30 GHz bandwidth 850 nm VCSEL with sub-100 fJ/bit energy dissipation at 25-50 Gbit/s

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E. Haglund, P. Westbergh, J. S. Gustavsson, E. P. Haglund, A. Larsson, M. Geen, and A. Joel

A high-speed and energy-efficient oxide-confined 850 nm VCSEL for optical interconnects is presented. A record-high modulation bandwidth of 30 GHz is reached for a 3.5 µm oxide aperture VCSEL, with 25 GHz bandwidth already at a bias current of 1.8 mA. The high bandwidth at low currents enables energy-efficient transmission with a dissipated heat energy in the VCSEL of less than 100 fJ/bit at 25, 40 and 50 Gbit/s.

Introduction: The GaAs-based vertical-cavity surface-emitting laser (VCSEL) is the dominating light source in short-reach optical interconnects in datacentres and supercomputers. Already today, a single supercomputer can use millions of optical interconnects and future systems are expected to employ tens or hundreds of million optical interconnects operating at >20 Gbit/s [1], making this application highly sensitive to cost and power consumption. The VCSEL is an ideal light source for such optical interconnects due to low manufacturing cost, high modulation bandwidth at low currents enabling power-efficient data transmission, and a small footprint enabling dense integration for large bandwidth densities [2]. Crucial for future optical interconnects are VCSELs with even higher bandwidth and lower energy consumption at higher data rates. Energy efficiency is commonly quantified by the heat-to-data ratio (HDR), defined as the dissipated heat energy in the VCSEL per transmitted bit [3]. It is calculated as $HDR = (P_{el} - P_{opt})/BR$, where P_{el} is the electrical DC power supplied to the VCSEL, P_{opt} is the optical output power and BR is the bit rate.

In recent years, there has been considerable progress in the development of energy-efficient high-speed VCSELs. 850 nm oxide-confined VCSELs, with a relatively small 3-4 µm oxide-aperture, have demonstrated HDRs of 56 fJ/bit at 25 Gbit/s [3] and 108 fJ/bit at 40 Gbit/s [4]. In addition, GaAs-based high-speed VCSELs emitting at 980 and 1060 nm are being developed, but are still somewhat behind 850 nm VCSELs in terms of energy efficiency [1,5], and lack the standardised high-speed multimode fibre available at 850 nm. We have previously reported 850 nm VCSELs with a bandwidth of 28 GHz [6], enabling error-free transmission (bit-error rate (BER) $< 10^{-12}$) at 57 Gbit/s using direct current modulation and on-off keying (OOK) [7]. Using transmitter and receiver equalisation, error-free transmission at 71 Gbit/s has been demonstrated with these VCSELs [8].

In this letter, we present the results from our latest generation of high-speed 850 nm VCSELs with bandwidths up to 30 GHz. High bandwidth at low currents enables error-free operation at record-high energy efficiencies at high bit rates, with an HDR of 73 fJ/bit at 40 Gbit/s and 95 fJ/bit at 50 Gbit/s.

VCSEL design: The VCSEL design is a further development of our previous generation high-speed VCSELs [6,9]. The epitaxial structure was grown by MOCVD, featuring an active region with five strained InGaAs quantum wells for high differential gain. Current and transverse optical confinement is provided by one primary oxide aperture on each side of the active region. Different oxidation rates were observed on the n- and p-side, resulting in the two primary oxide apertures having slightly different size. The oxide aperture diameter quoted in this letter is that of the smaller aperture on the n-side, below the active region. The primary oxide apertures are placed as close to the quantum wells as possible; at the first field nodes of the standing optical field on either sides of the quantum wells. This improves transverse carrier confinement compared to our previous design, where the closest aperture was placed at the second field node [9]. Whether the close proximity of strained InGaAs quantum wells and strained oxide layers compromises VCSEL reliability remains to be investigated. Four additional secondary oxide apertures, with a larger diameter, above the upper primary oxide aperture serve to reduce capacitance. The distributed Bragg reflectors (DBRs) feature graded interfaces and modulation doping schemes optimised for low free carrier absorption and low resistance [9]. The photon lifetime was fine-tuned, to maximise the small-signal modulation bandwidth, by a shallow surface etch using a precise Ar ion milling process. This modifies the reflectivity of the top DBR [10].

