REVIEW

of dissertation work
for the acquisition of educational and scientific degree " Doctor "
in professional field 4.1 Physical sciences
under the defense procedure at the Faculty of Physics (FZF)
of Sofia University "St. Kliment Ohridski "(Sofia University)

The review is prepared by: Assoc. Prof. Dr. Naoum Ivanov Karchev in his capacity as member of the scientific jury according to Order № РД 38-251 / 23.05.2022 ... of the Rector of Sofia University.

Topic of the dissertation: "Application of Coherent Quantum Control Schemes in Classical Physics "

Author of the dissertation: Mouhamad Al-Mahmoud

I. **General description of the submitted materials**

1. **Data on the submitted documents**

The candidate Mouhamad Al-Mahmoud has presented a dissertation and an abstract, as well as the mandatory tables for the Fakulty 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 7 other documents (diploma , CV , 5 publications related to the dissertation.

Notes and comments on the documents.

The documents submitted for the defense by the candidate meet the requirements of (ZRASRB, PPZRASRB) and the Requlations on the terms and conditions for obtaining scientific degrees and holding acamemic positions at Sofia University “St.Kliment Ohridski” (PURPNSZADSU) .

2. **Candidate details**

The candidate received a bachelor's degree in physics from the University of Lebanon in Lebanon in 2015. He received his master's degree from the University of Metz in France in 2018. In his master's program he studied quantum physics, electromagnetism and programming (Pyton & Mathlab). In the second year he studied photonics, optics and materials.

From 2017 to 2020 he is a freelance teacher. He teaches mathematics and programming at Metz University.

The candidate's research activity is dedicated to the study of various schemes for Coherent Quantum Control and the possibility of using the mathematical formalism describing these systems in solving problems related to classical optical systems. He is also involved in the design of optical systems.

3. General characteristics of the candidate's scientific achievements

The candidate's research work is dedicated to the study of various schemes for Coherent Quantum Control and the possibility of mathematical formalism describing these systems to be used in solving problems related to classical optical systems. He is also involved in the design of optical systems.

The scientific publications included in the dissertation meet the minimum national requirements (under Art. 2b, para. 2 and 2 for ZRASRB) and the additional requirements of Sofia University "St. Kliment Ohridski "for acquiring the educational and scientific degree
"Doctor" in a professional field 4.1 Physical sciences
The scientific publications included in the dissertation do not repeat those of previous procedures for acquiring a scientific title and academic position.
There is no legally proven plagiarism in the submitted dissertation and abstract.

4. Characteristics and assessment of the teaching activity of the candidate.

I have not information for the pedagogical activity of the candidate and cannot to appreciate it.

5. Content analysis of the scientific and scientific-applied achievements of the candidate contained in the materials for participation in the competition

The main goal of the Dissertation is theoretical research of optical systems with new or better properties than those of known systems. The theoretical results are experimentally confirmed by the author of the dissertation and his colleagues. The main idea is to use mathematical formalism in the study of quantum systems to study classical optical systems. This quantum-classical analogy is the driving force in obtaining new classical systems.

Chapter 2 of the dissertation is devoted to the techniques of coherent quantum control.

Coherent control aims to direct the quantum system from the initial state to the target state by means of an external field. For given initial and final (target) states, the coherent control is called state-to-state control. These coherent quantum control techniques are widely used in magnetic resonance imaging, quantum optics, and atomic physics.

The most widely used quantum systems are two- and three-level systems. They allow, using an external field, to obtain states that are superposition of the base states.

In the case of a two-level system, the basic notions are: **the detuning parameter** Δ which is the difference between the frequency of the applied field and the Bohr frequency and **the Rabi frequency Ω** which characterizes the strength of interaction of the quantum system with the external electric field.
A new step that leads to greater accuracy and stability of the parameters of the final state is the use of **composite pulses.** The idea is to simulate the effect of a single pulse through a series of consecutive pulses with constant amplitude, fixed frequency and different phases. Success depends on the choice of pulse phases. Time evolution is given by the Schrödinger equation in which the Hamiltonian is a 2x2 **H (t) matrix** that depends on the time. The solution of this equation is called **the evolution matrix U** which is used to calculate the Probability **P** of the transition from the initial state to the final one. For a series of N pulses, each with its own parameters, the evolution matrix is the product of all evolutionary matrices.

