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Survivable and Reliable WDM-PON System With Self-Protected Mechanism Against Fiber Fault

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ABSTRACT In the paper, we present and design a self-restored wavelength multiplexing division passive optical network (WDM-PON) configuration to prevent the fiber failure and data disconnection. Here, the new remote node (RN) and optical network unit (ONU) are proposed in the fiber network to provide the protection behavior to increase the network reliability and flexibility. Moreover, the network performances of WDM signals are also analyzed and discussed.

INDEX TERMS Fiber-fault, WDM-PON, self-protection, network reliability.

I. INTRODUCTION

Due to the strongly demand of broadly bandwidth for end user, the passive optical networks (PONs) are the best choice for fiber to the home (FTTH) system [1], [2]. Furthermore, the development of PON network would also progress from time division multiplexing (TDM) to wavelength division multiplexing (WDM) access owing to the current trend of 4K/8K video, online service, video conference, internet and multiple-play service for end-user [3]–[6]. Hence, the new generation WDM-PON with the reliable and survivable network architecture would be the best candidate to offer and maintain the multi-function of high bit rate, network security, larger capacity and assured quality of service (QoS). Moreover, the present WDM-PON architecture could be also applied to support the optical millimeter-wave (MMW) data access and 5G/B5G mobile fronthaul and backhaul links [7]–[9]. Therefore, the self-protection WDM-PON system is important issue to avoid the connection failure caused by the fiber breakpoint in the feeder or distribution fibers [10], [11]. To overcome the fault problem, the self-protected WDM-PON networks and standard ITU-T G.sup.51 have been proposed and demonstrated [12]–[14]. In 2006, Sue demonstrated a 1:N protection scheme based on the cyclic property of an array waveguide grating (AWG) and a specific connection pattern among the optical network units (ONUs). To achieve the fault protection, it also needed an additional decision circuit for routing control [15]. In 2008, Cheng *et al*. designed to combine two WDM-PON systems with multiple sub-ring to achieve self-protected function. Besides, the WDM network also required more monitor circuits (MC), photodiodes (PDs) and optical switches (OSWs) in the OLT and each ONU [16]. In 2003, Chan *et al*. also proposed a 1:1 self-protected WDM-PON architecture using the cyclic characteristic of an AWG. They also needed more WDM channels and the relative monitoring devices to reach self-protected operation [17]. In 2013, Zhou *et al*. presented a survivable WDM-PON by exploiting the centralized protection control together with the colorless ONUs. In their demonstration, the optical carrier suppression (OCS) technique and the additional electrooptical devices were needed for self-protection [18]. As mentioned above, the previous self-protected PON architectures are not only more complex but also require additional components for data reconnection via routing path [15]–[18], when a fiber fault is occurred. Moreover, more monitor circuit and PD components are required and exploited to control the OSW for routing operation. Therefore, the extra cost would be relatively high in their studies.

In this work, we present and investigate a self-protected WDM-PON configuration to circumvent the problem of fiber failure. In this investigation, we can design the new optical modules in the remote node (RN) and optical network unit (ONU) to generate the self-restored operation with

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simple mechanism for data link. In the RN, a 1 × 2 optical coupler (CP) and a 2 × 4 WDM multiplexer are used to connect the corresponding ONU. Besides, each OUN is consisted of an optical circulator (OC), a corresponding bandpass filter (BF) and a 1 × 1 optical switch (OSW). In the proposed network, two adjacent optical line terminals (OLTs) and the corresponding ONU groups can be used to mutually support self-healing operation against fiber breakpoint. Moreover, the extra monitor circuit and photodiode (PD) are not required to attune the OSW in the OLT and ONU modules of our proposed PON system. Here, we can exploit the medium access control (MAC) layer to turn on or off the OSW in each ONU to route the properly fiber path for signal reconnection. Compared with the previous works [15]–[18], our presented self-protected WDM-PON architecture is simple and cost-effective. To demonstrate the traffic performances of symmetric downstream and upstream signals, 10 Gbit/s on-off keying (OOK) modulation format is applied for measurement. The measured power sensitivity of each data signal can meet with the self-protection behavior, while the additional optical components are added in proposed network architecture. Therefore, the presented WDM-PON network can avoid the fiber cut incidence and improve the network reliability and flexibility.

