51.56 Gbps PAM4 Transmission over up to 2.3 km OM4 Fiber using Mode Selective VCSEL

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Abstract: Record bit-rate-distance-products of 118.6 and 51.6 Gbps×km were achieved for PAM4 and NRZ transmission over a single OM4 fiber using mode-selective VCSEL. The OMA penalty was 3.1 dB for 51.56-Gbps-PAM4 transmission over 1.6km OM4 at BER of 5×10^{-5}.
OCIS codes: (060.0060) Fiber optics communications; (060.4080) Modulation

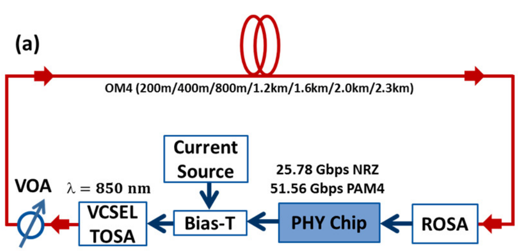
1. Introduction

Cost effective and large-scale installation of interconnects is necessary for modern data centers due to growth of bandwidth (BW) demand. There are several promising solutions based on different transceiver technologies including: directly modulated laser (DML), electro-absorption modulated laser (EML), and silicon photonics (SiPh). Low-cost, power efficiency, small form-factor, and reliable uncooled operation are critical requirements for the emerging solutions. In addition, achieving higher transmission rates and capacity over extended reach is essential to support the explosive demand in data traffic and cloud services.

Directly-modulated vertical cavity surface emitting lasers (VCSELs) have long been considered as a low cost and power efficient solution for short-reach communication over multimode fiber (MMF) within the datacenter [1]. In addition, transceivers with small footprint and reliable uncooled operation can be achieved using short wavelength VCSELs. While the need to increase link capacity could be addressed though utilization of short wavelength division multiplexing (SWDM) technology [2] and additional parallel fibers (IEEE P802.3bm) [3], these solutions would increase the cost of transceiver and the MMF cable plant as well as fiber management complexity. Currently, a combination of higher order modulation formats [2,4], such as four-level pulse amplitude modulation (PAM4) and digital signal processing (DSP) techniques [2,5] have been proposed to increase the capacity over single mode fiber (SMF) at 1310 nm [6] and a single conventional MMF at 850 nm [5]. In addition, the novel wideband MMFs enabled 100/200 Gbps data transmission over a single MMF up to 300m using SWDM and four 25 Gbps non-return-to-zero (NRZ) [7] as well as 51.56 Gbps PAM4 modulation formats [2]. However, higher transmission rates over extended reach >1 km are unrealizable due to inherently limited MMF link BW distance product induced by the modal dispersion and low VCSEL BW. To solve this limitation, high power (3.5 mW) single mode (SM) VCSELs were utilized for 48.92 and 20.3 Gbps discrete multitone (DMT) transmission over 2.2km OM4 fiber [4]. The bit-rate distance products of 107.6 and 44.7 Gbps×km were demonstrated at forward error correction (FEC) threshold of 3.8×10^{-3} and bit error ratio (BER) of 1×10^{-12}, respectively [4]. 54 Gbps NRZ SM VCSEL based transmission was also realized over 1km OM4 using the decision feedback equalizer (DFE) and feed forward equalizer (FFE) at BER of 3.8×10^{-3} and received average optical power (AOP) sensitivities of -6.3 and -4.6 dBm, respectively [5]. However, there is still a need for increasing the reach and data rate over MMF using modified VCSELs, equalizers, standard modulation formats (NRZ/ PAM4) at defined FEC thresholds with better sensitivities.

