IEEE Photonics Journal
An IEEE Photonics Society Publication

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Volume 10, Number 4, August 2018

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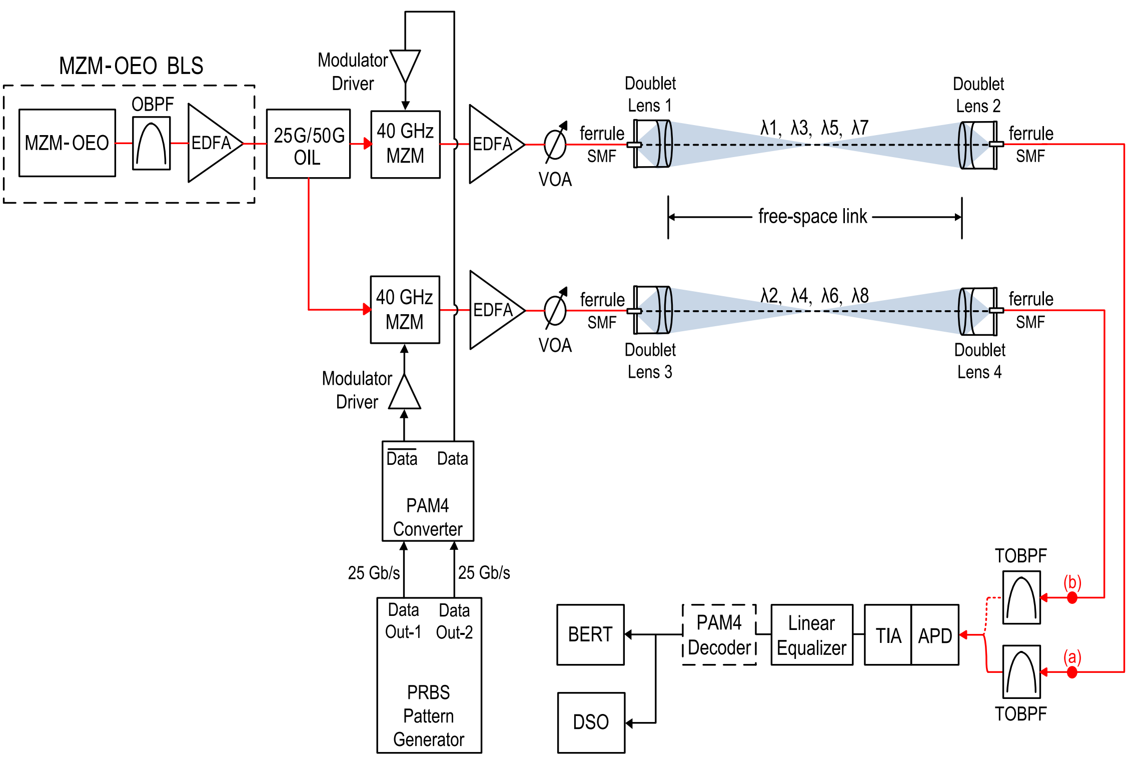

DOI: 10.1109/JPHOT.2018.2859321

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A High-Speed and Long-Reach PAM4 Optical Wireless Communication System

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DOI:10.1109/JPHOT.2018.2859321

Manuscript received June 1, 2018; revised July 20, 2018; accepted July 21, 2018. Date of publication July 24, 2018; date of current version August 8, 2018. This work was supported in part by the Ministry of Science and Technology of Taiwan under Grant MOST 107-2636-E-027-002 and Grant MOST 104-2221-E-027-072-MY3. Corresponding author: Hai-Han Lu (e-mail: hhlu@ntut.edu.tw).

Abstract: A high-speed (400 Gb/s) and long-reach (180 m) four-level pulse amplitude modulation (PAM4) optical wireless communication system employing Mach–Zehnder modulator (MZM)-optoelectronic oscillator (OEO) broadband light source (BLS) and doublet lenses is proposed. Analytic results show that the data rate is markedly improved by PAM4 modulation and MZM-OEO BLS with multiple wavelengths, and the free-space transmission distance is considerably increased by a couple of doublet lenses. With the support of PAM4 modulation, MZM-OEO BLS, and doublet lenses, good bit error rate performance and clear PAM4/nonreturn-to-zero eye diagram are achieved at a 400 Gb/s/180 m operation. The proposed system is presented to be an eminent one not only as a result of its evolution in free-space optical (FSO) links, but also on account of its high-speed and long-reach characteristics in FSO links.

