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# A 448-Gb/s PAM4 FSO Communication With Polarization-Multiplexing Injection-Locked VCSELs Through 600 M Free-Space Link

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**ABSTRACT** A 448-Gb/s four-level pulse amplitude modulation (PAM4) free-space optical (FSO) communication through 600 m free-space link was constructed, utilizing polarization-multiplexing injection-locked vertical-cavity surface-emitting lasers (VCSELs) for presentation. When uniting four-wavelength polarization-multiplexing and PAM4 modulation schemes, the transmission capacity of FSO communications is substantially multiplied, with an aggregate transmission rate of 448 Gb/s [56 Gb/s PAM4/wavelength × 4 wavelengths × 2 polarizations ($x$- and $y$-polarizations)]. The results show that four 1.55 $\mu$m VCSEL transmitters with injection locking technique are sufficiently powerful for 448 Gb/s PAM4 signal transmission. Adopting a tunable optical band-pass filter and a polarization beam splitter for wavelength filtering and polarization de-multiplexing, the polarized wavelengths are effectually filtered and de-multiplexed in each polarized state. As the polarization state is well preserved in the scenario over 600 m free-space transmission, a sophisticated polarization tracker is not required in this proposed FSO communication. High bit error rate performance and accepted PAM4 eye diagrams are attained through 600 m free-space transmission. The four-wavelength polarization-multiplexing PAM4 FSO communication established here reveals the prominent benefits of high aggregate transmission capacity and long-distance free-space link.

**INDEX TERMS** FSO communication, injection-locked VCSELs, PAM4 modulation, polarization-multiplexing scheme.

## I. INTRODUCTION

Free-space optical (FSO) communications are essentially signal transmission between two locations through the free-space. Line of sight is required between the transmitting site and the receiving end for FSO communications. License-free propagation, large available bandwidth, high directivity, high reliability, and strong confidentiality characteristics have made FSO communications very popular [1]–[6]. As wireless broadband access moves from 2.4 GHz wireless fidelity (WiFi) to 5 GHz WiFi, mobile telecommunication moves from 4G to 5G, and CATV moves from analog systems to digital ones, the transmission loading for network transmission and cloud server connection will increase noticeably. In the state of heavy transmission loading, a high-speed data transmission configuration should be built to alleviate the critical concern of heavy transmission loading. To resolve the concern, a 448-Gb/s four-level pulse amplitude modulation (PAM4) FSO communication with polarization-multiplexing injection-locked vertical-cavity surface-emitting lasers (VCSELs) through 600 m free-space link is thereby proposed and feasibly demonstrated. Four optical wavelengths are polarized in $x$ and $y$ orthogonal polarizations. The channel capacity of FSO communications is noticeably multiplied by combining polarization-multiplexing injection-locked VCSELs with

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PAM4 modulation. Injection locking technique is effective for enhancing VCSEL's modulation response, which can greatly enhance the VCSEL's 3-dB bandwidth [7], [8]. Polarization-multiplexing is an optical scheme utilized to multiply the channel capacity of FSO communications. The adoption of a polarization-multiplexing scheme allows multiplying the channel capacity, as different wavelengths can be delivered with orthogonal states [9]–[12]. PAM4 modulation is another optical scheme utilized to multiply the channel capacity of FSO communications. It reduces optical and electrical device's bandwidth requirement, which makes it proper to high-speed transmissions. For a given bandwidth, PAM4 doubles the transmission capacity compared with none-return-to-zero [13], [14]. Combining polarization-multiplexing and PAM4 modulation schemes opens up the way for maximizing the transmission capacity of FSO communications. Utilizing four-wavelength polarization-multiplexing and PAM4 modulation schemes [4 (four-wavelength) × 2 (polarization-multiplexing) × 2 (PAM4 modulation)] can remarkably multiply the aggregate transmission capacity by a factor of sixteen, compared to non-return-to-zero format in the single carrier and single polarization state. Employing a tunable optical band-pass filter (TOBPF) and a polarization beam splitter (PBS) at the receiving end for wavelength filtering and polarization de-multiplexing, the polarization-orthogonal wavelengths ($x$-polarized and $y$-polarized wavelength) can be attainably filtered and de-multiplexed.

