

60 Gbaud NRZ Transmission with 0.94 pJ/b Direct-Drive Optical Tx Using SM 1060 nm VCSEL Over 5 km SMF

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Abstract We present a direct-drive optical transmitter demonstrating 60 Gbaud NRZ transmission with single-mode (SM) 1060 nm VCSEL over 5 km single-mode fiber (SMF), achieving a bit-error-rate (BER) $< 1e-12$ after forward-error-correction (FEC) with a record-high FEC-corrected bitrate-distance product of 283.47 Gb/s.km and 0.94 pJ/b transmitter energy-efficiency. ©2025 The Author(s)

Introduction

The rapid growth in data traffic originating from high-performance computing clusters, computationally intensive artificial intelligence applications, hyper-scale data centers, and metro-scale optical interconnects require ultrafast, energy-efficient optical communication links. Traditionally, 850 nm vertical-cavity surface-emitting laser (VCSELs)^{[1]-[3]} have been widely adopted as the benchmark technology for short-reach optical interconnects. These lasers typically utilize multi-mode fiber (MMF), offering cost-effective, high-bandwidth optical transmission suitable for short-reach transmissions. However, as data rates continue to increase to 400 Gb/s and the optical link extends beyond 2 km range for large-scale intra-datacenter applications, the inherent limitations of 850 nm VCSEL links become increasingly apparent. In particular, significant modal dispersion and high MMF attenuation (around 2.3 dB/km) pose serious challenges in achieving efficient data transmission over extended reaches^[4]. To overcome these challenges, 1060 nm SM VCSELs appear as a more effective alternative for extended-reach optical links. Operating over SMF, 1060 nm VCSELs offer lower fiber attenuation (1 dB/km), reduced chromatic dispersion, and a higher bitrate-distance product, enabling efficient extended-reach optical transmission^[4]. As data rates continue to increase, energy-efficient optical links are essential to reduce power consumption as well as improve thermal management in data centers. Recent advancements in complementary metal-oxide-semiconductor (CMOS) technologies have substantially improved the performance of VCSEL drivers, enabling ultra-low energy-per-bit transmission through innovative direct-drive electro-optical designs.

In this work, we report the experimental demonstration of an integrated direct-drive optical transmitter comprising a 4-channel driver in 28 nm bulk CMOS technology, co-designed with SM 1060

nm VCSEL array. The transmitter successfully achieved 60 Gbaud non-return-to-zero (NRZ) optical transmission using SM 1060 nm VCSEL over a 5 km SMF with estimated BER $< 1e-12$ after forward-error-correction (FEC). Notably, the transmitter using SM 1060 nm VCSEL showcased a record-high FEC-corrected^[1] bitrate-distance product of 283.47 Gb/s.km, and exhibited an ultra-low sub-pJ/bit transmitter energy efficiency of 0.94 pJ/b.

Overview of CMOS-based Optical Transmitter Using Single-mode 1060 nm VCSEL

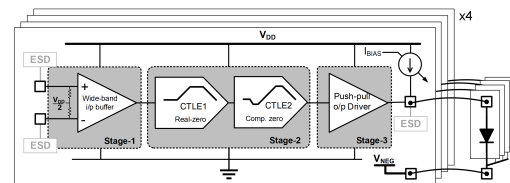


Fig. 1: Overview of the CMOS-based 4-channel VCSEL driver with 1060 nm common-cathode VCSEL array.

The direct-drive type integrated VCSEL driver in 28 nm bulk CMOS technology features 4 parallel differential electrical input channels, as shown in Fig. 1, each providing a single-ended output to drive the anode terminal of 1060 nm VCSELs in an array with the common-cathode terminal biased using a negative supply voltage. A wide-band amplifier at the input of the driver (stage 1) provides input impedance matching, differential to single-ended conversion, and compensates for input channel loss. A modified Cherry-Hooper type output driver (stage 3) with shunt-inductor peaking provides the bias current to the VCSEL and modulates the anode voltage. Between the stages, two consecutive continuous-time-linear-equalizers (CTLEs) based on CMOS inverters (stage 2) provide pre-emphasis, extending the baudrate-to-VCSEL bandwidth ratio up to 1.75 times. The first CTLE with active inductors extends the bandwidth to 1.5 times, while the second CTLE, using inductive feedback, extends it further to 1.75 times. At low bias currents, the

VCSEL showcases an underdamped modulation response with peaking, which leads to a distorted eye-diagram. The second CTLE also equalizes the peaking by compensating on-chip group-delay variation of the driver.

