Demonstration of a Fault-Tolerant WDM Add–Drop/Branching Unit for Long-Haul Optical Transmission Systems

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***Abstract*—We propose and demonstrate a fault-tolerant WDM add–drop/branching unit for long-haul optical transmission systems. This unit not only can perform the necessary optical amplification and wavelength add–drop functions with the local network, but also provide the much needed fault identification and fault recovery features.**

***Index Terms*— Fault diagnosis, optical transmission systems, wavelength-division multiplexing.**

I. Introduction

THE CONTINUOUS enormous growth in network traffic, such as experienced in the Internet and global businesses, has created an unprecedented demand in network capacity in long-haul transmission systems. Such demand can be met by the use of wavelength-division multiplexing (WDM) combining with erbium-doped fiber amplifier (EDFA), and can be realized in a network consisting of many local/metropolitan area networks interconnected by a trunk. Because of the large geographical span and the need of connectivity among the network nodes within the coverage, WDM add–drop branching unit (WADB) [1] (Fig. 1) is emerging as a principal data exchange and traffic router serving between the transmission trunks and the local networks. Reported WADB so far provides the normal wavelength add–drop and amplification functions. However, the much needed fault-recovery features are not available. In this letter, we propose and demonstrate experimentally a WADB with fault identification and recovery capabilities. The operational principle is a variation from [2], which was designed to detect fiber cuts and EDFA failures. The WADB module was tested under conditions of pump diode failure in the presence of data transmission using 1-Gb/s nonreturn-to-zero (NRZ) pseudorandom bit sequence (PRBS). The restoration time is measured to be about 300 ms.

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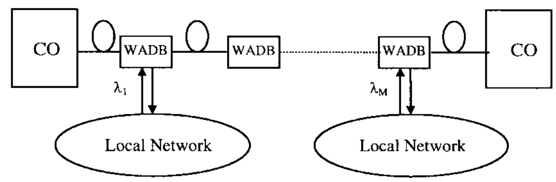

Fig. 1. A long-haul transmission system with M add–drop branching units. CO: Central office. WADB: Add–drop branching unit.

II. Fault-Tolerant Wavelength Add–Drop Branching Unit

Fig. 2 shows the architecture of the proposed WADB. It consists of two pieces of erbium-doped fiber (EDF1 and EDF2), two working (PLD1 and PLD2) and two backup pump laser diodes (PLD3 and PLD4), and two fiber Bragg gratings (FBG1 and FBG2) with identical centre wavelength at λ_i, λ_i being the added and dropped channel wavelength at WADB_i. EDF1 is forward-pumped by PLD1 while EDF2 is backward-pumped by PLD2. The FBG's are packed in temperature-compensated packages to minimize wavelength drift derived from changing temperature in the environment. A high performance FBG was reported recently with a temperature coefficient as little as 10^{-5} nm/°C [3].

The proposed WADB offers the following features simultaneously: 1) optical amplification; 2) wavelength channel add–drop; and 3) fault detection and recovery. The necessary optical amplifications are much needed in the WADB to compensate for the link loss. Two working pump diodes are used to enhance the gain performance of the EDFA within the WADB. For channel add–drop, data channel at λ_i destined to the local network connected at WADB_i is demultiplexed by $\mathrm{FBG1}_i$ and dropped to the local network via optical circulator C1 (see Fig. 2) [4]. The backward amplified spontaneous emission (ASE) from EDF2 may be present in the dropped channel but can be cleaned up by means of an optical filter placed at the input of the local network. To send data from the local network, data channel at λ_i is injected to the link through the optical circulator C3, where the reflection at $\mathrm{FBG2}_i$ will send the added data channel downstream. Note that because of the identical wavelength of the FBG's, the in-band crosstalk at λ_i will be much reduced. The optical circulators C1, C2 and C3 not only assist in channel multi-/demultiplexing functions, but also serve to suppress the back reflections within the WABD.