Index Terms: Doublet lenses, MZM-OEO BLS, Optical wireless communication system, PAM4.

1. Introduction

The development of the optical wireless communication (OWC) system is toward providing high-speed and long-reach free-space optical (FSO) links. OWC system delivers data by laser beam or light emitting diode light propagation and has received significant interest on account of its promising application in FSO links [1]–[4]. For an actual realization of OWC system, constructing high-speed and long-reach FSO links is the key concern of system engineers. To construct a high-speed and long-reach OWC system, however, system engineers should have to adopt an efficient method to solve the problem of heavy data loading for free-space transmissions. A previous study demonstrated a 150 m/280 Gbps FSO link based on optoelectronic oscillator (OEO) broadband light source (BLS) and afocal telescopes [5]. However, Mach-Zehnder modulator (MZM)-OEO BLS can be employed as an alternative for OEO BLS to overcome the bandwidth limitation due to distributed feedback (DFB) laser diode (LD) [6]. And further, non-return-to-zero (NRZ) modulation can be replaced by four-level pulse amplitude modulation (PAM4) to enhance the spectrum efficiency and increase the data rate. In addition, doublet lenses can be adopted as a substitute for afocal telescopes to reduce the divergence of laser beam and extend the free-space transmission distance. Other previous study demonstrated a 400 Gbps/100 m FSO link with dense-wavelength-division-multiplexing (DWDM) and space-division-multiplexing (SDM) schemes [7]. A 16-parallel 25-Gbps FSO link with an overall data rate of 400 Gbps over a 100-m free-space transmission is illustrated. Nevertheless, sophisticated 1×16 arrayed waveguide grating (AWG) multiplexer/demultiplexer (MUX/DEMUX) and complicated 16 pair of doublet lenses are required. These 1×16 AWG MUX/DEMUX and 16 pair of doublet lenses increase the complexity of FSO link. For a practical operation of 400 Gbps FSO link, it is needed to develop a configuration with low complexity. In this demonstration, we propose and practically demonstrate a high-speed and long-reach PAM4 OWC system with MZM-OEO BLS and doublet lenses. The data rate is significantly increased by PAM4 modulation and MZM-OEO BLS with multiple wavelengths, and the free-space transmission distance is considerably enhanced by doublet lenses. This demonstration shows a PAM4 OWC system with MZM-OEO BLS and doublet lenses employing two OWC links as an illustration. A total wavelength of 8 wavelengths (4 odd wavelengths for upper OWC link and 4 even wavelengths for lower OWC link) is attained, for each wavelength carrying PAM4 signal with a data rate of 50 Gb/s (25 Gbaud/s). A PAM4 OWC system with a total data rate of 400 Gb/s (50 Gb/s/λ × 8λ) over a 180-m free-space transmission is demonstrated. To authors' understanding, it is the foremost one to practically establish a 400 Gb/s/180 m PAM4 OWC system with MZM-OEO BLS and doublet lenses. The performances of the offered PAM4 OWC systems have been investigated by bit error rate (BER) and PAM4/NRZ eye diagrams in real-time. BER values remain well at 10^{-9} over a 180-m free-space transmission. Clear eye diagrams (PAM4 and NRZ eye diagram) are attained over a 180-m free-space transmission as well. This proposed high-speed and long-reach PAM4 OWC system with MZM-OEO BLS and doublet lenses is a prominent candidate for achieving high data rate and long free-space transmission characteristics.

