Multimode VCSEL Enables 42-GBaud PAM-4 and 35-GBaud 16-QAM OFDM for 100-m OM5 MMF Data Link

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ABSTRACT By enhancing the differential gain and reducing the capacitance of the 850-nm multi-mode vertical cavity surface emitting laser (VCSEL) with an analog bandwidth beyond 25 GHz via the use of InGaAs/AlGaAs quantum wells and multiple oxide confinement layers, the transmission of directly encoded 4-level pulse amplitude modulation (PAM-4) data at 42 GBaud and 16-quadrature amplitude modulation orthogonal frequency division multiplexing (16-QAM OFDM) data at 35 GBaud are demonstrated. After passing through 100-m OM5 multimode fiber (MMF), the detailed comparison between the VCSELs designed with different aperture sizes of 5.5/7.5 µm is performed. The 7.5-µm-aperture VCSEL provides the higher power with larger quantum efficiency but exhibits the narrower 3-dB bandwidth and higher noise level than those of the 5.5-µm-aperture VCSEL. Shrinking the oxide-confined aperture to 5.5 µm assists the VCSEL to expand its 3-dB bandwidth to 25.2 GHz and suppresses its relative intensity noise to -135 dBc/Hz, which contributes to support the highest data rate up to 84 and 140 Gbit/s, respectively, for PAM-4 and 16-QAM OFDM data under forward error correction criterion at optical back-to-back condition. Even after transmitting through 100-m-long OM5-MMF, the allowable data transmission rate still remains at 80 Gbit/s for PAM-4 and 120 Gbit/s for 16-QAM OFDM with their receiving power penalty of 3.24 and 3.1 dB, respectively, when the data is carried by the 5.5-µm-aperture VCSEL. Such a newly designed VCSEL structure promotes its allowable bandwidth to manifest the feasibility toward 50-GBaud per channel capacity for future data center applications.

INDEX TERMS Data center, vertical cavity surface emitting laser (VCSEL), 4-level pulse amplitude modulation (PAM-4), M-ary quadrature amplitude modulation orthogonal frequency division multiplexing (M-ary QAM-OFDM).

I. INTRODUCTION

Nowadays, more and more data-center has been constructed to confront a tremendous change of cyber city in recent years due to the incredible requirement from several applications such as cloud data computing, streaming, and mining. With the rapid growth on the demand of high resolution audio and video data streaming via wired and wireless communication, the unprecedented data exchanging and streaming capacity are thriving to urge the development on the optical interconnect of data centers. The 400GBASE-SR16 standard was established for 400 Gbit/s Ethernet with 25 Gbit/s per channel to fulfill the immediate demand on high-speed data transmission at current stage [1]. In practical applications, the optical transceiver for the 400 Gbit/s form-factor pluggable by transmitting
the 25 Gbit/s non-return-to-zero on-off keying (NRZ-OOK) data carried by vertical cavity surface emitting laser (VCSEL) through 100-m OM4-MMF has already emerged [2], which benefits from plenty of advantages including wide analog bandwidth, cost-effective package, low threshold current, and low power consumption [3]–[5]. Nevertheless, the VCSEL linked with graded-index multimode fiber (MMF) has also met its limitation on the effective modal bandwidth (EMB), which can only satisfy the short-reach communication in high-speed intra-data-center [6].

