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Energy efficiency of 100 fJ/bit for bit rates beyond 50 Gb/s for 940 nm single mode VCSELs

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Mansoor A. Maricar,[1,2] Ilya A. Derebezov,[1] Zi-Heng Zhou,[1,2] Yu-Hao Wang,[1,2] Georgiy A. Sapunov,[1] Si-Cong Tian,[1,3,a)] and Dieter Bimberg[1,3]

AFFILIATIONS

[1]Bimberg Chinese-German Center for Green Photonics & Key Laboratory of Luminescence Science and Technology, Chinese Academy of Sciences & State Key Laboratory of Luminescence Science and Applications, Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, Changchun 130033, China
[2]The University of Chinese Academy of Sciences, Beijing 100049, China
[3]Center of Nanophotonics, Institute of Solid-State Physics, Technische Universität Berlin, Hardenbergstr. 36, Berlin D-10632, Germany

[a)]Author to whom correspondence should be addressed: tiansicong@ciomp.ac.cn

ABSTRACT

We demonstrate major advancements in the energy efficiency of single mode, oxide-confined, vertical-cavity surface-emitting lasers at 940 nm wavelength, being promising for optical interconnects. We were able to show error-free operation (Bit Error Rate of 10exp -12) at 50 Gb/s and at 60 Gb/s, for Non-Return-to-Zero modulation across 100 m of multimode optical fiber with an energy efficiency of 98/168 fJ/bit, respectively. These are presently the most energy-efficient directly modulated light sources available for data transmission.

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The number of internet users has increased by four orders of magnitude between 1990 and 2020. Applications continue to emerge almost annually, including social networking via WhatsApp, cryptocurrencies, and more recently, artificial intelligence. Both effects together lead to a rapid increase in size and capacity of data centers resulting in an enormous increase in their power consumption from 1 million (2010) to 10 trillion of Btu (British thermal unit) predicted for 2030.[1] Many of the technologies used on a daily basis, from language translation tools to virtual assistants to the growing accuracy of predictive text, are powered by advancement in artificial intelligence (AI), particularly in the area of natural language processing (NLP). The time and computer resources required to process vast amounts of text data make real-time analysis difficult. Specifically, data centers are experiencing a huge increase in energy demand due to the training of NLP models, which is far surpassing the rise of renewable energy sources.[1] Research and development groups around the world are finding solutions to reduce the energy consumption of data centers, dominated by their millions of optical interconnects, in addition to larger data rates and reducing latency. The 2044 roadmap of the UD Department of Energy[2] demands to increase the efficiency of data centers by a factor of 1000 and advances on vertical-cavity surface-emitting lasers (VCSELs) and optical interconnects will contribute.

Optical interconnects account for consuming about 85% of electrical power of a data center. Bit rates of interconnects are expected to rapidly surpass 400 Gb/s[2] in order to meet bandwidth capacity demands, resulting in a significant rise in power consumption and need for cooling power. The conflicting demand is to reduce energy use, measured in energy per bit energy to data ratio (EDR).[3] Moser *et al.*[4] introduces the EDR value as a measure of power consumption, replacing the previous heat to bit rate (HDR) value, measuring only part of the total power consumption.

A single mode (SM)-VCSEL having a low EDR value was developed by research group at Technische Universität Berlin (TUB)[4] 12 years ago. The EDR was showing then a record low value of 56 fJ/bit at 25 Gb/s operation in a back-to-back (BTB) configuration at room temperature, due to larger D-factors, high maximum modulation bandwidth f3dB, and lower differential resistance for all oxide aperture diameters. An EDR of 168 fJ/bit was reported for data rates of 35 Gb/s for SM 980 nm lasers.[5] High-speed multimode VCSELs in the 850 nm spectral region with a heat-to-bit rate <100 fJ/bit at 25, 40, and 50 Gbit/s have been reported.[6] For bit rates of 40 Gb/s, EDR values for 850 nm SM lasers of 228 fJ/bit were published.[7] Larisch *et al.*[8] reported EDR values of 228–528 fJ/bit for bit rates up to 57 Gb/s of MM 980 nm VCSELs. For a different design approach of intra-cavity metal-aperture 1060 nm SM-VCSELs 50 fJ/bit and 48 fJ/bit for 40 Gbps Non-Return-to-Zero (NRZ) and 60 Gbps pulse amplitude modulation 4-level (PAM4), respectively[9] was reported.

