Temperature stable oxide-confined 850 nm VCSELs operating at bit rates up to 25 Gbit/s at 150°C

N. Ledentsov Jr. [*a], M. Agustin [a], J.–R. Kropp[a], V.A. Shchukin[a], V. P. Kalosha[a], K. L. Chi[b], Z. Khan[b], J. W. Shi[b], N. N. Ledentsov[a]

[a] VI Systems GmbH, Hardenbergstr. 7, Berlin 10623, Germany
[b] Department of Electrical Engineering, National Central University, Taoyuan 320, Taiwan

ABSTRACT

New applications in industrial, automotive and datacom applications require vertical-cavity surface-emitting lasers (VCSELs) operating at very high ambient temperatures at ultrahigh speed. We discuss issues related to high temperature performance of the VCSELs including temperature response and spectral properties. The influence of the gain-to-cavity wavelength detuning on temperature performance and spectral width of the VCSELs is discussed.

Performance of the oxide-confined 850 nm VCSELs with increased temperature stability capable of operating at bit rates up to 25 Gbit/s at ambient temperatures of 150°C is demonstrated and analyzed. Higher data rates are achieved at lower temperatures: 35 Gbit/s at 130°C, 40 Gbit/s at 105°C and 50 Gbit/s at room temperature.

Previous studies of VCSELs with large gain-to-cavity detunings demonstrated strongly increased spectral width and a strong redistribution of the mode intensities upon current increase. Contrary to previous observations, VCSELs demonstrated in this work show good reproducibility of a narrow spectrum in a wide range of currents and temperatures. This property strongly improves the transmission distance over multi-mode fiber and can reduce mode partition noise during high speed operation.

Keywords: vertical cavity surface–emitting laser, fiber, data transmission; high temperature

1. INTRODUCTION

New applications of 850nm vertical cavity surface-emitting lasers (VCSELs) require high speed operation at high ambient temperatures, in particular in high performance computing, on-board and on-chip, industrial and automotive applications. For example, automotive applications require reliable high speed operation at ambient temperatures of up to 105°C and higher. [1] Optical fiber or optical waveguide-based communication links for on board assemblies are also expected to reliably operate at close and above 100°C. [2]

During high speed operation of VCSELs at elevated temperatures current density has to be increased to compensate the leakage of non-equilibrium carriers from the gain region. [3],[4] Such current increase can decrease the lifetime of the devices and is thus undesirable. Furthermore significant temperature increase typically results in an increase in the threshold current of the device, further increasing the current densities necessary to achieve high speed operation. To solve these problems, VCSELs should be developed to operate at high speed and at high temperatures at lowest possible current densities. [5] In this view, development of single-mode devices [6] can form a satisfying solution, as it allows to reduce the influence of chromatic dispersion on data transmission as well as realize high-density small pitch parallel optical links, for example, for high density fiber ribbons or multicore fibers. [7]

So far, the highest temperature reported for high speed (20 Gbit/s NRZ) VCSEL operation was 150°C. [8] The device emitted however at 980 nm, the wavelength at which the realization of high temperature stability is easier to achieve due to much higher confinement energy for non-equilibrium carriers in the gain region. Presently 850 nm VCSELs with ~5 µm apertures were reported to be able to operate at 50 Gbit/s in NRZ at 85°C [9]. To achieve such performance the device was designed with gain peak-to-cavity detuning of 10 nm. [10]

[*] Corresponding author: Nikolay Ledentsov Jr., Tel.: +49 30 308314347; E–mail: nikolay.ledentsov-jr@v-i-systems.com

In detailed studies it was concluded that 850 nm high-speed oxide-confined VCSELs with different gain-to-cavity wavelength detuning demonstrate complex interconnection between temperature and spectral properties.

It was underlined that at larger (≥ 20 nm) negative detuning, the devices with oxide-aperture size ~6 μm, or larger, show an anomalous lasing via higher order modes, separated from the fundamental mode by as much as 15 nm, with a subsequent switching to lasing of the lowest order modes at higher currents. [11] These effects lead to significant spectral broadening in devices with large detuning limiting the transmission distance through MMF and increasing the mode partition noise. Spectral broadening can also influence the modulation response through mode competition and cause irregularities in the far-field profile of the device. Another problem for large detuning can be insufficient modal gain and degradation of high speed response at room temperature.

