# 60 Gbits error-free 4-PAM operation with 850 nm VCSEL

# 60 Gbits error-free 4-PAM operation with 850 nm VCSEL

K. Szczerba, P. Westbergh, M. Karlsson, P.A. Andrekson and A. Larsson

60 Gbits over 2 m, 50 Gbits over 50 m and 40 Gbits was transmitted over 100 m of OM4 multimode fibre using four-level pulse amplitude modulation and a directly modulated 850 nm vertical cavity surface emitting laser (VCSEL).

*Introduction:* The speed of optical interconnects has been steadily increasing because of the continued development of fast vertical cavity surface emitting lasers (VCSELs). The directly modulated VCSEL is the preferred solution in cost-sensitive applications, such as large volume datacentres. Today, most short-range interconnects use 850 nm directly modulated VCSELs and multimode fibre (MMF). The fastest reported 850 nm VCSELs to date operate at 47 Gbits, without forward error correction, equallisation or predistortion [1]. Earlier a 980 nm VCSEL was demonstrated operating at 44 Gbits [2]. The fastest reported link bit rate to date is 56.1 Gbits [3], which was demonstrated in a VCSEL-based link using on–off keying (OOK) with predistortion and a specially developed driver circuit to match the VCSEL. Multilevel modulation such as four-level pulse amplitude modulation (PAM) has the potential to increase throughput in a given bandwidth, at the cost of 3.3 dB worse sensitivity than OOK at the same bit rate [4]. An additional benefit of 4-PAM is that compared with OOK at the same bit rate, the symbol rate is reduced by half, which reduces the effects of intersymbol interference [4].

In this Letter, we present results from experimental 4-PAM transmission with an 8 μm oxide aperture diameter 850 nm VCSEL from the same wafer as the one reported in [1]. The highest achieved bit rate was 60 Gbits, with bit error rates (BERs) measured down to around $10^{-12}$. To the best of our knowledge, this is the highest bit rate obtained for any 850 nm VCSEL.

*Experimental setup:* The data transmission experiments were performed in real time using a setup similar to the one reported in [5]. The 4-PAM signal was generated from two decorrelated, phase-matched binary signals, which were combined in a microwave coupler. One of the signals had an amplitude of 900 mV and the other one 450 mV. For each binary signal a PRBS pattern of length $2^7 - 1$ was used. The 4-PAM signal was used to drive the directly modulated VCSEL through a bias-T. The VCSEL was biased at 12 mA and operated at room temperature without temperature control. The output of the VCSEL was coupled through a lens package to a multimode fibre. The following fibre lengths were tested: back-to-back (with a 2 m patch-cord), 50 m and 100 m. The type of MMF was OM4, with 4700 MHz·km bandwidth-distance product. At the receiver end, a New Focus 1484-A-50 integrated photoreceiver was used. The bandwidth of the photoreceiver was 22 GHz and the bandwidth of the VCSEL was around 24 GHz. Before the photoreceiver, a JDSU OLA-54 variable optical attenuator was inserted to vary the optical power into the photoreceiver. BER measurements were performed in real time using an ordinary error analyser designed for OOK, the technique was described in detail in [5]. In short, for 4-PAM modulation three decision thresholds are applicable, one between each pair of adjacent symbol levels. The total BER was derived from the error rate measurements carried out on all the 4-PAM thresholds. At each threshold, an error rate can be measured with the error analyser programmed with a corresponding pattern. If the error rates are denoted $ER_1$, $ER_2$ and $ER_3$ for the bottom, middle and top levels, the overall BER is approximately given by

$$\mathrm{BER} \simeq \frac{1}{2}\mathrm{ER}_1 + \mathrm{ER}_2 + \frac{1}{2}\mathrm{ER}_3 \tag{1}$$

under the assumption that errors between the adjacent symbols are dominating [5]. A general overview of the test setup is presented in Fig. 1.

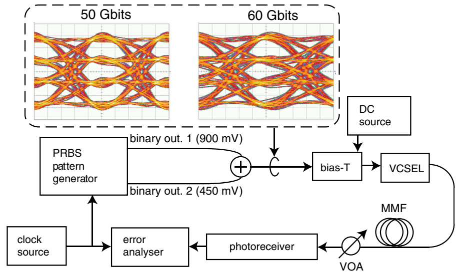


**Fig. 1** *Overview of test setup*

Insets: Eye diagrams of electrical 4-PAM signal used to drive VCSEL
Eye diagrams captured before bias-T

In practical implementations, a four-level electronic transmitter and receiver have to be included, but this is not expected to be a limiting factor. In 2006, a 20 Gbits 4-PAM receiver was demonstrated using 90 nm CMOS technology for backplane interconnections [6]. An integrated 56 Gbits 4-PAM VCSEL driver was demonstrated in [7] and 32 Gbaud eight-level digital-to-analogue converters are commercially available.