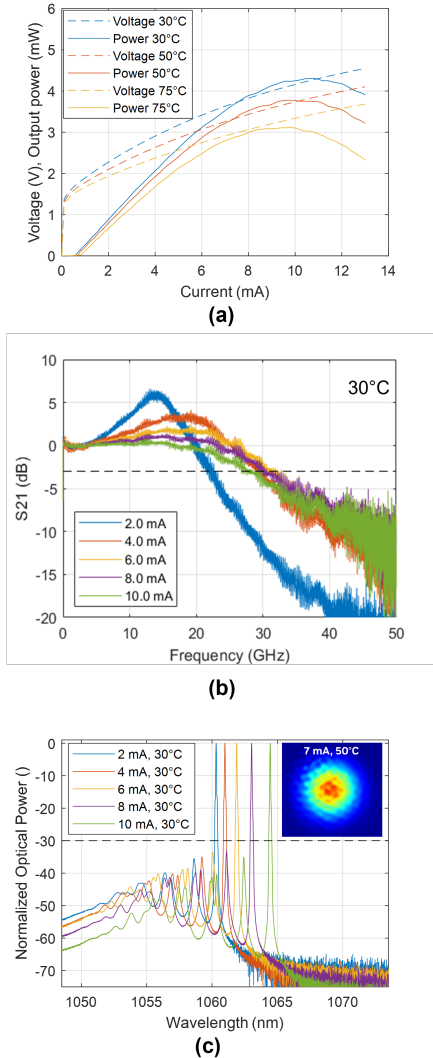


Fig. 2: (a) VCSEL static P-I-V characteristics for different temperatures, (b) VCSEL modulation response for different bias currents, and (c) optical spectra for different bias currents.

The static P-I-V characteristics of the GaAs-based VCSEL in this experiment at 30°C, 50°C, and 75°C are presented in Fig. 2(a). With a 6 mA current bias at 30°C, the VCSEL exhibits a forward voltage of 3.2 V and an optical output power of 3 mW. The measured threshold current and slope efficiency of the VCSEL are 0.63 mA and 0.58 W/A, respectively at 30°C. The modulation response of the VCSEL for various bias currents between 2 and 10 mA is shown in Fig. 2(b). The VCSEL achieves a maximum bandwidth of 31 GHz with a 6 mA current bias at 30°C. At low bias currents, the VCSEL suffers from a reduced bandwidth with increased peaking, which increases to 5 dB at a current bias of 2 mA. Fig. 2(c) shows the optical spectra measured from the output of the VCSEL

at different bias current levels. Under a 7 mA bias, the optical output reaches 5.1 dBm with side-mode suppression of more than 30 dB and beam divergence of around 18°.

Transmission Experiment

The measurement setup used for the electro-optical transmission experiment is elaborated in Fig. 3(a). A micrograph of the VCSEL array wire-bonded to the driver is shown in Fig. 3(b). The VCSEL driver assembly with the test printed-circuit-board (PCB) was probed using a fiber from the top as shown in Fig. 3(c). During the transmission characterizations, a 92 GSa/s arbitrary waveform generator (AWG) was used to generate a PRBS15 pattern, which was delivered through 2.5 inch multicoax TR70 connectors to the driver's differential inputs. The integrated electrical driver operated with a single supply voltage of 1 V, while a single VCSEL was biased using an on-chip generated 6 mA current through the anode terminal and -2.7 V voltage applied at the common-cathode terminal.