Previously,[10,11] we studied the effects of photon lifetime variations on the EDR for VCSELs in the wavelength range 850–940 nm. We

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reported a dependence of EDR on bandwidth and on photon lifetime. For 50 Gb/s, we observed an EDR of 400 fJ/bit.

Here, we report the results of a study focusing on 940 nm single mode VCSELs with 15 nm gain-to-cavity offset and varying numbers of top mirror pairs and quantum wells (QWs) in the active area.

We studied three types of SM-VCSELs under NRZ modulation and demonstrate error-free data transmission with only 98 fJ energy per bit at 50 Gbit/s and ~168 fJ/bit at 60 Gb/s across 100 m of OM5 multimode fiber, which are presently the lowest values ever reported.

Our VCSEL design is based our previous studies in Ref. 11, showing the importance of photon lifetime tuning and presenting an easy technology for doing so. The main goal of the present continuation is determining the factors that have the largest influence on optimum combination of low EDR and large data rate. We designed three distinct epitaxial wafers (designs A, B, and C), from which we fabricated oxide-confined SM-VCSELs. The epi-structures were grown by MOCVD on undoped 0-degree off (001)-oriented GaAs substrates. We employ $Al_{0.12}Ga_{0.88}As$/$Al_{0.90}Ga_{0.10}As$ distributed Bragg reflectors (DBRs) with compositionally graded interfaces using silicon-doping for the n-type bottom mirrors and carbon-doping for the p-type top mirrors. The upper Bragg mirror contains 22.5 periods (design A) or 18.5 periods (designs B and C). The lower Bragg mirror has 34 periods for all three designs, which ensures a high level of reflection, which is different from the design used in Refs. 8 and 11. In the active region, five (designs A and B) or three (design C), compressively strained $In_{0.17}Ga_{0.83}As$ quantum wells (QWs) embedded in $GaAs_{0.84}P_{0.16}$ barriers are employed, to offer significant differential gain at low current density, all in a $\lambda/2$-thick optical cavity. Double oxide apertures are used to realize both current and optical confinement by selectively wet-oxidizing the $Al_{0.98}Ga_{0.02}As$ layers. We employ a photosensitive benzocyclobutene (BCB) layer approximately 8 μm thick to planarize our VCSEL structure, which minimizes parasitic capacitances and facilitates coplanar high-frequency contact pads for on-wafer high-frequency testing. This design set allows us to directly compare the properties of VCSELs based on designs A and B, the difference in the numbers of top DBR pairs and designs B and C, the difference in number of QWs which changes the gain.

Shifting by 15 nm the cavity mode away from the quantum well active region gain peak is an important design modification in comparison to some of our previous VCSEL designs.[4,5] The cavity modes permitted by a VCSEL cavity design are narrowly spaced. The strongest lasing mode is the one most closely matching the peak gain with the cavity mode. Thus, heating causes changes in the effective cavity length and the spectral position of the gain, having a big impact on intensity. Temperature has a comparable effect on the threshold current density, since rising temperatures decrease the quantum wells' gain. Since the temperature of the active area is always higher than that of the surroundings, a temperature-robust VCSEL needs significant differential gain at high active area temperatures. Our calculations indicate that, in comparison to a negative offset of 10 nm, a 15 nm gain-to-etalon wavelength offset design will offer a smoother variation of the differential gain across the temperature range of 25–85 °C in agreement with our previous work.[12] This is obviously advantageous for temperature stability when operating at high bit rates and at high active area temperatures. Additionally, a larger D-factor results from this larger differential gain allowing to reduce the power consumption by reaching a larger bandwidth at a lower bias current.

