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Symmetry 28 Gbps/λ WDM Access Network Together With Confidential Connection Between Two Specific Clients

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ABSTRACT In this work, we demonstrate a symmetry 28 Gbps/λ on-off keying (OOK) wavelength-division-multiplexing passive optical network (WDM-PON) architecture together with confidential connection between two specific optical network units (ONUs). The presented PON access network also can prevent the Rayleigh backscattering (RB) induced interference noise. Here, to avoid re-deployment of optical fiber and increase cost, a ring-based fiber connection is proposed to connect each ONU for personal information link, when the data connection between two ONUs can be changed arbitrarily. Moreover, the corresponding signal performances of the presented WDM-PON system are also studied and discussed.

INDEX TERMS WDM-PON, Rayleigh backscattering, OOK modulation, confidential connection.

I. INTRODUCTION

Recently, due to the quick growth of multimedia and broadband services, such as the artificial intelligence (AI) application, data center, cloud link, video on demand, 4K/8K video, and online gaming, the transmission rate, 5G/B5G mobile and network bandwidth have been heightened to satisfy the demand of end user [1]–[3]. Hence, the optical access networks could be the unavoidable choice to support ever raising broadband service, due to its wide bandwidth characteristic [4]. To provide a high speed and broadband capacity in the last mile access, passive optical network (PON) has interested more concerns for data link, owing to its features of long-reach link, great capacity, extended coverage, high flexibility, and cost-effectiveness [5], [6]. To comply with the broadband requirement of end customer, the time-division-multiplexing (TDM), time- and wavelength-division-multiplexing (TWDM) and WDM access technologies have been proposed and demonstrated [7]–[9]. However, the TDM- and TWDM-PON networks will not meet the supply of broadband applications due to its limited data capacity. Therefore, compared to the data traffic of standard TDM- or TWDM-PONs for each optical network unit (ONU), the WDM access in a PON can provide higher capacity of nearly 10 Gbps and more to support the broadband requirement of end-user [10]–[12].

The WDM-PON is a point to point (PtP) connection network. Thus, they need multiple WDM wavelengths to regard as the downstream and upstream traffics. If the downstream and upstream signals utilize the same wavelength for bidirectional connection, it would cause the Rayleigh backscattering induce interference noise at the photodiode (PD) of optical line termination (OLT) and ONU, respectively [13]. To prevent the RB noise in WDM access, using the wavelength-shift modulation scheme at each ONU [14], dual wavelength bands for data division [15]–[17] and various fiber access architecture [18], [19] have been studied and discussed. In some cases, once two specific ONUs require confidential or personal signal connection and does not go through the OLT, a specific fiber deployment and additional transceiver (TRx) module are demanded to link the two ONUs [17], [18]. However, if the private connection is changed to two certain ONUs, the fiber link also needs to re-laying and increase the cost.

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In this demonstration, we investigate and present a symmetry and bidirectional WDM-PON architecture together with confidential connection between two specific ONUs. To achieve the private signal connection between two ONUs, we design a ring-based scheme to link each ONU and construct an optical module, which consists of an optical transceiver (TRx), an optical circulator (OC) and a corresponding fiber Bragg grating (FBG), in each ONU for demonstration. Here, we only need to adjust the connected wavelength (λ_{ONU}) and FBG in the ONU, and then we can produce the confidential link of any two ONUs without fiber re-deployment. Moreover, the presented WDM-PON system also can prevent the RB-induced noise for bidirectional data link.

In the demonstration, we choose four wavelengths of λ_1 to λ_4 and λ_2 to λ_5 for symmetry 28 Gbps/λ on-off keying (OOK) downstream and upstream transmissions in the proposed WDM-PON, respectively. All the observed power budgets of downstream and upstream signals are greater than 40 dB after 25 km fiber transmission under the forward error correction (FEC) target for bidirectional connections. Here, we also use other four wavelengths (λ_{ONU1} to λ_{ONU4}) to represent four pairs of ONUs for 10 Gbps OOK data demonstration. And the minimum power sensitivity of four wavelengths of >-29 dBm can be achieved through 10 km fiber connection.

