REVIEW

of dissertation

for obtaining the scientific degree "**Doctor of Physical Sciences**" 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 ”(Sofia University)

The review was prepared by Prof. Elena Vadimovna Stoykova, Institute of Optical Materials and Technologies, Bulgarian Academy of Sciences, as a member of the scientific jury according to Order № RD 20-127 / 22.01.2021 of the Rector of Sofia University.

Dissertation title: "Quantum-optical analogues"

Author of the dissertation: Assoc. Prof. Dr. Andon Angelov Rangelov

I. General description of the submitted materials

1. Description of the submitted documents.

The candidate Assoc. Prof. Dr. Andon Rangelov 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 6 other documents (curriculum vitae, diplomas for bachelor and PhD degree, declaration of authorship, list of citations 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. Research career

The candidate for defense Assoc. Prof. Dr. Andon Rangelov graduated as a bachelor from the Faculty of Physics at Sofia University “St. Kliment Ohridski ”in 2002 with excellent grades. In 2008, he successfully defended a dissertation at the same faculty to obtain the educational and scientific degree "Doctor". Since 2009, he has been an assistant professor, and since 2012 a chief assistant professor at the Faculty of Physics at Sofia University, and in 2015 he won a competition for the academic position of "associate professor". Assoc. Prof. Andon Rangelov works in the field of quantum-classical analogies, coherent quantum control, polarization optics, nonlinear and wave optics. He carries out international cooperation in the field of photoinduced waveguides with the University of Metz and Supélec, France, in the field of adiabatic techniques with Lawrence Livermore National Laboratory in the USA and in the field of composite pulses with the Institute of Applied Physics / Nonlinear Optics of the Technical University of Darmstadt, Germany.

Assoc. Prof. Andon Rangelov has teaching activity on "Quantum Transitions" in the master's program, on "Electrodynamics" for students majoring in Engineering Physics, as well as on

"Quantum Mechanics" for students majoring in Engineering Physics. He is currently a co-supervisor of a doctoral student and has been a co-supervisor of a successfully defended doctoral student. He has supervised three successful bachelors in physics.

Assoc. Prof. Andon Rangelov has 51 publications, 32 of which are included in the dissertation. The candidate's Hirsch index is 12 with a total of 575 citations.

3. General description of the candidate's scientific achievements

General description of the dissertation. The dissertation summarizes the research of Assoc. Prof. Andon Rangelov in the perspective field of quantum-classical analogies. The research was conducted with the leading participation of the candidate within a 10-year period. The dissertation is based on papers in scientific journals published from 2010 to 2019. The aim of the dissertation is to apply the technique of composite pulses and the concept of adiabatic evolution from the field of coherent quantum control of atomic and molecular processes to create broadband optical devices in polarization and nonlinear optics and in photoinduced waveguides.

Composite pulses, used for decades in nuclear magnetic resonance imaging as an effective discrete control method, are increasingly used in quantum optics and quantum information, as well as for analysis of other physical systems. Their main advantage is their stability to fluctuations of the parameters of their constituent pulses due to the mutual compensation of side effects caused by these fluctuations. Based on the analogies with coherent excitation in a two-state system, the dissertation provides precise analytical solutions for composite devices for achromatic conversion of light polarization in a birefringence medium and creation of a highly efficient broadband frequency summation technique based on composite crystals. The dissertation uses the mathematical description of coherent excitation in a stimulated Raman adiabatic passage (STIRAP) in quantum optics. The developed conversion techniques have the efficiency and stability inherent in STIRAP. The research in the dissertation comprises theoretical analysis, numerical modeling and experimental testing. As a result, new broadband devices for changing optical polarization, efficient broadband frequency converters, optical isolators and approaches for injecting light into waveguides are proposed.