2. Experimental Setup

Fig. 1 presents the configuration [Fig. 1(a)] and photographs [Fig. 1(b)] of offered high-speed (400 Gb/s) and long-reach (180 m) PAM4 OWC systems with MZM-OEO BLS and doublet lenses. An MZM-OEO BLS modulated with 25 GHz RF signal is utilized to generate multiple wavelengths with channel spacing of 0.2 nm. The output of MZM-OEO BLS is supplied to a 25G/50G optical interleaver (OIL) to split odd and even wavelengths. For OIL output with odd wavelengths, four optical wavelengths of λ_1, λ_3, λ_5, and λ_7 with channel spacing of 0.4 nm are inputted into an MZM with 40 GHz. For OIL output with even wavelengths, four optical wavelengths of λ_2, λ_4, λ_6, and λ_8 with channel spacing of 0.4 nm and are inputted into another MZM with 40 GHz. Each MZM is driven by a 50 Gb/s PAM4 signal with a pseudorandom binary sequence (PRBS) length of $2^{15} - 1$ (PRBS 15). Evidently, the same PRBS 15 test pattern is delivered over all 4 wavelengths. If each wavelength would carry its own modulation, then there would be crosstalk because of the incomplete isolation of the adjacent links. Such crosstalk would lead to worse BER performance. Furthermore, 8 PRBS generators are required to construct such a 400 Gb/s/180 m PAM4 OWC system. These 8 PRBS generators will increase the cost of systems. For a practical implementation of high-speed and long-reach PAM4 OWC systems, it is necessary to develop a configuration with potentially economic advantage. A two-channel PRBS pattern generator produces two binary PRBS data streams with an aligned clock at 25 Gb/s. A PAM4 converter, with data output and data bar output, is employed to convert two 25 Gb/s NRZ signals into one 50 Gb/s PAM4 signal. After electrical driving by a modulator driver, a 50 Gb/s PAM4 signal is sent to the MZM. Given that PAM4 linearity is a very important parameter, a modulator driver with high-linearity is used to drive the PAM4 electrical signal. The modulated light is then boosted by an erbium-doped filter amplifier (EDFA). To adapt the optical power sent to an OWC link, a variable optical attenuator (VOA) is placed at the beginning of OWC link. For an OWC link, a couple of doublet lenses is deployed to emanate laser beam from the ferrule of single-mode fiber (SMF) (transmitting side) into the free-space and to guide laser beam from the free-space into the ferrule of SMF (receiving side).