The three-level quantum system has initial, intermediate, and final states. In order to transfer the population from the initial state to the final one, two laser fields must be applied. Pumping, with Rabi Ω p frequency and Stokes field with Rabi Ω s frequency . The evolution of the system is described by the Schrödinger equation in which the Hamiltonian is a time-dependent 3 x3 matrix. The system has two detuning parameters. When they are equal, the task is simplified in a certain basis (light-dark basis) and even after a series of assumptions it is reduced to a Hamiltonian problem. which is a matrix of 2 x2 . This procedure will be used in the quantum-classical analogy. The ideas presented in Chapter 2 will be used in other chapters to describe classical optical systems.

In **Chapter 3** of the dissertation the author discusses classical optical systems by means of the analogy of the mathematical formalism which describes them and the formalism used for the quantum systems discussed in Chapter 2. The author considers three classical systems: a system in which the polarization is manipulated, in which there is a process of optical parametric amplification (OPU) of the signal and a system describing a lossy environment in which cascading nonlinear frequency conversion is performed.

Section 3.1 is devoted to the ***polarizing rotator*** . The wave plate is an optical device that changes the polarization of the light wave passing through it. In **3.1** of the dissertation a new design of a ***polarizing rotator is proposed.*** To accomplish it, the analogy between the equations describing the polarization of light and the Schrödinger equation for a two-level system is used. The polarization rotator proposed in the dissertation consists of three wave plates. The first and third plates are half the wavelength and they shift the direction of polarization of linearly polarized light, and the plate between them is a solid-wave plate of the same wavelength.
The dynamics of the polarization of light in Jones ' formalism is described by a two-component Jones vector that characterizes the state of light flux. It satisfies an equation analogous to Schrödinger's equation in quantum theory of two-level systems. Jones ' formalism is also based on a

Jones matrix describing the properties of the optical system. In this case, the matrix is 2x2 and depends on the angle of rotation Θ in the plane of polarization and the angle φ which is characteristic of the birefringence effect. The Jones Matrix , Eq. 3.8 in the dissertation is identical to the matrix of evolution in quantum mechanics of a two-level system (Eq. 2.18). This analogy of mathematical formulas allows us to write the Jones matrix for a sequence of optical plates as a product of the Jones matrices for each of the plates. The analogy is obvious, it suffices to compare Eq.3.12 for optical systems and Eq.2.1.1 for the matrix of evolution of a quantum system with several consecutive pulses. Finally, the author has defined the precision parameter Eq. 3.10 in the same way as is defined the parameter for quantum systems Eq. 2.20. Thus, the quantum-classical analogy allows theoretically to develop a stable broadband polarization rotator by means of three wave plates. This is a new result, as the rotators known so far consist of 6 or more plates. It is published in Physical Review Applied 13, № 1 (2020) 014048.

Chapter 4 describes a simple polarization rotator circuit consisting of only three wave plates. The scheme has been confirmed experimentally. The theory and experiment are published in Physical Review Applied 13, № 1 (2020) 014048.

Section 3.2 is devoted to ***nonlinear optics*** . When the polarization of a material to which a field is applied depends linearly on the field, we say that we have linear optics. When the polarization depends on the field of second or higher degree we say that we have nonlinear optics.

Nonlinear optics can be generated using two fields with different frequencies. The frequency of the received field can be the sum or difference of the frequencies of the input fields. There are two cases : SFG and DFG respectively . An important application of this process is the generation of controlled frequency radiation in the ultraviolet region by combining a frequency fixed laser with a frequency adjustable one. Both processes are illustrated in Figure 3.4 . The diagrams show an analogy with a three-level quantum system in Figure 2.1, which is particularly well demonstrated in the DFG process (Figure b) . This analogy was used to develop the theoretically stable generation of new frequencies in nonlinear crystals. This is a new theoretical result.

