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Using 10 Gb/s remodulation DPSK signal in self-restored colorless WDM-PON system

Chien Hung Yeh [a,*], Chi Wai Chow [b], Sien Chi [c]

[a] Information and Communications Research Laboratories, Industrial Technology Research Institute, Rm. 300, Bldg. 14, 195, Sed. 4, Chung Hsing Rd., Chutung, Hsinchu 31040, Taiwan
[b] Department of Photonics and Institute of Electro-Optical Engineering, National Chiao Tung University, Hsinchu 30010, Taiwan
[c] Department of Electrical Engineering, Yuan Ze University, Chung-Li 32003, Taiwan

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ABSTRACT

In this investigation, we propose and experimentally demonstrate the remodulation technique using DPSK format in both downlink and uplink traffics with high extinction ratio (ER) in colorless WDM-PON; together with a simple self-restored architecture against fiber fault. Error free operation was achieved in a 20-km-reach 10-Gb/s WDM-PON without dispersion compensation. Comparison with other wavelength remodulation schemes for WDM-PONs is also performed, showing the proposed scheme can be a potential candidate for next generation wavelength reuse WDM-PONs. In addition, the performance of self-protection has also been discussed and analyzed.

1. Introduction

Wavelength-division-multiplexed passive optical network (WDM-PON) is a potentially cost-effective technology to increase individual bandwidth capacity through the use of wavelength domain [1,2]. One of the great challenges in the WDM-PON is that the wavelength of the optical uplink signal generated from the optical networking unit (ONU) must be precisely aligned to the WDM grid wavelength of the wavelength multiplexers and demultiplexers. A cost-effective solution would use the same and colorless ONU for the PON. Furthermore, remodulation of downlink wavelength to generate uplink wavelength can further reduce the cost. Several remodulation schemes have been proposed for the WDM-PONs, such as using on–off keying (OOK), differential phase shift keying (DPSK), and inverse return-to-zero (IRZ) [3–7]. However, they are limited by various combinations of high chirp, limited speed, and reduced extinction ratio (ER). Using DPSK downlink and OOK uplink generated by a reflective semiconductor optical amplifier (RSOA) [8]; and using asymmetric OOK downlink and uplink have been proposed [9], but the data rate of uplinks are limited by the RSOA. Besides, a bi-directional WDM-PON has been demonstrated using RSOA-biased ONU working as a modulator and a photodetector time-divisionally [10], however the scheme reduces the bandwidth in both downlink and uplink signals. In addition, a reliable and survivable PON architecture with self-protection and self-restoration functions is highly desirable and necessary. Several reports have been presented to offer the protection capability in the PON access networks [11–13]. As the per channel data rate in WDM-PONs are envisioned to 10 Gb/s or more in the future, the network reliability and survivability of such high-speed networks need to be addressed.

In this paper, we propose and demonstrate a simple self-restoration scheme for a 10 Gb/s bi-directional WDM-PON. The self-protection scheme using dual distribution fibers has been suggested in ITU-T G.983.1 for conventional time division multiplexed (TDM)-biased G-PON, however this scheme requires a backup optical line terminal (OLT) and a backup ONU for each ONU. Here, we extends the studies to the 10 Gb/s bi-directional WDM-PON, enabling wavelength reuse and supporting DPSK format [14] [one of the promising advanced modulation formats for future network to mitigate fiber nonlinearities and to improve receiver (Rx) sensitivity] in both downlink and uplink. Detail self-restored mechanism using an optical switch (OS) instead of using a backup ONU and OLT is presented. Fast switching time of ∼10 ms is achieved in the self-restored WDM-PON. Comparison of Rx sensitivities and power budgets of the proposed scheme with other wavelength remodulation schemes is also performed by means of numerical simulations.