Research activity indicators. The dissertation is based on 32 publications in renowned international journals such as Opt. Commun., JOSA A, Opt. Lett., Phys. Rev. A, Appl. Opt., J. Opt., Photonics. Res., Adv. Chem. Phys., Rev. Mod. Phys., which are of category Q1 (25 publications) and Q2 (5 publications) and are included in group I in the requirements of the Faculty of Physics. Two of the publications are from group III. In 8 of the publications Assoc. Prof. Rangelov is the first author and in 16 of the publications he is the second author, having a leading contribution in almost all theoretical publications, as well as in the theoretical analysis of those with experimental research. He is a single author of two of the publications. Assoc. Prof. Rangelov has a leading participation in 17 of the publications, and 151 independent citations of the dissertation results were noted. The dissertation not only meets, but also exceeds the minimum national requirements (under Art. 2b, para. 2 and 3 of Development of Academic Staff in the Republic of Bulgaria Act a) and respectively the additional requirements of Sofia University for obtaining the scientific degree" Doctor of Physical Sciences" in a professional research field 4.1. Physical sciences. In group of indicators "B", the candidate has 30 publications from group I, included in the dissertation, with a requirement for a minimum of 14 publications from group I. In 17 of the publications he has a leading participation with a required minimum of 9 such publications. In group of indicators "D", the candidate has 151 independent citations in refereed editions (Web of Science or Scopus) with a requirement for a minimum of 100 citations. The scientific publications in the dissertation do not repeat those from previous procedures for acquiring a scientific title and academic position.

There is no legally proven plagiarism in the submitted dissertation and the Summary, based entirely on publications in renowned journals, which provide similarity check and review with more than one reviewer.

4. Analysis of the research results in the dissertation

The main scientific and applied contribution of the present dissertation is the creation of new optical elements by using approaches and techniques of coherent quantum control. The dissertation consists of 6 chapters, each of which is dedicated to the development and theoretical analysis of a certain type of optical elements. The first three chapters, which are significantly shorter than the others, are devoted to the use of quantum analogies in polarization optics. In the last three chapters, which are larger in volume, quantum analogies are used to solve problems in nonlinear optics and to light transmission in waveguides. In each chapter, the contribution results can be classified as creating theories and hypotheses, developing new methods and obtaining new facts. In summary, a theoretical description of composite delay plates in polarization optics, of the process of summation / subtraction of frequencies in an anisotropic medium with quadratic nonlinearity and of light transmission in photoinduced waveguides have been developed using approaches similar to the of composite pulses technique and adiabatic evolution in coherent quantum control. The developed theories enrich the knowledge in classical optics. New methods for construction of broadband composite optical elements in polarization and nonlinear optics have been developed, which are characterized by high efficiency and robustness with respect to variations of the parameters of the elements in the composition and changes in the environment. These results in the dissertation have great practical value. The obtained theoretical and experimental new knowledge about the behavior of optical elements allow optimization of their parameters and is a significant contribution. In order to better highlight the specific contributions in the theoretical and experimental development of new optical elements in the different areas, the contributions in the described 6 research areas are analyzed below in details.

