IEEE Photonics Journal
An IEEE Photonics Society Publication

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Volume 9, Number 1, February 2017

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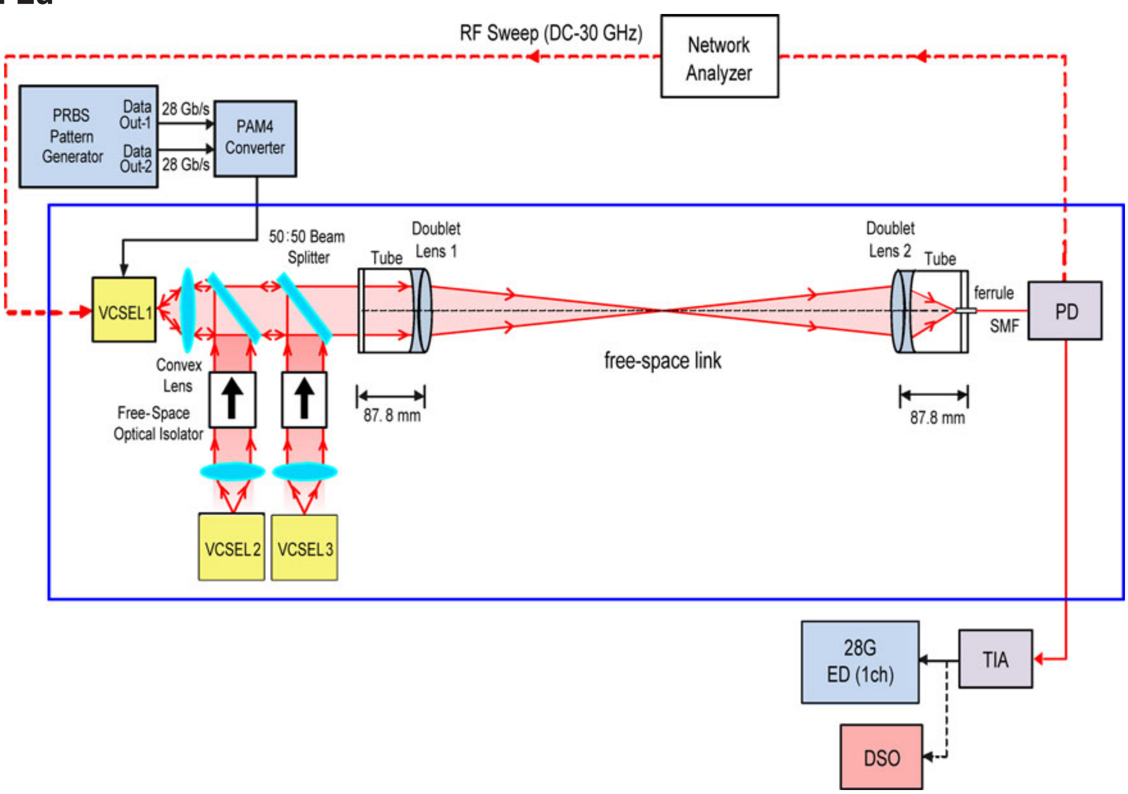

DOI: 10.1109/JPHOT.2016.2637564
1943-0655

A 56 Gb/s PAM4 VCSEL-Based LiFi Transmission With Two-Stage Injection-Locked Technique

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DOI:10.1109/JPHOT.2016.2637564

Manuscript received November 7, 2016; revised December 4, 2016; accepted December 6, 2016. Date of publication December 8, 2016; date of current version December 28, 2016. This work was supported by the Ministry of Science and Technology of the Republic of China under Grant MOST 104-2221-E-027-072-MY3 and Grant MOST 105-2633-E-027-001. Corresponding author: H.-H. Lu (e-mail: hhlu@ntut.edu.tw).

