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Abstract *We experimentally evaluated up to 96 Gb/s/λ PAM IM/DD transmissions with an EML and digital equalizations. Symbol-spaced FFE/DFEs with fewer than 10 taps are shown being sufficient for a high and stable performance over a 4 km SMF link.*

Introduction

Increasing demand for compact and low-cost transceivers supporting 400 Gb/s data rate is driven by rapidly growing bandwidth-intensive applications such as intra / inter data center interconnections. The intensity modulation and direct-detection (IM/DD) systems based on pulse amplitude modulations (PAM) together with integrated semiconductor lasers and modulators appear as promising candidates to fulfill the system requirements. 8-lane × 50 Gb/s/λ PAM-4 solutions are being considered for the forthcoming 400 Gb/s Ethernet (400GbE) transceivers[1]. Current research focuses on techniques to support 100 Gb/s/λ and above to support 4-lane 400GbE, thus further reducing the transceiver footprint, size and complexity[2]. There are mainly two ways: increasing signal baud rate, e.g. 50 Gbaud PAM-4, or increasing spectral efficiency with higher order modulations, e.g. 34 Gbaud PAM-8. Efforts have been reported in both ways to push the single lane capacity above 100 Gb/s or even 200 Gb/s with Mach-Zehnder modulators (MZM), directly modulated lasers (DML) and electro-absorption modulated lasers (EML) [3-6]. In these works, there are two main factors to ensure satisfying transmission performances: broad-bandwidth and high-linearity electro-optical components for signal modulation and detection, and high-performance digital equalization techniques, including feed-forward equalizers (FFE) and decision-feedback equalizers (DFE).

In this work we experimentally evaluate the performance and required complexity of digital equalizers when evolving from 32 Gbaud PAM-4 to higher baud rate of 40 Gbaud, or to higher modulation levels of PAM-8 respectively, with a broadband high linear EML[7]. We demonstrate that transmissions with bit-error-rate (BER) performance below 10^{-3} over 4 km standard single mode fiber (SMF) can be achieved with different digital equalization implementations of less than a total filter length of 10 taps. We also

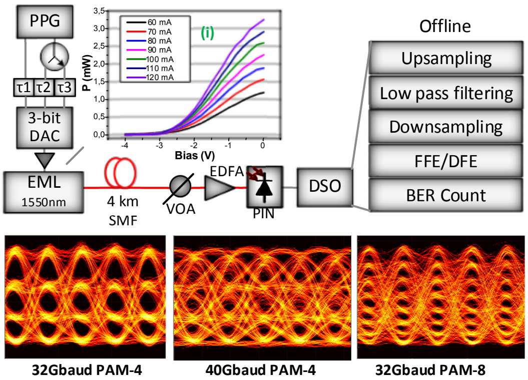

Fig. 1: Experimental setup and eyediagrams of the optical B2B PAM-4/8 signals at different baud rates. Inset (i), EML output power vs. bias voltage for different laser driving currents.

evaluate the stability of the transmission and the digital equalizers.

Experimental setup

Figure 1 shows the experimental setup. A pulse pattern generator (PPG) and a 3-bit digital-to-analog converter (DAC) with 3 dB analog bandwidth of 19 GHz were used to generate the electrical PAM signals consisting of multiple delayed patterns of PRBS 15. The signals were linearly amplified to 2.2 Vpp prior to modulating a 1550 nm EML, which has a 3-dB bandwidth of >70 GHz. The output optical power at different bias voltage of the electro-absorption modulator (EAM) for different laser driving current is shown in Inset (i) of Fig.1. The linear operational range of the EML is larger than 2 Vpp swing when biased at -1.6 V, ensuring low-distortion modulation of the PAM signals. The eyediagrams of the optical signals after modulation are shown in Fig.1. Clear eye openings are observed for both the 32 Gbaud PAM-4 and PAM-8 signals. The PAM-4 signal at 40 Gbaud was strongly filtered by the DAC frequency roll-off. After transmission over 4 km SMF the signal was detected by a p-i-n photodiode (PD) with >90 GHz bandwidth. Due to the low PD responsivity and the absence of

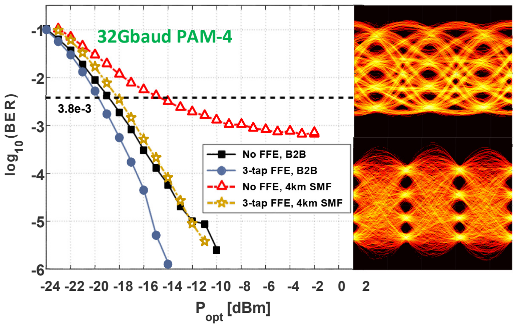

Fig. 2: BER vs. received optical power for 32Gbaud PAM-4 before and after 4km SMF transmission. Insets show the received signal eyediagrams after 4km SMF without/with the 3-tap FFE.