In polarization optics, a method is proposed for creating wave plates with a certain phase delay, whose optical action is stable with respect to the factors that change this delay (Chapter 1). The plates are not affected by inaccuracies in rotational power and thickness and can operate in a wide spectral range. Composite wave plates are proposed by combining several standard plates rotated at precisely defined angles with different phase delays. Precise solutions for the angles of rotation were obtained using the analogy with composite pulses. New half-wave and quarter-wave composite polarization plates, composed of a series of standard plates of this type with the same thickness, have been proposed and tested experimentally, and work in the ultra-wide frequency band has been achieved. The proposed devices are superior to the delay plates of several birefringent materials. Improvement is proposed by placing a mirror at the end of the series of standard plates. Achromatic devices have been proposed to change circular polarization by combining traditional half-wave plates rotated at certain angles with respect to their fast axes. Good stability is achieved with respect to variations in crystal temperature, incident light field frequency, crystal length and angle of incidence. Experiments with several laser sources with different wavelengths confirm the validity of the solutions. A broadband polarizing rotator is proposed, composed of two identical broadband composite half-wave plates by introducing an angle of rotation between them (Chapter 2). A method for constructing an alternative broadband rotator from an even number of half-wave plates has been developed. With Monte Carlo modeling, the angles of rotation are optimized and accurate analytical formulas are obtained for the case of four half-wave plates. Angularly controlled broadband polarization rotators of 2, 4, 6, 8 and 10 plates have been experimentally demonstrated, and there is a good agreement with the theory. Increase of the bandwidth is observed at a larger number of half-wave plates. Frequency-independent controlled adiabatic rotation and conversion of light polarization using an optically anisotropic medium with linear and circular birefringence have been proposed (Chapter 3). The transformation is based on the analogy between the torque equation of the Stokes vector in a medium with zero polarization-dependent losses and the time-dependent Schrödinger equation in the rotating wave approximation, describing the coherent excitation in STIRAP in quantum optics. Precise analytical solutions for different models for converting polarization into a birefringent medium are presented. The developed technique is efficient and stable and is applicable not only for the conversion of linear to linear or circular to linear polarization, but also for arbitrary conversion of light polarization through the implementation of the so-called partial STIRAP. An alternative scheme for partial adiabatic evolution for the Stokes vector has been proposed by discretely changing the direction of the birefringence vector using a sufficient number of crystals, each rotated at a small angle. Experimental broadband and ultra-broadband linear polarization rotators composed of two sets of 10 identical wave plates are demonstrated. The slow-varying amplitude approximation in the propagation of the light wave is used and the analogy with the Schrödinger time-dependent equation in the rotational wave approximation for two-level atoms is shown. The conditions for applying the concept of adiabatic evolution are indicated.

In nonlinear optics, approaches for broadband frequency conversion at phase synchronism by birefringence and quasi-phase synchronism by using composite nonlinear crystals are proposed (Chapter 4). The technique of universal composite pulses, recently developed with the participation of the Department of Theoretical Physics of Faculty of Physics, is applied to perform three-wave mixing in the approximation of slow-changing amplitude. The problem is solved for a pump light field with an amplitude much larger than the amplitudes of the other two fields, which leads to an analogy with the time-dependent Schrödinger equation for a two-level atom. It is proposed to replace the nonlinear crystal with a composite crystal as a set of segments with different local modulation periods. Numerical simulations with KTP crystal parameters show broadband conversion. The range of high efficiency parameters increases significantly with the number of segments. The efficiency of the composite crystals is high both for linear mode of operation, when the pumping field exceeds the other two fields, and in nonlinear mode with decreasing amplitude of the pumping field. The mixing of three waves in a medium, characterized with quadratic nonlinearity and birefringence phase synchronism, by using the technique of the composite sequences of Shaka and Pines with a change in the interaction sign is considered.

Optical frequency conversion is realized with *N* crystal domains with appropriately selected thicknesses and alternating positive and negative interactions. The range of parameters with high conversion efficiency greatly expands for longer composite crystals. The developed technique was verified by numerical calculations for ferroelectric nonlinear crystals such as MgO:$LiNbO_3$. Effective broadband generation of a second harmonic for ultrashort pulses by means of composite nonlinear crystals has been experimentally demonstrated. A conversion efficiency of 50% was obtained for pulses with of 100 fs duration and nano-joules of energy for a 31-segment crystal, showing stable operation at temperature changes in the range of 90 degrees for a 35 nm frequency band. A highly efficient generation of a second harmonic for ultra-short pulses in relatively short nonlinear crystals has been achieved. It is possible to efficiently convert pulses up to 25 fs. The technique is applicable to continuous and pulsed lasers in linear and nonlinear mode.