Abstract: A 56 Gb/s four-level pulse amplitude modulation (PAM4) light-based WiFi (LiFi) transmission based on a 680-nm/5.4-GHz vertical-cavity surface-emitting laser (VCSEL) with a two-stage injection-locked technique is proposed and demonstrated. Experimentally results show that a 5.4-GHz VCSEL with a two-stage injection-locked technique is effective for 56 Gb/s PAM4 LiFi transmissions. To the authors' knowledge, it is the first one to adopt a 680-nm VCSEL transmitter with two-stage injection-locked technique in a 56 Gb/s PAM4 LiFi transmission. A pair of doublet lenses is employed in the proposed PAM4 VCSEL-based LiFi transmissions to enhance the free-space link. The link performances of the proposed PAM4 LiFi transmissions have been analyzed in real time. Good bit error rate performance and three independent clear eye diagrams are obtained over a 20-m free-space link. Such a proposed 56 Gb/s PAM4 VCSEL-based LiFi transmission with two-stage injection-locked technique has the potential to play a significant role in future wireless infrastructure for providing high transmission rate and long free-space transmission distance effectively.

Index Terms: Four-level pulse amplitude modulation, light-based WiFi (LiFi) transmission, two-stage injection-locked technique, vertical-cavity surface-emitting laser (VCSEL).

1. Introduction

Currently, a higher order modulation format, such as four-level pulse amplitude modulation (PAM4), has been proposed to increase the transmission rate of lightwave transmission systems [1]–[8]. The PAM4 signal is generated by combining a two-channel non-return-to-zero (NRZ) signal and is considered as a good replacement because of its effective bandwidth utilization. The spectrum of the PAM4 signal is exactly half as wide as that of the NRZ signal, making this format potentially favorable in high-speed transmission. PAM4 modulation can enhance the spectrum efficiency and the transmission rate, thereby regarded as one of the key solutions for short-reach lightwave transmissions.

A 25 Gb/s NRZ vertical-cavity surface-emitting laser (VCSEL)-based light-based WiFi (LiFi) transmission with two-stage injection-locked technique has been demonstrated previously [9]. However, this two-stage injection-locked technique has not been utilized as a performance improvement technique in a 56 Gb/s PAM4 VCSEL-based LiFi transmission. Two-stage injection-locked technique, which can integrate the optical advantages of VCSEL and create an innovative approach of high-speed operation, is therefore expected to provide a high transmission rate in PAM4 VCSEL-based LiFi transmissions. Several benefits, such as high transmission rate and long free-space link, can be achieved by introducing visible laser light propagation in free space as LiFi penetrates into optical wireless networks [10]. LiFi transmissions can utilize the strengths of both optical and wireless communications. In this paper, a 56 Gb/s PAM4 LiFi transmission based on a two-stage injection-locked 680 nm VCSEL transmitter is proposed and experimentally demonstrated. We successfully show that a 56 Gb/s PAM4 signal can be transmitted to a maximum of 20 m free-space link at a 10^{-9} bit error rate (BER) operation. To the best of the authors' knowledge, it is the first to adopt a two-stage injection-locked 680 nm VCSEL transmitter in a 56 Gb/s PAM4 VCSEL-based LiFi transmission. Good BER performance of 10^{-9} and clear eye diagrams (three independent eye diagrams) are achieved over a 20-m free-space link in the proposed PAM4 VCSEL-based LiFi transmissions. Such a two-stage injection-locked 680 nm VCSEL transmitter-based PAM4 LiFi transmission offers the advantages of communication links for high transmission rate and long transmission distance, which is highly useful for optical wireless infrastructure.

