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81 fJ/bit energy-to-data ratio of 850 nm vertical-cavity surface-emitting lasers for optical interconnects

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Extremely energy-efficient oxide-confined high-speed 850 nm vertical-cavity surface-emitting lasers for optical interconnects are presented. Error-free performance at 17 and 25 Gb/s via a 100 m multimode fiber link is demonstrated at record high dissipation-power-efficiencies of up to 69 fJ/bit (<0.1 mW/Gbps) and 99 fJ/bit, respectively. These are the most power efficient high-speed directly modulated light sources reported to date. The total energy-to-data ratio is 83 fJ/bit at 25 °C and reduces to 81 fJ/bit at 55 °C. These results were obtained without adjustment of driving conditions. A high D-factor of 12.0 GHz/(mA)$^{0.5}$ and a K-factor of 0.41 ns are measured. © *2011 American Institute of Physics*. [doi:10.1063/1.3597799]

The power consumed by data-centers continues to grow exponentially wherein most of the power is consumed by sending data via interconnects within and between racks of servers. Today's copper-based interconnect technology is inefficient, becoming expensive, and slow. Interestingly metal interconnect distances must decrease as data rates increase to compensate for intrinsic losses. As a result the power consumption of data-centers is rapidly becoming environmentally significant.[1] To overcome the copper-bottleneck a technology transition to lower power and higher speed optical interconnects is crucial. In order to make this transition also economically feasible optical interconnects not only have to be faster, but also more energy-efficient than the present electrical interconnects. According to estimates and predictions based on the International Technology Roadmap for Semiconductors, lasers for optical interconnects should have energy efficiencies of a few ~10s of femto-Joules per bit (fJ/bit) in the next decade.[1,2] In 2015 energy-efficient high-speed lasers operating at ~100 fJ/bit (100 mW/Tbps) will be required. These numbers refer to the *dissipated electrical energy* per bit. In addition the *total energy* consumed per transmitted amount of data is of equal importance. We define the electrical energy-to-data ratio (EDR) (fJ/bit) and the heat-to-bit rate ratio (HBR) (mW/Tbps) as follows:

$$\mathrm{EDR} = P_{\mathrm{tot}}/\mathrm{BR} \quad \mathrm{HBR} = P_{\mathrm{diss}}/\mathrm{BR}, \tag{1}$$

where P_{tot} is the total consumed electrical power $P_{\mathrm{tot}}=VI$, V and I are the vertical-cavity surface-emitting laser (VCSEL) operating bias voltage and current, P_{diss} is the dissipated power $P_{\mathrm{diss}}=P_{\mathrm{tot}}-P_{\mathrm{optical}}$, P_{optical} is the VCSEL's output power and BR is the bit rate. In addition to low EDR and HBR temperature stable high-speed operation at constant current and voltage driving parameters is desired, providing the opportunity to dispose of cooling systems and to use simpler driver feedback circuits. The typical chip temperatures in optical transceiver modules as in IBM's Terabus system range from 75 °C without cooling to below 55 °C when using a heatsink and to below 40 °C when using a moderate air flow.[3] The present state-of-the-art energy-efficient high-speed VCSELs are listed in Table I. These values were achieved with 980 nm VCSELs at 35 Gb/s[4] and at the standard wavelength for multimode fiber (MMF) communication with 850 nm VCSELs at 32 Gb/s[5] and 12.5 Gb/s,[6] respectively. Good results were also achieved with 1060 nm VCSELs at 10 Gb/s.[7] Recently, we presented 980 nm VCSELs optimized for high-speed or extreme temperature stability, demonstrating up to 45 Gb/s[8] and error-free performance up to 155 °C,[9] respectively. In this work, we present the most energy-efficient VCSELs to date, working uncooled and unmonitored at the standard wavelength of 850 nm and at bit rates as high as 17 and 25 Gb/s, aiming at applications like Fibre Channel, Infiniband, 100 Gigabit Ethernet, IBM Terabus, and USB 4.0.

