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Use of Same WDM Channels in Fiber Network for Bidirectional Free Space Optical Communication With Rayleigh Backscattering Interference Alleviation

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ABSTRACT In the paper, we present and demonstrate experimentally a 10 Gbit/s on-off keying (OOK) bidirectional wavelength-division-multiplexing (WDM) free space optical (FSO) communication architecture integrated in fiber network together with 5 m free space transmission length and 25 km fiber link, respectively. To achieve bidirectional FSO link, the all WDM wavelengths can be used simultaneously to serve as the downstream and upstream traffics in the proposed FSO-WDM system. Here, four pairs of line terminations (LTs) and optical wireless units (OWUs) are integrated arbitrarily in fiber access network for confidential and bidirectional FSO connection based on the requirement of practical environment. In the measurement, the relationship of FSO signal performance and detected tolerance are also discussed and analyzed. Moreover, the WDM-FSO transmission can also avoid the Rayleigh backscattering (RB) beat noise in fiber connection.

INDEX TERMS Free space optical communication, wavelength-division-multiplexing (WDM), Rayleigh backscattering (RB).

I. INTRODUCTION

Recently, the free space optical (FSO) communication technologies could be utilized to offer the advantages of high-speed, broad capacity and cost-effectiveness, due to the bandwidth demands of multi-service and diverse applications for next generation communications [1]–[3]. Furthermore, the FSO transmission system, integrated in broadband fiber networks and wireless transmissions, has the high compatibility without signal interference for broadband data access [4]–[6]. As mentioned above, the FSO system would also be the gorgeous technology for the metropolitan network extension and the fronthaul and backhaul wireless cellular link [7], [8]. Hence, the FSO system could be the comprehensive platform to deliver the optical wireless connection everywhere for data traffic. However, the FSO traffic could be influenced by the atmospheric turbulence and weather status [9], [10]. These issues would also decide the availability and reliability of FSO transmission. To meet the broadband requirement for last mile access, the FSO and millimeter (mm)-wave communication can be combined in the passive optical network (PON) for wireless data link [11], [12]. Besides, the fiber network connection may be not suitable to build up due to the limited geographical environment. However, the MMW signal could only provide a shorter propagation length due to the atmospheric absorption [13]. Hence, the FSO transmission technology would be the alternative solution for data connection [14].

Furthermore, using LD and LED based visible light communication (VLC) for short distance communication have also been studied. Typically, the LED-based VLC systems are applied in the indoor access application due to the limited

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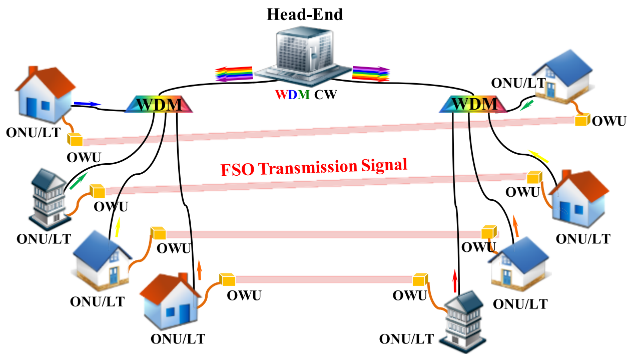

FIGURE 1. Schematic architecture of the proposed WDM-FSO transmission system.

bandwidth and illuminance [15]. Besides, the LD-based VLC are most utilized in the outdoor and underwater communications to maintain larger wireless data traffic [16], [17].

In this paper, we propose and demonstrate experimentally a bidirectional wavelength-division-multiplexing (WDM)-FSO system with 10 Gbit/s OOK wireless data, which is integrated in fiber access network, after 25 km fiber link and 5 m free space transmission length. Here, five WDM wavelengths are employed simultaneously for four pairs of line terminations (LTs) and optical wireless units (OWUs) based on our proposed WDM-FSO network architecture for bidirectional FSO traffic with the different downstream and upstream wavelengths. In the measurement, the FSO signals can transmit through a 25 km SMF first and then emit through a 5 m free space transmission length; and emit through a 5 m free space transmission length first and then transmit through a 25 km SMF for data detection, respectively for demonstration. The whole power sensitivities of < -24.2 dBm of five WDM FSO signals can be completed. Hence, the proposed WDM FSO transmission not only can be exploited for dedicated connection, but the RB beat noise can be also avoided. In addition, the available tolerance of ± 1.14 cm displacement ($\pm 0.1305°$ rotation angle) is allowed in the Rx side for FSO traffic to satisfy the forward error correction (FEC) target under a 5 m long wireless transmission length.