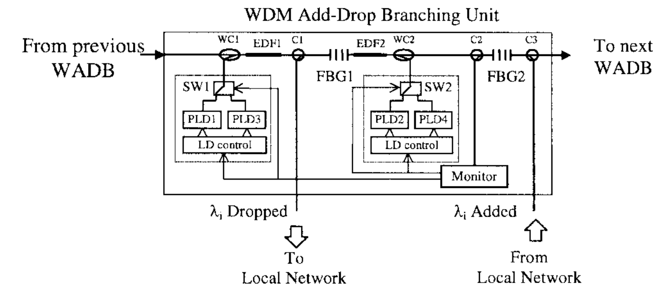

Fig. 2. Architecture of the proposed WDM add–drop branching unit. PLD1&2: Working pump laser diodes. PLD3&4: Backup pump laser diodes. FBG1&2: Fiber Bragg gratings. EDF1&2: Erbium-doped fibers. SW1&2: 1×2 optical switches. C1-3: Optical circulators. WC1&2: 980/1550 nm WDM couplers.

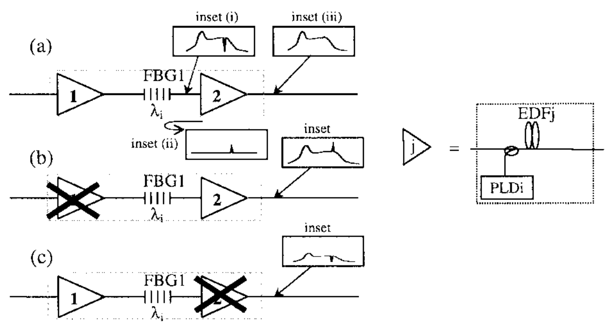

Fig. 3. Evolution of EDFA's ASE spectra to illustrate the operation principle of the fault detection. (a) Normal operation. (b) PLD1 fails. (c) PLD2 fails. PLD_i: Pump laser diode i. EDF_i: Erbium-doped fiber i. FBG1: Fiber Bragg grating.

For fault detection, a simple scheme derived from [2] is proposed to identify the exact faulty pump laser diode, which degrades the transmission performance of the WADB. It should also be noted that in contrast to [2], the monitoring wavelength coincides with the dropped and added channel and the monitoring process takes place during the period in between the channel dropping and adding at the WADB, thus no extra optical spectrum is needed for the monitoring signal. Such design allows simple and efficient monitoring, i.e., no additional light source is needed, and the same set of components can support both channel add–drop and pump laser diode monitoring.

Fig. 3 illustrates the operation principle of the fault detection scheme. For normal operation [Fig. 3(a)], FBG1 reflects the data wavelength and the ASE from EDF1 at and around λ_i (dropped channel), resulting in a notch at λ_i in the input optical spectrum to EDF2 [Fig. 3(a), inset (i)]. Nominally, this notched optical spectrum will induce EDF2 to emit in the forward-propagating direction a similar ASE profile. Since the backward-propagating ASE from EDF2 is reflected at λ_i by FBG1 and serves as input to EDF2 [Fig. 3(a), inset (ii)], the notch at λ_i in the resulting output forward-propagating ASE spectrum of EDF2 will be "filled" and appears less prominent than the input spectrum [Fig. 3(a), inset (iii)]. For failure in PLD1, but not in PLD2 [Fig. 3(b)], the lack of spectral influence from EDF1 will cause EDF2 to emit normally without a notch at λ_i. The reflection at λ_i from FBG1 generates an overall enhanced emission at λ_i in the output of EDF2 [Fig. 3(b), inset]. For failure in PLD2, but not in PLD1 [Fig. 3(c)], there will be a significant reduction in the entire output emission spectrum including the notch at λ_i from EDF2, [Fig. 3(c), inset] due to the intrinsic absorption by the unpumped EDF2. Simultaneous failure in both PLD's is highly unlikely. In such case, only very little signal power at λ_i will be detected. Detection of PLD failure can thus be achieved by continuously examining the power level at λ_i at EDF2's output by detecting the power reflected from FBG2, via optical circulator C2, at the monitor module (Monitor). At the same time, the spectrum at the wavelength λ_i will be cleared by FBG2 in the forward direction and thus a new wavelength channel from the local network can be added to the fiber trunk [see Fig. 3(a)].