Previously, Westbergh et al. demonstrated the optical back-to-back (BiB) transmission of 40-Gbit/s NRZ-OOK data in 2010 [7]. Later on, the bandwidth of the VCSEL was promoted to 28 GHz for encoding 44-Gbit/s NRZ-OOK data in 2012 [8]. A recent report on the NRZ-OOK data transmission via VCSEL has already reached 50 Gbit/s in 2015 by Haglund et al. [9]. With improving the driver circuit, Kuchtaet al. performed up to 71-Gbit/s NRZ-OOK data transmission with the VCSEL [10]. Although the data rate of the NRZ-OOK can be further upgraded with improving analog bandwidth of the VCSEL, it is still difficult to satisfy the exponentially rising requirement on data capacity for the near future. Therefore, numerous types of modulation data formats have been applied to efficiently utilize the finite bandwidth of the VCSEL with high spectral efficiency [11], [12]. For example, the 4-level pulse amplitude modulation (PAM-4) and PAM-8 with doubling and tripling the symbol rate of the NRZ-OOK format have respectively been demonstrated [13] at 70 and 56 Gbit/s by Szczerba et al. [14]. Furthermore, the M-level orthogonal frequency division multiplexed quadrature amplitude modulation (M-QAM OFDM) [15] with the data rate upscaled to log2M per symbol has enabled the 100-Gbit/s BiB broadband data transmission with VCSEL [16]. The 50-Gbit/s discrete multi-tone (DMT) transmission over 2.2-km MMF was also presented not long ago [17]. The multiband carrierless amplitude phase modulation for 107.5-Gbit/s data transmission through 100-m OM4 MMF was reported lately [18]. In 2019, Ralph et al. further enlarged the allowable transmission distance of the PAM-4 data in the OM4 MMF to 200 m at a data rate of 100 Gbit/s with utilizing modest equalization and pulse shaping technologies without the need of forward error correction [19]. To raise the transmission capacity of data center, the shortwave-wavelength division multiplexing covering four discrete wavelengths located from 850 to 940 nm at an increment of 30 nm has been introduced [20]. The new standard OM5 or wideband MMF has also emerged to fulfill the need of low modal dispersion under multi-wavelength carrier transmission [21]. In particular, the OM5 with ultrahigh EMB and extremely low modal dispersion can ensure much higher data transmission than the OM4 MMF [22], [23] for the established data-center infrastructure. However, a performance comparison of the PAM-4 and QAM-OFDM data formats carried by the multi-transverse-mode VCSEL (MM-VCSEL) with enhanced differential gain and reduced capacitance though the OM5 MMF has yet to be performed and analyzed.

In this paper, the comparison between the VCSELs with multi-layered oxide-confined aperture sizes of 5.5 and 7.5 µm are performed, including their power-to-current-to-voltage (L-I-V), lasing optical spectrum, small-signal analog bandwidth, and relative intensity noise (RIN) characteristics. The PAM-4 data transmission via these VCSELs is characterized through analyzing their eye diagrams, bit error ratios (BERs), and bathtub curves at BiB and OMS-MMF cases. To increase the bandwidth usage efficiency, the 16-QAM OFDM receiving performances including the time-domain waveform transformed RF spectrum, constellation plot, error vector magnitude (EVM), signal-to-noise ratio (SNR), and BER are analyzed after optimization. Moreover, the receiving power sensitivity and penalty of the data carried by two different kinds of VCSELs are also characterized and compared each other.

II. EXPERIMENTAL SETUP
A. DESIGN OF MM-VCSEL CHIP

The 3D cross-section structure of the homemade 850-nm MM-VCSEL and the top-view image of the bare VCSEL chip are shown in Fig. 1(a). In active region, the vertical double heterostructure is formed by inserting 5 pairs of In0.072Ga0.928As quantum well (QW), as sandwiched by 6 Al0.37Ga0.63As barrier layers. In comparison with the conventional GaAs/AlGaAs QWs used for typical VCSEL devices, the InGaAs/AlGaAs QW essentially provides the higher differential gain to ensure the broader analog bandwidth, which also enables high reliability with the suppressed dislocation motion [24]. Upon the active region, two sets of (mesa, aperture) sizes designed as (16 µm, 5.5 µm) and (18 µm, 7.5 µm) are employed to control the current flow and transverse mode number in the VCSEL. The size of the current-flow aperture is defined via the oxidation confinement of multiple AlGaAs thin layers, which can effectively benefit from the least heat accumulation so as to avoid the strong Auger effect. In this work, the top 4 pairs of p-type Al0.96Ga0.04As/Al0.12Ga0.88As are employed to reduce the parasitic capacitance of the MM-VCSEL and the bottom 2 pairs of Al0.99Ga0.02As/Al0.12Ga0.88As are set to form the oxide-confined layer. Furthermore, the specific design on top four pairs of multi-layer oxide-confined structure effectively reduces the overall capacitance of the VCSEL. On the other hand, the other two pairs of oxide-confined layer below the four-pair oxide layer help to offer better optical confinement because of the weaker lateral diffraction loss beneath interface [25]. When shrinking the oxide-confined aperture size below 5 µm, the significantly increased differential resistance and the seriously degraded differential quantum efficiency undoubtedly aggravate the power consumption to deteriorate the signal modulation efficiency [26], [27]. To construct the resonant cavity with high and low resistivity, both top and bottom distributed Bragg reflector (DBR) mirrors need to be doped with donor and acceptor defects. The p-type DBR mirror equipped at top 36964 VOLUME 8, 2020
side includes 14 pairs of $\text{Al}_{0.9}\text{Ga}_{0.1}\text{As}/\text{Al}_{0.12}\text{Ga}_{0.88}\text{As}$ layers. The n-type DBR mirror at bottom contains 8 pairs of n-type $\text{Al}_{0.9}\text{Ga}_{0.1}\text{As}/\text{Al}_{0.12}\text{Ga}_{0.88}\text{As}$ layers and 25 pairs of undoped AlAs/$\text{Al}_{0.1}\text{Ga}_{0.9}$As. In particular, the binary and ternary compound (AlAs/$\text{Al}_{0.1}\text{Ga}_{0.9}$As) sandwiched pair effectively reduces the self-heating induced by their thermal resistance so as to enable large photon density and high relaxation oscillation frequency [28].