II. EXPERIMENT AND RESULTS

Owing to some geographical limitations, utilizing the FSO technique, which can be combined in fiber network, would be the alternative to complete the wireless data link. Fig. 1 presents the scenario of schematic architecture for the proposed WDM-FSO network. In the presented FSO system, the multiple continuous-wave (CW) WDM wavelengths are emitted simultaneously from the head-end (HE) site and then through the WDM multiplexer launch into each FSO line termination (LT). The WDM wavelengths can be modulated in the OL to generate FSO signals and connect to corresponding optical wireless units (OWUs) for delivering bidirectional FSO traffics simultaneously. As illustrated in Fig. 1, the LT can be integrated in the optical network unit (ONU) of PON network for confidential data link via

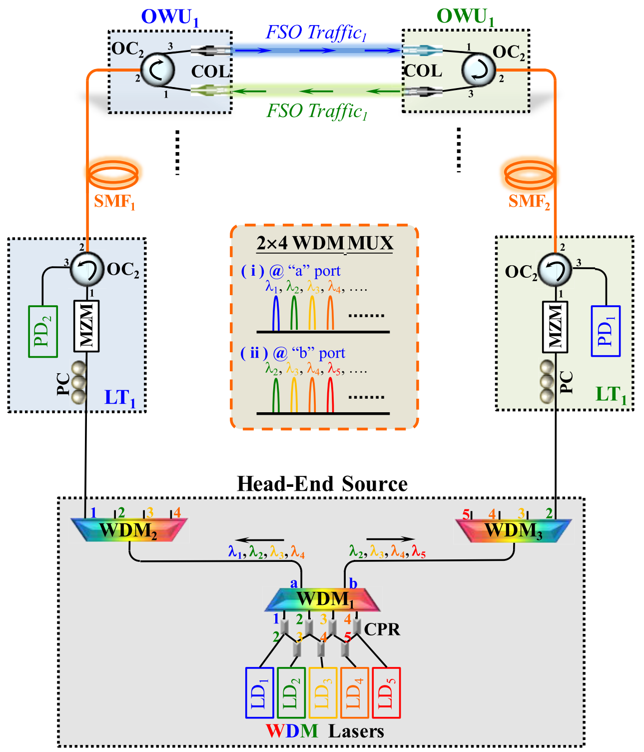

FIGURE 2. Proposed bidirectional WDM-FSO transmission architecture with RB beat noise mitigation.

bidirectional FSO connection. Moreover, the bidirectional WDM-FSO transmission is emitted from the corresponding OWU placing at the properly location for the dedicated point-to-point data connection.

Fig. 2 shows the proposed bidirectional WDM-FSO transmission architecture. In the HE site, there are five CW WDM lasers (LD_1 to LD_5) can be connected to the 2×4 WDM multiplexer (WDM_1) via seven 1×2 and 50:50 optical couplers (CPRs), as illustrated in Fig. 2. Hence, the LD_1 (λ_1) and LD_2 (λ_2), LD_2 (λ_2) and LD_3 (λ_3), LD_3 (λ_3) and LD_4 (λ_4), and LD_4 (λ_4) and LD_5 (λ_5) are connected to the input ports "1", "2", "3" and "4" of 2×4 WDM_1, respectively. Besides, based on the characteristic of 2×4 WDM_1, the wavelengths of λ_1, λ_2, λ_3 and λ_4; and λ_2, λ_3, λ_4 and λ_5 would be exported from the output port "a" and "b" of WDM_1, respectively, as seen in Fig. 2. Thus, the output wavelengths of λ_1 to λ_4 and λ_2 to λ_5 would enter the corresponding 1×4 WDM_2 and 1×4 WDM_3 in the left and right side of Fig. 2, respectively. Then, the left wavelengths of λ_1 to λ_4 would arrive at the corresponding FSO LT. Next, the WDM signals pass through a length of single-mode fiber (SMF_1) and then into each OWU for FSO transmission, as shown in Fig. 2. The LT is consisted of the polarization controller (PC), Mach-Zehnder modulator (MZM), optical circulator (OC) and a photodiode (PD). The OWU is constructed by an OC and two fiber-based collimators (COLs) for bidirectional FSO connection.

