Development of VCSELs and VCSEL-based Links for Data Communication beyond 50Gb/s

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Abstract: Recent advances in VCSELs and VCSEL-based links are reviewed. The impact of the VCSEL bandwidth extension from 22 GHz to 28 GHz on the performance of energy-efficient link capable of operating above 71 Gbit/s in NRZ modulation is studied.

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1. Introduction

Vertical cavity surface emitting lasers (VCSELs) represent a low cost and energy efficient light source. However, their suitability for applications in optical links for the next generation datacenter and high-performance computing (HPC) applications was questioned due to the increased demands for optical and electrical bandwidth.

It was demonstrated that with high order modulation formats data transmission at data rates significantly above 100 Gb/s on directly modulated VCSELs can be achieved [1], but for HPC, short distance transmission and other low latency applications, non-return-to-zero (NRZ) modulation is usually preferred. VCSEL-based NRZ-modulated links can therefore directly extend short distance copper links (for example in CEI-56G-usr and CEI-56G-xsr standards) to significant distances without additional components like multiplexing-demultiplexing schemes. It was previously shown that 28 Gbaud NRZ modulated multi-mode fiber (MMF) links offer the best link power budget margin with the least power dissipation [2]. Most recently, 102 Gbit/s NRZ and 160 Gbit/s 4-PAM data transmission were demonstrated with multi-mode (MM) and single-mode (SM) 850 nm VCSELs [1, 3]. Equalization strength applied in these demonstrations was compatible with the performance of modern electronics. However, in a path toward a complete transceiver design based on this technology, a perfect match of the optical components (VCSELs, PINs), the driving and amplifier integrated circuits (ICs), as well as proper design of the printed circuit board (PCB) are necessary.

2. Performance of State-of-the-art 850 nm VCSELs

As described in [1], significant advances were reached in bandwidth, spectral width and temperature stability of 850 nm oxide-confined VCSELs operating at moderate current densities needed for reliable operation. Figure 1(a) shows current highest data rates to multi-mode fiber length for throughputs above 50 Gbit/s. Recent results clearly demonstrate the feasibility of >100 Gbit/s NRZ and potential for >200 Gbit/s 4-PAM data transmission [1,3]. Furthermore, the use of high-speed SM VCSELs allows data transmission exceeding 2 km multi-mode fiber lengths with NRZ [4] and 1 km with 4-PAM modulation [1].

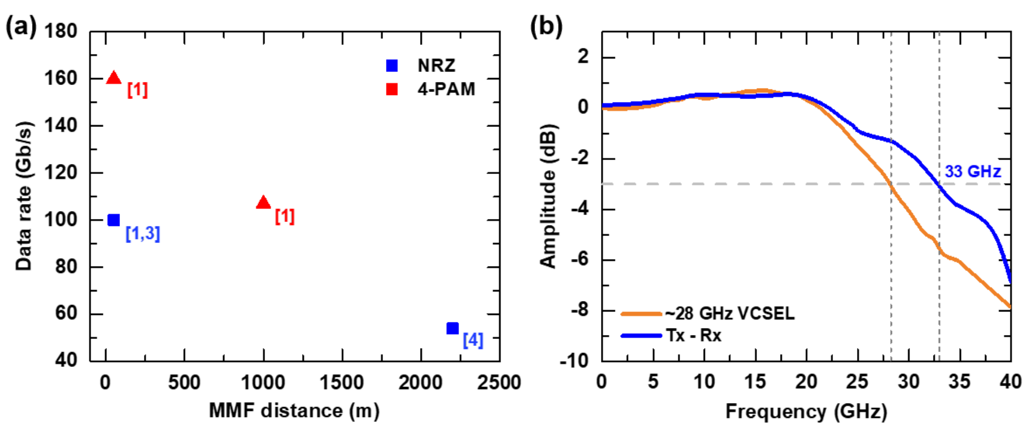

Figure 1. (a) Publications on directly modulated VCSELs operating above 50 Gbit/s (extract). (b) Frequency response of ~28 GHz VCSEL and a transmitter-receiver VCSEL-based link capable of operating at data rates above 70 Gbit/s in NRZ modulation.