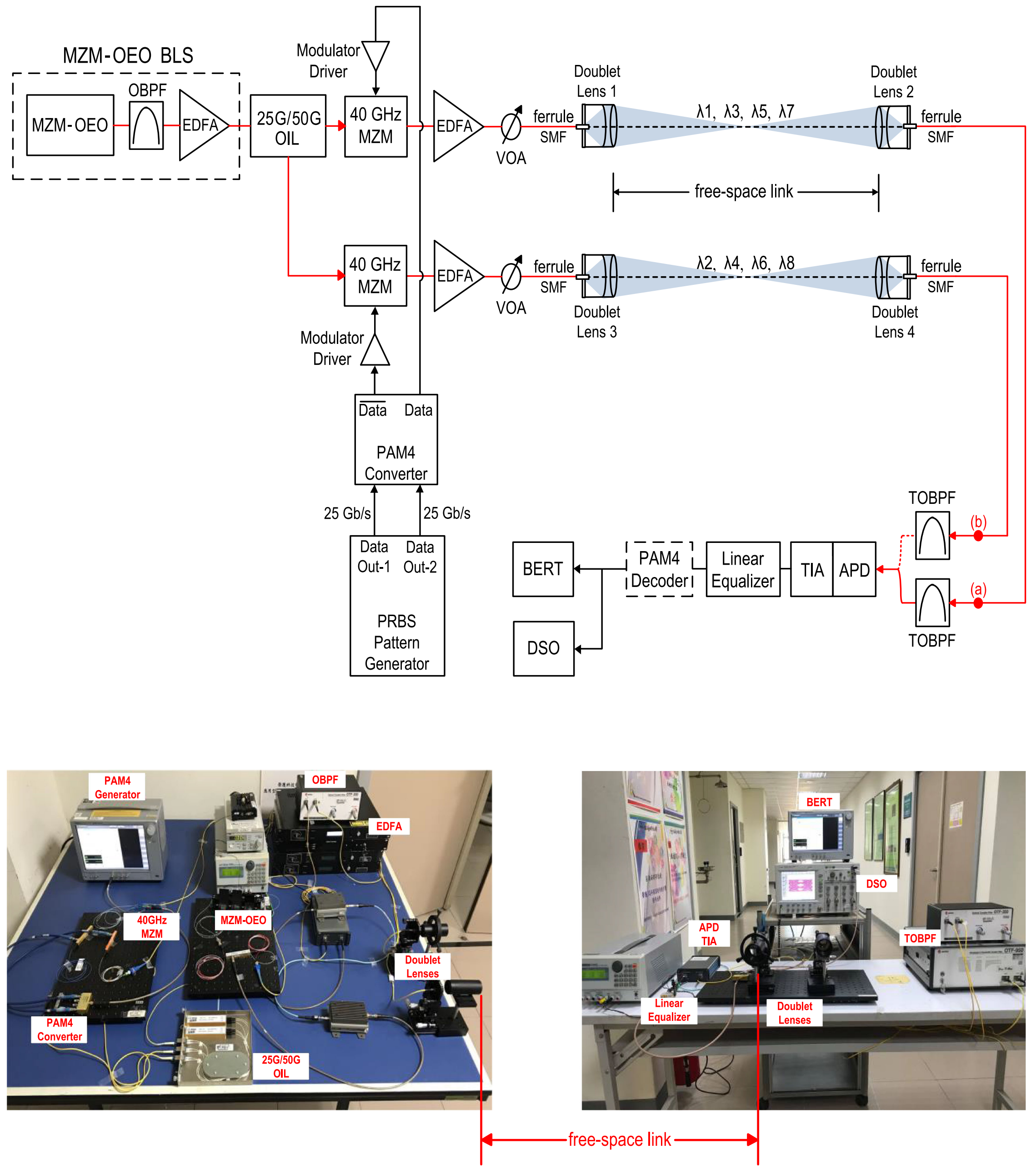


Fig. 1. (a). The configuration of offered high-speed (400 Gb/s) and long-reach (180 m) PAM4 OWC systems with MZM-OEO BLS and doublet lenses. (b). The photographs of offered high-speed (400 Gb/s) and long-reach (180 m) PAM4 OWC systems with MZM-OEO BLS and doublet lenses.

Each OWC link has various free-space transmissions in the span of 180–210 m. Over a long-reach free-space transmission, the laser beam reaches a tunable optical band-pass filter (TOBPF) to filter the desired wavelength. The filtered optical wavelength is detected by a 25-GHz avalanche photodiode (APD) with a trans-impedance amplifier (TIA) receiver. Here, an optical receiver that employs an APD with a TIA provides a high signal-to-noise ratio (SNR). Afterwards, the detected and boosted 50 Gb/s PAM4 signal is electrically equalized by a linear equalizer. A digital storage oscilloscope (DSO) is deployed to catch the eye diagrams of delivered 50 Gb/s PAM4 signal. Additionally, a PAM4 decoder is adopted at the receiving side to decode one 50 Gb/s PAM4 signal

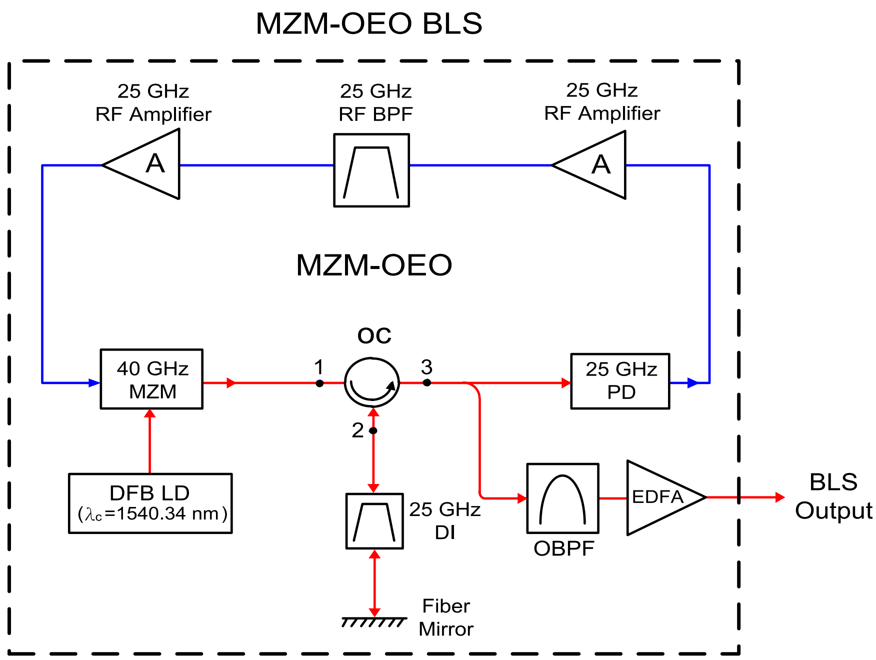


Fig. 2. The configuration of the MZM-OEO BLS.

into two 25 Gb/s NRZ signals. The performances of offered OWC systems are investigated by BER and eye diagrams in real-time. A 25 Gb/s NRZ signal is sent to a BER tester (BERT) for BER performance analysis, and the eye diagram of the 25 Gb/s NRZ signal is taken by a DSO.