2. Experimental Setup

Fig. 1 shows the experimental configuration of the proposed 56 Gb/s PAM4 VCSEL-based LiFi transmissions with a two-stage injection-locked technique and a pair of doublet lenses. Two binary pseudorandom bit sequence (PRBS) data streams at a length of $2^{15} - 1$ at 28 Gb/s are generated from a two-channel PRBS generator with aligned clock. The amplitudes of the binary data streams (NRZ signals) are 900 and 450 mV, respectively. These two 28 Gb/s NRZ signals are fed into a PAM4 converter to create a 56 Gb/s PAM4 signal with four levels and three independent eye diagrams. VCSEL1, with output power/3-dB bandwidth/wavelength range of 3 dBm/5.4 GHz/681.72–682.12 nm, is directly modulated by a 56 Gb/s PAM4 signal. For the injection locking part, the VCSEL2 is employed as the first injection light source with an injection power level of 3 dBm, and the VCSEL3 is employed as the second injection light source with an injection power level of 4.77 dBm. The output power of VCSEL1 with a two-stage injection-locked technique is around 3.4 dBm. Light is injected through the collimating objective of the VCSEL, a free-space optical isolator, and a 50:50 beam splitter. A pair of doublet lenses (doublet lenses 1 and 2) is employed to emit laser light from a two-stage injection-locked 680-nm VCSEL transmitter into the free space and to couple laser light from the free space into the ferrule of single-mode fiber (SMF) (receiver side). The PAM4 LiFi transmissions have different free-space links in the range of 0–30 m. The laser light reaches a 25-GHz photodiode (PD) with a trans-impedance amplifier (TIA) to transfer the laser light into a 56 Gb/s PAM4 signal. The PD has a detection wavelength range of 400–1100 nm, an active area diameter of around 0.2 mm, and a responsivity of 0.4 mA/mW (at 680 nm). The received 56 Gb/s PAM4 signal is inputted into a one-channel 28 Gb/s error detector (ED). BER measurement is conducted via auto search using a one-channel 28 Gb/s ED and the PAM4 three-eye (upper/middle/lower) sampling method. The eye diagrams of the 56 Gb/s PAM4 signal are captured with a digital storage oscilloscope (DSO) at the receiver side.

Meanwhile, the measurement setup of the frequency response of the 680 nm VCSEL transmitter-based LiFi transmissions is also shown in Fig. 1. RF sweep signal (DC – 30 GHz) generated from a network analyzer is fed into the VCSEL1. The function of the network analyzer is to measure the frequency response of the 680 nm VCSEL transmitter-based LiFi transmissions. After PD detection, the detected RF sweep signal is fed into the network analyzer. Thus, the frequency response of the 680 nm VCSEL transmitter-based LiFi transmissions is measured under the scenarios of free-running, and injection locking with one and two stages. It should be noted that two signals (56 Gb/s PAM4 signal and RF sweep signal) from two different ports to modulate VCSEL1 are not transmitted