Our previous study demonstrated a centralized-light-source two-way PAM8/PAM4 FSO communication based on parallel optical injection locking technique [15]. However, the free-space transmission rate of 84 Gb/s (downstream)/45 Gb/s (upstream) and the free-space transmission distance of 200 m are considerably lower than those of 448 Gb/s and 600 m adopted in this demonstrated FSO communication. Aboagye *et al.* achieved a 112 Gb/s/channel × 4-channel (448 Gb/s) wavelength-division-multiplexing (WDM) polarization-division-multiplexed (PDM)-differential quadrature phase shift keying (DQPSK) lightwave transmission system [16]. Its total transmission capacity of 448 Gb/s is equal to that of our proposed FSO communication. Nevertheless, eight expensive external modulators and one sophisticated polarization tracker are envisioned to construct such costly and complex 4-channel WDM PDM-DQPSK lightwave transmission system. For system concern, it is vital to construct a lightwave transmission system with low cost and low complexity. Directly modulated transmitters are attractive for a lightwave transmission system because they cost lower compared with externally modulated transmitters. In this study, a 448-Gb/s PAM4 FSO communication over 600 m free-space link is presented, using polarization-multiplexing injection-locked directly modulated VCSEL transmitters for demonstration. Since the 1.55 $\mu$m VCSEL with a single transverse mode has been developed to a few tens of GHz [17], the 1.55 $\mu$m VCSEL with injection locking technique is thus adopted for 600 m FSO communication.

To the author's understanding, this demonstration is the first to successfully construct a high-speed PAM4 FSO communication with a total transmission capacity of 448 Gb/s and a free-space transmission distance of 600 m. Four injection-locked VCSELs, with a large channel spacing of around 4 nm, are polarized and multiplexed at the transmitting site. Atmospheric turbulence and noise due to other lights are considered in bit error rate (BER) evaluation. With the deployment of doublet lenses between two buildings [18], [19], the BER and PAM4 eye diagrams perform well in this illustrated PAM4 FSO communication based on polarization-multiplexing injection-locked VCSELs. This demonstrated 448-Gb/s PAM4 FSO communication affords a prominent one for its high aggregate transmission capacity and develops the scenario realized by integrating four-wavelength polarization-multiplexing with PAM4 modulation schemes.

## II. EXPERIMENTAL SETUP

The framework of illustrated 448 Gb/s PAM4 FSO communication with polarization-multiplexing injection-locked VCSELs through 600 m free-space link is presented in Fig. 1. After enhancement by a broadband amplifier, a 56-Gb/s PAM4 signal produced from a PAM4 signal generator is separated and fed into VCSEL1, VCSEL2, VCSEL3, and VCSEL4. Given that PAM4's linearity is imperative for PAM4 signal transmission, a broadband amplifier with high-linearity is adopted to amplify the PAM4 electrical signal to operate the VCSELs in linear regions. The light from a distributed feedback (DFB) laser diode (LD) (DFB LD1/1533.47 nm, DFB LD2/1537.79 nm, DFB LD3/1541.75 nm, DFB LD4/1545.72 nm) is injected into a VCSEL (VCSEL1/1533.45 nm, VCSEL2/1537.76 nm, VCSEL3/1541.73 nm, VCSEL4/1545.69 nm) via a combination of a three-port optical circulator and a polarization controller. In this work, 56 Gb/s PAM4 signal is applied to the slave laser (VCSEL1, VCSEL2, VCSEL3, and VCSEL4). If instead of slave laser, master laser (DFB LD1, DFB LD2, DFB LD3, and DFB LD4) is modulated with 56 Gb/s PAM4 signal, there should be a large attenuation of the PAM4 signal [20], which might degrade the transmission performances. Afterward, the 56 Gb/s optical PAM4 signal is divided into two parts, along two orthogonal polarizations ($x$- and $y$-polarizations), utilizing a PBS. The $x$-polarized [insert (a)] and $y$-polarized [insert (b)] wavelengths are then recombined using a polarization beam combiner [insert (c)]. An optical delay line is utilized in one of optical paths to make up for phase mismatch between the two paths. Four optical PAM4 signals with parallel and orthogonally polarized dual wavelengths are then combined using a 4×1 optical combiner [insert (d)], amplified by an erbium-doped fiber amplifier (EDFA), optimized by a variable optical attenuator (VOA), and communicated through 600 m free-space link using a couple of doublet lenses. A VOA is placed at the start of

