168Gbps PAM-4 Multimode Fiber Transmission through 50m using 28GHz 850nm Multimode VCSELs

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Abstract: We experimentally demonstrate PAM-4 data rates beyond 160Gbps over 50m OM5 using unpackaged 850nm VCSELs. Power penalties of PAM-4 are examined demonstrating maximum data rates, with and without FEC, over 50m and 100m of fiber.

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1. Introduction

The increase in data center infrastructure to support growing cloud services has led to growing demand for energy-efficient, high-speed data links for server-to-server and server-to-rack interconnects. These links are dominated by Vertical-Cavity Surface Emitting Lasers (VCSELs) and multimode fiber (MMF) due to their excellent performance, low cost, low power, and high density form factor. Existing IEEE 802.3cm standard efforts support 50Gbps PAM-4 core rates in four (two lambda) and eight fiber configurations to support traffic up to 400Gbps [1]. To continue extending data rate capacity, both faster data rates and increases in shortwave division multiplexing (SWDM) lambda will be required. Experimental VCSEL links have demonstrated 100Gbps PAM-2 over 50m OM5 MMF [2], a 120Gbps PAM-4 Transceiver [3], and SWDM VCSEL links for 800Gbps/1.6Tbps solutions [4, 5]. The inclusion of equalization at the transmitter and receiver, as well as low-latency KP4 forward error correction (FEC) acceptance in IEEE standards, have allowed VCSEL MMF links to scale data rates competitively with silicon photonics and short reach coherent solutions while continuing to offer the most efficient bitrate in regards to cost and power consumption.

Here, we demonstrate greater than 160Gbps PAM-4 signaling over 50m of OM5 MMF [6], using 850nm unpackaged VCSELs with allocation for FEC. Equalization is implemented at the transmitter as pre-emphasis and receiver as a static feed-forward equalizer (FFE). Additionally, we include raised cosine (RC) filtering to demonstrate the benefits of shaping the electric signal for a typical equalized VCSEL link channel. We study the maximum achievable error-free (BER $<10^{-12}$) data rates for PAM-4 and reach 146Gbps over 50m of OM5. We conclusively show VCSELs are capable of reaching over 160Gbps PAM-4, demonstrating the continued capability of VCSEL MMF links to scale line rates with demand.

2. Experimental Setup

In this article we study the performance of a new generation of anti-waveguiding VCSELs with increased bandwidth above 28GHz [7]. It was previously shown that this generation of oxide-confined VCSELs operates at 60Gbps without pre-emphasis or signal processing in PAM-2 modulation and is expected to enable higher bit-rates if operated in combination with specialized electronics [8].

The VCSELs were driven by a 120GSa/s Arbitrary Waveform Generator (AWG) with 45GHz of analog bandwidth (Keysight Technologies M8194) with a PRBS-15 pattern, Fig. 1. The VCSELs that were investigated had ~28GHz bandwidth. A peak-to-peak voltage swing of 650mV was used to drive each VCSEL with a DC bias of ~4mA. Details of the experiment are similar to our previous work [2] with a few alterations. In the case of investigating shaped pulses, a 9-tap T/2 spaced time-domain raised cosine (RC) filter with 0.35 roll off factor was used. The transmitter pre-emphasis was generated by the AWG in a limited form, by restricting the DAC to a 6-tap filter. The filter at the receiver was applied through a real-time Keysight UXR1102A oscilloscope and compensates for remaining channel distortions using a static 5-tap FFE based on the baud rate. The optical signal was attenuated by 3dB to emulate the loss from a MUX/deMUX. The OM5 MMF was supplied by OFS. A Thor Labs DXM30BF Ultrafast Detector was used with an SHF 807 amplifier for the receiver. Direct bit error rate counting was done using the SHF 11100A error analyzer (BERT) for rates ≤120Gbps. For PAM-4, the error rate is evaluated by measuring the symbol error rate of each eye at identical sampling points, and then summing half the individual eye error rates. Probability density function (PDF) analysis was implemented for data rates >120Gbps using the real-time UXR. The BERT and PDF method was shown to be close to equivalent for rates up to 120Gbps. The BER PDF analysis was done over $>1\bullet10^{7}$ (oversampled) symbols. When the BER was $>10^{-6}$, offline error counting was done through the real-time scope.

