

4λ x 100Gbps VCSEL PAM-4 Transmission over 105m of Wide Band Multimode Fiber

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Abstract: We demonstrate 100 Gbps PAM-4 transmission over 105m of wideband-MMF for each of four wavelengths from 850nm to 940nm using 25G VCSELs and thereby demonstrate an architecture that enables 400G over a single MMF.

OCIS codes:

1. Introduction

Short reach links are dominated by VCSELs with MMF and direct detection since these links offer excellent performance, low power and high density. Existing IEEE 802.3bm standards efforts support 25Gbps and 10Gbps core rates in four fiber and ten fiber configurations to support traffic up to 100Gbps. However, a 400GbE solution as envisioned by the IEEE P802.3bs Task Force will require 16 fibers in each direction. Alternate solutions that require reduced fiber counts are needed to maintain the low cost and low power consumption of VCSEL MMF based links for 400Gbps and eventually 1Tbps interconnects. The path forward will include higher line rates and higher modulation formats [1] both enabled by FEC and signal processing. Additionally, short wavelength division multiplexing (SWDM) [2] in the 850nm to 940nm range is enabled by next generation wideband MMF (WBMMF). Recently, 40Gbps PAM-2 was demonstrated from 850nm to 940nm using VCSELs [3]. Additionally, 45Gbps-50Gbps PAM-4 was demonstrated over the same wavelengths of VCSELs up to 300m [4, 5, 6]

Here we demonstrate that 850nm to 940nm VCSELs support 107Gbps PAM-4 signaling (100Gbps effective data rate) over 100m of WBMMF. The four 107Gbps line rates allow a combined 400Gbps user rate with low latency forward error correction (FEC). The link includes unpackaged 850nm, 880nm, 910nm, and 940nm VCSELs designed for 25G PAM-2 (commonly but incompletely called NRZ) operation. Equalization strategies include transmitter based pre-emphasis and offline receiver based equalization and decoding. Furthermore, a raised cosine pulse shape was implemented to further limit channel bandwidth requirements. The VCSELs readily support 25G data rates, exhibit low RIN, and the signal processing methods are within the capabilities of current generation SiCMOS [7].

2. Experimental Setup for PAM-4 modulation

The 107Gbps electrical PRBS-7 PAM-4 signal is generated by the Keysight M8196A 92GSa/s Arbitrary Waveform Generator (AWG), Fig.1. Due to the bandwidth constraints of the link, a time-domain raised cosine pulse filter (RC) is used with 0.1 roll off to create the required signal. The AWG measures the channel response, Fig.1, and implements pre-emphasis to partially compensate for channel response as estimated by the AWG. The channel response with each of the VCSELs are similar since they have similar bandwidths and a common 28GHz bandwidth receiver. An adaptive filter after detection compensates the remaining channel distortions. Both the pre-emphasis filter at the transmitter and

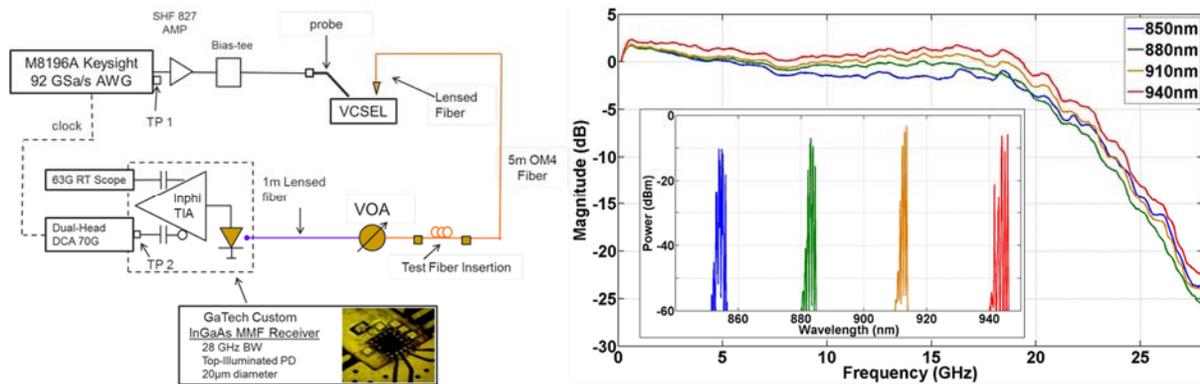


Fig. 1.: Block diagram of electrical setup for PAM-4 link (left), Response of channel for 850nm (blue), 880nm (green), 910nm (orange), and 940nm (red), with inset optical spectrum.

the adaptive filter at the receiver primarily add gain boost ($<10\text{dB}$) at the Nyquist frequency and can therefore be implemented with digital or analog filters of similar limited complexity. This pre-distorted signal is amplified and applied to the unpackaged VCSEL through a linear amplifier. 100m of next generation wideband fiber with $\geq 6\text{GHz-km}$ calculated effective modal bandwidth (EMBc) from 850nm to 950nm was used for the PAM-4 transmission experiments [6].

