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Energy-efficient 50+ Gbit/s VCSELs for 200+ Gbit/s optical interconnects

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Abstract— **Vertical-cavity surface-emitting lasers (VCSELs) for 200+ Gbit/s single fiber data transmission across OM5 multimode fiber with a heat to bit rate ratio (HBR) of only 240 fJ/bit based on coarse wavelength division multiplexing (CWDM) are presented. Tuning the cavity photon lifetime is demonstrated to lead to an increase of the data rate in concert with a reduction of the HBR. The VCSELs are emitting at 850 nm, 880 nm, 910 nm, and 940 nm, the present IEEE 802.3 coarse wavelength multiplexing standard.**

Index Terms—**Energy efficiency, optical interconnects, wavelength division multiplexing, vertical cavity surface emitting laser, single mode emission.**

I. INTRODUCTION

THE energy required to transmit information as encoded optical and electrical data bits within and between electronic and photonic integrated circuits, within and between computer servers, within and between data centers, and ultimately across the earth from one point to another one clearly must be minimized. This energy spans from typically tens of picojoules-per-bit to well over tens of millijoules-per-bit for intercontinental distances. We seek to meet the exploding demand for information within the terrestrial resources available, but more importantly as a common-sense measure to reduce costs and to become stewards of a perpetual Green Internet. The concept of a Green Internet implies a collection of highly energy-efficient, independent, and ubiquitous information systems operating with minimal impact on the environment via natural or sustainable energy sources. A key enabling optical component for the Green Internet is the vertical-cavity surface-emitting laser (VCSEL). We present our research on energy-efficient VCSELs, being sources for optical interconnects and optical fiber data communication, using four wavelengths CWDM between 850 nm and 940 nm according to the IEEE 802.3cd standard. In previous work presenting first results on CDWM no data on energy efficiency were presented [1]. We report here bit rates exceeding 50 Gbps with energy efficiencies of 240 fJ/bit approaching the magic number of 100 fJ per-bit [2].

II. STRUCTURE AND DESIGN OF THE LASERS

A. Epitaxial design

Our VCSELs are grown by MOVPE on 0-degree off (001)-oriented GaAs substrates and emit at 850 nm, 880 nm, 910 nm, and 940 nm at room temperature (RT). We use AlGaAs distributed Bragg reflector (DBR) mirrors with compositionally-graded interfaces and one 20-nm-thick oxide aperture layer above as well as underneath the active region. The quantum well active region consists of five compressively-strained InGaAs quantum wells surrounded by either strain-compensating GaAsP barrier layers or by unstrained AlGaAs barrier layers (depending on the desired emission wavelength), all in half-lambda-thick optical cavities.

B. Laser fabrication

The VCSELs are processed in a double mesa design to ensure a good heat conduction out of the active region. GSG (Ground-Signal-Ground) contact pads enable the evaluation of a large number of devices in a short time. The use of BCB (benzocyclobutene) reduces the parasitics by reducing the pad-capacitances [3]. A patented optimization step [4, 5], based on reflectance tuning of the out-coupling mirror by deposition of a dielectric, was used to increase the bitrate while reducing the energy consumption [6]. For optical and electrical confinement we employ oxide apertures fabricated by selective wet oxidation of $Al_{0.98}Ga_{0.02}As$ layers [7]. An optical in situ-controlled in-house designed and built steam oxidation furnace was used to form the apertures with a tolerance of 0.5 µm. Due to a large variation of upper mesa diameters provided by our mask set, 16 different aperture diameters are available with every process run [6].

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III. STATIC PROPERTIES

A. Demands of active cables

In the future, the requirements for optical links will not be satisfied only through high speed and low energy consumption laser sources. Integration of energy efficient driver circuits, optical waveguides, photodiodes and amplifiers is essential [8, 9] (see Fig. 1). The electrical and optical properties of the laser must be matched to the other components.

