To the Faculty at the Department of Microtechnology and Nanoscience (MC2),
Chalmers University of Technology

Licentiate Petter Westbergh will defend his doctoral thesis on May 20, 2011, at 10:00 in Kollektorn at the
Department of Microtechnology and Nanoscience (MC2). The thesis is entitled “High Speed Vertical Cavity
Surface Emitting Lasers for Short Reach Communication”. The faculty opponent is Professor Kevin L. Lear,
Colorado State University, Fort Collins, CO, USA.

The thesis consists of an introduction and the following appended papers:

A. P. Westbergh, J. S. Gustavsson, Å. Haglund, H. Sunnerud, and A. Larsson, “Large aperture 850 nm

B. P. Westbergh, J. S. Gustavsson, Å. Haglund, M. Sköld, A. Joel, and A. Larsson, “High-speed, low-current-
(invited paper)

C. P. Westbergh, J. S. Gustavsson, Å. Haglund, A. Larsson, F. Hopfer, G. Fiol, D. Bimberg and A. Joel,
“32 Gbit/s multimode fibre transmission using high-speed, low current density 850 nm VCSEL”,

D. Y. Ou, J. S. Gustavsson, P. Westbergh, Å. Haglund, A. Larsson, and A. Joel, “Impedance characteristics
and parasitic speed limitations of high-speed 850-nm VCSELs”, IEEE Photon. Technol. Lett., vol. 21,

E. S. B. Healy, E. P. O’Reilly, J. S. Gustavsson, P. Westbergh, Å. Haglund, A. Larsson, and A. Joel, “Active
region design for high-speed 850-nm VCSELs”, IEEE J. Quantum Electron., vol. 46, no. 4, pp. 506-512,
2010.

F. P. Westbergh, J. S. Gustavsson, B. Kögel, Å. Haglund, A. Larsson, and A. Joel, “Speed enhancement of

G. P. Westbergh, J. S. Gustavsson, B. Kögel, Å. Haglund, A. Larsson, A. Mutig, A. Nadtochiy, D. Bimberg,

H. P. Westbergh, J. S. Gustavsson, B. Kögel, Å. Haglund, A. Larsson, “Impact of photon lifetime on high
(invited paper)

Petter Westbergh received the Civ. Ing. degree from Engineering Physics at Chalmers in February 2007. In
March 2007 he started studies towards the PhD degree at the Photonics Laboratory, Department of
Microtechnology and Nanoscience (MC2). He received the Licentiate degree in May 2009.

Petter’s thesis deals with the development of high speed vertical cavity surface emitting lasers (VCSELs) for
short reach optical communication. Because of requirements of high speed, high efficiency and low cost, the
VCSEL has become the preferred light source for optical transmitters in local area networks, storage area
networks (in e.g. data centers) and high performance computing systems. In the near future it is also expected to
appear in high speed optical cables for consumer electronics. The main objective of Petter’s research has been to
extend the speed of directly (current) modulated VCSELs to 40 Gbit/s.

The first part of the thesis (Papers A-E) presents the design and performance of a first generation high speed
VCSELs where a number of design modifications were implemented to mitigate speed limitations due to the
intrinsic damping of the modulation response, thermal effects and electrical parasitics. This resulted in a
modulation bandwidth of 20 GHz and successful transmission over 100 m of multimode fiber at 32 Gbit/s. In the second part (Papers F-H), the modulation bandwidth was extended to 23 GHz by reducing the photon lifetime of the VCSEL resonator, thereby further reducing damping, and by a further reduction of capacitance. Error-free transmission at 40 Gbit/s over a short length of multimode fiber, and at 35 Gbit/s over 100 m multimode fiber, was demonstrated. This is the highest single channel data rate ever demonstrated with a VCSEL emitting at 850 nm, the standard wavelength in data communication.

Petters work has been published (or will be published) in leading scientific journals and has been presented at leading international conferences. Two of his papers are invited papers in IEEE Journal of Selected Topics in Quantum Electronics. He won the 2nd place poster award at the International Nano-Optoelectronics Workshop in Berlin 2009 and he was a finalist for the Maiman student paper award at the IEEE Conference on Lasers and Electro-Optics in Baltimore 2009. His work was featured in Electronics Letters, June 2010.

Below are short descriptions of the work presented in each paper included in the thesis. Petters contributions are also identified.