This paper describes a successful 51.56 Gbps PAM4 and 25.78 Gbps NRZ transmissions over up to 2.3km OM4 fiber by utilizing mode selective (MS) VCSEL with conditional launch introduced in [8] (<1 mW launch power). While a digital NRZ/PAM4 commercial PHY helps with modal/chromatic dispersion equalization, longer reach is achieved by removing modal dispersion degradation effect using MS VCSELs. The measured BERs as a function of

(a)



(b)

	VCSEL Type	
	MS	MM
RIN (dB/Hz)	-145	-142
3dB BW (GHz)	16	18

(c)

		VCSEL Type	
		MS	MM
NRZ	ER	4.2	3.0
PAM4	(dB)	3.3	2.3

(d)

	VCSEL Type	
	MS	MM
OM4 Length (m)	3 dB Optical BW (GHz)	
200	>25	18.2
400	>25	8.5
800	20.9	
1200	13.9	
1600	12.6	
2000	9.3	
2300	8.8	

Fig. 1 (a) Experimental setup for transmitting 25.78 Gbps NRZ and 51.56 Gbps PAM4 through different OM4 fiber lengths. (b) 3 dB BW and RIN measurements for two VCSEL types including: mode selective (MS) and standard multi-mode (MM). (c) The measured extinction ratios (ERs) for NRZ/PAM4 using two VCSEL types. (d) The measured 3 dB optical OM4 fiber BWs with two VCSEL types.

Optical Modulation Amplitude (OMA) are presented for NRZ/PAM4 system performance comparisons over various OM4 fiber lengths by using two VCSEL types and FFE. While MS VCSELs and FFE at RX enabled a reach extension up to 1.6km (2km) for 51.56 Gbps PAM4 (25.78 Gbps NRZ) over OM4 fiber, the standard MM VCSEL based transmission was limited to 200m OM4 fiber using the same equalizer. OMA penalties of 3.1 (4.8) dB were captured at BERs of 5×10^{-5} (1×10^{-12}) over 1.6km (2km) OM4 fiber using MS VCSEL for 51.56 Gbps PAM4 (25.78 Gbps NRZ). Using MS VCSEL and FFE, the bit-rate distance products were improved to 118.6 (51.6) Gbps×km for PAM4 (NRZ) over 2.3km (2km) OM4 fibers at BERs of 3.8×10^{-3} and 1×10^{-12} with lower launch powers in comparison with the reported results in [4]. 51.56 Gbps PAM4 MS VCSEL signaling doubled the bit-rate distance product reported in [5] to 118.6 Gbps×km over 2.3km OM4 fiber at BER of 3.8×10^{-3} and improved AOP sensitivity by 1.3 dB. We believe that this study opens a new horizon to utilize MS VCSEL based transmission over MMF and achieve higher capacity and longer reach interconnects for the next generation of data centers.

2. Experimental Setup and Results

Figure 1 (a) shows a schematic of the experimental setup comprising a TOSA, a ROSA, a variable optical attenuator (VOA), OM4 fiber spools with different lengths, and a single PHY chip. The chip performed the main functions, such as PAM4/NRZ clock and data recovery, pulse shaping at the transmitter, adaptive modal and chromatic dispersion equalization at the receiver, and real-time BER measurement. The 3-dB BWs of two Finisar VCSEL types used in this experiment ranged from 16 GHz to 18 GHz as shown in Fig 1 (b). The measured average relative intensity noises (RINs) were ~-142 dB/Hz and -145 dB/Hz (Fig 1 (c)). Seven OM4 fiber spools with various lengths were used for this experiment. The measured 3 dB optical BWs of OM4 fiber links and VCSEL type combinations were listed in Fig. 1 (d). To characterize root mean square (RMS) spectral bandwidths (SBWs) of these VCSELs, their optical spectra were measured as shown in Figures 2 (a-b). The optical power was adjusted using a mode preserving VOA. The receiver sensitivities were measured using a ROSA.

