IEEE Access
Multidisciplinary | Rapid Review | Open Access Journal

Received May 23, 2020, accepted June 1, 2020, date of publication June 4, 2020, date of current version June 16, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.2999929

Rayleigh Backscattering Noise Alleviation in Long-Reach Ring-Based WDM Access Communication

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This work was supported in part by the Ministry of Science and Technology, Taiwan, under Grant MOST-108-2221-E-035-072, and in part by the Chang Gung University, Taiwan, under Grant BMRP-740.

ABSTRACT In the paper, we propose and design a ring-topology wavelength-division-multiplexing (WDM) access network for long-reach signal transmission. Here, the new central office (CO) and optical network unit (ONU) modules are designed to construct the ring-based architecture for symmetric data connection. Thus, the Rayleigh backscattering (RB) beat noise can be prevented due to the unidirectional downstream and upstream signal connections. In the demonstration, eight WDM wavelengths with 10 Gbit/s on-off keying (OOK) modulation are applied to serve as the symmetric downstream and upstream traffic through 105 km fiber connection without dispersion compensation. In addition, the minimum power budgets of 33.8, 36.1 and 35.4 dB among the eight WDM wavelengths can be obtained at the back-to-back (BtB), 51 and 105 km fiber links, respectively, under the forward error correction (FEC) target.

INDEX TERMS Rayleigh backscattering (RB), WDM-PON, OOK modulation, ring-topology.

I. INTRODUCTION

In recent time, to content continually growing bandwidth request for end user in the access network, such as the 4k/8k video, big data, multi-service, on-line game, video conferencing and mobile TV, using the 5G/6G mobile and passive optical network (PON) technologies in last mile access would be the most hopeful future-proof wireless and wired network construction [1]–[4]. To accomplish the higher bit-rate request, the hybrid wireless and optical wired access networks, which could decrease the cost of network constructions, have been studied [5]–[7]. Hence, to provide ultra-broadband and high-speed data access, the wavelength division multiplexing (WDM) techniques would be more valuable than that of time division multiplexing (TDM) access [8], [9]. WDM access network should offer high quality and reliability for end user. To reduce the high cost per user in WDM-PON network, using colorless optical network unit (ONU) could solve the issue [10], [11]. Moreover, the PON systems of tree-, bus- and ring-based architectures have also been demonstrated for network infrastructure [12]–[14]. The PON networks also can be used to act as the backhaul and fronthaul connections for enhancing the coverage of wireless signal [15], [16].

The Rayleigh backscattering (RB) interferometric beat noise would be induced in colorless WDM-PON networks, while the downstream and upstream traffic are with the same wavelength [9], [17]. Hence, the RB noise would be generated at the receiver (Rx) in the central office (CO) and optical network unit (ONU) respectively. To reduce the RB noise effect in WDM access system, utilizing the advanced signal modulations, wavelength shifting method, matchless fiber architecture, and dual laser band wavelengths have been investigated [10], [18]–[20]. However, the mentioned techniques would result the network in complex and increase the cost in tree-topology network. Therefore, the ring-type WDM-PON could be applied to regarded as one of the crucial designs for new-generation access system [21].

The associate editor coordinating the review of this manuscript and approving it for publication was Rentao Gu.

In this paper, we demonstrate new ring-topology WDM-PON architecture for long-reach signal transmission. To achieve the ring-based WDM signal access, the designed central office (CO) and ONU modules could achieve the symmetric 10 Gbit/s on-off keying (OOK) downstream and upstream data connections unidirectionally. Due to the unidirectional signal propagation, the RB noise could be avoided in the presented WDM ring-based network configuration. Here, eight WDM wavelengths with 0.8 nm mode spacing are exploited to generate 10 Gbit/s on-off keying (OOK) format for downstream and upstream transmissions. Moreover, the related performance of each WDM wavelength is also experimented and discussed through 105 km single-mode fiber (SMF) transmission for long-reach connection.