The metallic contact with the ground-signal (GS) coplanar pads for the VCSEL chip is implemented not only to further increase the spacing usage efficiency on the wafer, but also to reduce its parasitic capacitance for improving the modulation bandwidth. At the bottom of the VCSEL, the benzocyclobutene passivation layer with relatively low capacitance is used to replace the typical SiO$_2$ passivation layer, which can provide shorter charging and discharging time of the equivalent RC circuit for the VCSEL.

B. ENCODING AND DECODING ARCHITECTURES FOR TESTING THE PAM-4 AND 16-QAM OFDM PERFORMANCES WITH MM-VCSEL CHIP

The encoding and decoding architectures for testing the PAM-4 and 16-QAM OFDM performances for the MM-VCSEL chip mounted on the probe station were displayed in Fig. 1(b). The arbitrary waveform generator (AWG, Keysight M8196A) delivered the PAM-4 data synthesized by the built-in program and 16-QAM OFDM generated from the homemade MATLAB code. The AWG with a sample rate of 92 GS/s can support the maximal Baud rate up to 46 GBaud, and the pseudo-random bit sequence pattern lengths of $2^{13} - 1$ and $2^{18} - 1$ were respectively provided for the PAM-4 and 16-QAM OFDM data. Note that the bit length of the 16-QAM OFDM data was defined by the formula $L_{\text{total}} = N_{\text{subcarrier}} \times N_{\text{bit}} \times N_{\text{symbol}}$, where $N_{\text{subcarrier}}$, $N_{\text{bit}}$, and $N_{\text{symbol}}$ denote the subcarrier number, bit per symbol, and symbol number, respectively. Because of the attenuation on the waveform amplitude caused by pre-leveling and the pre-emphasis technique, the 40 Gbit/s broadband pre-amplifier (AMP, Picosecond 5882) with a noise figure of 6 dB and a gain of 16 dB was employed for pre-amplification with a peak-to-peak waveform amplitude of 1.2 V. After combining the AC signal and DC bias with a bias tee (Anritsu V250, $f_{3\text{dB}} = 60$ GHz), the MM-VCSEL was driven via a coplanar GS microwave probe (Allstron ASP-GS-100-40-P) with a pitch interval of 100 $\mu$m through a microwave cable (HUBER + SUHNER, N4910-61601) with a length of 0.85-m and a bandwidth of 50 GHz. Subsequently, the lensed MMF (SHUODA) was utilized to couple the output of the MM-VCSEL controlled at 20$^\circ$C. After transmitting through BtB, 100-m long OM4 and OM5-MMFs, the MM-VCSEL
carried data was received by a photodetector (PD, New Focus 1484-A-50) with a 3-dB bandwidth of 22 GHz. After conversion, the received PAM-4 and 16-QAM OFDM data streams were sent to the digital serial analyzer (DSA, Tektronix DSA8300) and the real-time digital phosphor oscilloscope (DPO, Tektronix DPO70002SX) for waveform analysis. A DC blocker (Picosecond Pulse Labs, PSPL5509) with a bandwidth of 50 GHz was employed to avoid the damage caused by the DC offset. The received PAM-4 and 16-QAM OFDM data were decoded by the built-in program (Tektronix, 80SJNB) and homemade MATLAB code, respectively. For performing the pre-compensation of channel response, the data pre-emphasis for PAM-4 and QAM-OFDM was employed through the feedback of both the intensity and phase throughput spectral responses, which was measured by transmitting a broadband 16-QAM OFDM data through the condition of BtB and OMS MMF. Moreover, the pre-leveling technique for the 16-QAM OFDM was multiplying the RF spectra of the data waveform by a power-to-frequency slope (dB/GHz). Such a pre-emphasis effectively distorts the data waveform at the transmitting end in advance.