II. EXPERIMENT AND RESULTS

Fig. 1(a) is the schematic of conventional WDM-PON system via the point to point (PtP) connection to support N ONUs for information access. Here, there are multiple WDM lasers regarding as downstream signals (λ_1 to λ_N) could be integrated by a 1 × N WDM multiplexer (MUX) for data transmission in the OLT. Then, the downstream WDM signals would be divided by a 1 × N WDM demultiplexer (DEMUX) at the remote node (RN) to connect to each ONU (ONU_1 to ONU_N) for detecting signal. Next, the upstream wavelength of each ONU would also transmit through the same fiber path for upstream connection, as schemed in Fig. 1(a).

When a confidential or private connection between two certain ONUs is required and not transmitted via the OLT, an individual fiber link is needed to connect two ONUs commonly. For example, if the ONU_1 and ONU_3 need a private data connection, using a specific fiber is a simple way for data link, as illustrated in Fig. 1(b). Moreover, additional optical transceiver (TRx) is also needed for data connection in the two ONUs. Then the two ONUs need to re-route the fiber for connection. Moreover, if it becomes ONU_1 and ONU_5 that want to connect later, a new fiber connection also requires to be re-deployed at this time. This will cause increased costs and unnecessary complexity.

To solve and simplify the confidential connection between two specific ONUs, a new WDM-PON system is presented, as schemed in Fig. 2. To reach symmetry 28 Gbps/λ WDM access in such PON system, the corresponding WDM TRx (λ_1 to λ_N) are needed in the OLT for delivering downstream traffics. All the downstream WDM signals are connected to the 2 × N WDM multiplexer and transmit through the

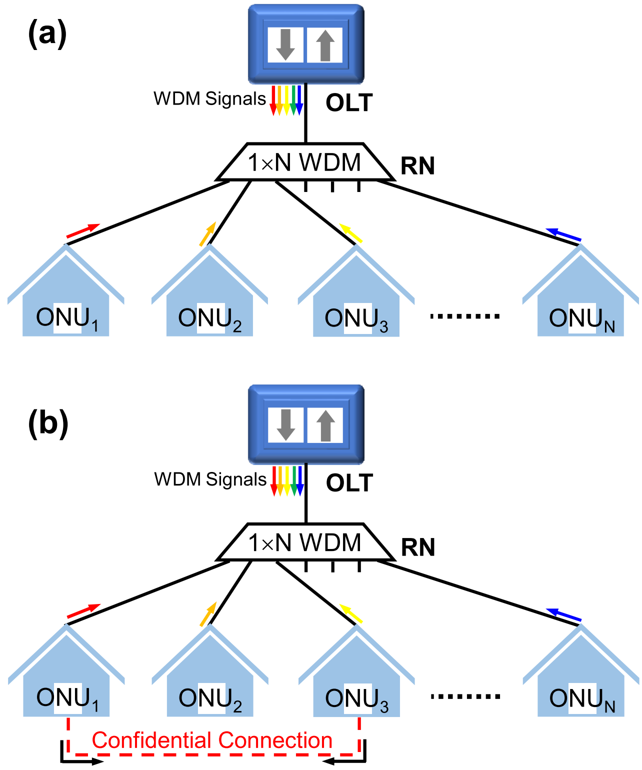

FIGURE 1. (a) Schematic of traditional WDM access network system. (b) Network architecture of confidential connection between two certain ONUs.

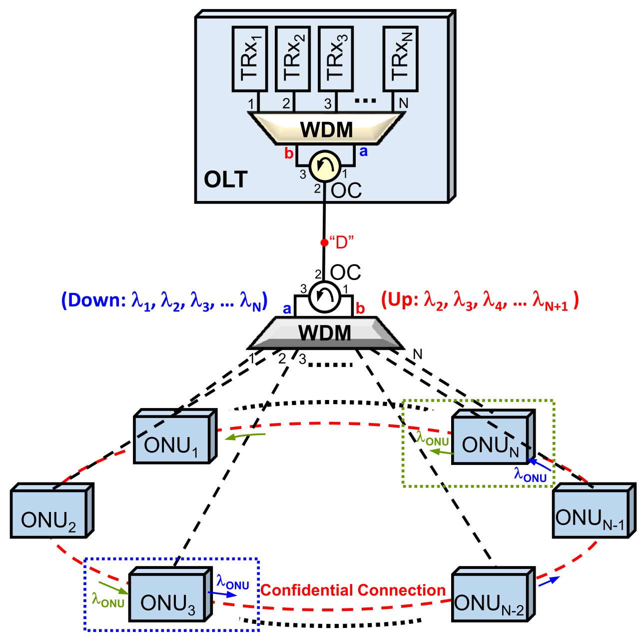

FIGURE 2. Proposed architecture of 28 Gbps/λ WDM-PON system with confidential connection between each ONUs.