In this paper, VCSELs are demonstrated capable of operating at high speed at high temperatures, low currents and with outstanding stability of the emission spectrum and beam profile.

2. DEVICES UNDER TEST

In this paper we investigate thin aperture anti–waveguiding AlAs–rich core VCSELs (A-VCSEL) discussed previously in Ref. 12 and Ref. 13. In our case the devices had a large ~ 15 nm gain-to-cavity wavelength detuning. We specifically look at the performance of two chips with different oxide aperture diameter. To visualize the lasing mechanisms of these VCSEL we address first the near-field (NF) patterns measured at different currents. Such an approach allows careful evaluation of the mode evolution in the device, as presented in Figure 1.

It was reported that VCSELs with standard oxide apertures having a λ/4 width after the oxidation show multimode lasing at low current densities, particularly, in pulsed operation [14] where the mode separation can reach up to 20 nm. Such strong mode hopping created mode partition noise, can affect chromatic dispersion-related pulse propagation through the MMF in digital data transmission, affect coupling to the waveguides and create back-reflections.

We benchmark the measurements to a basic multi-mode (MM) VCSEL with 7 nm detuning which shows a donut-shaped near field profile even at low currents associated with the lasing of high order modes, discussed above. (Figure 1.c.)

Contrary to the basic VCSEL, investigated A-VCSELs show a very different evolution of in the near-field profile with increasing current.

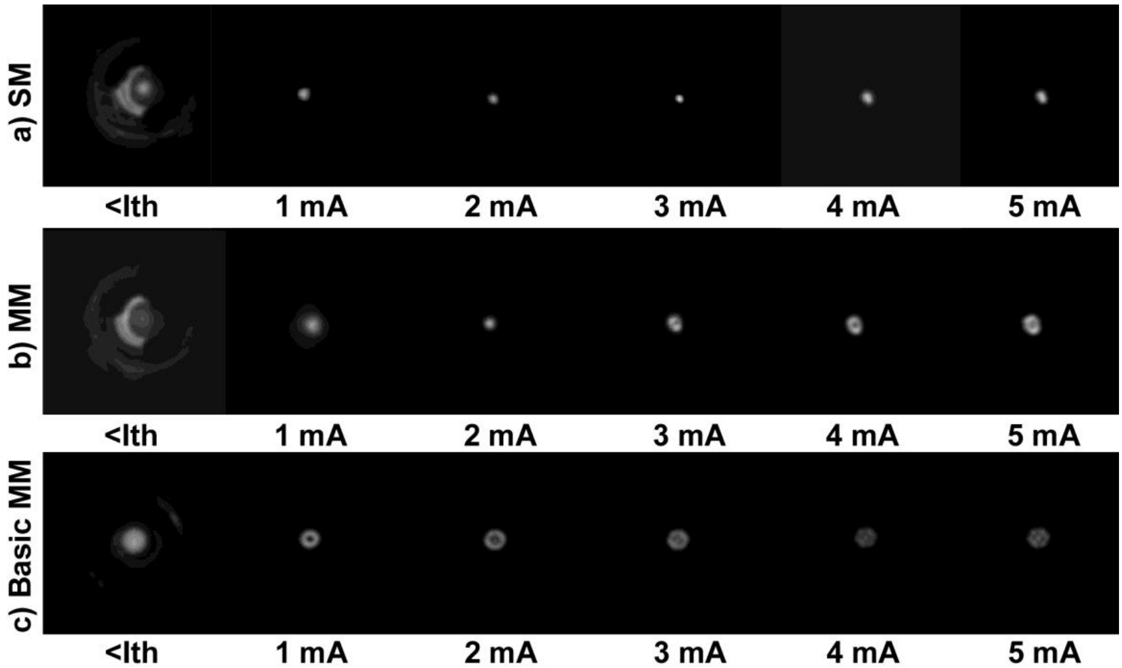

Figure 1. Near-field profile of a) single-mode chip, b) multi-mode chip and c) basic multi-mode chip at various currents.

At currents up to 2 mA, the fundamental mode (HE11) dominates in NF profiles of both VCSELs. (Figure 1.a-b) Above 2 mA one can see the evolution of the high order modes through a donut-shaped profile in case of the MM VCSEL while single-mode (SM) VCSEL profile continues to be dominated by the fundamental mode up to the highest currents exceeding the roll-over current (Figure 1.a) The near field profiles are in agreement with spectral studies displayed below (Figure 2) providing a big advantage of the present design over standard MM VCSELs.