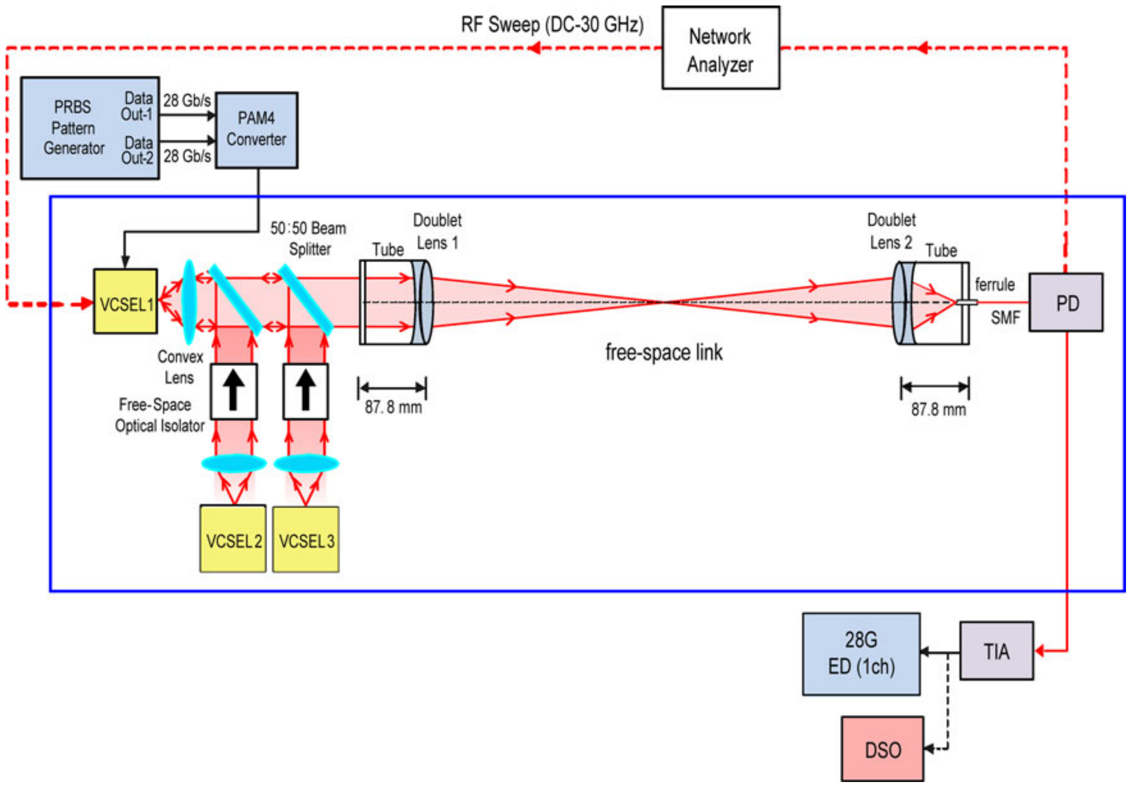

Fig. 1. Experimental configuration of the proposed 56 Gb/s PAM4 VCSEL-based LiFi transmissions with a two-stage injection-locked technique and a pair of doublet lenses.

at the same time. As the 56 Gb/s PAM4 signal modulate VCSEL1, we turn off the RF sweep signal. In the same manner, as the RF sweep signal modulate VCSEL1, we turn off the 56 Gb/s PAM4 signal.

3. Experimental Results and Discussions

For PAM-N (N is an integer) signal transmission, the symbol error rate (SER) is given by [11]

$$SER = \frac{1}{N} \sum_{i=0}^{N-1} \sum_{j=0,\ j\neq i}^{N-1} P_{ij} \tag{1}$$

where P_{ij} is the probability of receiving symbol j when symbol i is transmitted. Further, for PAM-N signal transmission, the BER is given by

$$BER = \frac{1}{N} \sum_{i=0}^{N-1} \sum_{j=0,\ j\neq i}^{N-1} \frac{d_{ij}}{\log_2 N} P_{ij} \tag{2}$$

where d_{ij} is the Hamming distance between the labels of symbols i and j [12]. From (1) and (2), BER can be approximated as

$$BER \approx d_{ij} \frac{SER}{\log_2 N}. \tag{3}$$

If Gray labeling is utilized, $d_{ij} = 1$, which yields

$$BER \approx \frac{SER}{\log_2 N}. \tag{4}$$

For PAM4 (N = 4) signal transmission, BER can be expressed in terms of SER:

$$BER \approx \frac{SER}{2}. \tag{5}$$

Thus, the total BER of the PAM4 signal can be obtained from the SER of the bottom (SER_{bot}), middle (SER_{mid}), and top (SER_{top}):

$$BER = \frac{1}{2}SER_{bot} + SER_{mid} + \frac{1}{2}SER_{top}. \tag{6}$$

Here, BER measurement is carried out by auto-searching using a one-channel ED and the PAM4 3-eye sampling approach. Such approach is worth employing due to cost-effective PAM4 BER measurement approach for counting the total BER.

LiFi transmissions can be divided into two categories: the diffused system and the line-of-sight (LOS) one. The former utilizes the diffused beam (such as LED light source) to cover the entire service area and to provide the mobile services to the user. It provides the user with internet connectivity and regular illumination. However, it is difficult to obtain high transmission rate and long free-space link due to limited bandwidth and irradiance decline with distance. On the other hand, the latter utilizes a narrow laser beam (such as VCSEL light source) to obtain high transmission rate and long free-space link. Nonetheless, no mobility is provided in LOS transmissions even though it can provide high transmission rate and long free-space transmission distance. It means that as blocking occurs, a rapid performance degradation happens in LOS transmissions. However, with the rapid progress of LiFi, the increasing requirements raise the needs for high transmission rate and long free-space link. As to the mobility problem, optical signal auto-tracking scheme can be added at the receiving side to overcome it. Optical signal auto-tracking scheme is worth employing due to the success of large coverage area. Furthermore, a bidirectional communication system would be preferred for LiFi transmissions. Asymmetrical transmission is usually deployed in a bidirectional communication system. Therefore, a bidirectional LiFi transmission can be demonstrated by employing a 56 Gb/s PAM4 VCSEL-based LiFi transmission with two-stage injection-locked technique for downlink transmission, and a 25-Gbps VCSEL-based LiFi transmission with two-stage injection-locked technique for uplink transmission [9]. Moreover, the infrared light-based LiFi transmissions can be employed to replace the visible 680-nm VCSEL-based ones. However, it is difficult to obtain good free-space transmission performance due to laser light misalignment. Since the infrared light is invisible, yet it is a challenge to aim the invisible laser light at the PD. To compare with the infrared light-based LiFi transmissions, the visible 680-nm VCSEL-based ones are attractive not only to have lower free-space attenuation but to provide easier laser light alignment as well.

