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Fiber- and FSO-Protected Connections for Long-Reach TWDM Access Architecture With Fault Protection

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ABSTRACT In this paper, we propose a long-reach star-ring-based time- and wavelength-division-multiplexing passive optical network (TWDM-PON) by using fiber- and free space optical (FSO)-protected architecture against fiber breakpoint. Here, the new fiber-based and FSO-based optical network unit (ONU) modules are designed in the PON system to achieve the self-protected operation. Thus, the adjacent ONU is linked to produce the fiber- or FSO-based reconnections. Thus, 4×10 Gbit/s downstream and 10 Gbit/s upstream signals can be reached through 70 km fiber transmission and a length of free space link without signal amplification and dispersion compensation. Moreover, the relationships of splitter ratio and FSO link length in the proposed TWDM access network are also analyzed and discussed.

INDEX TERMS Fault protection, free space optical (FSO), TWDM-PON, OOK signal, star-ring-architecture.

I. INTRODUCTION

Recently, the requirement of broad bandwidth has been grown speedily due to the huge number of internet user, cloud information, big data process, 4K/8K video, social networking, data center, and video gaming and conference [1]–[3]. Thus, the new generation optical access network must have the characteristics of long-reach, extended coverage, great capacity, high flexibility, and cost-effectiveness to provide the bandwidth of 1 Gbit/s to each end user or even high [4], [5]. Furthermore, the passive optical network (PON) has attracted more interests for last mile access owing to its several benefits of energy efficiency, service transparency, reliability, and salability [6], [7]. To meet with the capacity demand for user, utilizing time- and wavelength-division-multiplexing (TWDM) and WDM access technologies would be promising candidate [8], [9]. However, the WDM-PON could bring the higher cost due to the massive WDM laser source and bandpass filter. Thus, we could utilize the TWDM-PON to temporarily replace WDM-PON. And the TWDM-PON was chosen by the FSAN community in 2012 as a principal solution to NG-PON2 to support 40 Gbit/s downstream and 10 Gbit/s upstream traffic [10], [11].

Under such high-capacity signal transmission, the appearance of fiber breakpoint would cause signal interruption in PON network. To provide the fault protection in PON system against fiber fault, several self-restored fiber access networks have been proposed and analyzed in the star-based, ring-based, and star-ring-based architectures [12]–[15]. However, due to the certain environmental constraint or application scenario, using free space optical (FSO) communication technology is more suitable than the fiber link for signal connection [16]–[20]. Therefore, the blended FSO- and fiber-based communication systems would also provide the advantages of network reliability and flexibility for end user [21].

In this research, we present a 4×10 Gbit/s on-off keying (OOK) long-reach star-ring-based TWDM-PON architecture against fiber fault. To provide the fault protection function, the new optical network unit (ONU) modules with FSO- and fiber-protected connections are designed for demonstration. Here, we select four WDM wavelengths of 1540.16,

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1540.95, 1541.75 and 1542.54 nm to act as 4 × 10 Gbit/s TWDM downstream (DS) traffic for 50 to 70 km single mode fiber (SMF) connection and free space transmission. Besides, to avoid the signal interference, a 1543.33 nm wavelength is applied for serving as upstream (US) signal. To overcome the fault issue, two adjacent ONUs are connected to provide signal router by using the fiber- and FSO-protected configurations. In the fiber-based protection network, the maximum splitter ratios of 32 and 16 are reached after 50 and 70 km SMF transmission, respectively, according to the available power budget without using optical amplification and dispersion compensation. In addition, when we only consider to exploit the FSO-protected architecture through 50 and 70 km SMF transmissions, the achievable splitter ratios of 4 and 2 are obtained at the free space link length of 180 and 160 m, respectively.

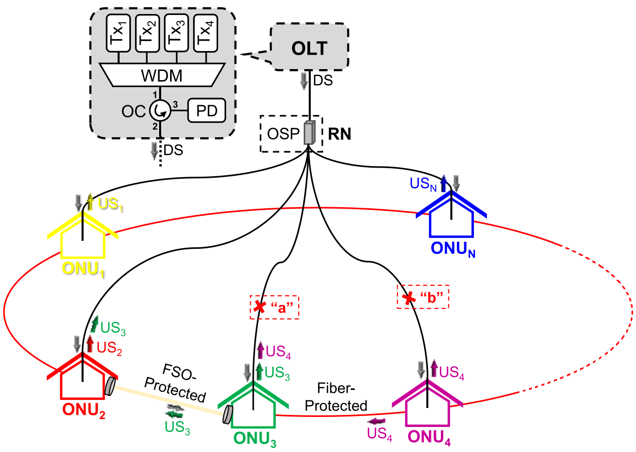

FIGURE 1. Proposed star-ring-based 4 × 10 Gbit/s TWDM-PON architecture with fiber- and FSO-protected operation mechanism against fiber fault.

