A 0.4 pJ/bit NRZ Voltage Mode VCSEL Driver for up to 224 Gbit/s SWDM Links

Urs Hecht*,1, Helia Ordouei*,1, Nikolay Ledentsov Jr[2], Philipp Scholz[1], Patrick Kurth[1], Ilya E. Titkov[2], Nikolay N. Ledentsov[2] and Friedel Gerfers[1]

[1] *Mixed Signal Circuit Design, Technische Universität Berlin, Einsteinufer 17, 10587 Berlin, Germany*
[2,*] *Vertically Integrated Systems GmbH (VIS), Hardenbergstraße 7, 10623 Berlin, Germany*

[*] *Joined first Co-authorship, hecht@tu-berlin.de, h.ordouei@tu-berlin.de*

Abstract: We present the first true voltage-mode VCSEL driver achieving 60 Gbit/s at peak efficiency of 0.36 pJ/bit with BER < 1e-12 improving the state-of-the-art by a factor of 2. Transmission experiments showcase error-free 56 Gbit/s transmission up to 100 m fiber. Advanced demonstration enables even 224 Gbit/s when using SWDM at a total efficiency of 0.4 pJ/bit.

1. Introduction

Cloud computing, video streaming and the internet of things experience a constant increase of usage, which creates a demand for low cost, high bandwidth and highly energy-efficient short-reach data links for the use in data centers. Transmitters (TX) utilizing a directly modulated vertical-cavity surface emitting laser (VCSEL) diode provide good bit error rate (BER) performance at very low cost, but are so far lacking in both speed/bandwidth and especially energy efficiency. Current State of the Art (SOTA) VCSEL drivers achieve up to 71 Gbit/s at an efficiency of 13.4 pJ/bit [1] and 56 Gbit/s at an efficiency of 0.71 pJ/bit [2]. Shortwave Wavelength Division Multiplexing (SWDM) enables to quadruple the data rate per fiber [3], hence overcoming the speed limitations of VCSEL based systems. Consequently, high efficiency is key for VCSEL based SWDM links. This paper presents an optical VCSEL driver enabling data rates of up to 60 Gbit/s at a record energy efficiency of 0.36 pJ/bit and up to 224 Gbit/s at an energy efficiency of 0.4 pJ/bit utilizing SWDM.

2. 60 Gbit/s VCSEL Driver

Previously, VCSEL drivers were either based on the Current Mode Logic (CML) topology (like [1, 4]) or push-pull current source based topologies (like [2, 5]). Both approaches come with the drawback of increased supply currents and hence sub-optimal efficiency. Lower supply current and better efficiency can be achieved by using a voltage-mode (VM) driver. A functional schematic is given in Fig. 1. After the input termination (which is tunable) and inverter-based pre-driving, switches are used to apply either V_{DD} (core supply of 0.9 V or lower) or a controlled voltage V_{Ref} to the VCSEL, relying on the IV behavior of the VCSEL to define the "low" and "high" signal levels. This is very similar to driving the VCSEL with a voltage-mode DAC and a bias-tee, as is common in lab experiments. The generation of the reference voltage V_{Ref} is implemented through the use of a source-follower (SF) topology, enabling easy tuning of the "low" signal level.