The enabling breakthrough for such high-speed data transmission is the extension of the -3 dB modulation bandwidth of the next generation VCSELs to >28 GHz (Fig. 1(b)) as well as a relatively slow roll-off up to -10 dB (~4 dB/decade). These properties as well as improved VCSEL linearity enable the efficient use of the linear equalization techniques like feed-forward equalization (FFE) or continuous time linear equalization (CTLE) that can be realized with modern high-speed electronics.

3. Performance of transmitters based on 28 GHz VCSELs

Details on the transmitter and receiver test packages and the utilized electronics, were previously described in [5]. The VCSEL driver integrated circuit used in the transmitter is a current source with ~63 GHz electrical bandwidth matched to the impedance of the VCSEL and includes inductive peaking. The receiver (Rx) circuit contained a limiting transimpedance amplifier with a variable-gain amplifier (TIA) of 47.5 GHz bandwidth (measured with a 50 Ω load). The receiver includes a 20 µm diameter p-i-n photodiode with ~30 GHz bandwidth biased at -5 V. The setup used in the experiment was also unchanged to the one described in [5] with the exception that in the experiments above 56 Gbit/s, the driving signal coming from the bit-pattern generator was multiplexed.

Figure 2 displays the eye-diagram acquired with 22 GHz and 28 GHz VCSEL based transmitters with the same receiver test-board at 50, 56 and 70 Gbit/s demonstrating much more open eye diagrams for the 28 GHz VCSEL-based transmitter.

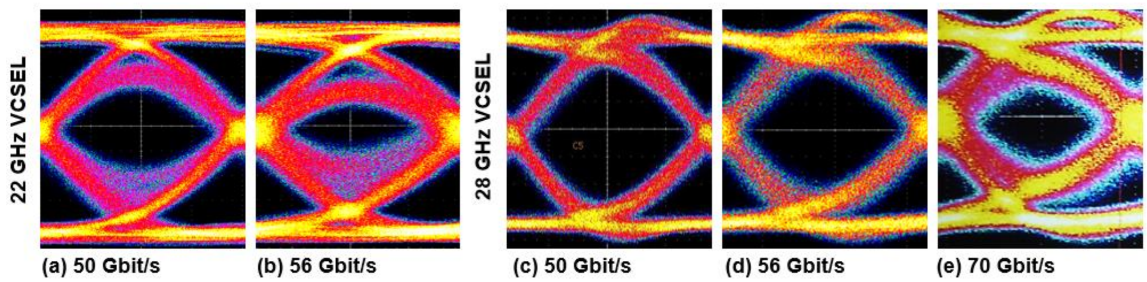

Figure 2. Eye-diagrams acquired on transmitter-receiver link described in [5] packaged with (a-b) 22 GHz VCSEL and (c-e) 28 GHz VCSEL at (a,c) 50 Gbit/s, (b,d) 56 Gbit/s with PRBS31 signals and (e) 70 Gbit/s with PRBS11 signal in back-to-back transmission without pre-emphasis or equalization.

Figure 3(a-c) displays the eye-diagram acquired at 71 Gbit/s and the corresponding horizontal and vertical BER bathtubs captured with the oscilloscope software. Despite an increased jitter and inter-symbol-interference, the bathtub curves suggest a stable error-free operation. With PRBS7 signals, open eye-diagrams up to 80 Gbit/s were achieved (Fig. 3(d)), albeit the signal was significantly limited by jitter. With additional 2-tap equalization, the eye opening could be widened. This is in line with the 33 GHz -3 dB bandwidth of the link, as estimated by the small-signal frequency response measured with an electrical vector network analyzer (Fig. 1(b)) and suggests, that even higher bit-rates can be achieved if the on-board signal distortions can be avoided.

