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Free Space Optical Communication in Long-Reach Unidirectional Ring-Architecture Fiber Network

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ABSTRACT In the work, a ring-constructed wavelength-division-multiplexing (WDM) access system for delivering multiple free space optical (FSO) wireless signals is investigated. To reach the FSO transmission through single-mode fiber (SMF) connection, the optical wireless unit (OWU) and remote OWU are designed in the WDM network. The downstream and upstream WDM FSO channels could be transmitted in unidirectional propagation with the same wavelength. Hence, the presented ring-based WDM network not only can transmit the FSO signal, but also can circumvent the Rayleigh backscattering (RB) interferometric beat noise. In addition, according to the experimental results, the SMF and FSO transmission lengths can reach 50 km and 500 to 1000 m at the forward error correction (FEC) level without using optical amplification and dispersion compensation, respectively, when four WDM wavelengths are exploited experimentally for demonstration.

INDEX TERMS Free space optical (FSO), Rayleigh backscattering (RB), WDM access, OOK modulation, ring-architecture.

I. INTRODUCTION

To comply with the ultra-broadband demands of end-user in the last mile communication network, utilizations of the 5G/B5G wireless network, visible light communication (VLC), free space optical (FSO) communication and passive optical network (PON) have been studied in recent years [1]–[5]. Furthermore, the FSO transmission technology could also be applied in the PON network to overcome some geographical environment limitations for providing the data connection [6]–[8]. In this way, the access networks with higher flexibility and reliability should be essential issue for communication. Hence, the integrated optical wired and wireless access technologies, will be the promising candidate, have been studied recently [9]–[11]. However, to achieve higher capacity for data transmission, wavelength-division-multiplexing (WDM) access technology could be the better choice [12], [13]. In addition, in the present PON architecture, the tree-, ring- and bus-based fiber networks have been built and demonstrated [14], [15]. Recently, using FSO technology in WDM access architecture to connect and transmit the data traffic for enhancing the network reliability and flexibility have been investigated [8], [16], [17]. Besides, utilization of WDM and FSO transmission techniques not only could provide the higher capacity, but also could solve environmental limitations and increase signal coverage. However, if the same wavelengths are exploited for bidirectional downstream and upstream traffic through conventional tree-based WDM-PON network simultaneously, the Rayleigh backscattering (RB) induced noise could be caused at the receiver (Rx) in the optical line termination (OLT) and optical network unit (ONU) to reduce the signal performance [18], [19]. Moreover, as the fiber transmission distance increases gradually, the RB-induced noise would become more serious. Utilization of the electrical filtering effect, separating dual-band wavelengths, wavelength-shifted modulation, and special

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fiber network architecture have been proposed and demonstrated to mitigate the RB beat noise in WDM-PON system for future practical application [20]–[22].

Furthermore, in 2002, Aburakawa *et al.* demonstrated a hybrid FSO and fiber transmission with 155 Mbit/s on-off keying (OOK) rate for 900 m free space connection [23]. In 2009, Yoshida *et al.* first proposed a method for adjusting an FSO system that links two fibers using collimators [24]. In 2015, Feng *et al.* investigated a 10 Gbit/s OOK FSO signal applying in PON access based on orbital angular momentum (OAM) multiplexing under 0.4 m free space transmission [25]. In 2019, Tsai *et al.* presented a polarization division multiplexing (PDM)-based bidirectional fiber-FSO integration system with 64 Gbit/s four-level pulse amplitude modulation (PAM-4) downstream and 10 Gbit/s OOK upstream through 200 m free space link [26]. As mentioned above, applying the 40 GHz bandwidth optical device, advanced modulation format, accurate FSO alignment and larger optical power were required to achieve higher FSO rate and transmission length. However, it would increase the cost of FSO-fiber transmission system.

In this study, a ring-topology fiber network to deliver WDM FSO signal for unidirectional transmission is proposed. To reach the unidirectional signal propagation, the optical wireless unit (OWU) and remote OWU are used. Hence, the RB-induced beat noise can be avoided when the same wavelength is utilized to act as the downstream and upstream signal in the ring-based access architecture. In the experiment, four WDM wavelengths are utilized to understand the FSO signal performance for proof of concept. Here, 10 Gbit/s on-off keying (OOK) signal with a pattern length of $2^{31}-1$ is exploited for the downstream and upstream FSO connection. According to the obtained power sensitivity experimentally and the simulation results, the four downstream and upstream WDM FSO signals can support the free space link length from 500 to 1000 m without optical amplification after 50 km SMF connection under the forward error correction (FEC) threshold.