II. EXPERIMENT AND RESULTS

To reach the self-protected fiber access network against fiber fault, a star-ring-based 4 × 10 Gbit/s TWDM-PON architecture is proposed and demonstrated, as observed in Fig. 1. In the OLT, four TWDM downstream (DS) wavelengths are combined by a 1 × 4 WDM multiplexer and delivered through the 3-port optical circulator (OC) and feeder fiber simultaneously. Then, the four TWDM DS signals will be split by a 1×N optical splitter (OSP) at the remote node (RN) for broadcasting. Next, the DS traffic can enter each ONU for decoding its own signal after passing through the distributed fibers. In the proposed PON architecture, each upstream (US) signal from the ONU transmits to the OLT via TDM access format. And the corresponding filter is applied in the optical receiver (Rx) for decoding information. Moreover, to avoid the traffic disconnection between the OLT and certain ONU, we apply ring-based fiber or FSO method to connect each ONU, as illustrated in Fig. 1. However, due to certain environmental or geographical restrictions, we can utilize the FSO-protected technique to connect two adjacent ONUs against fiber fault. As a result, the presented PON architecture can exploit the fiber-protected and FSO-protected connections simultaneously to complete the fault protection. For instance, if the fiber breakpoint occurs at the "a" and "b" point, respectively, the DS and US signals of ONU_3 and ONU_4 could be reconnected via the ONU_2 and ONU_3 via the fiber- and FSO-based link, as seen in Fig. 1.

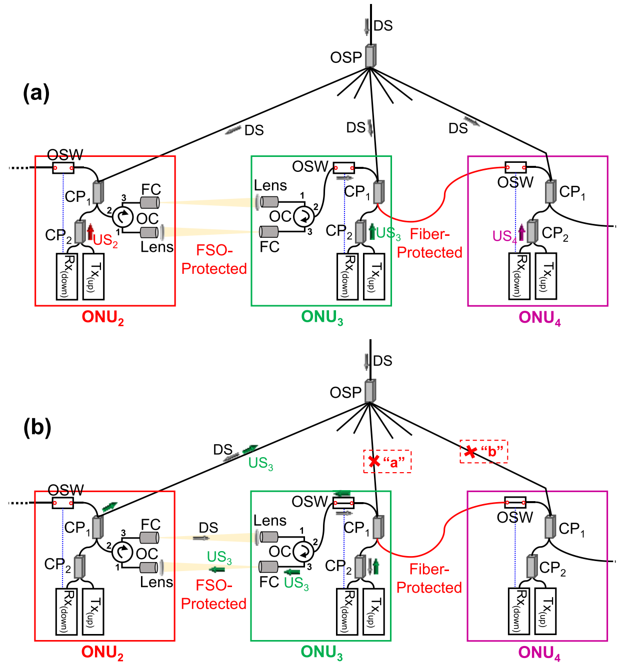

FIGURE 2. (a) FSO- and fiber-based ONU modules against fiber breakpoint under normal state. (b) Schematic of proposed fault protection TWDM-PON when a breakpoint occurs at the "a" and "b" point, respectively.

Then, we display the new designed ONU modules in the star-ring-based PON architecture to avoid the fault occurrence. Fig. 2(a) present the new FSO- and fiber-based ONU modules against fiber breakpoint under normal state. As plotted in Fig. 2(a), the ONU_2 and ONU_3 are constructed by a 2 × 2 and 50:50 CP_1, a 1 × 2 and 50:50 CP_2, a 1 × 1 optical switch (OSW), an OC, two fiber-based collimators (FCs) and a focus lens for FSO-protected connection, respectively. As seen in Fig. 2(a), the OSW of each ONU is off when there is no fault occurrence. The DS and US signals from adjacent ONU will be blocked by an OSW to avoid the DS signal interference. As plotted in Fig. 2(a), between the ONU_3 and ONU_4 are using the fiber-protected link for restoring signal connection. Besides, the ONU_4 is consisted of the CP_1, CP_2 and OSW.