Broadband optical insulators are proposed (Chapter 5). The first is an optical diode consisting of one achromatic reciprocal and one non-reciprocal quarter-wave plates placed between two polarizers with mutually perpendicular axes. Achromatic wave plates are designed applying the concept of the adiabatic evolution of the Stokes vector. A simple implementation with the help of fiber optics is proposed. The theory of a broadband optical insulator has been developed by applying the concept of composite pulses in polarization optics. As an element of a broadband optical insulator, a broadband Faraday rotator consisting of standard Faraday rotators and achromatic quarter-wave plates rotated at predetermined angles is theoretically substantiated. Faraday rotator realized with terbium gallium garnet crystal was analyzed. To increase the bandwidth, a Faraday rotator system is proposed with a given angle of rotation between two achromatic quarter wave plates rotated at different angles with respect to their fast axes. The single Faraday rotator is replaced by a series of *N* elements with different angles of rotation. It is shown numerically that realization of a broadband in both directions composite rotator with a rotation angle of 45 degrees requires not less than 4 elements, the parameters of which are determined by a system of nonlinear algebraic equations for 8 rotation angles. It is shown a possibility to create a broadband insulator of only three elements when there is no requirement for a 45 degree angle of rotation. The case of using standard Faraday rotators as well as non-standard angles of rotation is analyzed. An experimental test of a composite optical insulator with a composite Faraday rotator made of three parts, each composed of a simple Faraday rotator between two achromatic quarter wave plates, was performed. The composite optical insulator has an efficiency of over 95% in the spectral range 700-1000 nm. The realization of an optical diode as a nonlinear element is proposed by mixing three waves in a medium with quadratic nonlinearity at a strong pumping field, weak signal of the second frequency and high absorption for the generated sum or difference of frequencies, where the task becomes linear. Adiabatic frequency conversion into aperiodically polished quasi-phase crystals was used to operate in a relatively wide spectral range. The mathematical description is a photonic analogue of a two-level atomic system that interacts with an external electric field, and the excited state decays outside the system. The proposed method is illustrated by summing the frequencies in KTiOPO crystal.

The theoretical transmission of light in optical waveguides and development of a broadband splitter for optical waveguides (Chapter 6) based on the analogy with adiabatic evolution in STIRAP for two- and three-level atoms are considered. The paraxial approximation in weakly bended waveguides is fulfilled, for which the analysis of the evolution of light is within the framework of the theory of interaction only with the nearest neighbors. Different structures were analyzed. A three-dimensional achromatic beam splitter with one input and N waveguide outputs connected by means of an intermediate waveguide is proposed. Due to the analogy with STIRAP, this beam splitter shows stable performance in variations of experimental parameters, such as the magnitude of the interaction, the distance between the waveguides and their geometry. As an optical structure, allowing an analogy with STIRAP, a flat waveguide with multichannel light beam separation was analyzed. The structure includes an $N + 2$ waveguide with an input waveguide near a buffer waveguide and a subsequent array of N equidistant and parallel waveguides. An experiment was performed with a photo-induced waveguide structure with variable configuration at 633 nm and 850 nm to test achromaticity by lateral illumination of a photorefractive crystal by means of a spatial light modulator. Experiments confirm that the adiabatic process does not depend on the excitation wavelength. For an odd number of waveguides and a counterintuitive sequence, light is observed in the odd waveguides, and the intensity is insignificant in the even ones. The adiabatic achromatic light transmission between multiple intermediate waveguides in an array of waveguides was investigated experimentally with a special set-up for inducing a waveguide structure with a dynamic configuration, such as e.g. quasi-one-dimensional waveguides with arbitrary bending and geometry. The injection of light into an input slightly bended waveguide, which interacts with an array of N identical straight waveguides, was studied for the case when a weakly bended output waveguide is connected to the last waveguide in the array. Paraxial approximation and the theory of coupled modes are used. The transfer is described with the mathematical apparatus of a multicomponent STIRAP provided that the number of intermediate states guarantees adiabatic evolution. For an odd number of waveguides in adiabatic mode, light is transferred from the input to the output waveguide with very little light in the intermediate waveguides. With an even number of waveguides, optimal light transmission to the output waveguide is not achieved. Adiabatic transmission was demonstrated in 9 intermediate waveguides. A theoretical description of light transmission in waveguides has been developed, which is analogous to adiabatic elimination by quantum physics. The approach is effective for odd and even number of waveguides and for waveguides with variable geometry and distance between them. A system of three dielectric waveguides in a flat configuration is considered theoretically, and the adiabatic elimination of the middle waveguide is proved. The analysis is summarized for 4 waveguides and it is concluded that the approach is applicable to N waveguides. Simulations with real parameters for 3 and 6 waveguides are made. Theoretically and experimentally, it has been shown that a system of three straight waveguides with evanescent coupling demonstrates electromagnetically induced transparency by appropriate mutual rearrangement of the propagation constants in the waveguides. Thus, an array of waveguides shows properties analogous to the Autler-Townes effect. The problem is analyzed for a system of two identical and one different waveguide by analogy with the Schrödinger equation for a lambda system with three levels. Light transmission between two adjacent waveguides with different longitudinal propagation constants of the fundamental mode is considered and the analogy with a coupled two-level quantum system is shown.

