# Record High-baud-rate 128-Gbit/s NRZ-OOK Direct Modulation of 1060-nm Single-mode VCSEL for Transmission over 2-km Standard SMF

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***Abstract*— The BERs of 2.5E−3 for 128-Gbit/s NRZ-OOK have been obtained after 2-km SMF transmission, thanks to the coupled-cavity and receiver DSP. The record bit-rate x distance product of 288-Gbit/s·km is also obtained with PAM4.**

***Keywords—VCSEL, short-reach communication, PAM4, mobile front-hall.***

## I. Introduction

The importance of short-reach communications is dramatically increasing both in data-center and mobile front-hall networks, where the application distance is ranging from several tens meters to several kilometers, and high baud-rate modulation technologies of IM/DD have been intensively investigated [1-4]. In the future short-reach communications, huge number of communication lines will be needed, and low power consumption and high integrability will be the critical issue. A vertical-cavity surface-emitting laser (VCSEL) is promising to meet these demands. While 100-Gbaud data transmissions of 850-nm multi-mode VCSELs were demonstrated [2, 4], the link length has been limited below 100-m due to the dispersion of multi-mode fiber (MMF) links, and therefore it cannot satisfy a versatile demand, such as intra-data center interconnects in hyperscale datacenters and mobile front-hall applications. To meet with a versatile demands in short-reach communications, a VCSEL-based transmission system covering the distance ranging from tens meters to kilometers will be expected. From these aspects, the transmission over several km distance in standard single-mode fiber (SSMF) at longer wavelengths (>1060-nm) has an advantage over the MMF transmission systems at 850-nm [5]. The development of >100-Gbaud VCSELs is challenging for next-generation km-datacenter interconnects. Recently, we have demonstrated 65-Gbit/s with non-return-to-zero on-off keying (NRZ-OOK) and 90-Gbit/s with 4-level pulse amplitude modulation (PAM4) transmission over 2-km SSMF by transverse coupled intra-cavity metal-aperture VCSEL without the aid of digital signal processing (DSP) [6]. In this paper, we demonstrate further enhancement of the modulation

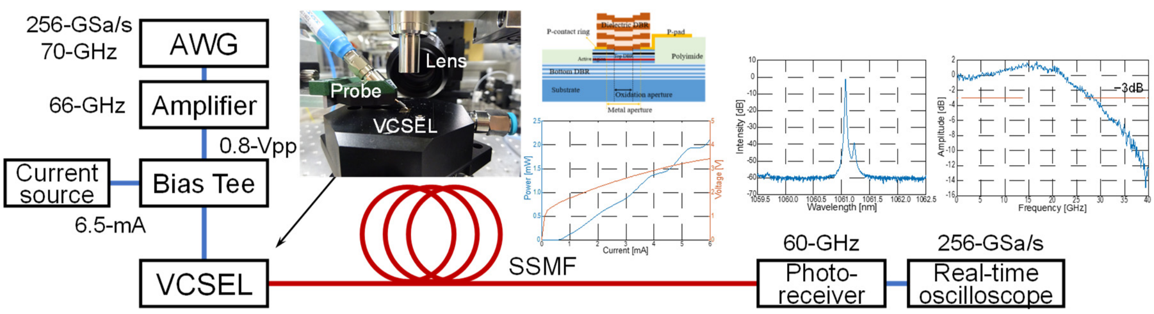


Fig. 1. Experimental setup and basic device characteristics.

data-rate with the aid of DSP, which is the combination of second order Volterra nonlinear equalizer (VNLE) and decision feedback equalizer (DFE). We have investigated the required design of the VNLE and finally exhibit 128-Gbit/s NRZ-OOK and 144-Gbit/s PAM4 transmission over 2-km SSMF, which are the record Baud rate as well as the highest data-rate and link-length product.

## II. Experimental Setup

Figure 1 illustrates the experimental setup, and the insets represent the device structure, I-L-V curve, continuous wave (CW) optical spectrum, and small-signal frequency response of single-mode intra-cavity metal-aperture VCSEL. The details of the device structure and characteristics are reported in [6]. Thanks to the lateral resonance in the intra-cavity metal aperture, we could realize the transverse-mode control and bandwidth enhancement at the same time [7]. A single-mode operation with side mode suppression ratio of 40dB is obtained even for an oxide aperture diameter of over 5μm, which is an important issue for high-reliability. The 3dB small-signal bandwidth is 28-GHz, and still useful intensity response is obtained at 40-GHz thanks to the coupled cavity effect [6], which will assist high baud-rate operation with DSP. It should be noted that the transmission in SSMF will enhance the bandwidth owing to the negative chromatic dispersion at 1060-nm wavelength and frequency chirp in direct modulation. Figure 2 shows the small signal response after a standard single-mode fiber (G.652) transmission with different fiber lengths. As can be seen, the bandwidth could be extended over 35-GHz for 2-km transmission, which could be long enough in intra-datacenter networks.