For example, when a fiber breakpoint is occurred at the "a" point of Fig. 2(b), then the corresponding DS and US wavelengths would be discontinued between the OLT and ONU_3. To reconnect the data traffic currently, the OSW of ONU_3 will be turned on by the medium access control (MAC) at this time, when the $Rx_{(down)}$ is not detected any signal. Then, the broadcasting DS signal also can transmit through the CP_1, OC and FC of ONU_2 to ONU_3 for data reconnection by FSO link. Here, the lens is exploited at the ONU to enhance the detected power of DS and US FSO signals. Next, the US signal of ONU_3 also can deliver to the OLT via the ONU_2 by FSO link, as seen in Fig. 2(b). When the fault is repaired, the OSW of ONU_3 would turn off for normal traffic operation. Hence, we can apply the FSO-protected method for data reconnection against fiber fault in the proposed star-ring-based PON network. Furthermore, if the fault appears between the RN and ONU_4 at the point "b", the DS and US traffic of ONU_4 also can relink by fiber-protected connection via the ONU_3, as displayed in Fig. 2(b). Even if two fault points "a" and "b" occur at the same time, the bidirectional signals of ONU_3 and ONU_4 also can relink via the ONU_2 by the proposed FSO- and fiber-protected methods for relink, when the OSW of ONU_3 and ONU_4 are turned on simultaneously. In this demonstration, the OSW is off or on in each ONU depending on whether the optical $Rx_{(down)}$ has received DS signal. Therefore, the exhibited fault protection network is very simple for operation.

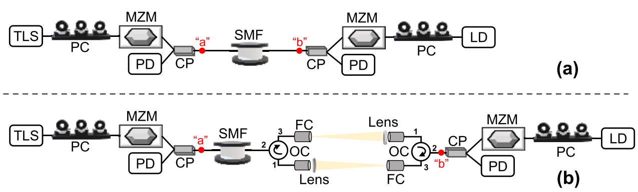

FIGURE 3. Experimental setup of DS and US BER measurements for (a) fiber-protected and (b) FSO-protected connection, respectively.

Next, to verify the DS and US performances under the fiber-based and FSO-based transmissions, an experimental setup is applied for the bit error rate (BER) measurement. Fig. 3(a) shows the experimental setup of fiber-protected transmission. Here, a tunable laser source (TLS) acting as the DS wavelength is connected to a polarization control (PC) and a 10 GHz Mach-Zehnder modulator (MZM). The PC is adjusted to achieve the optimal DS output power. We apply on-off keying (OOK) modulation format with a pattern length of $2^{31}-1$ on the MZM to generate 10 Gbit/s DS rate. Besides, we select four wavelengths of 1540.16, 1540.95, 1541.75 and 1542.54 nm, respectively, to regard as the four TWDM DS traffic for 4×10 Gbit/s BER measurement. Then, the TWDM DS signal via the CP connects to a length of single-mode fiber (SMF) and then launching into a 10 GHz PIN photodiode (PD) for DS demodulation, as plotted in Fig. 3(a). In the measurement, the detected output power of DS wavelength is around 7.6 dBm at the "a" point of Fig. 3. Moreover, we utilize a wavelength of 1543.33 nm to serve as the US signal. We also produce a 10 Gbit/s OOK via the 10 GHz MZM for US signal transmission.

For the FSO-based protection mechanism, we also can use the same optical devices for the BER measurement, as illustrated in Fig. 3(b). The only difference is applying the FSO technique for the DS and US signal connections. In the setup, a FC with 20 mm diameter is employed to transfer the DS and US wavelength to FSO signal with 7 mm spot beam. To execute the free space connection easily, a 2 m wireless transmission length is set for measuring FSO performance. To enhance the detected FSO power, a lens with 50.4 mm diameter is placed in front of FC at the received side. Besides, the focus lengths of FC and lens are 37.13 and 75 mm. As a result, we can measure the BER behaviors of DS and US FSO signals according to the setup of Fig. 3(b), respectively.