2. Experiments and results

Fig. 1 shows the proposed architecture of the self-restored bi-directional WDM-PON using centralized light sources for N ONUs. At the OLT, the continuous wave (CW) optical signal at 1550 nm wavelength produced by a distributed feedback laser diode (DFB-LD) was encoded to form the 10 Gb/s DPSK downlink signal via a $LiNbO_3$ phase modulation (PM). The PM was electrically driven by a differentially precoded 10 Gb/s, pseudorandom binary sequence

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* Corresponding author.
E-mail address: depew@itri.org.tw (C.H. Yeh).

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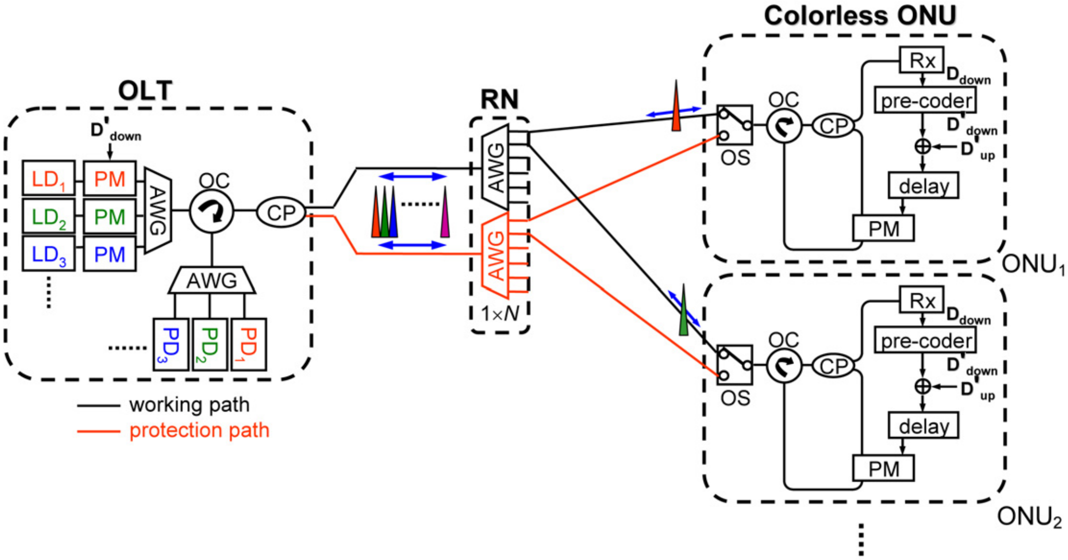

Fig. 1. The proposed self-protected WDM-PON architecture without any fiber fault using remodulation DPSK both in downlink and uplink signals.