Next, the left WDM wavelengths are emitted via COL and pass through a length of free space transmission and could be received by the right COL. Thus, the WDM FSO signals

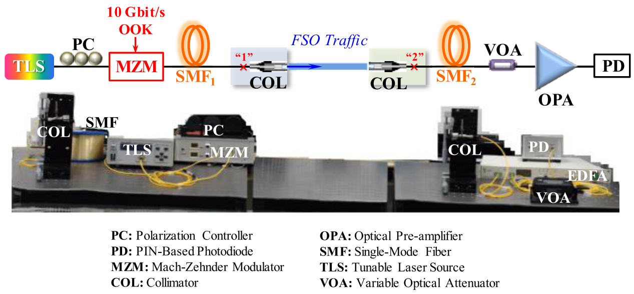

FIGURE 3. Experimental setup of the proposed WDM-FSO transmission. The photo is the related hardware diagram.

would launch into a length of SMF_2 and then into the right LT for FSO demodulation. Similarly, the WDM wavelengths of λ_2 to λ_5 would be emitted from the right side of the proposed FSO system architecture and detected in the left LT, as seen in Fig. 2. Here, the distributed lengths of SMF_1 and SMF_2 can be set for each OWU according to the practical environmental location. In accordance with the proposed WDM-FSO architecture, the five WDM wavelengths can result in four pairs of FSO LTs and OWUs. Hence, a pair wavelength of λ_1 and λ_2, λ_2 and λ_3, λ_3 and λ_4, and λ_4 and λ_5 are used for the OWU_1 to OWU_4 to produce the bidirectional FSO transmissions, respectively. In the demonstration, due to the bidirectional FSO traffic with different downstream and upstream wavelengths in fiber transmission, the proposed WDM-FSO system also can avoid the Rayleigh backscattering (RB) interferometric beat noise [18]. As a result, the proposed WDM-FSO system not only can use the same multiple WDM signals for bidirectional FSO traffic from the HE site, but also can mitigate the RB beat noise. In addition, the proposed FSO system also can lead to exclusive connection with confidentiality for end user.

Fig. 3 exhibits the experimental setup of the proposed WDM-FSO transmission for proof of concept. In the experiment, a tunable laser source (TLS) connects to the PC and 10 GHz MZM. Adjusting the polarization status of PC can maintain the optimal output power of WDM-FSO signal after through the MZM. The TLS is used to switch the different output wavelength for the demonstration of each WDM-FSO signal. Here, the WDM wavelengths of 1530.33, 1532.29, 1534.25, 1536.22 and 1538.19 nm are applied in the measurement for executing the bidirectional FSO transmissions, respectively. Fig. 4 displays the measured output wavelength spectra of five WDM-FSO signals. The output power of each wavelength is nearly 10 dBm before entering the MZM. In the experiment, the insertion losses of MZM and PC are 7 and 1 dB. To enhance the output power of each WDM channel, an erbium-doped fiber amplifier (EDFA) can be applied in the HE site. The saturation output power maximum noise figure (NF) of EDFA are 13 dBm and 6 dB over the wavelength range of 1528.0 to 1562.0 nm. Here, to avoid the nonlinearity effect of FSO signal in fiber link, a variable optical attenuator (VOA) is also utilized for power adjustment properly. Thus, the observed output power of each FSO wavelength

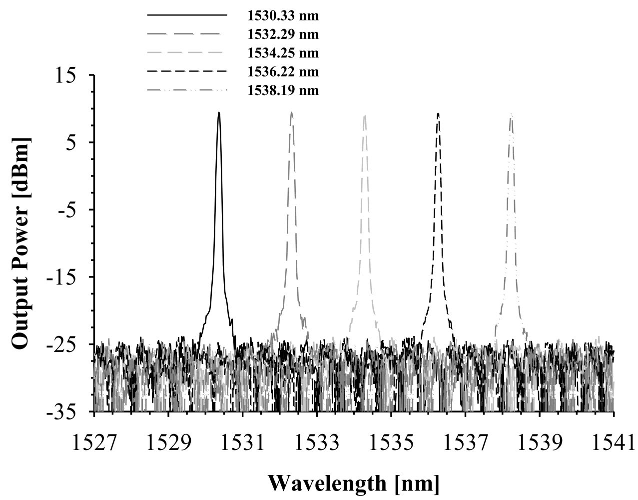

FIGURE 4. Measured output wavelength spectra of five WDM-FSO signals.