The VCSELs presented here are a more advanced version of our previously[10] reported oxide-confined 850 nm devices. To achieve very low threshold currents we reduced internal losses by further optimizing our mirror doping profile. We use multiple oxide-apertures formed by selective wet oxidation of $\mathrm{Al_{0.98}Ga_{0.02}As}$ layers with an optical *in situ* controlled oxidation furnace designed, built, and operated by our group. The VCSELs have a double mesa structure. The second bottom mesa is 30 μm larger in diameter than the first top mesa. The VCSEL structure is planarized with 8 μm thick photosensitive bisbenzocyclobutene to reduce parasitic capacitance. Ground-signal-ground contact pads are evaporated for ease of on-wafer high-frequency probing.

TABLE I. State-of-the-art of energy-efficient high-speed VCSEL.

Affiliation	UCSB[4]	Chalmers[5]	NCU/NTU[6]	Furukawa[7]	TUB/VIS
Bit rate (Gb/s)	35	32	12.5	10	17
EDR (fJ/bit)	357	460	272	180	83
HBR (mW/Tbps)	286	330	190	140	69

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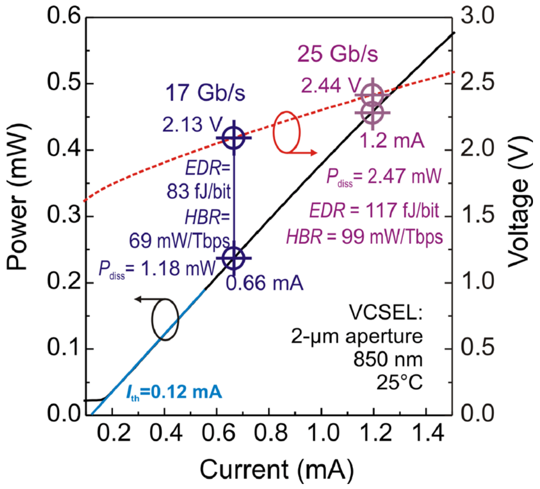

FIG. 1. (Color online) Measured *L-I-V* characteristics at 25 °C of an 850 nm VCSEL with a 2 μm oxide-aperture diameter.

On-wafer measurements are performed using a butt-coupled fiber. The device has a 2 μm oxide-aperture and a threshold current of 0.12 mA. The dissipated power at 25 °C is 1.18 mW at 0.66 mA and 2.47 mW at 1.2 mA, respectively. At 55 °C the dissipated power is 1.21 mW at 0.66 mA. The differential quantum efficiency derived from the *L-I* slope is 28.3% at 25 °C and reduces to 22.2% at 55 °C. The optical spectrum is highly single-mode across the entire current and temperature range with a side-mode suppression ratio exceeding 40 dB. We believe that the single-mode behavior of this device helps to achieve higher efficiencies, as only one mode has to be pumped resulting in higher *D*-factors and resonance-frequencies together with lower threshold currents and damping offsets. The measured *L-I-V* characteristics of the device are given in Fig. 1, including circular markers that indicate the driving conditions for the data transmission experiments.

Small-signal measurements (S_{21}) were performed at different currents and temperatures. In Fig. 2(a) the small-signal response of a VCSEL with a 2 μm oxide-aperture is shown at the driving currents of the data transmission experiments at 25 and 55 °C. At 0.66 mA the relaxation resonance frequency increases from 7.2 GHz at 25 °C to 8.2 GHz at 55 °C. Due to the etalon to peak gain wavelength detuning the VCSEL has a lower threshold current at 55 °C, resulting in a higher relaxation resonance frequency at elevated temperature. At 1.2 mA the relaxation resonance frequency increases from 12.0 GHz at 25 °C to 13.4 GHz at 55 °C.

A high *D*-factor of 12.0 GHz/(mA)$^{0.5}$ is extracted from the dependence of the relaxation resonance frequency on the square-root of (I-I_{th}) as shown in Fig. 2(b). The extracted *K*-factor of 0.42 ns is relatively high and the damping offset γ_0 of 8.1 GHz is low. The high *D*-factor and the low damping offset are very important for low-power/high-efficiency performance of the VCSEL, when high resonance frequencies have to be achieved at low currents above threshold.

