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A Survivable Optical Network for WDM Access Against Fiber Breakpoint

CHIEN-HUNG YEH[1], (Member, IEEE), LI-HUNG LIU[1], WEN-PIAO LIN[2,3], (Member, IEEE), HAN-SHIN KO[1], YI-TING LAI[1], AND CHI-WAI CHOW[4], (Senior Member, IEEE)

[1]Department of Photonics, Feng Chia University, Taichung 407802, Taiwan
[2]Department of Electrical Engineering, Chang Gung University, Taoyuan 333323, Taiwan
[3]Department of Holistic Medicine, Linkou Chang Gung Memorial Hospital, Taoyuan 333323, Taiwan
[4]Department of Photonics, National Yang Ming Chiao Tung University, Hsinchu 300093, Taiwan

Corresponding authors: Chien-Hung Yeh (yeh1974@gmail.com) and Wen-Piao Lin (wplin@mail.cgu.edu.tw)

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ABSTRACT To avoid the fault occurrence of fiber link, a simple self-restored wavelength-division-multiplexing passive optical network (WDM-PON) is presented. In the demonstration, the additional optical components are included in the optical line terminal (OLT), remote node (RN) and optical network unit (ONU) to produce the alternative fiber path for fault protection. Here, 10 Gb/s on-off keying (OOK) downstream and upstream wavelengths are exploited to measure the bit error rate (BER) performances at the back-to-back (B2B) and through 50 to 51 km fiber transmission, respectively. Moreover, all the modulation signals can achieve enough power budget under the forward error correction (FEC) level to meet with the total insertion loss caused by the various fiber links and additional devices.

INDEX TERMS Wavelength-division-multiplexing (WDM), fault protection, passive optical network (PON), self-protected.

I. INTRODUCTION

Recently, due to the rapid growth of quantum computing, artificial intelligence (AI), cloud service, big data, 4K/8K video, data center and 3D holographic display for end user, wavelength-division-multiplexing passive optical network (WDM-PON) is considered as the final solution to meet with the broadband demand [1]–[3]. This is because the WDM-PONs have the characteristics of point-to-point (P2P) transmission, protocol transparency, wide bandwidth, high capacity, upgradeability and network security to subscribers [4]. Furthermore, the WDM networks can provide 1.25 to 60 Gb/s data traffics for bidirectional signal access [2], [5]–[7]. The PON systems have presented by three topologies of ring, three and bus types actually for fiber deployment [7]–[9]. Hence, the network reliability and survivability are more important in such PON systems to avoid the fiber failure occurrence [10], [11]. Several architectures have exhibited to demonstrate the protectable and restorable operation for WDM-PON connection [12]–[16].

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In this paper, a simple network architecture of self-protected WDM-PON against fiber failure is proposed and demonstrated. In fact, fiber breakpoints may occur on the feeder or distribution fibers. To reach the protection mechanism of such PON, additional optical components are added in the optical line terminal (OLT), remote node (RN) and optical network unit (ONU). Once a fiber fault is happened, the presented WDM-PON system can be restored immediately via the routing fiber path for reconnecting data traffic. In the demonstration, eight WDM wavelengths are applied serving as four downstream (λ_{1D} to λ_{4D}) and four upstream signals (λ_{1U} to λ_{4U}) for testing the 10 Gb/s on-off keying (OOK) bit error rate (BER) performances, respectively. Here, the received power sensitivities of eight wavelengths are between −27.5 and −27 dBm through 50 to 51 km fiber links under the forward error correction (FEC) level. Hence, all the obtained power budget of the WDM signals is in a range of 34.5 to 35 dB. The whole budgets are enough to compensate the total insertion loss of additional devices and various fiber transmissions of the proposed PON network.

To achieve the fault protection of WDM-PON system, the previous works needed a complex architecture design to meet