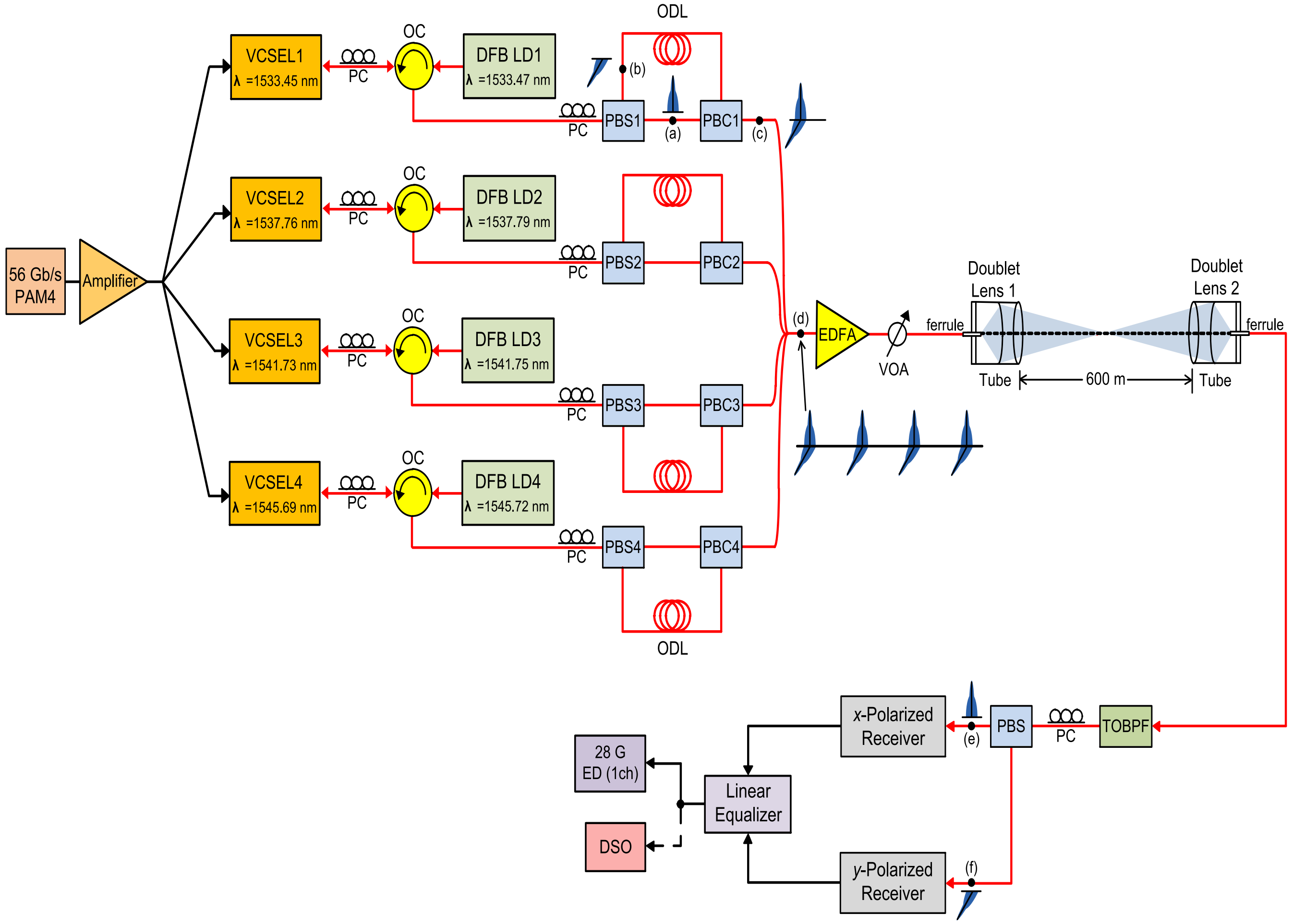

**FIGURE 1.** Framework of illustrated 448 Gb/s PAM4 FSO communication with polarization-multiplexing injection-locked VCSELs through 600 m free-space link.PAM4, four-level pulse amplitude modulation; VCSEL, vertical-cavity surface-emitting laser; DFB LD, distributed feedback laser diode; PBS, polarization beam splitter; PBC, polarization beam combiner; TOBPF, tunable optical band-pass filter; ED, error detector; DSO, digital storage oscilloscope.