The number of layers of the top DBR changes the photon lifetime. A larger bandwidth can be achieved by reducing the impact of the modulation current efficiency factor (MCEF) drop.[8] Additionally, modifying the photon lifetime offers opportunities to maximize the damping factor K, a crucial component of the dynamics of VCSELs.

Using an effective index optical model, considering internal optical loss through free carrier absorption and outcoupling through the DBRs, the photon lifetimes of the VCSELs A–C are derived to be 4.9 ps and 2.5 ps for designs A and B, these parameters and the experimentally observed maximum bandwidths (f3dB) are summarized in Table I.

As shown in Table I, the SM-VCSEL based on design A, with the highest τ_p, achieves the largest bandwidth, contrary to typical expectations. VCSEL performance is usually enhanced by reducing electrical parasitics, increasing resonance frequency via higher differential gain, and mitigating self-heating, while damping effects are less controlled. The damping (γ) depends on the K-factor, which is influenced by differential gain ($K \propto 1/(\partial g/\partial n)$) and cavity photon lifetime ($K \propto \tau p$). Although increasing differential gain or decreasing τp can improve the modulation bandwidth, τp has a non-monotonous relationship[13] with the bandwidth, with an optimal point beyond which reductions are counterproductive.[8] The bandwidth does not increase monotonically with decreasing photon lifetime. When optimizing the photon lifetime for maximum bandwidth, there is a trade-off between resonance frequency and damping.[13]

The static Light-Current-Voltage (LIV) properties of the devices were measured by an automatic wafer mapping system. All SM-VCSELs were processed with the same photo mask. We investigated devices with an oxide aperture diameter of 3 μm and a top mesa diameter of 21 μm. SM-VCSELs of design A typically show a threshold current of 170 μA. They can achieve a maximum optical output power of 0.91 mW at a rollover current of 4.1 mA. Design B shows a threshold current of 360 μA achieving 1.43 mW output power at 4.0 mA. Design C shows a threshold current of 260 μA at a rollover current of 3.9 mA, reaching an output power of 0.84 mW. Figure 1(a) displays the LIV values and Fig. 1(b) the optical emission spectra. All devices show side-mode suppression ratios (SMSR) 35–40 dB.

A Keysight PNA-X N5247B network analyzer is used for small-signal modulation tests. The modulation response (S21) is evaluated across a large current range. For design A, the maximum f3dB is slightly above 30 GHz; for devices based on designs "B" and "C," the largest f3dB is 26 and 28 GHz, respectively. Assuming, that M = 2.0, we conclude that design A device operates error-free (BER~10exp-12) at 60 Gb/s, whereas designs "B" and "C" operate error-free up to

TABLE I. VCSEL parameters.

Sample design	Pairs of top DBR	Number of QWs	Max. Bandwidth (GHz)	Photon lifetime τ_p (ps)
A	22.5	5	30	4.9
B	18.5	5	26	2.5
C	18.5	3	28	2.5

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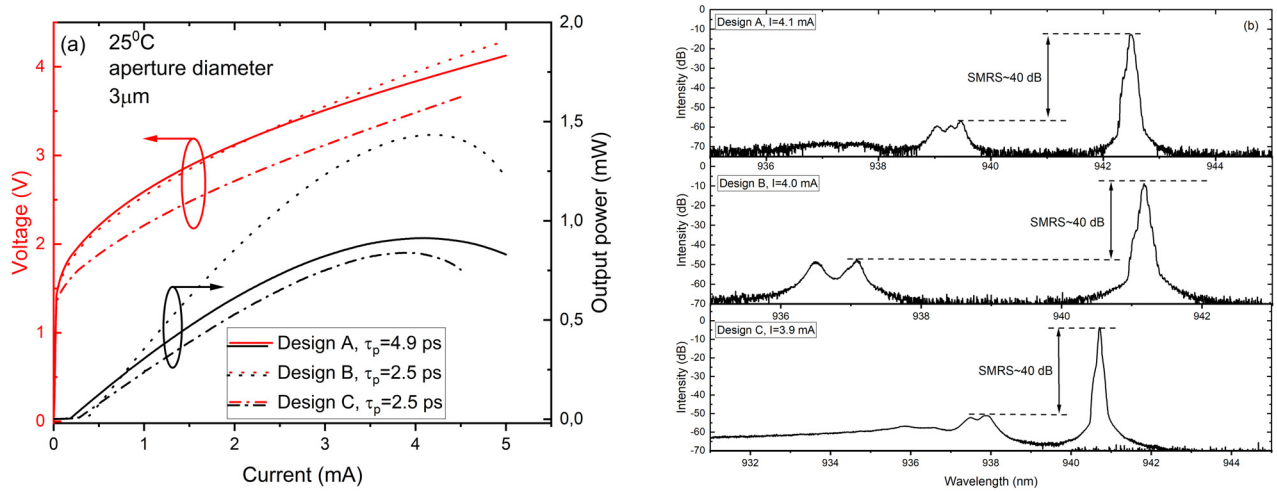