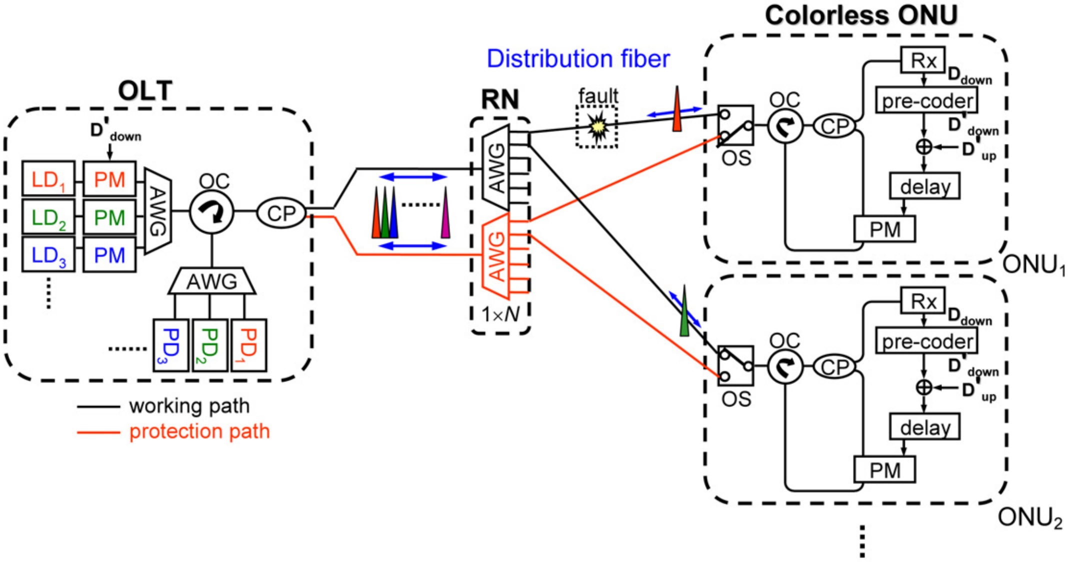

Fig. 2. Proposed self-protected WDM-PON architecture when a fault occurs on the distribution fiber (working fiber) between RN and ONU$_1$.

(PRBS) 2^{15}–1 nonreturn-to-zero (NRZ) data (D'_{down}, where 'prime' represents differentially precoded). The downlink signal was then transmitted through a 10-km feeder single-mode fiber (SMF) and 10-km distribution fiber. The optical fiber cannot be fully dispersion compensated in practice hence no dispersion compensation was used in the setup. Inside the OLT, the optical circulator (OC) connected to a 1×2 optical coupler (CP), and the two output ports of CP were used to connect the working and protection fiber paths in the remote node (RN), as shown in Fig. 1. The RN consisted of two arrayed waveguide grating (AWG) to serve as the working and protection paths. 10% of optical power from the downlink DPSK signal was received by an optically pre-amplified Rx with 10-Gb/s PIN at the ONU. The residual power was launched into a PM to produce the uplink signal. In order to recode the phase information onto the downlink signal, $D'_{\mathrm{down}} \oplus D'_{\mathrm{up}}$ is applied to the PM, where $\oplus$ is the exclusive-OR (XOR) logic operation. Since $D'_{\mathrm{down}} \oplus D'_{\mathrm{down}} = 0$, and $0 \oplus D'_{\mathrm{up}} = D'_{\mathrm{up}}$, the phase information was successfully recode and only D'_{up} remained in the phase, creating the uplink signal. The timing alignment between the downlink and the applied electrical signals to the PM is crucial, and this can be controlled by using electrical buffers. We measured the timing misalignment tolerance, and the 1-dB power penalty window at bit-error rate (BER) of 10^{-9} was about 20 ps.

Here, we would like to present the self-restored mechanism of the scheme. Inside each ONU, there was a 1×2 OS to select the working or protection mode. When there is no fiber fault in the PON, the OS inside each ONU was located to the working path, as illustrated in Fig. 1. It is worth to note that there are two places where fiber fault may occur: on the feeder fiber or the distribution fiber, as shown in Figs. 2 and 3 respectively. When a fault occurs on the distribution fiber as shown in Fig. 2, the ONU$_1$ cannot receive data from the OLT. Thus, the OS (consisted of an optical power monitor which keeps monitoring the downlink signal in the ONU) in the ONU$_1$ will immediately switch to protection mode connecting the protection fiber. Based on the same mechanism, when a fault occurs on working feeder fiber, as shown in Fig. 3, all the ONUs in the PON cannot communicate with the OLT. Then, the entire OSs in the ONUs will switch to link the protection fiber. In the experiment, the 1×2 OS was used as a protection switch, and the switching characteristic is shown in Fig. 4. The switch-

