REVIEW

of dissertation

for obtaining the scientific degree “Doctor”

in the professional research field 4.1. Physical sciences (Physics of atoms and molecules)

in defense procedure at the Faculty of Physics

at Sofia University “St. Kliment Ohridski”

The review was prepared by Assoc. Prof. Boyan Tonev Torosov, Institute of Solid State Physics, Bulgarian Academy of Sciences, as a member of the scientific jury according to Order № RD 38-321 / 06.07.2023 of the Rector of Sofia University.

Dissertation title: “Design of Composite Pulse Sequences for Quantum Tecnnologies”
Author of the dissertation: Hayk L. Gevorgyan

I. General description of the submitted materials

1. Description of the submitted documents

The candidate Hayk L. Gevorgyan has presented a dissertation and a thesis summary, as well as the mandatory tables for the Faculty of Physics from the Regulations on the terms and conditions for acquiring scientific degrees and holding academic positions at Sofia University “St. Kliment Ohridski ”. There are also additional documents (such as curriculum vitae, diploma for master degree, statement of authorship, anti-plagiarism statement, and reference for fulfillment of the minimum requirements), supporting the achievements of the candidate.
The documents submitted for the defense by the candidate comply with the requirements of the Development of Academic Staff in the Republic of Bulgaria Act and the Regulations for its application and the Rules of Procedure and the Regulations on the Terms and Conditions for Acquisition of Scientific Degrees and Academic Positions at Sofia University “St. Kliment Ohridski”.

2. Data for the applicant

Hayk L. Gevorgyan graduated as a “Physics” bachelor from the Yerevan State University in 2016. In 2018, he obtained a master’s degree in “Physics, Photonics and Nanotechnology” from the University of Burgundy in Dijon, France. He has been a PhD student at the Yerevan Physics Institute in the period 2018-2021. Finally, he has continued his PhD studies at Sofia University “St. Klimend Ohridski”, within the group of Quantum Optics and Quantum Information, supervised by prof. Nikolay V. Vitanov. His work during the PhD studies has been mainly focused on developing robust and high-fidelity quantum gates, based on composite pulses.

3. General description of the candidate's scientific achievements

The primary focus of the dissertation is the development of novel composite-pulse sequences with a focus on applications in quantum gates, as well as classical optics. The research was conducted under the supervision of prof. Nikolay V. Vitanov and in cooperation with other members of the Quantum Optics and Quantum Information Group at Sofia University. The dissertation is based on five scientific publications: one of these has been published in a high-impact journal (Q1), one is a conference paper, and three submissions to the arXiv. Being the first author, I assume that the contribution of the candidate in all five publications is essential. Therefore, the dissertation complies with the minimal requirements for acquisition of the scientific degree "Doctor". Furthermore, the scientific publications in the dissertation do not repeat those from previous procedures for acquiring a scientific title and academic position. Finally, according to the anti-plagiarism statement, there is no proven plagiarism in the submitted dissertation and the Summary.

4. Analysis of the basic and applied scientific achievements of the candidate as evident from the documents for participation in the procedure

The main scientific and applied contributions of the present dissertation are in the field of quantum control, with applications in quantum computing and classical optics. In particular, the powerful control tool of composite pulses is extensively used to generate a large number of sequences for robust and high-fidelity quantum gates, as well as to develop optical devices, such as broadband nonreciprocal polarization waveplates and optical isolators.

The dissertation is presented in eight chapters:

- The first chapter introduces the most common quantum gates used in the thesis and also explains the general idea behind the method of composite pulses.
- Five chapters, focused on deriving novel composite sequences for generation of quantum gates.
- A chapter in which composite pulses are used to create broadband nonreciprocal wave retarders.
- A conclusion chapter.

In each chapter, the contribution results can be classified as enrichment of existing knowledge and application of scientific achievements in practice.

Composite pulses are a technique used in quantum physics and quantum information processing to mitigate errors caused by imperfections in the control of quantum systems, particularly in quantum gates and quantum state preparation. The basic idea behind composite pulses is to apply a sequence of carefully designed pulses or gates that, when combined, effectively cancel out the errors that would otherwise accumulate during the operation. These sequences are tailored to the specific characteristics of the quantum system and the types of errors it is susceptible to. Composite pulses are particularly useful in the field of quantum computing, where precise control over qubits is essential for performing accurate quantum operations. By using composite pulses, researchers can enhance the fidelity and reliability of quantum gates and reduce the impact of noise in quantum hardware.

Initially developed in polarization optics and nuclear magnetic resonance, nowadays composite pulses are a widely used control technique with numerous applications in other areas, such as trapped ions, neutral atoms, quantum dots, superconducting qubits, optical clocks, atom optics, and magnetometry. In the present dissertation the composite-pulses method has been used to derive a large variety of broadband, narrowband, and passband quantum gates, as well as broadband nonreciprocal wave-retarders.

The dissertation starts with an introductory chapter, where some relevant background information is provided. First some commonly used gates are presented, such as the Pauli X, Y, and Z gates, the Hadamard gate, rotation gates and phase-shift gates. The chapter follows with a brief introduction to the composite-pulse idea, presenting some popular sequences, such as Wimperis, Tycko and SCROFULOUS pulses.

Chapter 2 dives deeper into the composite-pulse theory, providing information about the SU(2) method and details about how the composite sequences are being derived. The main results in this chapter are the derivation of composite sequences which produce robust (broadband) rotations on the Bloch sphere along the X axis. The composite sequences contain up to seventeen pulses and can compensate up to eight orders of experimental errors in the pulse area. Beside the general qubit rotations, two particular cases of interest are examined, namely the sqrt(X) gate (pi/2 rotation) and the X gate (pi rotation). The performance of all derived sequences has been tested by defining the fidelity of the operation as the Frobenius distance between the produced unitary and the target operation, and plotting it as a function of the deviation in the pulse area. The derived sequences show a very good robustness, as evident by the broadband profiles on the plot, and outperform the existing composite rotations by either speed or accuracy, or both. It is also worth saying that the author has chosen a very conservative fidelity measure, such as the Frobenius norm. A different fidelity choice would result in even more impressive excitation profiles.