FIG. 1. Static LIV characteristics at 25 °C of a 3 μm oxide aperture diameter VCSEL (a). Optical emission spectra (b).

52 Gb/s and 56 Gb/s, respectively. The calculated EDR values as a function of bit rates is shown in Fig. 2 for wafer design A, B, and C.

All lasers show an EDR minimum of 30 Gbit/s. When the bit rate increases, the EDR of devices with short photon lifetimes increases faster, compared to those with longer photon lifetimes for larger bit rates. All lasers finally move out of the transmission window of their mirror, the resulting EDR rises sharply. Thus, it is better to use VCSELs with a long photon lifetime for larger bit rate (>48 Gbit/s) operation, while it is better to use devices with a short photon lifetime for medium or lower bit rates.

NRZ transmission experiments were performed using a SHF bit pattern generator (SHF 12100 B) producing a pseudo-random binary sequence (PRBS 27–1). A 65 GHz broadband amplifier amplifies the signal, which is then applied to the VCSEL through a 65 GHz bias tee, linked to the power source that supplies the DC bias. Bit error ratio

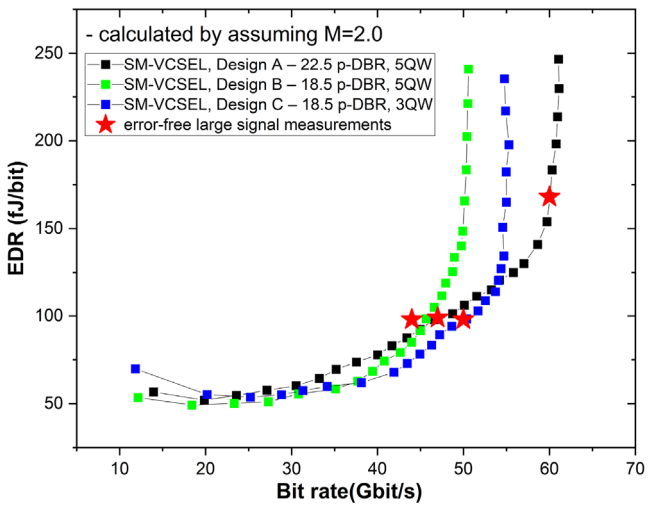

FIG. 2. EDR as a function of bit rate for three different SM-VCSEL designs.

(BER) measurements are performed using a SHF 11100 B Error Analyzer in conjunction with a 30 GHz Thorlabs photodiode equipped with an amplifier. An additional tool used to measure eye diagrams is a Tektronix real-time oscilloscope. For all of our measurements, peak-to-peak modulation voltages (VPP) of 450–1100 mV were used.

The output is coupled to a 1 m long multimode lensed fiber (MMF) and routed onto an optical variable attenuator, the output of which is linked to a 100 m OM5 fiber. Highest energy-efficient large-signal modulation of the SM-VCSELs is anticipated to attain at bitrates ranging from around 44 to 50 Gb/s, based on our small-signal modulation results. Figure 3 shows the BER at 25 °C for the three different designs when operating at bias currents, which provide EDR values close to 100 fJ/bit.