II. EXPERIMENT AND RESULTS

Fig. 1 presents the proposed WDM-PON architecture with self-protected mechanism against fiber breakpoint. As plotted in Fig. 1, assuming two adjacent optical line terminals (OLT_1 and OLT_2) are used in the WDM passive network. Primarily, we suppose two sets of four WDM wavelengths of λ_1, λ_2, λ_3 and λ_4, and λ_2, λ_3, λ_4 and λ_5 are applied in the OLT_1 and OLT_2 acting as the downstream traffics, respectively. The two sets of WDM wavelengths are connected to the corresponding 1 × 4 WDM multiplexers (WDM_a and WDM_b), respectively, as seen in Fig. 1. Here, the WDM signals transmit through optical circulator (OC) and feeder fiber, and then enter the remote node (RN). The RN is consisted of a 1 × 2 and 50:50 optical coupler (CP_1) and 2 × 4 WDM_{ab}. The downstream signals from the OLT_1 and OLT_2 are connected to the two input ports of "a" and "b" in the 2 × 4 WDM_{ab} via the CP_1 respectively. Besides, due to the features of 2 × 4 WDM_{ab}, the wavelengths λ_1, λ_2, λ_3 and λ_4; and λ_2, λ_3, λ_4 and λ_5 of OLT_1 and OLT_2 can be exported from the output ports of "1" to "4", respectively, as seen in Fig. 1. The OLT_1 and OLT_2 would bring two ONU groups of ONU_{11}, ONU_{12}, ONU_{13} and ONU_{14}; and ONU_{21}, ONU_{22}, ONU_{23} and ONU_{24}, respectively. Each ONU is constructed by a 1×1 optical switch (OSW), a 2 × 2 and 50:50 optical coupler (CP_2), an OC, a corresponding bandpass filter (BF) and an optical transceiver (TRx), as illustrated in Fig. 1. In the proposed WDM network, to prevent the data interruption caused by the fiber fault, we can set and connect the ONU_{11} and ONU_{21}, ONU_{12} and ONU_{22}, ONU_{13} and ONU_{23}, and ONU_{14} and ONU_{24} as a group respectively. Therefore, two adjacent ONUs would produce the protection route fiber, as plotted in Fig. 1. Although the downstream wavelength λ_1 and λ_2 from OLT_1 and OLT_2 would enter the ONU_{11} and ONU_{21} together, we can exploit a corresponding BF in the ONU to limit the passable wavelength for downstream access.

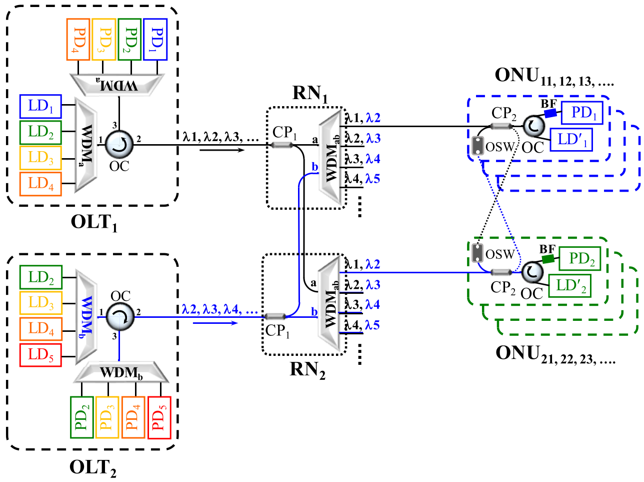

FIGURE 1. Proposed WDM-PON architecture with self-protected mechanism against fiber breakpoint.

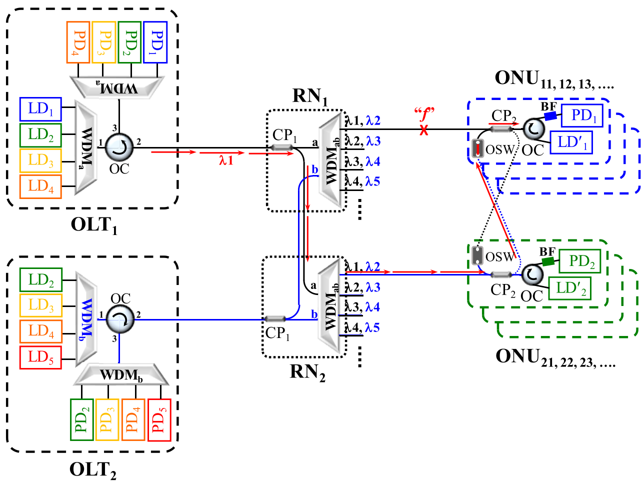

FIGURE 2. A fiber fault occurs in the presented WDM-PON system of Fig. 1.