In Chapter 3, a number of composite sequences are derived to produce robust phase-shift gates. Three particular gates of interest are investigated, namely the Z, S, and T gates. The composite sequences contain up to 18 pulses and can compensate up to eight orders of experimental errors in the pulse amplitude and duration. The short composite sequences (up to 8 pulses) are calculated analytically and the longer ones numerically.

In Chapter 4 the author presents narrowband and passband composite pulses for generation of single-qubit rotation gate. As in Chapter 2, the special cases of pi and pi/2 rotations are separately examined. Three types of optimization methods have been used — SU(2), modified-SU(2), and regularization. Two types of composite pulses are proposed – called *pari passu* PN and *diversis passum* DN, with different sensitivity and robustness orders. PN sequences are derived by the regularization method, and show systematic improvement in all the performance characteristics — sensitivity, ro-

bustness and rectangularity. DN sequences are derived by the SU(2) method, although regularization method can also be used. The results in this chapter could find applications to quantum sensing.
In Chapter 5, the interesting problem of generating well-defined very small excitation of a two-state quantum transition is examined. Once again, the method of composite pulses is applied by using sequences containing two, three, four and more pulses. Both symmetric and asymmetric, analytic and numeric classes of sequences have been presented and analyzed in detail. The results in this chapter can be useful in application such as single-photon generation by a cold atomic ensemble of N atoms. A composite sequence producing a transition probability of 1/N will make sure that only one excitation is shared within the ensemble. Another possible application is fine tuning of quantum gates, in which accurate small adjustments of the rotation angle are needed in order to reach high fidelity. Yet another application is the generation of huge Dicke states in cold atomic ensembles or trapped ions by global collective addressing.
Chapter 6 addresses the problem of ultrarobust and ultrasensitive control by using composite pulses. The idea is to sacrifice some of the ultrahigh fidelity of the composite pulses to gain extra robustness or sensitivity. The ultrarobust class plays a role for design of achromatic polarization retarders, while the ultrasensitive class corresponds to polarization filters.
Chapter 7 provides a technique for constructing broadband nonreciprocal wave retarder whose quarter-wave plate phase retardation is the same in forward and backward directions. The system is built using a number of sequential nonreciprocal waveplates with the optical axis of each rotated by appropriate angle. The proposed device can also be utilized to create a broadband optical diode, which consists of two achromatic quarter-wave plates, one reciprocal and the other non-reciprocal, that are sandwiched between two polarizers aligned in parallel.
The conclusions and the future perspectives of the dissertation work are summarized in Chapter 8. The publications used, as well as the conference presentations of the author, are summarized in the Appendix.

5. Critical remarks and recommendations

The dissertation is well written and easy to follow. I particularly enjoyed the adopted LaTeX style and the numerous hyperlinks within the PDF, which made the reading seamless. The Bulgarian translation of the abstract is not great, but I see this requirement only as a formality, so I wouldn't delve too much into it.
I have the following questions/comments on the dissertation:

- I find the definition of the single-qubit gates a little confusing. For instance, Eq. (1.7) [and also Eq. (2.12)] defines the X gate in the way in which traditionally is defined the Y gate (up to a –i factor). Furthermore, the Hadamard gate is defined as a pi/2 rotation along the Y axis [See Eq. (1.9)], while traditionally it is defined as a pi rotation along the XZ axis. In the dissertation, this pi/2 Y rotation is called a "pseudo-Hadamard form", but no reference to the literature is presented.

- Chapter 3 presents composite sequences for generation of phase-shift gates. It is not clear to me what would be the benefit of using such an approach, instead of what is now the standard method of virtual Z rotations, implemented virtually in hardware via frame changes, and having zero error and duration [See e.g. McKay et. al., Phys. Rev. A **96**, 022330 (2017)].

- The dissertation only considers errors in the pulse area and zero detuning. However, in many situations detuning errors are even more crucial. It would be nice to see some results (or at least comments) along this line, although I realize that this would require further investigation.

- The title of Chapter 4 suggests that some applications to quantum sensing would be examined. However, no such thing can be found in the chapter, apart from a short comment mentioning a few possible applications.

- At some places in the dissertation the author writes “in this paper” instead of “in this chapter”.

- Chapters with longer names (such as Chapters 5 and 7) have page headers which cannot fit the whole name length.

6. Personal impressions of the candidate

My limited interactions with the candidate were not enough to form an opinion.

7. Conclusion

After getting acquainted with the presented dissertation, summary and other materials, and based on the analysis of their significance and the contained in them research and applied contributions, I **confirm** that the scientific achievements in the dissertation meet the requirements of Development of Academic Staff in the Republic of Bulgaria Act and the Regulations for its application and the relevant Regulations of Sofia University "St. Kliment Ohridski” for obtaining the scientific degree “Doctor”. In particular, the candidate exceeds the minimum national requirements in the professional field and no plagiarism has been established in the dissertation, summary and scientific papers submitted at the competition.

I give my **positive** assessment of the dissertation.

II. OVERALL CONCLUSION

Based on the above, I recommend the scientific jury to award the educational and scientific degree “Doctor” in the professional field 4.1 Physical Sciences to Hayk L. Gevorgyan

18 Sept 2023 Reviewer signature: ....

(Assoc. Prof. Dr. Boyan Torosov)