III. RESULTS AND DISCUSSION

The L-I, power-to-current slope (dP/dI), I-V, and differential resistance (dV/dI) responses of the VCSEL are shown in Fig. 2. The P-I curve of the VCSEL with 5.5-µm aperture exhibits a threshold current (Ith) of 1.1 mA, a power-to-current slope of 0.49 W/A, and a maximal output power of 4.3 mW before saturation. In contrast, the VCSEL with 7.5-µm aperture enlarges its Ith to 1.5 mA, slope efficiency (dPout/dIbias) to 0.68 W/A, and maximal optical power to 9 mW. For short-reach 100-m-MMF transmission, the coupling in/out losses are inevitable to affect the effective optical power. After coupling into the lensed OM4-MMF with high coupling ratios of 0.61/0.43, the optical powers and external quantum efficiencies of the 5.5-/7.5-µm aperture VCSELs reduce to 1.6/1.38 mW and to 15.3%/24.1%, respectively. Note that the external quantum efficiencies for 5.5-/7.5-µm aperture VCSELs are obtained by calculating the formula ηext = (q/hv)(dPout/dIbias) = (q/hv)ηint with slope efficiencies (dPout/dIbias) of 0.19/0.3 W/A, where ηext and ηint denote the external and internal quantum efficiencies, respectively. On the other hand, the rollover of the P-I curve occurs by power saturation when operating the 5.5-/7.5-µm-aperture VCSEL at bias current up to 12/17 mA. The focal length of the lensed MMF is set as 10-20 µm to provide high coupling efficiency for collecting the VCSEL output with an acceptance angle of < 25 degree. Though the larger size of the 7.5-µm-aperture VCSEL can offer the wider dynamic modulation range as compared to 5.5-µm-aperture VCSEL, its larger divergent angle of the emission also causes the fewer coupling efficiency to deteriorate the throughput power as well as the SNR [29]. Later on, the differential resistances of 113/67 Ω for the 5.5/7.5-µm-aperture VCSEL biased at 10Ith are obtained with compliance voltages of 3/2.95 V. The 7.5-µm aperture VCSEL exhibits the electrical reflection coefficient (Γ), electrical return loss (RL), and voltage standing wave ratio (VSWR) of 0.145, 16.75 dB, and 1.34, as calculated by Γ = (ZRF-ZVCSEL)/(ZRF + ZVCSEL), RL = 20log|Γ| and VSWR = (1 + Γ)/(1 - Γ), which are better than those of 0.386, 8.25 dB, and 2.26 for the 5.5-µm aperture VCSEL. Obviously, the higher reflection coefficient and return loss of the electronic signal cause the larger power consumption for the 5.5-µm-aperture VCSEL as compared to the 7.5-µm-aperture VCSEL. In addition, the optical signal-to-noise ratios (OSNR) and the root-mean-square spectral width (ΔλRMS) of 51.8 dB and 1.06 nm for the 5.5-µm aperture VCSEL are slightly larger than those of 49.5 dB and 0.86 for 7.5-µm aperture VCSEL, when analyzing their peak mode at bias current of 10Ith [29]. Though the broader ΔλRMS is obtained for the 5.5-µm-aperture VCSEL, its better OSNR and fewer transverse-modes somewhat favor the high-speed data transmission in short-reach environment.

Fig. 3 illustrates the small-signal responses and RIN spectra of the 5.5/7.5-5.5-µm-aperture VCSELs. For the 5.5-µm-aperture VCSEL, its normalized 3-dB modulation bandwidth greatly broadens from 7.6 to 25.2 GHz with increasing the DC bias from 2.2 to 8.8 mA (2Ith to 8Ith). In contrast, the 7.5-µm-aperture VCSEL enlarges its normalized 3-dB modulation bandwidth only from 9.9 to 24.5 GHz with increasing the DC bias from 3 to 13.5 mA (2Ith to 9Ith). Both frequency responses for the 5.5-/7.5-µm-aperture VCSELs become flattened and beneficial for the modulation of the PAM-4 data. With respectively up-shifting relaxation oscillation correlated frequency peaks from 6.5 to 17.7 GHz (for 5.5-µm-aperture VCSEL) and from

![FIGURE 2. P-I curves, I-V curves with differential resistance, and optical spectra of VCSEL chip with oxide-confined aperture size of (a) 5.5/(b) 7.5 µm.](image-url)
with a peak-to-peak amplitude of 476.2 mV and a received 35 GBaud exhibits a slightly asymmetric eye pattern. For the relaxation oscillation dependent RIN response, the frequency and the power of the RIN peak for the 5.5-µm-aperture VCSEL are up-shifted from 7 to 18 GHz and reduced from -120.1 to -132 dBc/Hz, respectively, by enlarging the DC bias from 3 to 15 mA. Such a bias current optimization not only increases the allowable modulation bandwidth but also suppresses the RIN peak into background noise [30], which essentially improves the BER data transmission. Note that the noise level includes the intensity noise of electronic amplifiers and thermal/shot noises of the photodetector. Apparently, the relatively high noise level of the 7.5-µm-aperture VCSEL would deteriorate the SNR of the received data.

