High-efficiency, high-speed VCSELs with 35 Gbit/s error-free operation

Y.-C. Chang, C.S. Wang and L.A. Coldren

High-efficiency, high-speed, tapered-oxide-apertured 980 nm vertical-cavity surface-emitting lasers (VCSELs) with 35 Gbit/s error-free operation have been demonstrated. This is the highest data rate reported for directly modulated VCSELs to date. The devices are also highly efficient, showing a record-high data-rate/power-dissipation ratio of 3.5 Gps/mW.

Introduction: Recently, vertical-cavity surface-emitting lasers (VCSELs) have received considerable interest for their potential application in optical interconnects [1]. VCSELs are very attractive for short-distance optical interconnects owing to their small footprint, natural occurrence in arrays and, most importantly, cost effectiveness. To meet the bandwidth requirements for future datacom applications, researchers have been trying to improve the data rate of VCSELs [2–4]. VCSELs with data rate up to 30 Gbit/s and 3 dB bandwidth of 24 GHz at 1.1 µm have been demonstrated [4]. However, these devices use buried tunnel junctions and regrowth is required, which complicates the fabrication process and adds extra costs. In this Letter, we report high-efficiency, high-speed, tapered-oxide-apertured 980 nm VCSELs that do not require ion implementation and/or regrowth and can be mass manufactured easily. These devices demonstrate 35 Gbit/s error-free operation at a bias current of 4.4 mA. To the best of the authors' knowledge, this represents the highest data rate reported for directly modulated VCSELs to date. These devices also show the highest data-rate/power-dissipation ratio of 3.5 Gps/mW at 35 Gbit/s operation.

Device structure: The structure used in this work is *n*-intracavity, bottom-emitting, tapered-oxide-apertured 980 nm VCSELs, as shown in Fig. 1. Details of the device structure and fabrication process can be found in [5]. To achieve high-speed operation at low power dissipation, the mode volume needs to be reduced. This is accomplished by: (*a*) placing the *n*-contact layer five periods away from the active region to reduce the loss and provide better longitudinal mode confinement; and (*b*) using an optimised tapered oxide aperture with a 4 µm taper length and a thickness of $(1/2)\lambda$ to simultaneously achieve low scattering loss and better mode confinement.

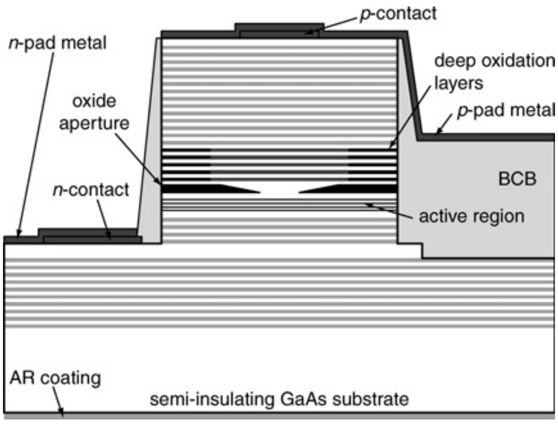

Fig. 1 *Schematic cross-section of VCSEL*

In addition to the improvements for the intrinsic laser properties, the extrinsic parasitic needs to be reduced. The series resistance is lowered by using an optimised *p*-doping scheme in the top mirror to balance the loss and resistance. The thicker oxide aperture, $(1/2)\lambda$ instead of the standard $(1/4)\lambda$ thick, and the employment of the deep oxidation layers [6] help to reduce the oxide capacitance, one of the main limiting factors of bandwidth. Another benefit of the high Al-content deep oxidation layers is that they also provide better mode confinement longitudinally owing to higher index contrast. The pad capacitance is further reduced by: (*a*) removing the *n*-contact layer (RF ground) beneath the *p*-pad (RF signal), (*b*) applying benzocyclobutene (BCB) between these two layers, and (*c*) shrinking the pad dimensions to 40 × 70 µm.

Results: Fig. 2 shows the voltage and output power against current (*L–I–V*) curves for a 3 µm-diameter device. The lasing wavelength is around 993 nm. The device has a differential quantum efficiency of 54% and a threshold current of 0.144 mA, relatively low for high-speed VCSELs previously reported. The threshold voltage is 1.47 V, which is very low for such a small device, as it is only 220 meV larger than the quasi-Fermi level separation for transparency. The series resistance is approximately 250 Ω at a bias current of 4.4 mA, where the large-signal modulation experiments are performed. The peak wallplug efficiency is 31%. The maximum output power is 3.1 mW at a bias current of 7 mA.