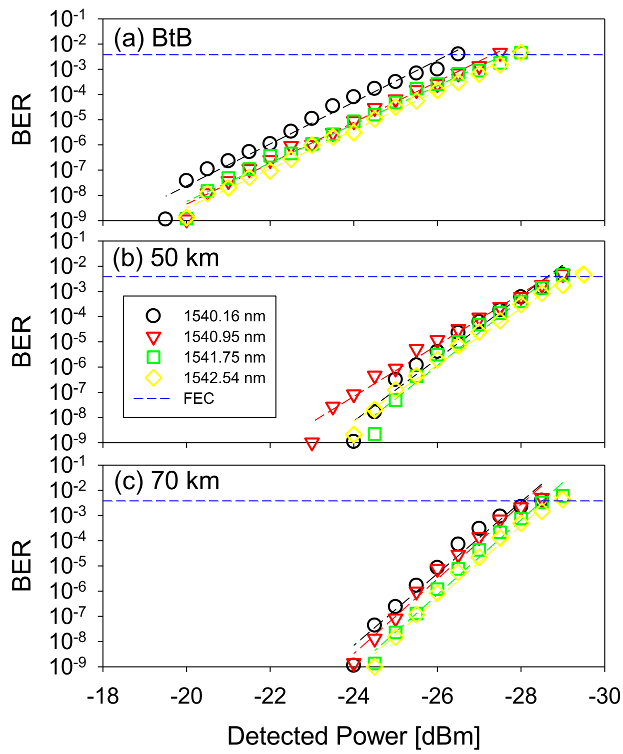

FIGURE 4. Measured BER performances of four 10 Gbit/s DS signals at the (a) BtB, (b) 50 and (c) 70 km SMF transmissions, respectively, under fiber-protected operation.

First, Figs. 4(a) to 4(c) exhibit the measured 10 Gbit/s OOK BER behaviors of four DS wavelengths at the back-to-back (BtB), 50 and 70 km SMF transmissions, respectively, under the fiber-based protection. The detected power sensitivities of four DS wavelengths can become lower and lower around the BER of 10^{-9}, when the SMF transmission length gets longer and longer, as seen in Figs. 4(a) to 4(c). This is because the chirp parameter of MZM is -0.7 in this measurement. The -0.7 chirp of MZM is fixed. Then, the chromatic fiber dispersion can be compensated due to the negative chirp effect. Furthermore, to achieve the forward error correction (FEC) target (BER $\leq 3.8 \times 10^{-3}$), the observed power sensitivities of four DS signals are -26, -27, -27.5 and -27.5 dBm, -28.5, -28.5, -28.5 and -29 dBm, and -28, -28, -28.5 and -28.5 dBm, respectively, at the BtB, 50 km and 70 km SMF transmissions. As a result, the smallest power budgets among the four DS signals are 35.6 and 37.6 dB, when the SMF link lengths are 50 and 70 km, respectively.

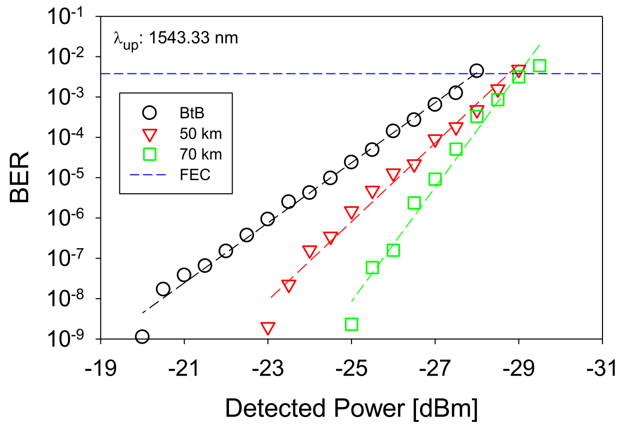

FIGURE 5. Measured BER performance of 10 Gbit/s US signal through (a) 50 and (b) 70 km SMF transmissions, respectively, under fiber-protected operation.

