REVIEW

of the PhD thesis

for obtaining the educational and scientific degree "Doctor"

in professional field 4.1 Physical sciences,

on defense procedure at the Faculty of Physics

of Sofia University St. Kliment Ohridski

The review is prepared by: Prof. Asen Enev Pashov, Sofia University St. Kliment Ohridski, Faculty of Physics, a member of the scientific jury according to Order РД38-251/23.05.2022 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

Candidate details

Mouhamad Al-Mahmoud obtained his BSc degree in the Lebanese University in 2015 and his MSc degree in the Université de Lorraine, Metz, France in 2019. Since then, he has been working in several scientific laboratories in the Université de Lorraine, Paris-Saclay University, Technische Universität Darmstadt and in the Sofia University. The projects were mainly in Optics, including waveguides and non-linear optics. His collaboration with prof. N. Vitanov and assoc. prof. Andon Rangelov turned out to be very successful and resulted in five papers, which are the base of his thesis. Since 2022 Mr. Al-Mahmoud become officially a PhD student in the Sofia University after he presented a significant part of his thesis, the list of publications and obtained a very positive response from the Department of theoretical Physics at the Sofia University. The supervisor is assoc. prof. DSc Andon Rangelov.

General characteristics of the candidate's scientific achievements

The dissertation by Mr. Al-Mahoud presents his research in the field of Quantum control, applied in classical physics. Such a contra-intuitive combination is possible due to the existing analogies between laws describing phenomena of quantum and classical physics. The basic idea of analogies is that if two phenomena are described by the same equations, it should be possible to observe similar (analogous) behavior of the described quantities. Also, the solutions of the equations describing one of the phenomena can be directly transferred to the other phenomenon.

In his thesis Mr. Al-Mahmoud demonstrates applications of experimental techniques developed and originally applied in Atomic and Molecular physics to prepare the small quantum system in arbitrary quantum state with nearly 100% efficiency. Such schemes (e.g. STIRAP) were proved to be indeed very efficient in some cases, but in general this happens when particular parameters (laser intensity and frequency, time of interaction of the system with the laser radiation etc.) are properly adjusted. In is not unusual that in practice it is very difficult to realize these idealized conditions and therefore, in the group of Quantum optics and quantum information several techniques were developed - generalized as Quantum control. These techniques are based on a series of interactions between the quantum system and coherent optical field, appropriately chosen to minimize the decrease of efficiency due to deviations of the above-mentioned parameters from their expected values. Chapter 2 of the thesis is devoted to brief introduction to the Quantum control and the main concepts are presented. Then, in chapter 3, possible applications of Quantum control in classical objects, relevant for the thesis are discussed, namely manipulation of the polarization and wave mixing in non-linear optical media.

In the following five chapters some particular realizations are discussed.

In Chapter 4 a broadband polarization rotator with tunable rotation angle composed of three wave-plates is presented. The analogy between the manipulation of the atom's state by light and the polarization state by birefringent media has been pointed out already in 2010 by A. Rangelov and co-authors (Opt. Commun. 283, 3891-3894 (2010)). Since then several devices for manipulation of the polarization of electromagnetic wave have been proposed. The design presented in the thesis and paper 1 of the author's list is simpler than earlier broadband composite rotators (including the one from paper 5). The rotation angle can be tuned by rotating only one of the wave-plates, it is robust against the initial polarization direction and this should be compared with the previous devices composed of a larger number of wave-plates.

In Chapter 5 a tunable non-reciprocal wave retarder is proposed. The goal is to realize a device whose phase retardation depends on the direction of light propagation. A typical example of such devices is the optical isolator, which is used in laser laboratories to prevent the illumination of the laser with back reflected or scattered light. The system, proposed by Mr. Al-Mahmoud is based on a combination of a reciprocal polarization rotator, a non-reciprocal magneto-optical rotator, and two quarter-wave plates. When compared to the traditional design (two polarizers and a magneto-optical rotator) the new device seems to be quite complicated. However, the goal of the authors is (i) to propose a broadband device and also (ii) to make the device insensitive to the polarization of the laser light. Such device is presented in the next Chapter 6. Here, the concept of the tunable non-reciprocal wave retarder is developed and demonstrated experimentally. At the end, the author discusses application of the retarder other, than the optical isolator.

A Polarization Independent Optical Isolator is described in Chapter 6. The design is based on two Faraday rotators, two half wave plates, polarization beam splitter and a linear polarizer. It is a smart solution, demonstrated in an experiment to provide isolation above 43 dB for all input polarizations. Usual optical isolators operate at linear input polarization and very often at the output the polarization of the laser light is changed. The device from this chapter operates at arbitrary input polarization and at the output the polarization state of the laser light is preserved. The price to pay for this are the two nonreciprocal polarization switches which rotate the polarization of the light by 90 degree. The device became quite sophisticated although it is justified by the new functionality. Moreover, at the end of Chapter 6 a version with only one Faraday rotator is presented. The device from this Chapter is not broadband. It is, however, at least tunable in the same way as the commercial isolators are – namely by changing the length of the Faraday crystal in the magnetic field. I am curious, how to build an isolator, working in a relatively broad wavelength region. Are the ideas proposed e.g. in Appl. Opt. 52, 8528 (2013) applicable?