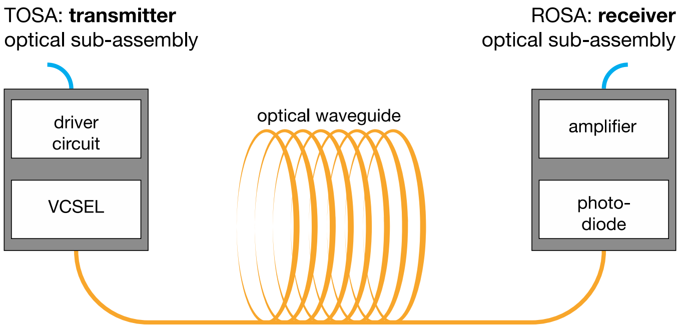

Fig. 1: Sketch of an optical link containing a driver circuit, a VCSEL, an optical waveguide, a photodiode, and an amplifier. Driver circuit and laser form the transmitter optical sub-assembly TOSA, amplifier and photodiode form the receiver optical sub-assembly ROSA.

B. Large optical power output at low bias current

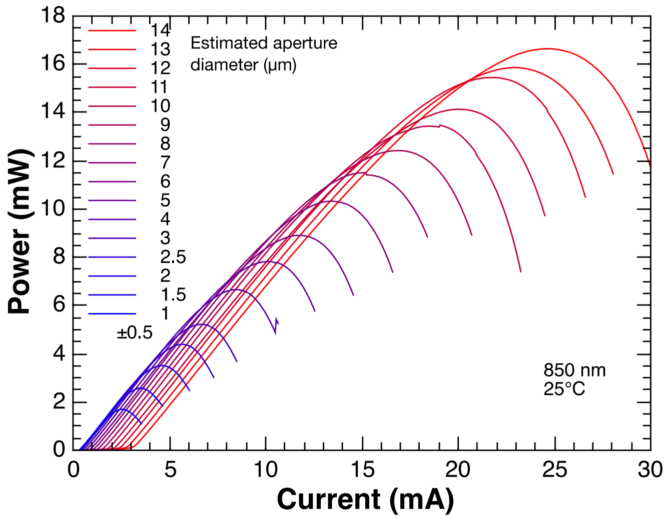

Fig. 2: L-I characteristics of 16 different aperture diameter VCSELs ranging between ~1 µm to ~14 µm emitting at 850 nm from the same wafer. A top mesa size variation of our mask set leads to this spread. All lasers show a slope efficiency larger than 1 W/A and a large linearity up to 95% of thermal roll-over of their L-I-characteristics.

A reduction of the VCSELs aperture size to reduce the input power consumption can only be done if the optical output power does not significantly decrease. Our approach here is based on increasing the slope efficiency by employing the photon lifetime optimization step, leading to an increase of optical power for relatively small aperture diameter VCSELs at low currents. Fig. 2 shows the L-I characteristics of 16 different aperture diameter VCSELs ranging between ~1 µm to ~14 µm provided by a top mesa size variation of our mask set. This variation allows the selection of lasers that satisfy the optical power demand of the photodiode at the lowest possible bias I and threshold current I_{th}. All lasers at all wavelengths have a very large slope efficiency of 1 W/A with a very linear L-I-curve up to 95% of thermal roll-over.

C. Large optical modulation amplitude due to large slope efficiency

Downsizing our lasers has the additional advantage of reducing the bias current and therefore decreasing the energy demand of the drive electronics. Since the power consumption of drivers is presently a magnitude larger than the power consumption of the lasers [10] the total power consumption of the optical link will be reduced dramatically.

A decrease of the aperture diameter results in a larger differential resistance. CMOS based drive electronics create typically a voltage swing ~1 V_{pp} [11-13]. A large slope efficiency results in a large optical modulation range and *optical modulation amplitude*. Fig. 3 shows the linear part of the L-V characteristics for the lasers shown in Fig. 2. Optical output power is plotted versus modulation voltage of maximum 1.2 V_{pp} around a bias voltage V_{bias} centered in the middle of the linear part of the L-I curve of Fig. 2. Fig. 3 also shows that the large slope efficiency enabled by our optimization leads to a large optical modulation range of nearly 3 mW, even for lasers with large differential resistance Showing single mode emission spectra (see Fig. 4) and small aperture diameter.