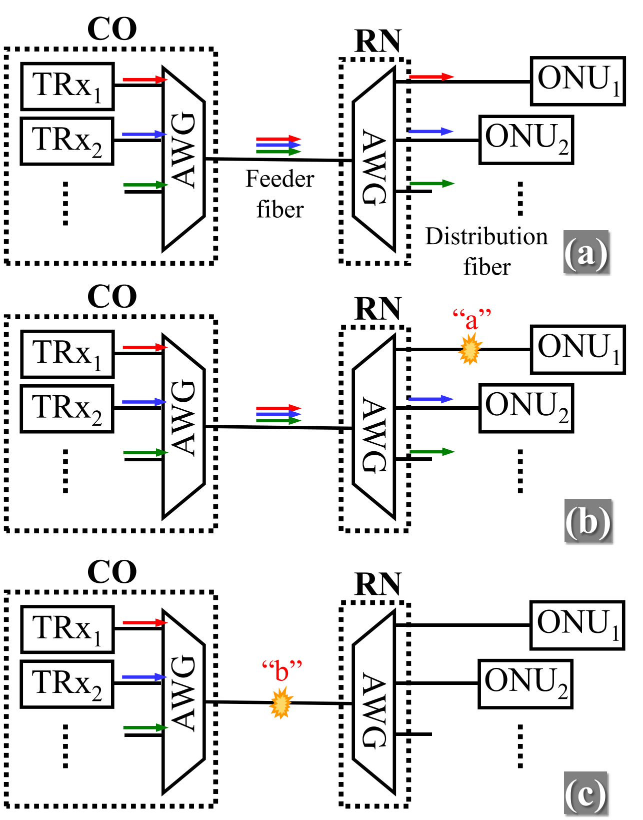

FIGURE 1. (a) Conventional WDM-PON system in the normal status. When a fiber fault occurs on the (a) distribution and (c) feeder fibers, respectively.

with the periodic output characteristics of arrayed waveguide grating (AWG) device [10]–[12], [15], [16]. They also required more optical components to achieve the breakpoint protection mechanism. In the demonstration, our proposed WDM-PON network is not only simple, but the operation mechanism is beneficial to realize. In addition, we don't add additional monitor device to control and route the connection path through 50 to 51 km fiber transmission.

II. DESIGNED WDM-PON NETWORK

Fig. 1(a) presents the traditional WDM-PON system. Here, there are N WDM optical transceiver (TRx) connected to the corresponding port of $1 \times N$ arrayed waveguide grating (AWG) multiplexer (MUX) in the optical line termination (OLT) for downstream transmissions through a length of feeder fiber. Then, all the downstream wavelengths can be separated by the $1 \times N$ AWG demultiplexer (DEMUX) in the remote node (RN) to deliver the WDM signal into the corresponding optical network unit (ONU) through the distribution fiber for decoding, as seen in Fig. 1(a). And the upstream wavelength of each ONU also transmits through the same fiber path into the OLT for bidirectional data connection. However, once a fiber fault occurs at the point of "a", the data connection will be interrupted between the RN and ONU_1, as schemed in Fig. 1(b). This will only affect the network connection of ONU_1's user. Moreover, if a fault is happened at the "b" point between the OLT and RN, all the WDM signals will not be connected for bidirectional traffic connections, as shown in Fig. 1(c). This will interrupt the data transmission of the entire PON system. Therefore, in the WDM-PON system, there will be two possible locations for fiber breakage, one is on the feeder fiber and the other is on the distribution fiber.

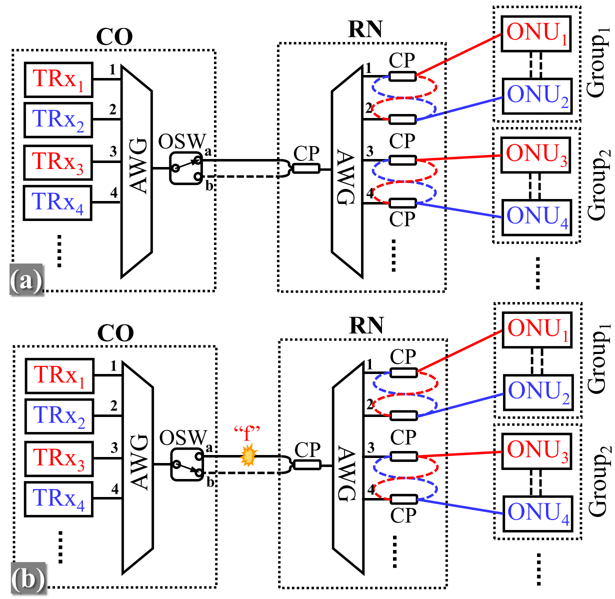

FIGURE 2. (a) Designed WDM-PON network with fault protection in normal state. (b) When a fault is happened at the "f" point in the proposed self-restored WDM-PON network.