II. EXPERIMENT AND RESULTS

Fig. 1 plots the proposed WDM-FSO PON access network with ring-based architecture for the proof of concept. In the central office (CO), we can apply N WDM wavelengths regarding as the downstream FSO signals to connect to the $1\times N$ array-waveguide-grating (AWG) multiplexer. Then, the WDM-FSO wavelengths could be delivered through the "a" port and enter the ring fiber path counterclockwise. Next, the WDM-FSO downstream channels would launch into the optical wireless unit (OWU) and drop the corresponding downstream WDM wavelength for FSO transmission. After a length of free space connection, the downstream FSO traffic would be received in the remote OWU (ROWU). Moreover, the other downstream WDM-FSO signals will enter the next OWU through ring-based path, as displayed in Fig. 1. Furthermore, each upstream WDM-FSO wavelength from the ROWU would be also received in the OWU through the same

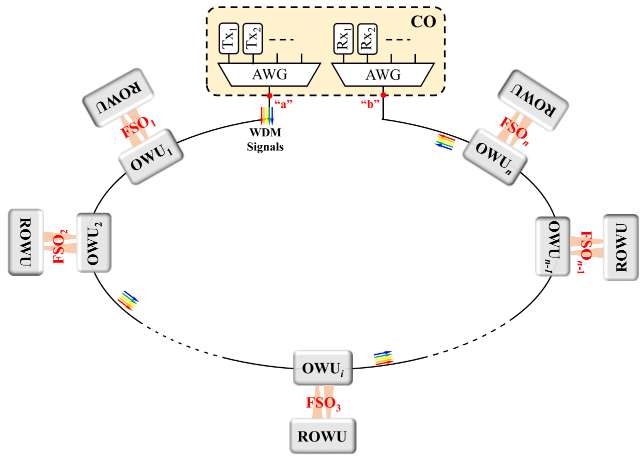

FIGURE 1. Schematic of proposed WDM-FSO ring-based access network with mitigation of RB interferometric beat noise. CO: Central office; AWG: Array waveguide grating; OWU: Optical wireless unit; ROWU: Remote optical wireless unit; WDM: Wavelength-division-multiplexing; FSO: Free space optical.

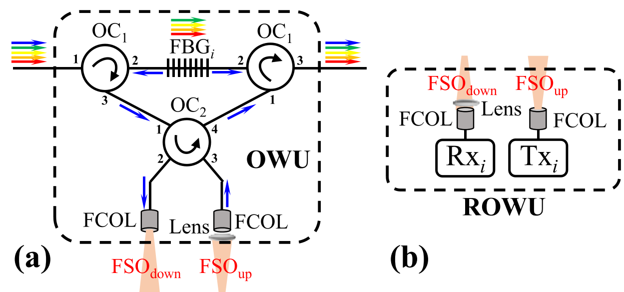

FIGURE 2. (a) Designed optical module of OWU and (b) ROWU. OC: Optical circulator; FCOL: Fiber-type collimator; FBG: Fiber Bragg grating. Tx: Optical transmitter; Rx: Optical receiver.

fiber path for signal connection. Therefore, the WDM-FSO downstream wavelength could be decoded in each ROWU from the corresponding OWU. All the upstream signals would be decoded in the CO via the same fiber transmission counterclockwise, as shown in Fig. 1.

To achieve the unidirectional downstream and upstream FSO signal propagation in the proposed WDM ring-based fiber network, the new OWU and ROWU modules are designed and applied for demonstration. The designed OWU is composed of two 3-port optical circulators (OC_1), a 4-port OC_2, a fiber Bragg grating (FBG), two fiber-type collimators (FCOLs), and a focusing lens, as exhibited in Fig. 2(a). Here, one of the downstream WDM wavelengths could be reflected by the FBG with the corresponding Bragg wavelength and launch into the right FCOL via the OC_1 and OC_2 for delivering FSO signal. Besides, the ROWU is constructed by a focusing lens, two FCOLs, an optical transmitter (Tx) and an optical receiver (Rx), as seen in Fig. 2(b). Hence, the downstream wavelength can be detected by the right lens and FCOL in the ROWU after FSO wireless transmission. The focusing lens is used to enhance the detected FSO power and corresponding signal to noise ratio (SNR). The corresponding upstream wavelength is emitted from the ROWU. After passing through the lens, FCOL, OC_2, OC_1, and FBG, respectively. the upstream wavelength would be also reflected via the same FBG and then into the next OWU for signal connection, as illustrated in Fig. 2. As we know, using the same wavelengths to act as bidirectional downstream and upstream signals in PON access would result in Rayleigh backscattering (RB) induced interferometric noise at the Rx in the CO and user side, respectively [17]. Furthermore, the RB would restrict the fiber transmission length and reduce the sensitivity of Rx. Therefore, according to the demonstrated ring-topology WDM access architecture, the RB induced noise effect could be avoided owing to the downstream and upstream traffic in unidirectional fiber transmission.