"a" output port. Then, the downstream wavelengths will be through an optical circulator (OC), a length of feeder fiber, an OC, a WDM DEMUX and a distributed fiber, and then into each corresponding ONU. As we know, the same wavelengths of downstream and upstream can lead to RB-induced noise at the PD of OLT and ONU for affecting the detected modulation signal [14]. To avoid the RB issue, the previous work has been proposed by using dual-band wavelength commonly [15]. Besides, the RB effect in PON has also been analyzed and discussed in [15]. In the proposed network architecture, to avoid the Rayleigh backscattering (RB) induced interference noise, we can use the WDM wavelengths of λ_2 to λ_{N+1} at each ONU serving as upstream signal, as seen in Fig. 2. To achieve the downstream traffics of λ_1 to λ_N and upstream traffics of λ_2 to λ_{N+1} for signal transmissions, we apply the $2 \times N$ WDM MUX and DEMUX in the OLT and remote node (RN), respectively, based on its periodic output characteristics. Here, the "a" and "b" ports of WDM MUX and DEMUX only allow the wavelengths of λ_1 to λ_N and λ_2 to λ_{N+1} for passing, respectively. This means that the connected port "1" permits the λ_1 and λ_2 to enter or output at the same time. By analogy, the connected port "2" output ports permit λ_2 and λ_3 to enter or output. Thus, the RB-induced noise can be avoided, while the two different wavelengths of downstream and upstream are exploited in such PON. Then, to connect and produce the confidential signal between specific two ONUs, each ONU can be linked via the ring-based scheme, as displayed in Fig. 2. Here, we can connect any two of the ONUs by the proposed ring architecture. We assume that only ONU_3 and ONU_N, which are a private data group, have confidential signal transmission. Therefore, the connected wavelength (λ_{ONU}) from ONU_3 and ONU_N will pass other ONUs for confidential connection, as illustrated in Fig. 2.

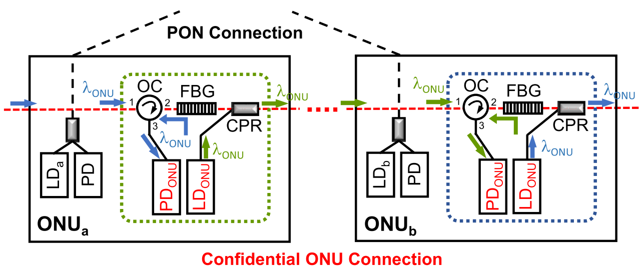

FIGURE 3. Designed new optical module in each ONU for confidential information link between ONU_a and ONU_b. LD: laser diode; PD: photodiode; OC: optical circulator; FBG: fiber Bragg grating; CPR: 1×2 and 50:50 optical coupler.

The detailed design is illustrated in Fig. 3. The additional optical module of ONU is applied for private data link via the fiber ring system, as seen in Fig. 3. The additional components are an OC, a fiber Bragg grating (FBG) with corresponding reflected wavelength, a 1×2 and 50:50 optical coupler (CPR), and an optical TRx including laser diode (LD_{ONU}) source and photodiode (PD_{ONU}) in the ONU, respectively. Here, suppose ONU_a and ONU_b want to communicate with each other. The ONU of WDM-PON system reserves the original TRx (LD_x and PD, x = a, b, c, ... etc.), as observed in Fig. 3. In the proposed module of ONU_a and ONU_b, the connected wavelength (λ_{ONU}) are the same for personal information link. Therefore, the λ_{ONU} of ONU_a could be transmitted to the right direction via the CPR. When the λ_{ONU} signal enters ONU_b and will be reflected via the corresponding FBG and OC into PD after a length of fiber link. Similarly, the ONU_b's λ_{ONU} signal is also transmitted in the same way as the ONU_a. Ring-based connection will not cause signal interference between ONU_a and ONU_b as the same connected signals are utilized, as exhibited Fig. 3. To change the signal connection between different ONUs, we only need to add or remove the additional optical modules in ONU based on proposed network architecture. As a result, any two ONUs to be connected can utilize the same connected wavelengths (λ_{ONU}), which are selected randomly, for unidirectional transmission, as long as the matching FBG is adjusted. The proposed confidential link method can avoid unnecessary fiber re-deployment and reduce cost, if the connected wavelength and FBG in the ONU are changed. Compared with the previous work [20], [21], the proposed private link between ONUs is not only simple and flexible but also be linked according to different needs.