Initially, the OSW of each ONU is closed in normal traffic status. Hence, each downstream and upstream wavelength could access the data signal through the corresponding ONU, as illustrated in Fig. 1. If a fiber fault occurs at the point of "*f*" as indicated in Fig. 2, the downstream wavelength λ_1 and upstream wavelength λ'_1 could not link for bidirectional data connection. At this moment, to reconnect the data signal, the OSW of ONU_{11} will turn on immediately. Thus, the λ_1 downstream and λ'_1 upstream traffics could relink through the protection fiber of ONU_{21}, as seen in Fig. 2. Here, the medium access control (MAC) in the ONU would turn on the OSW for reconnecting, when the PD cannot detect the downstream signal. After a period of time of traffic connection, the OSW would turn off. If the PD still could not receive any signal, the OSW would turn on again for reconnection. Identically, while a fault happens in the distribution fiber between RN_2 and ONU_{21}, the transmission signal can also reconnect through the ONU_{11} to enhance the reliability and survivability of WDM-PON network. As a result, each ONU group can be utilized to avoid the breakpoint existence of distribution fiber in the presented WDM-PON system.

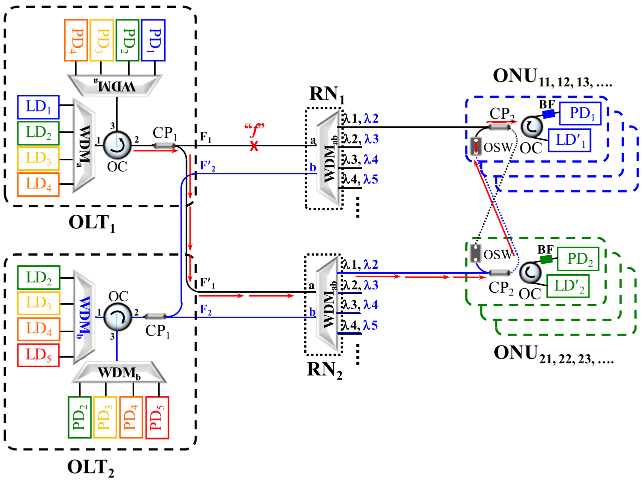

FIGURE 3. A fiber fault occurs between OLT_1 and RN_1 in the presented WDM-PON system.

However, if a breakpoint occurs at the feeder fiber between the OLT_1 and RN_1 or OLT_2 and RN_2, the downstream and upstream connections would result in interruption, as seen in Fig. 1. To solve this problem, we can remove the two CP_1 of RNs to OLT_1 and OLT_2 for resulting in two feeder fibers (F_1 and F'_1, and F_2 and F'_2), respectively, as plotted in Fig. 3. Therefore, each OLT will have two feeder fibers for the normal and protection transmission. Here, if a fault happens in the feeder fiber "F_1", the group of ONU_{11} to ONU_{14} would turn on the OSW immediately to reconnect the data signal through the corresponding ONU_{21} to ONU_{24} via the path "F'_1", as illustrated in Fig. 3. As a result, the self-protected WDM-PON architecture can avoid the fault problem in the feeder and distribution fibers and restore data communication instantly. Here, the self-restored operation would be controlled by each ONU and reduce the complexity of network management, when the fiber fault is occurred unexpectedly.

In this investigation, two fiber faults may be occurred at the distribution and feeder fibers in the proposed WDM-PON architecture, as seen in Fig. 2 and Fig. 3, respectively. In presented PON architecture, no matter where the fiber breakpoint is generated, the self-protected operation would depend on each ONU. When an ONU does not receive the corresponding downstream wavelength, the MAC layer could control the OSW for traffic reconnection to avoid the problem of signal interruption. Then, we could set the OSW to automatically turn off after a period of time via original fiber transmission path. Next, if the downstream signal is still not detected by the PD in the ONU, the OSW would be turned on again. As a result, we design the distributed control of self-protection against fiber fault to simplify the network complexity and reduce the component cost.

