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Skolkovo Institute of Science and Technology

Jury Member Report – Doctor of Philosophy thesis.

Name of Candidate: Nikita Stroev

PhD Program: Physics

Title of Thesis: Modelling of exciton-polariton condensates for unconventional computing

Supervisor: Professor Natalia Berloff

Name of the Reviewer: Jonathan Keeling

I confirm the absence of any conflict of interest Jonathan Keeling	**Date: 04-11-2021**

The purpose of this report is to obtain an independent review from the members of PhD defense Jury before the thesis defense. The members of PhD defense Jury are asked to submit signed copy of the report at least 30 days prior the thesis defense. The Reviewers are asked to bring a copy of the completed report to the thesis defense and to discuss the contents of each report with each other before the thesis defense.

If the reviewers have any queries about the thesis which they wish to raise in advance, please contact the Chair of the Jury.

Reviewer's Report

Reviewers report should contain the following items:

- Brief evaluation of the thesis quality and overall structure of the dissertation.
- The relevance of the topic of dissertation work to its actual content
- The relevance of the methods used in the dissertation
- The scientific significance of the results obtained and their compliance with the international level and current state of the art
- The relevance of the obtained results to applications (if applicable)
- The quality of publications

The summary of issues to be addressed before/during the thesis defense

This thesis presents various work on controlling exciton-polariton condensates, and using them to perform computational tasks. The thesis contains new and important work on several topics: (1) routes to improve the performance of gain-dissipative optimisation by using complex couplings; (2) using the nonlinearity of exciton-polariton condensates to build an optical implementation of a pre-trained neural network; (3) work on preparing specific periodic polariton states, by engineering of dissipation. As discussed below, these works are in a field of current interest, and represent significant research progress. In addition, the thesis contains significant discussion of the broader context of novel approaches to computing ("unconventional computing"), and the requirements for hardware implementations of various ideas from machine learning. This presents a useful summary that could guide future research on exciton-polariton systems.

The topic of using exciton-polaritons, or other optical systems, for unconventional computing is one of significant current interest. As the thesis describes, there are a number of experimental groups that have worked on exciton polaritons, coupled lasers, optical parametric oscillation, and other platforms. There is also growing industrial research interest in this general area. However, there are unsolved questions about the prospects for these devices as compared to conventional computers: What are the ultimate limits and scaling of resources required with problem size? Do these approaches provide constant factor speedups, or different scaling with problem sizes? What routes exist to build large-scale exciton-polariton devices? The novel work in this thesis, reported in chapter three, works toward addressing several of these questions.

- The work on complex coupling coefficients (in section 3.2) provides a route to significantly increase the success probability of solving optimisation problems. This is a key advance for exciton-polariton optimisation methods, as it identifies a route to improve success probability, and this method is one which is naturally suited to gain-dissipative simulators.
- The work on implementation of the basic blocks of a neural network with exciton-polariton systems (section 3.4) demonstrates the possibility to directly implement neural network algorithms exciton-polaritons. As discussed in this section, this can provide a route to use future flexible and programmable exciton-polariton networks for these tasks.
- The discussion of how to engineer particular inhomogeneous density profiles provides a new way to think about controlling and engineering polariton networks. The approach described builds on ideas of using desired density profiles to determine required trapping potentials, and extends this to the case of engineering dissipation. By showing a number of analytic forms of profile, this section makes it easy to identify how the profile changes with parameters.

These three key results (as well as others) have been published by the candidate in well-respected international journals. They represent a significant contribution to the field, and I believe are suitable work for the award of a PhD.

The thesis is generally written clearly, although as noted below, there are a number of minor typos that should be corrected, as well as a small number of more more significant issues. The scientific writing is of a clarity comparable with much published literature. The introductory material sets the context of the novel work appropriately. As mentioned below, it would be helpful if the thesis did make clearer the novel contributions of the candidate; in places the boundary between new and background work is not always clear. However overall, with the corrections described below, the thesis would then be suitable to proceed to the defence.

Substantive issues to be addressed in the thesis

The abstract should be revised to make clear the new research contributions in the thesis. These are all mentioned, but the abstract does not distinguish sufficiently what is new and what is background.

On a similar theme, the section headings in section 3 do not always indicate the novel aspects of the work in a given section. For example, section 3.2 on tensor sum minimisation introduces the novel approach of complex coupling switching as a route to solve this problem. This key feature is not clear from the section name, thus hard to locate when considering the table of contents. The same point appears to other sections. I would suggest updating section names (and possibly adding subsections) to highlight what new ideas are introduced.

Chapter six discusses some perspectives of work on topics somewhat related to other chapters. Part of this discussion involves poor citation practice, in that the material in this chapter is very close in structure and wording to material in the papers cited. Particularly the text of section 6.2 is very close to material in references 444 and 346. Substantial rewriting would be required to make this acceptable in a published thesis. Given the material is not required for the thesis, I would strongly suggest to remove this material (possibly this whole chapter) to avoid this problem. I note that because of this suggestion, the list of typos and minor errors below does not include chapter six.

Minor issues/typos in the thesis

Throughout the thesis, many figures are not referenced from the text.

In several places "Schrodinger" is misspelled as Shrodinger.

P13, discussion of Chapter 4: "general mistake" → "general error"

P14, "domineering"→"dominant"

P20. The discussion around Eqs. 2.1 and 2.2 do not seem to be consistent: the meanings given to various terms do not seem to be consistent with the overall expression. If rho_nu is the energy density of the radiation modes, I would assume that 2.1 is meant to be the Rayleigh-Jeans (classical) law for this, while Eq. 2.2 is the corrected Bose-Einstein quantum version. If so, there are several unclear points.

