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A. Mutig, J. A. Lott, S. A. Blokhin, et al.

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Highly temperature-stable modulation characteristics of multioxide-aperture high-speed 980 nm vertical cavity surface emitting lasers

A. Mutig,[1,a)] J. A. Lott,[2] S. A. Blokhin,[1,b)] P. Wolf,[1] P. Moser,[1] W. Hofmann,[1] A. M. Nadtochiy,[1,b)] A. Payusov,[1,b)] and D. Bimberg[1]
[1]*Institut für Festkörperphysik und Zentrum für Nanophotonik, Technische Universität Berlin, Hardenbergstrasse 36, 10623 Berlin, Germany*
[2]*VI Systems GmbH, Hardenbergstrasse 7, 10623 Berlin, Germany*

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We present multioxide-aperture 980 nm-range vertical cavity surface emitting lasers (VCSELs) with highly temperature stable modulation characteristics operating error-free at 25 Gbit/s at 25 and 85 °C. We perform small signal modulation experiments and extract the fundamental physical parameters including relaxation resonance frequency, damping factor, parasitic cut-off frequency, *D*-factor, and *K*-factor, leading to identification of thermal processes and damping as the main factors that presently limit high speed device operation. We obtain very temperature-insensitive bandwidths around 13–15 GHz. Presented results clearly demonstrate the suitability of our VCSELs for practical and reliable optical data transmission systems. © *2010 American Institute of Physics*. [doi:10.1063/1.3499361]

Human society's constantly increasing demand for more information, the on-going scaling of silicon-based integrated circuits to ever smaller dimensions, and the intrinsic limitations of copper-based electrical data links have led to our current need for lower cost, power efficient, readily manufacturable, reliable photonic devices. The unstoppable and progressive penetration of optical communication links into traditional copper interconnect markets greatly expands the applications of vertical cavity surface emitting lasers (VCSELs) for next-generations of board-to-board, module-to-module, and chip-to-chip interconnects.[1,2] The continued down-sizing of integrated photonics systems and quest for broader bandwidths leads naturally to interest in very short-reach (VSR) data transmission systems residing, e.g., among microprocessors, where the high temperature stability of the lasers is indispensable. In the recent years, great progress was achieved in increasing both the data rate and the temperature stability of VCSELs. At room temperature bit rates of 32 (Ref. 3) to 38 Gbit/s (Refs. 4 and 5) (850 nm), 35 Gbit/s (980 nm),[6] and 40 Gbit/s (1100 nm)[7] have been demonstrated. While 850 nm is the current standard wavelength for local and storage area networks and other short-reach optical link systems, potential competitive standards at 980 and 1100 nm have many critical advantages for VSR systems including: smaller operational voltages, deeper potential wells, and transparency of the GaAs substrate, which is important for bottom-emitting VCSELs. Hereby the wavelength of 980 nm is preferable for Si-based photodetectors, since the absorption coefficient of Si is much larger at 980 nm as compared to longer wavelengths.

Because the free carrier absorption coefficient increases with the wavelength, tolerances for adjustment of doping levels in the epitaxial structure for 980 nm are more strictly as compared to 850 nm. Additionally the application of highly strained materials for the active region and thus the proper strain handling creates new challenges, which are normally absent in 850 nm devices. While at elevated temperatures of 85 °C or even above bit rates of 25 Gbit/s have been demonstrated for VCSELs operating at 850 (Ref. 3) and 1100 nm,[7] however, at 980 nm the highest bit rate at 85 °C was still limited to 20 Gbit/s,[8] where VCSELs with InGaAs layers grown in the submonolayer growth mode by molecular beam epitaxy were applied. Here we indeed present 980 nm-range oxide-confined VCSELs operating error-free at data bit rates of up to 25 Gbit/s at temperatures as high as 85 °C, which were grown by metal-organic chemical-vapor deposition (MOCVD) with conventional multiple quantum wells (QWs), thus applying the mature and well approved large-scale mass production techniques. To facilitate our analysis of the limiting physical processes inside the VCSELs we perform small and large signal modulation experiments at various temperatures enabling us to determine the dominant factors that control the VCSEL's speed, notably at elevated temperatures.