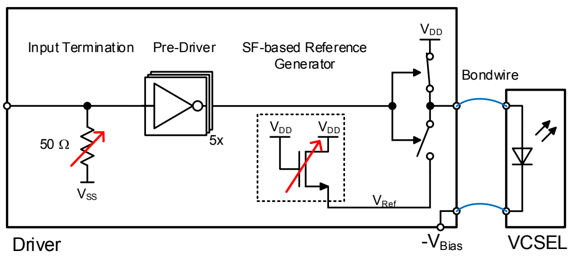


Fig. 1: Functional schematic of the VM driver

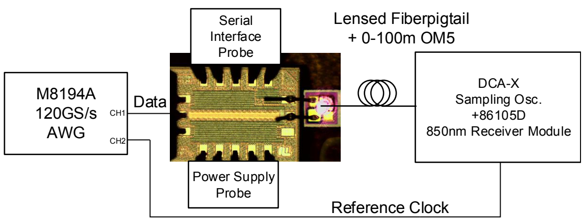
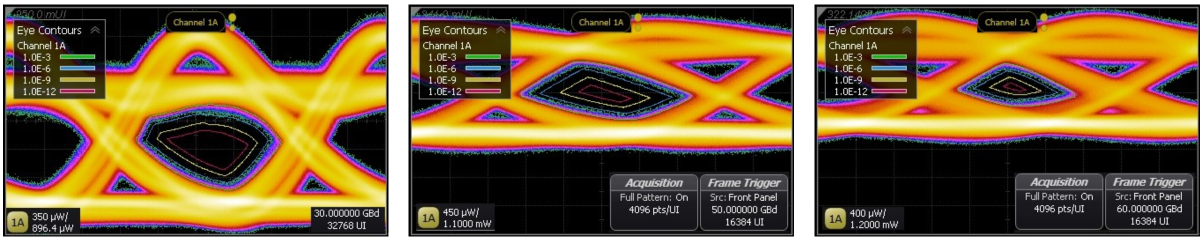


Fig. 2: Electro-optical measurement setup

To showcase the performance of the driver, measurements were performed with the setup shown in Fig. 2. A Keysight M8194A Arbitrary Waveform Generator (AWG) is used to generate 30...60 Gbit/s PRBS-11 data and a reference clock signal for the trigger and time-base inputs of the sampling oscilloscope. De-embedding was used to remove any bandwidth-related intersymbol interference (ISI) of the AWG, the 50 cm cable and the GSG probe. The driver circuit is supplied with 0.7 V, 0.85 V or 0.9 V (depending on bitrate) as well as roughly −2 V bias for the VCSEL. The emitted light of the VCSEL [6] is coupled into a lensed fiber which is connected to the optical 850 nm receiver module of the Keysight DCA-X sampling oscilloscope.



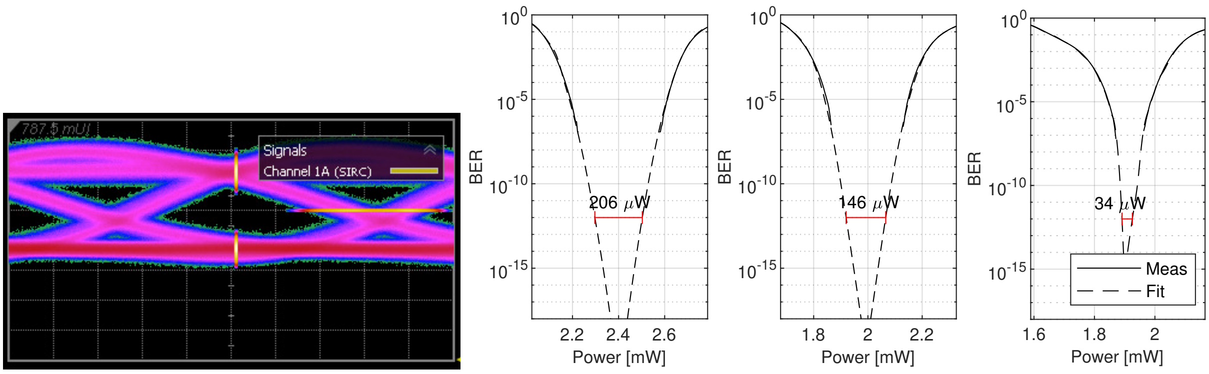
(a) 30 Gbit/s (b) 50 Gbit/s (c) 60 Gbit/s

Fig. 3: Measured back-to-back optical eye diagrams

Fig. 3 shows the results for single channel back-to-back (B2B) measurements at data rates of 30 Gbit/s, 50 Gbit/s and 60 Gbit/s. No receiver equalization was used except for the System Impulse Response Correction (SIRC) of the receiver module. The VCSEL bias voltage was adjusted to reach bias currents of 4.5...5.5 mA. As can be seen by the BER-contours, a error rate of under 10^{-12} is reached for all speeds. At 60 Gbit/s, the circuit draws a power of 21.4 mW, resulting of a peak efficiency of 0.36 pJ/bit.

3. Influence of Fiber Length

To emulate the use in data centers, transmission through different lengths of OM5 fiber is tested. BER is characterized by the common method for AWGN channels of exporting the TI histogram from the oscilloscope and fitting multiple superimposed Gaussian distributions. This is necessary because of the nonlinear behavior of the VCSEL [7] and the driver purposely lacking equalization, resulting in precise fitting with one Gaussian distribution per level not being possible and highly overestimating the noise.