EDFA so as to optimize the optical power launched into the free-space. The doublet lenses are used to send laser light from the fiber ferrule to the free-space and to guide laser light from the free-space to the fiber ferrule. Over 600 m free-space link, these combined optical PAM4 signals with $x$- and $y$-polarizations pass through a TOBPF and a PBS to filter and de-multiplex each polarized PAM4 signal. The TOBPF features a 0.56-nm bandwidth and a 1000-dB/nm filter slope. An $x$-polarized receiver receives the $x$-polarized carrier modulated with 56 Gb/s optical PAM4 signal [insert (e)]. After equalization by a linear equalizer, the PAM4 signal undergoes real-time BER measurement by a high-sensitivity error detector (ED). This high-sensitivity ED is used to support BER measurement up to 28.1 Gbit/s. And further, a digital storage oscilloscope (DSO) is utilized to catch the 56 Gb/s $x$-polarized PAM4 signal's eye diagrams. In the same manner, a $y$-polarized receiver receives the $y$-polarized carrier modulated with 56 Gb/s optical PAM4 signal [insert (f)]. This signal is then sent to an equalizer for signal equalization and launched into a 28G ED for BER performance analysis. Besides, a DSO is adopted to take the 56 Gb/s $y$-polarized PAM4 signal's eye diagrams.

## III. RESULTS AND DISCUSSIONS

A set of doublet lenses, as illustrated in Fig. 2, is erected on the roofs of two buildings to send laser light to a free-space and to concentrate laser light on the fiber ferrule. Transmitting a laser light over a free-space between the doublet lenses makes the FSO communication to perform as if the fiber was linked. A laser rangefinder is utilized to measure and determine the free-space transmission distance. A doublet lens, with focal length/back focal length/diameter of 150 mm/150 mm/50.8 mm, respectively, consists of one concave lens and one convex lens. Since the fiber's numerical aperture is 0.13, the laser light's diameter ($d$) can be calculated as:

$$d = 2 \times (150 \times 0.13) = 39\,(\text{mm}) \tag{1}$$

Obviously, the doublet lens 1's diameter (50.8 mm) is larger than that of laser light (39 mm) to make a free-space transmission with doublet lens 1 at the transmitting site workable. The spatial frequency cutoff ($SFC$) and the corresponding beam radius ($r$) are given as:

$$r = \frac{2.3}{SFC \times 2\pi} = 3.6\,(\mu\text{m}) \tag{2}$$

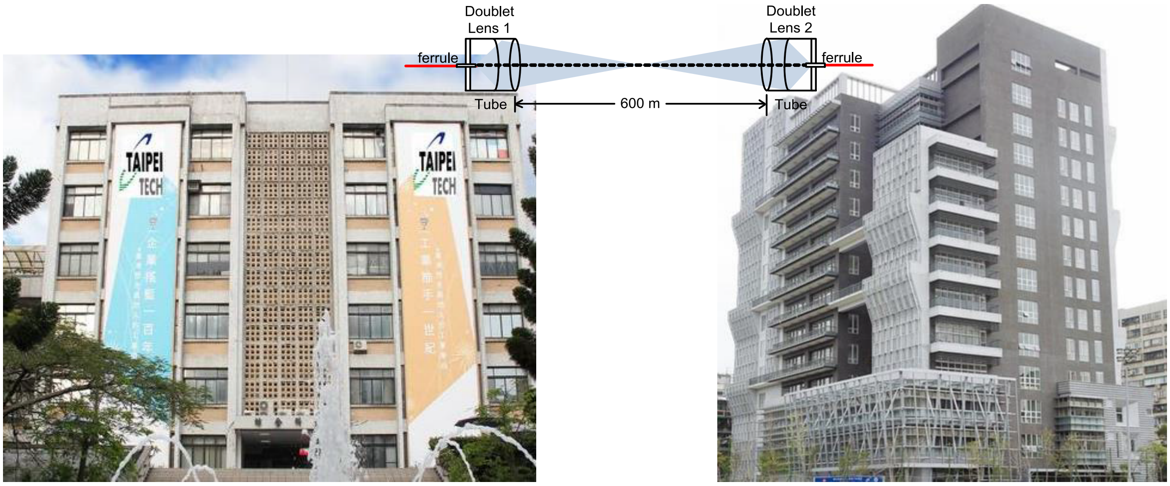

**FIGURE 2.** A set of doublet lenses are erected on the roofs of two buildings to send laser light to a free-space and to guide laser light to the fiber ferrule.