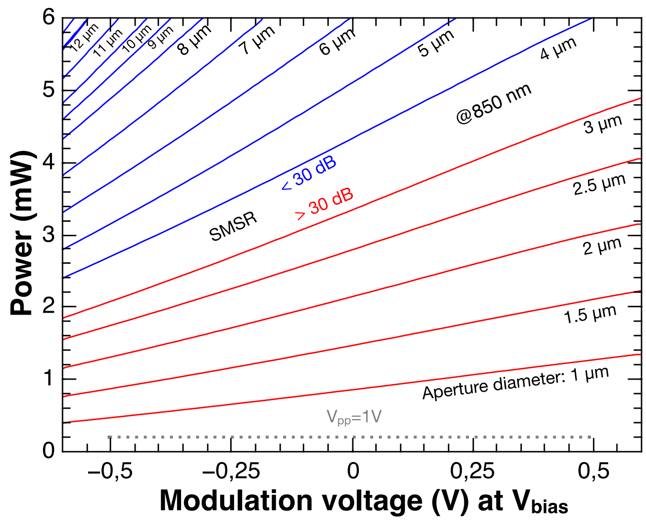

Fig. 3: Optical power output caused by a modulation voltage of 1 V_{pp} around the bias voltage V_{bias} for the lasers shown in Fig. 2. The bias voltage is set at the center of the linear part of the L-I curves. The color code distinguishes single mode lasers (red) defined by a side mode suppression ratio SMSR larger than 30 dB for small aperture diameter lasers and multimode lasers (blue).

D. Emission spectra

The distance a signal can be transmitted across an optical fiber depends on the amount of incurred optical losses and dispersion. The losses depend on the wavelength, and increase with the fiber length, Longer fibers require an increased optical launch power. Our single mode emission lasers show large optical power compared to previous single mode VCSEL approaches [14, 15] and are well suited for high-speed data transmission across both single mode and multi mode fiber for distances of a few hundred meters.

To increase data rates across single multimode fibers coarse wavelength division multiplexing (CWDM) according to the existing IEEE802.3 standard. We have fabricated VCSELs with emission wavelengths of 850 nm, 880 nm, 910 nm, and 940 nm which will be used in such a CWDM system. For all four wavelengths, almost identical L-I-V properties are observed, as shown typically in Fig. 2 and Fig. 3. Their emission spectra shown in Fig. 4 are also similar to each other. At all wavelengths, single mode emission with large optical output power was achieved for aperture diameters of 3 µm and below. The thermal wavelength shift is 0.069 nm/K.

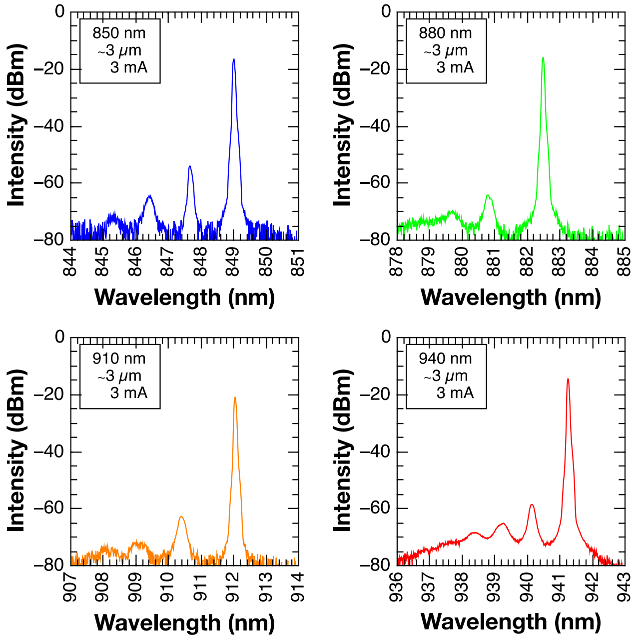

Fig. 4: Emission spectra of single mode emitting laser with optical power of ~3 mW at the wavelengths 850 nm, 880 nm, 910 nm, and 940 nm.

