# Up to 30-Fold BER Improvement Using a Data-Dependent FFE Switching Technique for 112Gbit/s PAM-4 VCSEL Based Links

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**Abstract:** In this paper, a dynamic non-linear data-dependent FFE coefficient switching technique, achieving an up to 30-fold decrease in BER in comparison to the linear FFE, is presented. Using the structure 56Gbaud PAM-4 is demonstrated. © 2020 The Author(s)

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## 1. Introduction

The low cost of high-speed vertical cavity surface emitting lasers (VCSELs) makes them a perfect fit for the use in data center environments. VCSEL-based single channel optical links capable of 71 Gbit/s NRZ operation were demonstrated in BiCMOS technology [1]. To further increase the bit-rate, PAM-4 modulation proves to be very popular due to its low complexity and low bandwidth requirements for the VCSEL. It was demonstrated that VCSELs can reach up to 112 Gbit/s PAM-4 data transmission with the use of a Volterra nonlinear equalizer [2]. However, the implementation of Volterra filters is complex and power hungry. In this paper, we showcase the effectiveness of a nonlinear TX pre-distortion technique which overcomes data dependent VCSEL bandwidth variations. The filter structures operating at baud-rate effectively equalize the VCSEL non-linearities and significantly improve the Bit Error Rate (BER), demonstrating 112 Gbit/s PAM-4 data transmission.

## 2. Experimental comparison between Switched Coefficients and traditional FFE

VCSELs exhibit non-linear behavior when varying the operation current [3], which happens with every change of the data symbol. VCSEL drivers implementing adaptive, Switched Coefficients (SC) Feed-Forward Equalization (FFE) pre-emphasis were already presented when using NRZ [4, 5]. Two proposals to adapt these schemes to PAM-4 were shown in [3]. Firstly, to switch the coefficients purely on the state of the main tap, yielding 4 different coefficients per tap. And secondly, to also incorporate the state of the respective pre- /post-tap, resulting in a total of 12 coefficients per tap (4 main tap states times 3 adjacent levels). Since the second solution proved to be more effective, this paper concentrates on comparing it to the traditional, linear FFE. One tap of the 12 SC FFE is depicted in Figure 1a. It could be easily implemented in already available DSP-DAC based transmitters like [6] by using a 4 bit lookup table per tap.

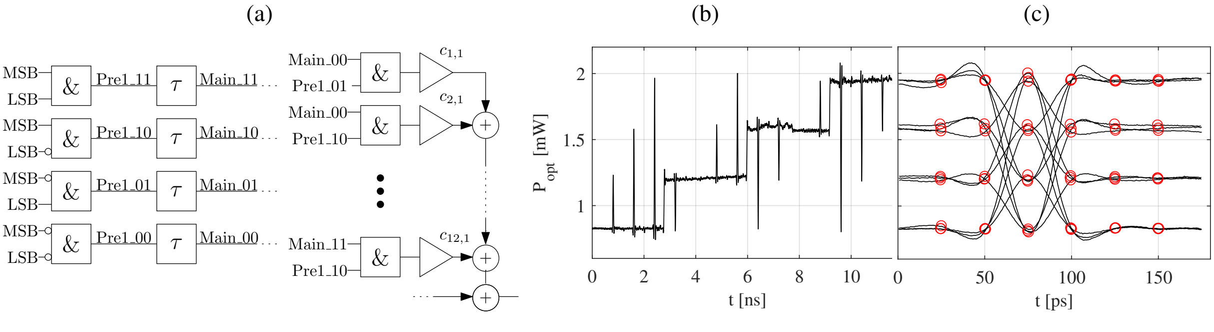
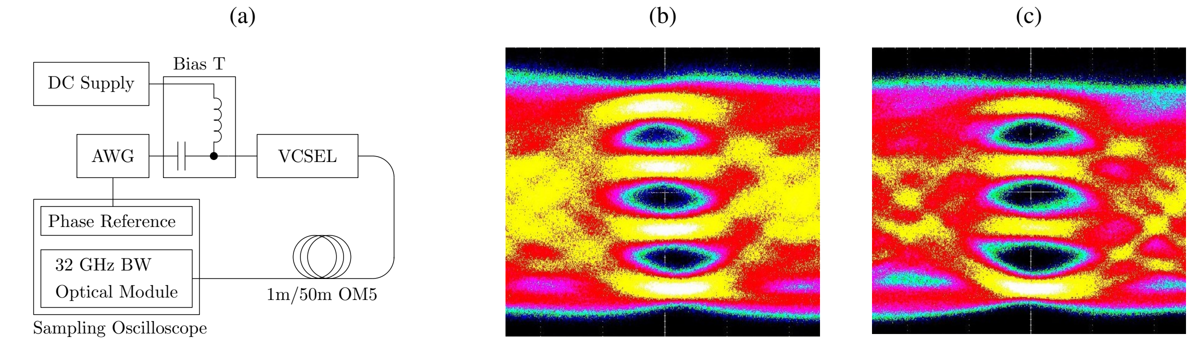