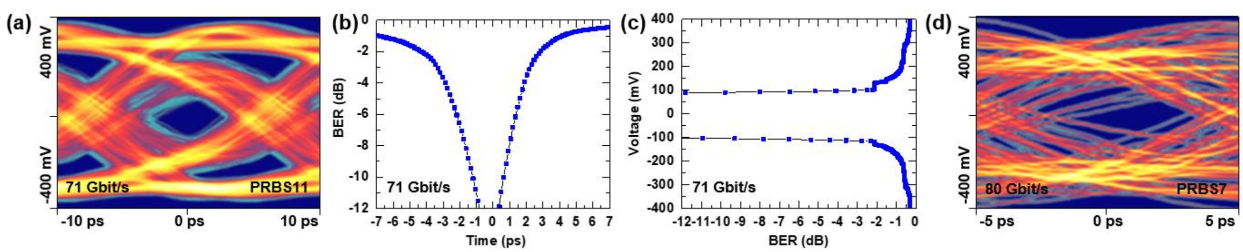

Figure 3. (a) 71 Gbit/s eye-diagram of a transmitter-receiver link with 28 GHz VCSEL, corresponding (b) horizontal and (c) vertical eye-diagrams driven with PRBS11 signal. (d) 80 Gbit/s eye-diagram after 2-tap FFE equalization driven with PRBS7 signal.

We note that signal deterioration above ~70 Gb/s is related, on one side, to the frequency doubling of the input signal to realize data rates beyond 56 Gb/s and, on the other side, to a parasitic -30 dB resonance dip revealed at 40 GHz in the electrical modulation response of the interconnect traces of the Rx printed circuit board. VCSEL and the driver IC demonstrated error-free operation during studies up to 90 Gbit/s [1,5].

Due to the absence of more complex and power-hungry equalization techniques, the transmitter consumed 240 mW power which results in an energy efficiency of 3.4 pJ/bit at 71 Gbit/s. With the receiver included, the whole link consumed 420 mW or ~5.9 pJ/bit. To the best of our knowledge this is the highest energy efficiency of an 850nm VCSEL-based link capable of >50 Gbaud operation, reported so far.

Table 1 summarizes key publications on 850nm VCSEL-based transmitters operating at data rates above 50 Gbit/s with underlined key characteristics of each driver design [5-9]. Significant progress was reached in the energy efficiency of the high capacity VCSEL based links since the first introduction in 2012 [6].

Compared to NRZ, 4-PAM offers higher bandwidth efficiency (bps/Hz ratio), but due to stricter requirements on signal-to-noise ratio, it is more sensitive to fiber attenuation and to electrical non-linearities. This, in turn, requires more complex equalization techniques and reduces the energy efficiency of current 4-PAM links.

Reference:	[6,7]		[8]	[5, This work]		[9]
Year	**2012**	2015	2017	2019	2020	2018
Modulation	**NRZ**					**4-PAM**
Technology	130nm SiGe	130nm SiGe	130nm SiGe	130nm SiGe	130nm SiGe	65nm CMOS
Data Rate (Gbps)	55	**71**	50	56	71	50
Equalization	2 FFE	2 FFE	3 FFE	no*	no*	2.5 FFE
PRBS	7	7	7	31	11	15
OMA (dBm)		0.7	0.7	0	3	3
VCSEL BW	24	26	18	22	**28**	11
VCSEL Bias	8.1	8.2	8	7	6	5.12
BWE (bps/Hz)	2.3	2.7	**2.8**	2.5	2.5	**4.5**
Efficiency (pJ/bit)	13.4	13.38	3.8	4.3	**3.4**	5.12

Table 1. Performance summary and comparison of reported VCSEL-based links. *Includes inductive peaking

4. Conclusion

The increase in bandwidth of the VCSEL from 22 GHz to 28 GHz allowed not only to achieve much better 56 Gbit/s transmission, but also enabled error-free operation range up to 71 Gbit/s without application of equalization, signal processing or any changes to the electronics or PCB design of the transmitter-receiver link. With additional equalization at the receiver side 80 Gbit/s data transmission was realized. Further reduction of the jitter, generated by the parasitic resonance in the interconnect traces should lead to significant increase in the data rate, as the link is not presently bandwidth limited.

5. References

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