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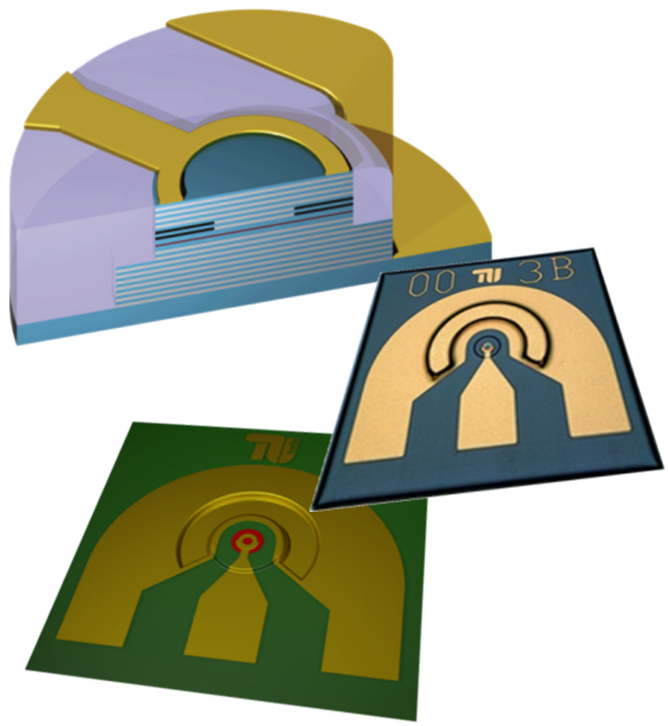

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Energy-Efficient VCSELs for Interconnects

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(Invited Paper)

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Manuscript received February 16, 2012; revised February 27, 2012; accepted March 6, 2012. Date of current version April 20, 2012. The lasers in the 850-nm waveband described here were developed at the Technical University of Berlin in cooperation with Vertically Integrated Systems GmbH, Hardenbergstraße 7, 10623 Berlin, Germany. Commercial samples are in progress. This work was supported by the German Science Foundation (DFG) through the Collaborative Research Centre SFB 787. Corresponding author: W. Hofmann (e-mail: Werner.Hofmann@tu-berlin.de).

Abstract: Vertical-cavity surface-emitting lasers (VCSELs) are particularly suited for energy-efficient optical interconnects in supercomputing. Consequently, several groups are developing VCSELs for energy-efficient interconnects with remarkable success. We give an overview over recent breakthroughs and present devices at the standard wavelength of 850 nm with record-low power consumption and heat dissipation per bit, achieving a value of only 69 mW/Tb/s at 17 Gb/s. This efficiency is exceeding the International Technology Roadmap for Semiconductors (ITRS) projection of 100 mW/Tb/s for 2015. If uncooled operation, ultradense arrays with smallest footprints, and highest ambient temperatures are required, the waveband around 1 μm is advantageous. At 980 nm, we could achieve an efficiency value in this waveband of 233 mW/Tb/s at an error-free 35 Gb/s.

Index Terms: Vertical-cavity surface-emitting laser (VCSEL), high-speed modulation, optical interconnects, energy-efficiency, green photonics.

1. Energy-Efficient Data Transmission

The exponential growth of Internet traffic is taken as an indicator for development and progress. On the other hand, this also means that the power consumed by data centers continues to grow exponentially. Keeping limited natural resources in mind, "green IT" is a crucial subject. As the copper-based interconnect technology is inefficient, expensive and slow, the transition to optical interconnects has become reality [1], [2]. With most of the power being consumed by sending data via interconnects within and between racks of servers, the power consumption of data centers is rapidly becoming environmentally significant [3]. According the International Technology Roadmap for Semiconductors (ITRS), lasers for future optical interconnects should highly energy efficient. In 2015, energy-efficient high-speed lasers operating at 100 mW/Tb/s (100 fJ/bit) will be required [3], [4]. These numbers refer to the *dissipated electrical energy* per bit to fit the cooling budget of the data center. We define this figure of merit as heat-to-bit rate (*HBR*) ratio [5] (in milliwatts per Terabit per second)

$$HBR = P_{diss}/BR \tag{1}$$

where P_{diss} is the dissipated heat ($P_{\text{diss}} = P_{\text{el}} - P_{\text{optical}}$) of the laser, and *BR* is the bit rate. We believe that "green photonics" means that the *total energy* consumed per transmitted amount of data is of