Then, the divergence the objective lens ($\theta$) is:

$$\theta = \frac{3.6\,(\mu\text{m})}{150\,(\text{mm})} = 24 \times 10^{-6} \tag{3}$$

When laser light transports over an $L$-m free-space transmission, it will spread. Through such a free-space link, however, the diameter ($d_L$) of laser light must be smaller than that of doublet lens 2 ($d_L < 50.8$ mm) to make a free-space link with doublet lens 2 at the receiving site workable:

$$d_L = \sqrt{d^2 + (2\theta L)^2} = \sqrt{39^2 + (0.048L)^2} < 50.8 \tag{4}$$

where $\theta$ is the laser light's divergent angle. $L$ is processed as 678.2 m, revealing the maximum free-space transmission distance. The free-space link operated in here is 600 m to satisfy the maximum free-space transmission distance requirement. After a certain free-space transmission distance, it is crucially imperative to fit laser light's diameter to the doublet lens 2's diameter to avoid large coupling loss. With a small laser light diameter, doublet lens 2 will collect more transmitted light. The received optical power undergoes an apparent increase, which follows high BER performance. With a large laser light diameter, nevertheless, doublet lens 2 will collect less transmitted light. The received optical power undergoes an obvious decrease, which accompanies low BER performance.

Given a Gaussian laser light, beam size increases with the increase of Rayleigh length:

$$L_R = \frac{\pi E_0^2}{\lambda} \tag{5}$$

where $L_R$ is the Rayleigh length, $E_0$ is laser light's waist radius, and $\lambda$ is laser wavelength. When laser light propagates through a 600-m free-space link, it is challenging to entirely couple laser light to the fiber ferrule due to beam spreading. A reduction setup must be deployed to reduce beam size so as to couple laser light to the fiber ferrule. In this demonstrated architecture, doublet lens 2 is a reduction setup to reduce and focus laser light on the fiber ferrule.

Atmospheric turbulence will affect the link performance of FSO communications. When optical signal travels through the free space, the atmospheric turbulence will cause atmospheric attenuation. For FSO communication, atmospheric attenuation varies with in accordance with weather conditions. Through 600 m free-space link, the aerial attenuation varies from 1.3 dB (good weather) to 50 dB (bad weather) [21]. Thick fog, heavy snow, and extreme rain are the main types of bad weather that can worsen the link accessibility of FSO communications. Severe atmospheric turbulence due to bad weather strongly influences the link performance of FSO communications [22], [23]. In this work, an atmospheric attenuation of about 1.5 dB (clear weather) /1.8 dB (sunny weather) occurs on account of 600 m free-space transmission. In clear/sunny weather, a 600-m free space transmission based on doublet lenses provides high link accessibility. In bad weather, nevertheless, an interruption occurs for a 600-m free space transmission with doublet lenses. In such worst scenario, microwave or millimeter-wave link could be adopted as a backup link [24], [25]. As for noise from other lights, noise will be produced when other lights form the atmosphere are received by the receiver. The optical signal-to-noise ratio (OSNR) of FSO communications is decreased as other lights form the atmosphere are received, by which bringing on higher BER. However, OSNR decrease owing to the noise from other lights can be compensated by higher injection power of DFB LD. Then, higher optical power will be launched into a 600-m free-space link and higher OSNR will be acquired to compensate for the OSNR decrease. As to the polarization state, the polarization state of the $x$- and $y$-polarized wavelengths are well preserved when propagating though the atmospheric channel [26]. To take full advantage of polarization stability, a 448-Gb/s PAM4 FSO communication with polarization-multiplexing