Firstly, in the Rayleigh-Jeans law, the quantity E, describes as "the mean energy of an oscillator" should presumably become kB T/2, via classical equipartition. As written, E is not defined, making this expression unclear. It may be that the idea is that E = 0.5 * (hbar nu) * nB(hbar nu), so that this equation is already the Bose-Einstein version. However that is not stated. In any case, this should be clarified.

Secondly, in Eq. 2.2, alpha_Delta is defined as a transition probability, and "Delta epsilon" is not defined. If rho_nu in 2.2. still means the radiation density (i.e. if the quantity rho_nu has the same meaning in 2.1 and 2.2), then it does not make sense to define it in terms of transition probabilities.

P22. I would avoid referring to authors by just their first name. As such, suggest change "Lazlo submitted" → "Tisza submitted"

P22. "These separation" → "This separation"

P25. "Another recent result.." This is referring to "Another result around the same time…". The word "recent" implies it being near to the present time, not near to the time about which you are writing.

P25. "evaporate cooling" →" evaporative cooling"

P27. "prevails the decay" → "exceeds the decay"

P28. "If one quantize the field operator…". This is unclear, since the field operator in Eq. 2.19 is already quantized (already an operator). What you really mean is "If one writes the field operator in the momentum basis"

P30 "called the Lindblad super-operator". This is not quite right: Eq. 2.26 is a Lindblad super-operator. Eq. 2.25 is a Liouvillian super-operator.

P30 "in the current work" → "in that work". "Current work" refers to the document the reader is reading, i.e. the thesis.

P33 "minimize the amount of matter". Should this not read "maximize…" ?

P34 "Despite the spatial coordinates" → "As well as the spatial coordinates"

P36 "The purpose of this article" → "The purpose of this section"

P38 In the unnumbered equation between 3.21, 3.22, a quantity "d" is introduced (first term I a_i d) that is not defined. Please add a definition of d.

P41. In Eq. 3.30, u_l(t) is not defined. Should this be x_l(t)?

P52 "sterngths" → "strengths"

P61/62 Over these pages, a number of different scenarios are presented, and forms of rho(x) presented. Some of these appear as displayed equations (i.e. numbered equations), while some are inline equations. There does not seem an obvious reason for this different treatment. I suggest to make the treatment uniform.

P62. Reference to Figs 2-4 probably means Fig. 3-14

P63. It would be helpful if the caption to Figure 3-14 explained the difference between panels (a,b), rather than just refer to equations.

P67 "can me mapped" → "can be mapped"

P68, Figure 4-2. The numbers on the arrows are very hard to see due to the dark shading of the arrow.

P68 "penalazing term". If this phrase is really wanted it should be spelled "penalizing term". However a better phrase is "cost function".

P69 "Lagrangean" → "Lagrangian"

P71 In Eq. 4.10 it is unclear why the penultimate term still involves powers of x; this may be a typo.

P71 In Eq. 4.11, the quantity x^l_{ij} has not been defined.

P71 "standartized" → "standardized"

P73 "reffers" → "refers"

P76 "it's a more narrow". Should this read "its more narrow"? The current phrasing does not make sense.

P76 "It is possible can" → "It is possible to"

P77 Does "original binary form" mean "original quadratic form"?

P84. There is a reference to "The next chapter will consider .." that seems to refer to material in chapter three. If this is the case, change this to read "In chapter three, we already discussed the dynamical aspect of the minima search." or equivalent.

In the references, there are a number of titles that ought to have capitalisation, e.g. of "bose-einstein condensates". I note also Ref. 120 misformats editor names

Topics to be addressed in the defence

Regarding the discussion in chapter 3 (particularly around page 40), I would like to discuss how one connects the introduction of complex coefficients in the rate equations to the heteroclinic structure. Is there direct evidence that the speedup is associated with heteroclinic connections? I would also like to discuss further how this process guarantees energy minimization: is the process autonomous, or does it require external intervention to introduce complex coefficients only when the energy is too high?

On page 45, there is a statement that an SLM can be used to produce a one-way connection between parts of the system. I am unclear how this works, and would like to explore this further. Specifically, it's unclear this element on its own breaks time-reversal symmetry, and thus unclear how it produces a one-way connection. In general I might have expected to require a magneto-optic Kerr effect, to break reciprocity.

It would be interesting to explore whether there are routes to using the exciton-polariton network approach not only to encode the output of a learning process, but also to support learning? i.e., does there exist an approach to fix the topology of the network, but dynamically update coefficients or inputs, so as to implement learning within the network.

I do not understand the meaning of the branching in the self-locking approach shown in Fig 3-10. The description suggests the idea of this approach is that the state is encoded in a fixed system that is then sequentially updated. As such it is unclear what branching of this means; does it require duplication of the system?

In the context of engineering periodic density profiles, it would be useful to discuss the reasons such a profile is desired. This would help explain what particular choices might be desired.

In chapter four, if there is time, I would like to see a further discussion of the link from Eq. 4.27 to Eq. 4.3.

Provisional Recommendation

☐ *I recommend that the candidate should defend the thesis by means of a formal thesis defense*

☒ *I recommend that the candidate should defend the thesis by means of a formal thesis defense only after appropriate changes would be introduced in candidate's thesis according to the recommendations of the present report*

☐ *The thesis is not acceptable and I recommend that the candidate be exempt from the formal thesis defense*