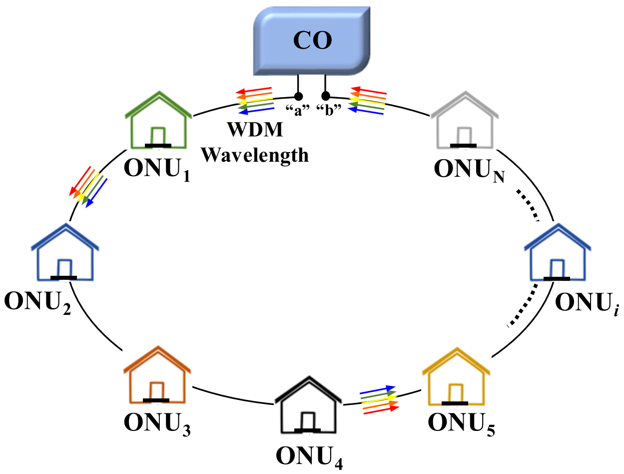

FIGURE 1. Proposed ring-type WDM-PON access architecture with mitigation of RB interferometric beat noise. CO: Central office; ONU: Optical network unit; WDM: Wavelength-division-multiplexing.

II. EXPERIMENT AND RESULTS

Fig. 1 displays the presented ring-type WDM-PON access architecture with beat noise mitigation of RB effect. We assume that N WDM downstream channels could transmit from the central office (CO) through the "a" port in counterclockwise propagation, as seen in Fig.1. The WDM signals would enter the corresponding optical network unit (ONU) for signal demodulation. Moreover, the matching WDM upstream wavelengths could also transmit through the same fiber path from each ONUs and then into the CO simultaneously via the "b" port for data connection. As a result, the WDM downstream and upstream traffic would transmit through the ring-based fiber path counterclockwise. As illustrated in Fig. 1, due to the same WDM downstream and upstream wavelengths through the unidirectional fiber path, the RB beat noise should be avoided in the presented ring-based architecture.

Fig. 2 presents the designed optical module of the CO for prove of concept. In the CO, N optical downstream transmitters (Tx) are connected to $1 \times N$ array-waveguide-grating (AWG) to serve as the WDM downstream wavelengths.

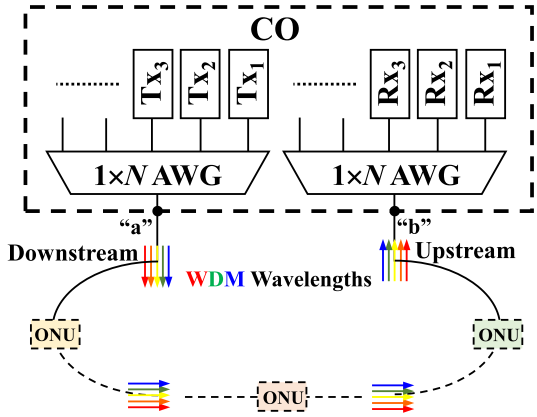

FIGURE 2. Designed optical module of CO. Tx: Transmitter; Receiver: Rx; AWG: Array waveguide grating.

The downstream channels would leave from the "a" output port through the counterclockwise fiber transmission. Then, the whole WDM downstream wavelengths would enter the first ONU through a length of fiber transmission. Next, the corresponding downstream wavelength λ_1 could be dropped in the ONU_1 for decoding.

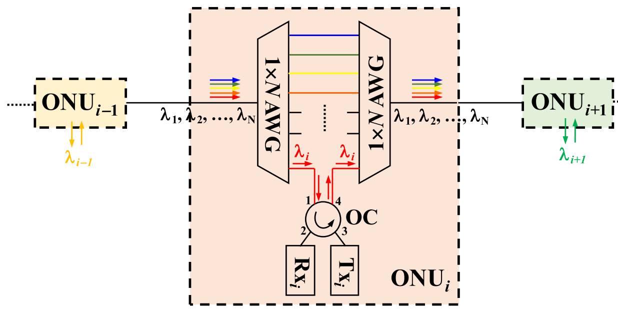

FIGURE 3. Schematic of proposed ONU module. OC: Optical circulator.