Furthermore, the proposed confidential connection between ONUs can reach more than 2 or more. We can add the same additional modules to ONUs in need for confidential link. While there are more than two ONUs, the signal connection between the ONUs can be achieved by time-division-multiplexed (TDM) access.

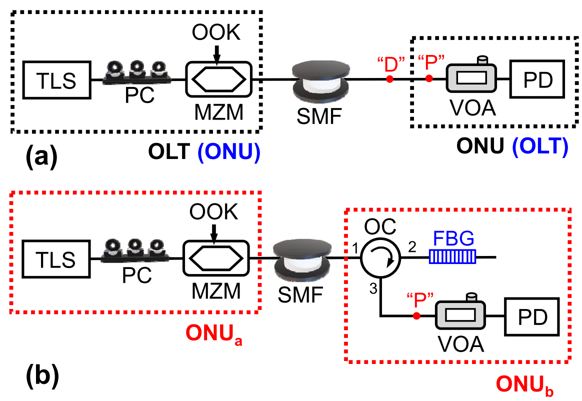

FIGURE 4. Experimental setup of signal transmission in the (a) original WDM-PON network and (b) personal connection between two ONUs, respectively.

Next, the experimental setup of symmetry and bidirectional signal transmissions will be executed in original WDM-PON for proof of concept, as schemed in Fig. 4(a). A tunable laser source (TLS) is exploited to represent the downstream and upstream WDM signals and connected to the polarization controller (PC) and 40 GHz Mach-Zehnder modulator (MZM). Here, we apply 28 Gbps on-off keying (OOK) modulation signal with pattern length of $2^{15}-1$, which is produced by a bit error rate (BER) tester, on MZM to generate signal data. A PC is applied to adjust the suitable polarization state and achieve a greatest output power. After passing through a length of single-mode fiber (SMF), the WDM signal can be detected via a 40 GHz PIN PD. A variable optical attenuator (VOA) is employed to adjust the launched power for measuring the BER performance of each WDM signal. The fiber length of SMF is 25 km. Moreover, to compensate the fiber dispersion effect, a dispersion compensation module (DCM) is exploited at the "D" point of Fig. 4(a), when 28 Gbps OOK modulation is used through 25 km fiber link. Then, to enhance the detected signal performance and compensate the total insertion loss, an erbium-doped fiber amplifier (EDFA) and an optical attenuator is employed at the "P" point regarding as an optical pre-amplifier, as seen in Fig. 4(a).

To demonstrate the network performance of confidential connection between two certain ONUs, an experimental setup is also illustrated in Fig. 4(b). Here, we utilize a TLS to serve the connected wavelength (λ_{ONU}) for personal data link. The output wavelength of TLS also connects to the PC and 10 GHz MZM. In the investigation, a 10 Gbps OOK modulation is applied on MZM for the unidirectional confidential connection of ONU_a to ONU_b (ONU_b to ONU_a) and performance verification. Through 10 km SMF link, the wavelength λ_{ONU} could be through the OC and corresponding FBG and then reflected launching into PD for signal demodulation. Similarly, a pre-amplifier is placed at "P" point and a VOA is used to verify the launching power for realizing the BER performance, as seen in Fig. 4(b).

