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P. Westbergh, E. P. Haglund, E. Haglund, R. Safaisini, J. S. Gustavsson, and A. Larsson

We demonstrate error-free transmission at bit-rates up to 57 Gbit/s back-to-back, up to 55 Gbit/s over 50 m fibre, and up to 43 Gbit/s over 100 m fibre using an oxide confined 850 nm high-speed VCSEL with a photon lifetime optimized for high-speed data transmission.

Introduction: Directly modulated vertical cavity surface-emitting lasers (VCSELs) operating in multimode at 850 nm are the standard light source in transmitters for large volume, cost-sensitive applications such as short range data centre interconnects. Even though 850 nm is the standard wavelength where high bandwidth multimode fibre (OM3 and OM4) is available, error-free transmission (defined as a bit-error-rate (BER) $< 10^{-12}$) using on-off keying (OOK) and directly modulated GaAs-based VCSELs has been demonstrated at bit-rates exceeding 40 Gbit/s at multiple emission wavelengths spanning 850-1090 nm [1-3]. The highest bit-rate at which error-free OOK transmission has been achieved to date is 56.1 Gbit/s, which was recently demonstrated for an 850 nm VCSEL based link employing specially developed equalization circuits [4]. However, the approach of including equalization electronics in the link results in an inevitable increase of link complexity with a potentially negative impact on power efficiency and cost as a consequence.

Using OOK without equalization, we have previously demonstrated error-free transmission at up to 47 Gbit/s and 40 Gbit/s at room temperature and 85°C, respectively [5]. In this Letter, we improve on the room temperature results and push the bit-rate for error-free transmission up to 57 Gbit/s back-to-back (BTB), 55 Gbit/s over 50 m OM4 fibre, and 43 Gbit/s over 100 m OM4 fibre without the use of equalization circuits, thereby keeping link complexity at a minimum. To the best of our knowledge, these represent the highest bit-rates at which error-free transmission using OOK has been demonstrated for a directly modulated VCSEL of any wavelength.

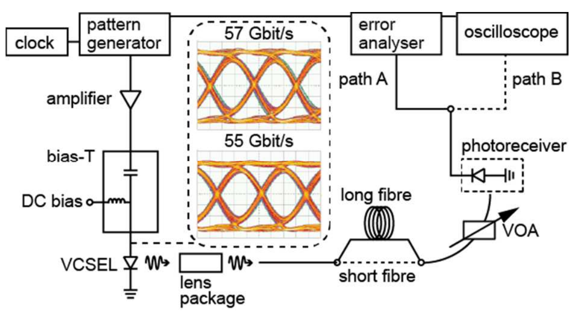

Fig. 1 *Schematic view of the experimental setup. The insets show eye diagrams of the 57 and 55 Gbit/s electrical signals used to modulate the VCSEL. The eye diagrams were captured after the bias-T.*

VCSEL structure and characteristics: The high-speed VCSEL structure used for the experiments presented here has been described in detail elsewhere [5]. In short, the design comprises five strained $In_{0.10}Ga_{0.90}As/Al_{0.37}Ga_{0.63}As$ quantum wells in a short cavity for high effective differential gain. Two primary and four secondary oxide layers are included on the *p*-side above the active region for a low parasitic capacitance. The VCSEL structure and fabrication process is fully compatible with large scale production at existing foundries. The design includes a GaAs anti-phase layer which enables post fabrication fine tuning of the photon lifetime through a shallow surface etch [6]. In earlier transmission experiments where these VCSELs were employed [5], [7], we focused mainly on using a VCSEL with a photon lifetime adjusted for maximum small signal modulation bandwidth [6]. However, this does not necessarily equate to the photon lifetime that yields the highest possible data transmission rate. For instance, if the photon lifetime (and consequently damping) is too low, resulting overshoot and jitter will impede signal quality and limit the possible transmission speed, even though the bandwidth may be at its maximum. If the photon lifetime is too high on the other hand, the bandwidth will suffer from excess damping with increased rise and fall times and degraded signal quality as a result. Rather than focusing on maximizing the small signal modulation bandwidth, we therefore aimed at optimizing eye quality and jitter to determine which photon lifetime would be best for large signal data transmission. We found that typically, the optimum photon lifetime for data transmission is somewhat higher than what yields the highest bandwidth, i.e. the ideal modulation response is slightly more damped, and the *K*-factor is slightly higher than for maximum modulation bandwidth. In addition, we used a VCSEL with a larger oxide aperture diameter than before in order to improve modulation efficiency and impedance matching to the 50 Ω test system. The VCSEL used in the experiment has an aperture diameter of ~8 µm and a differential resistance of ~70 Ω at the bias currents used for the transmission experiments. The *K*- and *D*-factors extracted from the modulation response for this VCSEL are ~0.17 ns and ~9.0 GHz/mA$^{1/2}$, respectively, and the maximum 3dB (electrical) bandwidth is ~24 GHz.

