RADA NAUKOWA DYSCYPLINY
INFORMATYKA TECHNICZNA I TELEKOMUNIKACJA POLITECHNIKI WARSZAWSKIEJ
zaprasza na
OBRONĘ ROZPRAWY DOKTORSKIEJ

mgr. Nikolay Ledentsov

która odbędzie się w dniu **22 stycznia 2024 roku,** o godzinie **10:00** w trybie zdalnym

Temat rozprawy:

„Selected methods of improving efficiency of the VCSEL-based optical interconnects"”

Promotor: dr hab. inż. Jarosław Turkiewicz, prof. uczelni – Politechnika Warszawska

Recenzenci: dr hab. inż. Mirosław Klinkowski – Instytut Łączności, Warszawa

prof. Eduward Tangdiongga – Eindhoven University of Technology , Holandia

prof. Sergei Popov – KTH Royal Institute of Technology , Szwecja

Obrona odbędzie się zdalnie na platformie MS Teams. Osoby zainteresowane uczestnictwem w obronie proszone są o zgłoszenie chęci uczestnictwa w formie elektronicznej na adres sekretarza komisji: dr hab. inż. Haliny Tarasiuk, email: halina.tarasiuk@pw.edu.pl, do dnia 19 stycznia 2024. godz. 12:00.

Z rozprawą doktorską i recenzjami można zapoznać się w Czytelni Biblioteki Głównej Politechniki Warszawskiej, Warszawa, Plac Politechniki 1.

Streszczenie rozprawy doktorskiej i recenzje są zamieszczone na stronie internetowej: mgr nikolay ledentsov / rada naukowa dyscypliny informatyka techniczna i telekomunikacja / wszczęte po 30 kwietnia 2019 r. / doktoraty / postępowania w sprawie nadania stopnia naukowego / bip pw - biuletyn informacji publicznej politechniki warszawskiej.

Przewodniczący Rady Naukowej Dyscypliny
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Praca koncentruje się na wybranych metodach przezwyciężania ograniczeń łączy optycznych opartych na laserach VCSEL, stosowanych w łączach krótkiego zasięgu w centrach danych i superkomputerach. Zaproponowano i przebadano trzy metody, które mogą poprawić wydajność łączy optycznych opartych na laserach VCSEL. Pierwsza metoda dotyczy wzrostu maksymalnej przepustowości łączy optycznych i ich wydajności energetycznej. Zaproponowano wykorzystanie modulacji Discrete Multi-Tone (DMT) do transmisji wykorzystującej lasery VCSEL, uzyskując rekordową przepływność 224 Gbit/s. Następnie badana była poprawa efektywności energetycznej połączeń krótkiego zasięgu. Wykorzystanie modulacji amplitudy bez powrotu do zera (NRZ), pozwala na realizację energooszczędnych układów elektronicznych, bez energochłonnej korekcji lub dodatkowego przetwarzania sygnału w dziedzinie elektrycznej. W pracy zademonstrowano kompletne łącze optyczne o efektywności energetycznej 3,4 pJ/bit. Druga metoda dotyczy zwiększenia zasięgu transmisji. Aby zmniejszyć szerokość widmową lasera VCSEL, a tym samym zmniejszyć negatywny wpływ dyspersji chromatycznej na maksymalny zasięg transmisji przez MMF, przebadano nowy typ lasera VCSEL z wyciekającym modem (*leaky*). Przeprowadzono symulacje działania lasera VCSEL w celu zbadania redukcji szerokości widmowej. Wyniki symulacji zostały następnie potwierdzone danymi eksperymentalnymi. Zrealizowano transmisję danych za pomocą VCSEL na dystansie 1km MMF z przepływnością 25 Gbit/s. Ostatnia metoda dotyczy wzrostu stabilności temperaturowej VCSEL do zastosowań motoryzacyjnych i przemysłowych. Przebadano laser 850 nm VCSEL z materiałem kropek kwantowych (QD) w obszarze aktywnym. Przeprowadzono analizy komponentu oraz eksperymenty transmisyjne w rekordowo wysokich temperaturach. Zaprezentowane metody znacznie zwiększają szybkość transmisji danych, zasięg transmisji, efektywność energetyczną oraz stabilność działania łączy danych krótkiego zasięgu. Badania te można zastosować w następnej generacji łączy danych krótkiego zasięgu – *data inteconnects*.