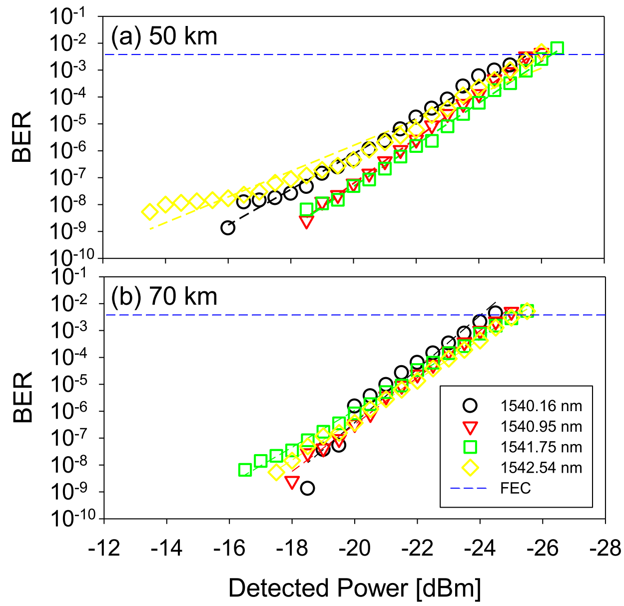

FIGURE 6. Measured BER performances of four 10 Gbit/s OOK DS signals through (a) 50 and (b) 70 km SMF transmissions, respectively, under the FSO-protected transmission.

Fig. 5 displays the BER measurement of 10 Gbit/s OOK US wavelength at the BtB, 50 km and 70 km SMF transmissions, respectively, under fiber-protected network configuration. In the experiment, the US output power of 7.6 dBm is observed at the "b" point of Fig. 3(a). The detected power sensitivities are −27.5, −28.5 and −29 dBm, respectively, at the BtB, 50 km and 70 km SMF transmissions under the FEC limit. Therefore, the available power budgets of 36.1 and 37.6 dB are achieved after the 50 and 70 km SMF connections.

Then, we will execute the BER performances of FSO-protected DS and US traffic connections according to the experimental setup of Fig. 3(b) for demonstration. In the experiment, the coupling loss between two FCs is measured around 2.6 dB through 2 m FSO link length. Figs. 6(a) and 6(b) present the measured BER performances of four 10 Gbit/s OOK DS signals after 50 and 70 km SMF transmissions under the FSO-protected operation, respectively. Here, the detected power sensitivities of four DS FSO signals are −25.5, −25.5, −25 and −25.5 dBm and −24, −24.5, −25 and −25 dBm, respectively, at the FEC level. Hence, the minimum power budget among the four DS wavelengths is 32.6 and 31.6 dB at 50 and 70 km SMF transmission, respectively. As seen in Figs. 4(b) and 4(c) and Fig. 5(a) and 5(b), the measured power sensitivities are similar under the FEC level between 50 and 70 km SMF transmissions at the fiber- and FSO-protected operations, respectively. The SMF transmission length of 50 to 70 km will be the better operation condition in the proposed PON architecture.

Next, we will investigate the US BER performance in the FSO-protected PON network. According to the setup of Fig. 3(b), the 10 Gbit/s OOK US will transmit through 2 m wireless FSO link and 50 km (and 70 km) SMF transmission for detection. Fig. 7 indicates the obtained BER measurement of US FSO signal after 50 and 70 km SMF link, when the FSO length is 2 m long. The observed power sensitivities

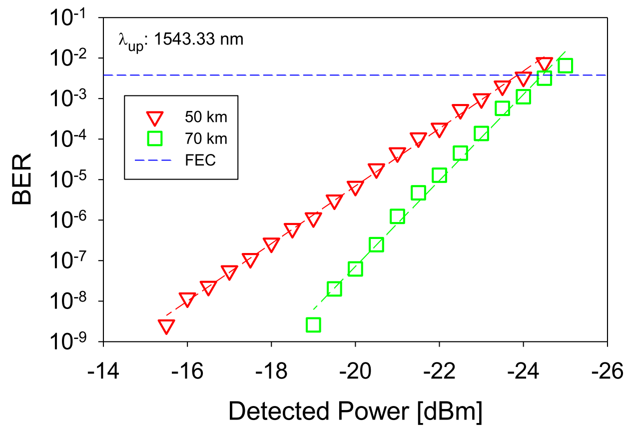

FIGURE 7. Obtained BER performance of 10 Gbit/s OOK US signal after (a) 50 and (b) 70 km SMF transmissions, respectively, under FSO-protected operation.

are −24 and −24.5 dBm at the FEC level after 50 and 70 km SMF connections. Therefore, the available power budgets of 31.6 and 32.1 dB are completed at the two FSO-based fiber links.