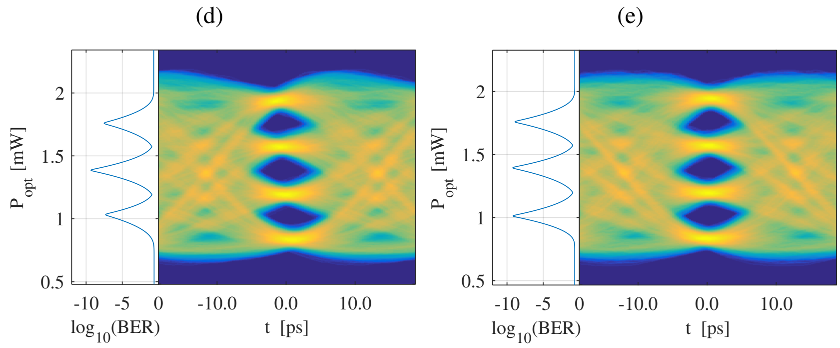

Fig. 1: (a) 1 Tap of Switched Coefficients FFE, (b) SC FFE training sequence, (c) overlaid pulse responses for all 12 combinations

A training sequence, shown in figure 1b is used to determine optimal tap coefficients. It contains all 12 possible single-pulse responses. A large amount of averaging is used when acquiring the sequence with the sampling oscilloscope to keep the influence of noise at a minimum. The common matrix-based method [7] is used to calculate the coefficients from the cursor values, but because the VCSEL is non-linear, it requires several runs until an optimal solution is found. Figure 1c shows the 12 overlaid pulse responses after the coefficient training. Pre-,main- and post-cursors were marked by red circles and show excellent overlapping with the DC-levels.

## 3. Experimental comparison between Switched Coefficients and traditional FFE

To showcase the effectiveness of the Switched Coefficients FFE, a transmission experiment was performed. The experimental setup is depicted in Figure 2a. A VCSEL [8] (wire-bonded to a RF-connector and coupled to a lensed MM fiber) is directly connected to a Bias T. The Bias T combines a DC path, which is fed by a current source driving a bias current of 5 mA, and an AC path, which is connected to an arbitrary waveform generator (AWG). It is used to create a $2^{14}$ long, 800 $mV_{pp}$ pseudo-random binary sequence (PRBS) which is pre-emphasized with a UI-spaced linear or SC FFE with 6 taps (2 pre-, 3 post-taps). The fiber pigtail of the VCSEL is connected to the 32 GHz receiver integrated into the sampling oscilloscope. A second channel of the AWG is used to synchronize the system by driving the phase reference module and clock input of the sampling oscilloscope. The Bit Error Rates were determined by exporting the Probability Density Function (PDF) eye diagram from the jitter and noise analysis software of the oscilloscope and calculating vertical bathtubs with the common method for additive white Gaussian noise (AWGN) channels of fitting normal distributions to the four PAM-4 levels and adding Q-functions [9]. The three bathtub curves for every eye were then combined into one vertical bathtub curve. This method of calculating Bit Error Rate is done because commercially available stand-alone linear receivers have bandwidth limitations of $\sim$22 GHz, limiting the performance in combination with a bit error tester.




