40 Gbit/s error-free operation of an oxide-confined 850 nm VCSEL

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Error-free transmission is demonstrated at bit rates up to 40 Gbit/s in a back-to-back configuration and up to 35 Gbit/s over 100 m multimode fibre using a directly modulated oxide confined 850 nm vertical cavity surface emitting laser.

Introduction: Vertical cavity surface emitting lasers (VCSELs) capable of error-free operation at bit rates beyond 25 Gbit/s will be required in near future, high capacity data communication links (e.g. 100 Gigabit Ethernet). Much effort has consequently been invested in extending the bandwidth and the performance beyond the 10 Gbit/s which today's commercially available data communication VCSELs are designed for. The highest bit rate where error-free transmission has been demonstrated with non-return-to-zero (NRZ) coding (error-free is here defined as bit error rate (BER) $< 10^{-12}$) in a directly modulated VCSEL is to date 40 Gbit/s for a device emitting at 1100 nm [1]. In this long-wavelength VCSEL design, heavily strained InGaAs quantum wells (QWs) are used to increase differential gain, thus significantly improving the intrinsic high speed capabilities. Deep, heavily strained QWs are also beneficial for temperature stability and 20 Gbit/s operation has been demonstrated up to 120°C for VCSELs emitting at 980 nm [2]. However, 850 nm is the standard wavelength in the data communication industry and since this is also where high speed multimode fibres (e.g. OM3 and OM4) are available, high speed VCSELs at this wavelength are of greatest interest. Recent achievements at 850 nm include modulation bandwidths exceeding 20 GHz and error-free transmission at bit rates

> 30 Gbit/s [3], [4]. In this Letter, we extend the modulation speed and demonstrate error-free transmission up to 40 Gbit/s; a record for 850 nm VCSELs.

Design and basic performance: The VCSEL design is based on our previous high speed design with a double oxide aperture to reduce capacitance and strained $In_{0.10}Ga_{0.90}As$ QWs to improve differential gain as compared to using the traditional GaAs QWs [5]. To further reduce capacitance, four layers of $Al_{0.96}Ga_{0.04}As$ were introduced in the distributed Bragg reflector (DBR) above the original two $Al_{0.98}Ga_{0.02}As$ layers, following the procedure outlined in [6]. Due to the exponential dependence of oxidation rate on Al-content, the 96% Al layers oxidize at approximately half the rate of the 98% layers, resulting in ~40% lower mesa capacitance and extending the parasitic cut-off frequency of the VCSEL.

After full processing, a shallow etch was applied to the top DBR to reduce the photon lifetime (τ_p) and improve the intrinsic high speed properties of the VCSEL [7]. With a 40 nm etch, τ_p is reduced from 6.4 ps to 3.3 ps. The maximum output power and the peak slope efficiency are then effectively doubled and the intrinsic, damping limited bandwidth is significantly increased.

Fig. 1 shows the power-voltage-current characteristics for a ~7 µm oxide aperture diameter VCSEL (after the shallow etch). The inset shows the optical emission spectrum at 8.0 mA. The threshold current is 0.4 mA and the peak slope efficiency and output power is 0.95 W/A and 6.4 mW, respectively. The series resistance of ~130 Ω is comparatively high and since this is due to a large *p*-contact resistance there is room for further improvements. The small signal modulation bandwidth was measured to be 23 GHz at room temperature, limited primarily by parasitics and thermal effects.