TABLE 1

Recent accomplishments in the field of energy-efficient VCSELs

Affiliation	TUB/VIS[5]	NCU/NTU[19]	Chalmers[11]	TUB[20]	UCSB[16]	Furukawa[9]
Bit rate (Gb/s)	17/25	12.5	32	35	35	10
EDR (fJ/bit)	83/117	227	470	287	357	180
HBR (mW/Tbps)	69/99	109	330	233	286	140
Wavelength (nm)	850	850	850	980	980	1060
Year of publication	2011	2011	2009	2011	2009	2010

equal importance [5]. Therefore, we define the electrical energy-to-data ratio (*EDR*, fJ/bit)

$$EDR = P_{el}/BR \tag{2}$$

where $P_{\mathrm{el}} = V \cdot I$ is the total consumed electrical power with V and I as the laser's operating bias point. Additionally, the modulation power absorbed by the laser should be taken into account. Even though, depending on the used electronics, it might be the case that the power actually consumed in the vertical-cavity surface-emitting laser (VCSEL) is smaller than the power needed by the driving electronics, we believe that it is the most crucial one. This is due to its multiplier effect of the energy consumed by the light-source on the power consumption of the whole system. Note that efficiency per bit is not the same as the wall-plug efficiency (*WPE*), which can actually be expressed in terms of *HBR* and *EDR*

$$WPE = 1 - HBR/EDR. \tag{3}$$

Furthermore, this means that the most power-efficient lasers in terms of data transmission are not necessarily the lasers with the highest *WPE*, nor is the driving condition for best *HBR* or *EDR* identical to the point of highest *WPE*.

Having explained the need for energy-efficient interconnects and having defined the figures of merit, we would like to state, that we believe that the VCSEL technology can be a workhorse for energy-efficient links. For IBM's Terabus project the GaAs-based VCSELs with wavelengths of 985 nm and 850 nm were evaluated with the 850-nm waveband having the advantage of being commercially available at that time [6]. Efficient high-speed VCSELs have been developed in the wavebands from 850 nm to 1550 nm [7] and can be potentially optimized for highest data-transmission efficiencies. In 2011, the topic of Green Photonics has become in the focus of public and scientific interest. Conferences focusing on that topic and scientific awards acknowledging achievements in this field were initiated [8]. VCSELs operating at 10 Gb/s at 1060 nm with 140 mW/Tb/s *HBR* have been reported lately [9]. Longer wavelengths use less energy per photon and have therefore an intrinsic advantage. Furthermore, active materials with better gain properties can be used [10]. Nevertheless, 850 nm remains the current standard wavelength for fiber-based links. On the other hand, for the application in short optical interconnects also proprietary solutions with other wavelengths can address the market. Vast efforts have been made in boosting both bit rate [10]–[15], [17], [18], [20] and energy efficiency [5], [8], [9], [11], [14], [16], [19]–[21] significantly to meet the requirements of future data centers and supercomputers. The recent major accomplishments in the field of energy-efficient interconnects are summarized in Table 1. Researchers in Taiwan could demonstrate single-mode devices with high *WPEs* and a remarkable *HBR* of 109 mW/Tb/s [19]. Note that higher bit rates require a quadratic increase in current densities at a given device-technology. This makes energy-efficient devices operating at higher bit-rates more challenging. *EDR* of 500 fJ/bit or more are usually needed to achieve bit-rates of 30 Gb/s or more [11]. Consequently, at bit-rates as high as 35-Gb/s *HBR* and *EDR* values on the order of 200–300 fJ/bit are also outstanding results [16], [20].

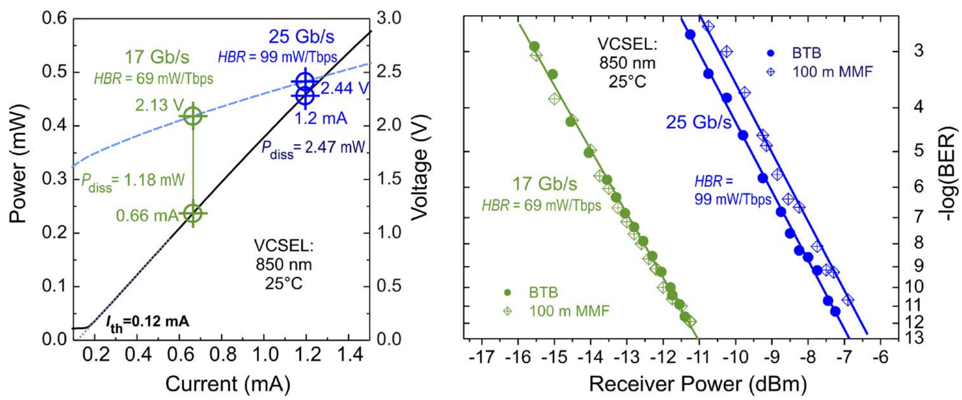

Fig. 1. Energy-efficient 850-nm VCSEL, room temperature: (Left) LIV-characteristics; the biasing point of the data-transmission experiment is indicated. (Right) Bit-error-rate measurement of that device at 17 Gb/s and 25 Gb/s. Energy efficiency: 17 Gb/s: HBR = 69 mW/Tb/s, EDR = 83 fJ/bit, Modulation energy = 10 fJ/bit 25 Gb/s: HBR = 99 mW/Tb/s, EDR = 117 fJ/bit, Modulation energy = 6 fJ/bit.