SM-VCSEL-A shows an EDR close to 100 fJ/bit based on a bias current of 1.5 mA at 47 Gb/s. The BERs as well as the optical eye diagrams are shown in Fig. 3(a). Error-free operation is achieved without pre-emphasis for 1 and 100 m long optical fibers. As shown in Fig. 4, we also achieved error-free operation at 60 Gbit/s for a bias current of 2.4 mA and an EDR of 168 fJ/bit.

Figure 3(b) shows the optical eye diagrams and BERs for SM-VCSEL-B. An EDR close to 100 fJ/bit was observed for a bias current of 1.5 mA at 44 Gb/s. For 1 and 100 m long optical fibers, error-free operation at 44 Gb/s was achieved without pre-emphasis for both lengths.

The optical eye diagrams and BERs for SM-VCSEL-C are displayed in Fig. 3(c). The EDR value was close to 100 fJ/bit, for a bias current of 1.7 mA for a bit rate of 50 Gb/s. Error-free operation at 50 Gb/s was attained without pre-emphasis of the driver for optical fibers that are 1 and 100 m long.

At 50 Gb/s, the EDR of 98 fJ/bit for design C is smaller than the values of 99 fJ/bit at 47 Gb/s and 98 fJ/bit at 44 Gbit/s for designs A and B, respectively. Even though SM-VCSEL-C and SM-VCSEL-B have the same photon lifetime, their maximum bit rates differ. SM-VCSEL-C has three and SM-VCSEL-B has five QWs, thus B heats up faster for a given current and current saturation (max bandwidth) is reached at lower currents. An additional reason for the lower EDR of

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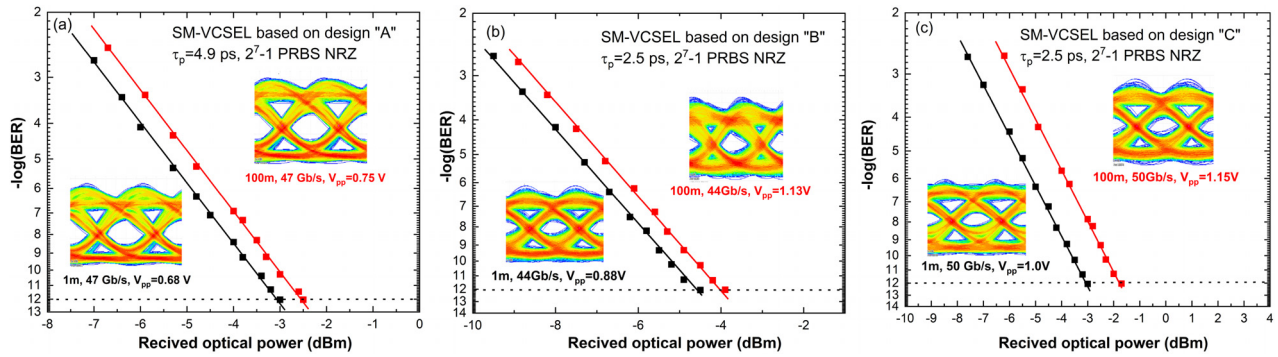

FIG. 3. BER vs received optical power in 1 and 100 m OM5 for SM-VCSEL based on (a) design A at 47 Gb/s, (b) design B at 44 Gb/s, and (c) design C at 50 Gb/s.

the present work, compared to that of our previously published one[8] is that in the present work, we focus on single mode lasers, and the target oxide aperture is 3 μm, whereas in Ref. 8, it is 6 μm. The smaller oxide aperture results in a larger D factor and a larger resonance frequency at a smaller current. Therefore, a larger bandwidth at a smaller current is realized by using a smaller oxide aperture. A smaller current results additionally in a smaller EDR. Both effects act together.

The number of top DBR pairs is the only variation between SM-VCSEL-A and SM-VCSEL-B. Since design A has a larger number of top DBR pairs than design-B, its photon lifetime is larger. Although a longer photon lifetime results in a larger K-factor and larger damping, the noise and the overshoot will be suppressed,[13] which in turn supports SM-VCSEL-A to operate at a larger max bitrate. The highest bitrate of 60 Gb/s at an EDR value of 168 fJ/bit is found for SM-VCSEL-A.