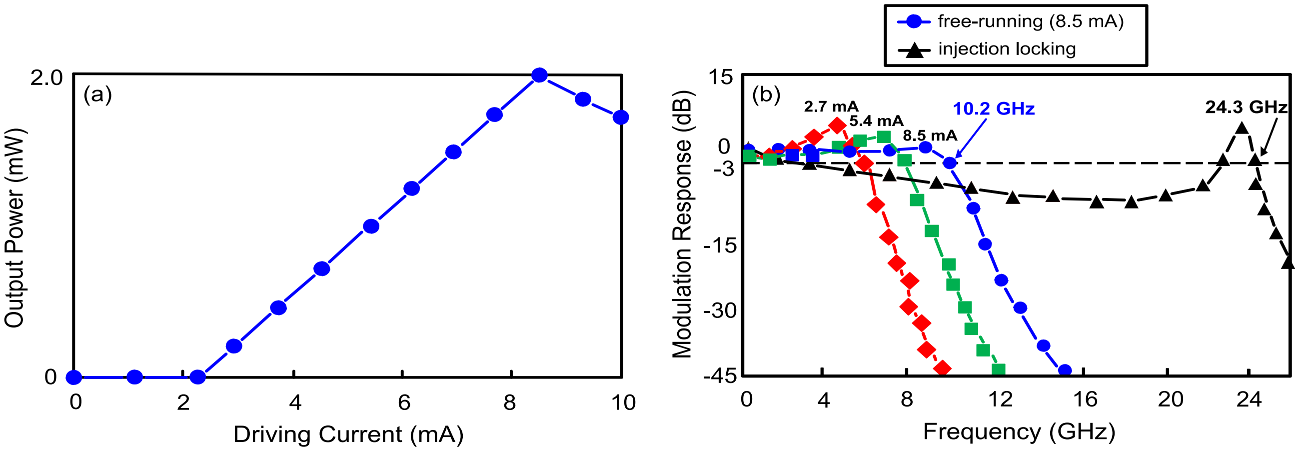

**FIGURE 3.** (a) P-I curve of VCSEL1 with a threshold current and a slope efficiency of 2.3 mA and 32.26 mW/mA. (b) The modulation responses of the free-running VCSEL1 with different driving currents.

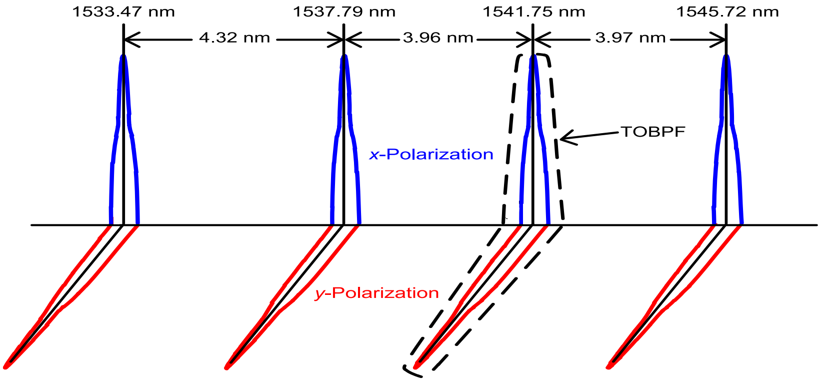

**FIGURE 4.** Polarization-orthogonal optical spectra ($x$- and $y$-polarizations) with four-wavelength polarization-multiplexing scheme.

injection-locked VCSELs through 600 m free-space link is thereby constructed.

Fig. 3(a) shows the optical power-driving current (P-I) curve of VCSEL1 with a threshold current and a slope efficiency of 2.3 mA and 32.26 mW/mA, respectively. As the driving current is 8.5 mA, a 2 mW maximum optical power is acquired. Fig. 3(b) presents the modulation responses of the free-running VCSEL1 with different driving currents. As the driving current increases to 8.5 mA, the 3-dB modulation bandwidth reaches 10.2 GHz. Thereby, we drive the free-running VCSEL1 at 8.5 mA to attain a maximum output power and a high 3-dB modulation bandwidth of 2 mW and 10.2 GHz, respectively. Besides, the modulation response of VCSEL1 with injection locking is also presented in Fig. 3(b). When injection-locked, VCSEL1 attains a considerable enhancement in 3-dB modulation bandwidth, and a high 3-dB modulation bandwidth of 24.3 GHz is acquired. Hence, a 448-Gb/s PAM4 FSO communication can be realistically realized when four VCSELs are used with injection locking technique [$24.3 \times \sqrt{2} \times 4$ (four-wavelength) $\times 2$ (polarization-multiplexing) $\times 2$ (PAM4 modulation) $> 448$].

