REVIEW

of the doctoral thesis
in the competition for the acquisition of the academic degree “Doctor of Science” in Physics,
in the professional field 4.1 Physical Sciences (Physics of Atoms and Molecules) in the Faculty of Physics of Sofia University “St. Kliment Ohridski”

Written by: **Prof. D.Sc. Ivan M. Uzunov,** Faculty of applied mathematics and informatics – Technical University Sofia, in his capacity of a member of the scientific jury in accordance with the order № РД 20-127 / 22.01.2021 of the Rector of Sofia University “St. Kliment Ohridski”.

Topic of the doctoral thesis: “Quantum-optical analogies”
Author of the doctoral thesis: Associate Professor Dr. Andon Angelov Rangelov

I. General description of the manuscript

1. Overview of the submitted set of documents

The candidate, Associate Professor Dr. Andon Angelov Rangelov, has provided the documents required by article 78 of the Rules for the conditions and order for the obtaining of academic degrees and acquiring academic positions at Sofia University “St. Kliment Ohridski”, as well as the following information, required by the Faculty of Physics: point of reference to being in accordance with the minimum national requirements and the minimum requirements of the Faculty of Physics, including a list of the noted citations in the first 26 papers used in the thesis.

The submitted set of documents corresponds to the national requirements as well as the specific requirements of the Faculty of Physics of Sofia University “St. Kliment Ohridski”.

2. Information about the candidate

Associate Professor Andon Angelov Rangelov has a bachelor’s degree in physics from the Faculty of Physics of SU “St. Kliment Ohridski” (2002). He completed his doctor’s degree in the Faculty of Physics during the period 2004 - 2008. From 2008 to 2012 he worked as an Assistant Professor and from 2012 to 2015, as a Senior Assistant Professor in the Faculty of Physics. Since 2015 he has been an Associate Professor in the Faculty of Physics of Sofia University “St. Kliment Ohridski”. The candidate’s sets of lectures include: Quantum Transitions (lectures and exercises for the Master’s program), Electrodynamics (lectures and exercises for students in the Engineering Physics department) and Quantum Mechanics (lectures and exercises for the students in the Engineering Physics department).

The main fields the candidate has worked in are: quantum-classical analogies, and coherent quantum control and optics, including: nonlinear, polarizing and waveguide optics. The vast overlap in the fields of the candidate’s researching and teaching interests is evident.

3. General characteristics of the scientific achievements of the candidate

The dissertation is devoted to the theoretical and experimental research of different optical devices: broadband devices for altering optical polarization (wave plates (chapter 1), rotators (chapter 2) and polarization converters (chapter 3)); broadband nonlinear frequency converters (chapter 4); broadband optical isolators (chapter 5); as well as different designs for light transfer in optical waveguides (chapter 6). There have been examined different problems in the field of polarization, nonlinear and waveguide optics. Each of these fields of optics has seen great development in the last decades and the result of their mutual development can be seen in nonlinear fiber optics. The most important applications of nonlinear fiber optics include the development of fiber optics communication systems, as well as the analysis of the work of solid-state and fiber-optic lasers and amplifiers. The other applications of the nonlinear fiber optics contain fiber-optic components: fiber-based gratings, couplers, interferometers, etc. Additionally, the development of nonlinear fiber optics has become a real experimental laboratory for the study of known and newly acquired solutions for nonlinear partial differential equations with the method of inverse scattering transform. The nonlinear Schrödinger equation, the Ginsburg-Landau equation, their perturbed variants, as well as systems of such equations have become fundamental mathematical models in this field. A defining moment in the theoretical, experimental and technological studies is the idea of the use of optical solitons as a carrier of information. From this point of view, the current dissertation deals with problems of the present day which are very important for the numerous applications. Moreover, the connections between quantum mechanics and wave optics has been the focus of investigations and has attracted the attention of the physical society since the very beginning of quantum mechanics.