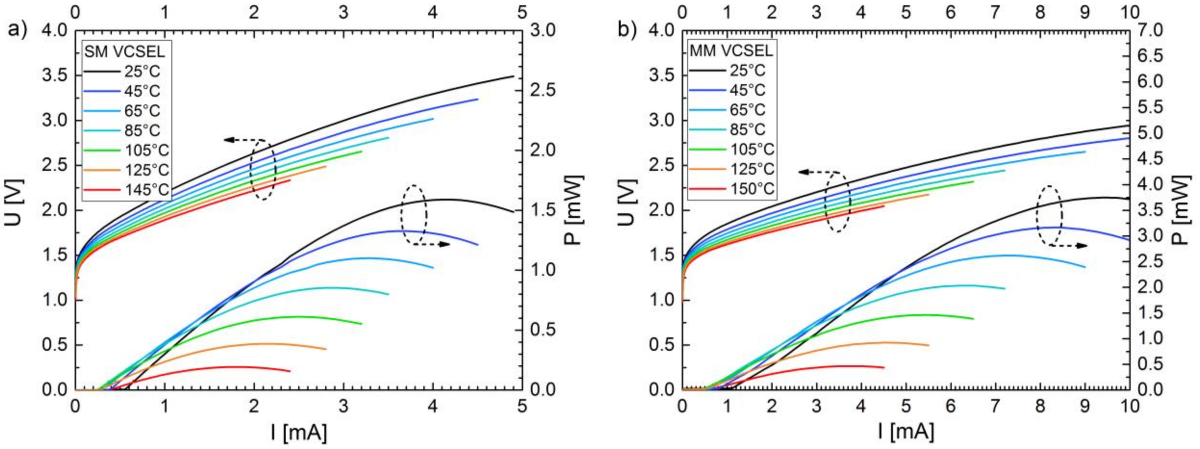

Figure 2. Light-Current-Voltage characteristics of a chip with a) larger aperture and multi-mode spectra (MM) and b) smaller aperture and quasi-single-mode spectra (SM) at different temperatures

Further we compare Light-Current-Voltage response of the chips (Fig. 2). As can be expected, the chip with a smaller oxide aperture, has a lower maximum optical power of 1.6 mW, higher differential electrical resistance of ~200 Ω and exhibits a single-mode operation. (Figure 2-3.a) The chip with a larger aperture emits power up to 3.7 mW at room temperature, has lower ~80 Ω differential resistance, and a multi-mode spectra. (Figure 2-3.b)

Figure 3 displays spectra of SM (a) and MM A-VCSELs (b) at different temperatures.

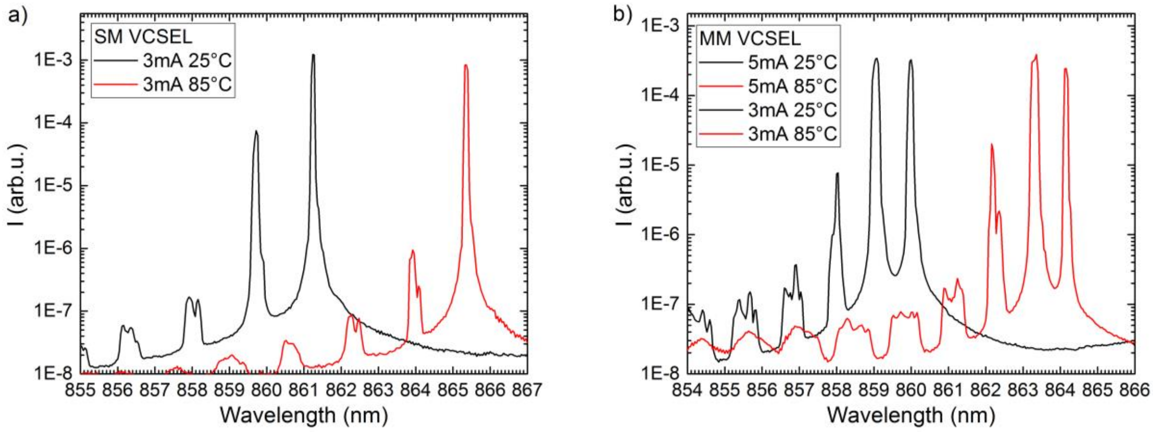

Figure 3. Spectral characteristics of (a) SM VCSEL at (b) MM VCSEL chip at 3 mA at 25℃ and 85℃.