IV. DYNAMIC PROPERTIES

A. *Laser physics and laser performance*

The most important application of the lasers presented here is large data transmission across optical fibers. The most important parameters defining their performance are the maximum error-free bit rate *BR*,

$$BR = \text{number of transmitted bits/time} \tag{1}$$

the energy to data ratio *EDR*

$$EDR = V \cdot A/BR, \tag{2}$$

with V bias voltage and A bias current as well as the most frequently used heat to bitrate ratio *HBR*

$$HBR = (V \cdot A - P_{opt.})/BR, \tag{3}$$

with the optical power P_{opt} [16].

We use standard single mode rate equations to describe the laser diode physics. Their solution yields the transfer function

$$H(f) = \frac{f_R^2}{f_R^2 - f^2 + j\left(\frac{f}{2\pi}\right)\gamma} \cdot \frac{1}{1 + j\left(\frac{f}{f_p}\right)} \tag{4}$$

with the relaxation resonance frequency (f_R), damping (γ), and parasitic cut off frequency (f_p). The value of $H(f)$ decreases with increasing frequency (f) [17]. The frequency where $H(f)$ is reduced by 3 dB as compared to the starting value defines the bandwidth f_{3dB}. According to the Shannon-Hartley Theorem laser performance and laser physics are connected by the spectral efficiency M [18], where

$$BR = M \cdot f_{3dB}. \tag{5}$$

To increase the bitrate *BR*, the bandwidth f_{3dB} needs to be increased. Using highly strained multiple quantum wells in the active region increases the gain. Reducing the cavity length to $\lambda/2$ and shrinking the aperture diameter reduces the active volume [19]. Both lead to an increase of the relaxation resonance frequency even at low bias currents. An additionally important increase of bandwidth can be achieved by a cavity photon lifetime tuning. Adding a dielectric layer to the top mirror surface or thinning the last layer of the outcoupling mirror are present approaches [20, 21]. Dielectric layers can be also used to repair etch damages [22]. Patterned dielectric layers lead to suppression of higher order modes [23].

We have deposited a Si_xN_y with a thickness that maximizes the f_{3dB}/f_R -ratio and the bandwidth with that at maximum relaxation resonance frequencies.

Assuming a reasonable spectral efficiency of $M = 2$ bit/Hz [24] bitrates larger than 50 Gbit/s, are feasible. Exceeding 50 Gbit/s presently a drop of M occurs in our experiments due to limitation of our equipment.

The maximum possible data rates which can be achieved depend equally on the properties of the passive fiber and the receiver. Receivers that are more sensitive than the presently commercially available ones enable larger distances and/or lower energy consumption per bit. Larger receiver cut-off frequencies would enable additionally larger data rates. Despite these limitations, we observed error-free data transmission rates of 52 Gbit/s for NRZ measurements for all the lasers shown in Fig. 4. By tuning the photon lifetime, the energy consumption at 50 Gbit/s has been decreased by 25% [6]. We assume, that all these values do not present the true limits of our devices. A significant drop of spectral efficiency at bit rates larger than 50 Gbit indicates the limit of our present measurement setup.

Presently the IEEE 802.3 standard asks for lasers emitting at the four wavelengths of 850 nm, 880 nm, 910 nm, and 940 nm, enabling a quadrupling of the data rate across the same optical fiber by using lasers with similar properties. Fig. 5 shows the bandwidth and the side mode suppression ratio versus bias current typical for all of our ~3 µm aperture diameter VCSELs. [25] Showing a bandwidth close to 30 GHz and side-mode suppression ratios of 35 dB from close to threshold till thermal rollover these lasers have the potential for further increasing the transmission distance beyond 100 m, and/or the bitrate beyond 50 Gbit/s.