The modulation signal was generated by an arbitrary waveform generator (AWG) with 256-GSa/s and amplified to 0.8-Vpp by a broad-band amplifier with 66-GHz bandwidth. The VCSEL was 6.5-mA biased via bias-T. The frequency response of electrical line was fully compensated by the AWG to generate an ideal modulation waveform for the VCSEL. The Nyquist pulse shaping with 0.2 roll-off was used for NRZ-OOK modulation for bandwidth saving, whereas standard rectangular pulse shaping with 1.0 roll-off was used for PAM4 modulation to avoid unwanted peaking in the waveform. The transmitted signal was received by a photo-receiver with 60-GHz bandwidth and digitized by a real-time oscilloscope with 256-GSa/s. The received optical power was 0-, −1.4-, and −1.8-dBm for back-to-back (BtoB), 1-, and 2-km transmission, respectively. The digitized waveform was resampled to 2-Sa/Symbol, and the VNLE and DFE were applied in the off-line process by MATLAB [8]. In general, VNLE can be described as

$$
\begin{aligned}
y(k) = w_0 &+ \sum_{k_1=0}^{M_1-1} w_1(k_1)x(k-k_1) \\
&+ \sum_{k_1=0}^{M_2-1}\sum_{k_2=k_1}^{M_2-1} w_2(k_1,k_2)x(k-k_1)x(k-k_2) \\
&+ \sum_{k_1=0}^{M_3-1}\sum_{k_2=k_1}^{M_3-1}\sum_{k_3=k_2}^{M_3-1} w_3(k_1,k_2,k_3)x(k-k_1)x(k \\
&\quad - k_2)x(k-k_3)\ ,
\end{aligned}
\tag{1}
$$

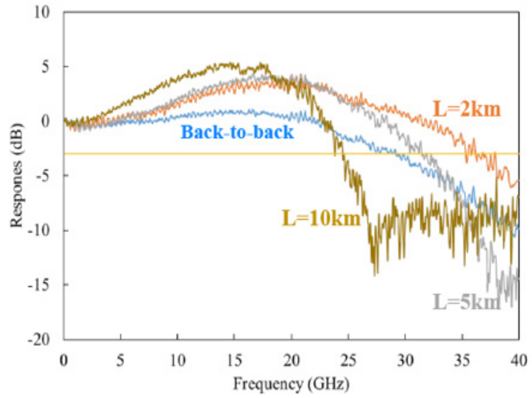


Fig. 2. Small signal response after a standard single-mode fiber (G.652) transmission with different fiber lengths.

where $x$ and $y$ are the input and output signals, $w_i$ are the coefficients of $i$-th order terms, and $M_i$ represents the tap length of $i$-th order terms. In the following investigation, the configuration of VNLE, i.e., the design of $\boldsymbol{M}$=($M_1$, $M_2$, $M_3$) will be discussed. The coefficients of the VNLE and DFE were first trained by the training sequence which is pseudo random binary sequence (PRBS) with $2^{11}-1$ length, and the operation mode was switched to decision directed mode after the convergence. The signal quality was evaluated by the bit-error-ratio (BER), where $2^{15}-1$ PRBS was used.

## III. Results and Discussion

First, we examined the transmission performance with linear filter, i.e., $w_2$=$w_3$=0, which is the simplest DSP and therefore easy to implement with little complexity. Figure 3(a) shows the measured BER of NRZ-OOK signal as functions of bit-rate, when the tap length of the filter is fixed at 15, and Fig. 3(b) shows the eye-diagrams of the equalized signals after 1-km transmission. As can be seen, although the signal quality of 70-Gbit/s is high enough, the BERs of 90-Gbit/s after 1-km transmission and 80-Gbit/s after 2-km transmission exceed 7% forward-error-correction (FEC) limit (=3.8E−3).