The VCSEL structure is grown on an {001}-oriented 2°-off n-doped GaAs-substrate using MOCVD. Doped $Al_{0.12}Ga_{0.88}As/Al_{.90}Ga_{0.10}As$ distributed Bragg reflectors (DBRs) with 20 nm thick linear graded interfaces with 24/37 periods for the top/bottom mirror are employed. The active region contains five 4.2 nm thick compressively strained $In_{0.21}Ga_{0.79}As$ QWs with 6 nm thick $GaAs_{0.88}P_{0.12}$ tensile strained barrier layers. The 4.7% smaller lattice constant of $GaAs_{0.88}P_{0.12}$ as compared to GaAs partially compensates the larger lattice constant of $In_{0.21}Ga_{0.79}As$ and the corresponding lattice constant mismatch of 1.55%. Carefully designing of the layer thicknesses leaves both the local and the global strain well below values critical for the high quality growth. To improve the temperature stability of the gain and differential gain optimized detuning of 15 nm between the QW photoluminescence peak and the cavity resonance was applied, helping to compensate the gain decrease at elevated temperatures and leading to the very temperature insensitive

a)Electronic mail: mutig@sol.physik.tu-berlin.de.
b)On leave from the St. Petersburg Physical Technological Centre for Research and Education RAS, Khlopina 8/3 and Ioffe Physical-Technical Institute RAS, Polytekhnicheskaya 26, Saint-Petersburg, 194021 Russian Federation.

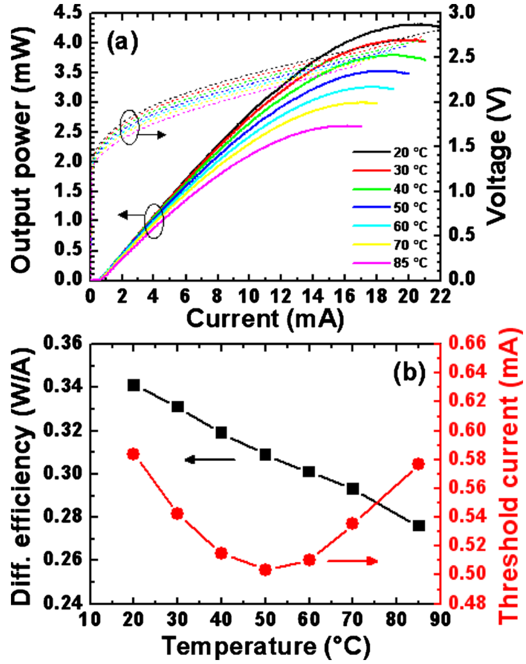

FIG. 1. (Color online) Output power-current-voltage (L-I-V) characteristics of a 980 nm double oxide-aperture VCSEL at temperatures from 20 to 85 °C (a), and the corresponding extracted values for the maximum differential efficiency and threshold current (b).

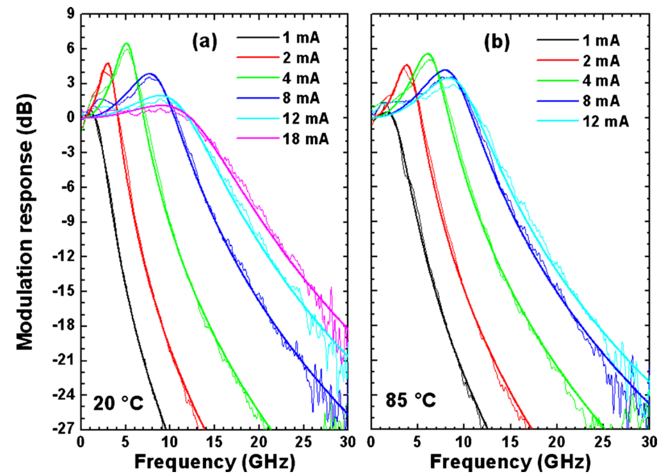

FIG. 2. (Color online) Magnitude of the small signal modulation response (2-port scattering parameter S_{21}) for different applied forward bias currents and the corresponding curve-fits at 20 °C (a), and at 85 °C (b).