Finally, we will analyze and discuss the maximum number of ONUs and the longest FSO transmission length that the proposed fiber-based and FSO-based fault protection system can provide. As seen in Fig. 2, the total losses are induced by the 1×N OSP, CP_1 (3 dB), CP_2 (3 dB), OSW (0.5 dB), OC (0.5 dB), and 50 (10 dB) and 70 km SMF (14 dB) transmission length, respectively, for the fiber-protected network. Besides, the FSO-protected configuration also involves the coupling loss between two FCs and the laser beam divergence in atmosphere. Moreover, the beam divergence loss can be estimated and obtained depending on the wireless FSO

TABLE 1. The relationship of corresponding insertion loss and redundant budget for TWDM DS traffic under the (a) fiber- and FSO-protected connection against fiber fault, respectively.

(a) Fiber-Protected Link

Splitter Ratio (Loss)	Fiber Loss	ONU's Coupler	OC and SW	Total Loss	Power Budget
16 (12 dB)	50 km (10 dB)	3 × 3 dB = 9 dB	1	32	35.6
32 (15 dB)				35	35.6
8 (9 dB)	70 km (14 dB)	3 × 3 dB = 9 dB	1	33	37.6
16 (12dB)				36	37.6

(b) FSO-Protected Link

Splitter Ratio (Loss)	Fiber Loss	ONU's Coupler	2 OCs and SW	FSO Link Loss	Total Loss	Power Budget	FSO Length
2 (3 dB)	50 km (10 dB)	3 × 3 dB = 9 dB	1.5	2.6	26.6	31.6	260 m (5 dB)
4 (6 dB)					29.6	31.6	180 m (2 dB)
1 (0 dB)	70 km (14 dB)	3 × 3 dB = 9 dB	1.5	2.6	27.6	32.1	240 m (4.5 dB)
2 (3 dB)					30.6	32.1	160 m (1.5 dB)

communication length in the previous study [17]. When a fault occurs in the proposed PON network, the signal reconnected path will pass through two adjacent ONUs. Thus, the downstream signal would experience three OCPs, as seen in Fig. 2. Tab. 1 presents the relative insertion losses of the optical devices which are used in the fiber-based and FSO-based protection systems. Due to the pre-chirp MZM, the attained power sensitivity through 70 km SMF link is better than that of 50 km. Thus, the minimum power budgets are 35.6 and 37.6 dB and 31.6 and 32.1 dB, respectively, in the fiber- and FSO-protected network against fiber breakpoint through 50 and 70 km SMF links. As viewed in Tab. 1, the maximum power splitter ratio can achieve 32 and 16 through 50 and 70 km SMF transmission, respectively, under the fiber-protected architecture based on its corresponding power budget without using wavelength amplification and dispersion compensation.

However, the FSO-protected network not only need to consider the splitter ratio but the FSO link length. To satisfy the power budget by applying the FSO-based connection in the star-ring-based TWDM-PON system, the splitter ratio only can reach 4 and 2 through 2 m FSO transmission while the SMF connection is 50 and 70 km, respectively, as shown in Tab. 1. Then, the remaining power budgets are 2 and 1.5 dB, respectively. According to the previous study [17], the two remained budgets can support 180 and 160 m wireless FSO connections based on the same optical FSO system, respectively, when the FSO alignment is accurate and atmosphere is pure. Generally, an optical amplifier could be applied in the RN to enhance the power budget for long-reach PON access [22]. Hence, to compensate the larger insertion loss in FSO-protected PON network, we can employ an erbium-doped fiber amplifier (EDFA) with 20 dB gain in the RN to increase the splitter ratio and FSO link length. Besides, the beam divergence loss of 15.5 dB could be induced after 1 km FSO transmission in previous work [17]. As a result, the splitter ratio can increase to 16 and 8 after 50 and 70 km SMF link through 1 km FSO connection based on the available budget, respectively, when an EDFA is used. In this analysis, if we want to extend a higher splitter ratio and achieve a longer FSO link in the proposed PON system, an EDFA is required in each ONU to compensate the insertion loss.