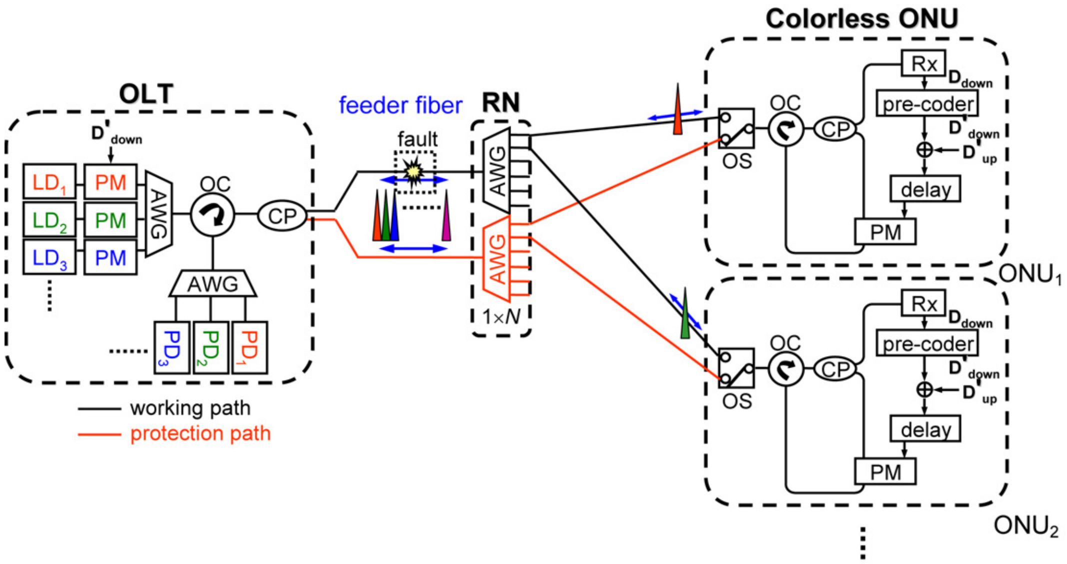

Fig. 3. Proposed self-protected WDM-PON architecture when a fault occurs on the feeder fiber (working fiber) between OLT and RN.

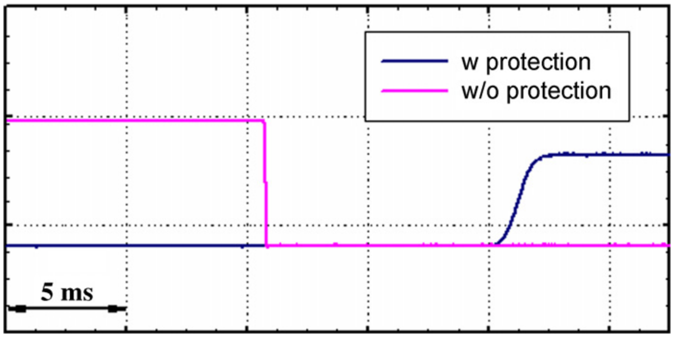

Fig. 4. Protection switching time measurement for the self-protected system.

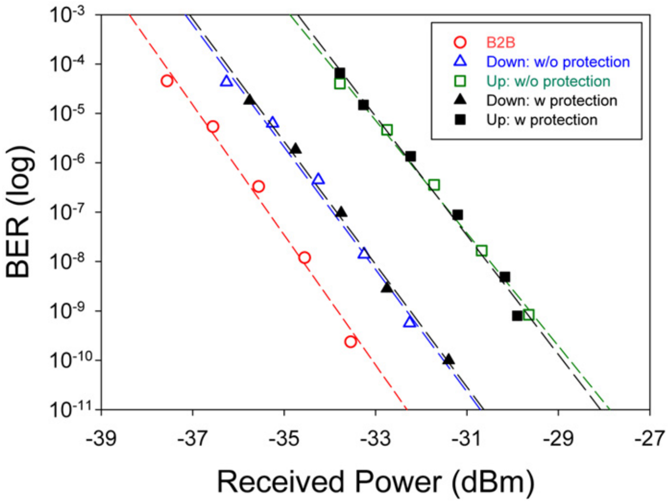

Fig. 5. BER measurements of the 10 Gb/s DPSK-based downlink and remodulation uplink signals without and with protection through 20-km SMF in the proposed protection PON network.

ing and restoration time is measured within ∼10 ms, showing that the proposed self-protection architecture can protect and restore the WDM-PON effectively when the fiber fault occurs.