threshold current behavior. To facilitate electrical and optical confinement and to reduce electrical parasitics two 30 nm thick $Al_{0.98}Ga_{0.02}As$ oxide aperture layers[3] with tapered fingers are formed by selective wet oxidation. The VCSELs are planarized with ~10 μm thick bisbenzocyclobutene to reduce the parasitic capacitances. Ground-source-ground metal contact pads are evaporated for ease of on-wafer high-frequency probe characterization.

We show in Fig. 1 the measured output power-current-voltage characteristics for a VCSEL with a 10 μm diameter oxide aperture and the corresponding values for differential efficiency and threshold current. The maximum output power is 4.3 mW at 20 °C and decreases little to 2.6 mW at 85 °C. The maximum differential efficiency decreases by only 18% from ~0.34 W/A at 20 °C to ~0.28 W/A at 85 °C. The applied redshifted detuning of nominally 15 nm between the QW photoluminescence peak wavelength (~965 nm) and the cavity resonance wavelength (~980 nm) resulted in a minimum threshold current appearing at a temperature around 50 °C as seen in Fig. 1(b). The threshold current of ~584 μA at 20 °C, decreasing to ~504 μA at 50 °C, and again increasing to ~579 μA at 85 °C. The variation in the threshold current across the whole range from 20 to 85 °C is less than ~16% of the minimum value. The detuning effect decisively contributes to the improved temperature stability of the device by keeping the threshold current density to a minimum. The small threshold current density helps to maintain a large differential gain[9] and thus high speed VCSEL operation. The differential resistance of the VCSEL is ~45 Ω at 12 mA, practically perfectly matched to the standard impedance of 50 Ω. The thermal resistance is ~2.2 K/mW, which can be further improved in the future by using, e.g., binary alloys in the bottom DBR.

To determine the factors that control high speed operation, we measure the small signal modulation response (S_{21}) and input impedance (S_{11}) using a network analyzer and a calibrated photodetector at three temperatures of 20, 50, and 85 °C. These data are used to extract the relaxation resonance frequency f_r, damping factor γ, D-factor, K-factor, parasitic cut-off frequency f_p, and –3 dB frequency $f_{-3\ \mathrm{dB}}$. These key physical parameters are commonly used to characterize the high speed properties of VCSELs and are based on the standard laser diode rate equation formalism.[9]

Small signal modulation response for different currents at 20 and 85 °C with corresponding curve fits are shown in Fig. 2. All fits show excellent agreement with the measured data. The maximum parasitic cut-off frequency extracted from the measured S_{11} data is at all temperatures larger than 22 GHz. In Fig. 3 we present the extracted values of the relaxation resonance frequency f_r and the –3 dB-frequency $f_{-3\ \mathrm{dB}}$ as a function of the forward bias current for 20, 50, and 85 °C. The maximum bandwidth is 15.3 GHz at 20 °C and decrease to 14.5 GHz at 50 °C. At 85 °C the maximum bandwidth is still 13.2 GHz, which is only by ~2 GHz lower than the value at 20 °C. The overall change in the maximum bandwidth within the investigated temperature range is only ~2 GHz, which is a result of the gain-cavity detuning and the highly temperature stable multi-QW active region. The maximum relaxation resonance frequency is 12.9 GHz at 20 °C and decreases to ~9.8 GHz at 85 °C. This decrease corresponds to higher temperatures inside the VCSEL at higher ambient temperatures (internal temperature at 12 mA at 85 °C is ~140 °C), leading to saturation of the relaxation resonance frequency at lower currents.