3. Experimental Results and Discussions

As indicated in Fig. 2, the MZM-OEO BLS consists of one DFB LD with a central wavelength of 1540.34 nm, one 40-GHz MZM, one optical circulator (OC), one delay interferometer (DI) with 25 GHz free spectral range (FSR), one fiber mirror with reflectance of 98%, one 1×2 optical splitter, one 25-GHz PD, two 25-GHz RF amplifiers, and one 25-GHz RF BPF. Part of the output is utilized as a BLS with multiple wavelengths, whereas the other part of the output is utilized for an optoelectronic feedback loop. The amount of optical wavelengths counts on the amplitude of RF signal created by the optoelectronic feedback loop. As to the channel spacing of multiple wavelengths, it is essentially decided by the frequency of RF BPF utilized in MZM-OEO. The MZM is driven by a 25-GHz RF signal, thereby leading to the generation of multiple wavelengths with channel spacing of 25 GHz (0.2 nm). The generated multiple wavelengths are then sent to an OBPF to take away the outer wavelengths, and boosted by an EDFA to obtain higher output power.

The optical spectra of the MZM-OEO BLS with/without DI and EDFA are presented in Fig. 3. Clearly, approximately 7 to 10 dB OSNR value improvement is attained for each wavelength when DI and EDFA are utilized simultaneously. We set the generated multiple wavelengths periodically according to the FSR of DI to enhance the OSNR owing to noise reduction between every two wavelengths. Following that, an EDFA is utilized to amplify the multiple wavelengths filtered by an OBPF. As the filtered wavelengths ($\lambda_1 \sim \lambda_8$) pass through an EDFA, these filtered wavelengths are amplified to enhance the OSNR owing to carrier level promotion for each wavelength.

The optical spectra of OWC link with four odd optical wavelengths (λ_1, λ_3, λ_5, λ_7) [inset (a) of Fig. 1] and four even optical wavelengths (λ_2, λ_4, λ_6, λ_8) [inset (b) of Fig. 1] are displayed in Fig. 4(a) and (b), respectively. For Fig. 4(a) and (b), apparently, a channel spacing of 50 GHz is attained. To have an actual operation of PAM4 OWC system, the wavelengths of λ1, λ3, λ5, and λ7 (λ2, λ4, λ6, and λ8) from the OWC link have a wide channel spacing of 50 GHz, instead of a narrow channel

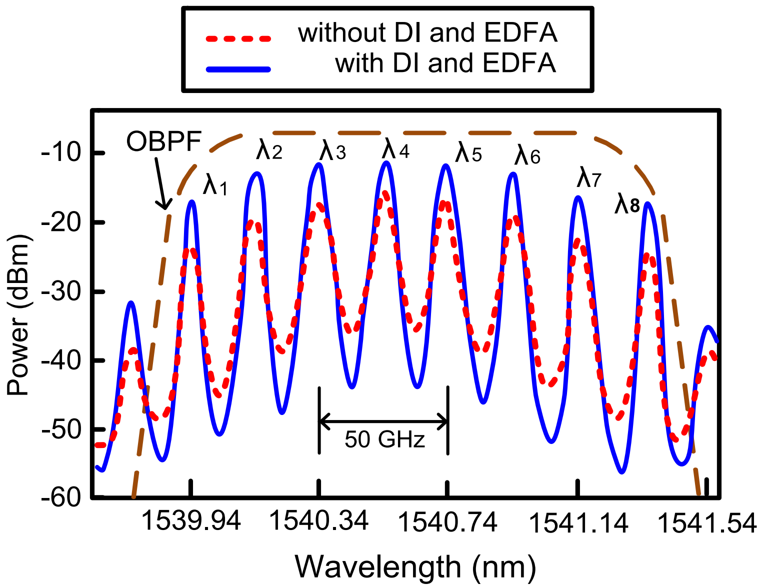


Fig. 3. The optical spectra of MZM-OEO BLS with/without DI and EDFA.