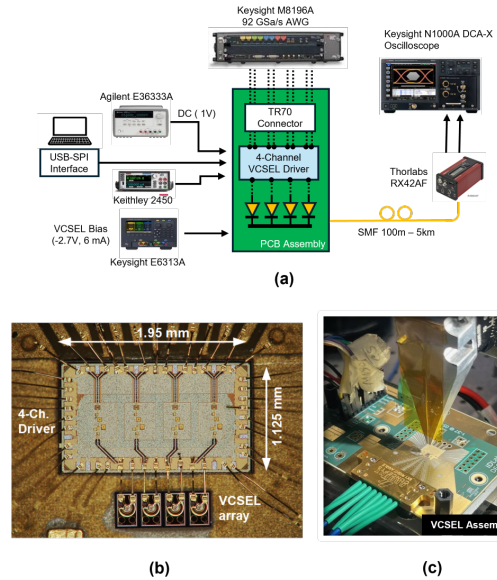


Fig. 3: (a) Measurement setup for electro-optical transmission experiment, (b) micrograph of driver chip, and (c) VCSEL assembly with test PCB.

The 1060 nm VCSEL's optical emission was first coupled into a truly single-mode lensed fiber and then propagated over standard SMF^[5] of varying lengths from 100 m to 5 km. In these experiments, an optical receiver from Thorlabs (RX42AF), featuring a responsivity of 0.425 A/W with a 39 GHz bandwidth, was used. The receiver, with a gain of 2125 V/W at 1060 nm, converted the optical signals to capture and visualize the signal waveforms using the oscilloscope. The bit error rate (BER) was measured by counting erroneous bits from transmitted 2^{15} bit sequences targeting a KP4-FEC BER threshold of $2.2e-4$ with 95% confidence level.

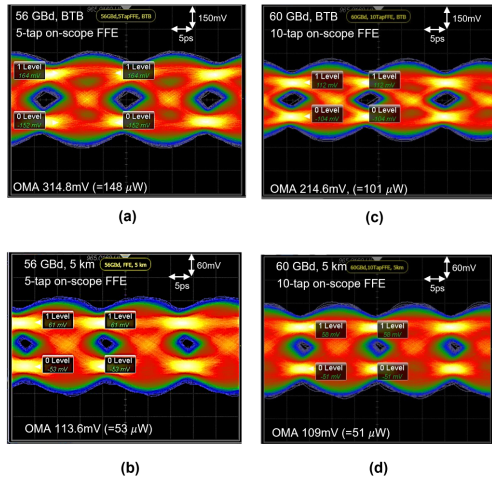


Fig. 4: Electro-optical eye diagrams for 56 Gb/s over (a) BTB, (b) 5 km SMF, and 60 Gb/s over (c) BTB, (d) 5 km SMF.

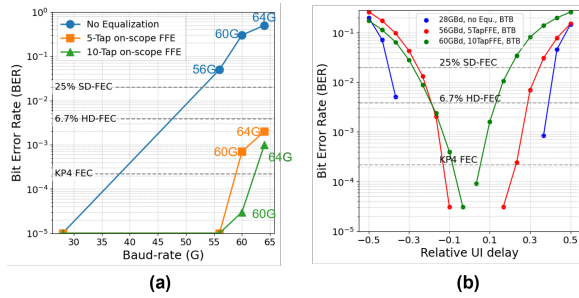


Fig. 5: (a) BER vs. baud-rate for 5 km SMF with different FFE configurations and (b) horizontal bathtub curves for 28, 56, and 60 Gb/s BTB links.

Measurement Results

The VCSEL driver exhibited a tunable electrical bandwidth of 50 GHz to 60 GHz upon measurement, enabled by on-chip pre-emphasis. The 1060 nm VCSEL-based optical transmitter achieved error-free transmission with $BER < 1e-12$ up to 60 Gb/s over 5 km SMF after FEC. The eye diagrams in Fig. 4(a) and (c) depict back-to-back (BTB) transmission at 56 Gb/s using an on-scope 5-tap feed-forward equalizer (FFE) reaching an OMA of $148 \mu W$, while at 60 Gb/s with an on-scope 10-tap FFE, the OMA was $101 \mu W$. Over 5 km of SMF, as shown in Fig. 4(b) and (d), the attenuation and dispersion of the fiber reduced the OMA to $53 \mu W$ and $51 \mu W$ for 56 Gb/s and 60 Gb/s, respectively.