The K-factor that characterizes the damping limitation can be extracted by fitting a linear function to a plot of the damping factor as a function of the squared relaxation resonance frequency,[9] as shown in Fig. 3(b). The K-factor is in the range of 0.4 ns between 20 and 85 °C and is temperature insensitive. One of the main reasons for the relatively large K-factor is a relatively high mirror reflectivity, since the K-factor increases with the photon life time.[9] On the other hand, the high mirror reflectivity reduces the mirror losses and thus the threshold carrier density, which increases the differential gain and thus the relaxation resonance frequency. Since the relaxation resonance frequency is lower than the bandwidth [Fig. 3(a)], especially at 85 °C, a proper compromise between the acceptable high damping and the reason-

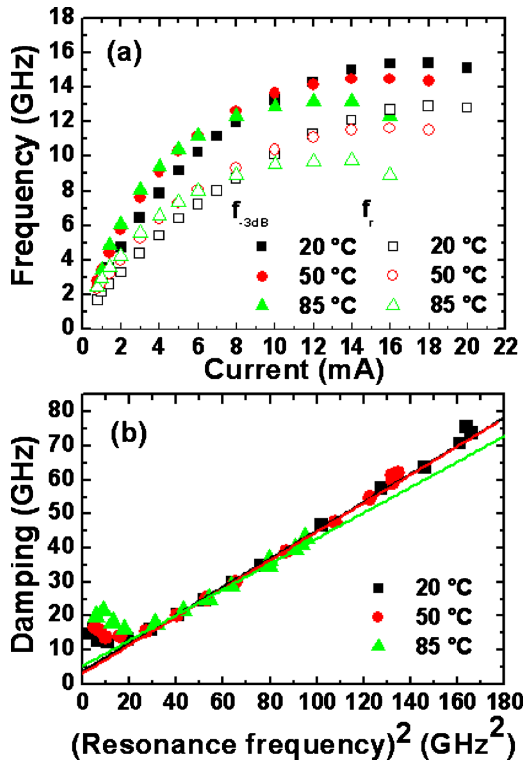

FIG. 3. (Color online) Relaxation resonance frequency f_r and –3 dB frequency $f_{-3\text{ dB}}$ vs VCSEL forward bias current (a), and damping factor γ vs f_r-squared with corresponding linear fits (b), both at temperatures of 20, 50, and 85 °C.

able high relaxation resonance frequency has been found. The extracted values of the *K*-factor correspond to a maximum damping limited bandwidth of ~21–23 GHz, clearly demonstrating its noticeable limiting effect.

The important *D*-factor can be obtained by fitting a linear function to the extracted squared relaxation resonance frequencies as a function of the current above threshold.[9] The *D*-factor is practically constant over the whole temperature range, and is ~3.5 GHz/sqrt(mA). The high temperature stability of the *D*-factor is caused by the gain—cavity detuning, which prevents the decrease in the differential gain at higher temperatures.

Next, we performed data transmission experiments using a nonreturn to zero (NRZ) data format with a (2^7-1) pseudorandom binary sequence (PRBS) in a standard back-to-back measurement configuration (BTB) (~3 m fiber). In Fig. 4 we show the measured bit error rates (BER) at the data bit rate of 25 Gbit/s and temperatures of 25 and 85 °C. The drive current and the peak-to-peak modulation voltage $V_{p\text{-}p}$ are held constant in both data transmission experiments at 12 mA and 0.8 V, respectively. This makes the expensive driver electronics redundant, reducing the application costs. At both temperatures error-free data transmission with BERs smaller than 10^{-12} is demonstrated. Received optical power for the lowest BER is at both temperatures smaller than –1 dBm, well below 1 mW. The power penalty for the lowest BER for the higher temperature of 85 °C in respect to 25 °C is smaller than 0.8 dBm and is caused by the reduction of the output power at higher temperatures [Fig. 1(a)]. These results clearly demonstrate the maturity of the presented devices for future high speed VSR interconnects, where high temperature stability is indispensable.

