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Report on the PhD work of Mr. Rafał Mirek
(Institute of Experimental Physics, Faculty of Physics, University of Warsaw)

After examining the thesis dissertation of Mr. Rafał Mirek, entitled "*Nonlinear effects of exciton polaritons applied in neuromorphic networks*", I consider that it fulfils all the requirements to grant him with a doctoral degree.

The manuscript contains new, original, and interesting results on the applicability of exciton-polaritons, and their non-linear properties, for future photonic devices, in particular for achieving optoelectronic neural networks.

It is also demonstrated that the candidate has acquired and mastered during the training period of his thesis the experimental competences to cope with the complex process of accomplishing the realization of these full optical neural networks.

The quality of the thesis results is also established by the papers related to the work, which are published in prestigious journals such as Physical Review Applied and Nanoletters, and by the Polish patent application on "*A device implementing a polariton optical neural network and a polariton optical neural network*". A further publication on "Spin polarization of exciton-polariton condensate in a photonic synthetic effective magnetic field" (arXiv:2211.02708) has also been submitted for publication. Moreover, the high-quality training received by the applicant, which is essential for receiving a doctoral degree, is very well established by his co-authoring of other fifteen publications, not contained in the thesis manuscript, realized under the supervision of Dr. Barbara Piętka, as well as by the additional Polish patent on "*Tunable optical microcavity for modulation and generation of specific radiation*".

Concerning the background, state of the art and collaborations of the work, the manuscript deals very satisfactorily with previous results of the systems investigated, presenting in great detail what is known about them and giving a large number of references. The state of the art, with the more recent studies, results and subjects that still need to be investigated is also very well given. The parts of the thesis manuscript that are made in collaboration with other researchers is clearly specified.

As for the scientific quality, methodology, and experiments realized in the work, it is clear the very high scientific quality of the work and that the methodology to study the optical and spin properties of polaritons, fabricating and characterizing the samples (including semimagnetic semiconductors), investigating their non-linear behaviour and creating neural networks is very appropriate: light transmission and emission, also under the presence of external magnetic

fields, provide the needed information, to walk through the full process for the final accomplishing of novel optoelectronic neural networks. The experiments and the results are of very high quality, made with great care and obtaining very reliable signals that can be analysed and treated to extract a great deal of novel and important information.

Let me insist a bit more on the personal contributions, originality, exploitation and application of results, and the prospects of the work. As already mentioned, the results are well based on what is already known about these materials in the literature but going well beyond this knowledge and contributing with new results to achieve the construction of new neural networks bases on exciton polaritons in semiconductor microcavities. Some of these experiments are reported for the first time and are therefore completely original, the contribution of the candidate to the experiments appears quite clearly in the manuscript and reflects the fact that he has himself contributed to the experimental setups. Aspects related with exploitation and possible applications of the results are summarized at the end of the corresponding chapters. There is also a full chapter (#12) dedicated to a comparison of the performance and energy efficiency of the investigated neural networks with other results available in the literature and the possible prospects for future improvements.

The writing of the manuscript and its organization is well done. In a first chapter the main concepts, ideas and start-of-the-art of the knowledge of polaritons in microcavities are presented. In the second chapter, neural networks as architectures that perform efficient data classification are introduced and the importance of nonlinear data transformation is shown. The main works existing in the literature are properly referenced to. A brief description of the samples and experimental details is presented in the third chapter. The following chapter describes and analyses natural photonic potentials existing in disordered samples and its use to create nonlinear systems and to achieve flow of polaritons between different localization centres. In chapter six, a way to improve the energy efficiency of components used for neuromorphic computing, based on lowering the condensation threshold of polaritons condensates, is investigated. The two following chapters make a small excursion on the path followed so far, and deal with the formation of half vortices and the phase build-up induced by polariton-polariton interactions, respectively, showing that the latter constitutes an easy manner to attain nonlinearities. A smart and attractive way to decrease the nonlinear threshold is presented in chapter nine, reusing the output signal from a condensate to re-pump it. Finally, as the ultimate goal of the work, the realization of an all-optical polariton-based neural network is presented in chapters ten and eleven, in the former using nonlinearities created in a single condensation site with a negative differential response and two auxiliary paths to perform logic operations with high energy efficiency and in the latter creating a binarized neural network using time-dependent interactions. Chapter twelve presents a brief outlook on the field. All

along the manuscript is clearly seen the ability of the candidate to conceptualize, design and implement his work to obtain novel and important results.

In summary, I believe that the manuscript presents new and very valuable results on polariton physics and the possibility to use their high nonlinearities to create efficient and reliable optoelectronic neural networks. It is well presented and clearly shows the degree of maturity reached by the candidate to obtain his doctoral degree. This piece of research is undoubtedly at the forefront of the research being undertaken nowadays in semiconductor microcavities.

There are no major weaknesses in the manuscript, along the manuscript the use of articles could be revised, sometimes definite instead of indefinite articles are used (or articles are missing), this in not very important but it would improve the readability and the quality of the, otherwise very good, manuscript. There are also some small typos in the manuscript and some figure captions that could be improved (adding for example extra labels or omitting some tic-marks), but which are not essential to correct.

Said all that, I think that Mr. Rafał Mirek´s thesis deserves a distinction. The experimental work is of high quality and novel, covering many aspects that the candidate demonstrates to master, with the results being published in high level scientific journals.

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