III. CONCLUSION

We demonstrated and executed a long-reach star-ring-based 4 × 10 Gbit/s OOK TWDM-PON with fiber- and FSO-protected architecture again fiber breakpoint. In the investigation, the new fiber-based and FSO-based ONU modules were proposed in the PON system to achieve the self-protected operation. Here, two adjacent ONUs were connected to provide signal router by using the fiber- or FSO-based protections. Owing to the certain environmental constraint or application scenario, the FSO-based connection would be the better method for fault protection. Once the DS signal could not be detected in the ONU, the OSW of ONU would be turned on by the MAC for data relink to avoid the fault problem. Here, 40 Gbit/s OOK DS TWDM and 10 Gbit/s OOK US traffic could be reached through a length of free space link for 50 to 70 km fiber connection. In the fiber protected PON network, the maximum splitter ratio of 32 and 16 could be reached after 50 and 70 km SMF transmission, respectively, based on the available power budget without optical amplification and dispersion compensation. Moreover, when we only considered to exploit the FSO-protected architecture through 50 and 70 km SMF transmissions, the achievable splitter ratio of 4 and 2 could be obtained at the free space link length of 180 and 160 m, respectively. Because the other optical devices were exploited in the ONU, larger insertion losses would be induced and reduce the splitter ratio. Hence, the FSO link length would also be limited for long-reach fiber transmission. We believed that the splitter ratio and FSO length could be enhanced while the EDFA was applied in the proper location of TWDM-PON architecture.

REFERENCES

[1] R. Zhang, F. Lu, M. Xu, S. Liu, P.-C. Peng, S. Shen, J. He, H. J. Cho, Q. Zhou, S. Yao, and G.-K. Chang, "An ultra-reliable MMW/FSO A-RoF system based on coordinated mapping and combining technique for 5G and beyond mobile fronthaul," *J. Lightw. Technol.*, vol. 36, no. 20, pp. 4952–4959, Oct. 15, 2018.

[2] Y.-H. Lin, H.-S. Lin, W.-L. Wu, C.-T. Tsai, C.-H. Cheng, T.-T. Shih, and G.-R. Lin, "100-Gbit/s/λ EML transmitter and PIN-PD+TIA receiver-based inter-data center link," *J. Lightw. Technol.*, vol. 38, no. 8, pp. 2144–2151, Apr. 15, 2020.

[3] C.-H. Yeh, C.-W. Chow, and C.-H. Hsu, "40-Gb/s time-division-multiplexed passive optical networks using downstream OOK and upstream OFDM modulations," *IEEE Photon. Technol. Lett.*, vol. 22, no. 2, pp. 118–120, Jan. 2010.

[4] *10-Gigabit-Capable Passive Optical Networks (XG-PON): Transmission Convergence (TC) Specifications*, document ITU-T Recommendation G.987.3, Oct. 2010.

[5] X. Hu, L. Zhang, P. Cao, K. Wang, and Y. Su, "Energy-efficient WDM-OFDM-PON employing shared OFDM modulation modules in optical line terminal," *Opt. Express*, vol. 20, no. 7, pp. 8071–8077, 2012.

[6] C.-H. Yeh, C.-W. Chow, W.-P. Lin, J.-R. Chen, and W.-Y. You, "Utilizing single-wavelength for OFDM wireless downstream and remodulated OOK upstream in colorless access network to mitigate Rayleigh backscattering noise," *Opt. Fiber Technol.*, vol. 58, Sep. 2020, Art. no. 102268.

[7] Z.-K. Weng, Y.-C. Chi, H.-Y. Wang, C.-T. Tsai, and G.-R. Lin, "75-km long reach dispersion managed OFDM-PON at 60 Gbit/s with Quasi-Color-Free LD," *J. Lightw. Technol.*, vol. 36, no. 12, pp. 2394–2408, Jun. 15, 2018.

[8] C.-H. Yeh, C.-W. Chow, M.-H. Yang, and D.-Z. Hsu, "A flexible and reliable 40-Gb/s OFDM downstream TWDM-PON architecture," *IEEE Photon. J.*, vol. 7, no. 6, Dec. 2015, Art. no. 7905709.

[9] R. Murano, W. F. Sharfin, and M. J. L. Cahill, "Tunable 2.5 Gb/s receiver for wavelength-agile DWDM-PON," in *Proc. OFC*, 2008, Art. no. PDP32.