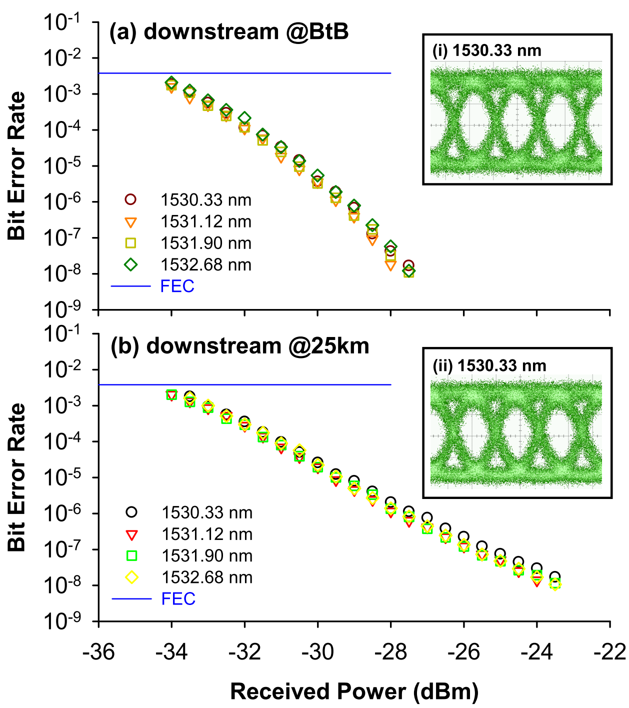

FIGURE 5. Measured 28 Gbps OOK BER performances of four downstream wavelengths (λ_1 to λ_4) (a) at the BtB and (b) 25 km SMF transmission, respectively. Insets are the obtained corresponding eye diagrams of 1530.33 nm.

In the presented WDM-PON transmission, we select four wavelengths of 1530.33, 1531.12, 1531.90 and 1532.68 nm (λ_1 to λ_4) serving as the downstream signals for the BER observation, respectively. Here, the output power of Fig. 4(a) from MZM is around 7 dBm. Then, the 28 Gbps OOK BER measurements are observed at the back-to-back (BtB) state and 25 km SMF transmission, respectively, as displayed in Figs. 5 (a) and 5(b). To be below the forward error correction (FEC) threshold (BER of $\leq 3.8 \times 10^{-3}$), the power sensitivities of -34 to -34 dBm and -34 to -33.5 dBm are observed at the BtB and 25 km SMF link, respectively, as shown in Figs. 5(a) and 5(b). The power penalty of 0 to 0.5 dB is obtained under the FEC level. However, suppose we want to achieve the BER of 10^{-8}, as seen in Fig. 5, the corresponding power sensitivities are from -28 to -27.5 dBm and -24 to -23.5 dBm at the BtB and 25 km fiber link, respectively. As seen in Fig. 5, the observed power penalties of four signals are both ~4 dB through 25 km SMF connection due to the fiber dispersion. In addition, the insets (i) and (ii) of Fig. 5 are the corresponding eye diagrams at the wavelength of 1530.33 nm under the BER of 10^{-8}. The observed two eyes are clear and open. Therefore, the achievable power budgets of the four selected wavelengths are 40.5, 41, 41 and 40.5 dB through 25 km SMF transmission at the FEC target, respectively.

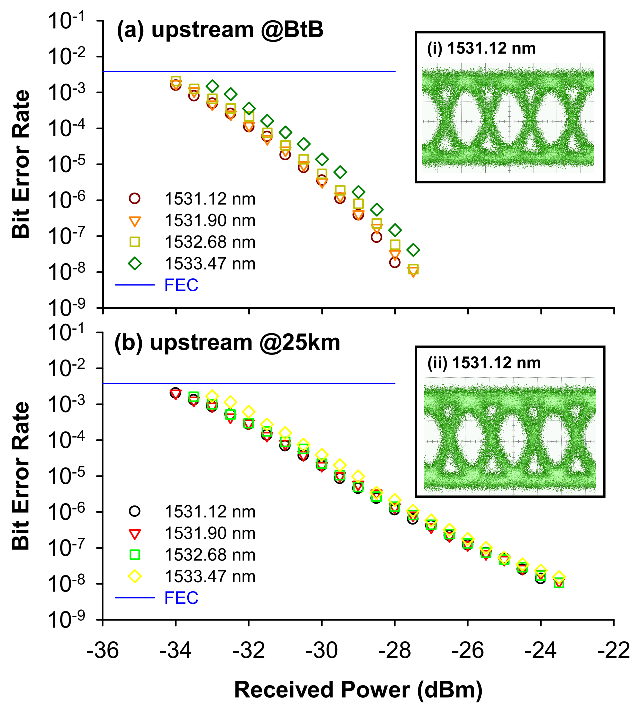

FIGURE 6. Measured 28 Gbps OOK BER performances of four upstream wavelengths (λ_2 to λ_5) (a) at the BtB and (b) 25 km SMF transmission, respectively. Insets are the obtained corresponding eye diagrams of 1531.12 nm.