The laser resonance frequency f_0 can be expressed as

$$f_0^2 = \frac{g_0 P}{4\pi^2 \tau_\rho} \tag{7}$$

where g_0 is the gain coefficient, P is the photon density, and τ_ρ is the photon lifetime. Two-stage injection locking increases the photon density significantly, which leads to a significant improvement of laser resonance frequency. Therefore, the frequency responses of the 680 nm VCSEL transmitter-based LiFi transmissions can be improved greatly. The frequency responses of the 680 nm VCSEL transmitter-based LiFi transmissions for free-running, and one- and two-stage injection-locked scenarios are illustrated in Fig. 2. The 3-dB bandwidth is 5.4, 12.8, and 26.8 GHz for the scenarios of free-running, one-stage injection-locked, and two-stage injection-locked, respectively. To compare with the previous study [9], the bandwidth expansions by one- and two-stage injection-locked scenarios are consistent with data reported in literature. Two-stage injection-locked technique further enhances the VCSEL frequency response to around 5 times (26.8/5.4 $\sim$ 4.96), indicating that such a two-stage injection-locked 680 nm VCSEL transmitter is forceful for 56 Gb/s (28 Gbaud/s) PAM4 signal transmission. Theoretically, PAM4 VCSEL-based LiFi transmissions with a multistage injection-locked technique can be implemented to enhance the transmission rate to 112 Gb/s (56 Gbaud/s), on the condition that each master laser (VCSELn, n = 2, 3, 4, ...) has enough optical

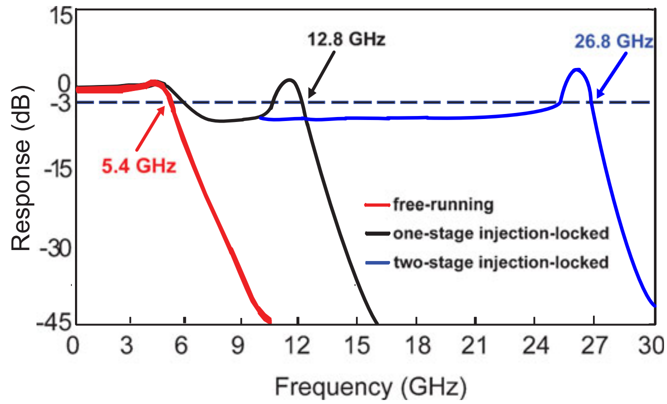

Fig. 2. Frequency responses of the 680 nm VCSEL transmitter-based PAM4 LiFi transmissions for free-running and one- and two-stage injection-locked scenarios.