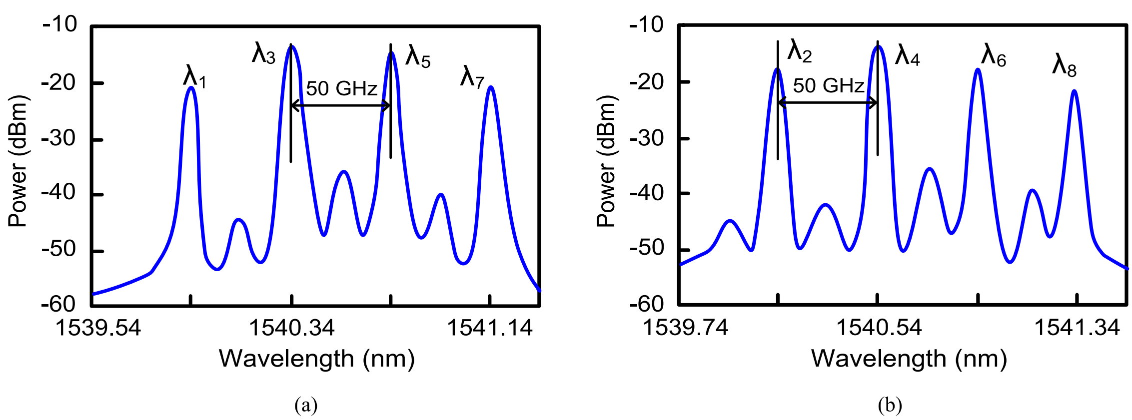


Fig. 4. The optical spectra of OWC link with (a) four odd optical wavelengths (λ_1, λ_3, λ_5, λ_7) [inset (a) of Fig. 1], and (b) four even optical wavelengths (λ_2, λ_4, λ_6, λ_8) [inset (b) of Fig. 1].

spacing of 25 GHz. If two OWC links are integrated by an optical combiner with a whole wavelength of 8 wavelengths, then there will be a narrow channel spacing of 25 GHz. Nevertheless, it will be quite challengeable to individualize each optical wavelength in such narrowly spaced optical wavelengths.

There are two applications for OWC systems, one is OWC-based indoor system, and the other is OWC-based outdoor system. For OWC-based indoor system, it has been developed with favorable optical features. OWC has attracted much attention as a potential alternative given its many advantages over RF wireless communication. Additionally, the influence of atmospheric turbulence will not exist owing to indoor system. Accordingly, OWC-based indoor system is a notable one to increase the coverage of optical wireless networks.

For OWC-based outdoor system, it is a challenge to construct a high-speed and long-reach PAM4 OWC systems because of the influence of atmospheric turbulence. In clear weather (visibility $>$2 km), the prediction of atmospheric attenuation at 1550 nm is predictable. Whereas in heavy fog/heavy snow/heavy rain weather (10 m $<$ visibility), the prediction of atmospheric attenuation at 1550 nm is unpredictable. Heavy fog, heavy snow, and heavy rain are the main factors of weather that can affect the OWC links. Atmospheric attenuation can change from 0.02 dB/100 m in clear weather to 30 dB/100 m in heavy fog/heavy snow/heavy rain weather [8], [9]. Large attenuation in heavy fog/heavy snow/heavy rain will significantly reduce the accessibility of PAM4 OWC systems. Therefore, system designers must address the high accessibility to ensure the overall performance of PAM4 OWC systems. If the link margin for atmospheric attenuation is 30 dB, then the maximum link will have to be 100 m (or less) to overcome the worst case of 30 dB/100 m. Given that the link margin of this 180 m PAM4 OWC system is much lower than the corresponding value of worst case, this proposed PAM4 OWC system satisfies the high accessibility requirement. As for the interference from stray light, noise is generated when stray light form the environment is received by APD. The received optical SNR (OSNR) is decreased as stray light form the environment is received by APD, resulting in worse BER performance. This OSNR decrease can be compensated by controlling VOA with lower attenuation. Thus, higher optical power can be launched into a 180-m OWC link, and higher OSNR can be obtained to make up for OSNR decrease owing to the interference from stray light.

The amplitude modulation scheme is shown not to be the efficient way of optical communications due to the uncertainty in detecting information from various light intensities specially in high-speed and long-reach scenarios. For PAM4 modulation, it can reduce the bandwidth requirement for optical and electrical devices, which is suitable for high-speed transmission. As for the scenario of long-reach free-space link, PAM4 signal can be electrically equalized by a linear equalizer at the receiver side to enhance the data rate and free-space link. Linear equalization indicates an operation designed to dominate the levels of high frequencies compared with the levels of low frequencies. The operation of the linear equalizer is to recompense the frequency response, leading to the enhancement of data rate and free-space link [10]–[12].