As can be seen from the spectral measurements performed on the chips at low currents, the devices operate as single-mode (Fig 1 a, b), and at higher currents at larger diameters of the oxide aperture become multimode (Fig. 1(b), Fig. 3.b) become multi-mode. The chip with a small oxide aperture has a quasi-single-mode spectrum and the fundamental mode is dominating during at room temperature and high temperatures. The chip with larger aperture becomes multimode at higher currents, but keeps low values of the root mean square (RMS) spectral width below 1 nm within all the regimes of operation.

As observed in the near-field profiles, no significant change in emission properties of the devices takes place with current increase. We observe even an increase of the side- mode suppression ratio (SMSR) with increasing temperature on the spectra of the SM device. (Figure 3.a) As discussed above, reduced spectral width is extremely important in increasing the distance of the data transmission through MMF due to reduced influence of chromatic dispersion. [15]

In Fig. 4 we show the dependence of the threshold current (a) and the maximum optical power (b) on the temperature of the heat chuck on which the investigated VCSELs were placed during the measurements. The VCSEL were not soldered and the actual temperature of the device was higher due to limited thermal conductivity. The threshold current has a minimum in the temperature range between 85℃ and 105℃. (Figure 4.a) This trend of the threshold current dependence on the temperature is consistent with the detuning of 15 nm. The maximum optical power decreases linearly with temperature (Figure 4.b).

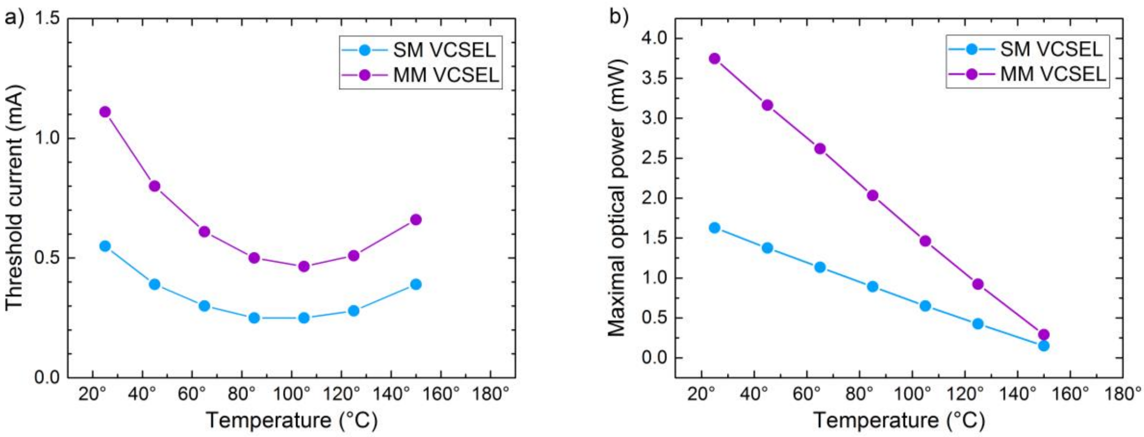

Figure 4. (a) Threshold current and (b) maximum optical power at different temperatures for the MM and SM chips.

2. HIGH FREQUENCY PERFORMANCE

Data transmission experiments were performed on the chip level with a VCSEL probe station with a heating chuck. The experimental set up is presented in Figure 5.

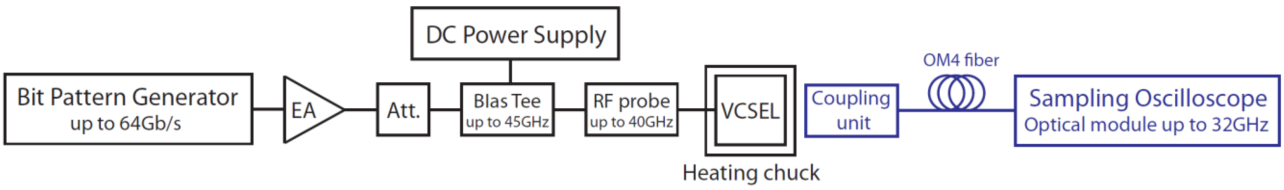

Figure 5. Experimental setup for high frequency optical transmission tests.