A common feature of practically all the optical phenomena examined in the presented material is the neglecting of the influence of the group-velocity dispersion. In other words, the thesis investigates the continuous wave regime of the electrical fields (independent of time) and the different interactions between them leading to the transformation of the general mathematical models into systems of ordinary differential equations. The other main assumptions are: approximation of the slowly changing amplitude, the undepleted pump approximation (one of the fields that is stronger than the others and practically does not change during the interactions), the fulfilment of the condition for phase matching, etc.

The methods of time-dependent quantum mechanics of atoms and molecules, recently also applied in the field of coherent quantum control, are actively used. Some of the main theoretical methods and techniques, which are worth mentioning, used in this thesis, are: resonant coherent excitations (Rabi oscillations) in two-level quantum systems (ch. 4.1 , ch.4.2 and 4.4), the Landau-Zener model for a coherently driven two-state quantum system (without and with population loss) (ch.4.5 and ch. 5.4), adiabatic population transfer via level crossing (ch.3.3, and ch. 4.4), stimulated Raman adiabatic passage (STIRAP) with related phenomena, Autler-Town splitting, electromagnetically induced transparency (ch.3.1, ch.5.1, and ch.6) and others. A great amount of work on these methods and their applications has been performed in the group of Prof. N. Vitanov. The results of the work of Dr. Rangelov on this topic are part of the content of his PhD thesis. In this respect, the continuity and consistency in the work of Dr. Rangelov is evident.

A principal feature of the thesis is the extensive account of the experimental results which are directly compared with the theoretical results and predictions. As a rule, the obtained experimental results are in very good agreement with the respective theoretical predictions. Dr. Rangelov has shown excellent skills in the organizing and performing of joint scientific collaborations with different research groups.

For Requirement A the applicant has successfully defended his PhD so he gets 50 points. According to Requirements B 4 and Γ 7 the applicant has 32 scientific publications. 30 of them are in the scientific journals with impact factor: 24 with Q1 and 6 with Q2. Two of the scientific publications are with SJR. The publications of the applicant are in the most renowned scientific journals in physics and optics: Phys. Rev. A, Rev. Mod. Phys., J. Opt. Soc. Am., Opt. Lett., Opt. Commun., Appl. Opt., and others. The points collected are 740. In 17 of these scientific publications the applicant has played the leading role. In accordance with all the requirements, the number of the candidate's points satisfies and exceeds the national minimum requirements for the scientific degree "Doctor of Science", as well as the additional requirements of the Faculty of Physics of Sofia University "St. Kliment Ohridski" for the acquisition of the academic position "Doctor of Science" in Physics, in the professional field 4.1 Physical Sciences.

4. Main scientific and applied scientific contributions

Using the Jones matrixes in a system of HV basis, composite wave plate broadband half-wave retarders and quarter-wave retarders have been constructed. The predicted conversion efficiency has been experimentally confirmed for 7 different laser wavelengths between 405 nm and 1550 nm. There has been proposed a composite polarization device for the conversion of left circularly polarized light into right polarized light (and vice versa) which is maximally resistant to variations in the phase shift.

A composite broadband polarization rotator has been theoretically analyzed and constructed. The experimentally obtained dependences of transmittance on wavelength for composite broadband rotators constructed from different numbers of half-wave plates (between 2 and 10) correspond very well to the theoretical predictions.

There have been proposed several techniques for controlled and stable transformation between linearly polarized light and circularly polarized light as well as transformation from left circularly polarized light to right circularly polarized light and vice versa in birefringent media. The first one is based on the analogy of the optical model with that of stimulated Raman adiabatic passage in three-level quantum systems using a counterintuitive pulse ordering. As is well known, this technique makes it possible to achieve effective and stable nearly complete population transfer. Experimental confirmation of the theoretically predicted properties of the broadband linear polarization rotator has been achieved by discrete adiabatic change of the fast polarization axes of N=10 birefringent crystals. The second technique is based on the analogy between the derived model for the two components of the electrical field of the propagating plane wave through an optically active uniaxial linear crystal with that of the rapid adiabatic complete population transfer in two-level quantum systems.