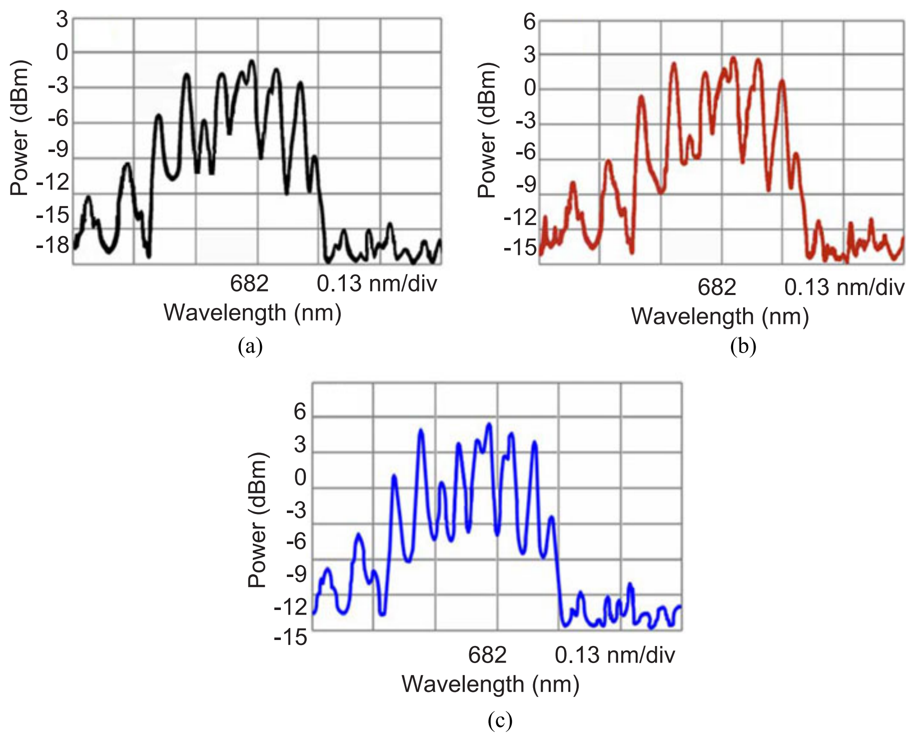

Fig. 3. Optical spectrum of VCSEL1 for (a) free-running, (b) one-stage injection-locked, and (c) two-stage injection-locked scenarios.

power to inject into the slave laser (multi-stage injection-locked VCSEL1), and the injection locking for each stage is within the injection-locked range [13].

The optical spectrum of VCSEL1 for the free-running scenario (681.72–682.12 nm) is presented in Fig. 3(a). If VCSEL1 is one-stage injection-locked, its optical spectrum shifts to a longer wavelength (681.74–682.15 nm) with a small extent, as presented in Fig. 3(b). Conversely, if VCSEL1 is two-stage injection-locked, its optical spectrum shifts to a shorter wavelength (681.72–682.12 nm) with a small extent, as presented in Fig. 3(c). To compare with the previous study [9], the optical spectrum shifts by one- and two-stage injection-locked scenarios are consistent with data reported in literature. One important characteristic of injection locking is that the injected laser is coerced to oscillate at the injection wavelength rather than the free-running wavelength [14]. Therefore, the wavelength range of VCSEL2 is 681.74–682.15 nm, and that of VCSEL3 is 681.72–682.12 nm. To obtain a high 3-dB bandwidth, the wavelengths of the injected lights must be carefully chosen to ensure optimum enhancement in the frequency response of the two-stage injection-locked VCSEL transmitter. The wavelength of the master laser (VCSEL2) must be longer than that of the slave laser (VCSEL1) with a small extent (0.02–0.03 nm) to achieve a flat frequency response for the first-stage injection-locked scenario. However, the wavelength of the master laser (VCSEL3) must be shorter than that of the slave laser (one-stage injection-locked VCSEL1) with a small extent (0.02–0.03 nm) to achieve a high-frequency resonance peak for the second-stage injection-locked scenario. On the other hand, if the wavelength of the master laser (VCSEL2) is slightly shorter than that of the slave laser (VCSEL1) for the first-stage injection-locked scenario and the wavelength of the master laser (VCSEL3) is slightly longer than that of the slave laser (one-stage injection-locked VCSEL1) for the second-stage injection-locked scenario, then the frequency response will have almost the same 3-dB bandwidth but drop a large value (around 12-15 dB) in the middle frequencies [9], [13].

