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DOCTORAL DISSERTATION REVIEW

Title of dissertation: Selected methods of improving efficiency of the VCSEL-based optical interconnects

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1. Purpose, scope, and nature of the dissertation

The reviewed dissertation deals with optical-fiber communication technologies, in particular, the problem of overcoming the limitations of the Vertical Cavity Surface Emitting Lasers (VCSELs) based optical interconnects utilized in the high-speed short-reach links (data interconnects) in data centers and supercomputers. In this context, the main objective of the dissertation is to develop and analyze solutions for the VCSEL-based transmission systems capable of enhancing (a) the maximum data throughput of the optical interconnects, (b) the energy efficiency of short-reach interconnects, (c) the transmission reach of the data interconnects, and (d) the VCSEL temperature operation range for data transmission in automotive and industrial applications.

I assess the dissertation topic as timely and relevant to the information and communication technology (ICT) sector. The dissertation is both theoretical and useful. Regarding theoretical considerations, Nikolay Ledentsov, M.Sc., proposed and developed several methods that effectively improve the performance of the VCSEL-based transmission links, including a detailed analysis, characterization, and optimization of their operation considering various transmission conditions and system parameters. The useful aspect of the dissertation is related to implementing the proposed methods in laboratory and simulation environments and realizing real transmission in experimental setups, which allowed for obtaining performance results and demonstrating the feasibility of the proposed solutions.

2. Structure and content of the dissertation

The dissertation is built on a series of 11 related articles published in journals and conferences (labeled from [P1] to [P11]), presenting and analyzing the proposed methods. The articles are completed by the introduction to the topic of the dissertation, the discussion on related works, and a detailed presentation of the scientific contributions of the author of the thesis. The dissertation consists of seven chapters, which can be divided into three parts: introductory (Chapters 1-3), devoted to the proposed methods (Chapters 4-6), and concluding (Chapter 7), which cover the following topics.

- Chapter 1 contains an introduction to the topic of the dissertation and includes a presentation of the motivations behind the research conducted, the goals of the thesis, its outline, the author's contribution, and his scientific and professional achievements.

- Chapter 2 provides the background information regarding the dissertation topic, i.e., the optical interconnects realized using the VCSEL transmission in Multi-Mode Fibers (MMFs). Issues such as VCSEL design, characteristics, production, modeling, and properties of MMFs are discussed.

- Chapter 3 is devoted to a literature review of works related to the dissertation topic, with a detailed summary of the performance of reference and proposed solutions, including the data rates achievable with modern VCSELs, the energy efficiency of short-reach transceivers operating over 56 Gb/s, MMF transmission distances, and temperature operational range of VCSELs.

- Chapter 4 presents and analyzes the methods proposed to increase the data rates (article [P1]) and the energy efficiency (articles [P2]-[P3]) in the VCSEL-based links.

- Chapter 5 focuses on the spectral width reduction in leaky VCSEL designs and its influence on data transmission. Namely, papers [P4, P5, and P7] analyze the leaky approach and the transmission performance it can achieve, whereas papers [P6] and [P8] demonstrate and analyze the extended reach data transmission with the single mode VCSELs through an MMF.

- Chapter 6 addresses the maximal temperature at which the VCSELs can operate at high speed and presents a method based on the use of the quantum dots to increase the temperature operational range. The results of the analysis have been published in papers [P9], [P10], and [P11].

- Chapter 7 is a summary of the dissertation, including the presentation of the main achievements of the dissertation and a discussion of challenges and further research concerning the optical VCSEL-based interconnects.

The structure of the work is correct. The dissertation was written in English at a very good level with no difficulty in understanding its content and the ideas discussed. The dissertation contains a good introduction to the subject of the VCSEL-based interconnects and an illustrative presentation (using charts) of the achieved performance of proposed methods compared to of the stat of the art solutions. Particular solutions, presented in detail in the included journal and conference articles, are supported by suitable abstracts and summaries at the beginning of Chapters 4-6, which facilitate identifying the author's contributions. I did not notice any typos in the work apart from some mismatch in labeling the references, which I commented in Section 6 of this review.

3. Correctness and originality of the thesis and evaluation of research methods

The theses of the dissertation have been formulated as follows:

Thesis 1: It is possible to achieve data rates above 100 Gb/s and achieve energy efficiency below 5 pJ/bit with optical interconnects.

Thesis 2: It is possible to increase the transmission distance of the high-speed multi-mode-fiber based interconnects to over 1 km with a "leaky" VCSEL design.

Thesis 3: It is possible to realize the optical interconnects operating at >105℃ temperatures for automotive applications.

In my opinion, the theses of the dissertation are original and were formulated correctly. Nikolay Ledentsov, M.Sc., based on the literature review and his knowledge, correctly defined the scope of his work and demonstrated the theses in the dissertation by, respectively:

1. Developing and evaluating transmission methods based on the Discrete Multi-Tone (DMT) and the on-off keying non-return-to-zero (NRZ) modulation techniques for VCSEL-based interconnects.
2. Proposing and evaluating a new leaky VCSEL design capable of decreasing the spectral width of the VCSEL and thus reducing the limiting effect of the dispersion on the maximum transmission reach through MMF.
3. Proposing and evaluating experimentally the use of quantum dots (QD) in the active region of VCSELs for increasing the temperature operating range of short-reach data interconnects.