There have been proposed novel approaches for stable, efficient and broadband frequency convertors based on the usage of the process with three-wave mixing in composite nonlinear crystals with $\chi^{(2)}$. To achieve phase matching, birefringence phase matching and quasi-phase-matching (QPM) has been used. The QPM has been obtained by using composite crystals with different number of segments or by implementing a particular spatial dependence of the period of modulation on the periodic structure.

a) In the first case, there has been established a complete control on the length of the modulation period as well as the introduced free parameters additions in the effective phase mismatch of every segment. The performed numerical simulations have revealed that in the case of e-ee interaction of sum-frequency generation (SFG) in Potassium Titanium Oxide Phosphate (KTP) with 13 segments, there has been observed enhanced efficiency and larger bandwidth frequency (up to 20 nm) of SFG in comparison with the ordinary crystal structure.

b) In the second case, sequences of different signs of the nonlinear susceptibility $\chi^{(2)}$ of the segments have been applied. The length of the segments has been optimized. The performed numerical simulations have shown that in the case of oo->e, the interaction of SFG in Magnesium Oxide Lithium Niobate with 6 and 15 segments, there is an enhanced robustness and a larger frequency bandwidth of the SFG compared to the ordinary crystal.

c) A second-harmonic generation (SHG) for short optical pulses (100 fs) via a composite crystal with 15 and 31 segments of Magnesium Oxide Lithium Niobate with $\chi^{(2)}$ nonlinearities of alternating signs is experimentally and numerically demonstrated. It has been shown that with the design of 31 segments the SHG conversion efficiency can reach 50 percent within a bandwidth of 35 nm. The proposed designs are resistant to temperature changes in the interval of 90°C. Designs allow efficient conversion of pulses as short as 25 fs. The available bandwidth for SHG with the proposed composite design is larger than the one with the standard periodic design.

d) Based on the analogy with the adiabatic population transfer through a phase jumping in the two-level quantum system, a frequency conversion technique is suggested for SFG with two Gaussian-shaped light beams in the case of oo->e interaction in a crystal of Magnesium Oxide Lithium Niobate. The nonlinear crystal is with a sign flip in $\chi^{(2)}$ in the center. The dependencies of the efficiency of SFG in the bulk crystal and in the crystal with a sign jump in the coupling on the intensity of the pump, temperature and the frequency of the signal wave have been studied numerically. There have been identified two symmetric regions of high conversion efficiency around the point of exact phase matching. It has been found that the total temperature acceptance and total spectral acceptance bandwidth are approximately as wide as a 20 times shorter single bulk crystal.

e) Inspired by the analogy with the adiabatic population transfer in the three-level quantum system, there has been proposed an efficient broadband SFG technique (including third harmonic generation). QPM has been implemented by using a period of modulation dependent on the distance, which leads to linearly z-dependent phase mismatches. The latter could be interpreted as “intuitive chirp” and “counterintuitive chirp” related to the model of Landau-Zener, which is used to formulate a condition for adiabatic evolution. It has been numerically shown that for the SFG process the “counterintuitive” phase matches lead to a better transfer of energy in the final wave of fourth frequency and to a weaker transfer of energy in the transitional wave of third frequency.

Novel broadband optical isolators have been proposed.

a) Based on the analogy with the description of the stimulated Raman adiabatic passage process in quantum optics an optical isolator has been proposed which consists of two crossed polarizers and two achromatic optical elements: a standard quarter wave-plate and a non-reciprocal quarter wave-plate. In the latter, prepared from single-mode optical fiber doped with paramagnetic terbium (bismuth) ions (provisioning the necessary value of the Verdet constant), the usage of the Faraday effect allows the creation of non-reciprocal circular birefringence. The numerically obtained results have confirmed a high level of isolation over the whole range of wavelengths considered (500-1000 nm).