Commonly, the ring-based access architecture could deliver the downstream and upstream traffic simultaneously in unidirectional fiber transmission and prevent the RB interference at the WDM access or even time-division-multiplexing (TDM) status [18], [20]. In fact, the bidirectional ring-based WDM and time-division-multiplexing (TDM) networks have been proposed to produce the fiber fault protection based on single- or dual-fiber connection [15], [18], [27]. However, to achieve the fault protection, the extra optical components, which could increase the cost, are needed for network development. Compared with the conventional tree-based WDM-PON, the extra optical devices of FBG, OC, Lens and FCOL are needed to apply in the OWU and ROWU for FSO connection, as illustrated in Figs. 2(a) and 2(b). Hence, the extra optical components would increase the cost of the presented FSO-fiber network.

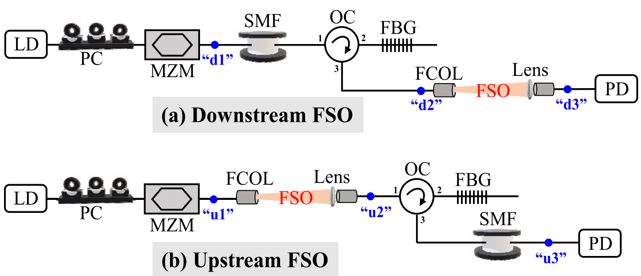

FIGURE 3. Experimental setup for (a) downstream and (b) upstream WDM-FSO transmissions for proof of concept. LD: Laser diode; PC: Polarization controller; MZM: Mach-Zehnder modulator; PD: Photodiode; SMF: Single-mode fiber.

Then, according to the designed optical modules of Fig. 2, we build a simple experimental setup of the downstream and upstream FSO measurement, respectively, as seen in Figs. 3(a) and 3(b) for the proof of concept. As displayed in Fig. 3(a), in the downstream FSO transmission, a laser diode (LD) connects to the polarization controller (PC) and 10 GHz bandwidth Mach-Zehnder modulator (MZM). The PC is exploited to attain the polarization state and reach the ideal output power. A 10 Gbit/s on-off keying (OOK) format with the pseudo randomness binary sequence (PRBS) pattern length of $2^{31}-1$ is applied on MZM to generate FSO signal. In the measurement, we select four wavelengths of 1530.33 ($\lambda 1$), 1534.25 ($\lambda 2$), 1538.19 ($\lambda 3$) and 1542.14 nm ($\lambda 4$) to regard as the WDM-FSO downstream signals, respectively. As displayed in Fig. 3(a), through 50 km single-mode fiber (SMF) connection, an OC, and a corresponding FBG, respectively, the wireless FSO signal can be emitted from the FCOL. Four FBGs with corresponding Bragg wavelength and 94% reflectivity are employed to reflect the downstream and upstream signals for data connection. To facilitate the wireless FSO traffic in the experiment, 2 m free space link is set for demonstration. Here, after 2 m free space transmission, the FSO signal would enter the doublet lens and FCOL. Then, the downstream traffic is detected by a 10 GHz PIN based photodiode (PD) for decoding. As seen in Fig. 3(a), the diameter, divergence angle and focal length of FCOL is 20 mm, 0.016° and 37.13 mm, respectively. The diameter and focal length of lens are 50.4 mm and 75 mm. The distance between doublet lens and FCOL is 4.5 cm for coupling FSO signal. Here, the lens can collect and enhance the detected FSO power. Thus, the designed optical system can support the bidirectional FSO connection between OWU and ROWU. Moreover, the same optical devices are also exploited for the upstream FSO measurement, as shown in Fig. 3(b). The SMF and FSO transmission lengths of 50 km and 2 m are also employed. In the experiment, the measured output power at the points of "d1", "d2" and "d3" and "u1", "u2" and "u3" are 7.6, −3.4 and −7.4 dBm, and 7.6, 3.6 and −8.4 dBm, respectively, as seen in Figs. 3(a) and 3(b). The insertion loss of ~4 dB is attained between two FCOLs also including the misalignment.