Transmission experiments: Large signal modulation experiments were performed using a NRZ data pattern with a 2^7-1 bit long pseudo random bit sequence (PRBS) generated by an SHF 12100B pattern generator in combination with an SHF 801P amplifier (+8dB; 58 GHz), resulting in a 1.0 V_{p-p} drive signal. The VCSEL was probed directly on wafer, without any special efforts for heat-sinking, using a high frequency probe in a ground-signal-ground (GSG) configuration. The output light was collected through a butt-coupled 62.5 µm-core multimode fibre (coupling efficiency ~50%) connected, either via 100 m OM3+ fibre (bandwidth distance product 4700 MHz·km) or via a short patch-cord, to a JDSU OLA-54 variable optical attenuator after which the signal was converted back to the electrical domain by a high speed photodetector module from VI-Systems GmbH (model D30-850M). To increase the voltage swing of the detected signal it was fed to an SHF 803EA amplifier (+20dB; 45 GHz) resulting in ~150 mV_{p-p} signal amplitude. Finally, the signal was studied in the form of eye diagrams using a 70 GHz Agilent 86100C digital oscilloscope with a precision timebase and BER was measured using an SHF 11100B error analyzer.

Fig. 2 shows BER measured as function of detected optical power for the ~7 µm oxide aperture VCSEL at 25 and 40 Gbit/s in a back-to-back (BTB) configuration. The insets show the corresponding eye diagrams. The VCSEL was biased at 6.5 and 8.0 mA at the 25 and 40 Gbit/s bit rates, respectively, corresponding to bias current densities of 17 and 21 kA/cm^2. Error-free transmission (BER<10^{-12}) was achieved at both bit rates, with a power penalty of ~4dB when increasing the bit rate from 25 to 40 Gbit/s. Even so, error-free transmission was reached with less than 0 dBm of detected optical power at 40 Gbit/s.

Fig. 3 displays BER for the same VCSEL at 25 and 35 Gbit/s transmitted over 100 m of OM3+ fibre, with insets of corresponding eye diagrams. The VCSEL was biased at 7.5 mA (19 kA/cm^2) at both bit rates. Error-free transmission could not be reached for the 40 Gbit/s bit rate when propagating the signal over the 100 m length of fibre. This is due to the relatively broad VCSEL emission spectrum (~1 nm root-mean-square) under modulation, inducing a dispersion penalty and reducing the effective bandwidth of the fibre. Nonetheless, $BER<10^{-12}$ could be reached for bit-rates up to 35 Gbit/s when transmitting over 100 m of fibre.

The measurements above were conducted using a ~7 µm oxide aperture diameter VCSEL biased at ~20 kA/cm^2. Measurements were also made for a larger device with ~9 µm aperture biased at 10 kA/cm^2 (6.3 mA), consistent with the industry benchmark for reliability. For this VCSEL, with a maximum 3dB modulation bandwidth of 22 GHz, error-free transmission was achieved up to 38 Gbit/s in a BTB configuration.

Conclusions: We have demonstrated open eye diagrams and error-free transmission at bit rates up to 40 Gbit/s for a high speed 850 nm VCSEL in a BTB configuration and up to 35 Gbit/s over 100 m of multimode fibre. We believe the results show that directly modulated 850 nm VCSELs are well suited for near future high speed data communication networks.