The measured TDEC (NRZ) for 56 Gb/s and 60

Gb/s transmission over 5 km SMF were 1.93 dB and 3.58 dB, respectively.

Fig. 5(a) indicates that 60 Gb/s transmission could meet the KP4-FEC threshold with a 10-tap FFE, while 56 Gb/s requires only a 5-tap FFE. Horizontal bathtub curves for BTB transmission at 28, 56, and 60 Gb/s are illustrated in Fig. 5(b). The proposed driver, operating at 1 V, with a 31 GHz VCSEL biased with 6 mA current (cathode at -2.7 V), achieves an ultra-low transmitter energy efficiency of 0.94 pJ/b .

The performance of this work is compared with driver-less 1060 nm VCSEL demonstrations^{[6],[7]} and also with state-of-the-art VCSEL drivers^{[8]-[10]} in Tab. 1. The driverless 1060 nm VCSEL in the work^[7] achieved a FEC-corrected bitrate-distance product of 425.2 Gb/s.km but lacked a driver, PCB, RF connectors, and used shorter PRBS9 bit patterns. However, this work with driver used PRBS15 bit patterns and demonstrated the record high FEC-corrected^[1] bitrate-distance product of 283.47 Gb/s.km among 1060 nm VCSELs with integrated drivers. Compared to the 1060 nm VCSEL driver in the work^[8] using 20-tap FFE, our transmitter demonstrated a higher bitrate-distance product with only 10-tap FFE.

Conclusions

This work presents a direct-drive type 28 nm CMOS-based optical transmitter using SM 1060 nm VCSEL, achieving a transmitter energy efficiency of 0.94 pJ/b . The VCSEL, featuring a 31 GHz bandwidth, was assembled with the driver to successfully demonstrate 60 Gb/s NRZ optical transmission over 5 km of SMF enabled by on-chip pre-emphasis and a 10-tap on-scope FFE with an estimated $BER < 1e-12$ after FEC. Furthermore, we achieved a record-high FEC-corrected bitrate-distance product of 283.47 Gb/s.km , among integrated drivers using 1060 nm VCSEL-based optical communication links.

Tab. 1: Performance comparison with state-of-the-art VCSEL drivers.

	OFC'24 ^[6]	ECOC'23 ^[7]	OFC'24 ^[8]	OFC'23 ^[9]	ISSCC'24 ^[10]	This work
Wavelength	1060 nm	1060 nm	1060 nm	850 nm	850 nm	1060 nm
Integrated Driver Technology	no driver	no driver	with driver	22 nm FDSOI	22nm FinFet	28nm CMOS
VCSEL Bandwidth, Current Bias	35 GHz, 10 mA	27 GHz, 8 mA	30 GHz, 8 mA	28 GHz, 6 mA	26 GHz, 9 mA	31 GHz, 6 mA
Baud-rate per channel, Modulation	60 Gb/s, NRZ	45 Gb/s, NRZ	53.125 Gb/s, PAM4	56 Gb/s, NRZ	64 Gb/s, NRZ	60 Gb/s, NRZ
Fiber Length	2 km	10 km	2 km	100m	BTB	5 km
On-scope Equalization	5-tap FFE	5-tap FFE	20-tap FFE	No FFE	No FFE	10-tap FFE
Transmitter Energy Efficiency	-	-	5 pJ/b (*full link)	0.4 pJ/b	1.3 pJ/b	0.94 pJ/b
Bitrate-Distance Product (*FEC-corrected)	113.4 Gb/s.km	425.2 Gb/s.km	200.8 Gb/s.km	-	-	283.47 Gb/s.km

Acknowledgements

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