5. Critical remarks and recommendations

The dissertation is presented in English, which in my opinion is correct in view of the use of this work by a wider scientific audience. The dissertation is formed as a summary of the results of the papers related to it. They are systematized in the presented 6 chapters. The narration is concise but precise. The style of the dissertation is very good, and the same is true for the style of the papers on which the dissertation is based. Practically everywhere in the dissertation the figures from the papers themselves are used, but some figures such as fig.4.4 and fig.4.5 are given without captions and without a scale bar for the showing quantities. The numbering of some equations in the text differs from their actual numbering, for example, in Chapter 1 on page 3 equation (5.22) is cited, and on page 30 equation (3.18) is indicated as (4.22). There is no list of abbreviations used. The author's contributions are formulated only in the thesis summary. These technical omissions should be corrected before the dissertation is distributed electronically. Assuming that a doctoral dissertation is essentially a monograph, one can only regret that the author did not include in the individual chapters a more extensive systematic review of the achievements of other authors in the field of research. The individual thematic sections in each chapter begin with a brief description of the task to be addressed in this section, and linking this description to previous research in the field would only be useful. About 163 sources are cited, but usually in cases where they are directly related to the described results. Despite the lack of a traditional review of the literature, the good knowledge of the research area and deep theoretical insights of the author are impressive. The conducted theoretical analyzes are at a high level, the explanations of the results are clear and logical. The accuracy and completeness of the results is also unquestionable. The inclusion in the dissertation of a rich experimental data, as well as of various numerical experiments, illustrating the stability and reliability of the developed optical elements, makes a very good impression.

My main criticism in the review is focused on the thesis summary, which according to procedural requirements is given in Bulgarian. Compared to the elegant style of the papers with the participation of the candidate, including both independent papers, and the dissertation itself, the summary is unacceptable as a text due to the large number of terminological inconsistencies in Bulgarian. I strongly recommend editing of the summary before its electronic distribution. There is also a discrepancy between the English and Bulgarian versions of the dissertation title. The shortcomings I noticed are easily removed and in no way diminish the significant contribution of Assoc. Prof. Andon Rangelov in creating modern approaches for analysis and design of broadband optical elements in polarization and nonlinear optics. The presented results are not only significant, but also provide important applications.

6. Personal impressions of the candidate

I do not know Assoc. Prof. Andon Rangelov personally.

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 of Physical Sciences ”. 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 scientific degree "Doctor of Physical Sciences" in the professional field 4.1. Physical Sciences to Assoc. Prof. Dr. Andon Angelov Rangelov.

21st of April 2021 Reviewer signature:

/Prof. DSc. Elena Stoykova/