To avoid the fiber fault occurs on the feeder and distribution fibers, a self-protected WDM-PON system is proposed to solve the fiber fault problem. Hence, Fig. 2(a) displays the designed WDM-PON network with fault protection. Here, the OLT is constructed by the WDM TRx, $1 \times N$ AWG, and a 1×2 optical switch (OSW). The connected ports "a" and "b" of OSW are applied to link the upper and lower feeder fibers serving as the working and protecting fibers for signal transmission, respectively. In normal state, the OSW is connected to the port "a". Then, all the WDM downstream wavelengths are through the working fiber to deliver the data signals into the RN. The RN is consisted of a $1 \times N$ AWG, a 1×2 optical coupler (CP) and N 2×2 CPs, as plotted in Fig. 2(a). Each output port of AWG is connected to the 2×2 CP. And two adjacent 2×2 CPs are also linked to connect the corresponding ONU as a traffic set, respectively. Thus, we can turn the ONU_1 and ONU_2, ONU_3 and ONU_4, ..., and ONU_{N-1} and ONU_N into the connected groups to result in the dual routing path for fault protection, respectively, as presented in Fig. 2(a).

As mentioned above, the fiber fault maybe happens on the feeder and distribution fibers. First, we suppose a fiber break occurs at the "f" point on upper feeder fiber, as shown

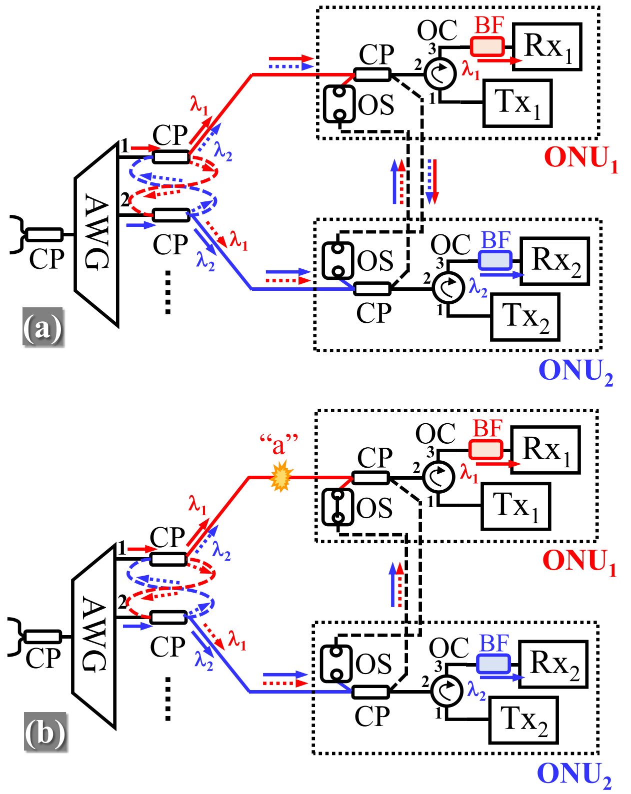

FIGURE 3. (a)The data link between ONU_1 and ONU_2 without fault occurrence in the proposed PON network. (b) Assume a fault occures at the "a" point between AWG and ONU_1.

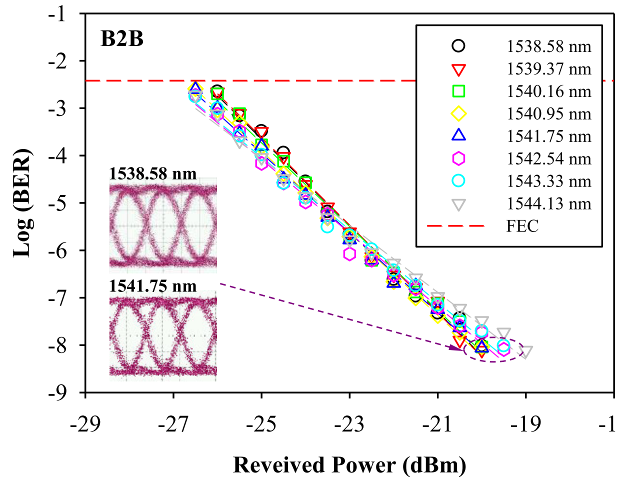

FIGURE 4. Measured 10 G/s OOK BERs of eight WDM signals at the B2B state.

in Fig. 2(b). At this moment, all the optical receivers (Rx) of the OLT and every ONU will not detect any upstream wavelength. This means that all the data link of PON is stop due to the fiber break. So, we can determine that the breakpoint is arising on the feeder fiber. Then, the media access control (MAC) of OLT can switch the connected port of OSW to "b" point through the protecting fiber for reconnecting the data traffic, as displayed in Fig. 2(b). As a result, the simple network design can avoid the fault occurrence on the feeder fiber.