is ~7 dBm after leaving MZM to prevent the nonlinearity, as seen in Fig. 3. Then, a 10 Gbit/s on-off keying (OOK) modulation signal with a pattern length of $2^{15}-1$ is applied on the MZM for FSO data traffic. The FSO wavelength would experience through the SMF_1, COL, and a 5 m long free space transmission length. And then the wireless FSO signal could be collected by a COL and into a 10 GHz PIN-based PD after passing through a length of SMF_2. In the experiment, the divergence angle of COL is 0.016°. An optical pre-amplifier, which is consisted of an EDFA and a VOA, can be utilized to enhance the detected power sensitivity of FSO signal for measuring the bit error ratio (BER) performance in the Rx site. In addition, the observed insertion losses, including the atmospheric absorption and coupling loss, between two COLs are 3.2, 3.0, 3.0, 2.8 and 2.6 dB, respectively, when the FSO wavelengths of1530.33, 1532.29, 1534.25, 1536.22 and 1538.19 nm are utilized.

The FSO wavelength of 1530.33 nm is selected for measurement. The wireless FSO transmission length is set at 5 m. When the COL is rotated by θ angle, then it would cause a corresponding vertical displacement (d or $-$d) in the receiver (Rx) side, as illustrated in Fig. 6(a). As mentioned above, the observed power sensitivity of 1530.33 nm is -23.5 dBm at the BER of 1×10^{-9}. Hence, Fig. 6(b) presents the obtained BER measurement under the different displacements of 0 to 1.19 cm when the SMF_1 and SMF_2 are 0 and 0 km and the θ is rotated from 0° to 0.137°, respectively. With the increase of displacement d (rotation angle θ) slightly, the observed BER performance also becomes worse. When the displacement d is 0 and 1.19 cm, the measured BERs are error free ($\leq 1\times10^{-9}$) and 1×10^{-3}, respectively. When the θ is larger than 0.137°, the BER cannot be observed in this measurement. It means that the obtained sensitivity power would be below -30.5 dBm (BER$<3.8\times10^{-3}$). Here, to keep the obtained BER within the FEC threshold, the available tolerance of ±1.19 cm displacement ($\theta = \pm 0.137°$) in the Rx side is permissible in the experiment. According to the

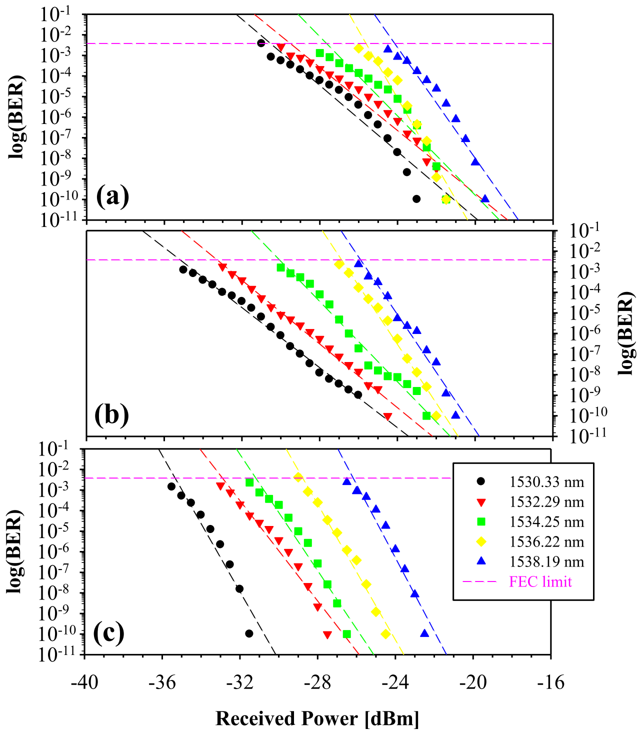

FIGURE 5. Measured BER performances of five FSO signals with 10 Gbit/s OOK modulation after 5 m long free space transmission, when the SMF_1 and SMF_2 are set (a) at the BtB and BtB, (b) 25 km and BtB, and (c) BtB and 25 km, respectively.