Because the throughput power declination and finite modulation bandwidth concurrently cause the distorted waveform, the pre-emphasis technique is used to offer the pre-compensation in the finite channel response for the PAM-4 data. Moreover, the wider 3-dB bandwidth and lower noise level make the 5.5-µm-aperture VCSEL to be the better choice for enabling the short-reach data transmission at lower power consumption.

Subsequently, Fig. 5(a) shows the receiving sensitivity versus the PAM-4 Baud rate after passing through BtB and 100-m OM5-MMF. At BtB transmission condition, the received 42-Gbaud PAM-4 eye pattern shows a peak-to-peak amplitude of 94.1 mV and the top/middle/bottom-eye jitter tolerances of 8.9/12/7.6 ps, as shown in Figs. 5(b) and 5(c). Even at 42 Gbaud, the received eye diagram can perform the distinct PAM-4 data pattern, even while the limited bandwidths of all other components are set below this bandwidth. That is, the pre-emphasis reveals the extraordinary compensating ability to approach such high modulation data rate. With such low receiving amplitude, the 84-Gbit/s BtB condition after the pre-emphasis of data waveform.
FIGURE 5. (a) Receiving BER, (b) eye diagram, and (c) bathtub curve performances of the PAM-4 data stream directly modulated onto the VCSEL carrier at different Baud rates under BtB and OM5-MMF transmission cases.

FIGURE 6. Eye diagrams and BER bathtub curves of 40-GBaud PAM-4 data under (a) BtB and (b) 100-m OM5-MMF transmission conditions.

FIGURE 7. Receiving power sensitivity of 40-GBaud PAM-4 data carried by MM-VCSEL under BtB and 100-m OM5-MMF transmissions.

the 100-m OM5-MMF, although this record is somewhat lower than the transmission capacity of 42 GBaud through BtB case. The VCSEL carried PAM-4 data transmission in the 100-m OM5-MMF declares superior performance with only 2 GBaud consumption. In more detail, the transmissions of the PAM-4 data at 40 GBaud passing through BtB and 100-m OM5-MMF are compared in Fig. 6. The BtB transmitted 40-GBaud PAM-4 data shows a peak-to-peak amplitude of 100.1 mV and a BER of $2.7 \times 10^{-5}$ with the corresponding top/middle/bottom-eye jitter tolerances of 5.4/8.8/4.8 ps.

After transmitting thorough 100-m OM5-MMF, the peak-to-peak amplitude and the BER of the PAM-4 data attenuates to 75.7 mV and to $1.3 \times 10^{-4}$, respectively. Nonetheless, the 40-GBaud PAM-4 data can maintain perfectly symmetric and distinct eye pattern with slightly downscaling the jitter tolerances to 3.8/8.4/4.4 ps for the top/middle/bottom eye patterns. 80-Gbit/s PAM-4 data transmission with the KP4-FEC certificated BER can successfully be achieved after 100-m OM5-MMF transmission, which mainly relies on the waveform pre-emphasis procedure before encoding the VCSEL with extremely high 3-dB bandwidth. The BER performance of the PAM-4 data at the receiving power of 0 dBm significantly degenerates from $2.1 \times 10^{-5}$ to $6 \times 10^{-4}$ with nearly 300-time degradation after lengthening the OM5-MMF distance to 100 m, as shown in Fig. 7. Under the KP4-FEC of $2.2 \times 10^{-4}$ for the 80-Gbit/s data transmission, the receiving power penalty of 3.24 dB is obtained by comparing the receiving powers of -2.15 and 1.09 dBm for the BtB and OM5 cases. Such a degradation on the receiving power sensitivity is inevitable due to the modal dispersion induced by the multi-transverse-modes of the VCSEL. Owing to the systematic limitation at current stage, it can thus be speculated that the VCSEL could enable PAM-4 direct encoding up to 100-Gbit/s per channel with improving the device and channel responses in addition to further enlarge the bandwidth of the VCSEL.

