School of Engineering Sciences
Department of Applied Physics

## Ref: Evaluation report of PhD thesis by Nikolay Ledentsov, M.Sc.

**Title and subject**

PhD thesis "Selected methods of improving efficiency of the VCSEL-based optical interconnects" is focused on technology of the Vertical Cavity Surface Emitting Lasers (VCSELs) and its implementation for optical interconnects utilized in the high speed short-reach links (data interconnects) in datacenters and supercomputers.

**General structure and layout**

The thesis has well defined logical structure bringing main points required to evaluate importance of the research topic and obtained results, and provide critical assessment of solutions found during the project realization. Chapter 1 (Introduction) gives a comprehensive overview of basic information needed to understand the research topic and its impact on rapidly growing high technology branch covering high-capacity information systems and, in particular, data centers and supercomputers. Chapter 2 provides an informative and concise introduction into interconnects, which is the subject of main implementation addressed in the considered PhD project. The aim of Chapter 3 is to make an overview of the state of the art for main "enabling" components in high-capacity information systems – VECSELs, and interconnects required to operate high-throughput data centers and computer systems. Chapter 4 analyses limitations of the developed VECSEL technology to achieve the highest possible data rate in information transmission, and investigates trade-off solutions for proper use of complex modulation formats. Chapter 5 is actually a core of the research, presenting the achieved results of maximum transmission distance at the highest available transmission rate, and assessment of the efficiency of suggested solutions. Chapter 6 considers another important aspect, analysing operation of the devices (and subsystems) under harsh working conditions, specifically in high temperature environment. Finally, Chapter 7 brings into attention further problems requiring urgent solutions in the area and makes an outline for perspective solutions.

The whole thesis is perfectly supported with proper data and graphical materials, and demonstrates proven importance of the topic with numerous publications in acknowledged professional journals.

**Literature references**

The extensive reference list demonstrates author's deep knowledge of the research area. Up to date literature selection also gives a solid impression that the author is well oriented in the field of his expertise and aware about recent achievements on the topic. It is an additional argument supporting the high quality of the presented thesis.

**Motivation and goal of the thesis**

Rapidly growing capacity of diverse information systems, especially for short-reach applications, such as data centers, supercomputers, multi-user information exchange sub-systems (for example, inter-communicating automotive ethernet) are facing severe bottlenecks of the data throughputs. Other serious challenges are related to energy efficiency and heat dissipation. To keep exponentially growing energy consumption of information systems in reasonable limits, energy efficiency (counted as the amount energy per bit of transmitted information) should be dramatically


**KTH SCI-Skolan – Applied Physics, Hannes Alfvens väg 11,** – SE–114 19 Stockholm
Tel: +46 8 790 42 73, E-mail: sergeip@.kth.se
Momsreg.nr/VAT: SE202100305401, www.kth.se

improved. On the other hand, continually growing density of integration of high throughput information systems pushes ahead the problem of heat dissipation and operation in high temperature environment. All above questions demand urgent solutions.

The PhD thesis topic is aimed to study, demonstrate, and assess certain solutions (of the mentioned proplems) based on implementation of VECSEL technology. Among others, suggested approaches cover the use of discrete multi-tone modulation (DMT) format, certain improvement in utilization of non-return-to-zero modulation (NRZ) format with increased energy efficiency, and demonstration of applicability of considered technology in high temperature working conditions. In particular, data rate of over 100 Gb/s with energy efficiency below 1 pJ/bit can be achieved in interconnects using VCSEL platform and multi-mode optical fibers (MMF) to provide inter- and intra-board communication in high-speed data servers. Next, using “leaky” VECSEL design, interconnect distance about 2 km can be achieved with high-speed communication. Finally, capability of the interconnects based on the quantum dot VECSEL technology to operate in high temperature conditions (close to 200 C) is demonstrated.

Carrying out the PhD project, the author succeeded to demonstrate strong professional expertise and offered efficient solutions for the outlined tasks.

**Methodology and research results**

The proposed research methodology was carefully thought out and planned with many significant details. The formulated tasks were considered in well-structured and sequential manner, showing important relations between obtained results and their impact on following steps for finding further scientific and engineering solutions.

Milestones of the thesis results include demonstration of energy efficient transmission of NRZ modulated signal over short-reach link, using VECSEL based approach. The transmission speed over 56 Gb/s with record low energy of 0,4 J/bit was achieved. Another significant achievement is implementation of “leaky” VECSEL design together with MMF link to reach transmission rate 60 Gb/s over the interconnect link about 1 km. Last, but not least, quantum dot design to increase the temperature tolerance close to 180 C was implemented.

To demonstrate these results, a set of complex design and technical problems was solved, in particular, dealing with the decrease of VECSEL current, improving operation stability and modulation performance of an electro-optical modulator VECSEL, and many others.

**Professional qualification and independence**

Carrying out his PhD program, the PhD candidate, Mr. N. Ledentsov has completed a set of complicated scientific tasks which clearly demonstrate his scientific qualification to run demanding research projects.

In particular, these tasks include ability to identify and formulate scientific and engineering problems, plan research experiments, properly select methodologies for the study, process and analyze obtained results, discover and provide explanation of observed phenomena, and draw motivated conclusions.

Another important aspect of the project was inter-disciplinary approach to tackle problems from different scientific subjects – physics, electronics, information technology, and material science.

On the other hand, working in multidisciplinary environment brings a specific challenge – to keep track of own project plan and collaborate efficiently with various scientific teams. Mr. N. Ledentsov has successfully completed this task also, and demonstrated his ability of highly qualified and independent researcher.



**KTH SCI-Skolan – Applied Physics, Hannes Alfvens väg 11,** – SE–114 19 Stockholm

Tel: +46 8 790 42 73, E-mail: sergeip@.kth.se
Momsreg.nr/VAT: SE202100305401, www.kth.se

**Novelty and originality**

The results obtained within the thesis project are of high scientific and technical value. Most of them can be explicitly stated as the break-through solutions, and demonstrate world record achievements. The international recognition and originality of the presented data is documented by impressive author's publication list in leading journals and presentations at many top level conferences in the field of expertise, such as OFC and others.

**Conclusion**

After completing his PhD program, Mr. N. Ledentsov has clearly demonstrated appropriate professional skills to plan, run, and report results of scientific work. He has also strong ability to work both independently and in a team.

Summarizing the above, I consider Mr. N. Ledentzov is fully qualified to be awarded the PhD degree.

Prof. Sergei Popov
Department of Applied Physics
School of Engineering Sciences
KTH Royal Institute of Technology
Stockholm, Sweden

Phone: +46 (0)8 790 4273
Email: sergeip@kth.se



**KTH SCI-Skolan – Applied Physics, Hannes Alfvens väg 11,** – SE–114 19 Stockholm
Tel: +46 8 790 42 73, E-mail: sergeip@.kth.se
Momsreg.nr/VAT: SE202100305401, www.kth.se