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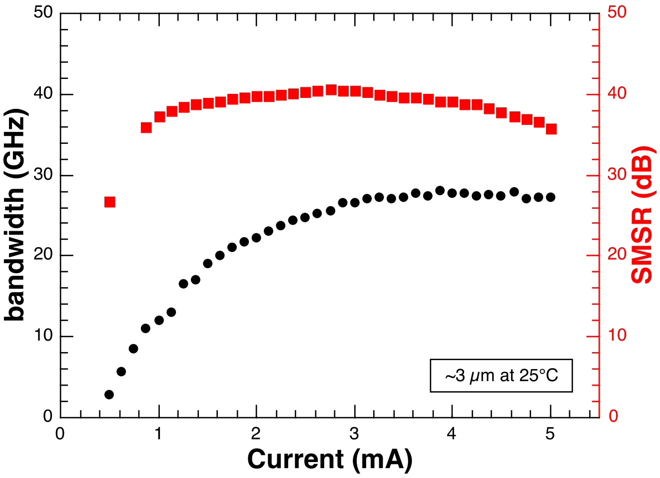

Fig. 5: Small signal bandwidth and side-mode suppression ratio of a typical ~3 µm VCSEL being is the same for all wavelengths.

B. Small signal measurements

We measured the scattering parameters with a Hewlett-Packard 8722C vector network analyzer with a constant modulation amplitude of -25 dBm and a New Focus 1434-50 photoreceiver with a bandwidth of 26.1 GHz. Considering the response of the receiver we fitted the S21 data to the standard laser diode transfer function (4) to extract the relaxation resonance frequency f_R, the -3 dB bandwidth (BW) f_{3dB}, the damping γ, and the parasitic frequency f_p.

C. Data transmission experiments

The purpose of data transmission experiments is to demonstrate the performance of a device under test in a data link like environment.

The signal, a pseudorandom binary sequence with a word length of 2^7−1, was generated by a SHF 12100B bit pattern generator (BPG). The electrical signal provided by that bit pattern generator was evaluated by a SHF 11100B error analyzer showing that an error free signal can be generated up to 52 Gbit/s.

The BPG was followed by a +8 dB amplifier (SHF 801 P) driving the VCSEL through a bias-tee. The VCSELs are mounted on a temperature-controlled probe station. The VCSEL emission is butt-coupled to the cleaved end of a 2 m-long novel OM5 multimode fiber (MMF), to ensure $M(f,P)$ is independent of the emission wavelength.

To characterize the single mode VCSELs at 850 nm, 880 nm, 910 nm and 940 nm without changing the receiver we used a 33 GHz optical probe (Tektronix DPO7OE1) with large sensitivity and low noise in a wide band from 750 nm to 1650 nm. The optical probe perfectly matches the Tektronix 70 GHz real time oscilloscope (DPS77004SX). To compensate the disadvantage of the linear amplifier in the optical probe by receiving non-return to zero (NRZ) bit patterns we have used software filtering provided by the oscilloscope.

Fig. 6 shows the result of a non-return to zero data transmission experiment across the 2 m OM5 MMF which has been used at all wavelengths. Fig. 6 has been taken with the Tektronix 70 GHz real time oscilloscope and the 33 GHz optical probe. Since the lasers at all wavelengths show very similar bandwidths and output power, the data transmission results are the same. The eye diagram and bit error ratio BER of an 850 nm laser shown here is representative for all such lasers. By multiplexing the wavelengths, a transmission rate exceeding 200 Gbit/s can be achieved on a single multimode fiber.

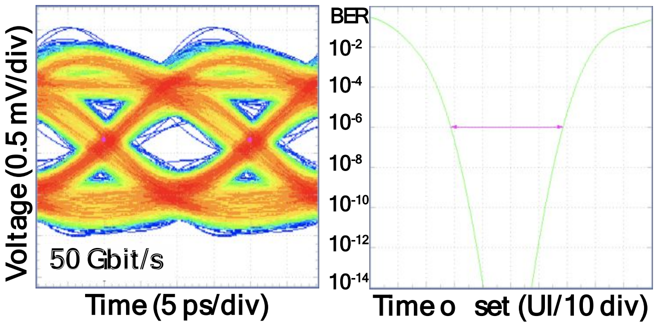

Fig. 6: The eye diagram (left) and bit error ratio (right) bath tub curve for a back-to-back data rate of 50 Gbit/s for an ~3 µm oxide aperture diameter VCSEL emitting at 850 nm, which is representative of all our devices.

Fig. 7 shows the measured bit error for all four wavelengths. For this experiment we used a wide band Thorlabs photodetector (DXM30BF), that covers the emission wavelengths of all of our lasers, combined with an +8 dB linear amplifier (SHF 801 P). The slight disadvantage of this configuration is larger noise due to the wide sensitivity band of the detector.