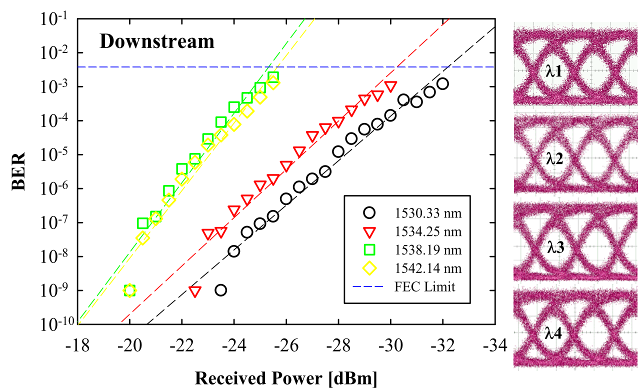

FIGURE 4. Obtained 10 Gbit/s OOK BER measurement of downstream FSO signal, when the WDM wavelength of λ1 to λ4 is used, respectively. Insets are the corresponding eye diagrams of four FSO signals at the EF level.

Fig. 4 displays the attained 10 Gbit/s OOK bit error rate (BER) measurement of WDM-FSO downstream transmissions after 50 km SMF connection and 2 m free space link, when the WDM-FSO wavelength of $\lambda 1$ to $\lambda 4$ is applied, respectively. In the experiment, the observed power sensitivities of four selected wavelengths are −23.5, −22.5, −20.0 and −20.0 dBm at the error free (EF) status under the BER $\leq 1 \times 10^{-9}$, respectively. Additionally, the four corresponding eye diagrams are also plotted in the insets of Fig. 4 at the EF level. To allow the larger power budget for WDM FSO connection, the forward error correction (FEC) target (BER $\leq 3.8 \times 10^{-3}$) can be applied in the presented ring-based access system. Hence, the obtained four power sensitivities are −32.3, −30.2, −25.3 and −25.7 dBm without dispersion compensation, respectively, as presented in Fig. 4.

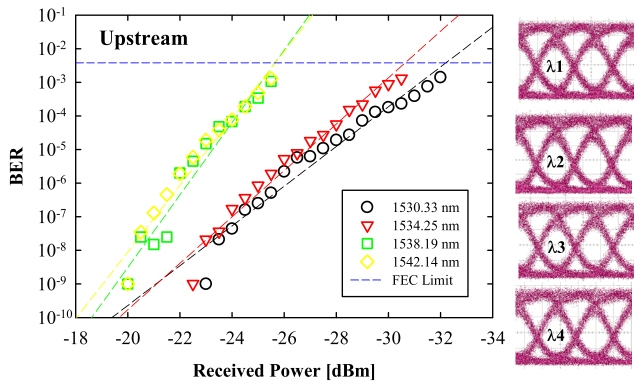

FIGURE 5. Obtained 10 Gbit/s OOK BER measurement of upstream FSO signal, when the WDM wavelength of λ1 to λ4 is used, respectively. Insets are the corresponding eye diagrams of four FSO signals at the EF level.

For the FSO upstream traffic, the same wavelengths of λ1 to λ4 are also employed regarding as the upstream signals based on the experimental setup of Fig. 3(b). Fig. 5 indicates the BER behavior of 10 Gbit/s OOK FSO upstream traffic. As displayed in Fig. 5, the measured optical sensitivities are −23.0, −22.5, −20.0 and −20.0 dBm under the EF threshold, respectively. The insets of Fig. 5 are the corresponding observed eye diagrams at the EF level. All corresponding eye diagrams of Fig. 4 and Fig. 5 are not only open but also clear without using dispersion compensation after 50 km SMF and 2 m FSO connections. Furthermore, the optical sensitivities of −32.2, −30.7, −25.6 and −25.6 dBm are also obtained at the four wavelengths under the FEC threshold, respectively, as plotted in Fig. 5. As a result, the observed power sensitivities of four downstream and upstream signals are similar as mentioned above. As seen in the previous study [18], it could achieve 5 Gbit/s symmetric downstream and upstream traffic through 50 km SMF link. Besides, the BER of 10^{-3} was referenced for evaluating the baseband signal performance [18]. The proposed ring-based WDM FSO network not only can avoid the RB-induced noise, but also can deliver the symmetric 10 Gbit/s FSO signal through 50 km SMF connection and 500 to 1000 m free space transmission without dispersion compensation and signal amplification. In addition, compared with [18], the smallest sensitivity of −32.3 dBm can be reached at the BER of 3.8×10^{-3} in the presented network.

