REVIEWER’S REPORT

of a thesis submitted for awarding the scientific degree „Doctor of Sciences“

in Physical sciences according to the procedure pursued in

Faculty of Physics of Sofia University “St. Kliment Ohridski”

The report is prepared by Prof. Dr.Sci. Alexander Alexandrov Dreischuh from Faculty of Physics of Sofia University “St. Kliment Ohridski” in his capacity of a member of the jury according to order РД 20-127/22.01.2021 г. of the Rector of Sofia University.

Title of the Thesis: Quantum Optical Analogues

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

I. General description of the submitted documents

1. Data for the submitted documents

The applicant Assoc. Prof. Andon Rangelov has submitted a Dissertation (in English) and an Abstract, as well as the mandatory tables for the Faculty of Physics as required by the Regulations for the conditions and the order for acquiring scientific degrees and holding academic positions in Sofia University “St. Kliment Ohridski” (ПУРПНСЗАДСУ). There are also 37 other documents supporting the candidate's achievements (2 diplomas, CV, copies of 32 publications applicable to this procedure, a list of independent citations and a Declaration of authorship and originality of the results). It is noteworthy that the Abstract, evaluated by the number of pages of the, has a volume that is 70% higher than this of the Dissertation. The detailed acquaintance with the two materials showed that, in fact, the Abstract is a translation of the Dissertation into Bulgarian. Of course, the decision regarding the volume and essence of the Abstract belongs to the applicant. However, as far as I know, it differs significantly from the usual practice. The documents submitted by the applicant for the defense comply with the requirements of the laws (ЗРАСРБ, ППЗРАСРБ, and ПУРПНСЗАДСУ).

2. Data for the applicant

During the period January 2004 - June 2008 the applicant was a PhD student at the Faculty of Physics at Sofia University. After acquiring the educational and scientific degree PhD, in the period March 2009 - September 2012 he was an Assist. Prof. Subsequently, until September 2015, he was a Head Asst. Prof. in Faculty of Physics. Since September 2015 he is holding the academic position of an Associate Professor at the same faculty. His teaching activities are related to lectures and seminars in Quantum Transitions and in Electrodynamics and with seminars in Quantum Mechanics. He has been co-advisor of one successful doctoral student and supervisor of three graduated bachelors in physics. He has successful international collaborations with research groups from France, the United States and Germany. The total 51 articles published by Assoc. Prof. Andon Rangelov have attracted more than 575 independent citations and the Hirsch index is h = 12.

3. General evaluation of the scientific achievements of the applicant

In view of the content of the Dissertation, the applicant's interests are in the field of the analogies between processes in quantum optics and those in classical (wave, polarization and nonlinear) optics. The scientific publications included in the presented Dissertation meet the minimum national requirements (under Art. 2b, paragraph 2 and 3 of the law ЗРАСРБ) and the additional requirements of Sofia University "St. Kliment Ohridski" for acquiring the scientific degree "Doctor of Sciences" in the professional field of Physical sciences. From the table below it is evident that these requirements are fulfilled and even significantly surpassed.

Group of indicators	Indicator	According to the requirements of the law ПУРПНСЗАДСУ and of the Faculty of Physics Required for „Doctor of Sciences"	For the applicant, according to the submitted documents
А	**1**	**50 points**	**50 points**
Б	**2**	**100 points**	**Subject of this procedure**
Г	**5+6+... +10**	**Total, at least 14 papers from Group I (at least 100 points from indicators 5 to 10)**	**Group I (Q1, Q2)** 27 x 25 points (Q1) = **675** points 2 x 20 points (Q2) = **40** points **Group II (Q3, Q4) -** none **Group III (SJR, without IF)** 2 x 10 points = **20** points **TOTAL: 735** points
Д	**11**	**At least 100 citations (i.e. at least 200 points)**	**575** citations x 2 points = **1150 points**
Additional requirement in Faculty of Physics		**At least 9 papers from Group I with a substantial contribution of the applicant**	**17** papers
Additional requirement in Faculty of Physics		**Hirsch index h>6**	**h=12**
Е	**12 +... 20**	**Doctoral advisor of a successful PhD student**	**one : 50 points / 2 = 25 points**