Afterword we will illustrate the schematic of designed ONU module. The ONU is constructed by two $1 \times N$ AWGs, 4-port optical circulator (OC), and corresponding optical Tx and Rx, respectively, as seen in Fig. 3. Here, we suppose that the WDM downstream wavelengths enter the i-th ONU. As shown in Fig. 3, the left AWG would filter the corresponding wavelength $\lambda_{i(\text{down})}$ and pass through the OC ("1"→"2") and Rx_i for data detection. The other downstream channels would immediately connect to the right AWG and then into the next ONU. Moreover, the upstream signal $\lambda_{i(\text{up})}$ from the optical Tx_i could pass through the OC ("3"→"4") and right AWG to connect to next ONU. If we utilize a 2×2 optical coupler (OCP) to replace the OC in ONU, the upstream signal will transmit in both clockwise and counterclockwise directions, as seen in Fig. 2. Hence, using the OC only can allow upstream traffic in counterclockwise propagation. Next, all WDM upstream signals from each ONU would enter the CO via the "b" port, as shown in Fig. 2. As a result, each ONU module could drop the corresponding downstream signal and add the upstream wavelength through the ring-type fiber path counterclockwise.

Practically, the ONU is not prone to failure in the proposed ring-based WDM network due to the passive components used. In the designed ONU, the only way that can cause disconnection of WDM signal is damage to the AWG multiplexer. However, a fiber breakpoint between two ONUs would cause a higher probability of signal disconnection. Hence, to solve the fiber fault problem in ring-based access network, using dual-fiber architectures with different ONU designs have been demonstrated [22], [23]. Moreover, the previous work [23] used three OCs and a corresponding fiber Bragg grating (FBG) to produce the signal add-drop multiplexing in the ring-based WDM-PON.

To achieve the WDM signal access in the ring-based network together with fault protection and RB noise mitigation, employing more passive and active components in the remote node (RN) or ONU side have been demonstrated [22]. Hence, to reach the high flexibility and reliability in the previous and proposed ring-based PON systems, paying higher costs are inevitable.

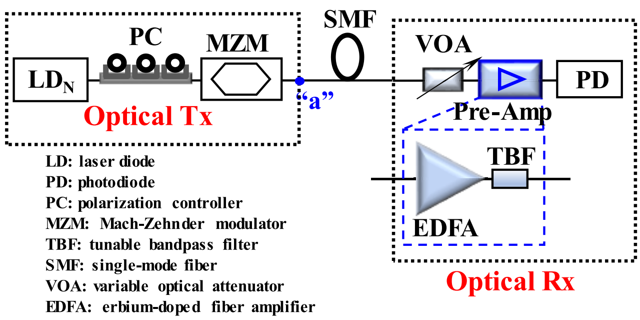

FIGURE 4. Experimental setup for verifying the performances downstream and upstream traffic. LD: Laser diode; PD: Photodiode; PC: Polarization controller; MZM: Mach-Zehnder modulator; SMF: Single-mode fiber; VOA: Variable optical attenuator; EDFA: Erbium-doped fiber amplifier.