In summary, record energy efficiencies for high-speed, directly modulated 940-nm single mode VCSELs were studied. EDR values of 98 fJ/bit and 168 fJ/bit are achieved error-free at 50 Gb/s and 60 Gb/s,

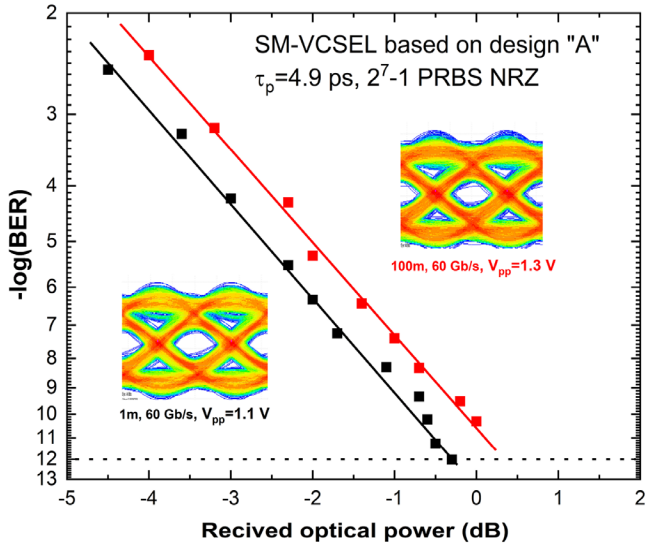

FIG. 4. BER vs received optical power 60 Gb/s in 1 and 100 m OM5 for SM-VCSEL-A.

respectively. EDR values close to 100 fJ/bit were achieved at 47 Gb/s, 44 Gb/s, and 50 Gb/s for designs A, B, and C, respectively. Differences in maximum gain and photon lifetime are due to differences in the number of QWs and top DBR pairs (see Table I). These are the lowest EDR values that have been reported up to this point at the mentioned bit rates for SM VCSELs. Energy efficiency is clearly influenced by photon lifetime, QW gain-peak-to-cavity-mode offset, and the aperture diameter. Maximum bit rates up to 60 Gb/s with only 168 fJ/bit EDR are observed for a design with max number of DBR pairs and QWs. These results present one step forward toward reducing the power consumption of large data centers in the AI age.

See the supplementary material for details on the VCSEL layer design engineered to optimize single mode operation by carefully considering gain-to-cavity offset, current-induced wavelength tuning, and oxide aperture dimensions. The fabricated devices exhibit a current-wavelength tuning coefficient of approximately 0.9 nm/mA and a temperature-wavelength tuning coefficient of 0.63 nm/°C, in close agreement with reported values for GaAs-based VCSELs. A gain-to-cavity offset of 15 nm at room temperature ensures precise spectral alignment between the gain peak and the cavity resonance at elevated active region temperatures, enhancing device performance and stability.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

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Author Contributions

Mansoor A. Maricar: Data curation (equal); Formal analysis (equal); Investigation (equal); Methodology (equal); Visualization (equal); Writing – original draft (lead); Writing – review & editing (lead). **Ilya A. Derebezov:** Data curation (equal); Formal analysis (lead); Investigation (equal); Methodology (equal); Visualization (lead); Writing – original draft (lead); Writing – review & editing (equal). **Zi-Heng Zhou:** Data curation (equal); Formal analysis (equal); Investigation (equal); Methodology (equal); Visualization (equal). **Yu-Hao Wang:** Data curation (equal); Formal analysis (equal); Investigation (equal); Methodology (equal); Visualization (equal). **Georgiy A. Sapunov:** Data curation (equal); Formal analysis (equal); Investigation (equal); Methodology (equal); Visualization (equal). **Si-Cong Tian:** Funding acquisition (lead); Project administration (lead); Resources (lead); Supervision (equal); Validation (equal); Writing – review & editing (equal). **Dieter Bimberg:** Conceptualization (lead); Data curation (lead); Formal analysis (lead); Funding acquisition (lead); Investigation (lead); Methodology (lead); Project administration (lead); Resources (lead); Software (lead); Supervision (lead); Validation (lead); Visualization (lead); Writing – original draft (lead); Writing – review & editing (lead).