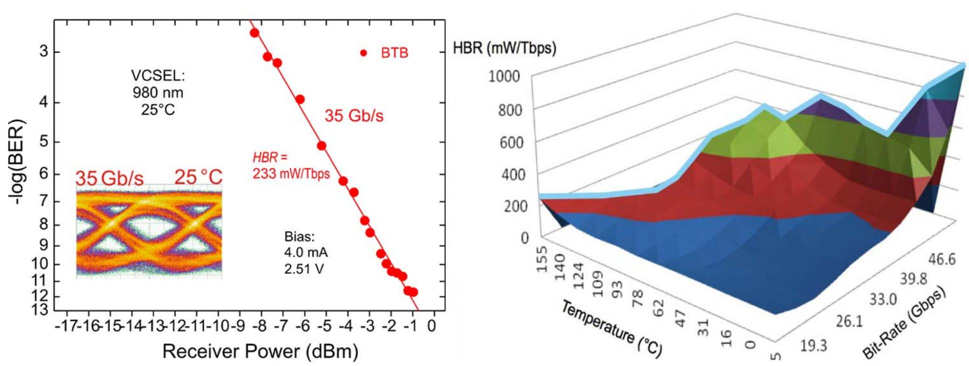

Fig. 2. Energy-efficient 980-nm VCSEL. (Left) Bit-error-rate measurement of that device at 35-Gb/s. Energy efficiency: HBR = 233 mW/Tb/s, EDR = 287 fJ/bit, Modulation energy = 26 fJ/bit. (Right) Dependence of Energy efficiency (here: HBR) on ambient temperature and bit-rate.

After having summarized the major accomplishments on energy-efficient VCSELs for optical interconnects achieved in 2011, we give some details on the achievements made at the Center of Nanophotonics at the Technical University of Berlin.

2. Energy-Efficient VCSELs for Interconnects

In a first-order approximation, for a given directly modulated VCSEL device, the resonance frequency rises with the square root of the VCSEL power. Therefore, it is trivial to understand that high-speed VCSELs typically consume more energy per bit when they are operated at higher bit rates. However, VCSELs designed to work at ultrahigh bit rates do not necessarily get more energy efficient just by simply reducing the pumping current and the bit rate. In order to realize energy-efficient high-speed performance, large resonance frequencies must be achieved at a low drive current. We characterized our latest VCSELs optimized for highest energy efficiency at different wavelengths and modulation speeds by transmission experiments characterizing the bit error rate (BER) with standard nonreturn-to-zero (NRZ) coding and a $2^7 - 1$ bit pattern length. The results for the 850-nm devices are given in Fig. 1. The *HBR* is 69 mW/Tb/s at 17 Gb/s and 99 mW/Tb/s at 25 Gb/s, respectively. A 100-m fiber link shows negligible power penalties. By heating up the device to 55 °C, we yield a record-low *EDR* of 81 fJ/bit and an *HBR* of 70 mW/Tb/s at 17 Gb/s. Data transmission over 1 km of multimode fiber is has also been accomplished [21].

In order to determine the modulation energy dissipated, we measure the true root mean square power absorbed by the VCSEL at the respective bit rate and modulation voltage.

In Fig. 2, we show the results of our 980-nm devices. The BER measurement with corresponding eye is presented in the left figure. Error-free data transmission at 35 Gb/s was accomplished at efficiencies of $EDR = 287$ fJ/bit and $HBR = 233$ mW/Tb/s. These devices also allow operation in a wide temperature range with little impact on the device performance [10]. Record-high data rates and efficiencies are not achieved at the same driving conditions, on the right-hand side of Fig. 2. On the other hand, as the efficiency of the device is not affected by ambient temperature in a wide range, uncooled systems saving large amounts energy are feasible.

3. Conclusion

In 2011, record energy-efficient directly modulated high-speed VCSELs were presented by several groups. Record error-free operation at data rates of 10 to 35 Gb/s could be achieved with NRZ coding at wavelengths ranging from 850 nm to 1060 nm. A total energy consumption within the VCSEL device of only 93 fJ/bit is sufficient for data transmission at 17 Gb/s. The devices are based on the mature GaAs-VCSEL technology and are suitable for industrial mass-fabrication in existing foundries. Based on this kind of devices, energy-efficient interconnects can be realized.

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