Nikolay Ledentsov, M.Sc., solved the scientific problems posed using appropriate research methods involving the measurements in the designed experimental setups of the transmission systems in the laboratory and performing computer simulations. To demonstrate the thesis of the dissertation, the PhD candidate compared the obtained results with the performance of the state-of-the-art reference solutions. The research methodology is described in detail, while the results in the dissertation are accompanied by appropriate analysis and extensive discussion.

In summary, the doctoral dissertation presents original solutions to a set of significant scientific problems, and the goals set in the work have been achieved.

4. Analysis of sources (including world literature and the state of the art) demonstrating the author's sufficient knowledge of the scientific discipline

The PhD candidate conducted a thorough bibliographic review related to the dissertation topic. In particular, Chapter 1 provides adequate references motivating the research concerning VCSEL-based optical interconnects utilized in the high-speed short-reach links in datacenters, supercomputers, automotive, and industrial applications, whereas Chapter 2 discusses specific issues related to the VCSELs and MMFs based on the literature sources. Moreover, Chapter 3 presents the state of the art solutions related to the goals addressed in the dissertation. In overall, the list of literature references contained at the end of the dissertation manuscript has 117 items. Besides, each of the published scientific papers included in the dissertation contains its own list of references. References in the text to sources are appropriate and demonstrate a good knowledge of the contemporary literature related to the dissertation topic.

In my opinion, there is sufficient evidence to assess that the PhD thesis demonstrates the candidate's overall theoretical and practical knowledge to carry out impact and quality research work in the field of optical networking, more specifically in the subfield of VCSELs-based transmission technologies. There are also convincing signs (e.g. first author role of the candidate in all scientific publications included in the dissertation) of independence in the scientific work, a feature of the candidate that can be also recognized through the logical organization of the PhD manuscript.

5. Position of the dissertation to the state of the art represented by the world literature and relevance of the results obtained to the scientific discipline

The topic of the dissertation of Nikolay Ledentsov is related to the important and topical problem of overcoming the limitations of Vertical Cavity Surface Emitting Lasers utilized in high-speed and short-reach links in optical interconnects in a wide area of applications, among others, in data centers, supercomputers, or in industry. In this context, the solutions proposed in the dissertation aim to improve the performance of the optical interconnects in terms of their throughput, transmission reach, energy efficiency, and temperature operating range. The literature review presented by the PhD candidate testifies to the topicality and relevance of these issues, where the related works and reference solutions cited in this area are from recent years.

The most important original achievements of the dissertation of Nikolay Ledentsov are as follows:

1 Development, implementation, and experimental analysis of the optical transmission system based on the use of single-mode VCELS and DMT modulation format, allowing to achieve the record data transmission up to 224 Gb/s.
2 Development, implementation, and experimental analysis of a complete VCSEL-based NRZ-modulated optical link capable of 71 Gb/s at 3.4 pJ/bit energy efficiency.
3 Development, implementation, and simulation as well as experimental analysis of the leaky VCSEL-based transmission in an MMF, achieving the transmission reach up to 1 km at the 25 Gb/s data rate.
4 Development, implementation, and experimental analysis of the system based on the use of quantum dots in the active region of VCSELs, which achieved the temperature operational range up to 180°C at high-speed transmission rates.

The dissertation demonstrated the effectiveness of the all the above VCSEL-based transmission methods, which outperformed the reference solutions at the moment of the publication of results.

The position of the work is also evidenced by the publication of the research results in recognized scientific journals with Impact Factor, such as IEEE Journal of Quantum Electronics, Electronics Letters, and Solid-State Electronics (5 articles in these three journals), and within renowned international conferences, including the Optical Fiber Communication Conference (2 papers), which were subject to the reviewing process. Hence, in my opinion, the methods developed by the PhD candidate are novel and enrich the current state of knowledge represented by the world literature in the area of information and communication technology.

6. Main flaws of the dissertation, weaknesses along with critical specific comments

No serious flaws have been identified, and only minor improvements could be made. For instance, there is some inconsistency in presenting the state-of-the-art solutions in Section 3. Namely, in the discussion on energy-efficient VCSELs, the references used in the text (namely, [64-67] and [71, 72]) do not correspond to the references presented in Table 2. Moreover, the references in Figure 11 are not mentioned in the subsection discussing the state-of-the-art MMF transmission distances, and the proposed solution [P8] is not shown in Figure 11. A similar problem is with Figure 12, where the presented references are not discussed, and labels [P9-P11] are missing.

7. Conclusions

The reviewed dissertation of Nikolay Ledentsov, MSc., meets the statutory criteria required for awarding a doctoral degree, as specified in Article 187 of the Law of July 20, 2018 – Law on Higher Education and Science – as it presents novel, impactful concepts that push forward the discipline of science Information and Communication Technology. This fact is further supported by the numerous and prestigious scientific journals and venues in which the dissertation's material has already been published (e.g., IEEE Journal of Quantum Electronics, Electronics Letters, Optical Fiber Communication Conference 2019 and 2020), as well as broad scientific activity of the Candidate that has resulted in 23 journal articles and 59 conference publications during last ten years (20 publications as first author and 5 invited publications). Any critical remarks presented above should not detract from my indisputably positive assessment. Therefore, I request that the doctoral degree be awarded to Nikolay Ledentsov, MSc, and due to the prestige and overall impact the work has already gathered, I recommend the degree be awarded with honors.

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