For doublet lens scheme, the doublet lens1 and the doublet lens2 have a focal length (FL) of 100 mm, a diameter of 30 mm, and a back FL (BFL) of 87.8 mm. The numerical aperture (NA) of the SMF is 0.14, and thus, the diameter (d) of the laser beam is

$$d = 2 \times (100 \times 0.14) = 28 \ \text{(mm)}. \tag{8}$$

Since the diameter of the laser beam (28 mm) is smaller than the diameter of the doublet lens1 (30 mm), doublet lens1 is feasible for LiFi transmissions. This lens has a spatial frequency cutoff (SFC) and a corresponding beam radius (r). The relationship between the SFC and the corresponding beam radius (r) is as following:

$$r = 2.3 \times \frac{1}{SFC \times 2\pi} = 3.6 \quad (\mu\text{m}). \tag{9}$$

The divergence out of the objective lens (θ) is

$$\theta = \frac{3.6(\mu\text{m})}{100(\text{mm})} = 36 \times 10^{-6}. \tag{10}$$

Over a 20-m (L) free-space link, spot size (ω_o) has become

$$\omega_o = [d^2 + (2\theta L)^2]^{1/2} = [28^2 + (1.44)^2]^{1/2} = 28 \ \text{(mm)}. \tag{11}$$

Since the spot size (28 mm) is smaller than the diameter of the doublet lens2 (30 mm), a 20-m free-space link is established in LiFi transmissions. The doublet lenses can focus and collimate the laser beam, providing a long free-space link in PAM4 VCSEL-based LiFi transmissions. A pair of convex lenses could be employed to replace a pair of doublet lenses to establish a LiFi transmission. However, it is difficult to establish a LiFi transmission with a 30-m free-space link by employing a pair of convex lenses [15].

The measured BER curves of the 56 Gb/s PAM4 VCSEL-based LiFi transmissions over different free-space links in the range of 0–30 m are shown in Fig. 4. Obviously, as the free-space link increases the BER value increases as well. As the free-space link increases, however, the received optical signal-to-noise ratio (OSNR) decreases because the received optical power includes additional distortion lights. The decrease of OSNR leads to the decline of BER performance. Therefore, there is a trade-off between the free-space link and the BER performance. System designers should address the maximum free-space link to guarantee a successful construction of PAM4 LiFi transmission. At a 10^{-9} BER operation, the received optical power is -2 dBm for the scenario of back-to-back (BTB), whereas the received optical power is -0.3 dBm for the scenario of over a 20-m free-space link. A 1.7-dB power penalty exists between BTB and over a 20-m free-space link scenarios at a 10^{-9} BER operation. Since the 680 nm visible laser light has an attenuation of 0.085 dB/m in free space, the power penalty for the BER measurement is about 1.7 dB ($0.085\,\text{dB/m} \times 20\,\text{m} = 1.7\,\text{dB}$) between BTB and over a 20-m free-space link scenarios. And further, as the free-space link is larger than 20 m, the BER value is higher than 10^{-9}.

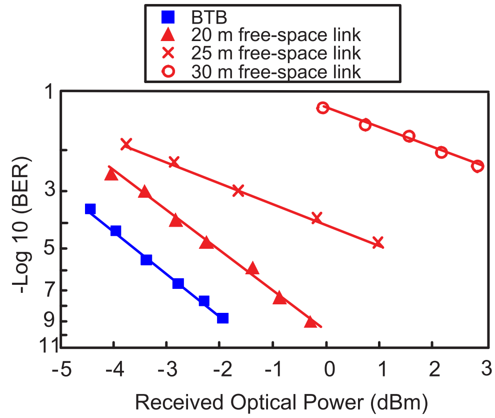

Fig. 4. Measured BER curves of the 56 Gb/s PAM4 VCSEL-based LiFi transmissions over different free-space links in the range of 0–30 m.

