because of the low intrinsic absorption of InGaAs QWs) without disrupting the overall reflectance features of the DBR. The position and composition of the InGaAs QWs within the DBR is chosen to negate the effects of background absorption and QCSE-induced chirp [3] with the 4-period semitransparent DBR above the QWs acting as a passive filter.

Fig. 2 shows 0–5V bias reflection spectra of the MBE-grown DBR of Fig. 1. The spectra are taken with a 0.5nm-resolution Bentham M300 monochromator, tungsten-halogen source and Si