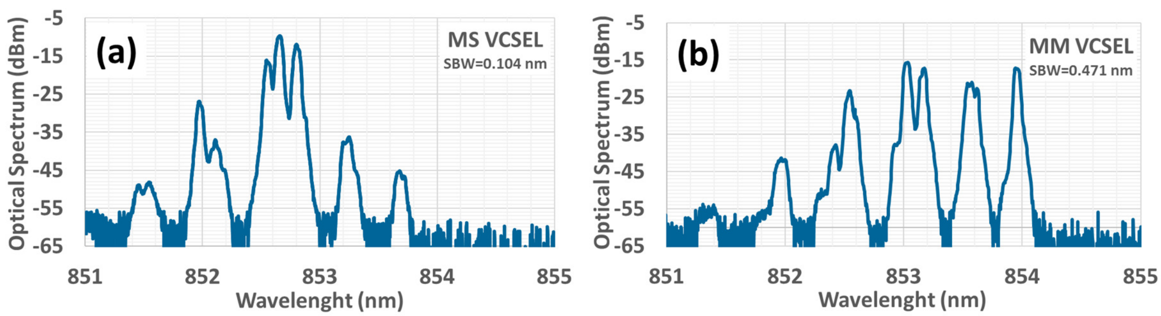


Fig. 2 Measured optical spectra for two VCSEL types with RMS SBWs of a) 0.104 nm (MS) and b) 0.471 nm (MM).

25.78 Gbps NRZ and 51.56 Gbps PAM4 optical streams were generated by directly and differentially driving the VCSELs using 25.78-Gbaud scrambled pseudo-random bit sequences (PRBS) of length 2^{31}-1. These sequences were produced by integrated DACs, with ~0.8 Vpp electrical signal. The PHY chip DSP provided functionality for pre-emphasis compensation. The bias current and pre-emphasis were adjusted to optimize B2B optical system performance for both transmission configurations. While MS VCSEL was biased at ~8 mA, the bias point was ~11 mA for MM VCSEL. Figure 3 shows the measured received NRZ optical eyes with the pre-emphasis compensation turned on at TX.

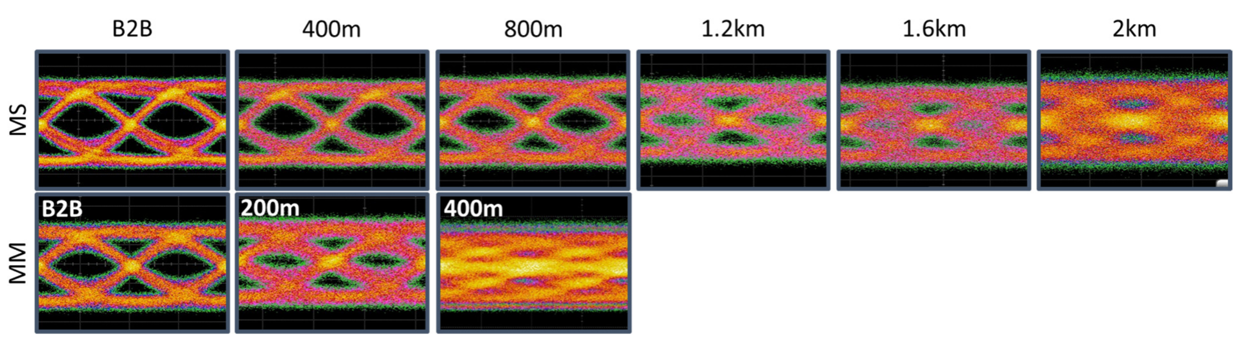


Fig. 3 The received optical eyes for 25.78 Gbps NRZ after transmission through different OM4 fiber lengths using MS/MM VCSELs.

As shown in Fig 1 (c), The measured transmitter ERs ranged from 3.0 dB (2.3 dB) to 4.2 dB (3.3 dB) for NRZ (PAM4). Open NRZ eyes were observed at 800m OM4 using MS VCSELs as well as 200m OM4 using standard MM VCSEL. While total eye closure was observed at 400m OM4 using a standard MM VCSEL, open eyes were captured up to 2km using a MS VCSEL.