We have additionally compared bit error measurements for the present standard bit rate of 25Gbit/s in a back-to-back configuration and across 100 m of a novel OM5 multimode fiber from Corning Incorporated. The power penalty for the longer distance is observed to be nearly wavelength independent.

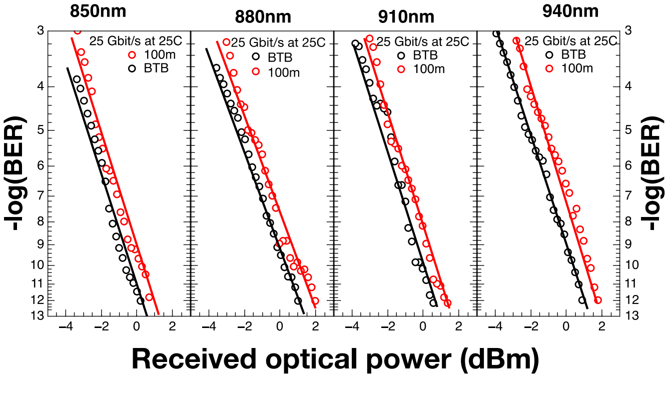

Fig. 7: Bit error measurement at 25 Gbit/s back-to-back (black) and across 100 m of OM5 multimode fiber by using lasers with the emission wavelength 850 nm, 880 nm, 910 nm, and 940 nm.

V. CONCLUSION

VCSELs for 200+ Gbit/s data transmission via multiplexing 850 nm, 880 nm, 910 nm, 940 nm emitting VCSELs are presented. The large linearity of the L-I-characteristics will easily allow still larger data rates via, for example PAM 4. The HBR is as low as 240 fJ/bit. Due to the large optical power for single mode emission our VCSELs are well suited for long distance OM5 optical fiber transmission, up to 100 m or beyond.

VI. REFERENCES

[1] T. N. Huynh, F. Doany, D. M. Kuchta, D. Gazula, E. Shaw, J. O'Daniel, J. Tatum, and Ieee, “4x50Gb/s NRZ Shortwave-Wavelength Division Multiplexing VCSEL link over 50m Multimode Fiber,” *2017 Optical Fiber Communications Conference and Exhibition (Ofc)*, pp. 3, 2017.

[2] D. A. B. Miller, “Device Requirements for Optical Interconnects to Silicon Chips,” *Proceedings of the IEEE,* vol. 97, no. 7, pp. 1166–1185, 2009.

[3] P. Wolf, P. Moser, G. Larisch, W. Hofmann, and D. H. Bimberg, “High-Speed and Temperature-Stable oxide-confined 980-nm VCSELs for Optical Interconnects,” *IEEE Journal of Selected Topics in Quantum Electronics,* vol. 19, no. 4, pp. 1–7, 2013.

[4] G. Larisch, J. A. Lott, and D. Bimberg, *VERTICAL-CAVITY SURFACE-EMITTING LASER*, U.S. 9,9791,58, 2018.

[5] G. Larisch, J. A. Lott, and D. Bimberg, *VERTICAL-CAVITY SURFACE-EMITTING LASER*, EP 19 174 870.6.

[6] G. Larisch, P. Moser, J. A. Lott, and D. Bimberg, “Large Bandwidth, Small Current Density, and Temperature Stable 980-nm VCSELs,” *IEEE Journal of Quantum Electronics,* vol. 53, no. 6, pp. 1-8, 2017.

[7] J. M. Dallesasse, N. Holonyak, A. R. Sugg, T. A. Richard, and N. El-Zein, “Hydrolyzation oxidation of AlxGa1−xAs-AlAs-GaAs quantum well heterostructures and superlattices,” *Applied Physics Letters,* vol. 57, no. 26, pp. 2844-2846, 1990.

[8] D. Kuchta, A. Rylyakov, C. Schow, J. Proesel, F. Doany, C. W. Baks, B. Hamel-Bissell, C. Kocot, L. Graham, R. Johnson, G. Landry, E. Shaw, A. MacInnes, and J. Tatum, "A 56.1Gb/s NRZ Modulated 850nm VCSEL-Based Optical Link," *Optical Fiber Communication Conference*, p. OW1B.5.