For PAM4 signal transmission, the connection between BER and symbol error rate (SER) is given by [13]:

$$BER \approx d_{ij} \frac{SER}{log_2 4} = d_{ij} \frac{SER}{2} \tag{1}$$

where d_{ij} is the Hamming distance between the labels of symbols i and j. The total BER can be determined by measuring the SER of top, middle and bottom eyes of PAM4 signal:

$$BER = \frac{1}{2} SER_{top} + SER_{mid} + \frac{1}{2} SER_{bot} \tag{2}$$

Real-time BER is calculated by adopting PAM4 three-eye sampling method. This method is worthy of adopting due to the use of low cost PAM4 BER measurement method. A PAM4 OWC system with BER real-time measurement is attractive because complicated offline calculation by MATLAB is not required. As to orthogonal frequency-division multiplexing (OFDM) signal transmission, OFDM OWC systems have been proposed in previous studies [14], [15]. However, the OFDM signal must be produced offline by MATLAB program and uploaded into an expensive arbitrary waveform generator (AWG). At the receiver side, the OFDM signal must be calculated offline by MATLAB for the analysis of BER performance and the corresponding constellation map. This offline calculation increases the complication of OWC systems. In comparison with OFDM OWC systems, such proposed PAM4 OWC systems does not use complicated offline calculation and expensive AWG. It reveals a prominent one with simpler and more economic advantages.

The BER curves of PAM4 OWC systems at a filtered wavelength of $\lambda 1$ over various free-space transmissions in the span of 180–210 m are shown in Fig. 5. Apparently, BER value increases with increased free-space transmission. As the FSO link is 180 m, the BER value is improved to 10^{-9}. Over a 190-m free-space transmission, the BER value reaches 10^{-8} on account of OSNR decrease owing to more 10-m free-space transmission (comparison of the scenario over a 180-m free-space transmission). Over a 210-m free-space transmission, however, the BER value degrades to 5×10^{-3} as a result of large OSNR decrease and laser beam misalignment owing to more 30-m free-space transmission (comparison of the scenario over a 180-m free-space transmission). More 30-m free-space transmission causes higher transmission loss (higher attenuation), thereby

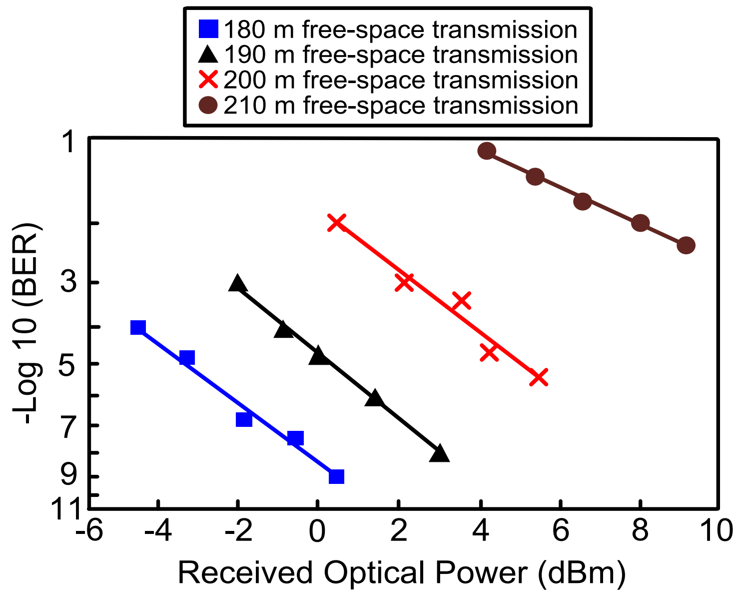


Fig. 5. The BER curves of PAM4 OWC systems at a filtered wavelength of λ_1 over various free-space transmissions in the span of 180–210 m.