(f)

| | TX\RX EQ | none | 4 Tap |
|---|---|---|---|
| BER | 6Tap x 1C | 9.9e-8 | 8.1e-8 |
| | 6Tap x 12C | 6.7e-9 | 2.6e-9 |
| RLM | 6Tap x 1C | 96,1% | 95,9% |
| | 6Tap x 12C | 97,7% | 98,1% |

Fig. 2: (a) Experimental measurement setup, 80 Gbit/s eye diagrams using 6 TX taps of (b) linear FFE and (c) SC FFE, 80 Gbit/s eye diagrams with additional 4 taps linear FFE in the receiver using 6 TX taps of (d) linear FFE, (e) SC FFE, (f) overview of BER values

Figure 2b shows the resulting eye diagram for the traditional, linear FFE and Figure 2c for the SC FFE at a baud rate of 40 Gbaud. The SC FFE clearly corrects any skewing of the eyes and increases the eye openings, enabling an approx. 15-fold decrease in Bit Error Rate, as shown by the values in Table 2f. When using four additional taps of linear UI-spaced FFE in the receiver, an over 30-fold decrease in BER is reached. Looking at the vertical bathtub in Figure 2d, it is obvious that the skewing is manly limiting the eye performance because the BER is dominated by the top and bottom eye. Choosing a sub-par sampling point or large values of jitter would even amplify this effect since moving the sampling point to the right, the top eye's BER would significantly increase and moving it to the left, the bottom eye would act accordingly. The vertical bathtub using the SC FFE shown in Figure 2e, shows that all three eyes share roughly the same BER at the optimal sampling point, making it less susceptible to jitter. The SC FFE structure also slightly improves the linearity of the eyes (as can be seen by the RLM values in Table 2f), but the effect is only minor.

## 4. Performance at 56 Gbaud

The Switched Coefficients FFE was also tested at a baud-rate of 56 Gbaud. Instead of the packaged VCSEL, a chip exhibiting a higher bandwidth [10] was used, the measurement setup was identical as in [11]. A total of 7 taps were used in the transmit SC FFE and the bias current was reduced to 4.5 mA. This leads to the bottom eye dragging behind when using a traditional FFE because of the reduced bandwidth of the VCSEL at low currents.

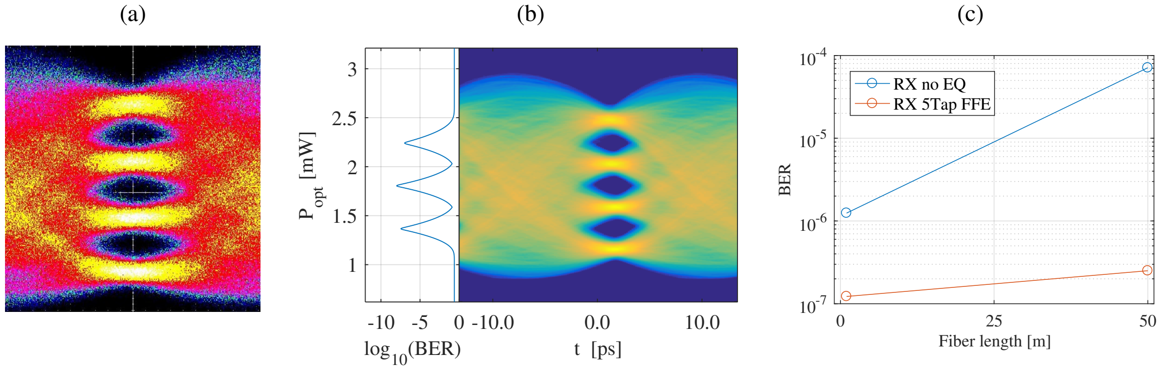



Fig. 3: 112 Gbit/s eye diagrams using (a) no RX EQ and (b) 5 RX taps, (c) BER using different lengths of fiber

As can be seen in Figure 3a, the SC FFE is able to re-synchronize the eyes. When using 5 additional taps of linear FFE in the receiver (Figure 3b), the Bit Error Rate can be improved from $2.5 \cdot 10^{-6}$ to $1.5 \cdot 10^{-7}$. The transmission was also tested using 50 m of OM5 fiber, simulating the use in server-rack environment. Figure 3c reveals, that the BER does not drop significantly for fiber lengths up to 50 m when using receiver equalization.

## 5. Conclusion

This work proposed and demonstrated an effective dynamic data-dependent FFE coefficients adaptation structure to counteract the nonlinear behavior of high bandwidth VCSEL Diodes. The technique achieved an up to 30x BER improvement in comparison to a linear UI-spaced FFE considering the same number of taps. Using a TX SC FFE with 7 taps and additional 5 taps in the receiver, data throughput of up to 112 Gbit/s is achieved at a BER of approximately $10^{-7}$. The novel equalization scheme can easily be implemented within integrated transmitter circuits using lookup table implementations at minor power and silicon area penalty.

## 6. Acknowledgments

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