To protect and avoid the fiber fault on the distribution fiber between the RN and ONU, the new RN and ONU modules are proposed in the self-healing PON system. As mentioned before, two adjacent ONUs can be connected as a group by dual-fiber paths for producing the fault protection mechanism, as illustrated in Fig. 3(a). Each ONU is consisted of a 1 × 2 CP, a 2 × 2 CP, a 1 × 1 OSW, a corresponding bandpass filter (BF), an optical circulator (OC) and a TRx, respectively. As displayed in Fig. 3(a), in normal state, the downstream wavelengths of λ_1 and λ_2 output from the ports "1" and "2" respectively, and then enter the ONU_1 and ONU_2 simultaneously through the 2 × 2 CPs. Since the OSW is closed, the downstream signals from port 1 and port 2 of AWG cannot enter the ONU_2 and ONU_1 without fault appearance between the RN and ONU. Although the downstream λ_1 and λ_2 will enter ONU_1 and ONU_2 at the same time, another unrelated wavelength will not enter the Rx due to the corresponding BF, as seen in Fig. 3(a).

If a fiber breakpoint is happened at the point "a", the downstream and upstream signals will be interrupted between the OLT and ONU_1, as plotted in Fig. 3(b). When the Rx of ONU_1 cannot detect traffic signal λ_1, the MAC of ONU_1 will open the 1 × 1 OSW to reconnect the downstream signal and transmits the upstream traffic through the protecting fiber via the ONU_2, as illustrated in Fig. 3(b). In the demonstration, the additional optical components are not required in each ONU to monitor the downstream signal for switching the OSW. Similarly, if the fault is occurred between the RN and ONU_2, the bidirectional downstream and upstream traffics also can be routed by the protecting fiber for reconnecting data signal according to the proposed PON system. As previously described, we only need to switch the OSW of the OLT and each ONU to route the fiber path to prevent breakpoints. As a result, the presented self-protected WDM-PON architecture not only has a simple system design, but also can avoid the fault happening on the feeder and distribution fibers simultaneously.

III. EXPERIMENT AND RESULTS

An experimental setup is according to the proposed PON network of Figs. 2 and 3 for measuring the bit error rate (BER). Here, a laser diode (LD) with various WDM wavelength is connected to the polarization controller (PC) and 10 GHz Mach-Zehnder modulator (MZM) to generate 10 Gb/s on-off keying (OOK) format signal with $2^{15}-1$ pattern length for acting as the WDM downstream and upstream Tx. Two wavelength sets of 1538.58 (λ_{1D}), 1539.37 (λ_{2D}), 1540.16 (λ_{3D}), and 1540.95 (λ_{4D}); and 1541.75 nm (λ_{1U}), 1542.54 (λ_{2U}), 1543.33 (λ_{3U}), and 1544.13 (λ_{4U}) are selected in the measurement regarding as the downstream and upstream WDM signals, respectively. According to the periodic output characteristics of

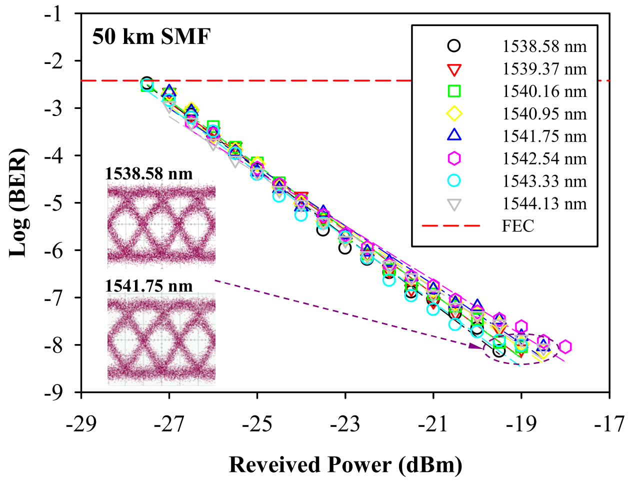

FIGURE 5. Measured 10 Gb/s BER performances of eight wavelengths after 50 km fiber transmissions, respectively.

