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High-speed 850 nm VCSELs with 28 GHz modulation bandwidth operating error-free up to 44 Gbit/s

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A new generation of high-speed oxide confined 850 nm vertical cavity surface-emitting lasers is presented. A record high modulation bandwidth of 28 GHz is achieved and error-free data transmission at bit-rates up to 44 Gbit/s is demonstrated.

Introduction: Optical interconnects based on multimode fibre and directly modulated vertical cavity surface-emitting lasers (VCSELs) emitting at 850 nm have become the standard solution for short reach datacom networks due to the VCSEL's attractive characteristics of high modulation bandwidth at low currents, high reliability, low production cost, and low power consumption. As data rates for these applications are being standardized at increasingly higher bit rates, much effort is continuously being invested in improving the modulation speed of VCSELs to meet the demands. As a result of this effort, significant progress has been made and multiple groups have now demonstrated VCSELs capable of error-free transmission (defined as a bit-error-rate (BER) < 10^{-12}) at bit rates $\geq$ 40 Gbit/s for emission wavelengths of 850, 980 and 1090 nm [1-3].

In this Letter, we present the first results from our new generation of high-speed oxide confined 850 nm VCSELs and demonstrate a modulation bandwidth of 28 GHz which, to the best of our knowledge, is the highest modulation bandwidth measured for a VCSEL emitting at any wavelength. We also improve on previously reported data rates for 850 nm VCSELs and demonstrate error-free transmission at bit-rates up to 44 Gbit/s, where the maximum bit-rate is set mainly by the photodetector.

VCSEL design and structure: The VCSEL structure investigated here is a further development of the design presented in [4] and contains a number of design improvements. The epitaxial material was grown by MOCVD at IQE Europe using a newly developed process with improved dynamic range of Carbon doping necessary to achieve the sophisticated p-doping schemes employed in the design. Both the p- and n- distributed Bragg reflector (DBR) grading and doping schemes have been optimized to minimize resistance and optical absorption to delay thermal rollover caused by current- and absorption-induced self-heating. As in the previous design, the majority of the n-doped bottom DBR consists of AlAs/AlGaAs layers, which facilitate effective heat extraction from the active region through the high thermal conductivity of binary AlAs. The top DBR is p-doped and contains two $Al_{0.98}Ga_{0.02}As$ layers which are wet oxidized to form the optical and current confining apertures defining the lateral dimensions of the VCSEL. Four $Al_{0.96}Ga_{0.04}As$ layers, which oxidize at approximately half the rate of the primary oxide layers, are included above to reduce the parasitic capacitance over the 30 nm thick oxide layers. Five 4 nm thick, strained $In_{0.10}Ga_{0.90}As$ quantum wells separated by 6 nm thick $Al_{0.37}Ga_{0.63}As$ barriers are used as active region in a short, half-λ cavity for improved transport and increased longitudinal optical confinement [5]. The $\lambda/2$ thick, GaAs p-contact layer acts as an anti-phase layer which gives the possibility of mode filter integration [6], and for post fabrication fine tuning of the photon lifetime: by selectively removing 0-59 nm of the top layer through a shallow surface etch, the photon lifetime can be tuned between 0.5-4.1 ps and the static and dynamic characteristics can be optimized [7].

VCSELs with oxide aperture diameters ranging from 2 to 11 µm were fabricated in a coplanar ground-signal-ground (GSG) BCB planarized contact pad layout for minimized contact parasitics. After full fabrication, the VCSELs were first characterized with the anti-phase layer intact. The anti-phase layer gives a very short photon lifetime and consequently a very low K-factor (~ 0.10 ns) and an excessively high threshold current which impacts the D-factor negatively [4]. To find the optimum photon lifetime for this new structure, the VCSEL wafer was cleaved into smaller pieces after the initial characterization and subsequently etched to different depths using low power Ar ion milling, resulting in varying degrees of damping. In the following, results from the optimized VCSELs are presented (K-factor $\approx$ 0.16 ns).

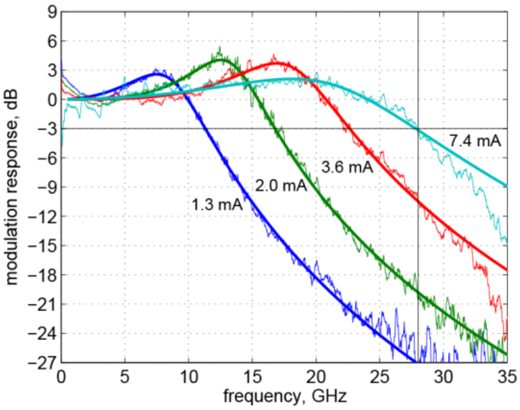

Fig. 1 *Measured small signal modulation response (S_{21}) at increasing bias currents for a ~4 µm oxide aperture VCSEL. The maximum 3dB bandwidth of 28 GHz at 7.4 mA is indicated.*

Dynamic characteristics: The small signal modulation response (S_{21}) was measured using an Anritsu 37397C network analyser (0.04-65 GHz). The VCSEL under test was probed at room temperature directly on wafer using a Picoprobe 40A GSG probe. An AR-coated lens package was used to couple the output light to a short OM4 multimode fibre (coupling efficiency ~50%) connected to a New Focus 1481-S-50 25 GHz photodetector. Corrections were made to the measured data before analysing the results to compensate for the limited frequency response of the detector and the frequency dependent probe insertion loss. Fig. 1 shows the measured modulation response for a ~4 µm aperture diameter (22 µm mesa diameter) photon lifetime optimized VCSEL at increasing bias currents. The response is flat and a maximum bandwidth of 28 GHz is reached at 7.4 mA. This is more than a 20% improvement of our previous report on the highest bandwidth measured for an 850 nm VCSEL [7] and, to the best of our knowledge, the highest bandwidth ever measured for a VCSEL at any wavelength.