In order to obtain a higher accuracy in determination of the *D*- and the *K*-factor we evaluated far more small-signal measurements than usually required. The data is plotted versus square-root of current above threshold. In our VCSEL, however, the threshold current is a function of temperature. Furthermore, our VCSELs are electrothermally heated by the driving current. The current changes the emission wavelength which, therefore can be used to estimate the internal device temperature. This means that different driving currents lead to a change in internal device temperature and consequently also result in different threshold currents. This affects the correct evaluation of several common laser parameters such as initial slope, and also *D*- and *K*-factor. The emission wavelength of the laser was used to estimate the internal device temperature. The laser wavelength at threshold was characterized over a wide temperature range enabling us to correlate these values to a certain driving current resulting in the identical emission wavelength. For the data depicted in Fig. 2(b) we plotted the threshold currents corresponding to the internal device temperature yielding a more accurate determination of our figures of merit.

Data transmission experiments at standard bit rates were performed using a nonreturn to zero (NRZ) data pattern with a 2^7-1 pseudorandom binary sequence. Error-free transmission across 100 m MMF (OM3 standard) was achieved for 17 and 25 Gb/s (Fig. 3) at low currents of 0.66 mA and 1.2 mA, respectively. In Fig. 4, the bit error ratio (BER) measurement at 17 Gb/s at 55 °C is shown, demonstrating a record low energy-to-data ratio of 81 fJ/bit. For each bit rate the BER measurements at higher temperature or across fiber were performed without adjusting the driving parameters in-

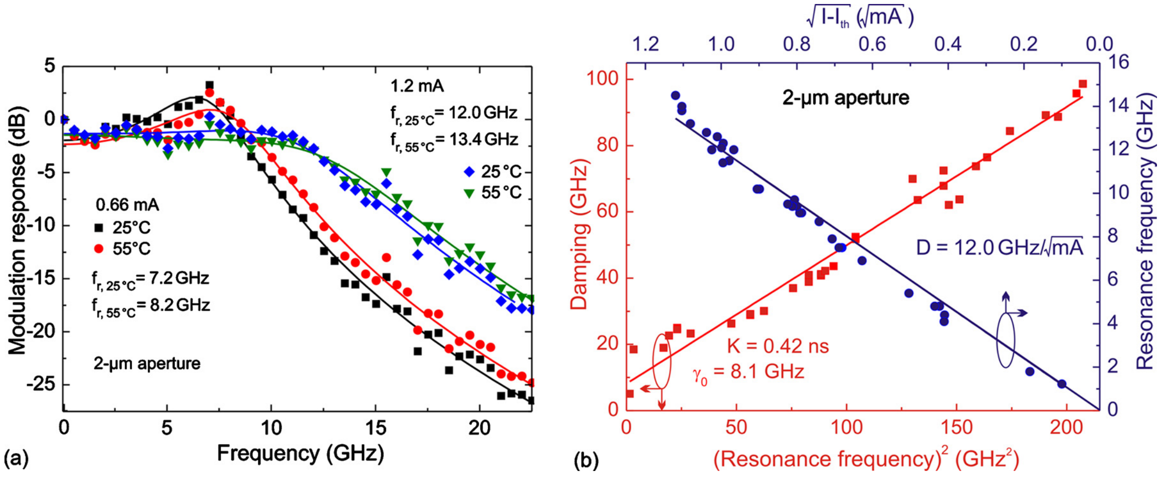

FIG. 2. (Color online) Small-signal modulation response of a 2 μm aperture VCSEL at 25 and 55 °C and the currents used for data transmission experiments (a). Extracted *K*-factor and *D*-factor of a 2 μm aperture VCSEL (b).