Originally, four WDM wavelengths are selected for serving as the downstream and upstream signals for demonstration. According to the measured results of Figs. 4 and 5, observed penalty differences of downstream and upstream

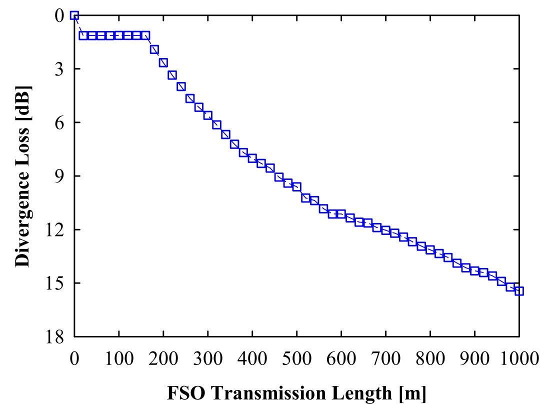

FIGURE 6. Observed divergence loss of FSO signal between OWU and ROWU in the free space link of 0 to 1000 m.

traffic between the four wavelengths are 3.5 and 3 dB and 6.6 and 6.6 dB at the EF and FEC levels, respectively. Moreover, when moving towards longer wavelengths, the resulting FSO sensitivity will deteriorate accordingly, as seen in Figs. 4 and 5. The larger power penalty is caused by the fiber chromatic dispersion effect. Here, the measured power budget of selected four WDM FSO wavelengths could be used to forecast the longest FSO traffic length in the ring-based access system based on the practical demands of different FSO transmission lengths. Moreover, the proper WDM wavelength can be applied to reach the better FSO sensitivity in the proposed network architecture.

Next, to understand the longest wireless FSO traffic length of each WDM signal, the related analysis of power budget is discussed for the downstream connection in the following. In accordance with the proposed ring-based WDM-FSO access network as seen in Fig. 1 and Fig. 2, a 50 km SMF transmission length and each OWU (including two OC_1 and FBG) would cause around 10 and 2 dB insertion losses, respectively. Between the OWU and ROWU, the misalignment and coupling connection also cause ~4 dB loss. Besides, as the downstream enter the corresponding OWU for delivering FSO signal, an OC_2 would produce the insertion loss of < 1 dB. Here, in accordance with the detected power sensitivities of λ1 to λ4 at the FEC target, the total downstream power budgets of 39.9, 37.8, 32.9 and 33.3 dB are obtained, respectively. Therefore, the FSO transmission length based on the redundant power budget of each WDM FSO signal can be estimated, as listed in Tab. 1. In the previous study [28], the divergency loss of FSO signal between the OWU and ROWU could be simulated under the different free space traffic length based on the designed optical system, assuming the weather condition is clean for outdoor application. So, Fig. 6 exhibits the observed result of divergence loss under the FSO transmission length of 0 to 1000 m. As seen in Fig. 6, the corresponding divergence loss is 9.6, 14.60, 15.22 and 15.45 dB, respectively, when the FSO link is 500, 940, 980 and 1000 m. Assuming the same four WDM OWUs are used in the ring-based access system, the OWUs would

TABLE 1. The observed relationship of power sensitivity, corresponding loss and redundant budget for each downstream and upstream WDM wavelength, respectively.