Transmission experiments: Large signal modulation experiments were conducted using a non-return-to-zero (NRZ) data pattern with 2^7-1 bit long pseudorandom binary sequence generated by an SHF 12103A bit pattern generator. The drive signal was amplified to 1.0 V_{p-p} by an SHF 804 TL amplifier (22dB gain, 55 GHz) in series with 10+3dB attenuators and combined with the DC bias via a bias-T before connecting to the VCSEL under test. The same probe and output light coupling system as for the S_{21} measurements were used here. Before detection, the light was coupled to a JDSU OLA-54 variable optical attenuator to allow for adjusting the received optical power for the BER measurements. It was found that the responsivity and speed of the New Focus detector was insufficient to provide the required eye opening for error-free transmission at bit-rates > 40 Gbit/s, and instead a high-speed photodetector module from VI-Systems GmbH was used (D30-850M). While this detector provided a larger signal amplitude and better rise time, it was not electrically matched to the rest of the equipment which led to eye degradation. To reduce the impact from the impedance mismatch, we added a 3dB electrical attenuator between the photodetector's external bias-T and the following Centellax OA4MVM3 inverting amplifier (27dB gain, 65 GHz). The electrical signal was then either connected to an Agilent Infiniium DCA-J 86100C 70 GHz oscilloscope with a precision time base to investigate eye diagrams, or to an SHF 11100B error analyser to perform BER measurements.

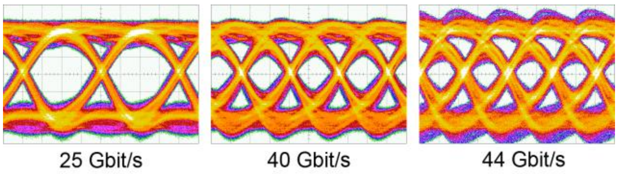

Fig. 2 *Inverted eye diagrams at 25, 40, and 44 Gbit/s in a BTB configuration for a ~7 µm oxide aperture VCSEL at 13.5 mA. The scale is 100 mV/div and 10 ps/div for all bit-rates.*

Fig. 2 shows back-to-back (BTB) inverted eye diagrams at 25, 40, and 44 Gbit/s for a ~7 µm aperture diameter (26 µm aperture mesa) VCSEL biased at 13.5 mA. A larger aperture diameter VCSEL was used in the data transmission experiments since the high differential resistance of the small ~4 µm aperture diameter VCSEL (~170 Ω at 7.4 mA) led to an impedance mismatch and eye degradation due to unwanted microwave reflections. Despite having a larger aperture, the ~7 µm diameter aperture VCSEL has a modulation bandwidth of 27 GHz while exhibiting a better matched differential resistance of ~80 Ω at 13.5 mA.

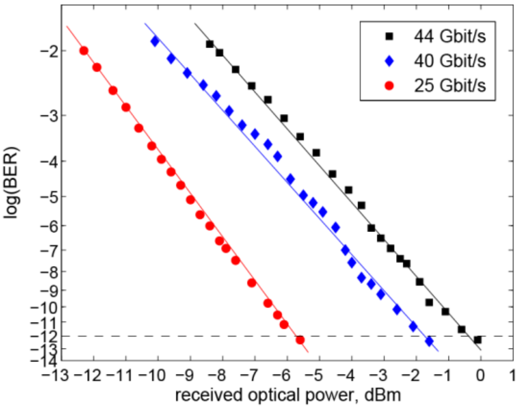

Fig. 3 *BER against received optical power at 25, 40, and 44 Gbit/s in BTB configuration for a ~7 µm oxide aperture VCSEL at 13.5 mA.*

Fig. 3 shows BER measurements at the 25, 40, and 44 Gbit/s bit-rates in the BTB configuration. BER below 10^{-12} is reached for all bit-rates with less than 0 dBm of detected optical power. The power penalty for error-free detection when increasing the bit-rate from 25 to 40 Gbit/s is ~4dB, and an additional ~1.5dB when moving to 44 Gbit/s. Compared to the results in [1], the sensitivity is improved by ~1.5dB at both 25 and 40 Gbit/s. To the best of our knowledge, 44 Gbit/s is the highest bit rate at which error-free transmission has been demonstrated for 850 nm VCSELs. However, the high bandwidth of these VCSELs indicate that, with a more suitable optical receiver system, error-free transmission at bit-rates up to 50 Gbit/s could be supported. A high bandwidth (> 30 GHz) photodetector with an integrated trans-impedance amplifier could, for example, effectively reduce the noise level and improve the signal quality to allow taking advantage of the full potential of these VCSELs.

Conclusion: A new generation of high-speed oxide confined 850 nm VCSELs has been presented, demonstrating a record high modulation bandwidth of 28 GHz and error-free transmission BTB at bit-rates up to 44 Gbit/s.

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