In view of the information in the candidate's documents I am drawing the conclusion that the scientific publications included in the Dissertation do not coincide with those from previous procedures for acquiring a scientific degree or an academic position. All articles have been published in highly-reputed international journals after successful review procedures. I consider this indicative that the published results, as well as those in the Dissertation and the abstract, are original scientific contributions of Assoc. Prof. Rangelov. I hereby reject the possibility of plagiarism in any form.

4. Characterization and evaluation of the teaching activity of the candidate

The teaching activity of Assoc. Prof. Rangelov is related to lectures and seminars in Quantum Transitions (for master's students), with lectures and seminars in Electrodynamics (for undergraduate students in Engineering Physics) and with seminars in Quantum Mechanics (for undergraduate students in Engineering Physics). He has supervised three successfully defended bachelor's theses. He has been co-supervisor of a PhD student who successfully defended his dissertation and is currently a co-supervisor of another doctoral student.

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

The key problems analyzed in the Dissertation of Assoc. Prof. Andon Rangelov are related to new possibilities for creating and, in many cases, to experimentally proving new ways for creating new devices for changing the polarization of broadband beams, new effective broadband frequency conversion schemes, new wavelength-independent optical isolators and new schemes for light manipulation in planar waveguides. His approach is based on discovering analogies between the description of processes in quantum mechanics and processes in classical (wave, polarization and nonlinear) optics. The adiabatic approximation and the concept of composite pulses, which are often used later, are correctly introduced. The concepts of rapid adiabatic passage and the stimulated Raman adiabatic passage are introduced by citing sources from the literature.

In Section 1.2. the goal of the analysis is to propose wave plates that operate in a wide spectral range, providing the desired phase shift. The idea is to replace a phase plate providing the desired phase shift at a particular wavelength in a particular orientation with a sequence of plates introducing smaller phase shifts when rotated, each one separately, at smaller angles. In Section 1.3., in order to use a smaller number of plates, the use of a mirror at the end of the sequence is analyzed, i.e. double passage through polarized optical elements is considered. Four configurations are predicted. The experimental studies are conducted at wavelengths of 1064 nm and 1550 nm (from an optical parametric oscillator), at 405 nm, 532 nm, 780 nm, and 850 nm (obtained from semiconductor lasers), and at 633 nm (from a He-Ne laser). The obtained experimental data are in a very good agreement with the numerical simulations based on the derived analytical result. Section 2.1. is devoted to the analysis of the possibility to create a broad bandwidth polarization rotator using a sequence of two achromatic λ/2-plates with an additional rotation in between. The data show successful operation of the device in a 50-60nm wide spectral range. It is clear that "white light" does not mean a supercontinuum (as it seems, given the quoted optical octave), but an unpolarized beam from a 10W halogen lamp which beam is polarized externally. My question here is whether the 50-nanometer width of the intervals, in which data are shown, are due to the use of an interference filter with such a spectral bandwidth or for some other reason? The data in Section 2.4. for the measured variance of the transmission coefficient of the broadband polarization rotators composed by 2,4,6,8, and 10 pcs. λ/2-plates at different rotation angles are in the same spectral range. Independent on this question, the feasibility of the device in a broad spectral range is a very good result.

In Section 3.2. adiabatic evolution of the Stokes vector means that its rotation takes place not continuously but in a sequence of discrete steps. Experimentally, this is achieved using a sequence of 10 crystals, each one rotated at an appropriate angle. For this purpose, each individual crystal should not play the role of more than a λ/2-plate. The data show (see Fig. 13 in Abstract) that using 10 achromatic λ/2-plates a nearly wavelength-independent operation in an interval of a width of more than 550 nm is possible.