Fig. 5 shows the 10 Gb/s BER measurements of the proposed scheme with and without protection. Power penalty was measured of about 1.3 dB at BER of 10^{-9} for the demodulated DPSK downlink signal at the ONU after the 20 km SMF in the working and protection paths. Power penalty of 4.5 dB was measured for the remodulated uplink DPSK signal at the OLT. The power penalty was due to the accumulated dispersion of the 40-km SMF and the remodulation process. The results show that low ER downlink signal is not required for the uplink remodulation, when compared with other remodulation scheme [6].

Comparison with previously proposed remodulation schemes was made to show the advantages of the proposed remodulation scheme. Numerical analysis using VPI Transmission Maker V7.5 was performed to evaluate the back-to-back Rx sensitivity penalty of different remodulation schemes when compared with the NRZ modulation (Table 1). 10 Gb/s PRBS 2^7−1 was used for all the schemes in both uplink and downlink signals. The signal power in each case was 0 dBm. The NRZ signal was generated by using a Mach–Zehnder modulator (MZM) with electrical bandwidth = 10 GHz. The NRZ signal was detected by an optical pre-amplified Rx (noise figure = 5 dB) with optical filter bandwidth = 50 GHz and photodiode electrical bandwidth = 7.5 GHz. We compared the DPSK [with and without balance detection (BD)] with the previously proposed remodulation schemes, including downlink IRZ and uplink OOK [5]; downlink low ER-OOK and uplink DPSK [6]. First, we studied the remodulation of the DPSK scheme. The DPSK was generated by a PM with electrical bandwidth of 10 GHz. It was detected by using the same Rx as in the case of NRZ signal. No power penalty was observed, and in principle, Rx sensitivity improvement of 3 dB can be observed when BD was used. For the IRZ downlink and OOK uplink remodulation scheme, an electrical IRZ data was applied to the intensity modulator to produce the optical IRZ signal. The duty cycle of the IRZ used was 50%, as in Ref. [5]. Power penalty of 6.8 dB was observed in the IRZ signal at BER of 10^{-9}. The power penalty was due to the relative high residual CW background between adjusted IRZ pulses. It was worth to mention that there is a tradeoff between the duty cycle of the IRZ and the remodulated uplink OOK data [15]; and the duty cycle of the IRZ can affect the Rx sensitivity. The simulation results of the normalized Rx sensitivities of the IRZ against the IRZ duty cycle are shown in Fig. 6. We observed a negative power penalty of 0.5 dB in the uplink OOK because it was return-to-zero (RZ)-liked. For the low-ER OOK downlink and DPSK uplink scheme, a low-ER OOK downlink signal was required to provide enough residual optical power for the uplink remodulation. The reduced ER = 4.9 dB was generated by adjusting the dc-bias of the MZM. Hence, a high power

Table 1
Comparison of different remodulation schemes at back-to-back Rx penalty with NRZ signal.

	DPSK (down)/ DPSK (up)	DPSK (down)/ DPSK (up) BD	IRZ (down)/ OOK (up)	Low ER-OOK (down)/ DPSK (up)	Low ER-OOK (down)/ DPSK (up) BD
Power penalty (down)	0 dB	−3 dB	+6.8 dB	+7.2 dB	+7.2 dB
Power penalty (up)	0 dB	−3 dB	−0.5 dB	Error floor at BER 10^{-8}	+10 dB

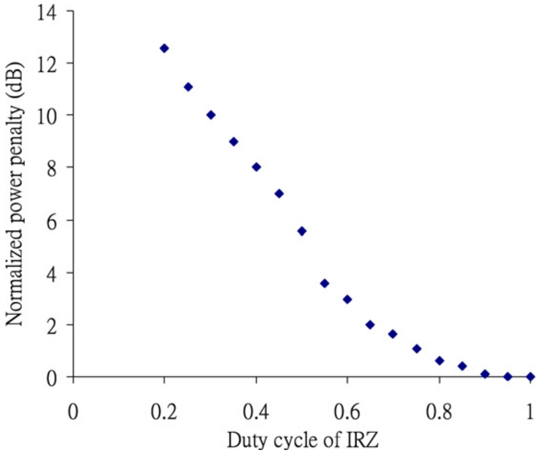

Fig. 6. Simulation of the normalized Rx sensitivities of the IRZ against the IRZ duty cycle.

penalty of 7.2 dB was observed. BER $< 10^{-9}$ DPSK uplink detection was not possible unless BD (power penalty of 10 dB) was used. The power penalty was due to the conversion of the low-ER OOK downlink signal to amplitude fluctuation in the uplink DPSK signal.