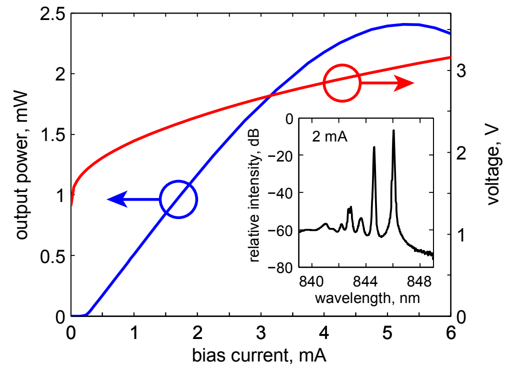

Fig. 1 *LIV-characteristics for a 3.5 µm oxide aperture VCSEL.*
Inset: Optical spectrum at 2 mA.

Static and dynamic performance: The basic static device performance can be seen in Fig. 1. Improved transverse confinement of carriers leads to a high internal quantum efficiency of 87%, measured on 8 µm oxide aperture VCSELs with different top DBR reflectivities [10]. This is significantly higher than the 65-70% measured for our previous design [9]. The threshold current is 0.25 mA for a 3.5 µm oxide aperture VCSEL (Fig. 1) and 0.75 mA for an 8 µm aperture VCSEL. The differential resistance is ~180 and 50 Ω, respectively, which is about 30% lower than our previous VCSEL generation [9].

A 65 GHz Anritsu 37397C network analyser was used to measure the room-temperature small-signal modulation response (S_{21}). The VCSEL was probed on chip using a 40 GHz Picoprobe 40A GSG probe. An AR-coated lens package was used to couple the output light into a short multimode OM4 fibre connected to a 25 GHz New Focus 1481-S-50 photodetector. A fibre coupling efficiency exceeding 80% was readily achieved. The measured response was corrected by compensating for the frequency response of the detector and the probe insertion loss. Fig. 2 shows the measured modulation response for the 3.5 µm VCSEL, reaching 30 GHz at a bias current of 4.1 mA. This is the highest bandwidth ever reported for a conventional VCSEL.

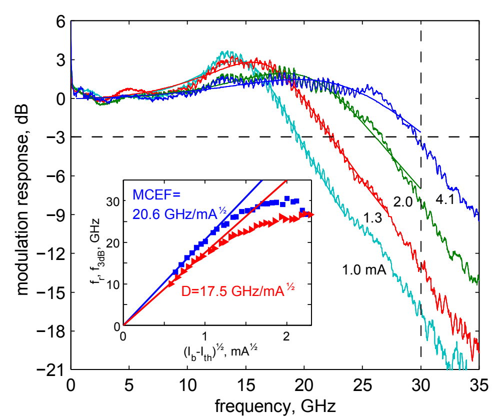

Fig. 2 *Measured small-signal modulation response at different bias currents for a 3.5 µm oxide aperture VCSEL.*
Inset: Resonance frequency and 3 dB bandwidth plotted against the square root of bias current above threshold with D-factor and MCEF fits.

Due to the small oxide aperture, the resonance frequency increases rapidly with bias current at a rate of 17.5 GHz/mA^{½} (the D-factor), reaching a maximum value of 27 GHz, see Fig. 2. Similarly, the modulation bandwidth increases rapidly with current at a rate of 20.6 GHz/mA^{½} (the modulation current efficiency factor, MCEF), reaching a value of 25 GHz already at 1.8 mA. The larger 8 µm aperture VCSEL reaches a maximum bandwidth of 27 GHz at a bias of 13 mA.