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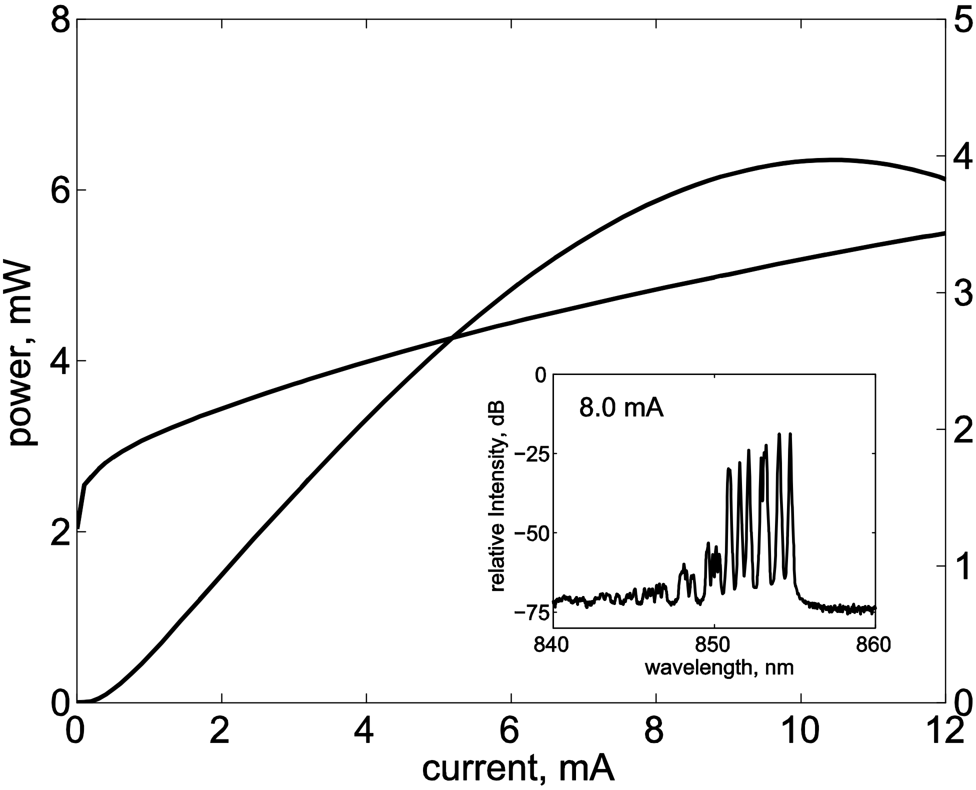
Figure captions:

Fig.1 Output power and voltage as a function of bias current for a ~7 µm oxide aperture VCSEL. Inset: optical spectrum at 8.0 mA bias current.

Fig.2 BER vs. received optical power at 25 and 40 Gbit/s in BTB configuration for the ~7 µm oxide aperture VCSEL. Insets: corresponding eye diagrams.

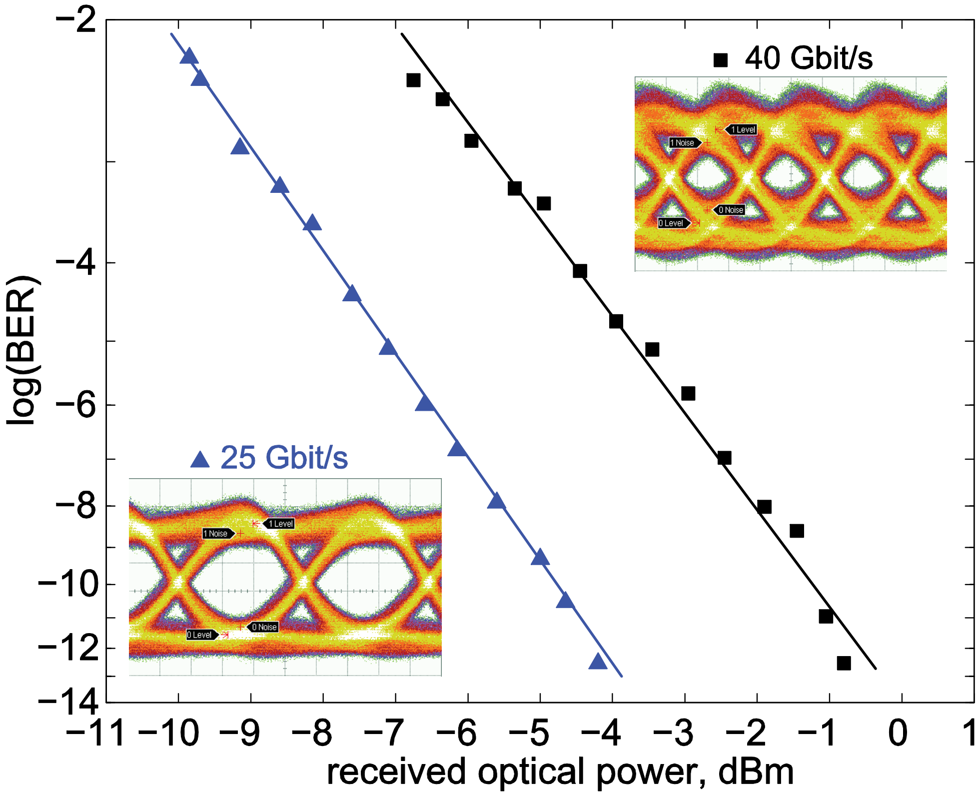
Fig.3 BER vs. received optical power at 25 and 35 Gbit/s after transmission over 100 m of OM3+ fibre for the ~7 µm oxide aperture VCSEL. Insets: corresponding eye diagrams.