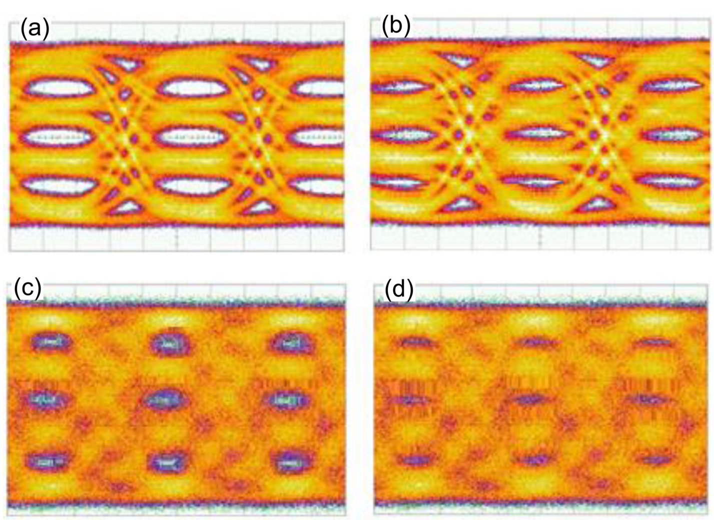
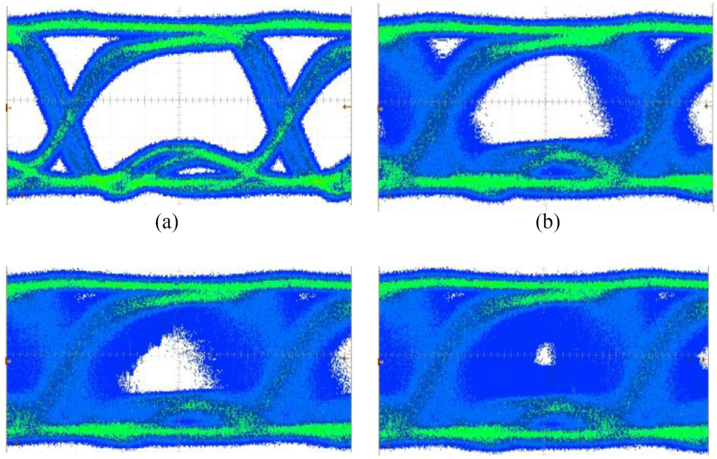


Fig. 6. The eye diagrams of 50 Gb/s PAM4 signal at a filtered wavelength of λ_8 (a) over 180 m free-space transmission, (b) over 190 m free-space transmission, (c) over 200 m free-space transmission, and (d) over 210 m free-space transmission.

leading to lower OSNR and higher BER. The laser beam alignment at the receiving side plays an important role for transmission performances [16], [17]. Particularly, a laser beam misalignment rapidly degrades the overall performances of the PAM4 OWC systems. Since that the laser beam is very narrow and the receiving area of the ferrule of SMF (receiving side) is very small, keeping the PAM4 OWC systems for an acceptable optical wireless link is quite challengeable. An infrared detection card, with wavelength span of 1500–1595 nm, is utilized to track, align, and point the laser beam for achieving qualified free-space transmission performances. As optimal laser beam alignment occurs, the PAM4 OWC systems have brilliant performances with a quite low BER value and a quite qualified eye diagram.



(a) (b) (c) (d)

Fig. 7. The eye diagrams of 25 Gb/s NRZ signal at a filtered wavelength of λ_8 (a) over 180 m free-space transmission, (b) over 190 m free-space transmission, (c) over 200 m free-space transmission, and (d) over 210 m free-space transmission.

At the receiving side, a PAM4 decoder is deployed to transform one 50 Gb/s PAM4 signal into two 25 Gb/s NRZ signals. The eye diagrams of 50 Gb/s PAM4 signal (without PAM4 decoder at the receiving side)/25 Gb/s NRZ signal (with PAM4 decoder at the receiving side) at a filtered wavelength of λ8 over various free-space transmissions are displayed in Fig. 6(a)–(d)/Fig. 7(a)–(d), respectively. Clear eye diagrams are observed for the conditions of over 180 m and 190 m free-space transmissions [Fig. 6(a) and (b)/Fig. 7(a) and (b)]. However, a large amount of amplitude and phase variations exist for the condition of over 200 m free-space transmission [Figs. 6(c) and 7(c)]. Additionally, compact eye diagrams are observed evidently for the condition of over 210 m free-space transmission [Figs. 6(d) and 7(d)] due to more 30-m free-space transmission (in comparison with the condition of over 180 m free-space transmission).

4. Conclusion

A high-speed (400 Gb/s) and long-reach (180 m) PAM4 OWC system that adopts MZM-OEO BLS and doublet lenses is offered. The data rate is greatly enhanced by PAM4 modulation and MZM-OEO BLS with multiple wavelengths, and the free-space transmission is significantly extended by doublet lenses. A whole data rate of 400 Gbps is effectively transmitted at a 180-m free-space operation. This finding shows that such a PAM4 OWC system with MZM-OEO BLS and doublet lenses can provide the benefits of FSO links for high data rate and long free-space transmission characteristics. A future study is to fabricate such high-speed and long-reach PAM4 OWC systems for practical applications. PAM4 OWC systems can cover the areas with the potential for faster speed and longer free-space link. High-speed and long-reach PAM4 OWC systems could be deployed in the near future.

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