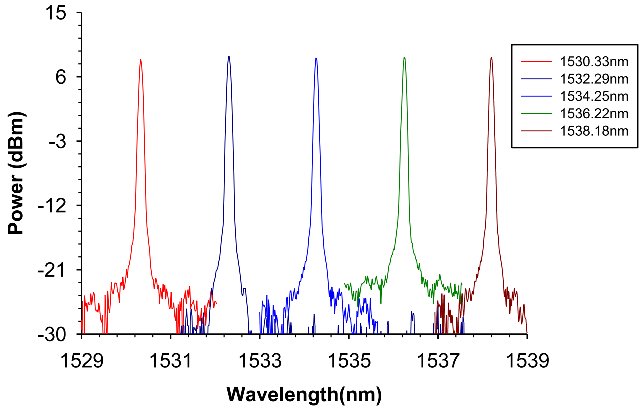

FIGURE 4. Measured output spectrum of the five wavelengths used for downstream and upstream traffic.

To realize the signal performance of presented self-restored WDM-PON, 10 Gbit/s on-off keying (OOK) modulation signal is applied for demonstration. In the experiment, five CW wavelengths of 1530.33 (λ_1), 1532.29 (λ_2), 1534.35 (λ_3), 1536.22 (λ_4) and 1538.18 nm (λ_5) are utilized to demonstrate the symmetric downstream and upstream traffics respectively. Here, the output spectrum of each wavelength is plotted in Fig. 4. Each CW wavelength can connect to the polarization controller (PC) and 10 GHz Mach-Zehnder modulator (MZM). Moreover, 10 Gbit/s OOK modulation signal with $2^{15}-1$ pattern length is carried on MZM serving as the symmetric downstream and upstream traffics, respectively. We adjust the PC to maintain the polarization state and accomplish the optimal output power. After transmitting through the corresponding optical devices and a length of single-mode fiber (SMF), the 10 Gbit/s OOK traffic can be amplified by an optical pre-amplifier (OPA) and received via the 10 GHz PIN-based photodiode (PD) for decoding.

Fig. 5(a) to Fig. 5(c) show the measured bit error ratio (BER) performance of 10 Gbit/s OOK modulation at the back-to-back (BtB), 25 km and 26 km SMF transmission, respectively, when the wavelength λ_1 to λ_5 are utilized. In the experiment, the MZM with -0.7 chirp parameter can be employed to pre-compensate fiber chromatic dispersion and achieve better signal performance simultaneously. Here, the obtained optical sensitivities of λ_1 to λ_5 are -27, -26.5, -25, -22.5 and -22 dBm, -27.5, -27, -26.5, -22.5 and -22 dBm, and -27.5, -27, -26.5, -24 and -23.5 dBm at the BER of 1×10^{-10}, respectively, as indicated in Fig. 5(a) to Fig. 5(c). Inserts of Fig. 5(a) to Fig. 5(c) are the measured eye diagrams of λ_5 (1538.18 nm) at the BER of 1×10^{-10}, respectively. The observed eye diagrams are clear and open fully. Due to the negative chirp feature of MZM, the observed sensitivities of Fig. 5(a) and Fig. 5(b) are better than that of Fig. 5(c). Moreover, the SMF transmission length of present WDM-PON access is between 0 and 20 km, the pre-chirp

MZM could enhance the signal sensitivity after fiber transmission. Therefore, the pre-chirp characteristic could provide the longer SMF transmission in future WDM-PON.