[9] C. L. Schow, A. V. Rylyakov, C. W. Baks, F. E. Doany, and J. A. Kash, “25-Gb/s 6.5-pJ/bit 90-nm CMOS-Driven Multimode Optical Link,” *IEEE Photonics Technology Letters,* vol. 24, no. 10, pp. 824–826, 2012.

[10] J. E. Proesel, B. G. Lee, C. W. Baks, and C. L. Schow, "35-Gb/s VCSEL-Based optical link using 32-nm SOI CMOS circuits," *Optical Fiber Communication Conference (OFC/NFOEC), 2013*, pp. 1–3, {Los Angeles, CA, USA}, 2013.

[11] D. Schoeniger, R. Henker, and F. Ellinger, "An 850-nm common-cathode VCSEL driver with tunable energy efficiency for 45 Gbit/s data transmission without equalization." pp. 1103-1106.

[12] L. Szilágyi, G. Belfiore, R. Henker, and F. Ellinger, "A high-voltage DC bias architecture implementation in a 17 Gbps low-power common-cathode VCSEL driver in 80 nm CMOS." pp. 2385-2388.

[13] T. Shibasaki, W. Chaivipas, C. Yanfei, Y. Doi, T. Hamada, H. Takauchi, T. Mori, Y. Koyanagi, and H. Tamura, "A 56-Gb/s receiver front-end with a CTLE and 1-tap DFE in 20-nm CMOS." pp. 1-2.

[14] V. Shchukin, N. N. Ledentsov, J. Kropp, G. Steinle, N. Ledentsov, S. Burger, and F. Schmidt, “Single-Mode Vertical Cavity Surface Emitting Laser via Oxide-Aperture-Engineering of Leakage of High-Order Transverse Modes,” *IEEE Journal of Quantum Electronics,* vol. 50, no. 12, pp. 990-995, 2014.

[15] M. P. Tan, S. T. M. Fryslie, J. A. Lott, N. N. Ledentsov, D. H. Bimberg, and K. D. Choquette, “Error-Free Transmission Over 1-km OM4 Multimode Fiber at 25 Gb/s Using a Single Mode Photonic Crystal Vertical-Cavity Surface-Emitting Laser,” *IEEE Photonics Technology Letters,* vol. 25, no. 18, pp. 1823–1825, 2013.

[16] P. Moser, W. Hofmann, P. Wolf, J. A. Lott, G. Larisch, A. S. Payusov, N. N. Ledentsov, and D. H. Bimberg, “81 fJ/bit energy-to-data ratio of 850 nm vertical-cavity surface-emitting lasers for optical interconnects,” *Applied Physics Letters,* vol. 98, no. 23, pp. 231106-1–3, 2011.

[17] L. A. Coldren, and S. W. Corzine, *Diode lasers and photonic integrated circuits*, New York, NY, USA: Wiley, 1995.

[18] C. E. Shannon, “Communication in the Presence of Noise,” *Proceedings of the IRE,* vol. 37, no. 1, pp. 10-21, 1949.

[19] H. Li, P. Wolf, P. Moser, G. Larisch, J. A. Lott, and D. H. Bimberg, “Temperature-Stable, Energy-Efficient, and High-Bit Rate Oxide-Confined 980 nm VCSELs for Optical Interconnects,” *IEEE Journal of Selected Topics in Quantum Electronics,* vol. 21, no. 6, pp. 1700409, 2015.

[20] P. Westbergh, J. S. Gustavsson, B. Kogel, A. Haglund, and A. Larsson, “Impact of Photon Lifetime on High-Speed VCSEL Performance,” *Ieee Journal of Selected Topics in Quantum Electronics,* vol. 17, no. 6, pp. 1603-1613, Nov-Dec, 2011.