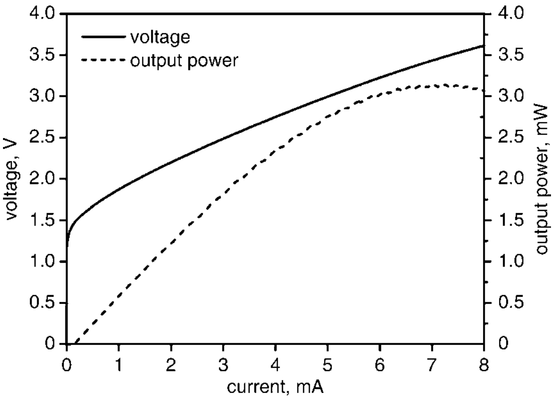

Fig. 2 *L–I–V curves for 3 µm diameter device at 20°C*

Fig. 3 shows the test setup for large-signal modulation experiments. The non-return-to-zero (NRZ) signal with $2^7 - 1$ word length from the pattern generator was amplified using a 38 GHz SHF 806E amplifier with 26 dB gain and then attenuated 6 dB using a fixed attenuator to reduce the voltage swing to $\sim 0.84\ V_{p\text{-}p}$. The RF signal was combined with the DC bias through a 65 GHz Anritsu V255 bias tee and fed to the device using a 67 GHz ground–signal–ground RF probe. The output power was collected into a 9/125 singlemode fibre using a dual-lens focuser. The eye diagrams were measured using an Agilent 86109A oscilloscope with an internal 30 GHz photodiode. To measure the bit error rate (BER), the optical signal was fed to a 25 GHz New Focus 1414 photodiode coupled with a 40 GHz SHF 810 amplifier and sent to the error analyser.

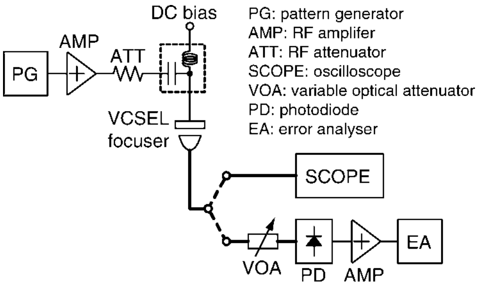

Fig. 3 *Experiment setup for BER and eye diagram measurements*

Thicker lines denote the optical fibre. Eye diagram is measured through upper path to oscilloscope and BER is measured through lower path to error analyser

Fig. 4 shows the BER curve at 35 Gbit/s for a 3 µm device at 20°C. The bias current is 4.4 mA and the voltage swing is $\sim 0.84\ V_{p\text{-}p}$. The 3 dB bandwidth at this bias current exceeds 20 GHz. The inset of the Figure shows the optical eye diagram at 35 Gbit/s and the eye is clearly open with an extinction ratio of 5.4 dB. In the BER curve, all the data points except the lowest one were taken with a variable optical attenuator (VOA). Owing to the ~3 dB insertion loss of the VOA, the BER in the range of 10^{-4} to 10^{-7} could not be measured. Thus, the lowest data point at a received power of −4.7 dBm was taken without the VOA. The BER is 9.2×10^{-12}, gated for 30 min with a total of 583 errors to ensure the accuracy of the measurement. In fact, the BER was $\sim 2 \times 10^{-12}$ for the first 10 min and increased slowly with time, possibly owing to fibre drift. This is statistically evident of error-free operation at 35 Gbit/s. To the best of the authors' knowledge, this represents the highest data rate for directly modulated VCSELs. At a bias current of 4.4 mA, the power consumption and dissipation, excluding the RF driver circuitry, are only 12.5 and 10 mW, respectively. This corresponds to a data-rate/power-dissipation ratio of 3.5 Gps/mW, also the highest value ever reported.

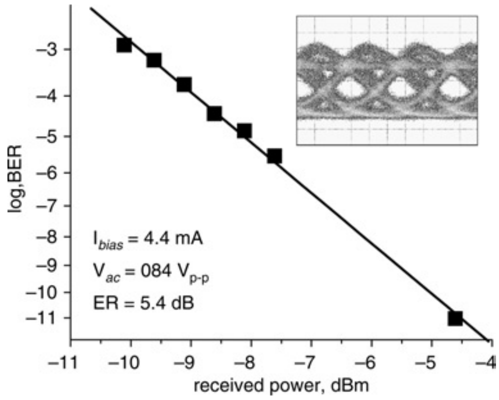

Fig. 4 *BER measurement at 35 Gbit/s at 20°C*

Bias current 4.4 mA and voltage swing ~0.84 $V_{p\text{-}p}$. Lowest data point, taken without VOA, gated for 30 min to ensure measurement accuracy.
Inset: corresponding optical eye diagram with extinction ratio of 5.4 dB

Conclusions: High-efficiency, high-speed, tapered-oxide-apertured 980 nm VCSELs with 35 Gbit/s error-free operation have been demonstrated. This represents the highest data rate achieved for directly modulated VCSELs. In addition, the devices show a record high data-rate/power-dissipation ratio of 3.5 Gps/mW, making these devices suitable for interconnect applications.

Acknowledgments: The authors thank Prof. D.J. Blumenthal, H.N. Poulsen and L.A. Johansson at University of California, Santa Barbara, for helping with the RF test setup. This work was supported by a UC-MICRO with IBM and gift funds from Agilent.

14 July 2007
Electronics Letters online no: 20072074
doi: 10.1049/el:20072074

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