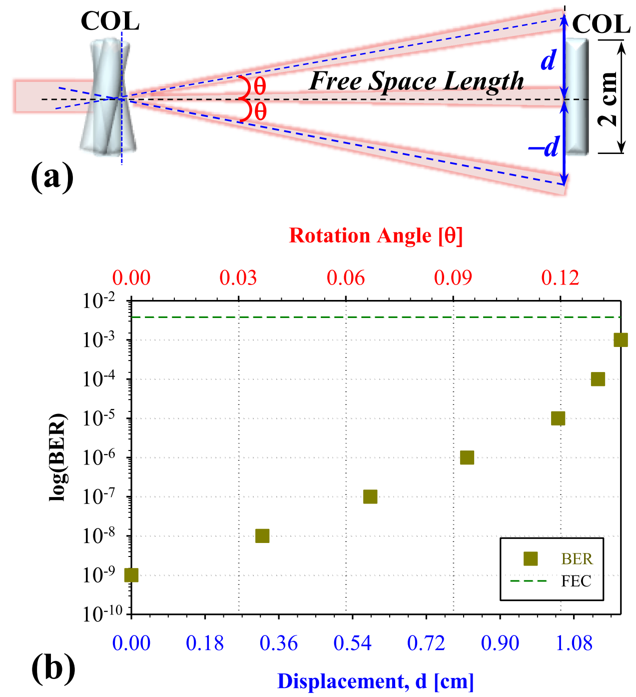

FIGURE 6. (a) Experimental setup of by rotating angle for the BER measurement. (b) Obtained BER performance under the different displacements of 0 to 1.18 cm at the BtB status.

above results, the rotation angle would affect the detected FSO power in the PD. With increasing the rotation angle of COL slowly, the detected power would also reduce. Hence, if the detected sensitivity power can meet the FEC limit no matter how long the wireless transmission lengths, the measured FSO signal also should be demodulation.

Figs. 5(a) to 5(c) show the measured BER performances of five FSO signals with 10 Gbit/s OOK modulation after 5 m long free space transmission, when the SMF_1 and SMF_2 are set at the 0 km [back-to-back (BtB)] and 0 km, 25 km and 0 km, and 0 km and 25 km, respectively. As indicated in Figs. 5(a) to 5(b), the observed power sensitivities of 1530.33, 1532.29, 1534.25, 1536.22 and 1538.19 nm are −30.5, −29.6, −27.6, −25.6 and −24.2 dBm, −35.2, −33.3, −30.0, −26.9 and −25.9 dBm, and −35.3, −32.9, −31.1, −28.7 and −26.2 dBm, respectively, under the forward error correction (FEC) level, which means the BER = 3.8×10^{-3}. Thus, the maximum and minimum power budgets are 42.3 and 31.2 dB in the experiment. In the measurement, as the FSO wavelength moves toward longer wavelengths, the obtained corresponding sensitivity will gradually deteriorate. Moreover, we observe that the measured BER performance after through 25 km SMF is better than that of the BtB status, as exhibited in Figs. 5(a) to 5(c). This is because the chirp parameter of MZM is −0.7. The negative chirp could pre-compensate the chromatic fiber-dispersion of FSO signal and result in a better BER performance after through a 25 km SMF transmission length. Moreover, the observed results of Fig. 5(c) are also better than that of Fig. 5(b). The obtained sensitivity of FSO signal could determine the free space transmission length under an optimal optical system design. In the measurement, we select 1535±5 nm wavelength range for the proof of concept in WDM-FSO transmission. Certainly, we can also utilize the other WDM wavelengths for FSO traffics in the proposed network architecture. Moreover, based on the measured results of Fig. 5, when the FSO signal gradually moves toward long wavelengths slowly, the obtained power sensitivity would also increase.

According to the previous study [19], the RB beating noise would decrease the signal to noise ratio (SNR) of ∼6.5 dB when same wavelengths were used for bidirectional traffic. The lower SNR would result in poor BER performance. Moreover, as the length of the fiber decreases gradually, the effect of RB interference would also decrease [19]. If the SMF length is less than 25 km, the RB beat noise would be reduced.