Section 3.2.5 is devoted to **Optical Parametric Amplification (OPA)** . Optical parametric amplification is an optical process that results in signal amplification at the expense of an applied field-pump. This is a special case of DFG , as the two input fields are that of the signal and the pump. Optical parametric amplification is based on the nonlinear interaction of three waves. Two waves with longer wavelengths and a pumping wave that is the shortest. In order to achieve high amplification of broadband bandwidth, the author considers a model with a segmented crystal. At the domain boundaries, the effective second-order susceptibility (the coefficient in front of the square of the applied field in the polarization expression) changes its sign. This is done to have an analogy with the composite pulses discussed in Chapter 2 of the dissertation in Nuclear Magnetic Resonance Imaging. Thus, the three equations for mixing waves are similar to the Schrödinger equation. In the quantum mechanics the wave function depends on the time, while in the present case the amplitude depends on one of the coordinates. The solutions are obtained numerically, which allows to reach the broadband frequency band where the amplification takes place. This is done for lithium niobate (LiNbO h). These studies are theoretically and numerically discussed in **Chapter 7** of the dissertation where the possibilities for increasing the stability of optical processes in a circuit are discussed. The result is published in Applied Science 10,, № 4 (2020): 1220 . It is a new scientific result.

Section 3.2.6 reveals the analogy between **Cascading Nonlinear Frequency Conversion in a Lossy Environment** and a non-Hermitian quantum system with three states. Using this analogy, the goal is to create a nonlinear crystal that maintains a stable spatially stable intensity. The analogy is illustrated in Figure 5.1 in the Abstract where a three-level Lambda quantum system suggests how to perform a cascading nonlinear frequency conversion. A second-order nonlinear crystal is considered. The frequency of the input wave ω_1 is converted by the process of generating a total frequency using an intensive pump with frequency ω_{p1} into an intermediate wave with frequency ω_2 which is absorbed and interacts with the second intensive pump to generate the target wave with frequency ω_3. The basic idea is to use strong losses for the intermediate wave while the other waves remain lossless. Ultimately, using the analogy between a three-state quantum system and the cascade generation of a nonlinear frequency in a lossy medium, the author creates a model for the sustainable generation of new frequencies in nonlinear crystals. This is a new theoretical result.

Two problems are described by the author, and their solution does not require the use of analogy with quantum systems. The first is **the design of a non-reciprocal wave plate.**

The conventional wave plate is a lossless optical element and as such allows light to propagate back and forth through the plate with the same phase shift. Chapter **6** offers an idea for creating a wave plate with adjustable non-reciprocity. The non-reciprocal polarization wave plate designed by the author and colleagues is based on a combination of reciprocal and non-reciprocal rotator placed between two quarter wave plates. This is a new idea and the result has been published in *OSA Continuum* **4** , 2695-2702 (2021).

The second task is to design and experimentally test a **Polarized Independent Optical Isolator in a specific configuration.** The scheme is based on a new type of annular optical isolator. The advantage is that there is no difference between the optical paths of the two orthogonal polarizations. The designed optical insulator is resistant to changes in length.

6. Critical remarks and recommendations

The most important critical note is the difficult connection between the dissertation and the abstract. Some figures in the abstract are not included in the dissertation, such as fig. 5.1 which is very useful figure. The numbering of the chapters and sections in the dissertation is not used in the abstract. The order of presentation has even changed.

I would also like to point out a few technical errors: page 27 of the dissertation and three rows above it.

7. Personal impressions of the candidate

I do not know the canditate personally and I have no personal impressions.

8. Conclusion

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

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

II. GENERAL CONCLUSION

Based on the above, I **recommend** the scientific jury to award the **educational and scientific degree "Doctor"** in a professional direction 4.1. Physical Sciences of Mouhamad Al-Mahmoud

17.06.2022 г. Prepared by the review : Associate Professor Dr. Naoum Ivanov Karchev

(academic position, scientific degree, name, surname)