Single-mode 850nm VCSELs Demonstrate 96 Gb/s PAM4 OM4 Fiber Link for Extended Reach to 1km

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Abstract: Due to modal dispersion in OM4 fiber, multi-mode VCSELs have a limited high-speed NRZ and PAM4 transmitting distance of below 100 meters. The single-mode VCSELs with integrated mode-selective filter has been developed and demonstrated 96 Gb/s PAM4 transmitting distance to 1km with 1.78 dB TDECQ and 112Gb/s over 100 m OM4 fibers.

1. Introduction

850 nm oxide-confined VCSELs have been widely deployed as transmitters for short reach optical links in large scale data centers. With 800G optics and ethernet standards officially under discussion, VCSEL speed is advancing into 100G per channel which can be realized with 50 Gbaud pulsed amplitude modulation 4-level (PAM4). Despite the advantage of low cost and energy efficiency, VCSEL applications have been limited to transmission below 100 m distance because of its multi-mode nature which causes modal dispersion in addition to chromatic dispersion in multi-mode (MM) optical fibers. Therefore, single-mode (SM) VCSELs with fundamental mode dominant are being developed with reduced oxide aperture size or surface relief structures to deliver 20 Gb/s NRZ error-free transmission up to 2km [1] [2] and 107 Gb/s PAM4 eye diagrams beyond 100 m but without qualification of TDECQ [3].

In UIUC, we have designed and fabricated SM VCSELs with integrated mode-selective filter (IMSF) which brings the benefits of extended transmission distance and stable high-temperature operation [3] [4]. Previously, we have focused on applications of SM VCSELs through standard single-mode fibers (SSMF), demonstrating 38 Gb/s error-free NRZ transmission over 1km SSMF with > 95% confidence level as well as 26 Gbaud/s and 32 Gbaud/s PAM4 eye opening over 500m and 1km SSMF [5]. Stable high-temperature operation has also been verified though 40 Gb/s NRZ BERT transmission up to 70 °C. In this work, we will present room temperature PAM4 transmission of both SM and MM VCSELs with MM VCSELs showing up to 112 Gb/s over short distance and SM VCSELs demonstrating 96 Gb/s over 1 km OM4 fibers with a TDECQ ~ 1.78 dB.

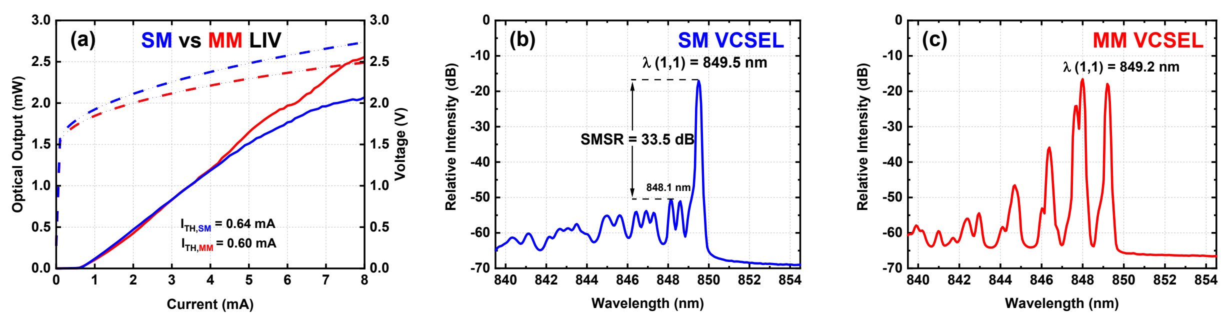


Fig. 1: (a) Typical L-I-V characteristics of 850 nm oxide-confined SM and MM VCSELs measured at room temperature. The laser threshold is 0.64 mA for SM VCSEL and 0.6 mA for MM VCSEL. (b) SM VCSEL optical spectrum at bias current of 7 mA with SMSR = 33.5 dB. (c) MM VCSEL optical spectrum at bias current of 7 mA.