Chapter 4 is devoted to the analysis of new approaches for efficient frequency conversion in a wide spectral interval by phase matching achieved by birefringence and by quasi-phase matching. The model presented in Section 4.1. is for continuous waves. My question is, can the method be modified for nanosecond pulses? Can this be done for picosecond pulses, taking into account the mismatch of the group velocities, but still neglecting the group velocity dispersion. The reason for my question is that on the abscissa of Fig. 16 (please see the Abstract) units of GW/cm^2 are seen, and such intensities are not achieved with continuous wave laser radiation. In Section 4.3. experimental data are presented for the efficient and broadband process of generation of a second harmonic of ultrashort laser pulses by means of composite nonlinear crystals (crystals with periodic inversion of the sign of the second-order nonlinear susceptibility). The results are well described and illustrated and are indicative for a successful experiment. Pulses from a femtosecond oscillator with a duration of 100 fs and with energy in the nJ-range are used and a conversion efficiency of about 50% in a second harmonic is achieved. The technique has been shown to be effective in a spectral range with a width of about 35 nm. This should mean that, in principle, the technique is applicable down to sub-20-fs pulses. I am interested in the opinion of the applicant on this issue. A nonlinear $LiNbO_3$ crystal doped with Mg is used. It is known that this crystal (as well as the mentioned Lithium Tantalate crystal) have also a well-pronounced photorefractive properties at wavelengths around and below 500 nm. Because a conversion efficiency of about 50% is achieved in the experiment, is a change in the beam shape observed, e.g. of the second harmonic, after an illumination time of about a minute or two. My question is motivated by the fact that the photorefractive effect is both non-local and anisotropic with respect to the c-axis of the crystal. In Section 4.4. a technique for a frequency conversion is proposed that is based on an analogy with the adiabatic population transfer technique between two quantum states by means of a phase jump in the "interaction". In this technique, adiabaticity requires dependence of the effective phase mismatch Δk on the propagation length, which can be achieved by quasi-phase matching. If a part of the nonlinear crystal is polarized in one direction, the rest - in the opposite direction, a change of the sign of the second-order nonlinear susceptibility (i.e. of the "interaction") is achieved. This technique, in space, I am personally considering as better intuitively motivated than its time analog, which assumes that there is a phase jump in the pulse, and the phase jump implies a sharp decrease (possibly down to zero) of the amplitude/intensity, i.e. it requires the use of a dark pulse. The analysis is performed in the approximation of a relatively weak nonlinear frequency conversion. The numerical simulation is based on a sum-frequency generation process (750nm + 1500nm → 500nm). The type of the interaction in the $MgO:LiNbO_3$ crystal is *oo-e*. In my view, the question of the manifestation of photorefraction arises here again. In Section 4.5. a second-order cascade processes (sum-frequency mixing processes) are analyzed, which are, in a certain context, analogous to the coherent population transfer in a three-level quantum system. The results shown in Figs. 27 (please, see the Abstract) are interesting, but, for me, there is some ambiguity. The right graph does not represent a mathematical function (correspondence between an unique argument and an unique functional value). Are isolines of the conversion efficiency presented in the nonlinear case? An interesting effect with an analogue in quantum optics is that in the "counterintuitive" case of modulation almost no energy is transferred to the wave of the intermediate frequency. In this regard, I have two related questions: Is it possible to apply this approach to the direct process of third harmonic generation accompanying the cascade process? Can the third-order nonlinearity be used for intensity-dependent phase matching / mismatch adjustment?