The electrical 50 Gbit/s Pseudo-Random non-return to zero Binary Sequence (PRBS) is generated by an SHF 12104A Bit Pattern Generator (BPG). DC current is provided to the VCSEL and combined with AC signal by a bias tee with a 45 GHz -3dB bandwidth. The emitted light signal is coupled into an OM4 fiber. The received optical signal is analyzed using a Tektronix sampling oscilloscope DSA 8300 with optical module having a -3dB bandwidth of 32 GHz. No digital signal processing or pre-emphasis were applied in the study.

The single-mode and multi-mode chips demonstrated similar high frequency performance. At room temperatures high speed operation is achieved from 25 Gbit/s up to 50 Gbit/s. (Figure 6.)

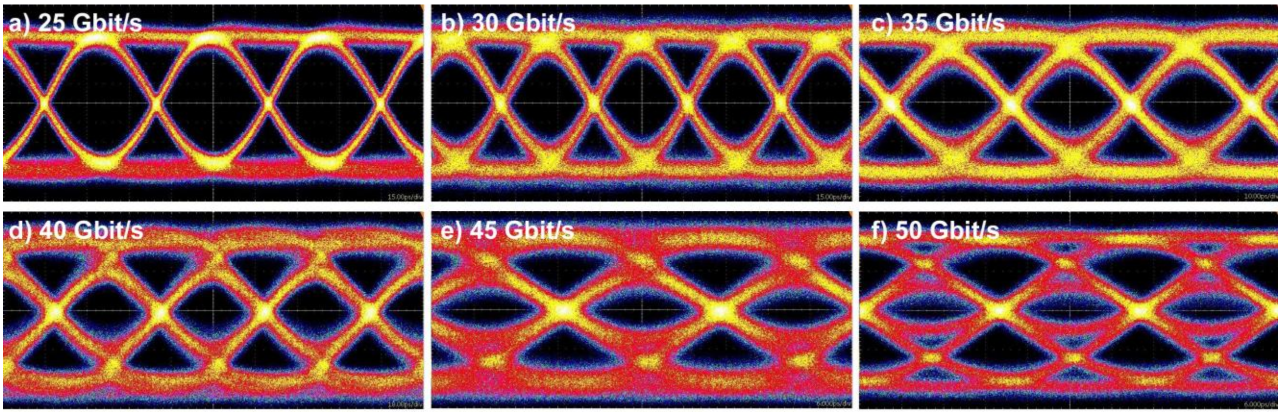

Figure 6. 25℃ optical eye diagrams of SM VCSEL at data bit rates a) 25 Gbit/s and b) 30 Gbit/s (15 ps/div), c) 35 Gbit/s and d) 40 Gbit/s (10 ps/div), e) 45 Gbit/s and f) 50 Gbit/s (6 ps/div)

High temperature performance at 25 Gbit/s was analyzed for various temperatures in a range from 25℃ to 150℃ and demonstrates open eye diagrams for NRZ back-to-back data transmission.