By considering the insertion losses of the AWG, OC, OS, PM and the intensity modulator (IM) (used in IRZ/DPSK scheme) are 4 dB, 1 dB, 1 dB, 4 dB and 4 dB respectively, fiber loss is 0.2 dB/km, and the Rx sensitivities of the DPSK, IRZ, remodulated OOK from the IRZ, low-ER OOK, and amplitude-fluctuated DPSK from the low-ER OOK are −37 dBm (BD is used), −27.2 dBm, −34.5 dBm, −26.8 dBm and −24 dBm (BD is used) [14] respectively, we can calculate the power budgets of the network using different remodulation schemes. We also assume BD was used for the DPSK detection. In order to avoid fiber nonlinear effects, launch power of 8 dBm was used in each case. For the proposed DPSK/DPSK scheme, error free BER can be detected both in downlink and uplink, and 4 dB power margin can be observed at the remodulated uplink DPSK signal at the head-end Rx. Optical amplifier can be included in the transmission fiber to improve the power margin. For the IRZ/OOK scheme, error free BER can also be achieved in both downlink and uplink, and 1.5 dB power margin was observed. For the low-ER OOK/DPSK scheme, error free BER can be observed in the downlink detected at the ONU, however, there is not enough power budget (lacking of 9 dB) for the uplink DPSK signal.

3. Conclusion

We proposed and investigated a new self-restored WDM-PON to avoid the fiber fault in both feeder and distribution fibers. Besides, in this experiment, we also used the remodulation method in both uplink and downlink at 10 Gb/s, with high ER signals in both directions. A 20 km-reach PON without dispersion compensation was demonstrated and error free transmission was achieved during the remodulation process and in working and protection paths. As a result, the proposed scheme can be a potential candidate for next generation wavelength reuse WDM-PON.

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Chien Hung Yeh received the B.S. and M.S. degrees from the Physics Department, Fu Jen Catholic University, Taiwan, in 1998 and 2000, respectively. He received his Ph.D. degree from the Institute of Electro-Optical Engineering, National Chiao Tung University, Taiwan, in 2004. He is working in the Information and Communications Laboratories, Industrial Technology Research Institute, Taiwan. His research interests are optical fiber communications, fiber lasers, fiber amplifiers, WDM transmissions, and fiber access network technologies.

Chi Wai Chow received the B.Eng. (First-Class Hons) and Ph.D. degrees both from the Department of Electronic Engineering, the Chinese University of Hong Kong, in 2001 and 2004, respectively. After graduation, he was appointed as a Postdoctoral Fellow at the CUHK, working on hybrid integration of photonic components and silicon waveguides. Between 2005 and 2007, he was a Postdoctoral Research Scientist, working mainly on two European Union Projects: PIEMAN (Photonic Integrated Extended Metro and Access Network) and TRIUMPH (Transparent Ring Interconnection Using Multi-wavelength Photonic switches) in the Tyndall National Institute and Department of Physics, University College Cork in Ireland. In 2007, he joined the Department of Photonics, National Chiao Tung University in Taiwan, as an Assistant Professor.

Sien Chi received his Ph.D. in electrophysics from the Polytechnic Institute of Brooklyn, New York, in 1971, and joined the faculty of National Chiao Tung University, where he is currently a professor of electro-optical engineering. From 1993 to 1996 he received the Distinguished Research Award sponsored by the National Science Council, Taiwan. Since 1996 he has been the chair professor of the Foundation for Advancement of Outstanding Scholarship. His research interests are optical fiber communications, optical solitons, and optical fiber amplifiers. He is a fellow of the Optical Society of America and the Photonics Society of Chinese-Americans.