In the next measurement, we use four wavelengths of 531.12, 1531.90,1532.68 and 1533.47 nm (λ_2 to λ_5) acting as the upstream signals, respectively. To reach symmetry signal transmission, 28 Gbps OOK format is also applied on 40 GHz MZM. The output power from MZM is around 7 dBm. Figs. 6(a) and 6(b) show the obtained BER measurements at the BtB and 25 km SMF link, respectively. The detected four power sensitivities are -34, -34, -34 and -33.5 dBm and -34, -34, -33.5 and -33 dBm within the FEC target at the BtB status and 25 km fiber transmission, respectively. Hence, the obtainable power budgets are 41, 41, 40.5 and 40 dB after 25 km SMF communication, respectively. Moreover, the power sensitivities are observed between −28 and −27.5 dBm and −24 and −23.5 dBm at the BER of 10^{-8} at the BtB and 25 km fiber link, respectively. The corresponding penalties are measured around 4 dB after 25 km SMF uplink, as shown in Fig. 6. The insets (i) and (ii) of Fig. 6 are the corresponding eye illustrations at 1531.12 nm at the BtB and 25 km SMF link under the BER of 10^{-8}. In the measurement, to achieve the better BER performance, an optical pre-amplifier can be applied in front of PD to replace the RF amplifier for enhancing the power sensitivity [14]. Therefore, the measured BERs of 28 Gbps OOK in Fig. 5 and Fig. 6 can be below the FEC threshold (BER $\leq 3.8 \times 10^{-3}$) at the lower detected power range of −34 to −33 dBm.

In the experiment, we select four wavelengths with 0.8 nm mode-spacing in the proposed PON access architecture for demonstration. The 36 WDM downstream wavelengths can be from 1530.33 to 1558.24 nm (λ_1 to λ_{36}) over C-band range. Hence, the total capacity of 28 × 36 Gbps can be achieved in the presented network.

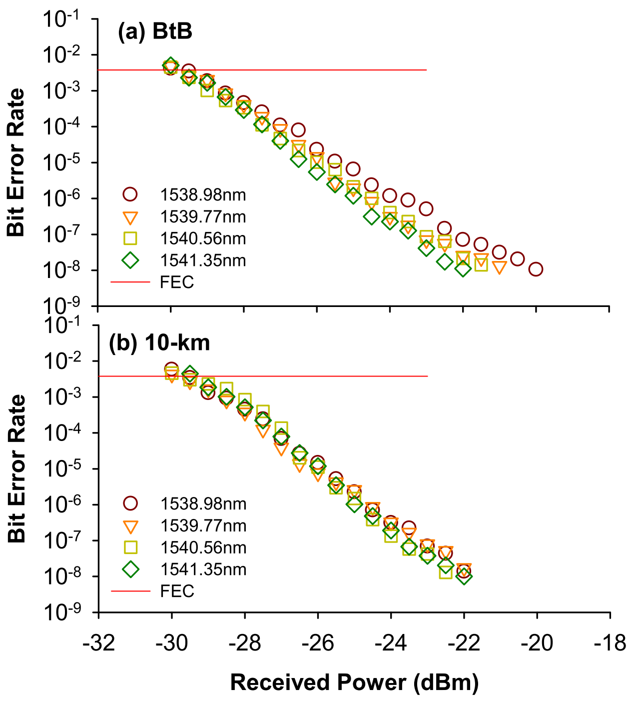

FIGURE 7. Measured 10 Gbps OOK BER performances of four connected wavelengths of 1538.98, 1539.77, 1540.56 and 1541.35 nm (a) at the BtB and (b) 10 km SMF transmission, respectively.