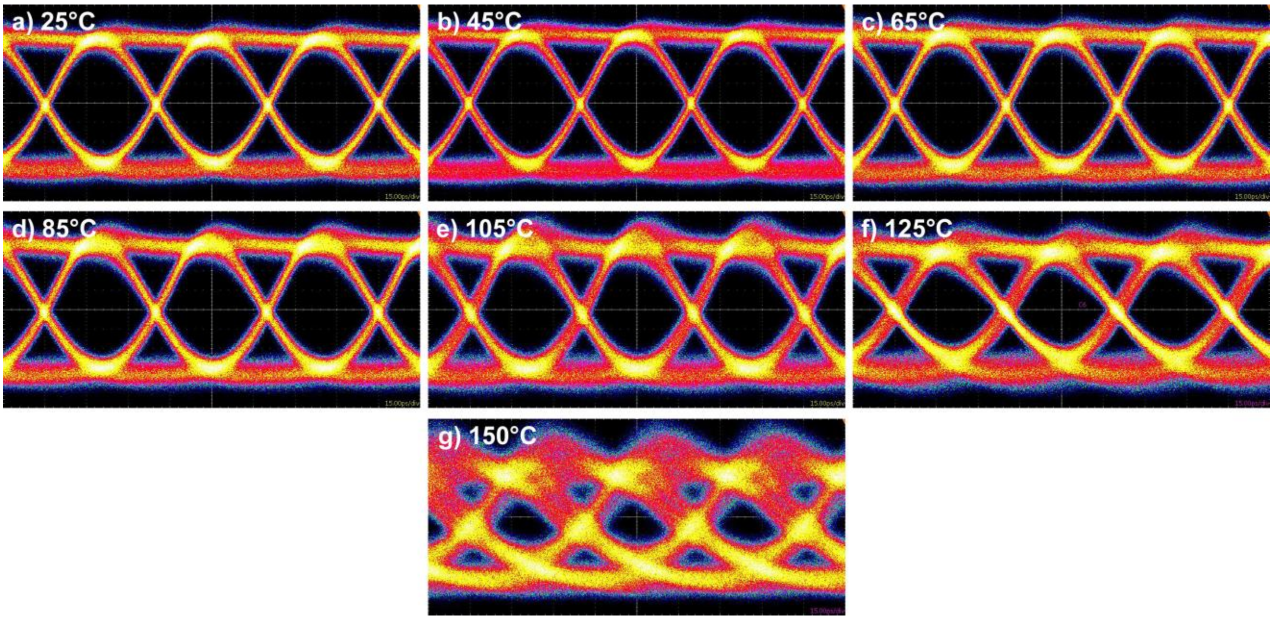

Figure 7. Optical 25 Gbit/s NRZ transmission at temperatures ranging from 25℃ to 150℃. (15 ps/div)

At lower heat sink temperatures the devices could operate at higher bit data rates. In Fig.8 we show 35 Gbit/s NRZ eye diagram recorded at 130ºC.

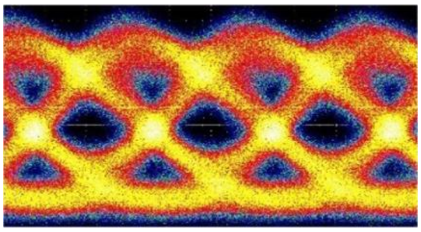

Figure 8. 35 Gbit/s optical eye of SM VCSEL eye at 130℃ heat sink temperature (NRZ, PRBS9)

7. CONCLUSIONS

We studied VCSELs in an antiguiding cavity design with large gain-to-cavity detuning of ~15nm. Opposite to previous research narrow emission spectra are demonstrated in a large range of temperatures and operation currents. The devices operate up to 25 Gbit/s at heat sink temperatures of 150°C and 35 Gbit/s at 130°C.

7. ACKNOWLEDGMENTS

The work is supported by the European Regional Development Fund through Project OVERSCAN.

REFERENCES

[1] IEEE 802.3 Multi-Gigabit Automotive Ethernet Study Group http://www.ieee802.org/3/NGAUTO/public/adhoc/index.html (at 01.01.2018)

[2] Tabbert, C., and Charles K., "Chip scale package fiber optic transceiver integration for harsh environments," International Conference on Space Optics—ICSO 2014, vol. 10563, p. 1056335, 2017.

[3] Hawkins, B. M., Hawthorne R. A., Guenter J. K., Tatum J. A., Biard J. R., "Reliability of various size oxide aperture VCSELs," IEEE Electronic Components and Technology Conference, 2002. vol. 52, p. 540-550, 2002.

[4] Kropp, J.-R., Steinle, G., Schäfer, G., Shchukin, V. A., Ledentsov, N. N., Turkiewicz, J. P., Zoldak, M., "Accelerated aging of 28 Gb s− 1 850 nm vertical-cavity surface-emitting laser with multiple thick oxide apertures," Semiconductor Science and Technology, vol. 30, no. 4, p. 045001, 2015.

[5] Wu, B., Zhou, X., Ma, Y., Luo, J., Zhong, K., Qiu, S., Feng, Z., Luo, Y., Agustin, M., Ledentsov, N., Kropp, J., "Close to 100 Gbps discrete multitone transmission over 100m of multimode fiber using a single transverse mode 850nm VCSEL," Proc. SPIE Vertical-Cavity Surface-Emitting Lasers XX, vol. 9766, p. 97660K, 2016.