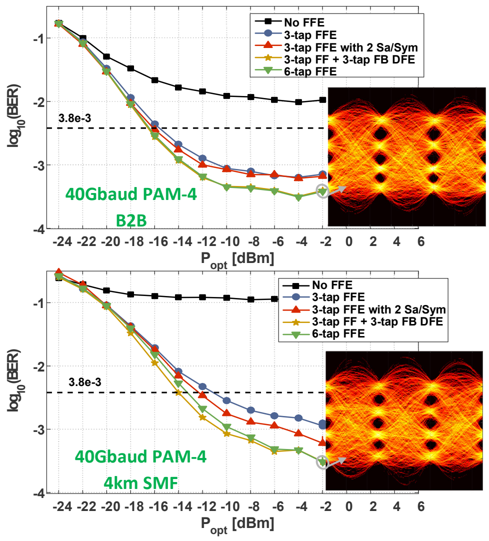

Fig. 3: BER vs. received optical power for 40Gbaud PAM-4 before and after 4km SMF transmission. Insets show the received signal eyediagrams after 4km SMF equalized with 6-tap FFE.

transimpedance amplifier (TIA), an automatic gain-controlled EDFA with fixed output power was employed as a pre-amplifier. A variable optical attenuator (VOA) is used to adjust the input power to the EDFA, resulting in an amplified spontaneous emission (ASE) noise dominated scenario. In practical system this receiver structure can be substituted with either a PIN-TIA or avalanche PD (APD). After PD the signal was sampled at 80 GSa/s by a 33 GHz real-time digital storage oscilloscope (DSO) and processed offline. The sampled digital signals were firstly resampled to 4 Sa/Sym to perform low-pass filtering and clock/timing recovery. Then they were downsampled to either 1 or 2 Sa/Sym for symbol-spaced (T-spaced) or fractional spaced (T/2-spaced) equalizations, respectively. The equalizer weights were firstly adapted with training data using the normalized least-mean-square (NLMS) algorithm before being applied to all other data traces. A total number of 1.2 M bits are used for BER counting.

Results and discussions

Figure 2 shows the BER performances for 32 Gbaud PAM-4 in both back-to-back (B2B) and 4 km SMF transmission cases. These measurements were set as starting references for our investigation upon moving towards a higher baud rate or modulation order. It shows that a 3-tap T-spaced FFE was adequate to compensate the fiber dispersion-induced signal inter-symbol-interference (ISI) and was able to recover the data from an error floor to the same state as the B2B case without FFE, which was mainly limited by noise. In addition, the 3-tap FFE in the B2B case further improved the performance by cancelling the filtering from the DAC frequency roll-off. Eyediagrams for the received signal after 4 km without and with FFE are also shown in Fig. 2.

Figure 3 presents the BER performances for the 40 Gbaud PAM-4 cases. A clear error floor is already seen for the B2B case without any equalization, which is in accordance with the observation of DAC-induced filtering shown in Fig. 1. Subsequently, four different equalization implementations were evaluated for this scenario, namely, a 3-tap T-spaced FFE, a 3-tap T/2-spaced FFE (3×2 taps), a DFE with 3 T-spaced feed-forward (FF) taps plus 3 feedback (FB) taps, and a 6-tap T-spaced FFE. Even numbers of taps for T-spaced FFE were chosen for an equal comparison with the T/2-spaced FFE cases. Clearly, the 3-tap T-spaced FFE is able to improve the performance significantly in both B2B and 4 km transmission cases, from error floors far above the 3.8×10^{-3} BER threshold of 7%-overhead (OH) hard-decision forward error correction (HD-FEC) code, to BER levels of $\sim1\times10^{-3}$. Marginal improvements were seen by employing the fractional spaced FFE, which was clearly out-performed by the DFE and FFE, all with 6 total numbers of taps. Insets of Fig. 3 also show the eyediagrams after the 6-tap FFE, where clear eye openings were achieved by reducing the ISI. It is also noted that in this case there are no fundamental limiting factors compared with the 32 Gbaud PAM-4 except for the limited analog bandwidth of the DAC used for this experiment. Thus by employing a higher bandwidth DAC, the residual error floors are expected to be eliminated owing to the relaxed bandwidth limitations.