2. SM & MM VCSEL Fabrication & Characteristics

The novel device structure concept of SM VCSEL with the integrated mode-selective filter was first proposed and demonstrated by Feng and Yu [6]. In this work, the VCSEL epitaxial structure was grown on top of semi-insulating GaAs substrate with MOCVD by Landmark (Taiwan). The 1/2-λ cavity design consists of 5 pair of InGaAs quantum wells with $Al_{0.37-0.90}Ga_{0.63-0.10}As$ as the cladding layers. 20 pairs of p^+ doped $Al_{0.12}Ga_{0.88}As/Al_{0.90}Ga_{0.10}As$ DBR on top and 30 pairs of n^+ doped $Al_{0.12}Ga_{0.88}As/Al_{0.90}Ga_{0.88}As$ DBR at the bottom construct the mirror structure. Double layers of 30 nm $Al_{0.98}Ga_{0.02}As$ forms the oxide aperture after lateral oxidation. The fabrications steps of SM VCSELs were modified based on previously reported MM VCSEL process [8] with the additional integrated mode-selective filter structure formed by oxidizing top P^+-DBR pairs.

DC and small-signal response characterization were performed with lensed fiber probe coupling at room temperature. In Fig. 1, we compare the LIV and spectra characteristics of SM and MM VCSEL devices with similar aperture sizes. MM VCSELs were fabricated with the same epi materials and without IMSF which exhibit a typical threshold current of 0.6 mA and 2.5 mW output power at 8 mA. Optical spectrum shows four modes produced with a current bias of 7 mA as shown in Fig. 1(c). For SM VCSELs with IMSF implemented, higher order modes can be successfully suppressed with a side mode suppression ratio of 33.5 dB as shown in Fig. 1(b). SM VCSEL threshold current increases slightly to 0.64 mA and output power becomes 2.1 mW at 8 mA. The increased differential resistance from the IV curves can be attributed to the increased p-contact resistance. Small-signal response was measured with 30GHz photodetector, showing a typical bandwidth of around 28 GHz for both SM and MM devices.

3. High Speed PAM4 Data Transmission over Distance up to 1 km

Room temperature PAM4 eye diagram measurements were performed with on-wafer probing. The device under test was held at a constant DC current bias of 7 mA. PRBS13 driving signals with 800mV peak-to-peak amplitude were generated by Keysight 120 GSample/s M8194A arbitrary waveform generator (AWG). The generated modulation signal was applied to the device through a 500 mm RF cable, a bias tee and a GS probe without amplifiers used. All electrical parts on the transmitter side had a bandwidth above 65 GHz. The optical output from the VCSEL device was first collimated and then guided into OM4 fibers with varying length through free space coupling. The coupling efficiency was found to be 70%~82% as compared to measurement from a large area photodetector which can completely cover the beam waist when placed 2~3 mm above the device. The optical signals after propagation were converted into electrical signals with a New Focus 1484-A-50 22 GHz photoreceiver. The resulting electrical signals were analyzed using a Keysight N1000A DCA-X sampling scope with an 86118A remote sampling module. 4-tap FFE was applied to the received signals to generate the eye diagrams shown in Fig. 2. TDECQ was calculated with a target symbol error rate (SER) of 4.8e-4.

The PAM4 eye diagrams of single-mode VCSEL operation tested at a data rate of 64, 96 and 112 Gb/s over 100 m, 300 m and 1 km OM4 fibers are demonstrated in Fig. 2. For 100 m transmission, SM VCSELs can deliver up to 112 Gb/s with eye opening. Over 1km OM4 fiber, 64 Gb/s and up to 96 Gb/s transmission over 1 km OM4 fibers has been recorded with a TDECQ less than 1.76 dB, demonstrating the capability for SM VCSELs to be implemented in datacenter-reach optical links. In our case, testing at higher data rates are limited by both the receiver unit bandwidth and the available power from the VCSEL. And it is the target of our next generation design to increase the output power of SM VCSELs. As a comparison, we also list here MM VCSELs results in Fig. 3 which shows significantly degrading performance with distance extended to 100 m and beyond. On the other hand, for short distance, it can deliver 112 Gb/s transmission with better eye opening and a TDECQ value of 2.71 dB (2m back-to-back) due to higher optical power.

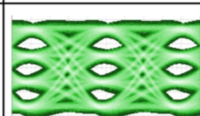
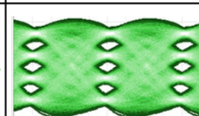
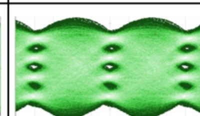
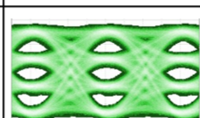
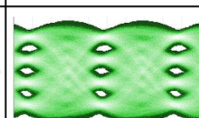
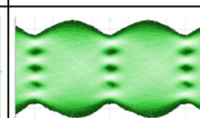
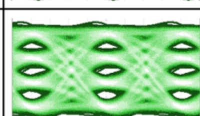
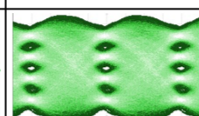
SM VCSEL	64 Gb/s	96 Gb/s	112 Gb/s
OM4 100 m			
OM4 300 m			
OM4 1000 m			-
TDECQ over 1000 m	0.96 dB	1.78 dB	-

Fig. 2. PAM4 eye diagrams of single-mode VCSEL high-speed data rate transmission over 100 m, 300 m and 1 km OM4 fiber channels after 4-tap FFE.