The studies in Chapter 5 are devoted to the analysis of new broadband optical isolators. An isolator is described that requires two crossed polarizers, achromatic reciprocal and a non-reciprocal quarter-wave plates. The required non-reciprocal birefringence is obtained in an optical fiber to which an external magnetic field is applied. The required birefringence in the fiber can be induced by mechanical pressure or by an external electric field. Numerical simulations show the feasibility of the idea in a spectral range with a width of almost 500 nm. The experiment described in Section 5.3. is performed using three Faraday polarization rotators and six achromatic quarter-wave plates. (Here, in the Abstract, is practically the only place where the term is used correctly in Bulgarian.) Each ordinary Faraday rotator is set between two achromatic quarter-wave plates. The middle Faraday rotator rotates the polarization at 90°, the first and third one - at 45°. As with a conventional optical isolator, both input and output polarizers are rotated at 45° relative to each other. The optical system has shown a high spectral transmission in the range from 600 nm to 1000 nm. As noted in the Dissertation, the experimental data deviate somewhat from the numerical ones, but, in general, the results of the analysis are confirmed. The idea in Section 5.4. is significantly different. It is based on a sum-frequency generation process ($\omega_3 = \omega_1 + \omega_2$) in a second-order non-linear medium. It is assumed that the generated wave of the sum frequency ω_3 experiences strong absorption in the process of its generation and along the medium (nonlinear crystal). The presence of a phase synchronism is taken into account in this forward direction. When the signal is propagating backwards, the phase synchronism is absent and the crystal is completely transmitting the field with a frequency ω_2. The calculated spectrum for the KTP crystal is covering a 60-nm-wide spectral range around a central wavelength of 925 nm and show an isolation of at least 35dB everywhere.

In Chapter 6 of the Dissertation schemes for controlling the switching of broadband signals between planar waveguides are analyzed. In Section 6.1. an achromatic optical beam splitter with one input and N outputs (waveguides) connected by an intermediate "mediator" waveguide is considered theoretically. The device is analyzed on the base of an analogy with the stimulated Raman adiabatic passage. To understand the results, the process of discrete diffraction of a beam entering a waveguide from a structure of parallel planar waveguides has to be kept in mind. In Section 6.2. a multi-channel beam splitting in a structure of 1 input, 1 control and N output parallel waveguides is realized. The efficiency of the device is tested at wavelengths of 633 nm and 850 nm. The experimental scheme is ingenious and well presented. The spatial modulator is a purely phase modulator rotating the polarization. Amplitude modulation is obtained due to its combination with a polarizing beamsplitting cube. This is evident from the text in the Dissertation. A photorefractive crystal SBN:61 is used. With an odd number of waveguides (N = 5) and a counterintuitive sequence of interaction, the light is split almost equally into three output ports. In particular, in the odd waveguides a significant signal is propagating, in the even waveguides – negligible signal. It was found that the result does not depend on the excitation wavelength, i.e. the interaction scheme is achromatic. In my opinion, the experimentally obtained higher interaction coefficient for 850 nm than for 633 nm can be explained by the stronger diffraction of the beams at longer wavelengths. In Section 6.4. a scheme for light transmission in waveguides is proposed by analogy with the adiabatic elimination in quantum physics. A system of three waveguides is considered. The external waveguides have the same profile of the refractive index, which is different from that of the central waveguide. The analysis shows that if initially there is no light in the middle waveguide, there may be no light in it at all times. This effect is the equivalent to the mentioned adiabatic elimination. It is possible that the internal waveguides are more than one (e.g. N) and all of them are eliminated. The situation for N = 4 is analyzed in the Dissertation. Figs. 48 and 51 (please see the Abstract) are indicative of the positive result of this analysis. In Section 6.5. an analogue of the electromagnetically induced transparency is studied as well. A coupler consisting of three closely spaced planar optical waveguides coupled with evanescent waves (The term "evanescent" is not translated in the Abstract) is considered. Formally, the system with three waveguides is analogous to a three-level Λ-system. The distance between the waveguides is chosen so that their length corresponds to one coupling length. Similar considerations are used for resonant couplers (splitters) in optical communications. The operation of the device is controlled by changing the position of the third waveguide relative to the second one. The results in Section 6.6. are really interesting.