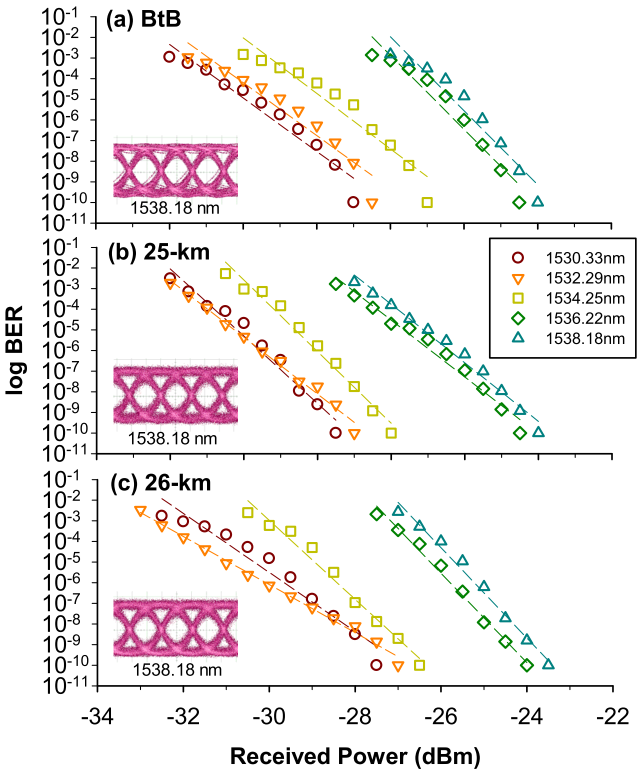

FIGURE 5. Observed 10 Gbit/s BER performance at the (a) BtB status, (b) 25 km and (c) 26 km SMF transmission, respectively. Insets are the measured corresponding eye diagrams at 1538.18 nm wavelength.

According to the presented WDM-PON network, it causes the total power loss of 21 dB, including the 25 km SMF (5 dB), two CPs (6 dB), WDM multiplexer (6 dB), OC (1 dB), and BF (3 dB) respectively, in normal traffic, as illustrated in Fig. 3. When the protected mechanism is started, the total loss will become 25.2 dB, containing the 26 km SMF (5.2 dB), three CPs (9 dB), WDM multiplexer (6 dB), OC (1 dB), OSW (1 dB) and BF (3 dB) respectively, as shown in Fig. 3. In the experiment, the output power of each 10 Gbit/s OOK wavelength is nearly 7 dBm for bidirectional connection. Besides, the obtained minimum power budget in the proposed network is 29 dB, as mentioned above. Based on the self-protected WDM network, the obtained power budget of each wavelength can meet with the requirement of total power loss for symmetric 10 Gbit/s OOK transmissions.

In the demonstration, Tab. 1 presents the comparisons of previous self-protected WDM-PON architectures. As seen in Tab. 1, the additional optical components in our designed PON scheme are less than that of the previous studies [15]–[18]. The operation mechanism of our proposed self-protection network is simple and easy. Here, we could use N WDM wavelengths for providing N ONUs for traffic connection. As exhibited in Tab. 1, refs. 15 to 18 need the more additional PD, MC and optical device to route the properly

TABLE 1. Comparisons of previous self-protected WDM-PON architectures.

		Scheme [15]	Scheme [16]	Scheme [17]	Scheme [18]	Proposed
Protection Scheme		1:M	1:1	1:1	1:1	1:1
RN	WDM	3×N	1×N	1×N	2·(1×N)	2×N
	CP	0	0	N	0	0
OLT	No. of OLT	1	2	1	1	2
	WDM	1×N	1×N	1×N	4·(1×N)	1×N
	Interlever	0	0	0	4	0
	OSW	1	0	0	2	0
	CP	1	2	0	0	1
	R/B Filter	1	0	1	0	0
	MC	1	1	0	1	0
	Extra PD	1	1	0	1	0
ONU	OSW	2	1	2	0	1
	CP	2M	2	1	1	1
	Interlever	0	0	0	1	0
	B/R Filter	0	1	1	0	1
	MC	1	1	2	0	0
	Extra PD	1	1	2	0	0
Required Wavelength		N	2N	2N	2N	N
Switching Time		×	1.5 μs	18 ms	1.2 ms	7 ms
Self-Protected Operation		Complexity	Normal	Complexity	Normal	Simple

fiber path against fiber fault according to their own network architecture. Fewer optical components are exploited in our demonstrated PON system to achieve fiber fault protection. Consequently, the extra cost would be relatively high in the prior studies. In addition, the switching time of OSW is ~7 ms in the proposed WDM-PON. However, the speed of switching time depends on the characteristic of OSW used in the fault protection network.

III. CONCLUSION

A reliable and flexible self-protected WDM-PON system was proposed and designed to avoid the fiber breakpoint. In the demonstration, we presented a WDM access architecture with new designed optical module to produce self-restored function. Here, we applied five wavelengths with 10 Gbit/s OOK modulation data for symmetric downstream and upstream transmissions. The obtained minimum power sensitivities were −22 and −23.5 dBm below the error-free (BER $\leq 1 \times 10^{-9}$) among these modulated wavelengths after 25 and 26 km SMF transmission. According to the total power loss of presented WDM-POM architecture, the practical power budget of 10 Gbit/s OOK wavelength could meet with the requirement completely for data connection. As a result, the designed PON system could avoid the fiber fault and enhance the reliability and flexibility concurrently.

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