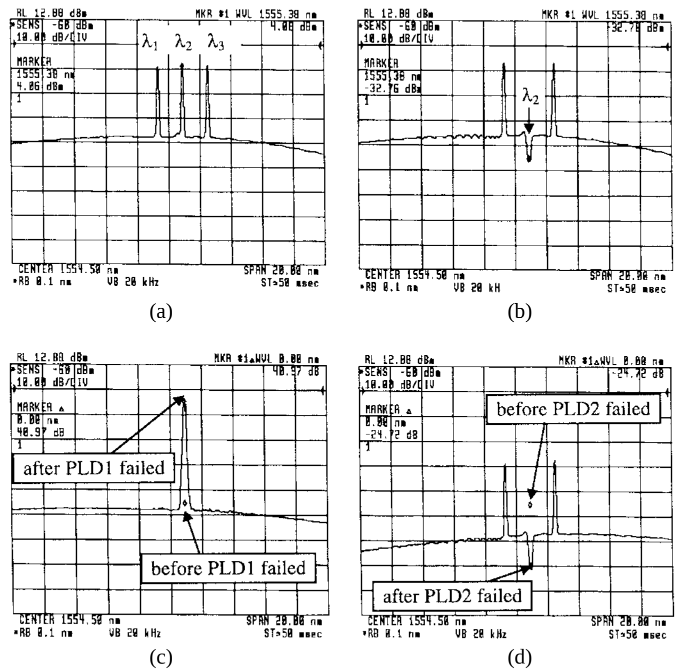

Fig. 4. (a) Input optical spectra showing all three wavelength channels. Tapped output spectra at location before FBG2 when (b) both PLD1 & PLD2 are working properly and data wavelength λ_2 is dropped by FBG1. (c) PLD1 fails but not PLD2, (power change at λ_2: +40.97 dB). (d) PLD2 fails but not PLD1, (power change at λ_2: −24.72 dB).

The monitor module is used to control the fault identification and recovery functions. The reflected power from FBG2 will be first detected by a photodiode and then amplified, followed by a control logic circuitry. When a failed PLD is identified, the monitoring circuitry will activate the corresponding backup PLD and switch the fiber connection from the failed PLD to the backup PLD, thus achieving the fault-tolerant function.

III. Experimental Demonstration

The architecture of the WADB module in our experiment is the same as shown in Fig. 2. Each EDF (EDF1 and EDF2) is about 10 m long and is pumped by an average pump power of 50 mW at 980 nm, generating an optical gain of about 22 dB. FBG1 is identical to FBG2 and has a center reflection wavelength at 1555.38 nm, a 3-dB full-width of 0.4 nm and an out-of-band rejection of 50 dB. Each optical circulator has an insertion loss of 1 dB and a directivity of 60 dB. Three data wavelengths [Fig. 4(a)] at $\lambda_1 = 1553.78$ nm, $\lambda_2 = 1555.38$

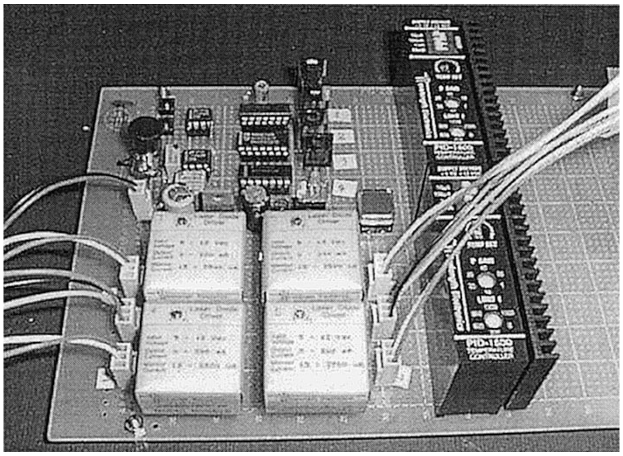

Fig. 5. Photograph of the monitor module in the experiment.