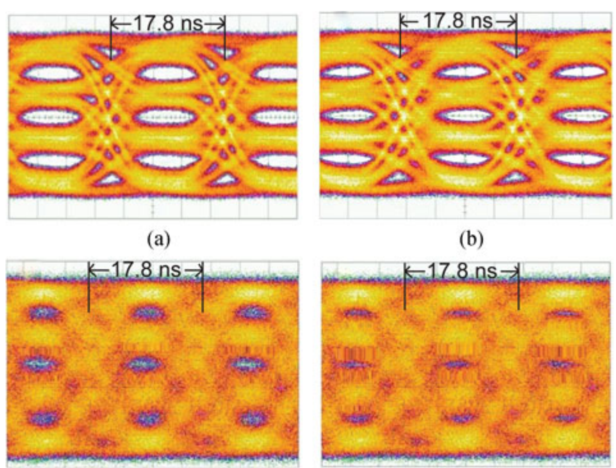

Fig. 5. Eye diagrams of the 56 Gb/s PAM4 signal (a) for BTB, (b) over a 20-m free-space link, (c) over a 25-m free-space link, and (d) over a 30-m free-space link scenarios.

At a free-space link of 25 m, the BER value declines to 10^{-5} due to the decline of OSNR. Over a 30-m free-space link, however, an error floor exists clearly because of the significant decline of OSNR and divergent focal spot size between the doublet lens 2 and the ferrule of SMF (receiver side). The focal spot size between doublet lens 2 and SMF ferrule is decisive for the transmission performances of 56 Gb/s PAM4 VCSEL-based LiFi transmissions. Long free-space link generates a divergent focal spot size and leads to poor transmission performances. System devisers must address the acceptable divergent focal spot size (the maximum focal spot size) to assure the real implementation of 56 Gb/s PAM4 VCSEL-based LiFi transmissions. It can be concluded that as the free-space link is shorter than 20 m, the BER performance degradation due to the decline of OSNR and divergent focal spot size is tolerable. The maximum free-space link by which 10^{-9} BER operation can be reached is about 20 m. However, as the free-space link is 30 m, the BER performance degradation due to the decline of OSNR and divergent focal spot size is intolerable. The BER performance can be improved by using a clock/data recovery (CDR) at the receiver side since that the data signal can be recovered and regenerated by a CDR.

Additionally, a multimodal VCSEL often induces modal noise in systems and deteriorates the BER performance. Multiple modes are generated in a VCSEL as the optical output power increases.

However, an optimum bias current is employed to drive the multimodal VCSEL to decrease the modal noise. Thus, poor BER performance caused by modal noise because of the multimodal VCSEL is confined. Further, as far as we know, the maximum modulation bandwidth of the 680 nm VCSEL is 5.4 GHz. Therefore, a multimodal VCSEL is utilized to implement the PAM4 LiFi transmissions instead of the single-mode VCSEL.

The eye diagrams of the 56 Gb/s PAM4 signal over different free-space links in the range of 0–30 m are shown in Fig. 5(a)–(d), respectively. Inner eye optical modulation amplitudes (OMAs) range from –10.6 dBm [see Fig. 5(a)], –11.1 dBm [see Fig. 5(b)], –18.7 dBm [see Fig. 5(c)], to –21.4 dBm [see Fig. 5(d)] over different free-space links in the range of 0–30 m. The qualities of the 56 Gb/s PAM4 signal are observed in BTB [see Fig. 5(a)] and over a 20-m free-space link [see Fig. 5(b)] scenarios. Nevertheless, amplitude and phase fluctuations exist for over a 25-m free-space link scenario [see Fig. 5(c)]. Further, close eye diagrams exist for over a 30-m free-space link scenario [see Fig. 5(d)]. It indicates that the minimum inner eye OMA by which 10^{-9} BER operation can be reached is around –11.1 dBm.

4. Conclusion

A 56 Gb/s PAM4 VCSEL-based LiFi transmission with two-stage injection-locked technique is proposed and demonstrated. Experimental results show that a 5.4-GHz VCSEL with two-stage injection-locked technique is effective for a 56 Gb/s PAM4 LiFi transmission. To authors' knowledge, this study is the first to adopt a 680-nm VCSEL transmitter with two-stage injection-locked technique in a PAM4 LiFi transmission. The link performances of the PAM4 LiFi transmissions have been evaluated on-line. Good real-time BER performance of 10^{-9} and three independent clear eye diagrams are achieved at a 20-m free-space operation. Such an innovative PAM4 LiFi transmission possesses an attractive feature that accelerates the visible laser light communication deployment.

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