*Experimental results:* The system performance was quantified with a measurement of the BER against the received optical power. The results are presented in Fig. 2 for BTB operation and in Fig. 3 for transmission over longer distances of fibre. The plots show aggregate BER calculated from the BER at each of the three threshold levels using (1). The individual error rates at each level were within the same order of magnitude. To show signal quality, eye diagrams are inserted in Figs. 2 and 3. The vertical eye openings are roughly the same between each of the two adjacent signal levels.

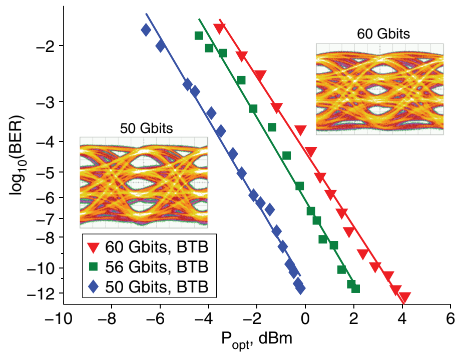


**Fig. 2** *Experimental 4-PAM BERs in back-to-back configuration*

Insets: Eye diagrams of received signal at 50 and 60 Gbits
Eye diagrams inverted because of inverting amplifier in photoreceiver

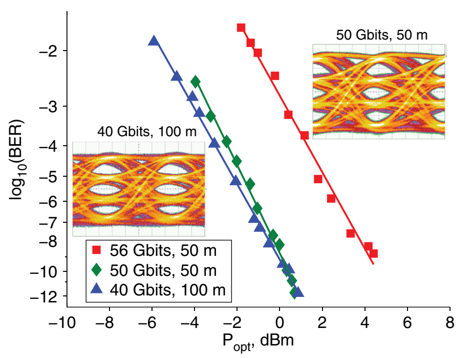


**Fig. 3** *Experimental 4-PAM BERs after propagation over 50 and 100 m of OM4 fibre*

Insets: Eye diagrams of received signal at 40 and 50 Gbits
Eye diagrams also inverted as in Fig. 2

The highest bit rate in the BTB case was 60 Gbits and a BER below $10^{-12}$ could be obtained at that bit rate. After transmission over 50 m of the OM4 fibre, the highest error-free bit rate was 50 Gbits. 56 Gbits was attempted, but the lowest achieved BER was around $10^{-9}$, short of the target $10^{-12}$. After 100 m of fibre, the maximum bit rate was 40 Gbits. Receiver sensitivity at 60 and 50 Gbits after the BTB test was around 4 and 0 dBm, respectively. It could most probably be improved with a photoreceiver with higher conversion gain. At 60 Gbits, energy dissipation in the VCSEL was 420 fJ per bit.

Apart from the BER against received optical power curves, bathtub curves were extracted for the three eye levels of 4-PAM at 50 Gbits in the BTB configuration. The bathtub curves are illustrated in Fig. 4. The length of a unit interval (UI), which in the case of 4-PAM is the symbol duration interval, is 40 ps at 50 Gbits. For the middle eye, the horizontal eye opening at BER of $10^{-12}$ is almost 0.3 UI or 12 ps. This compares favourably, e.g. with OOK at 50 Gbits reported in [3], where the horizontal eye opening was 7.3 ps. The reason for the improved horizontal eye opening of 4-PAM is that the symbol rate of 4-PAM is half of the bit rate. On the other hand, as seen in the eye diagrams in Figs. 2 and 3, the more complicated transition patterns of 4-PAM limit the timing budget. The top and bottom eyes have a reduced timing budget. The horizontal eye opening at the bottom eye is around 0.23 UI (9.2 ps) and at the top eye it is 0.1 UI (4 ps). Visually, all three eye levels in the 50 Gbits eye diagram in Fig. 2 seem to have the same horizontal eye opening, but the top and bottom eye are asymmetric; hence, the widest eye opening does not occur at the optimal sampling point, which was assumed to be halfway between the symbol levels. This problem could probably be reduced by adding pre-emphasis to reduce the rise- and fall-time. Jitter values were also extracted from the bathtub curves using the dual Dirac model. The deterministic jitter values for the top, middle and bottom eyes were correspondingly 20.9, 20.6 and 21.5 ps. The random jitter values were correspondingly, 1.1, 0.6 and 0.64 ps.