Downstream

λ (nm)	Power (dBm)	Sensitivity (dBm)	50 km SMF (dB)	4 OWUs (dB)	Power Budget (dB)	Between OWUs (dB)	OC Loss (dB)	Redundant Budget (dB)	FSO Link (m)
1530.33	7.6	–32.3	10	8	39.9	4	1	16.9	1000
1534.25	7.6	–30.2	10	8	37.8	4	1	14.8	940
1538.19	7.6	–25.3	10	8	32.9	4	1	9.9	500
1542.14	7.6	–25.7	10	8	33.3	4	1	10.3	500

Upstream

λ (nm)	Power (dBm)	Sensitivity (dBm)	50 km SMF (dB)	4 OWUs (dB)	Power Budget (dB)	Between OWUs (dB)	OC Loss (dB)	Redundant Budget (dB)	FSO Link (m)
1530.33	7.6	–32.2	10	8	39.8	4	1	16.8	1000
1534.25	7.6	–30.7	10	8	38.3	4	1	15.3	980
1538.19	7.6	–25.6	10	8	33.2	4	1	10.2	500
1542.14	7.6	–25.6	10	8	33.2	4	1	10.2	500

cause around 8 dB for the last transmitted FSO wavelength. Besides, the insertion losses of two AWGs in the CO could be ignored in Tab. 1, when an erbium-doped fiber amplifier (EDFA) is applied. The output power of FSO wavelength can be set at 7.6 dBm after leaving the CO. And the received power of FSO signal can be amplified by an EDFA for loss compensation. Therefore, based on the obtained redundant power budget of each FSO wavelength and the simulation results, the longest FSO transmission length can be estimated for delivering wireless signal, as shown in Tab. 1. In the investigation, the downstream and upstream FSO wavelengths of $\lambda 1$ to $\lambda 4$ can reach 1000, 940, 500 and 500 m, and 1000, 980, 500 and 500 m free space link lengths without optical amplification, respectively. In the investigation, the FSO transmission length is based on the power budget of WDM wavelength. In fact, a longer SMF transmission distance would result in larger power penalty. This is not good for long-distance FSO transmission. To enhance the budget of FSO signal, we can reduce the transmission length of SMF for improving. If the presented ring-based PON network want to support more OWUs and achieve longer FSO transmission length, the EDFA could be utilized in the properly location to compensate the insertion loss and amplify the FSO signal. In addition, to achieve the flexible FSO connection in the ring-based WDM architecture, a variable FBG could be used in the OWU for dynamic operation depending on the practical environment and requirement.

Compared with the conventional tree-based WDM-PON architecture, the presented ring-based WDM FSO network has the benefits of RB noise mitigation, symmetric wireless FSO connections, long-reach SMF transmission, and smaller detected sensitivity. However, the proposed network would add the additional passive components and bring the less OWU number for network connection. In the proposed WDM ring-based network, only extra passive components are exploited in the OWU and RWOU for FSO traffic connection. Besides, the additional active component is not required in the CO and ROWU. Hence, the total power consumption would not be increased comparing with the commercial PON network.

In the designed ring-based WDM network, each OWU only needs one FBG with corresponding Bragg wavelength to drop and add the downstream and upstream signal, respectively. Here, extra FBG is not required in the same OWU for FSO add-drop connection. According to the previous colorless ONU study [29], to achieve the colorless FSO in the presented WDM network, adding another FBG in the OWU to reflect a continuous-wave (CW) injection light regarding as the upstream traffic with various modulations might be achieved. Moreover, using the advanced modulation with same wavelength and various modulation formats would also reach the colorless operation [30].

III. CONCLUSION

A 10 Gbit/s OOK WDM ring-based PON access architecture for downstream and upstream FSO connection was presented. Based on the proposed OWU design, the corresponding downstream FSO wavelength could be dropped for delivering wireless data. Besides, the same upstream FSO wavelength could be added in the OWU and then back to the CO through the same fiber path. Hence, the downstream and upstream WDM-FSO signals could propagate in unidirectional fiber path. Due the unidirectional traffic path in ring-based network, the RB-induced noise would be avoided. In the experiment, the obtained four downstream and upstream WDM-FSO wavelengths of $\lambda 1$ to $\lambda 4$ were -32.3, -30.2, -25.3 and -25.7 dBm and -32.2, -30.7, -25.6 and -25.6 dBm through 50 km SMF and 2 m free space transmission lengths, respectively, under the EFC target of BER $\leq 3.8 \times 10^{-3}$. Based on the observed result of designed optical system and observed signal sensitivity, the longest FSO transmission length could be estimated in the proposed ring fiber network. Therefore, the achieved longest FSO lengths of λ1 to λ4 were between 500 to 1000 m for downstream and upstream transmissions when the weather state is pure and the FSO alignment is accurate.

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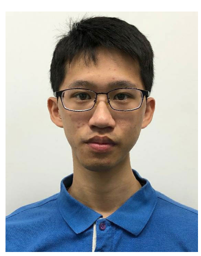

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