At the next step, the 16-QAM OFDM format is directly encoded onto the 5.5-/7.5-µm-aperture VCSELs, and the corresponding waveforms and RF spectra of the 30-GHz QAM-OFDM data stream are individually shown in Fig. 8(a). Note that the higher throughput of the 7.5-µm-aperture VCSEL leads to the larger amplitude of the received waveform in time domain as compared to that of the 5.5-µm-aperture VCSEL. Nevertheless, both the transformed RF spectra reveal similar slope of the overall
power-to-frequency declination. For the SNR responses observed at different OFDM subcarrier frequencies, the higher coupling loss occurred on collecting the 7.5-μm-aperture VCSEL output causes the larger deterioration at data bandwidth covering from 0 to 25 GHz, as shown in Fig. 8(b). The 7.5-μm-aperture VCSEL delivered QAM-OFDM data provides an average SNR of 15.8 dB with corresponding EVM of 16.1% and BER of 2.1 × 10⁻³ below the FEC criterion (17.3% for the EVM and 3.8 × 10⁻³ for the BER) [31]. In contrast with the 7.5-μm-aperture VCSEL, the 5.5-μm-aperture VCSEL carried QAM-OFDM data can provide more concentrated constellation plot with the lower EVM of 15.4%, the higher SNR of 16.2 dB, and the smaller BER of 1.4 × 10⁻³. That is, even with the larger throughput, the higher noise level of the 5.5-μm-aperture VCSEL leads the carried QAM-OFDM data to exhibit worse performance than that of the 5.5-μm-aperture VCSEL.

Nonetheless, both the 5.5-μm- and 7.5-μm-aperture VCSELS can successfully deliver the 120-Gbit/s BtB transmission when carrying the 30-GHz wideband 16-QAM OFDM data. Furthermore, the maximal modulation bandwidth can be broadened up to 31 GHz for 7.5-μm-aperture VCSEL and to 33 GHz for 5.5-μm-aperture VCSEL, as illustrated in Fig. 8(e), which respectively enables 124-Gbit/s and 132-Gbit/s BtB data transmission even without pre-leveling. As the DC bias point is also an important to affect the 3-dB bandwidth, dynamic modulation range, differential resistance, and the mode distribution of the MM-VCSEL, the adequate optimization of the bias current is performed to unveil the best operation of the MM-VCSEL for carrying the 16-QAM OFDM data stream. Fig. 8(d) shows the received waveforms and spectra of the 25-GHz 16-QAM OFDM data obtained with detuning the bias current of the 5.5-μm-aperture VCSEL from 8 to 12 mA, which induces the slight saturation and noise suppression on the waveform. The subcarrier SNRs as shown in Fig. 8(e) are significantly improved with enlarging the bias from 8 to 10 mA to improve the 3-dB bandwidth of the 5.5-μm-aperture VCSEL, which enhances the average EVM, SNR and BER of the carried QAM-OFDM data from 13.1% to 11.1%, from 17.6 to 19 dB, and from 2.3 × 10⁻⁵ to 2.5 × 10⁻⁴, respectively. Inversely, over-biasing the MM-VCSEL up to 12 mA degrades the average EVM, SNR and BER of the QAM-OFDM data to 12%, 18.3 dB, and 8 × 10⁻⁵, respectively, due to the serious saturation of the waveform. Therefore, the operating bias of the MM-VCSEL is optimized at 10 mA to encode the broadband data at the highest bit rate, as shown in Fig. 8(f).

To check the allowable data capacity of the MM-VCSEL, the received BER versus modulation bandwidth for the 16-QAM OFDM data is examined after passing through BtB and 100-m OM5-MMF transmissions, as shown in Fig. 9(a). Apparently, the BtB transmitted BER is deteriorated from 1.4 × 10⁻³ to 5.7 × 10⁻³ as the modulation bandwidth enlarges from 30 to 35 GHz. Without OFDM pre-leveling process, the maximal modulation bandwidth of the MM-VCSEL carried QAM-OFDM data can reach 33 and 28 GHz after propagating through BtB and 100-m OM5-MMF, respectively. Under such high SNR requirement, the QAM-OFDM data encoding still maintains the superiority in OM5-MMF transmission with bandwidth degradation.
of only 5 GHz. The average SNR of QAM-OFDM data after passing through 100-m OM5-MMF degenerates from 16.2 to 14.6 dB as the subcarrier frequency expands from 5 to 20 GHz, which also blurs the constellation plot with the corresponding EVM enlarged from 15.4% to 18.4%, as illustrated in Fig. 9(b). Such a deterioration is mainly attributed to the modal dispersion and power fading induced waveform distortion. Note that even without any pre-compensating process, up to 132-Gbit/s for BtB and 112-Gbit/s for OM5-MMF transmission of the 16-QAM OFDM data carried by the 5.5-\(\mu\)m-aperture VCSEL can be achieved under the FEC criterion. To effectively allocate the energy of data to every OFDM subcarrier for adapting the finite throughput bandwidth, the pre-leveling of OFDM subcarrier amplitude for re-allocating the 16-QAM OFDM data throughput power is further employed to upgrade the transmission capacity. By multiplying the QAM-OFDM data spectrum with a positive power-to-frequency slope, the power reallocation can upscale the SNR of the OFDM subcarriers at high frequency region by sacrificing the power of low-frequency OFDM subcarriers. Such a pre-leveling technique inevitably suffers from the slight reduction on time-domain waveform amplitude. The decoded waveform, RF spectra, constellation plot, subcarrier SNR, and average BER of the 16-QAM OFDM data obtained at different pre-leveling slopes for both BtB and 100-m OM5-MMF transmission are performed and compared in Figs. 10(a) and 10(b). By setting the encoding bandwidth at 35 GHz in BtB case, the origin data waveform without pre-leveling exhibits the decoded EVM/SNR/BER of 18.3%/14.7 dB/5.5 \(\times\) 10\(^{-3}\) with blurred constellation plot, which fails to pass the FEC criterion.