Fig. 1



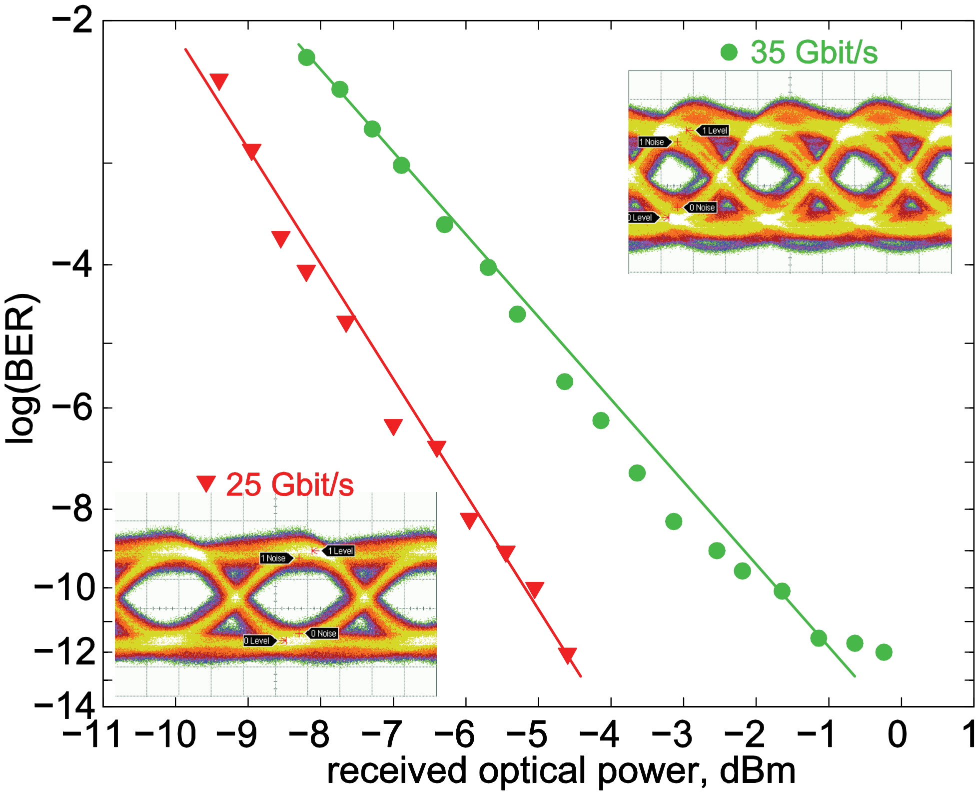
8
6
4
2
0
power, mW
5
4
3
2
1
0
voltage, V
0
2
4
6
8
10
12
current, mA
8.0 mA
relative Intensity, dB
0
−25
−50
−75
840
850
860
wavelength, nm

Fig. 2



40 Gbit/s
25 Gbit/s
1 Level
1 Noise
0 Noise
0 Level
log(BER)
−2
−4
−6
−8
−10
−12
−14
−11 −10 −9 −8 −7 −6 −5 −4 −3 −2 −1 0 1
received optical power, dBm

Fig. 3



35 Gbit/s
1 Level
1 Noise
0 Noise
0 Level
25 Gbit/s
1 Noise
1 Level
0 Level
0 Noise
log(BER)
−2
−4
−6
−8
−10
−12
−14
−11
−10
−9
−8
−7
−6
−5
−4
−3
−2
−1
0
1
received optical power, dBm