Wrocław, 30th of November 2023

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DOCTORAL DISSERTATION REVIEW

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

Author: Nikolay Ledentsov, M.Sc.

Supervisor: Jarosław P. Turkiewicz, Ph.D., D.Sc.

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.

M. Klinkowski

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

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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.

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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.

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DOCTORAL THESIS REVIEW

1. Title of the PhD dissertation on which the candidate is applying in the current procedure for the award of PhD degree

Selected Methods of Improving Efficiency of the VCSEL-based Optical Interconnects, written by Nikolay Ledentsov

2. Assessment of the layout of the dissertation, including information on its various components

The thesis is well written and it has a well-defined structure that consists of seven chapters. In general, the thesis is a collection of published papers by the candidate added with some sections of introduction to the topics discussed in the papers. Chapter Introduction provides a general context of optical interconnects which is the main motivation of the research. Chapter 2 summarizes the fundamentals of optical interconnects. Chapter 3 focusses on VCSELs and presents the state of the art of optical interconnects utilizing VCSEL as the light source. Chapter 4 delves into modulation formats to maximize the throughput of a VCSEL taking into account complexity/simplicity and energy consumption. Chapter 5 looks into the spectral width in order to enhance transmission distance. Effect of the thermal properties on the overall VCSEL performance is discussed in Chapter 6. A special design using quantum-dots is discussed to enhance its thermal operational range, thereby minimizing the thermal effect on data rates. The thesis is closed with a chapter of conclusion and outlook to the possible improvement for the future VCSEL-based ultrahigh-speed interconnects. I think that the thesis presents in a logical way some important research challenges that VCSEL designers and manufacturers have experienced to deploy VCSELs in high-performance data centers and other short-haul communication use cases.

3. Evaluation of the literature used within the dissertation

The list of literatures is sufficient and up to date. They consist of material, device, and system/network papers. Because the thesis also presents published papers, sub-literature lists are also mentioned in each paper, which is very helpful for readers who only want to know specific topics of VCSEL.

4. Indication and assessment of the purpose of the candidate's work

The purpose of the work is largely formulated in Chapter 1 Introduction, but for specific topics the candidate has given brief motivation in each published paper. The overall purposes are to design and fabricate VCSELs that can offer additional benefits to the system suppliers and network operators in terms of data rates, link distances and operational conditions such as temperature for use cases in automotives. It is quite interesting to know the candidate thoughts on VCSEL application for both communication and non-communication where reliable light sources are required and VCSELs could be a promising alternative to traditionally side-emitting lasers.

5. Indication and evaluation of the testing methods used

One of the interesting features of this thesis is that the work has resulted in different forms of VCSEL prototypes that serve for different purposes according to the research questions formulated in each chapter. For example, to increase the operating thermal range to fit with the requirements for automotives, VCSELs made of quantum dot materials are designed and fabricated. All these fabricated VCSELs have to be tested and integrated into system trials. The method used for testing follows the common standards for reliable and thrustworthy experimental and validation results. This way of working guarantees other researchers to have similar results when their work is conducted under similar experimental conditions.

6. Evaluation of the part of the dissertation concerning the discussion of research results

Results coming from the candidate research work are discussed in more detail in his papers as they form consolidated sections of a chapter. Therefore, the length and depth of discussions are largely determined by the type of published journals: short journals present short discussions and long journals long discussions. After each paper, the candidate summarizes his own scientific contribution to the joint work with others. This is a valuable information for reviewers and readers because we can understand the role of candidate within the context of the joint works and his contribution to the beyond state-of-the-art of VCSELs.