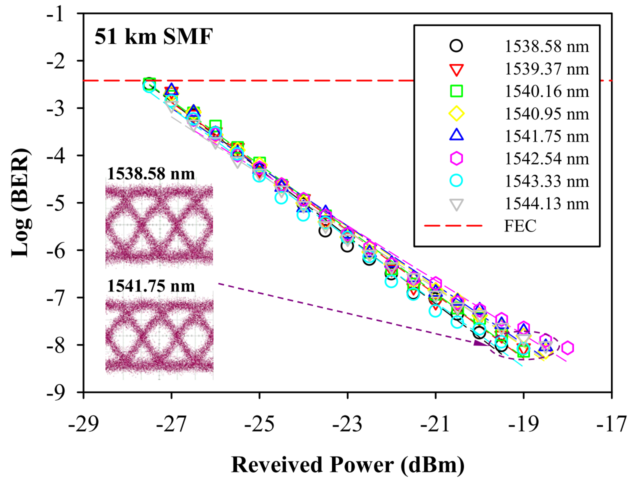

FIGURE 6. Measured 10 Gb/s BER performances of eight wavelengths after 51 km fiber transmissions, respectively.

1 × 4 AWG, a pair wavelength of 1538.58 (λ_{1D}) and 1541.75 nm (λ_{1U}) can be utilized through the same output port "1" of AWG for downstream and upstream connections between the OLT and ONU_1, respectively. Hence, the remaining three sets of selected wavelengths can be used for bidirectional signal transmissions for the ONU_2 to ONU_4, respectively.

First, Fig. 5 show the measured 10 Gb/s OOK BER performances of four downstream (λ_{1D} to λ_{4D}) and four upstream wavelengths (λ_{1U} to λ_{4U}) at the back to back (B2B) status for verification of signal performance, respectively. The observed power sensitivities of the eight selected wavelengths are −26, −26, −26, −26.5, −26.5, −26.5, −26.5, and −26.5 dBm, respectively, under the forward error correction (FEC) level at the BER of $\leq 3.8 \times 10^{-3}$. Moreover, two insets of Fig. 4 are the measured eye diagrams of 1538.58 (λ_{1D}) and 1541.75 nm (λ_{1U}) at the detected power −20 dBm, respectively. And the observed eyes are open and clean.

Then, after 50 km fiber link, the corresponding 10 Gb/s BERs of selected eight wavelengths are measured as shown in Fig. 5. To satisfy the FEC target, the corresponding power sensitivities of eight wavelengths are lower than −27.5, −27, −27.5, −27, −27, −27, −27.5, and −27 dBm, respectively. The inserts of Fig. 5 are the observed eye diagrams of λ_{1D} and λ_{1U} at the received power of −19.5 and −18.5 dBm. The observed eyes are clean and open. In the measurement, the output power of each downstream wavelength is about 7.5 dBm before leaving the OLT. And the output power of each upstream Tx is 7.5 dBm. Thus, the power budgets of downstream λ_{1D} to λ_{4D} are between 34.5 and 35 dB. Moreover, the downstream traffic will transmit through a 50 km fiber (50 × 0.2 = 10 dB), a 1 × 4 AWG (6 dB), three CPs (3 × 3 = 9 dB), an OC (0.5 dB) and a BF (1.5 dB) when no fault is occurred. And the total insertion loss of downstream transmission path is 27 dB. In this demonstration, if a breakpoint is occurred on the feeder fiber between the OLT and RN at the "f" point, the transmission loss of protecting fiber path is the same as the working fiber, as seen in Fig. 2(b). Besides, the switching time of OSW is 7 ms in the demonstration. According to the power budgets of measured results, each downstream wavelength can meet with the insertion loss of the proposed PON network. Here, the upstream traffics of λ_{1U} to λ_{4U} also transmit through the same fiber link and result in the power budget of 34.5 to 35 dB. As mentioned above, the insertion power loss will not influence the upstream performance, while an optical amplifier is applied in the OLT.

If a fault is happened at the "a" point, as illustrated in Fig. 3(b), the data connection between the OLT and ONU_1 will be relinked through the working fiber via the ONU_2. In the next measurement, the λ_{1D} signal will pass through four CPs (4 × 3 = 12 dB), a 1 × 4 AWG (6 dB), an OC (0.5 dB) and a BF (1.5 dB) and a fiber length of 51 km (51 × 0.2 = 10.2 dB). Use of 51 km fiber transmission is due to the addition of a protecting fiber connection. So, the total insertion loss will become 30.2 dB, while the fault protection is exploited. The corresponding BER performances of 10 Gb/s OOK downstream and upstream channels after 51 km fiber transmission are exhibited in Fig. 6. Here, the measured power sensitivities of the eight wavelengths are around −27.5, −27, −27.5, −27, −27, −27.5, −27.5, and −27 dBm below the FEC threshold, respectively. Thus, the obtainable power budgets of downstream and upstream channels are both between 34.5 and 35 dB. Besides, the insets of Fig. 6 are the measured eye diagrams of λ_{1D} and λ_{1U} at the received power of −19.5 and −18.5 dBm. And the obtained eyes are open and clean after 51 km fiber link without dispersion compensation. As mentioned above, the insertion power losses induced by the additional optical devices in the OLT, RN, ONUs and fiber length are less than that of the obtained power budgets of downstream and upstream transmissions in the presented self-protected WDM-PON system.