Transmission experiments: Large-signal modulation experiments were performed using a non-return-to-zero (NRZ) pseudorandom binary sequence (PRBS) pattern with 2^7-1 bits, generated by an SHF12103A bit pattern generator. The same probe and lens system were used as for the S_{21} measurements. A 22 GHz New Focus 1484-A-50 photoreceiver with an integrated linear amplifier was used to receive the optical signal after transmission over a 4 m long OM4 fibre. The photoreceiver has a 3 dB bandwidth of 22 GHz, but a relatively slow frequency response roll-off with a 6 dB bandwidth of ~33 GHz. The received optical power was measured using an integrated DC monitoring output from the photoreceiver. The BER measurements were performed with an SHF11100B error analyser, using an EXFO FVA-3150 variable optical attenuator to vary the optical power just before the photoreceiver. Eye diagrams were recorded with a 70 GHz Agilent 86100C digital oscilloscope with a precision timebase.

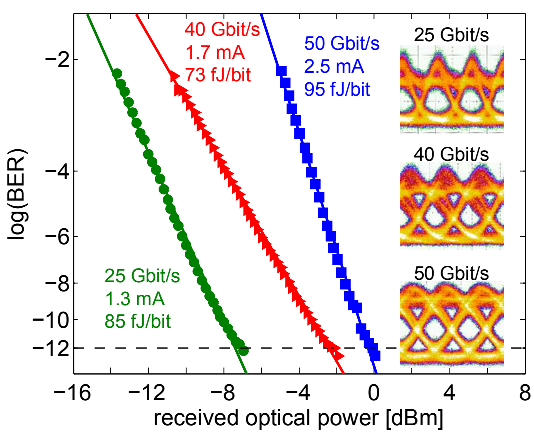

Fig. 3 *BER vs. received optical power for a 3.5 µm oxide aperture VCSEL at 25, 40 and 50 Gbit/s, with eye diagrams recorded at the point of error-free operation.*

Fig. 3 shows the BER as a function of received optical power, together with the recorded eye diagrams. Obviously, for low HDR, the VCSEL should be operated at the lowest possible bias current. However, with a too low bias current, the VCSEL current will be close to the threshold current at the off-state, which reduces speed and induces severe timing jitter. This means that a lower bias current may necessitate a reduced modulation voltage, in turn reducing the optical modulation amplitude which leads to vertical eye closure. The result is a trade-off between HDR and sensitivity through the bias current and the modulation voltage. Error-free transmission at 25 Gbit/s was possible at a bias current of 1.3 mA (13.5 kA/cm^2), corresponding to an HDR of 85 fJ/bit. At 40 Gbit/s transmission, the bias current had to be increased to 1.7 mA (17.7 kA/cm^2) to enable error-free transmission, resulting in an HDR of 73 fJ/bit. At 50 Gbit/s, the bias current had to be further increased to 2.5 mA (26.0 kA/cm^2) for sufficient VCSEL bandwidth, giving an HDR of 95 fJ/bit. The modulation voltage at 40 and 50 Gbit/s was 380 mV (peak-to-peak). At 25 Gbit/s it had to be reduced to 330 mV due to the low bias current of 1.3 mA. The lower slope of the 40 Gbit/s line in Fig. 3 comes from modulating the VCSEL too close to threshold. If the bias current was increased to 1.8 mA (increasing the HDR to 78 fJ/bit), or the modulation voltage reduced to 350 mV, the BER-line had a slope similar to those at 25 and 50 Gbit/s. However, with 350 mV modulation voltage, error-free transmission was not possible at 40 Gbit/s at 1.7 mA. The received optical power for error-free transmission was below 0 dBm at all bit rates.

Conclusion: An 850 nm VCSEL with a record-high modulation bandwidth of 30 GHz is presented. Because of the high bandwidth at low bias currents and the relatively low differential resistance, error-free transmission was achieved at record HDRs of 73 fJ/bit (40 Gbit/s) and 95 fJ/bit (50 Gbit/s).

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