Fig. 4 displays the polarization-orthogonal optical spectra ($x$- and $y$-polarizations) with a four-wavelength polarization-multiplexing scheme. The four wavelengths for directly modulated 56 Gb/s PAM4 signals are 1533.47, 1537.79, 1541.75 and 1545.72 nm (∼4 nm channel spacing), respectively. With the adoption of TOBPF and PBS at the receiving end, the polarized wavelengths can be filtered and de-multiplexed, due to modulation at different wavelengths and polarization with orthogonal states. For four optical wavelengths with parallel polarizations, interferences that arise from the adjacent wavelengths will worsen the performance of FSO communications. Given a large channel spacing of ∼4 nm, however, the interferences are trivially small. Furthermore, given the orthogonal trait of the $x$- and $y$-polarized wavelengths, the cross-beating term will not exist [27], [28]. For these four orthogonally polarized optical wavelengths with orthogonal polarizations, since that the interferences are very small and the cross-beating term is almost zero, high transmission performances in view of low BER and qualified PAM4 eye diagrams are expected.

For an FSO communication, high free-space transmission rate and long free-space transmission distance are the key concerns of system designers. The realization of 448-Gb/s/600-m PAM4 FSO communication is quite challenging, particularly for qualified transmission

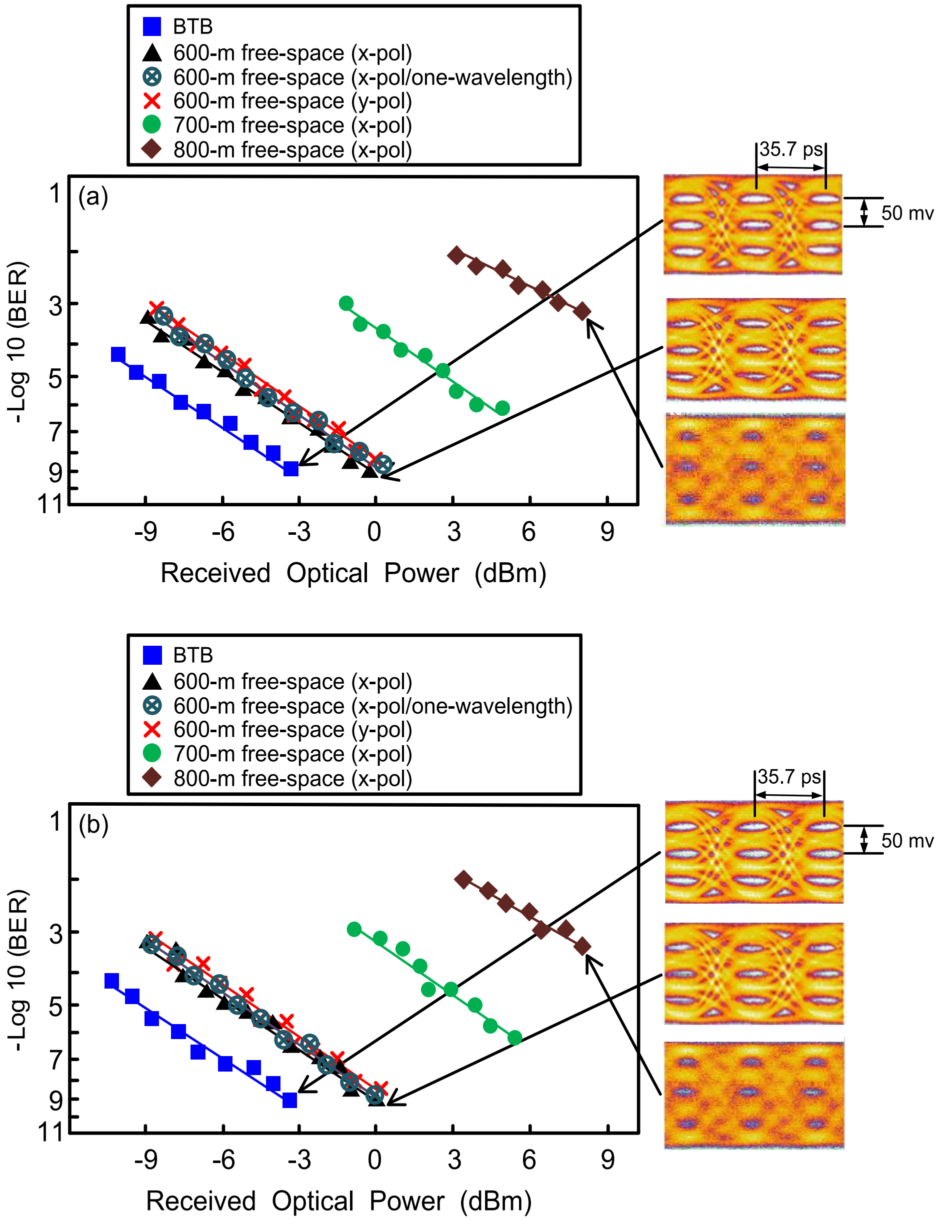

**FIGURE 5.** BER performances of 56 Gb/s PAM4 signal at filtered wavelengths of (a) 1533.47 nm and (b) 1545.72 nm in the states of BTB, through 600 m free-space link ($x$- or $y$-polarization), through 700 m free-space link ($x$-polarization), and through 800 m free-space link ($x$-polarization).