[10] N. Cheng, "Flexible TWDM PON with WDM overlay for converged services," *Opt. Fiber Technol.*, vol. 26, pp. 21–30, Dec. 2015.

[11] Y. Luo, X. Zhou, F. Effenberger, X. Yan, G. Peng, Y. Qian, and Y. Ma, "Time-and wavelength-division multiplexed passive optical network (TWDM-PON) for next-generation PON stage 2 (NG-PON2)," *J. Lightw. Technol.*, vol. 31, no. 4, pp. 587–593, Feb. 2013.

[12] C.-H. Yeh, C.-M. Luo, Y.-R. Xie, C.-W. Chow, Y.-W. Chen, and T.-A. Hsu, "Survivable and reliable WDM-PON system with self-protected mechanism against fiber fault," *IEEE Access*, vol. 7, pp. 165088–165092, 2019.

[13] T.-K. Chan, C.-K. Chan, L.-K. Chen, and F. Tong, "A self-protected architecture for wavelength-division-multiplexed passive optical networks," *IEEE Photon. Technol. Lett.*, vol. 15, no. 11, pp. 1660–1662, Nov. 2003.

[14] H. Yao, W. Li, Q. Feng, J. Han, Z. Ye, Q. Hu, Q. Yang, and S. Yu, "Ring-based colorless WDM-PON with Rayleigh backscattering noise mitigation," *IEEE/OSA J. Opt. Commun. Netw.*, vol. 9, no. 1, pp. 27–35, Jan. 2017.

[15] Z. Zhou, S. Xiao, M. Bi, T. Qi, P. Li, and W. Hu, "Survivable wavelength-division multiplexing passive optical network system with centralized protection routing scheme and efficient wavelength utilization," *Opt. Eng.*, vol. 52, no. 9, Sep. 2013, Art. no. 096109.

[16] J. Zhang, J. Wang, Y. Xu, M. Xu, F. Lu, L. Cheng, J. Yu, and G.-K. Chang, "Fiber–wireless integrated mobile backhaul network based on a hybrid millimeter-wave and free-space optics architecture with an adaptive diversity combining technique," *Opt. Lett.*, vol. 41, no. 9, pp. 1909–1912, 2016.

[17] C.-H. Yeh, J.-R. Chen, W.-Y. You, W.-P. Lin, and C.-W. Chow, "Free space optical communication in long-reach unidirectional ring-architecture fiber network," *IEEE Access*, vol. 8, pp. 159574–159580, 2020.

[18] Z. Zhao, Z. Zhang, J. Tan, Y. Liu, and J. Liu, "200 Gb/s FSO WDM communication system empowered by multiwavelength directly modulated TOSA for 5G wireless networks," *IEEE Photon. J.*, vol. 10, no. 4, Aug. 2018, Art. no. 7905908.

[19] I.-C. Lu, C.-H. Yeh, D.-Z. Hsu, and C.-W. Chow, "Utilization of 1-GHz VCSEL for 11.1-gbps OFDM VLC wireless communication," *IEEE Photon. J.*, vol. 8, no. 3, Jun. 2016, Art. no. 7904106.

[20] R. Zhang, P. C. Peng, X. Li, S. Liu, Q. Zhou, J. He, Y.-W. Chen, S. Shen, S. Yao, and G. K. Chang, "4 × 100-Gb/s PAM-4 FSO transmission based on polarization modulation and direct detection," *IEEE Photon. Technol. Lett.*, vol. 31, no. 10, 2019, Art. no. 755758.

[21] C.-H. Yeh, Y.-R. Xie, C.-M. Luo, and C.-W. Chow, "Integration of FSO traffic in ring-topology bidirectional fiber access network with fault protection," *IEEE Commun. Lett.*, vol. 24, no. 3, pp. 589–592, Mar. 2020.

[22] C.-W. Chow and C.-H. Yeh, "Mitigation of Rayleigh backscattering in 10-Gb/s downstream and 2.5-Gb/s upstream DWDM 100-km long-reach PONs," *Opt. Express*, vol. 19, no. 6, pp. 4970–4976, 2011.

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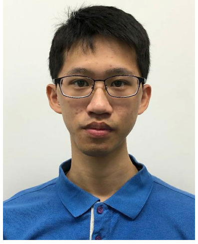

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