Chapters 7 and 8 present ideas from a different area of physics, that of nonlinear optics. In Chapter 7 Mr. Al-Mahmoud takes advantage of the analogy between the equations describing the dynamics of three level quantum system and the mixing of three electro-magnetic waves in a non-linear media and suggests a technique for composite Optical Parametric Amplification (OPA). In general, OPA allows for mixing of two waves to produce a wave with the sum of their frequencies ($\omega_1+\omega_2$) or with the difference ($\omega_1-\omega_2$). The process attracts a lot of attention in modern optics, it is the principle of operation of many commercial devices. The problem of the three-wave mixing is the phase matching (Eq. 3.50 of the thesis). For relative long laser pulses (few ns and narrow-band radiation), the OPA may be used as a tunable light source. Then the phase matching is realized through rotation of the nonlinear crystal as a function of the generated wavelength, which is a tedious, but still possible operation. When using OPA together with very short pulses (broad-band radiation) the phase matching cannot be realized simultaneously for the whole spectral region, and this is a serious limitation. Mr. Al-Mahmoud presents an overview of the existing solutions and then suggests a new approach. It is borrowed from the composite pulses' technique in the Nuclear-Magnetic-Resonance, later extensively utilized in quantum physics for coherent control and already applied for second harmonic generation. The idea is to use a series of non-linear crystals, stacked together, with alternating sign of the non-linear susceptibility. Parameters for optimization are the lengths of the crystals and the author demonstrated very impressive simulation where very high efficiency is achieved within a ca. 200 nm spectral region. This technique was not demonstrated experimentally, unfortunately, but it is clear that contrary to the experiments with polarization (Chapters 3-6), the experimental conditions here are much more demanding and the fabrication of a composite crystal with the desired properties is a task, which requires special equipment, unavailable in the standard optical laboratories. Hopefully the idea will inspire companies able to produce such crystals.

In Chapter 8 of the thesis, we read about the application of the composite pulses' technique for nonlinear frequency conversion. The nonlinear media again, as in Chapter 7, is constructed as a series of stacked plates with alternating signs of the non-linearity. The concept of cascaded nonlinear frequency conversion is not new, and the author provides sufficient references, illuminating the progress in the field, the achievements and also the problems so far. The novel idea here is to use the losses in the non-linear media as effect and stabilize the number of photons of the interacting waves. The goals were achieved by optimizing thickness of the segments of the crystal. I appreciate the limitations set during the optimization procedure, namely, to avoid thicknesses bellow 5 μm. Apparently, like in the rest of the thesis, the author is always trying to push his theoretical considerations to a working, at least proof-of-principle device and similarly to the composite Optical Parametric Amplification, this idea again requires much more sophisticated equipment.

Critical remarks and recommendations

The PhD thesis is written in a very good English, the presentation is clear. The organization of the thesis also facilitates the reding. Before each chapter there is a brief introduction and at the end – conclusions.

I do not have general remarks, just a comment on the style of the presentation. Parts of the thesis provide a lot of details on selected topics (theoretical chapters 2 and 3 for example), some issues, however, are much less detailed (details of the numerical calculations and optimizations, software, used for calculations etc.). For me such details are suitable for a PhD thesis, which is supposed to demonstrate, among others, the broad spectrum of expertise of the author.

I have few questions, to be addressed during the defense:

1. What is TE and TM? These terms are used, but not defined.
2. In Chapter 6, it is said, that the device is based on two Faraday rotators in combination with two half-wave plates …. In fact I see two more polarizers. Why these are not mentioned?
3. Why the isolation in Fig. 6.7 depends on the polarization? What is the origin? The theory does not predict it.
4. Chapter8. Show, please, an example of optimized cascade nonlinear media (number and lengths of the crystals, non-linear parameters).

The dissertation is based on five publications in good journals, Mr. Al-Mahmoud is the first author in the list of authors in four of them, which expresses the recognition of the co-authors that his contribution is significant. The last paper is in a co-authorship with Ms. Elena Stoyanova and I can find it also in the list of publications for her PhD thesis. Mr. Al-Mahmoud, however, does not claim to have significant contribution in this study, the results are not reported in his thesis, so I see no contradiction.

Conclusions

The results, presented in the thesis, are impressive. I am convinced that his contribution to the work reported in the thesis is significant, the research is at a very good level. The dissertation, the abstract and the scientific publications of Mr. Al-Mahmoud cover the minimum national scientific requirements of ZRAS and the Regulations to it, as well as the requirements of the Faculty of Physics of Sofia University St. Kliment Ohridski. I support the award of the educational and scientific degree "Doctor".

17-06-2022

Sofia

Asen Pashov

Digitally signed by Asen Pashov
Date: 2022.06.17 13:36:03 +03'00'