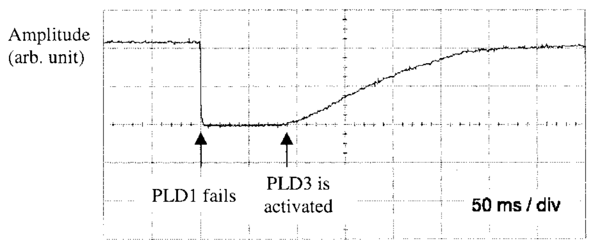

Fig. 6. Measured power excursion at data wavelength λ_1 (with no data modulation) in case of failure in PLD1. Measured restoration time is about 300 ms. Note that PLD1 is automatically replaced by PLD3 when PLD1 is detected failure.

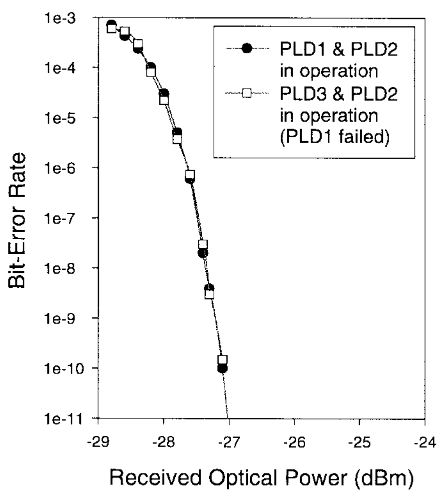

Fig. 7. BER measurement of a 1-Gb/s $2^{10}-1$ PRBS NRZ data on a data wavelength λ_1, before and after PLD1 fails. Note that PLD1 is automatically replaced by PLD3 when PLD1 is detected failure.

nm, and $\lambda_3 = 1556.98$ nm, are inputted into the WADB. Prior to FBG2, the spectrum exhibits a notch at λ_2 [Fig. 4(b)], showing the input data wavelength channel at λ_2 has been dropped by FBG1. The spectrum returns to the input profile after channel adding at λ_2 from the local network.

We then simulate a failure in any one of the two PLD's by intentionally reducing the corresponding pump current such that more than 25-dB gain reduction in the EDF is generated. Fig. 4(c) and (d) shows the output spectra measured prior to FBG2 for failure in PLD1 and PLD2, respectively. For failure in PLD1, there is a substantial increase (>40 dB) in output power at λ_2. For failure in PLD2, however, the output power at λ_2 drops by about 24 dB. Such drastic change (several tens of decibels) in optical power at λ_2 can be easily detected at the monitor module via the back reflection from FBG2 through the optical circulator C2. The monitor module we have built is shown in Fig. 5. It consists of a photodiode, a logic control circuitry and several laser diode driver and temperature controller modules. Once the failed PLD is identified, PLD1 for example, the control logic circuitry of the monitor module will activate the laser diode driver and temperature-controller modules for the backup PLD3 and switch the EDF fiber connection from PLD1 to PLD3 via the 1×2 optical switch (SW1). Thus, the normal operating conditions of the WADB can thus be restored. The restoration time is measured to be about 300 ms, as shown in Fig. 6, by examining the power excursion of channel λ_1 at the end of the WADB. The possible data loss during fault recovery can be recovered by data retransmission. The BER measurements are also performed at channel λ_1, which carries 1-Gb/s $2^{10}-1$ NRZ PRBS data, before and after PLD1 is failed (turned off). The results (Fig. 7) show that no power penalty is observed for such failure in PLD1 as it has been automatically replaced by PLD3 and thus the normal operation of the module has been restored.

IV. Summary

We have proposed and experimentally demonstrated a simple yet practical WADB which provides not only the essential functions in optical amplifications and wavelength add–drop, but fault identification and fault recovery functions as well. The fault detection scheme is nonintrusive and is based on the ASE power at the data wavelength during the period in between the channel dropping and adding, and no dedicated monitoring light source is needed. The proposed WADB can enhance the reliability and network availability of the long-haul WDM optical transmission systems.

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