After pre-leveling with a power-to-frequency slope of 0.3 dB/GHz, the significantly improved SNRs at high subcarrier frequency is clearly observed with an average value of 15.2 dB. The constellation plot shows more centralized points with corresponding EVM of 17.2% and BER of 3.5 \(\times\) 10\(^{-3}\), which is qualified by the FEC. Over pre-leveling the data spectrum with increasing the slope up to 0.5 dB/GHz excessively sacrifices the power of the low-frequency subcarrier data to lower the compensating efficiency for conversely degrading the average EVM/SNR/BER of the QAM-OFDM data to 17.5%/15.1 dB/4 \(\times\) 10\(^{-3}\). Monotonically increasing the power-to-frequency slope on the OFDM data spectrum only contributes to the finite amelioration on the receiving performance of the high-frequency subcarrier due to the inherent bandwidth limitation of MM-VCSEL. For 100-m OM5-MMF transmission, the 16-QAM OFDM data at the modulation bandwidth up to 30-GHz can improve its EVM, SNR and BER to 17.1% 15.3 dB and 3 \(\times\) 10\(^{-3}\) after pre-leveling at a slope of 0.5 dB/GHz, respectively. The decoded constellation plot becomes blurred again when over pre-leveling the OFDM spectral power with the slope up to 0.6 dB/GHz, which degrades the related EVM, SNR, and BER to 17.3%, 15.2 dB and 3.7 \(\times\) 10\(^{-3}\), respectively. With appropriate pre-leveling, the 5.5-\(\mu\)m-aperture VCSEL can support high data rate of 140 and 120 Gbit/s for BtB and OM5-MMF transmissions within modulation bandwidths of 35 and 30 GHz, respectively.

In more detail, the receiving power sensitivity characterized by BER versus receiving power for the broadband 16-QAM OFDM data at 120 Gbit/s with and without pre-leveling process after passing through BtB and 100-m OM5-MMF are compared in Fig. 11. Without applying pre-leveling process, the BtB and OM5 cases require the receiving powers of 0.8 and > 4 dBm to meet the FEC criterion, which reveals the power penalty of >3.2 dB in between. After pre-leveling, the receiving sensitivities for BtB and OM5-MMF transmission cases are individually improved to -1.8 and 1.3 dBm with corresponding power penalty of 3.1 dB. Moreover, the pre-leveling can respectively upgrade the BER in BtB and OM5-MMF transmissions from 4 \(\times\) 10\(^{-3}\) to 2 \(\times\) 10\(^{-3}\) and 6.4 \(\times\) 10\(^{-3}\) to 4.2 \(\times\) 10\(^{-3}\) at the same receiving power of 0 dBm, which provides the improvement by more than 35% due to reduced power penalty and enhanced receiving sensitivity with employing the OFDM spectral power pre-leveling process.