We then performed the same evaluation for 32 Gbaud PAM-8 and show the BER performances and corresponding equalized eyediagrams in Fig. 4. Similarly, without any equalization both B2B and 4 km transmission cases suffered from error floors above the 7%-OH HD-FEC threshold. Slight compression in the eyediagrams can be observed between the

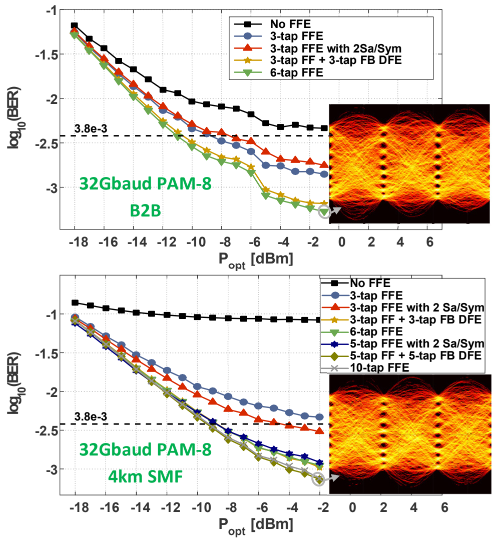

Fig. 4: BER vs. received optical power for 32Gbaud PAM-8 before and after 4km SMF transmission. Insets show the received signal eyediagrams after 4km SMF equalized with 6/10-tap FFE, respectively.

2 lower levels due to a compromising optimal point by balancing the linearity and modulation depth for a higher receiver signal-to-noise ratio (SNR). This can be improved by employing a receiver structure with lower noise level. The B2B error floor was less pronounced than the 40 Gbaud PAM-4 because the nonlinear distortion was less severe compared to the strong DAC filtering. 3-tap T/2-spaced FFE resulted in a slightly worse performance than the 3-tap T-spaced FFE in B2B due to a more sensitive tolerance to timing errors in PAM-8, however it outperformed the T-spaced FFE after 4 km fiber transmission since it provided more accurate channel estimation for ISI reduction. Both of the 3-FF+3-FB-tap DFE and the 6-tap FFE were able to reduce the error floor to $<1\times10^{-3}$ BER in the B2B case, while after 4 km transmission more taps were required. We show that a 5-FF+5-FB-tap DFE or a 10-tap T-spaced FFE was enough to achieve BER below 1×10^{-3}.

Finally, we performed tests to evaluate the performance stability of the EML-based link and the digital equalizers and show the results in Fig. 5. Four cases were chosen, including 32 Gbaud PAM-4 without FFE (P_{opt} = -2 dBm) and with 3-tap FFE (P_{opt} = -10 dBm), 40 Gbaud PAM-4 (P_{opt} = -2 dBm) and 32 Gbaud PAM-8 (P_{opt} = -2 dBm) with 6-tap FFE respectively. We kept the system running while collecting and processing the received data traces on the fly. Each case consists of 230 traces with 1 million sample points per trace. From the figure it is observed that for all cases the system could maintain the Q-factor performance within a small fluctuation range well above the 7%-overhead HD-FEC threshold during the test. The results

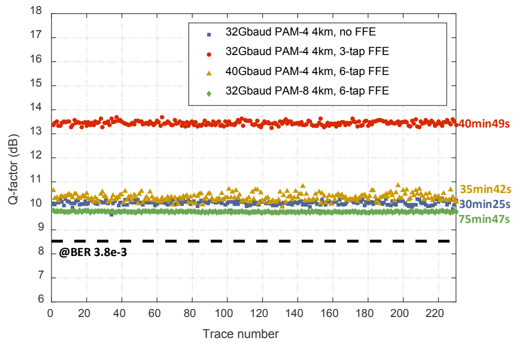

Fig. 5: Link stability tests. Each test case consists of 230 consecutively processed time traces (1M Sa/Trace).

confirm the stability of the demonstrated EML-based IM/DD link in operation with PAM modulations and digital equalizations.

Conclusions

We experimentally demonstrated and evaluated the performance of evolving a 32 Gbaud PAM-4 EML-based IM/DD link to either 40 Gbaud PAM-4 or to 32 Gbaud PAM-8, resulting in up to 96 Gb/s/λ single lane capacity. The broad bandwidth and high linearity of the optoelectronic components employed in the system are able to ensure a stable performance with only low-complexity digital equalizations. BER performances below 1×10^{-3} are achieved for all test cases within a total number of 10 equalizer taps. With higher bandwidth DACs and lower noise receiver structures we foresee further improvements in system baud rate and sensitivity.

Acknowledgements

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