[6] Mutig, A., Fiol, G., Moser, P., Arsenijevic, D., Shchukin, V.A., Ledentsov, N.N., Mikhrin, S.S., Krestnikov, I.L., Livshits, D.A., Kovsh, A.R. and Hopfer, F., "120°C 20 Gbit/s operation of 980 nm VCSEL," Electronics Letters, Vol. 44, Issue 22, p. 1305-1306, 2008.

[7] Iwase, M., Shiino, M., Yagi, T., Tanaka, M., Takakahashi, K., Nekado, Y., Nasu, H., Morimoto, M., Aoyagi, H., Suematsu, K. and Miyazaki, H., "Optical components for high-density optical inter-connect system: OptoUnity," Furukawa Review, vol. 32, p.26-33, 2007.

[8] Ledentsov, N. N., Lott, J. A., Shchukin, V. A., Quast, H., Hopfer, F., Fiol, G., Mutig, A., Moser, P., Germann, T., Strittmatter, A., Karachinsky, L. Y., Blokhin, S. A., Novikov, I. I., Nadtochi, A. M., Zakharov, N. D., Werner, P., Bimberg, D., "Quantum dot insertions in VCSELs from 840 to 1300 nm: growth, characterization, and device performance," Proc. SPIE Physics and Simulation of Optoelectronic Devices XVI, vol. 7224, p.7224-23, 2009.

[9] Liu, M., Wang, C.Y., Feng, M. and Holonyak, N., "850 nm Oxide-Confined VCSELs with 50 Gbit/s Error-Free Transmission Operating up to 85 °C," Conference on Lasers and Electro-Optics, p. 1-2, 2016.

[10] Wang, C. Y., Liu, M., Feng, M., Holonyak, N., "Temperature dependent analysis of 50 Gbit/s oxide-confined VCSELs," 2017 Optical Fiber Communications Conference and Exhibition (OFC), p. 1-3, 2017.

[11] Blokhin, S.A., Bobrov, M.A., Maleev, N.A., Kuzmenkov, A.G., Sakharov, A.V., Blokhin, A.A., Moser, P., Lott, J.A., Bimberg, D., Ustinov, V.M., "Impact of a large negative gain-to-cavity wavelength detuning on the performance of InGaAlAs oxide-confined vertical-cavity surface-emitting lasers," Proc. SPIE Vertical-Cavity Surface-Emitting Lasers XIX, vol. 9381, p. 93810W, 2015.

[12] Ledentsov, N. N., Shchukin, V. A., Kalosha, V. P., Kropp, J-R., Agustin, M., Stępniak, G., Turkiewicz, J. P., Shi, J-W., "Anti–waveguiding vertical–cavity surface–emitting laser at 850 nm: From concept to advances in high–speed data transmission," Optics express, vol. 26, no. 1, p. 445-453, 2018.

[13] Ledentsov, N. N., Shchukin, V. A., Kalosha, Ledentsov, N., V. P., Kropp, J-R., Agustin, M., Turkiewicz, J. P., "Progress in design and development of anti-guiding vertical cavity surface emitting laser at 850 nm: Above 50 Gbit/s and single mode," IEEE 19th International Conference on Transparent Optical Networks (ICTON), Girona, 2017, pp. 1-9, 2017.
[14] Blokhin, S.A., Maleev, N.A., Kuzmenkov, A.G., Lott, J.A., Kulagina, M.M., Zadiranov, Y.M., Gladyshev, A.G., Nadtochiy, A.M., Nikitina, E.V., Tikhomirov, V.G., Ledentsov, N.N., "Multi-mode to single-mode switching caused by self-heating in bottom-emitting intra-cavity contacted 960 nm VCSELs," Proc. SPIE Vertical-Cavity Surface-Emitting Lasers XVI, vol. 8276, p. 82760W, 2012.
[15] Turkiewicz, J. P., Shchukin, V. A., Kalosha, V. M., Kropp, J-R., Augustin, M., Ledentsov, N., Ledentsov, N. N., "High speed transmission with 850 nm SM and MM VCSELs," IEEE 19th International Conference on Transparent Optical Networks (ICTON), Girona, 2017, pp. 1-9, 2017.