DATA AVAILABILITY

The data that support the findings of this study are available within the article.

REFERENCES

[1]B. Osibo and S. Adamo, "Data centers and green energy: Paving the way for a sustainable digital future," Int. J. Latest Technol. Eng. Manage. Appl. Sci. **12**(11), 15–30 (2023).
[2]J. Booth, "Energy efficiency scaling for 2 decades (EES2) roadmap for computing," in *28th Annual IEEE High Performance Extreme Computing Virtual Conference, CO, USA* (IEEE, 2024).
[3]S.-C. Tian, M. Ahamed, G. Larisch, and D. Bimberg, "Novel energy-efficient designs of vertical-cavity surface emitting lasers for the next generations of photonic systems," Jpn. J. Appl. Phys. **61**(SK), SK0801 (2022).
[4]P. Moser, J. A. Lott, P. Wolf, G. Larisch, H. Li, N. N. Ledentsov, and D. Bimberg, "56 fJ dissipated energy per bit of oxide-confined 850 nm VCSELs operating at 25 Gbit/s," Electron. Lett. **48**(20), 1292–1294 (2012).
[5]H. Li, P. Wolf, P. Moser, G. Larisch, J. A. Lott, and D. Bimberg, "Temperature-stable 980-nm VCSELs for 35-Gb/s operation at 85 °C with 139-fJ/bit dissipated heat," IEEE Photonics Technol. Lett. **26**(23), 2349–2352 (2014).
[6]E. P. Haglund, P. Westbergh, J. S. Gustavsson, E. P. Haglund, A. Larsson, M. Geen, and A. Joel, "30 GHz bandwidth 850 nm VCSEL with sub-100 fJ/bit energy dissipation at 25–50 Gbit/s," Electron. Lett. **51**(14), 1096–1098 (2015).
[7]K.-L. Chi, J.-L. Yen, J.-M. Wun, J.-W. Jiang, I.-C. Lu, J. Chen, Y.-J. Yang, and J.-W. Shi, "Strong wavelength detuning of 850 nm vertical-cavity surface-emitting lasers for high-speed (>40 Gbit/s) and low-energy consumption operation," IEEE J. Sel. Top. Quantum Electron. **21**(6), 470–479 (2015).
[8]G. Larisch, S. Tian, and D. Bimberg, "Optimization of VCSEL photon lifetime for minimum energy consumption at varying bit rates," Opt. Express **28**(13), 18931 (2020).
[9]H. R. Ibrahim, A. M. A. Hassan, X. Gu, S. Shinada, M. Ahmed, and F. Koyama, "1060 nm single-mode metal-aperture VCSEL array with transverse resonance and low power consumption below 50 fJ/bit," *2021 European Conference on Optical Communication (ECOC), Bordeaux, France* (IEEE, 2021), pp. 1–4.
[10]G. Larisch, P. Moser, J. A. Lott, and D. Bimberg, "Large bandwidth, small current density, and temperature stable 980-nm VCSELs," IEEE J. Quantum Electron. **53**(6), 1 (2017).
[11]G. Larisch, P. Moser, J. A. Lott, and D. Bimberg, "Impact of photon lifetime on the temperature stability of 50 Gb/s 980 nm VCSELs," IEEE Photonics Technol. Lett. **28**(21), 2327–2330 (2016).
[12]H. Li, P. Wolf, P. Moser, G. Larisch, A. Mutig, J. A. Lott, and D. H. Bimberg, "Impact of the quantum well gain-to-cavity etalon wavelength offset on the high temperature performance of high bit rate 980-nm VCSELs," IEEE J. Quantum Electron. **50**(8), 613–621 (2014).
[13]E. P. Haglund, P. Westbergh, J. S. Gustavsson, and A. Larsson, "Impact of damping on high-speed large signal VCSEL dynamics," J. Lightwave Technol. **33**(4), 795–801 (2015).

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