The differential receiver is custom designed at Georgia Tech consisting of an InGaAs photodiode and a low noise Inphi TIA for a combined bandwidth of 28GHz. The entire link shows roughly 20GHz of bandwidth back-to-back with either VCSEL, and 19GHz bandwidth with the fiber and either VCSEL. The received signal is captured by both a DCA 81600D 70G sampling scope and DSA-X 96204Q 160 GSa/s real-time scope. The sampling scope is used to record the received eyes without any receiver equalization and the real-time scope records the waveform for offline equalization.

The received optical signal is direct detected, digitized and equalized from the recorded waveforms of the real-time scope. We implemented the Oerder-Meyr [8] algorithm which is effective in compensating for fractional baud rate errors due to RC pulse shaping. The signal is then low-pass filtered to suppress out-of-band noise followed by an adaptive equalization technique using a training sequence. We compare two different digital feedback equalizer (DFE) and feed forward equalizer (FFE) combinations. One combination consists of a 7-tap FFE and 3-tap DFE, the other combination consists of a 5-tap FFE and 1-tap DFE. The FFE/DFE filter coefficients are adaptively determined using the Least-Mean-Square (LMS) algorithm. The receiver signal processing complexity is consistent with currently available PAM-4 receivers although at a higher baud rate [7].

3. Results

All VCSELs produce fiber coupled power greater than 3dBm with bias currents of 13.5mA, 12.1mA, 12.6mA, and 12.2mA for 850nm, 880nm, 910nm, and 940nm respectively. The RMS spectral widths of the VCSELs were 0.54nm, 0.47nm, 0.43nm, and 0.56nm from shortest to longest wavelength and the average power RIN of the VCSELs varied between -141dB/Hz and -146dB/Hz. There is a small fiber-imposed power penalty of $\sim 1\text{dB}$ in the equalized signal for the wideband fiber, Fig. 2. However, the slope of the BER curves remain the same between the back to back and fiber cases. However, this is mostly attributed to the high frequencies being far above the cutoff of the channel and the limiting amplifier in the TIA. Adding more taps lowers the BER and increases the BER slope suggesting revealing no floor above 10^{-6} BER.