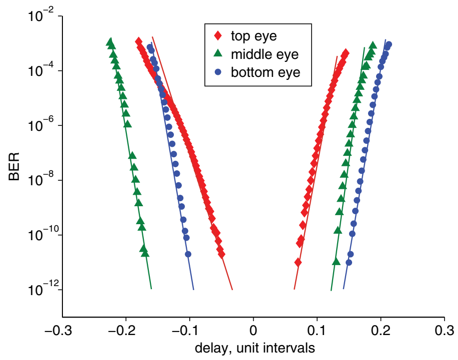


**Fig. 4** *Bathtub curves obtained for each of the three eyes for 4-PAM at 50 Gbits in BTB configuration*

*Conclusion:* We have demonstrated real-time error-free transmission using 4-PAM and an 850 nm VCSEL with 24 GHz bandwidth at up to 60 Gbits in the BTB configuration and up to 50 Gbits over 50 m of MMF. The experimental results were obtained with off-the-shelf electronics and no specially developed circuits to match the VCSEL. We have also presented bathtub curves and measured jitter on the three 4-PAM decision levels.

*Acknowledgment:* This work has been supported by the Swedish Foundation for Strategic Research.



*23 May 2013*
doi: 10.1049/el.2013.1755
One or more of the Figures in this Letter are available in colour online.

K. Szczerba, P. Westbergh, M. Karlsson, P.A. Andrekson and A. Larsson (*Department of Microelectronics and Nanoscience, Photonics Laboratory, Chalmers University of Technology, Göteborg SE-412 96, Sweden*)

E-mail: krzysztof.szczerba@chalmers.se

## References

1 Westbergh, P., Safaisini, R., Haglund, E., Gustavsson, J.S., Larsson, A., Geen, M., Lawrence, R., and Joel, A.: ‘High-speed oxide confined 850 nm VCSELs operating error-free at 40 Gb/s up to 85°C’, *IEEE Photonics Technol. Lett.*, 2013, **25**, (8), pp. 768–771

2 Hofmann, W., Moser, P., Wolf, P., Mutig, A., Kroh, A., and Bimberg, D.: ‘44 Gb/s VCSEL for optical interconnects’. Proc. Optical Fiber Communication Conf., Los Angeles, CA, USA, 2013, paper PDPC.5

3 Kuchta, D., Rylyakov, A., Schow, C., Proesel, J., Doany, F., Baks, C., Hamel-Bissell, B., Kocot, C., Graham, L., Johnson, R., Landry, G., Shaw, E., MacInnes, A., and Tatum, J.: ‘A 56.1 Gb/s NRZ modulated 850 nm VCSEL-based optical link’. Proc. Optical Fiber Communication Conf., Anaheim, CA, USA, 2013, paper OW1B.5

4 Szczerba, K., Karlsson, M., Andrekson, P., and Larsson, A.: ‘Intersymbol interference penalties for OOK and 4-PAM in short-range optical communications’. Proc. Optical Fiber Communication Conf., Anaheim, CA, USA, 2013, paper OW4A.3

5 Szczerba, K., Westbergh, P., Karout, J., Gustavsson, J.S., Haglund, Å., Karlsson, M., Andrekson, P.A., Agrell, E., and Larsson, A.: ‘30 Gbps 4-PAM transmission over 200 m of MMF using an 850 nm VCSEL’, *Opt. Express*, 2011, **19**, (26), pp. 203–208

6 Toifl, T., Menolfi, C., Ruegg, M., Reutemann, R., Buchmann, P., Kossel, M., Morf, T., Weiss, J., and Schmatz, M.L.: ‘A 22 Gb/s PAM-4 receiver in 90 nm CMOS SOI technology’, *IEEE J. Solid-State Circuits*, 2006, **41**, (4), pp. 954–965

7 Quadir, N., Ossieur, P., and Townsend, P.D.: ‘A 56 Gb/s PAM-4 VCSEL driver circuit’. Proc. Irish Systems and Signals Conf., Maynooth, Ireland, 2012