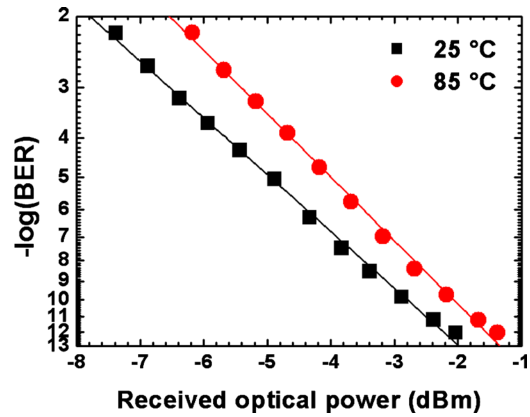

FIG. 4. (Color online) Bit error rates at 25 Gbit/s at 25 and 85 °C at the corresponding VCSEL drive current of 12 mA and $V_{P\text{-}P}$ of 0.8 V for a BTB measurement configuration with a (2^7-1) PRBS in the conventional NRZ excitation scheme.

To summarize and conclude, 980 nm VCSELs with highly temperature stable modulation characteristics are presented. We demonstrate maximum bandwidths around 13–15 GHz that are very temperature insensitive. By using a standard small signal analysis, we identify a saturation of the relaxation resonance frequency, due to the limits of heat dissipation in our current VCSELs, and damping as the strongest factors that limit high speed operation. We measure error-free data transmission at data bit rates of up to 25 Gbit/s at temperatures of up to 85 °C, and thus demonstrate the suitability of our VCSELs for practical high speed and high temperature stable short-reach optical link applications.

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[1]D. Collins, N. Li, D. Kuchta, F. Doany, C. Schow, C. Helms, and L. Yang, Proc. SPIE 6908–09 (2008).
[2]F. E. Doany, L. Schares, C. L. Schow, C. Schuster, D. M. Kuchta, and P. K. Pepeljugoski, Proceedings of the IEEE Optical Fiber Communication Conference and Exposition, Anaheim, CA, USA, 2006.
[3]P. Westbergh, J. S. Gustavsson, Å. Haglund, A. Larsson, F. Hopfer, D. Bimberg, and A. Joel, Proceedings of CLEO/IQEC, IEEE Standards Office, 2009.
[4]S. A. Blokhin, J. A. Lott, A. Mutig, G. Fiol, N. N. Ledentsov, M. V. Maximiv, A. M. Nadtochiy, V. A. Shchukin, and D. Bimberg, Electron. Lett. **45**, 501 (2009).
[5]A. Mutig, S. A. Blokhin, A. M. Nadtochiy, G. Fiol, J. A. Lott, V. A. Shchukin, N. N. Ledentsov, and D. Bimberg, Appl. Phys. Lett. **95**, 131101 (2009).
[6]Y.-C. Chang and L. A. Coldren, IEEE J. Sel. Top. Quantum Electron. **15**, 704 (2009).
[7]N. Suzuki, T. Anan, H. Hatakeyama, K. Fukatsu, K. Tokutome, T. Akagawa, and M. Tsuji, IEICE Transactions on Electronics **E92-C**, 942, (2009).
[8]A. Mutig, G. Fiol, K. Pötschke, P. Moser, D. Arsenijevic, V. A. Shchukin, N. N. Ledentsov, S. S. Mikhrin, I. L. Krestnikov, D. A. Livshits, A. R. Kovsh, F. Hopfer, and D. Bimberg, IEEE J. Sel. Top. Quantum Electron. **15**, 679 (2009).
[9]L. A. Coldren and S. W. Corzine, *Diode Lasers and Photonic Integrated Circuits* (Wiley, New York, 1995).