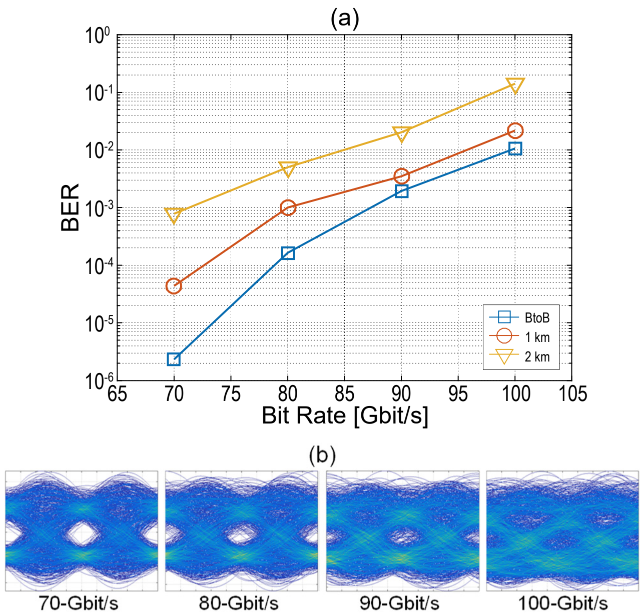


Fig. 3. Linear equalization. (a) BERs as functions of bit-rate and (b) eye-diagrams of equalized signals after 1-km transmission.

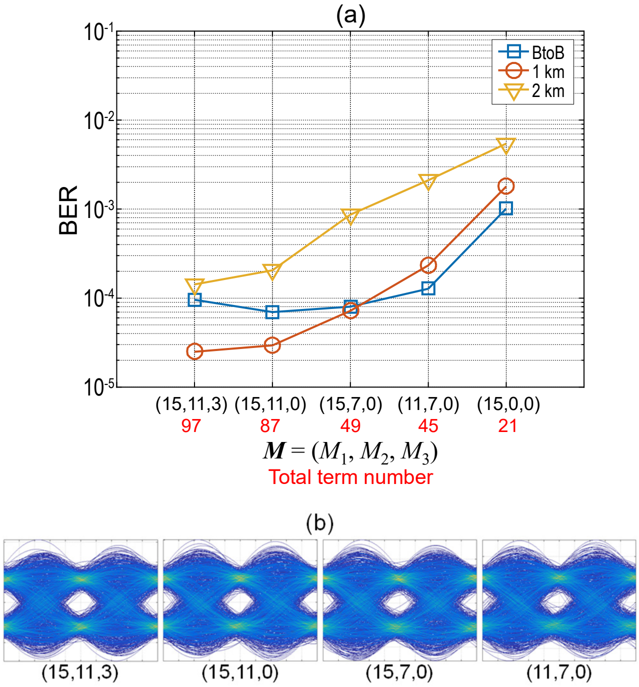


Fig. 4. Equalized by VNLE and DFE. (a) BERs as functions of different filter taps and (b) eye-diagrams of equalized signals after 1-km transmission.

Increasing the tap length has no impact on the performance; the BER of 100-Gbit/s was 2E−2 even with 21-tap filter. The results indicate that beyond 100-Gbit/s cannot be achieved with linear equalization.

Next, we examined several different VNLE configuration, i.e., different tap length of the first, second, and third order terms $\boldsymbol{M}$=($M_1$, $M_2$, $M_3$), to find the optimum filter configuration. Figure 4(a) shows the BERs as functions of tap lengths $\boldsymbol{M}$=($M_1$, $M_2$, $M_3$) and total term numbers, and Fig. 4(b) shows the eye-diagrams of equalized signals after 1-km transmission. The modulation format is fixed at 100-Gbit/s NRZ-OOK. The tap length of DFE is fixed at 5. The data at $\boldsymbol{M}$=(15,0,0) are same condition as 100-Gbit/s in Fig. 3 except that 5-tap DFE is used. By including the second order terms and longer tap length, the signal qualities are significantly improved. However, including third order terms has little impact on the signal qualities, whereas the computational complexity become higher, as can be seen in eq. (1). We think $\boldsymbol{M}$=(15,11,0) is the optimum VNLE configuration for this transmission system, where the total number of terms was 87. Therefore, in the following experiments, we fix the filter configuration of VNLE at $\boldsymbol{M}$=(15,11,0) with 5-tap DFE.

Figure 5(a) shows the measured BERs as functions of bit-rate of NRZ-OOK signal, and (b) shows the eye-diagrams of 128-Gbit/s signals. Even after 2-km transmission of 128-Gbit/s signal, the eye is clearly open and the BER is below 3E−3, although the extinction ratio of 128-Gbit/s signal is degraded from 5-dB of 100-Gbit/s to less than 3-dB due to the bandwidth limitation, as can be seen in Fig. 5(c). As a result, 128-Gbit/s NRZ-OOK, which is the ever highest baud-rate of VCSEL direct modulation, has been achieved.