(a) (b) B2B (c) 50m (d) 100m

Fig. 4: Single channel measurements at 56 Gbit/s (a) B2B eye diagram, (b)...(d) vertical bathtubs

As can be seen in the results in Fig. 4, fiber lengths between 0...50 m enable excellent BER$< 10^{-18}$. Between 50...100 m, BER$< 10^{-12}$ is possible. For fibers longer than 100 m, dispersion and reflections in the fiber inhibit error-free transmission. Additional receiver equalization could open the eyes further to enable longer fiber lengths, however this contradicts the ultra low power approach. For all lengths, the driver reached an efficiency of 0.4 pJ/bit sending PRBS-11 at a data rate of 56 Gbit/s.

4. SWDM Experiment

As stated in the introduction, SWDM enables higher speed by sending multiple signals over one fiber. To test this, the measurement setup was extended, as can be seen in Fig. 5. A Huber+Suhner Color Cube SWDM mux was used to combine the 850 nm output of the VCSEL+driver combination with the 880 nm output of a packaged VCSEL, acting as a aggressor. The aggressor VCSEL was biased at 4.5 mA through a bias-tee and driven at 56 Gbit/s from the AWG. After being fed through 0...50 m of OM5 fiber, the wavelengths are again separated through another Color Cube acting as SWDM demux. The 880 nm signal was controlled (not shown) and the 850 nm signal analyzed with the methods described in section 3.

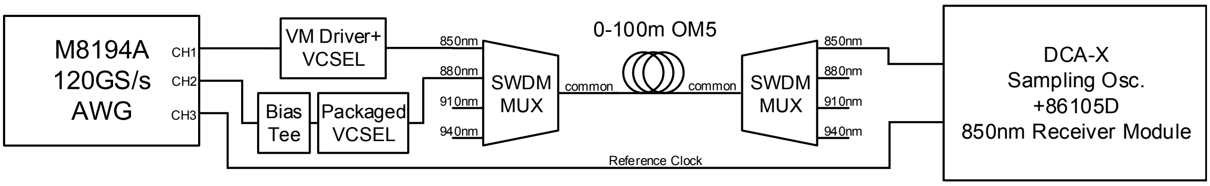
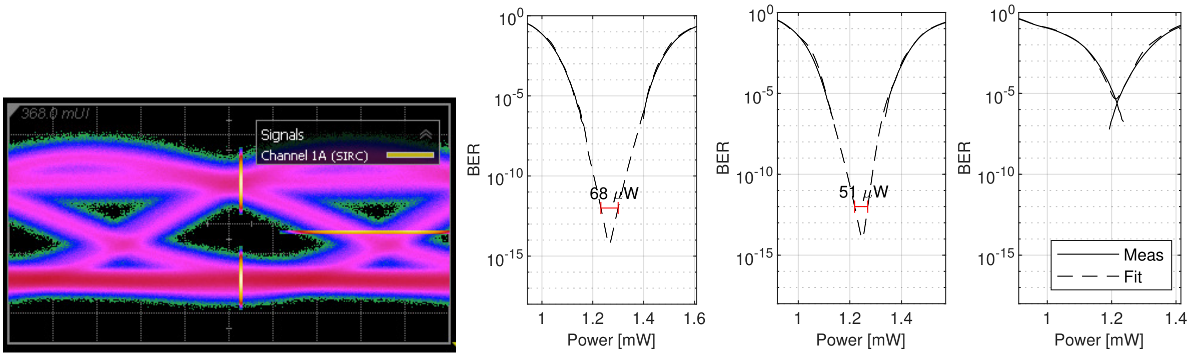


Fig. 5: SWDM experiment measurement Setup

The measurement results are shown in Fig. 6. As before, the driver reaches an efficiency of 0.4 pJ/bit. For lengths of fiber of up to 50 m, the eye is error-free, but the slicer level only has a very limited range of 68...51 µW. At a fiber length of 100 m, the signal is already strongly degraded, resulting in the need of either further equalization or forward error correction (FEC) for error-free transmission.



(a) (b) B2B (c) 50m (d) 100m

Fig. 6: SWDM measurements at 56 Gbit/s (a) B2B eye diagram with marked slicer values, (b)...(d) vertical bathtubs

5. Conclusion

This paper presents a VCSEL driver setup achieving up to 60 Gbit/s at an efficiency of 0.36 pJ/bit. In transmission experiments, driving the VCSEL with 56 Gbit/s it enabled error-free single channel transmission up to 100 m of OM5 fiber and (projected) 224 Gbit/s when using SWDM up to 50m at an efficiency of 0.4 pJ/bit.

References

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