b) There have been proposed compound broadband optical isolators consisting of a number of elements every one of which includes a single Faraday rotator sandwiched with two quarter-wave plates rotating at different angles with respect to their fast polarization axes. A procedure is suggested for identifying these angles to achieve maximum transmission when moving forward as well as maximum isolation for backward movement. The more elements are used, the greater the range of the rotation angles at which the isolator works effectively. In agreement with the theoretical predictions, the performed experiments confirm that the proposed compound optical isolator displays a larger transmittance (95%) than that of a single element Faraday isolator (90%) for the spectral range of the wavelengths considered.

c) Using the analogy with the adiabatic population transfer in a two-level quantum system, there has been suggested a nonlinear optical isolator operating through three-wave mixing processes in a nonlinear medium within non-periodically-poled quasi-phase-matched crystals. The effective local phase mismatch is linearly dependent on the distance which can be interpreted as a “linear chirp” leading to a dissipative Landau-Zener model with an exact solution. In the forward direction of propagation, a phase match is achieved and the SFG wave, created through adiabatic passage, is absorbed. In the backward propagation, no phase match is achieved and the signal propagates through the crystal unchanged. The performed numerical simulations using crystal of potassium titanyl-phosphate have confirmed the possibility to obtain a good isolation (> 35 dB) over a spectral range of 60 nm.

Inspired by the analogy with the stimulated Raman adiabatic passage process in quantum optics, there have been suggested several schemes applying photo-induced waveguide structures for optical beam splitting and switching of light between different waveguide channels. There has been applied an optical induction technique in photorefractive crystals, which allows the generation of quasi one-dimensional waveguides with arbitrary curvature and geometry in the direction of propagation.

a) Using the Morris-Shore transformation, there has been proposed a beam splitter which includes one input, N-output waveguide channels and one mediator waveguide. The relative amplitude distribution at the output channels has been theoretically calculated. In agreement with the theoretical predictions, it has been experimentally confirmed (for two different wavelengths: 633nm и 850nm) that in the case of N=5 and counterintuitive order, light splits into three nearly equal odd-number waveguides (1,3 and 5), whereas in the output channels with even numbers (2 and 4) the light intensity is rather insignificant.

b) Inspired by the analogy with the generalized multiple STIRAP from quantum physics, an optically-induced waveguide structure has been proposed to achieve broadband light transfer in waveguide arrays. The waveguide structure includes: an input waveguide, an array of N identical straight waveguides, and an output waveguide. The amplitude ratio between the output waveguide and the input waveguide has been theoretically calculated. In agreement with the theoretical predictions, it has been experimentally confirmed that practically all light from the input waveguide is transferred towards the output waveguide (for two different wavelengths: 633nm и 850nm, for odd number of N (N=5,7,9,11), if the condition for adiabatic evolution in the STIRAP process is fulfilled, and the coupling constants are in counterintuitive order. Furthermore, it has been shown that an increase in the number of intermediate waveguides can lead to a drop in the efficiency transfer due to the unfulfilled adiabatic condition.

c) Based on the ideas of adiabatic elimination and the subsequent rapid adiabatic process in two-level quantum systems, a waveguide structure has been proposed to achieve broadband light transfer. A complete light switching between only the two outer waveguides has been suggested irrespective of the number (odd or even) of inner waveguides for both the counterintuitive and intuitive order of couplings. The predicted switching of light has been numerically confirmed by numerical simulations with the BPM method, using a split-step Fourier method for structures of N=3 and N=6 waveguides. For the case of N=3 there have been calculated the z-dependencies of the quantities presenting the adiabatic elimination criterion and the adiabatic criterion. For the same situation there has been established the transfer efficiency of light with wavelength over more than 600 nm.

d) An optical system composed of three coupled waveguides has been theoretically suggested and experimentally obtained, which demonstrates the possibility for the light introduced in the first waveguide to remain there (the first waveguide becomes completely transparent). This phenomenon is analogical to the electromagnetically induced transparency in a three-level quantum system. Introducing a suitable change in the propagation constant of the first waveguide (detuning) with respect to the constant of propagation for the other two waveguides, and calculating the spectrum of the light transfer from the first to the other two waveguides as a function of this change, two peaks have been identified which could be considered as analogical to the two Autler-Towns resonances.