Finally, we examined PAM4 modulation and transmission to further increase the bit-rate. The BERs and eye-diagrams are shown in Fig. 6. The BERs are below 7% FEC limit except for 144-Gbit/s PAM4 BtoB case, which is slightly above FEC limit. Although the maximum baud-rate of PAM4 is lower

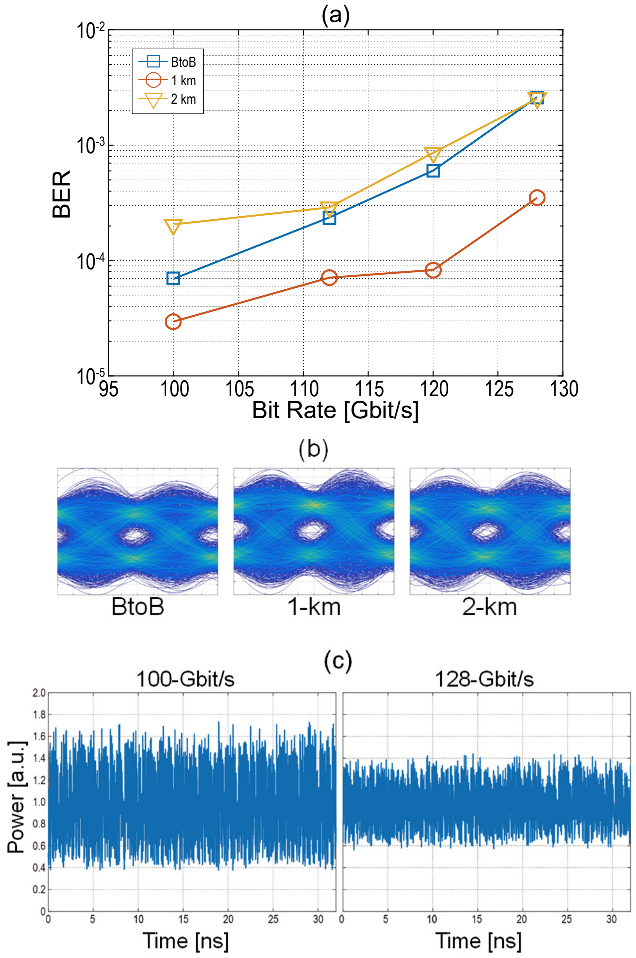


Fig. 5. (a) BERs as functions of bit-rate ,(b) eye-diagrams of 128-Gbit/s NRZ-OOK signals, and (c) time series waveform of 100- and 128-Gbit/s signals.

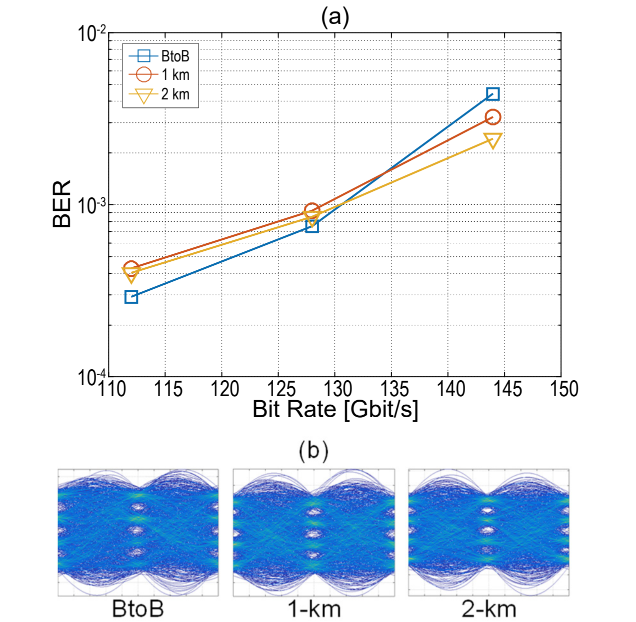


Fig. 6. (a) BERs as functions of bit-rate and (b) eye-diagrams of 144-Gbit/s PAM4 signals.

than that of NRZ-OOK, due to higher required linearity, signal-to-noise ratio and flatter frequency response, the ever highest bit-rate and distance product of VCSEL system 288-Gbit/s・km have been achieved.

## IV. CONCLUSION

We have experimentally demonstrated 128-Gbit/s NRZ-OOK and 144-Gbit/s PAM4 transmission over 2-km SSMF using a 1060-nm single-mode VCSEL with the aid of DSP, achieving the BERs below FEC limit. First, we have examined linear equalization and found that achievable bit-rate was below 90-Gbit/s. By including the second order terms, the BERs were drastically improved, whereas third order terms had little impact on the performance. The required design of VNLE was investigated, and the combination of second order VNLE with $\boldsymbol{M}$=(15,11,0) and DFE successfully compensated the linear and non-linear distortion in direct-modulation and transmission, which enabled the record Baud rate of 128-Gbaud and the highest data-rate・link-length product of 288 Gbit/s・km for directly-modulated VCSELs.


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