Generally, the experiments are convincing and confirm the theoretical predictions.

The results of the applicant are published in highly-reputed international scientific journals: Reviews of Modern Physics (APS, 1 paper, IF=45), Photonics Research (OSA, 1 paper, IF=6.1), Optics Letters (OSA, 4 papers, IF=3.7), Physical Review A (APS, 10 papers, IF=2.8), Journal of Optics (IOP, 3 papers, IF=2.4), Optics Communications (Elsevier, 4 papers, IF=2.1), J. Opt. Soc. Am. A (OSA, 2 papers, IF=1.791), Applied Optics (OSA, 3 papers, IF=1.96) and Adv. Chem. Phys. (1 paper, IF=1.771). They are cited more than 575 times in papers of other authors. The impact-factor of his publications exceeds 120. One of his most highly cited publication (with more than 280 citations) is in Reviews of Modern Physics. It is devoted to the applications of the stimulated Raman adiabatic passage in physics, chemistry and in other fields. According to the criteria formulated in the Additional regulations of the Faculty of Physics for applying the law (ПУРПНСЗАДСУ) for significant contribution of the applicant in the publications presented for the procedure, the data of Assoc. Prof. Rangelov regarding this indicator are almost twice higher than the minimum required.

The scientific achievements of Associate Professor Rangelov are convincing. I would qualify them as formulation of new hypotheses for analogies between quantum and wave optics, theoretical development and, in many cases, experimental proof of new or improved existing experimental methods. They contribute to the enrichment of existing knowledge and have certain prospects for applications.

6. Critical remarks and recommendations

The Abstract practically completely reproduces the Dissertation. There are no conclusions neither in the Dissertation, nor in the Abstract, which is also unusual. In the Abstract, some of the figures significantly precede the text introducing them. The completeness of the information in the Abstract and, in general, the literary awareness of the applicant are beyond any doubt. My criticism is that some of the terms from the classical optics (not from the quantum optics) are used inaccurately, partly - without repeatability, in a single case - without translation from English. In contrast, the terms used in the Dissertation (written in English) are the correct ones. (The opposite would be very surprising, since the Dissertation is based on publications in renowned journals published in English.) The Abstract has its own value, but also the value of a material that can be provided to graduates and to doctoral students. In this sense, the use of the correct terminology in Bulgarian is mandatory. In the next edition of the Abstract I recommend Dr. Rangelov to eliminate all inconsistencies in the terminology. Here I prefer to refrain from giving specific examples of such problems, but I am ready, on his initiative, to give him my full assistance in this aspect. The use of the correct terminology in Bulgarian is mandatory for a lecturer. The award of the required scientific degree, logically, I am considering as a step towards an upcoming professorship.

7. Personal impressions of the candidate

My personal impressions are of a highly motivated and capable young professional, who grew up in the scientific group of Professor Nikolay Vitanov, who took his own path in science and is enjoying the respect of his colleagues.

8. Conclusion

After getting acquainted with the presented Dissertation, Abstract and other documents, based on the analysis of their significance and scientific and applied scientific contributions, **herewith I confirm that the scientific achievements meet the requirements** of the law (ЗРАСРБ) and of 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 applicant significantly exceeds the minimum national requirements in the professional field 4.1. Physical Sciences. No plagiarism was found neither in the Dissertation, nor in the Abstract and in the scientific papers submitted for the procedure.

Herewith, I give my positive assessment of the Dissertation.

II. GENERAL CONCLUSION

Based on the above, I recommend the scientific jury to award Assoc. Prof. Dr. Andon Angelov Rangelov the scientific degree "Doctor of Science" in professional field .4.1. Physical Sciences.

19/04/2021 Reviewer's report prepared by: ....

(Prof. Dr.Sci. Alexander Dreischuh)