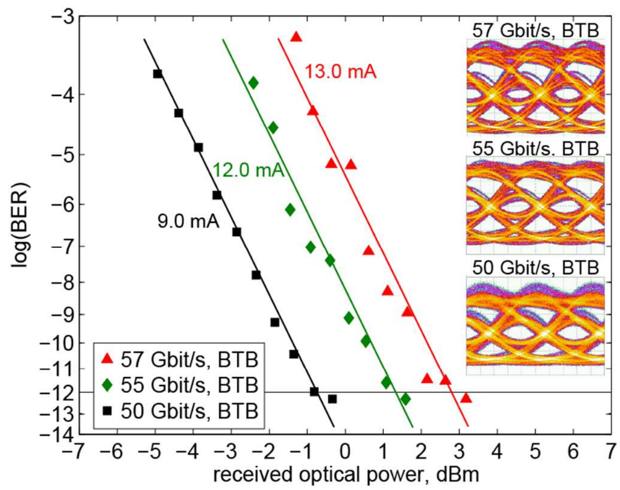

Fig. 2 *BER vs. received optical power at 57, 55, and 50 Gbit/s in the BTB configuration with the ~8 µm VCSEL biased at the indicated current. The insets show the corresponding eye diagrams at 57, 55, and 50 Gbit/s.*

Experimental setup: Fig. 1 shows an overview of the experimental setup used in the experiments, with insets showing the electrical eye-diagrams at 57 and 55 Gbit/s (captured after the bias-T). The transmission experiments were performed using a non-return-to-zero (NRZ) data pattern consisting of a 2^7-1 bit pseudorandom binary sequence generated by an SHF12103A bit pattern generator. The data signal was amplified by an SHF 804 TL broadband amplifier (22dB gain, 55GHz bandwidth) in series with a 10dB or a 10+3dB RF attenuator to produce a 0.99 or 1.35 V_{p-p} modulation voltage while keeping unwanted microwave reflections from the impedance mismatch to the VCSEL at a minimum. The VCSEL under test was probed directly on wafer at room temperature (with no effort for temperature control) using a Picoprobe 40A GSG probe with a 100 µm pitch matched to the layout of the VCSEL bondpad. An AR-coated lens package was used to couple the light from the VCSEL to an angled 1 m (BTB), 50 m, or 100 m OM4 fibre with ≥ 4700 MHz·km effective modal bandwidth. Before detection, the signal was connected to a JDSU OLA-54 variable optical attenuator to allow for varying the power into the photoreceiver and perform BER measurements. At the receiver end, a New Focus 1484-A-50 photoreceiver with an integrated linear amplifier was used. An integrated DC monitoring output from the photoreceiver was used to measure the received optical power for the BER measurements. The (electrical) 3dB bandwidth of the receiver is 22 GHz, but the frequency response roll-off is relatively slow up to ~37 GHz and the 6dB bandwidth is ~33 GHz. After the receiver, the electrical signal was connected either to an Agilent Infiniium DCA-J 86100C 70 GHz oscilloscope with a precision time base to record eye diagrams (path B in Fig. 1) or to an SHF 11100B error analyser to perform BER measurements (path A in Fig. 1).