performance. Figs. 5(a) and 5(b) show the BER performances of 56 Gb/s PAM4 signal at filtered wavelengths of 1533.47 nm [Fig. 5(a)] and 1545.72 nm [Fig. 5(b)] under different states in clear/sunny weather. It is to be observed that there is almost no difference between the BER values of $x$- and $y$-polarizations, indicating that the association between BER performance and the polarization state is extremely small. At a BER value of $10^{-9}$, a 3.2-dB [Fig. 5(a)]/3.3-dB [Fig. 5(b)] power penalty appears between the back-to-back (BTB) state and that over a 600-m free-space transmission ($x$- or $y$-polarization). These 3.2 and 3.3 dB power penalties are ascribed to the atmospheric attenuation owing to 600 m free-space transmission and coupling loss for laser light coupling to the fiber ferrule. Laser light alignment between doublet lens 2 and fiber ferrule's receiving area is definitively important to the performance of FSO communications. Aligning a laser light can pose many challenges. Laser light misalignment that accompanies a large coupling loss will bring on poor BER performance. It is vital to introduce laser light within fiber ferrule's receiving area so as to avoid large coupling loss. When the free-space transmission distance increases to 700 m ($x$-polarization), BER deteriorates to an order of $10^{-6}$ due to more coupling loss. When the free-space transmission distance further increases to 800 m ($x$-polarization), BER deteriorates to an order of $10^{-3}$ because of higher coupling loss. As the laser light travels through an 800-m free-space link, it will spread. With spread laser light, it is difficult to wholly introduce laser light within fiber ferrule's small receiving area. The received optical power is thus considerably reduced, which brings a high BER value. Conclusively, BER performance decreases with the increase of free-space transmission distance. Regarding eye diagrams, open PAM4 eye diagrams exist in BTB state. In the state through a 600-m free-space link, eye diagrams with qualified attributes are acquired. In the state through an 800-m free-space link, nevertheless, turbid PAM4 eye diagrams are observed.

To have a close connection with the four-wavelength polarization-multiplexing scheme and the BER performance, the BER values, given one-wavelength with orthogonal polarizations, are measured through 600 m free-space link ($x$-polarization). Figs. 5(a) and 5(b) show that there is almost no difference between the BER values of one-wavelength and four-wavelength schemes with orthogonal polarizations. Clearly, no BER performance degradation is observed when the four-wavelength polarization-multiplexing scheme is adopted, due to a large channel spacing of ∼4 nm.

## IV. SUMMARY AND CONCLUSION

In this study with a novel framework on the FSO communication, polarization-multiplexing scheme is adopted to transport PAM4 data signal through a free-space link. The performances of 448 Gb/s PAM4 FSO communications utilizing a four-wavelength polarization-multiplexing scheme are explored and discussed. Significant 3-dB modulation bandwidth improvement is acquired using 1.55 $\mu$m VCSEL with injection locking technique. By adopting TOBPF and PBS at the receiving end, the polarized wavelengths are simply filtered and de-multiplexed in each polarized state. Through 600 m free-space transmission, high BER performance of $10^{-9}$ and accepted PAM4 eye diagrams are attained, with a total transmission capacity of 448 Gb/s [56 Gb/s PAM4/wavelength × 4 (four wavelengths) × 2 ($x$- and $y$-polarizations)]. This demonstrated PAM4 FSO communication meets the target of high-speed FSO communication, given its feasibility for providing a high 448-Gb/s transmission rate over a 600-m free-space link. It brings vital developments to optical wireless communications with high-speed and long-distance free-space transmissions.

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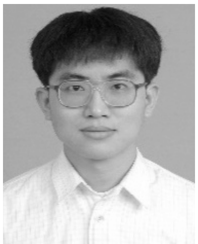

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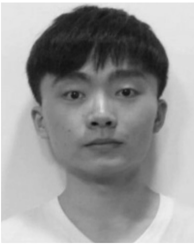

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