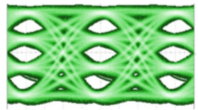
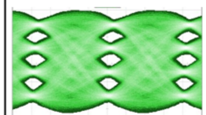
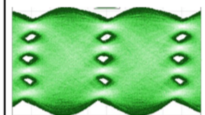
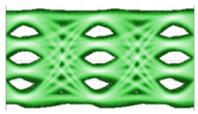
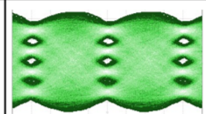
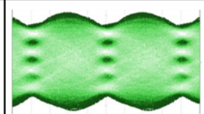
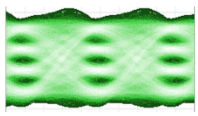
MM VCSEL	64 Gb/s	96 Gb/s	112 Gb/s
OM4 BTB			
OM4 100 m			
OM4 300 m		-	-
TDECQ over 100 m	0.25 dB	2.71 dB	-

Fig. 3. PAM4 eye diagrams of multi-mode VCSEL high-speed data rate transmission over BTB, 100 m and 300 m OM4 fiber channels after 4-tap FFE.

In conclusion, comparison of SM and MM VCSEL high-speed PAM4 data rate transmission over distance in Fig. 2 and 3, single-mode VCSEL demonstrates 96 Gb/s PAM4 transmission extended reach up to 1km in OM4 fiber. Further improved SM VCSEL device bandwidth over 30 GHz and higher linear power up to 3 mW should qualify low energy-per-bit 112 Gb/s PAM4 transmitting OM4 distance up to 2 km.

4. Acknowledgement

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5. References

[1] P. Moser, J. A. Lott, P. Wolf, G. Larisch and Hui Li, "85-fJ Dissipated Energy Per Bit at 30 Gb/s Across," *IEEE Photonics Technology Letters,* vol. 25, pp. 1638-1641, 2013.

[2] R. Safaisini, E. Haglund, P. Westberg, J. S. Gustavasson and L. A, " R. Safaisini, E. Haglund, P. Westberg, J. S. Gustavasson and A, Larsson, "20 Gb/s data transmission over 2km multimode fibre using 850 nm mode filter VCSEL," *Electronics Letters,* vol. 50, pp. 40-42, 2014.

[3] N. Ledentsov, V. Shchukin, V. Kalosha, N. Ledentsov, L. Chorchos, J. Turkiewicz, U. K. P. Hecht, F. Gerfers, J. Lavrencik and S. Varughese, "Optical interconnects using single-mode and multi-mode VCSEL and multi-mode fiber," in *Optical Fiber Communication Conference(OFC)*, 2020.

[4] H. L. Wang, J. Qiu, X. Yu, W. Fu and M. Feng, "The Modal Effect of VCSELs on Transmitting Data Rate Over Distance in OM4 Fiber," *IEEE J. Quantum Electron,* vol. 56, pp. 1-6, 2020.

[5] J. Qiu, X. Yu and M. Feng, "85°C Operation of Single-Mode 850 nm VCSELs for High Speed Error-Free Transmission up to 1 km in OM4 Fiber," in *Optical Fiber Communication Conference (OFC)* , 2019.

[6] J. Qiu, H.-L. Wang, D. Wu, X. Yu and M. Feng, "850nm Single-Mode VCSEL Delivered Record NRZ and PAM4 Data Rates over SMF-28 Fiber up to 1 km," in *Optical Fiber Communication Conference (OFC)* , 2021.

[7] M. Feng and X. Yu, "Single mode vcsels with low threshold and high-speed operation". United States of America Patent US20200119521A1, 11 10 2019.

[8] F. Tan, M.-K. Wu, M. Liu, M. Feng and J. Nick Holonyak, "850 nm Oxide-VCSEL With Low Relative Intensity Noise and 40 Gb/s Error Free Data Transmission," *Photonics Technology Letter,* vol. 26, pp. 289-292, 2014.