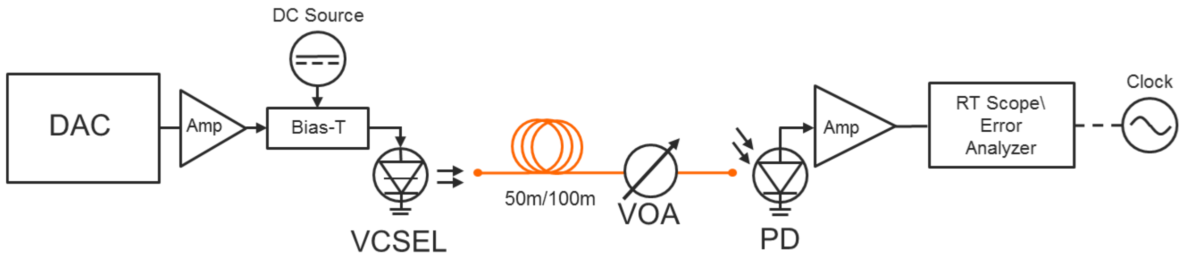

Fig. 1: Experimental setup. The 'channel' is defined from the DAC to the ADC

3. Transmitter Equalization and Error-Free PAM-4

In order to keep equalization simple for analog implementation, a static UI-spaced 6-tap FFE filter response was applied based on the channel response, Fig. 2a inset. With regards to equalization, the channel response roll-off, the choice of filter length, optical power, extinction ratio, baud rate and RIN all contribute to the optimum equalized 3dB bandwidth. For experimental simplicity, we determined the optimum equalized 3dB bandwidth by maximizing link data rates for the VCSEL, which was >40GHz. As a result, the filter may not be optimum for low baud rates and the observed received power is slightly higher than that possible with a filter optimized for low baud rates.

The minimum optical power to achieve error-free PAM-4 through 100m OM5 fiber was experimentally measured by sweeping the bit rate to just beyond 120Gbps, Fig. 2a. The minimum received power is consistent at ~-6dBm to 80Gbps, limited by the thermal noise and responsivity of the receiver. Beyond 80Gbps, the residual ISI from the channel and nonlinearities of the PAM-4 eyes begin to exponentially increase the power penalty as the bitrate increases. Regardless, at 100Gbps the power penalty increase is less than 1dB, demonstrating that 100Gbps PAM-4 over 100m is achievable with a 6-tap FFE transmitter equalizer. As the data rate increase to 120Gbps, the power penalty increases to 3.6dB, still having some power margin. Beyond 120Gbps, PDF analysis was used to calculate the BER and the power penalty begins to increase >1dB for every 3Gbps improvement.

Several BER curves were taken below 120Gbps for comparison, Fig. 2b. No noise floor can be seen in any of the BER curves. At 50Gbps and 80Gbps, PAM-4 exhibits nearly the same shape. At 100Gbps and above, the BER curves have slightly varying shapes due to the non-optimal equalization resulting in some eye nonlinearity which be seen in the eyes, Fig. 2 (right). Note at 120Gbps there is less nonlinearity than at 100Gbps. Re-optimizing the equalization for a 100Gbps will significantly reduce the nonlinearity without the need for a Volterra filter.

4. RC Filtering, Receiver Equalization, and FEC with PAM-4

An RC filter, as described in the experimental setup, is added for deliberate shaping of the drive signal to match the equalized channel and thereby reduce ISI. Through 100m OM5, the RC filter improves the bit rate by 12Gbps. The RC filter improves the bitrate by 15Gbps through 50m OM5, to an error-free 146Gbps. At high bit rates, the performance through 50m OM5 becomes significantly better than 100m due to dispersion effects. Compared to the maximum achievable error-free bitrates through 100m OM5, 50m OM5 provides 1.8dB and 2dB of extra power margin for non-filtered and RC filtered pulses, respectively. Considering the 100m OM5 has only ~0.1dB more loss than 50m OM5, this was a substantial reduction in the dispersion power penalty.

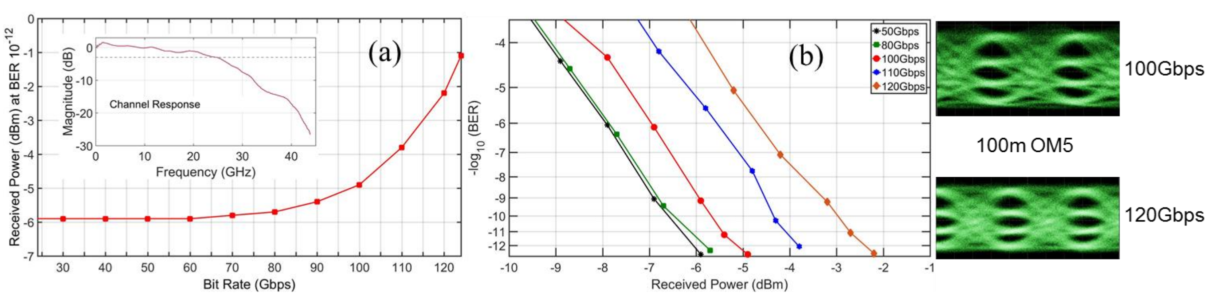

Fig. 2: (a) Received power for error-free transmission with PAM-4 on an equalized channel through 100m (red) OM5 fiber with VCSEL channel response (inset); (b) BER vs. received power for PAM-4 for various bit rates on an equalized channel through 100m OM5 fiber; Eye diagrams (right) for equalized error-free 100Gbps and 120Gbps PAM-4 through 100m OM5 fiber.