Finally, we perform the experiment of private connection between two ONUs according to the setup of Fig. 4(b). Here, we utilize four wavelengths of 1538.98, 1539.77, 1540.56 and 1541.35 nm (λ_{ONU1} to λ_{ONU4}) to provide four various pairs of ONUs for confidential data connection. Besides, we apply four FBGs with corresponding Bragg wavelengths for reflecting wavelength in the measurement. The reflectivity and 3 dB bandwidth of four FBGs both are around 92% and 0.4 nm respectively. A 10 Gbps OOK modulation is used on 10 GHz MZM to generate the connected wavelength λ_{ONU}. The output power from the MZM is set at 7 dBm. Figs. 7(a) and 7(b) present the obtained 10 Gbps OOK BER performances at the BtB and 10 km SMF connection, respectively. To reach the FEC boundary, the four power sensitivities are both −29.5 dBm at the BtB state. And the observed four sensitivities are −29.5, −29.5, −29.5 and −29 dBm through 10 km SMF connection, respectively. The maximum penalty of −2 dB is obtained through 10 km fiber link at the BER of 10^{-8}, as seen in Fig. 7, due to the −0.7 chirp parameter of 10 GHz MZM for dispersion pre-compensation. Therefore, the available power budgets are observed between 36 and 36.5 dB after 10 km signal link. Here, the 10 km SMF length is chosen for demonstration because the fiber distance between two ONUs should not be longer than the 25 km of the present PON system. Actually, a longer SMF transmission distance between ONUs at 10 Gbps OOK rate also can be achieved from 10 to 100 km without using dispersion compensation [2].

III. CONCLUSION

We investigated a symmetry 28 Gbps/λ OOK WDM-PON network together with 10 Gbps/λ OOK confidential connection between two specific ONUs. In traditional PON network, once two certain ONUs required a confidential or personal information connection and did not go through the OLT, a specific fiber link was needed to build up. However, if the two certain ONUs was changed for connection, a new fiber deployment was also demanded to reconstruct. This would increase the engineering cost and complexity. To reach the personal connection in such WDM-PON system, we designed an optical module based on ring architecture to connect each ONU and to avoid the issue of fiber reconstruction. In this investigation, we only needed to switch the connected wavelength (λ_{ONU}) and corresponding FBG in each ONU, and then two specific ONUs could be reconnected without re-laying optical fibers. In the measurement, four WDM wavelengths of λ_1 to λ_4 and λ_2 to λ_5 were selected to regard as the symmetry 28 Gbps OOK downstream and upstream traffics for testing the BER presentations, respectively. All the obtained power budgets of downstream and upstream wavelengths were larger than 40 dB through 25 km SMF transmission at the FEC object for bidirectional connections. Here, the presented WDM-PON also could prevent the RB-induced noise according to the fiber network design. Moreover, we also applied other four wavelengths (λ_{ONU1} to λ_{ONU4}) to represent four various pairs of ONUs for individual 10 Gbps OOK link. And the smallest power sensitivity of four wavelengths could be greater than −29 dBm after 10 km SMF connection. As a result, whether it is the WDM-PON transmission or the confidential connection between two ONUs, all the obtained BER performances of each WDM signal were excellent in the proposed PON network.

REFERENCES

[1] J. Yu, S. Zhu, and D. Kilper, "Evolution to mesh 5G X-haul networks," in *Proc. OFC*, 2020, paper T3E.4.

[2] C.-H. Yeh, C.-W. Chow, C.-H. Wang, Y.-F. Wu, F.-Y. Shih, and S. Chi, "Using OOK modulation for symmetric 40-Gb/s long-reach time-sharing passive optical networks," *IEEE Photon. Technol. Lett.*, vol. 22, no. 9, pp. 619–621, May 1, 2010.

[3] D. Nesset, "NG-PON2 technology and standards," *J. Lightw. Technol.*, vol. 33, no. 5, pp. 1136–1143, Mar. 1, 2015.

[4] J. S. Wey, D. Nesset, M. Valvo, K. Grobe, H. Roberts, Y. Luo, and J. Smith, "Physical layer aspects of NG-PON2 standards—Part 1: Optical link design," *J. Opt. Commun. Netw.*, vol. 8, no. 1, pp. 33–42, 2016.

[5] 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.

[6] Y.-Y. Sung, Y.-C. Liu, P. D. Pukhrambam, H.-W. Hung, and S.-L. Lee, "Symmetric 4×25-Gbit/s TWDM-PON transmission by using spectrum reshaping," in *Proc. OECC/PS*, 2016, paper WA1-2.

