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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.