7. Information concerning the practical application of the research results obtained

The thesis work relies on the research questions derived from practical implementations of VCSELs on high-performance optical interconnects and computing. There are still key issues necessary to be well addressed if massive implementation of VCSELs is aimed in those areas. His results from experiments with prototypes can serve as the starting point of new research questions for other researchers to develop new ideas or solution that enables simple, compact but high throughput VCSEL-based communication systems.

8. Information on possible irregularities which appeared in the evaluated dissertation

No irregularities or flaws can be found in the thesis. The use of proper English language and scientific and technical terms are largely correct. A few improvements in quality and readability of the thesis can be done. These recommendations are listed as an appendix to this document.

9. Assessing whether the dissertation provides an original solution to a scientific problem

Based on my work and the candidate scientific publications in the highly competitive journals and letters, I believe that the work has a high degree of novelty and innovation in presenting own solutions to the significant scientific challenges on this area. As I mentioned above, the solution offered in this thesis can be a basis for further research efforts by others to offer an alternative or even a better solution for low-cost optical interconnects which today is dominated by high-cost edge-emitting lasers.

10. Assessing whether the PhD thesis demonstrates the candidate's overall theoretical knowledge of the discipline or disciplines and his or her ability to carry out scientific or artistic work independently.

The thesis has contentwisely more focussed on experimental works rather than theoretical work. Throughout the thesis, studies were done to improve the working of VCSELs regarding specific research questions. For such works, solid theoretical background is required to predict which variables in fabrication are critical for overall performance. The candidate has demonstrated a high degree of finesse in giving solutions to the challenges of making devices and testing them in an system testbed. The thesis convinces me that the candidate has the ability to conduct scientific work independently.

11. Conclusion

After taking into account all 10 evaluated aspects of the thesis, the conclusion of my review is very positive. The candidate has delivered a thesis that features high quality of analyses from experimental setups employing designed and fabricated devices. The high quality of his work is shown by his publication in the prestigious / high impact journals and conferences. Therefore, I would like to request admission of Nikolay Ledentsov to the next steps of the PhD procedure.

12. Awards / Distinctions

The candidate has proven his ability to conduct high-impact research towards ultrahigh-speed communication systems using potentially low-cost VCSELs for various use cases. The results can be classified as a significant research achievement. Hence, I would like to recommend the degree of distinction / with honors to be awarded for his work.

Eindhoven, 22 November 2023

Appendix List of Questions for Thesis of Nikolay Ledentsov, MSc.

Page 13: MMF is preferred for short-link interconnects. For light source, we have multi and single-mode VCSELs. For launching single-mode light into MMF the launching position and angle becomes critical to have maximum throughput. When launching light along the axis of fiber (precise in the middle), the link behaves like a single-mode link, hence a maximum throughput can be obtained. When making an offset (and angle), the throughput decreases due to multi-mode effect. My comment is when a single-mode VCSEL and MMF are used, how much gain in throughput could be achieved when compared to multi-mode VCSEL and MMF.

Page 14:

The thesis mentioned only a limited set of VCSEL applications: data centers and automotives. My suggestion is to mention and explain a bit the advantages of using VCSEL for more advanced applications like VCSEL-based LiDAR or indoor optical wireless communication. Those applications need cheap but high-performance light sources.

Page 25 Optical Fibre

Instead of mentioning the attenuation per wavelength, my suggestion is put a graph of loss versus wavelength so that readers can retrieve necessary information. On dispersion, there should be a separation between chromatic dispersion, waveguide, and eventually polarization mode dispersion. Modal dispersion only occurs when fiber sees more than one mode. These dispersions can also be visualized by dispersion graphs versus wavelengths. It should be emphasized in this section that whether a fiber is working as a single mode or multimode depends on the size with respect to wavelength. For example, the “single-mode fibers” with 8-12 micron core diameters work only as a single mode when operating wavelengths are approximately 1 micron or above. For 850 nm or shorter (visible light), the 10-12 micron SMF works as multi-mode.