[7] *40-Gigabit-Capable Passive Optical Networks (NG-PON2)*, document ITU-T G.989 Series Recommendations, 2010.

[8] C.-H. Yeh, W.-H. Hsu, B.-Y. Wang, W.-Y. You, J.-R. Chen, C.-W. Chow, and S.-K. Liaw, "Fiber- and FSO-protected connections for long-reach TWDM access architecture with fault protection," *IEEE Access*, vol. 8, pp. 189982–189988, 2020.

[9] X. Xue, W. Ji, K. Huang, X. Li, and S. Zhang, "Tunable multiwavelength optical comb enabled WDM-OFDM-PON with source-free ONUs," *IEEE Photon. J.*, vol. 10, no. 3, Jun. 2018, Art. no. 7202008.

[10] Y. Lee, D. Lee, H. Yoo, Y. Kim, and Y. Kim, "Fast management of ONUs based on broadcast control channel for a 10-gigabit-capable passive optical network (XG-PON) system," *J. Commun. Netw.*, vol. 15, no. 5, pp. 538–542, Oct. 2013.

[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. 15, 2013.

[12] T. Dong, Y. Bao, Y. Ji, A. P. T. Lau, Z. Li, and C. Lu, "Bidirectional hybrid OFDM-WDM-PON system for 40-Gb/s downlink and 10-Gb/s uplink transmission using RSOA remodulation," *IEEE Photon. Technol. Lett.*, vol. 24, no. 22, pp. 2024–2026, Nov. 15, 2012.

[13] Q. Feng, W. Li, Y. Wang, Q. Zheng, Z. He, Q. Yang, and S. Yu, "Colorless long-reach duplex WDM-PON with Rayleigh backscattering noise mitigation using orthogonal codes," *J. Lightw. Technol.*, vol. 34, no. 3, pp. 845–853, Feb. 1, 2016.

[14] C. H. Wang, C. W. Chow, C. H. Yeh, C. L. Wu, S. Chi, and C. Lin, "Rayleigh noise mitigation using single-sideband modulation generated by a dual-parallel MZM for carrier distributed PON," *IEEE Photon. Technol. Lett.*, vol. 22, no. 11, pp. 820–822, Jun. 1, 2010.

[15] S.-C. Lin, S.-L. Lee, H.-H. Lin, G. Keiser, and R. J. Ram, "Cross-seeding schemes for WDM-based next-generation optical access networks," *J. Lightw. Technol.*, vol. 29, no. 24, pp. 3727–3736, Dec. 15, 2011.

[16] P. Mandal, K. Mallick, B. Dutta, B. Kuiri, S. Santra, N. Sarkar, and A. S. Patra, "Intensification of noise tolerance against Rayleigh backscattering for bidirectional 10 gbps WDM-FSO network by employing dual band of OFDM signal," *Results Opt.*, vol. 4, Aug. 2021, Art. no. 100108.

[17] P. Mandal, K. Mallick, S. Santra, B. Kuiri, B. Dutta, and A. S. Patra, "A bidirectional hybrid WDM-OFDM network for multiservice communication employing self-injection locked Qdash laser source based on elimination of Rayleigh backscattering noise technique," *Opt. Quantum Electron.*, vol. 53, no. 5, p. 263, May 2021.

[18] C.-H. Yeh, J.-R. Chen, W.-Y. You, and C.-W. Chow, "Hybrid WDM FSO fiber access network with Rayleigh backscattering noise mitigation," *IEEE Access*, vol. 8, pp. 96449–96454, 2020.

[19] P. Mandal, K. Mallick, B. Dutta, B. Kuiri, S. Santra, and A. S. Patra, "Mitigation of Rayleigh backscattering in RoF-WDM-PON employing self coherent detection and bi-directional cross wavelength technique," *Opt. Quantum Electron.*, vol. 53, no. 2, p. 77, 2021.

[20] A. K. Garg and V. Janyani, "WDM-PON network for simultaneous upstream transmission with ONU interconnection capability," in *Proc. 13th Int. Conf. Fiber Opt. Photon.*, 2016, paper Tu4A.13.

[21] C. Zhang, J. Huang, C. Chen, and K. Qiu, "All-optical virtual private network and ONUs communication in optical OFDM-based PON system," *Opt. Exp.*, vol. 19, no. 24, pp. 24816–24821, 2011.

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