[21] D. Ellafi, V. Iakovlev, A. Sirbu, G. Suruceanu, Z. Mickovoc, A. Caliman, A. Mereuta, and E. Kapon, "Impact of Selective DBR Surface Etching on the Performance of 1300 and 1500-nm Wafer-Fused VCSELs," *2014 International Semiconductor Laser Conference (ISLC)*, pp. 211–212, 2014.

[22] P. O. Leisher, J. J. Raftery, A. M. Kasten, and K. D. Choquette, “Etch damage and deposition repair of vertical-cavity surface-emitting lasers,” *Journal of Vacuum Science & Technology B: Microelectronics and Nanometer Structures Processing, Measurement, and Phenomena,* vol. 24, no. 1, pp. 104-107, 2006/01/01, 2006.

[23] B. Kesler, T. O'Brien, G.-L. Su, and J. M. Dallesasse, “Facilitating Single-Transverse-Mode Lasing in VCSELs via Patterned Dielectric Anti-Phase Filters,” *IEEE Photonics Technology Letters,* vol. 28, no. 14, pp. 1497–1500, 2016.

[24] P. Moser, J. A. Lott, G. Larisch, and D. H. Bimberg, “Impact of the Oxide-Aperture Diameter on the Energy-Efficiency, Bandwidth, and Temperature Stability of 980 nm VCSELs,” *Journal of Lightwave Technology,* vol. 33, no. 4, pp. 825–831, 2015.

[25] N. N. Ledentsov, J. A. Lott, J.-R. Kropp, V. A. Shchukin, D. H. Bimberg, P. Moser, G. Fiol, A. S. Payusov, D. Molin, G. Kuyt, A. Amezcua, L. Y. Karachinsky, S. A. Blokhin, I. I. Novikov, N. A. Maleev, C. Caspar, and R. Freund, "Progress on single mode VCSELs for data- and tele-communications," *Proc. of SPIE 8276, Vertical-Cavity Surface-Emitting Lasers XVI*, 2012.

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Ricardo Rosales received the Ph.D. degree in 2012 from the University of Pierre et Marie Curie, Paris, France, for his work on quantum-dash mode-locked lasers for optical communications which he conducted at the Laboratory for Photonics and Nanostructures of the French National Research Center (CNRS). From 2013 to 2015, he was a Marie Curie Postdoctoral Fellow at the Institute of Solid State Physics of the Technical University of Berlin (TUB), Germany, where he was involved

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in the development and fabrication of broadband quantum-dot semiconductor optical amplifiers for low coherence light applications. From 2015 to 2018 he continued at the TUB, where he worked on novel concepts for high power semiconductor lasers and high-bandwidth vertical-cavity surface-emitting lasers for Datacom applications. He is currently a research scientist at Huawei Technologies where he works on innovative components for optical communications.

Dieter Bimberg (LF'16) received the Ph.D. degree from Goethe University, Frankfurt, Germany, in 1971. He held a Principal Scientist position at the Max Planck-Institute for Solid State Research, Grenoble, France until 1979. After serving as a Professor of Electrical Engineering, Technical University of Aachen, Germany, he assumed the Chair of Applied Solid-State Physics at Technical University of Berlin. He is the Founding Director of its Center of Nanophotonics. He held guest professorships at the Technion in Haifa, University of California at Santa Barbara, CA, USA, and at Hewlett-Packard in Palo Alto, CA. He was Distinguished Adjunct Professor at KAU, Jeddah from 2012-18 and Einstein Professor at the Chinese Academy of Sciences in 2017/8. Since 2018 he is the Director of the "Bimberg Chinese-German Center for Green Photonics" of the CAS at CIOMP, Changchun. He is a Member of the Russian Academy of Sciences and the German Academy of Sciences Leopoldina, a Foreign Member of the National Academy of Engineering of USA, and a Fellow of the US National Institute of Inventors. The American Physical Society and IEEE elected him as fellow/life fellow, respectively. Numerous international awards like the UNESCO award and medal for Nanoscience and –technology or the Russian State Prize for Science and Technology were bestowed to him. He has authored more than 1500 papers, 60 patents, and six books. The number of times his research works have been cited exceeds 58 000 and his Hirsch factor is 107. His research interests include physics and technology of nanostructures, nanostructured photonic and electronic devices and energy efficient data communication.