Page 27 choice of NRZ and PAM4 for short-reach interconnect

My perception is the choice for modulation formats in short reach interconnect such as the data centers does not heavily rely on energy efficiency. I think that this choice has more to do with link performance, in particular the latency. NRZ and PAM4 do not require complex modulation formats like QPSK, m-QAM and even OFDM. These complex modulation formats give additional processing time, which increases latency. Regarding power consumption, OFDM requires approximately the same energy as NRZ but with equalization. DSP now requires less and less energy but the processing time or latency remains more or less the same. OFDM would hardly be the preferred choice of modulation for data centers due to the FFT operation requiring a lot of time and processing power. If we do not consider data center application, like access and metro-core networks, then quadrature modulation like QPSK/m-QAM and multi-carrier DMT/OFDM may be used. The requirement for low power consumption only occurs after a certain performance has been achieved, for example how to create almost zero latency for a certain bitrate.

Page 28

For clarity, I suggest you to explain a bit what you mean by inductive peaking and the slight version of it. What are the (dis)advantages of this technique when compared to conventional FFE?

Page 29

A SM VCSEL in MMF transmission will create speckle patterns which move around the aperture of MMF. This pattern generates power fluctuations when the receiving aperture is less than fiber diameter. Have

you observed these speckles when analyzing the link performance. Are these speckles the same as the modal partition noise?

Page 33

Perhaps a brief introduction of DMT/OFDM including water filling should be put here to guide readers towards these multi-carrier modulations. Theoretically, an optimized single-carrier modulation could be better than multi-carrier modulations, but there are special conditions where multi-carrier performs better than single-carrier modulations. Perhaps, the candidate should explain why he prefers to employ multicarrier DMT/OFDM.

Page 37

Like in my previous comments on the use of DMT/OFDM with power and bitloading in combination with FEC is not recommended for latency-sensitive data centers. For access and LAN they are recommended. When you apply DMT/OFDM with bit/power loading, you need a return channel which gives the SNR values of the link as a function of frequencies. These return channels are not trivial in data centers.

Page 46

On the phase shifter for differential inputs to a BER analyzer, for such high data rates, the cable lengths should be made equal and as short as possible in order to guarantee an in-phase arrival of differential outputs. A modern BER analyzer for very high data rates to my knowledge has a delay for each of differential paths. Perhaps in your case, you have used a different type of BER analyzer in 2019.

Page 49 Line 1-4

How did you measure power consumption of a link? Communication is a bi-directional action, so each side has a transceiver (a transmitter and a receiver). Therefore, you need to consider both the transmitter and receiver per side in a link. For clarity, which part of the sub-system which consumes the most power so that a minimization effort should be done for that particular sub-system.

Page 78

Figure 14 is too small to read it on paper, hence should be enlarged. More importantly, the graphs should be better explained because they contain key information to understand the design. The same can also be said to Figure 13 in terms of explanation. It should be explained why the curve is not symmetric (indicating different slope efficiencies) around the wavelength corresponding to the minimum threshold (843nm at 0.15mA).

Summary / Outlook

Page 110: The intention mentioned in the thesis is to come up with a solution that allows for high bandwidth but with lower energy consumption. The future work described on this page is only mentioned for obtaining high bandwidth, but still at expense of higher power consumption. Is there any future work that specifically targets the lower power consumption of VCSELs.

Page 110: The solution using EOM is interesting although I have some doubts about the signal quality. When refractive index is modulated for EOM, the spectrum broadening (chirp) will appear significantly, hence when dense WDM concept is applied, the spectral distance needs to be increased to prevent overlapping channels, causing higher crosstalk. And also when VCSELs emit at C+L band for example, then dispersion in high speed links become a serious bottleneck due to this chirp. For 25 Gbps and beyond, even for short-link fibers dispersion will have to be managed due to this additional chirp.