IV. CONCLUSION

A new self-restored WDM-PON architecture was designed and demonstrated. To achieve the fault protection in the presented WDM-PON architecture, the additional optical components were applied in the OLT, RN and ONU for reconnecting the data traffic via the protecting fiber path. When a breakpoint was occurred on the feeder or distribution fiber, the bidirectional signal data can be reconnected by the proposed PON network. In the measurement, eight wavelengths of λ_{1D} to λ_{4D} (1538.58 to 1540.95 nm) and λ_{1U} to λ_{4U} (1541.75 to 1544.13 nm) were used to perform the corresponding 10 Gb/s OOK BER performances at the B2B and through 50 to 51 km fiber link, respectively. Here, the power budgets of downstream and upstream links were obtained between 34.5 and 35 dB under the FEC target. In addition, the total insertion loss caused by different fiber lengths and optical components was below the obtained power budget of the downstream and upstream link. As a result, the designed PON not only supported 51 km long-haul fiber link, but also provided self-restored function against fiber breakpoint.

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CHIEN-HUNG YEH (Member, IEEE) received the Ph.D. degree from the Institute of Electro-Optical Engineering, National Chiao Tung University, Taiwan, in 2004. In 2004, he joined the Information and Communications Research Laboratories (ICL), Industrial Technology Research Institute (ITRI), Taiwan, as a Researcher, where he was promoted to a Principal Researcher for leading the ITRI Industrial-Academic Projects, in 2008. In 2014, he joined the Faculty of the Department of Photonics, Feng Chia University, Taiwan, where he is currently a Professor. His research interests include optical fiber communications, fiber laser and amplifier, PON access, MMW communication, fiber sensor, and VLC and FSO-based Li-Fi communications.

LI-HUNG LIU received the B.S. degree from the Department of Photonics, Feng Chia University, Taiwan, in 2020, where he is currently pursuing the M.S. degree. His research interests include optical communication and erbium fiber laser.

WEN-PIAO LIN (Member, IEEE) received the Ph.D. degree from the Institute of Electro-Optical Engineering, National Chiao-Tung University, Taiwan, in 2002. From 1985 to 1987, he joined Hua-Eng Company, Kaohsiung, Taiwan, where he engaged in research in the area of optical fiber subscriber loops. In 2003, he joined the Faculty of the Department of Electrical Engineering, Chang Gung University, Taoyunan, Taiwan, where he is currently a Full Professor. His research interests include EDF-based tunable ring fiber lasers and photonic millimeter-wave radio-over-fiber access networks.

HAN-SHIN KO received the B.S. degree from the Department of Photonics, Feng Chia University, Taiwan, in 2020, where he is currently pursuing the M.S. degree. His research interests include optical communication and erbium fiber laser.

YI-TING LAI received the B.S. degree from the Department of Photonics, Feng Chia University, Taiwan, in 2021, where he is currently pursuing the M.S. degree. His research interests include optical communication and erbium fiber laser.

CHI-WAI CHOW (Senior Member, IEEE) received the B.Eng. (Hons.) and Ph.D. degrees from the Department of Electronic Engineering, The Chinese University of Hong Kong (CUHK), in 2001 and 2004, respectively. His Ph.D. was focused on optical packet switched networks. He was appointed as a Postdoctoral Fellow with CUHK, involved in silicon photonics. From 2005 to 2007, he was a Postdoctoral Research Scientist, involved mainly in two European Union Projects ''Photonic Integrated Extended Metro and Access Network (PIEMAN)'' and ''Transparent Ring Interconnection Using Multi-wavelength Photonic switches (TRIUMPH)'' with the Department of Physics, Tyndall National Institute, University College Cork, Ireland. In 2007, he joined the Department of Photonics, National Chiao Tung University, Taiwan, where he is currently a Professor.