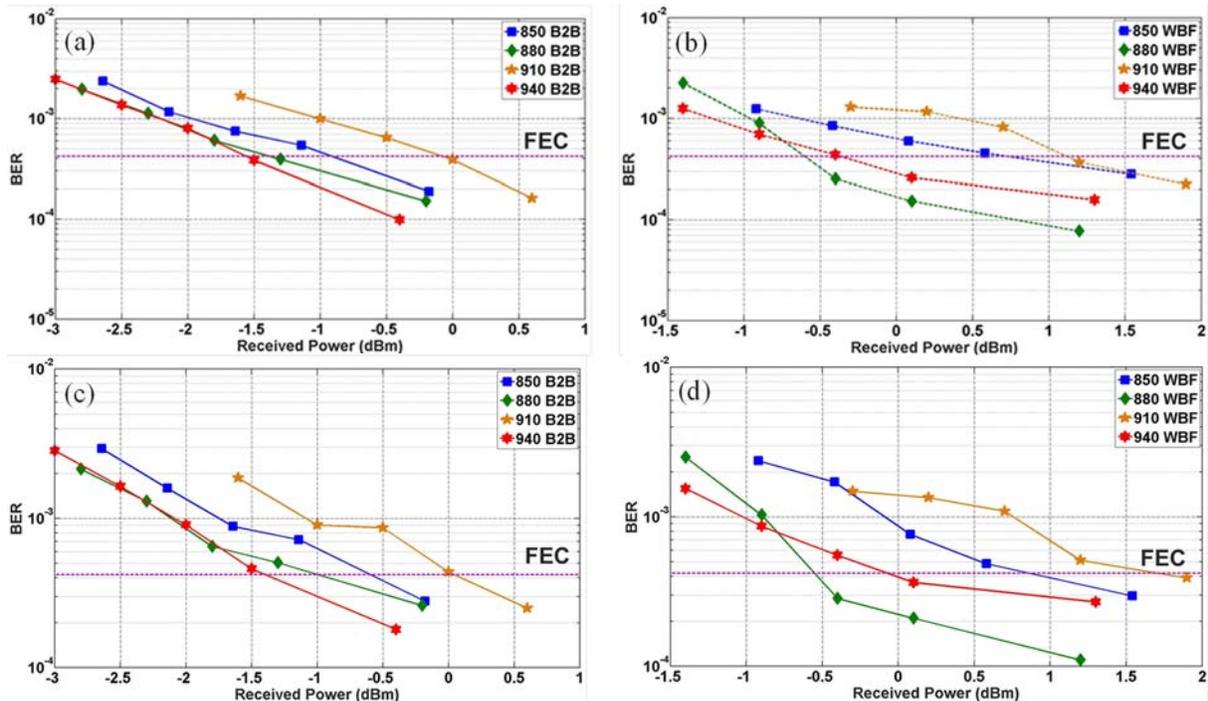


Fig. 2.: BER after equalization for back to back (B2B) link (a) and WBMMF link (b) with 7-tap FFE and 3-tap DFE. BER after equalization for back to back (B2B) link (c) and WBMMF link (d) with 5-tap FFE and 1-tap DFE.

The BER behaviors were consistent across the VCSELs examined. There was excess power available at the receiver across all VCSEL wavelengths and >2dB optical attenuation was required to avoid receiver nonlinearities. The recovered but unequalized PAM-4 eye through the fiber, Fig. 3, reveals a slight eye skew of ~0.05 UI which was the same in the back to back and fiber configurations. This skew imposes a slight penalty due to the RC filter shape. The skew is attributed to VCSEL nonlinearities and the limiting amplifier receiver, but can be further mitigated with additional signal management. However, the penalty without such additional processing is sufficiently low to ensure sufficient individual eye width for achieving a BER below the FEC limit.

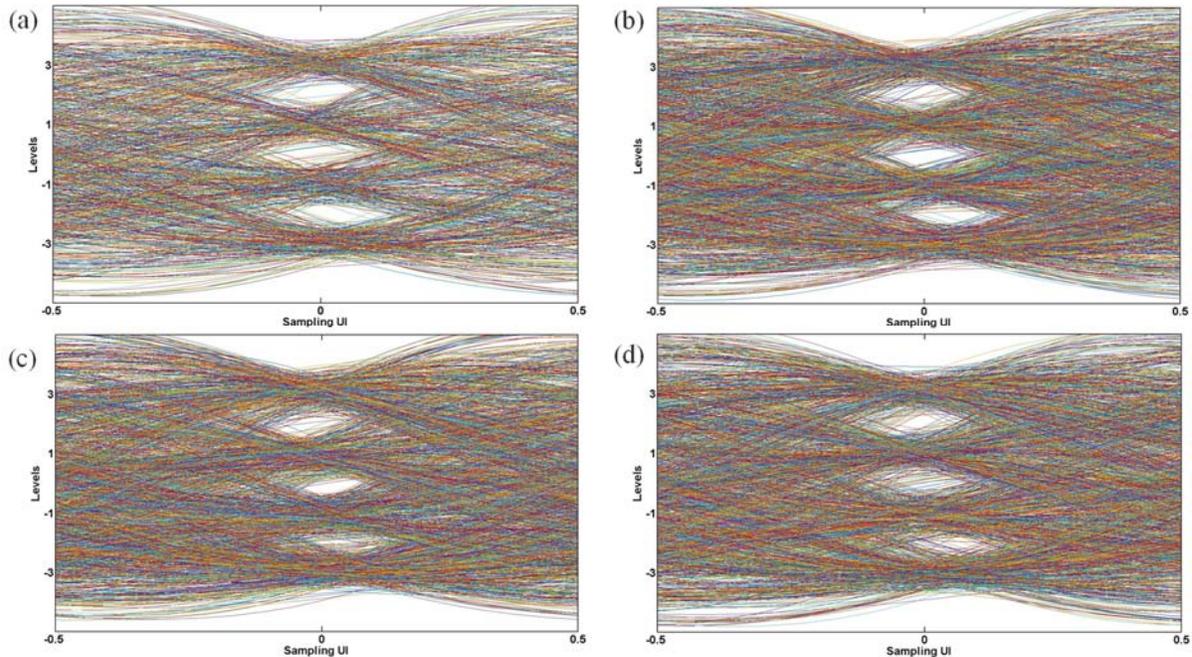


Fig. 3.: Received eye diagrams after 100m WBMMF before receiver equalization: 850nm(a), 880nm(b), 910nm(c), 940nm(d).

4. Conclusions

We have demonstrated 100Gbps PAM-4 transmission below the FEC threshold using 850nm, 880nm, 910nm, and 940nm VCSELs over 100m wideband MMF. There was no evidence of a significant RIN or MPN penalty. We used signal processing strategies at both the transmitter and receiver that may soon be available in silicon electronics. The 100Gbps line rate may be combined with short wave multiplexing and the next generation wideband MMF to yield 400Gbps links with only a single fiber for each direction. These results demonstrate a feasible path to 400Gbps single MM-fiber solutions.

Acknowledgements

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