Fig. 4 exhibits the experimental setup to verify the performance downstream and upstream traffic. In the measurement, in the optical Tx side, a laser diode (LD) with different output wavelength is utilized to connect to the polarization controller and 10 GHz Mach-Zehnder modulator (MZM). Here, to tune the WDM wavelength, we exploit a tunable laser source (TLS) with 13 dBm output power to regard as the downstream and upstream LDs, respectively. The PC is applied to control the polarization state and achieve maximum output power, as illustrated in Fig. 4. We apply 10 Gbit/s on-off keying (OOK) modulation format with a pattern length of $2^{31}-1$ on MZM to regard as the downstream and upstream traffic, respectively, by using the bit error rate (BER) tester (produced by *Alnair Labs*, SeBERT-100E). Hence, the BER performance of each WDM wavelength can be obtained and recorded. Here, the chirp parameter of MZM is −0.7. The negative chirp MZM could improve the fiber chromatic dispersion and enhance the signal performance. Through a length of single-mode fiber (SMF) link, the modulation signal would enter the optical Rx side for decoding. The different SMF length can be applied to act as the downstream or upstream transmission length. As displayed in Fig. 4, the optical Rx is consisted of a variable optical attenuator (VOA), an optical pre-amplifier and a 10 GHz PIN photodiode (PD). The sensitivity of the PIN PD is −19 dBm in the experiment. Besides, an erbium-doped fiber amplifier (EDFA) and tunable bandpass filter is used to construct the pre-amplifier, which is used to enhance the detected power sensitivity. The VOA is exploited to gradually decrease the input power of modulation wavelength for confirming the bit error rate (BER) performance. We select eight WDM wavelengths of 1540.16 (λ_1), 1540.95 (λ_2), 1541.75 (λ_3), 1542.54 (λ_4), 1543.33 (λ_5), 1544.13 (λ_6), 1544.95 (λ_7) and 1545.72 nm (λ_8) for downstream and upstream demonstrations, respectively. In the measurement, the detected power of 7.6 dBm is obtained at the "a" point, as seen in Fig. 4.

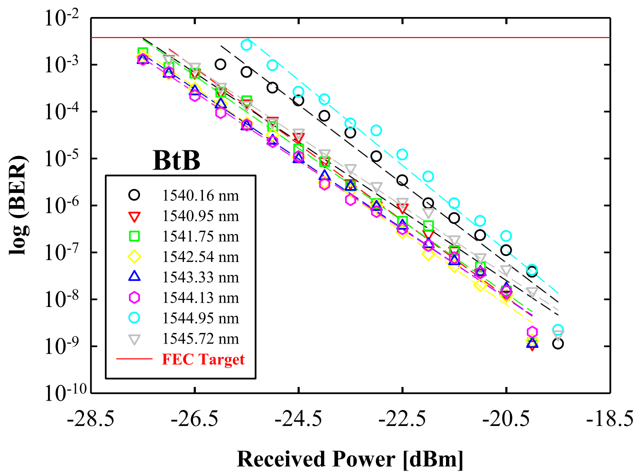

FIGURE 5. Measured 10 Gbit/s OOK BER performance of λ_1 to λ_8 at the BtB status, respectively.

Fig. 5 presents the measured 10 Gbit/s OOK BER output of eight selected wavelengths of λ_1 to λ_8 at the back-to-back (BtB) status. The measured power sensitivity of λ_1 to λ_8 is around −19, −20, −20, −20, −20, −20, −19.5 and −19.5 dBm, respectively, under the error-free (EF) level (BER $= 1 \times 10^{-9}$). Moreover, the red line of Fig. 5 is the forward error correction (FEC) level at the BER of $\leq 3.8 \times 10^{-3}$. Hence, to increase the power sensitivity of each modulated wavelength, we also can choose the FEC target for signal detection.

Then, 51 km SMF transmission length is employed in the proposed ring-based PON network for measurement. Fig. 6 indicates the measured 10 Gbit/s OOK BER performance of λ_1 to λ_8 after 51 km SMF connection, respectively. As shown in Fig. 6, the power sensitivity of −24, −23, −24.5, −24, −23, −23, −23 and −24 dBm is observed at the wavelengths of λ_1 to λ_8 under the EF threshold, respectively. Therefore, the eight wavelengths could also be regarded as the downstream or upstream traffic here, respectively.

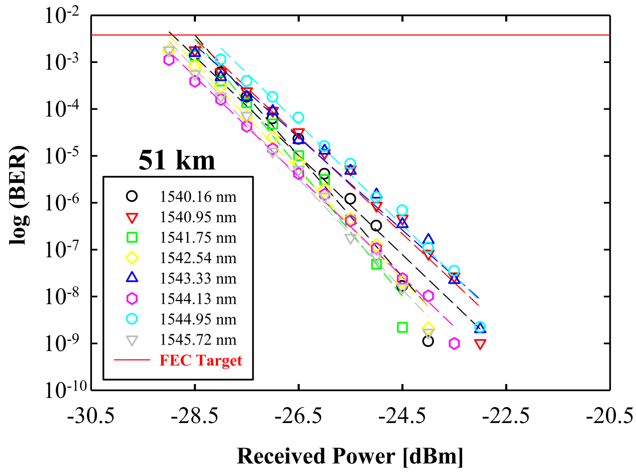

FIGURE 6. Observed 10 Gbit/s OOK BER performance of λ_1 to λ_8 after 51 km SMF connection, respectively.