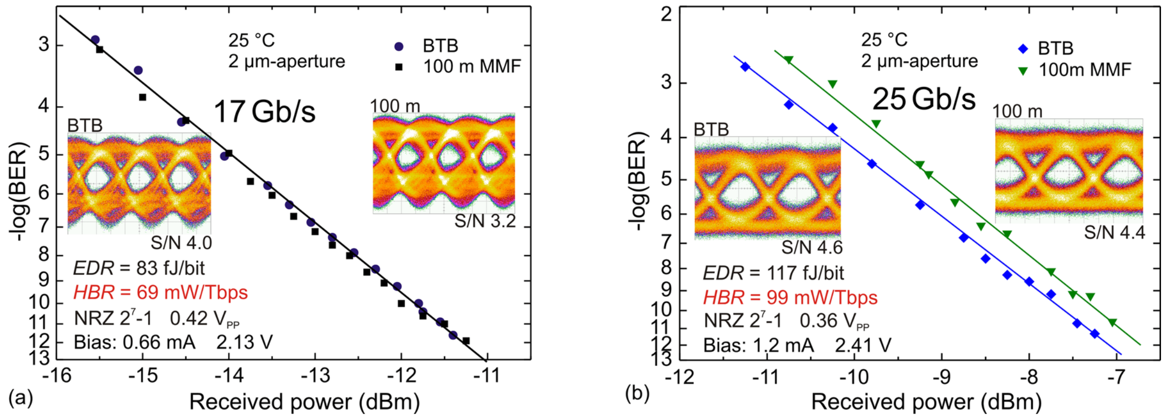

FIG. 3. (Color online) BER vs received power for a 2 μm aperture VCSEL at (a) 17 Gb/s and (b) 25 Gb/s both in the BTB-configuration and across 100 m of MMF at 25 °C with optical eye diagrams as insets.

cluding the bias current and the peak-to-peak modulation voltage V_{PP}. The recorded optical eye diagrams at 25 °C in a back-to-back (BTB) configuration and with an additional inserted 100 m of MMF are shown as insets in the plots of the respective BER plots in Fig. 3. Please note that these eyes were not recorded at the optimum driving conditions for eye-opening or signal-to-noise ratio but at working points optimized for record high efficiencies and error-free performance at the standard data communication bit rates of 17 and 25 Gb/s.

We used a 30 GHz photo detector (VIS D30-850M) for the measurements at 25 Gb/s, Fig. 3(b), and a 10 GHz (CS P-101) photo receiver for recording of the optical eye diagrams and BER-measurements at 17 Gb/s, Fig. 3(a). The power penalty due to insertion of 100 m fiber is only ∼0.5 dB at 25 Gb/s. At 17 Gb/s no power penalty is observed demonstrating potential for energy-efficient data transmission across even larger MMF link lengths.

We have presented the most power efficient high-speed directly modulated light sources reported to date. These are the first lasers meeting the future HBR requirements (<0.1 mW/Gbps) for optical interconnect applications in data-centers. Our devices emit at the standard wavelength of 850 nm, and are able to accommodate the very attractive bit rates of 17 and 25 Gb/s with simple NRZ coding. The devices are based on the mature GaAs-VCSEL technology and are ready for industrial mass-fabrication in existing foundries. Very high data-rate/power dissipation ratios up to 14.4 Gbps/mW were achieved at 17 Gb/s corresponding to a HBR of 69 fJ/bit. The total energy-to-data ratio is 83 fJ/bit at 25 °C and reduces to 81 fJ/bit at 55 °C. At 25 Gb/s and 25 °C, we demonstrated 99 fJ/bit and 117 fJ/bit, respectively. A high *D*-factor of 12.0 $\mathrm{GHz}/(\mathrm{mA})^{0.5}$ was measured.

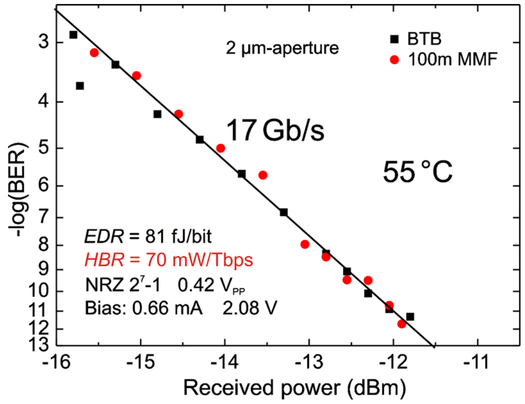

FIG. 4. (Color online) BER vs received power for a 2 μm aperture diameter VCSEL at 17 Gb/s at 55 °C in a BTB-configuration and across 100 m of MMF. A record low energy-to-data ratio of 81 fJ/bit is achieved.

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