e) Using the analogy with the rapid adiabatic passage in the two-level quantum system, there has been proposed and experimentally studied a structure of two coupled waveguides, where a complete light transfer from one waveguide to another can be achieved. The role of the coupling constant is then taken by the Rabi frequency and the difference between the two propagation constants (waveguide detuning) is equivalent to the atom-laser detuning. The obtained experimental results confirm all the theoretical predictions. The fulfilment of the adiabatic condition has been numerically studied as a function of the coupling constant and the waveguide detuning. The obtained results have been applied for the analysis of STIRAP in two-level quantum systems. It has been established that for the case where the waveguide detuning is spatially preceding the coupling constant, the pulse is equivalent to a counterintuitive sequence in a three–state STIRAP process, whereas the opposite order corresponds to the intuitive sequence in the same system. It has been numerically and experimentally verified that equal intensity of light distribution is observed in the two waveguides.

The main scientific and applied scientific contribution of the presented material can be summarized as developing new methods, techniques, designs and devices for analyzing and describing different phenomena in the field of nonlinear, polarizing and waveguide optics. The presented results create possibilities for a number of practical applications and enrich the existing knowledge and understanding of the studied optical phenomena. In my opinion the main aim of Dr. Rangelov for establishing useful analogies between the methods of time-dependent quantum mechanics of atoms and molecules and polarizing, nonlinear and wave optics has been very successfully accomplished.

To the best of my knowledge, the included scientific publications in this dissertation do not repeat those from other procedures for the obtaining of scientific degrees and positions. I am not aware of any proved plagiarism in the presented dissertation and its abstract.

5. Scientific and practical importance of the candidate's contributions

According to Scopus, Dr. Rangelov has 619 citations. More than 151 of them are from the scientific publications included in this thesis. The Hirsh factor of Dr. Rangelov is h=11 (excluding self-citations and citations of co-authors). These facts prove the serious interest of the international scientific community to the presented results. The respective points he has gathered satisfy both the national minimum requirements for the scientific degree "Doctor of Science" and the additional requirements of the Faculty of Physics of Sofia University "St. Kliment Ohridski" for awarding the academic position "Doctor of Science", in the professional field 4.1 Physical Sciences (Physics of Atoms and Molecules).

6. Critical comment and recommendations

The dissertation and the abstract of the dissertation are well written with properly chosen figures which help to understand the obtained results. The abstract of the dissertation correctly describes the content of the dissertation.

As a weakness of the presented material I could indicate the absence of formulation of the main scientific achievements both in the dissertation and its abstract.

7. Personal impressions and opinion of the reviewer

My personal impressions from Dr. Rangelov date back to the period preceding the start of his work on the present dissertation. He impressed me as a thorough and questioning scholar. My acquaintance with the results presented in this dissertation not only confirm my previous opinion, but also show his further development as a successful theoretician and research scientist.

8. Conclusion

After I got acquainted with the presented dissertation, abstract and other materials, and based on the analysis of their significance and their scientific and practical importance, I **confirm** that the scientific contributions of the applicant satisfy and exceed the national minimum requirements for the scientific degree "Doctor of Science", as well as the additional requirements of the Faculty of Physics of Sofia University "St. Kliment Ohridski" **for awarding the academic position "Doctor of Science" in Physics,** in the professional field 4.1 Physical Sciences (Physics of Atoms and Molecules). I have not discovered plagiarism in the presented dissertation or its abstract.

I give my **positive** evaluation of the presented dissertation.

II. GENERAL CONCLUSION

Therefore, I **strongly recommend** to the Honorable Scientific Jury **Associate Professor Dr. Andon Angelov Rangelov** to be awarded **the scientific degree "Doctor of Science" in Physics**, in the professional field 4.1 Physical Sciences (Physics of Atoms and Molecules).

15.04.2021. Reviewer:

/Prof. D.Sc. Ivan M. Uzunov/