In the selected work [32], Zuo et al. utilized a 25-Gbit/s VCSEL to carrying the 13-level duobinary PAM-4 data for demonstrating 100-/300-/500-m MMF transmission at data rates of 150/100/70 Gbit/s, respectively. This work upgraded the allowable data rate and transmission distance of the 850-nm VCSEL based MMF link to a new record in 2016, but the least-mean-square and maximum likelihood sequence estimation equalization algorithms must be implemented to correct the MMF transmitted PAM-4 data at receiving end. In contrast, our work only employs the front-end pre-emphasis technology to facilitate PAM-4/16-QAM OFDM
transmissions. Without additional digital signal processing at receiving end, only the front-end pre-emphasis is used to pre-compensate the amplitude/phase distorted channel response, which makes the receiver module design simplified, compact and cost-effective as compared to previous work. On the other hand, the OM5 reveals higher effective modal bandwidth at 850 nm [6], [33] and smaller dispersion (with the interacted compensation between modal and chromatic dispersions) than that of the OM4 MMF [22], [23]. The observations in these literatures elucidate why the OM5 MMF can perform better transmission than the OM4 MMF. Our experiments exhibit consistent results to confirm the improved performance of the OM5 MMF for carrying complex data format. Moreover, the multimode VCSEL has approached its bandwidth limitation. Further shrinking the oxide-confined aperture of the multimode VCSEL can reduce its root-mean-square spectral linewidth for suppressing the modal dispersion during MMF transmission. Modifying the pre-leveling process with power loading algorithm at transmitting end can somewhat facilitate the PAM-4 data to accurately adapt and compensate the channel response of MMF transmission. In the future work, the aforementioned hardware and software techniques will be introduced to further upgrade the allowable data rate of the proposed PAM-4 transmission.

IV. CONCLUSION
By fabricating the multi-mode VCSELs with different mesa/aperture sizes through employing the multi-layered oxidation and adding 5 pairs of In$_{0.07}$Ga$_{0.93}$As QWs for reducing parasitic capacitance, their allowable encoding bandwidths can be significantly improved to enforce the digital broadband data transmission in data centers. In this work, both the transmission performances of the PAM-4 and 16-QAM OFDM data delivered by the VCSELs with different aperture sizes of 5.5 and 7.5 µm are compared after propagating through BtB and 100-m OM5-MMF. The active layer built up with InGaAs/AlGaAs QWs and the mesa confined with multi-oxide layers facilitate the VCSEL to reduce its capacitance for offering high differential gain and wide analog bandwidth. Although the 7.5-µm-aperture VCSEL exhibits the larger power of 3.6 mW with higher quantum efficiency of 24.1% at bias current of 15 mA, its narrower 3-dB bandwidth of 24.5 GHz and higher RIN level of -132 dBc/Hz are still beaten by the 5.5-µm-aperture VCSEL with 3-dB bandwidth of 25.2 GHz and RIN level of -135 dBc/Hz.

Under BtB transmission, the 5.5-µm-aperture VCSEL can deliver the PAM-4 data at 42 GBAud after compensating the data waveform distortion with pre-emphasis technique, which reveals jitter tolerances of 5/8/4.7 ps for the top/middle/bottom eye patterns at the BER of 1.7 × 10$^{-3}$. After transmitting through 100-m OM5-MMF, the 40-GBaud
PAM-4 data stream carried by the 5.5-µm-aperture VCSEL can still pass the KP4-FEC criterion at the BER of $1.3 \times 10^{-4}$ and top/middle/bottom eye jitter tolerances of 3.8/4.4/4.4 ps with a bandwidth budget of only 2-Gbaud and a receiving power penalty of 3.24 dB.

In contrast to PAM-4 transmission, the 5.5-µm-aperture VCSEL can further support beyond 132-Gbit/s 16-QAM OFDM transmission with the BER of $1.4 \times 10^{-3}$, SNR of 16.2 dB, and EVM of 15.4% after the bias current optimization in BtB case. After 100-m OM5-MMF transmission, the maximal allowable bandwidth for 16-QAM OFDM data carried by the 5.5-µm-aperture VCSEL can still reach 28 GHz with 5-GHz decrement. Although the OM5-MMF ensures the lower modal dispersion than conventional OM4-MMF, the transmitted data is still distorted with the residual modal dispersion and power fading when lengthening the OM5-MMF distance. With employing the pre-leveling algorithm for pre-compensating the QAM-OFDM data distortion, the subcarrier SNRs at high frequencies are significantly resumed to exceed the FEC criterion. Such data distortion, the subcarrier SNRs at high frequencies are still reach 28 GHz with 5-GHz decrement. Although the 5.5-µm-aperture VCSEL can further support beyond 132-Gbit/s 16-QAM OFDM transmission with the BER of $10^{-4}$, the maximal allowable bandwidth for 16-QAM OFDM transmission over 100 m multimode fiber is minimized to 3.1 dB. Up to 140-Gbit/s BtB and 120-Gbit/s OM5-MMF transmissions carried by the 5.5-µm-aperture VCSEL are achieved with the pre-levelled 16-QAM OFDM data format, which enables the realization of ultrahigh capacity data link for future applications.

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