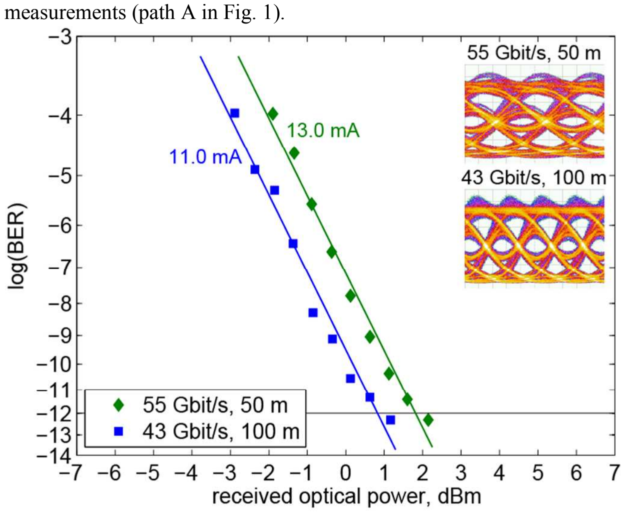

Fig. 3 *BER vs. received optical power at 55 and 43 Gbit/s over 50 and 100 m of OM4 fibre, respectively. The ~8 µm VCSEL was biased at 13.0 mA at 55 Gbit/s, and 11.0 mA at 43 Gbit/s. The insets show the corresponding eye diagrams.*

Experimental results: Fig. 2 shows BER measured as a function of received optical power at 57, 55, and 50 Gbit/s for the ~8 µm aperture diameter VCSEL biased at the current which allowed for error-free transmission at the lowest received optical power (13.0, 12.0, and 9.0 mA, respectively). The insets show the corresponding eye-diagrams. At 50 Gbit/s, BER<10^{-12} is reached using < 0 dBm of received optical power. There is then a ~2dB penalty up to 55 Gbit/s and an additional penalty of ~1.5dB when increasing to 57 Gbit/s. The energy dissipated in the VCSEL was 510, 470, and 340 fJ/bit at the 57, 55, and 50 Gbit/s bit-rates, respectively. At these high bit-rates, the test equipment is at the limit of its capacity and 57 Gbit/s was the highest bit-rate at which the error analyser could operate. The modulation voltage at the two lowest bit-rates was 0.99 V_{p-p}. At 57 Gbit/s, this was increased to 1.35 V_{p-p} which improved SNR and jitter enough to allow for error-free transmission also at this bit-rate. To the best of our knowledge, 57 Gbit/s is the highest bit-rate at which error-free transmission has been demonstrated using a VCSEL based OOK link, irrespective of wavelength.

Fig. 3 shows BER measurements for the same VCSEL at 55 and 43 Gbit/s when transmitting over 50 and 100 m of OM4 fibre with the VCSEL biased at 13.0 and 11.0 mA, respectively. The insets show the corresponding eye-diagrams. Transmission over 50 m fibre only introduces a minor penalty of ~0.5dB at 55 Gbit/s. Over the 100 m link however, the limited bandwidth of the fibre combined with the relatively large spectral width of the VCSEL ($\Delta\lambda_{RMS} \approx 0.9$ nm at 11.0 mA) starts to influence the signal quality and the maximum bit-rate for BER<10^{-12} is reduced to 43 Gbit/s. Nonetheless, this is, to the best of our knowledge, the highest bit-rate at which error-free transmission has been demonstrated for a VCSEL based 100 m long multimode fibre link.

Conclusion: We present an 850 nm oxide confined high-speed VCSEL with a photon lifetime optimized for high-speed data transmission and demonstrate BER<10^{-12} at record high bit-rates up to 57 Gbit/s BTB, 55 Gbit/s over 50 m OM4, and 43 Gbit/s over 100 m OM4.

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