To quantitatively demonstrate the advantage of MS VCSEL over standard MM VCSEL, real-time BER measurement was performed over different OM4 fiber lengths and OMA sensitivity curves were compared for standard MM and MS VCSELs with an equalizer. Figures 4 (a-b) show the BER measurements after adaptive equalization at RX as a function of inner eye OMAs for 25.78 Gbps NRZ and 51.56 Gbps PAM4 using two VCSEL types. The KR4 FEC threshold (BER<5×10^{-5}) and error free (BER<1×10^{-12}) determined the required inner eye OMAs for PAM4 and NRZ transmissions through each OM4 fiber length. The measured OMAs were -11.6, -11.2, -10.6, -9.8, -9, and -6.8 dBm for NRZ MS transmission through B2B, 400m, 800m, 1.2km, 1.6km, and 2.0km OM4 fibers at BER of 1×10^{-12}, respectively. While the measured OMA penalties over 200m OM4 fiber were 1.9 dB (at BER of 1×10^{-12}) and 4.8 dB (at BER of 5×10^{-5}) for NRZ and PAM4 using standard MM VCSEL, the corresponding OMA penalties were negligible (<0.4 dB) over 400m OM4 fiber using MS VCSEL. The measured OMA penalties were 0.3 dB, 1.6 dB, and 3.1 dB for PAM4 MS based transmission through 800, 1200, and 1600 meters of OM4 fiber at BER of 5×10^{-5}, respectively. Record bit-rate distance products of 118.6 (51.6) Gbps×km were demonstrated over 2.3km (2.0km) OM4 fiber for 51.56 Gbps (25.78 Gbps) PAM4 (NRZ) transmission at FEC threshold of 3.8×10^{-3} (BER of 1×10^{-12}).

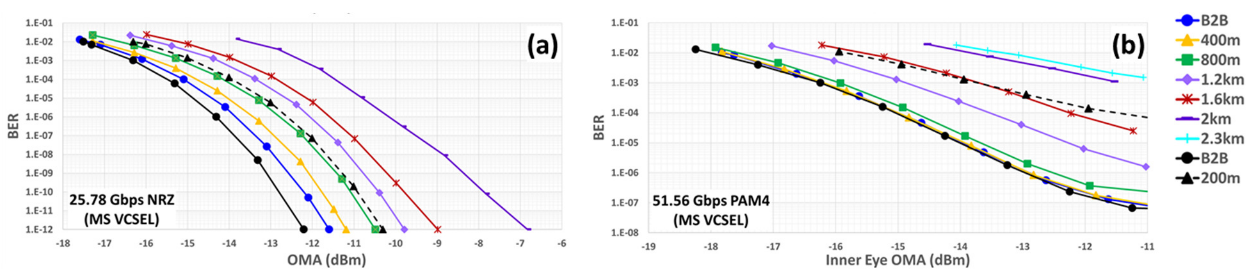


Fig. 4 Measured BERs over different lengths of OM4 fiber for a) 25.78 Gbps NRZ and b) 51.56 Gbps PAM4 transmission using MS VCSEL. Black lines show standard MM VCSEL transmission sensitivities.

3. Conclusion

We experimentally demonstrated 51.56 Gbps PAM4 and 25.78 Gbps NRZ transmission over up to 2.3km OM4 fiber using MS VCSEL with an equalizer at the receiver. The record bit-rate distance products of 118.6 (51.6) Gbps×km were achieved for PAM4 (NRZ) over 2.3km (2km) OM4 fibers at BERs of 3.8×10^{-3} (1×10^{-12}). OMA penalties of 3.1 dB (4.8 dB) were captured at BERs of 5×10^{-5} (1×10^{-12}) over 1.6km (2km) OM4 fibers for 51.56 Gbps PAM4 (25.78 Gbps NRZ) using MS VCSEL. These results show that the MS VCSEL based transmission over OM4 fiber can increase the reach to 2.3km and achieve higher capacity for the next generation of data centers with highly dense switches.

4. Acknowledgement

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