**Paper A** presents the performance of oxide confined 850 nm VCSELs with strained InGaAs quantum wells (QWs) for improved differential gain, a binary compound in the bottom distributed Bragg reflector (DBR) for reduced thermal impedance and a double oxide aperture for reduced capacitance. A modulation bandwidth of 20 GHz and modulation up to 25 Gbit/s are demonstrated at a low bias current density.  
**Contributions:** Petter participated in the design work and fabricated the VCSELs. He performed all measurements and the analysis of the results. He wrote the paper and presented the results at the IEEE International Semiconductor Laser Conference 2008 (Sorrento, Italy).

**Paper B** (invited) presents the results from a detailed investigation of the static and dynamic characteristics of the VCSELs presented in Paper A. Results from a comparative study of VCSELs with unstrained GaAs QWs are also presented. Clear speed improvements, due to higher differential gain, are observed with strained QWs. The modulation speed is extended to 30 Gbit/s.  
**Contributions:** Petter participated in the design work and fabricated the VCSELs. He performed all measurements and the analysis of the results. He wrote the paper and presented the results at the International Nano-Optoelectronics Workshop 2009 (Berlin, Germany).

**Paper C** presents results from transmission experiments using the VCSELs in Papers A-B. Error-free transmission at 32 Gbit/s over 50 m multimode fiber, and at 25 Gbit/s over 100 m multimode fiber, is demonstrated.  
**Contributions:** Petter fabricated the VCSELs and performed all measurements at TU Berlin. He also did the analysis of the results. He wrote the paper and presented the results at the International Nano-Optoelectronics Workshop 2009 (Berlin, Germany).

**Paper D** presents results from impedance measurements and equivalent circuit modeling of the VCSELs in Papers A-C. The results indicate that device parasitics have a major impact on the modulation speed and that an additional few oxide layers, for a further reduction of capacitance, should allow for a modulation bandwidth sufficient for 40 Gbit/s modulation.  
**Contributions:** Petter fabricated the VCSELs and aided Y. Ou in the impedance measurements and the equivalent circuit modeling. He co-authored the paper and was the corresponding author.

**Paper E** presents results from gain calculations for strained InGaAs/AlGaAs QWs with the gain peak at 850 nm, with the purpose of optimizing the design with respect to differential gain and threshold carrier density. A design enabling a doubling of the differential gain (compared to unstrained GaAs/AlGaAs QWs) is presented. The improvement is confirmed by extracting values for the differential gain from modulation response measurements on fabricated VCSELs.  
**Contributions:** Petter fabricated the VCSELs and performed all temperature dependent measurements and the analysis of measurement results. He co-authored the paper and was the corresponding author.
Paper F demonstrates that a significant increase of the modulation bandwidth can be achieved by reducing the photon lifetime, thereby reducing the damping of the intrinsic modulation response. An additional four oxide layers were also used for reducing the capacitance. A record modulation bandwidth of 23 GHz is demonstrated.

Contributions: Petter proposed the parametric investigation of the effects of reduced top DBR reflectivity (reduced photon lifetime). He participated in the design work and fabricated the VCSELs. He performed all measurements and the analysis of the results. He wrote the paper and presented the results at the International Semiconductor Laser Conference 2010 (Kyoto, Japan).

Paper G demonstrates error-free transmission at 40 Gbit/s over a short length of multimode fiber, and at 35 Gbit/s over 100 multimode fiber, using the VCSELs in Paper F. This is the highest transmission speed ever demonstrated with an 850 nm VCSEL.

Contributions: Petter fabricated the VCSELs and performed all measurements at TU Berlin. He also did the analysis of the results. He wrote the paper and presented the results at the International Semiconductor Laser Conference 2010 (Kyoto, Japan) and at Photonics West 2011 (San Francisco, USA).

Paper H (invited) presents the results of a detailed analysis of the static and dynamic characteristics of the VCSELs in Papers E-G. In particular, the impact of reduced photon lifetime on all basic laser parameters is studied. It is found that, due to a trade-off between resonance frequency and damping, there is an optimum photon lifetime for maximum modulation bandwidth.

Contributions: Petter participated in the design work and fabricated the VCSELs. He performed all measurements and the analysis of the results. He wrote the paper and presented part of the results at the International Semiconductor Laser Conference 2010 (Kyoto, Japan) and at Photonics West 2011 (San Francisco, USA).

The epitaxial material used for VCSEL fabrication was provided by IQE Europe, Cardiff, UK, according to designs developed by the group at Chalmers.

Petter's primary advisors have been Associate Professor Johan Gustavsson, Assistant Professor Åsa Haglund and myself.

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For a copy of the thesis, please contact Petter Westbergh at ext. 1598 or by e-mail: petter.westbergh@chalmers.se

Sincerely,
Anders Larsson
Professor and examiner