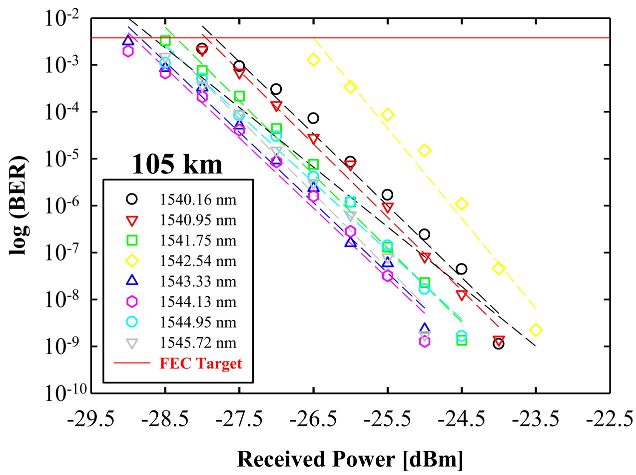

FIGURE 7. Observed 10 Gbit/s OOK BER performance of λ_1 to λ_8 after 105 km SMF transmission, respectively.

Next, we extend the SMF transmission length to 105 km in the presented access network. Fig. 7 plots the 10 Gbit/s OOK BER measurement of λ_1 to λ_8 through 105 km SMF connection for downstream and upstream traffic. Here, the power sensitivity of −24, −24, −24.5, −24.5, −25, −25, −24.5 and −25 dBm are obtained without using fiber compensation respectively, under the EF status. In addition, Fig. 8 exhibit the corresponding 10 Gbit/s OOK eye diagrams of λ_1 to λ_8 after 105 km SMF link under the EF level, respectively. The measured eyes not only are clear, but also are open. According to the measured results of Fig. 7, the measured power sensitivity is smaller than −24 dBm among the eight selected wavelengths to reach 105 km SMF transmission length at the BER $= 1 \times 10^{-9}$. Therefore, the achievable fiber transmission length of downstream and upstream signal is 105 and 105 km in the ring-type WDM-PON architecture, respectively.

Finally, to realize the obtained sensitivity of EF and FEC thresholds for each WDM wavelength at the BtB, 51 and 105 km SMF transmissions, respectively, the whole measured results are consolidated for exhibition, as shown in Tab. 1. Here, as increasing the transmission length of SMF, the observed power sensitivity would be enhanced under the EF state no matter which wavelength is used, as seen in Tab. 1(a). This is because the negative chirp MZM is utilized to pre-compensate fiber dispersion for enhancement. While we set the reference level at the FEC target, the observed sensitivity among these wavelengths can be extended from 3.5 to 4.1 dB through 105 km SMF transmission. As seen in Tab. 1(b), the measured sensitivity differences (ΔP) of the eight selected wavelengths are not too large at the various conditions. The maximum and minimum sensitivity variations of 3.1 and 0.9 dB are achieved at the wavelengths of 1544.95 and 1543.33 nm, respectively. As listed in Tab. 1(b), the detected sensitivity can be larger than −28.3 and −27.8 dBm after 51 and 105 km SMF links, respectively, at the FEC level. Additionally, the minimum power budgets of 33.8, 36.1 and 35.4 dB among the eight wavelengths are also reached at the BtB, 51 and 105 km SMF transmissions, respectively.