In the investigation, we can use the Kolmogorov model to express the atmospheric turbulence. Moreover, the detailed model statements have been also studied in ref. 21. Here, the OOK format-based channel models in FSO wireless transmission have also been analyzed in great detail in ref. 22. In addition, in the FSO traffic system, the haze- and rain-induced attenuations are the main atmospheric turbulences. The related analyses of haze- and rain-induced atmospheric attenuations have been also demonstrated in ref. 23. Hence, when the weather condition is under the status of light-haze, heavy-haze, light-rain and heavy-rain, respectively, the corresponding attenuation would reach 0.61, 2.62, 6.8 and 19.77 dB/km.

TABLE 1. Comparisons of FSO traffic characteristics in our proposed WDM-FSO network and previous works.

	Ref. [3]	Ref. [10]	Ref. [14]	Ref. [23]	Proposed
FSO Rate (Gbps)	56	4	10	10	10
Wavelength Range (μm)	1.5	1.5	1.5	1.5	1.5
Modulation	PAM-4	OFDM	OOK	OOK	OOK
Bandwidth (GHz)	28	1	10	10	10
WDM Channel	No	No	Yes	Yes	Yes
Bidirectional	Yes	No	Yes	Yes	Yes
Tolerance Analysis @ Rx	No	No	No	No	Yes
SMF Length (km)	40	20	/	40	25
RB Noise Mitigation	No	No	/	No	Yes
Min. Sensitivity (dBm) @FEC (BER≤3.8×10^{-3})	−6	/	−18	−19.5	−35.3
FSO Length (m)	50	0.9	25	10	5

We would like to realize the effect of rotation angle (θ) of COL on the observed BER in the OWU, the relative analysis is performed experimentally. In the experiment, the diameter (φ) and focal length of COL used is 2 and 3.173 cm. Here, In the demonstration, we also compare the characteristics of proposed FSO system with the previous works, as shown in Tab. 1. In 2018, Huang *et al.* demonstrated 56 Gbit/s PAM-4 FSO traffic for 50 m free space transmission link with the power sensitivity of −6 dBm under the FEC target indoors. However, due to the lower sensitivity of FSO signal, the network system needed more optical amplifiers to compensate the insertion losses of the longer SMF length and FSO link to support 50 m free space link [3]. In 2016, Zhang *et al.* mentioned 4 Gbit/s OFDM FSO traffic under 0.9 m free space link. However, they didn't present the detected sensitivity. Thus, it could not predict the maximum length of FSO transmission in their demonstration [10]. In 2017, Liaw *et al.* utilized four WDM wavelengths for bidirectional 10 Gbit/s OOK FSO transmission under 25 m free space link. Nevertheless, the demonstrated FSO system was not through the SMF for data link [14]. In 2015, Yu *et al.* investigated a 10 Git/s OOK FSO system with 10 m FSO traffic link through 40 km SMF for outdoor bridge application [23]. As mentioned above, the previous works does not consider the interference effect of RB beat noise in WDM fiber access. As shown in Tab. 1, the corresponding power sensitivities of prior arts are greater than our proposed FSO system. In addition, the lower sensitivity of FSO signal can result in larger power budget to reach the longer SMF and free space transmission lengths for traffic link. As shown in Tab. 1, we also investigate the available tolerance in the Rx side for FSO channel to meet the FEC target. As a result, the presented WDM FSO transmission network can not only apply the multiple WDM wavelengths for bidirectional connection successfully but can also avoid the RB beat noise.

III. CONCLUSION

In summary, we proposed and experimentally demonstrated a bidirectional WDM-FSO transmission system with 10 Gbit/s OOK traffic data in a 5 m free space transmission length. Here, the five WDM signals could be employed simultaneously for four pairs of OWUs based on our proposed WDM-FSO network architecture for bidirectional FSO traffic together with different downstream and upstream wavelengths. The proposed WDM-FSO signal could transmit through a 25 km SMF first and then emit through a 5 m free space transmission length; and emit through a 5 m free space transmission length first and then transmit through a 25 km SMF for data detection. Besides, the corresponding power sensitivity of each WDM FSO signal was also executed and discussed in the measurement. Hence, according to the proposed bidirectional WDM-FSO network, the FSO link not only was dedicated connection, but the RB beat was also avoided significantly. In addition, the available tolerance of ±1.19 cm displacement (rotation angle of ±0.137°) was allowed in the Rx side for FSO traffic to satisfy the FEC limit under a 5 m long wireless transmission length.

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