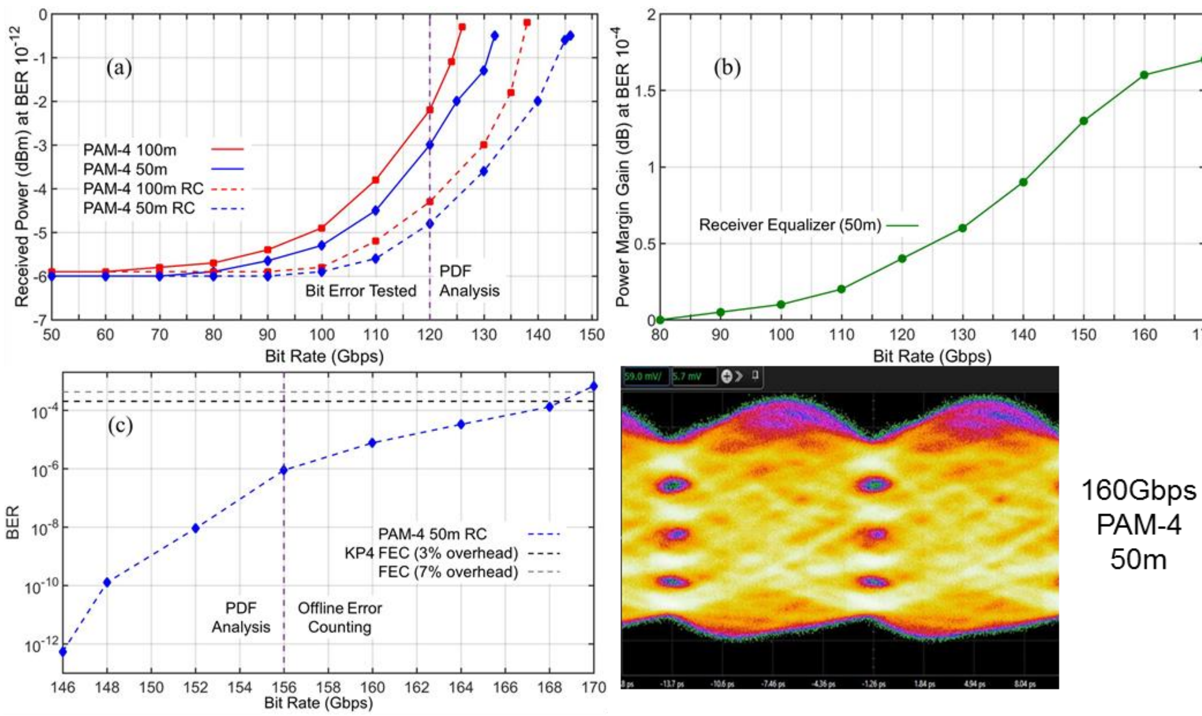

Fig. 3: (a) Received power for error-free transmission with PAM-4 on an equalized channel through 100m (red) and 50m (blue) OM5 fiber. Pulse shaping was added to the equalization to increase data rates (dashed); (b) Receiver equalizer power margin gain over 50m OM5 at 10^{-6} BER; (c) Bit error rate (BER) of RC PAM-4 through 50m OM5 fiber. FEC limit marked by black (3%) and gray (7%) dashed line; (bottom right) PAM-4 eye diagram at 160Gbps before receiver equalization.

To extend the data rate, FEC and a receiver equalizer were added to the system. The static 5-tap T-spaced receiver equalizer consisted of 1 pre- and 3 post-taps and was optimized for each bit rate, while overhead was allocated for the well-accepted KP4 FEC. We note that over the $>10^7$ symbols analyzed, no burst errors were found. The receiver equalizer steadily improved optical power margin to a 1.7dB maximal gain, Fig. 3b, due to the increase in residual ISI from the increasing bit rate. Combining both transmitter and receiver equalization with RC filtering, we measured the BER versus bit rate with allocation for FEC, Fig. 3c. At BERs $>10^{-6}$, the symbol errors were physically counted offline. Through 50m OM5, data rates reached 168Gbps with FEC allocation for an effective >163Gbps, conclusively demonstrating a >160Gbps VCSEL solution for data centers and continued growth in VCSEL MMF line rates.

5. **Conclusions**

We have demonstrated 146Gbps PAM-4 error-free transmission and 168Gbps PAM-4 with FEC allocation transmission using unpackaged 850nm VCSELs over 50m OM5. Moreover, we demonstrate the advantages of few tap equalizers and RC filtering for increasing data rates in a band limited VCSEL MMF system. We have shown the capability of VCSEL MMF links to scale with growing bandwidth demand while maintain their low-power low-latency characteristics.

Acknowledgements

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6. References

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