According to the proposed PON architecture, two AWG (6 + 6 dB) and OC (1 dB) of the ONU could cause 13 dB insertion loss. Besides, the SMF also could produce the propagation loss of 0.2 dB/km. Thus, each ONU would induce 12 dB power loss for the downstream signals. Hence, to maintain the downstream and upstream transmission performances, we could add properly number of EDFA in the position of ONU to compensate the insertion loss caused by AWG, OC and SMF according to the power budget of each

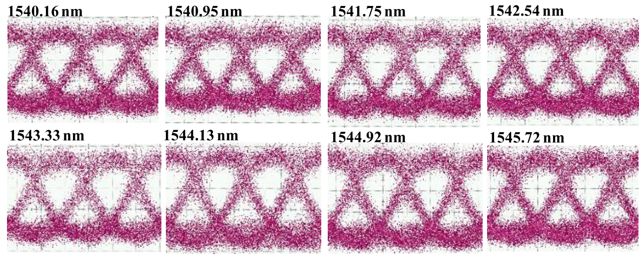

FIGURE 8. Observed corresponding 10 Gbit/s OOK eye diagrams of λ_1 to λ_8 after 105 km SMF transmission under the EF state, respectively.

TABLE 1. Obtained power sensitivity of the EF and FEC thresholds for each WDM wavelength as the BtB, 51 and 105 km SMF transmissions, respectively.

(a) EF status

	λ_1	λ_2	λ_3	λ_4	λ_5	λ_6	λ_7	λ_8
BtB	−19.5	−20	−20	−20	−20	−20	−19.5	−19.5
51 km	−24	−23	−24.5	−24	−23	−23	−23	−24
105 km	−24	−24	−24.5	−24.5	−25	−25	−24.5	−25

(b) FEC target

	λ_1	λ_2	λ_3	λ_4	λ_5	λ_6	λ_7	λ_8
BtB	−26.2	−27.3	−27.5	−27.8	−27.9	−28.1	−25.5	−27.3
51 km	−28.5	−28.6	−28.6	−29	−28.7	−29	−28.3	−29.1
105 km	−27.8	−27.9	−28.3	−28.5	−28.8	−28.9	−28.6	−28.5
ΔP	2.3	1.3	1.1	1.2	0.9	0.9	3.1	1.8

WDM signal. In the demonstration, the minimum power budget of 35.4 dB is observed at the wavelength λ_1 under the FEC level after 105 km SMF transmission. Hence, the obtained budget can allow the λ_1 passing through two ONUs for data connection. To solve the insufficient power budget, we can apply an EDFA in the $ONU_{(m\cdot 3)}$ for signal amplification, where m =1, 2, 3..., n. Moreover, the used AWG also can filter the optical background noise.

III. CONCLUSION

We designed and investigated a unidirectional 10 Gbit/s OOK ring-based WDM-PON network to avoid the RB beat noise, while the same wavelengths were applied for downstream and upstream traffic. Here, the new CO and ONU modules were designed to construct the ring-type WDM network architecture. The experimental results showed that the obtained power sensitivity was between −23 and −24.5 dBm, and −24 and −25 dBm, respectively, at the EF level through 51 and 105 km SMF link. In the demonstration, to extend the power sensitivity, we could apply the FEC target for each wavelength. When the 105 km SMF was applied in the proposed access network, the obtained power budgets of λ_1 to λ_8 were 35.4, 35.5, 35.9, 36.1, 36.4, 36.5, 36.2 and 36.1 dB, respectively. Hence, 210 km total SMF transmission could be reached for long-reach connection in the proposed WDM architecture. Moreover, to compensate the insertion losses of optical components and enhance the signal performances, the accurately number of EDFA could be added in the ring-based architecture depending on the available power budget of WDM signal.

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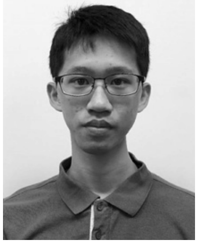

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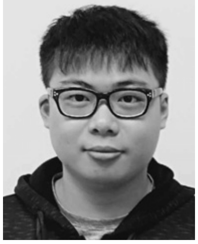

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