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Review of the PhD thesis entitled '*Towards Autonomous Operation of Optical Atomic Clocks and Tweezers Machine*' submitted by Mehrdad Zarei

Introduction

The dissertation entitled '*Towards Autonomous Operation of Optical Atomic Clocks and Tweezers Machine*' was submitted as monograph by Mr. Mehrdad Zarei. It is based on experimental and engineering investigations conducted at Nicolaus Copernicus University in Toruń in the National Laboratory of Atomic, Molecular, and Optical Physics (KL FAMO) group and during a research stay at the University of Amsterdam in the Strontium Quantum Gas group. It comprises 146 pages of English text, prefaced by abstracts in both English and Polish. The main text is divided into 7 chapters and 4 supplementary appendices, in which the author presents both the fundamental theoretical concepts of quantum metrology, as available in the literature, and a detailed description of his original contributions to this field of science.

Assessment

Lasers used in quantum metrology must meet some of the most demanding criteria, including exceptional frequency stability, intensity stability, absolute wavelength control, beam directionality, and mode quality. These stringent requirements stem from the delicate nature of quantum systems and the exacting standards of precision measurements. Ultrastable lasers are expected to demonstrate fractional frequency stabilities on the order of 10^{-16} over a 1-second integration time. Furthermore, the most precise time and frequency measurement devices, such as optical clocks, which rely on these ultrastable lasers, are designed to achieve fractional uncertainties as good as 8.6×10^{-18}. Addressing these challenges aligns with the primary objective of the dissertation presented by the Doctoral Candidate. The thesis is focused on two key thematic areas: the development of autonomous systems for stabilizing and controlling lasers employed in atomic clocks and optical tweezer setups, and the implementation of these systems in experiments aimed at achieving highly precise measurements.

The first two chapters of Mr. Mehrdad Zarei's doctoral dissertation focus on outlining the well-established theory concerning the physical principles underlying the operation of optical atomic clocks and tweezers machines.

Chapter 1 discusses the role of lasers in cold atom experiments, particularly focusing on how advancements in laser technology have driven progress in quantum physics, including cooling and trapping techniques for atoms. It highlights the importance of laser frequency stability and precision,

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such as external cavity diode lasers (ECDLs), which provide narrow-bandwidth light. The chapter also covers methods for stabilizing laser frequencies, such as the Pound-Drever-Hall (PDH) technique, and the use of lasers in atomic spectroscopy, employing Rabi and Ramsey techniques to study atomic resonances. Furthermore, it explores the applications and parameters of atomic clocks as well as the use of optical tweezer traps in quantum simulations in the context of the KL FAMO set up.

Chapter 2 presents the theory underlying the optical atomic clock procedure, which closely mirrors the operation of the optical tweezers machine. The procedure begins with the magneto-optical trap (MOT) apparatus. Subsequently, the properties of the strontium (Sr) atom are described, as it is the chosen species for both the optical atomic clock and the optical tweezers machine. After cooling the Sr atoms, the optical lattice is introduced as the final step for trapping. The chapter concludes with an explanation of clock spectroscopy, Rabi oscillations, and the evaluation of systematic shifts.

Conducted within the KL FAMO group at Nicolaus Copernicus University in Toruń and the Strontium Quantum Gas Group at the University of Amsterdam, the research presented in Chapters 3–7 and Appendices A–D successfully addresses an original and substantial contribution of Mr. Mehrdad Zarei's PhD work to the automation and stability enhancement of the optical atomic clocks and quantum systems. The thesis comprises three such projects implemented in the optical atomic clocks and described in detail in chapters 3, 4, and 5. These projects successfully introduced improvements to the robustness and operability of most parts of the optical atomic clocks, even enabling their remote operation. A key outcome of this research is the development and successful deployment of auto-relocking programs, which allow lasers to remain locked for much longer durations than before, often for several weeks.

Chapter 6 delineates a strategic roadmap for the further optimization of optical atomic clocks. Employing sophisticated spectroscopic techniques, the temperature of Sr atoms was precisely measured, and systematic shifts were rigorously evaluated. Comparative analysis of cavity stability data from the 2022 and 2015 campaigns indicates improved long-term system performance. The thesis also explores preparations for investigating the effects of the magic-zero wavelength on trapped Sr atoms in the lattice, complemented by sideband spectroscopy of the excited $^3P_0$ atoms. The results, including measured atom temperatures and the observed red sideband dominance, align well with theoretical predictions.

Chapter 7 expands the scope of the research to the automation of ECDL lasers in the Sr optical tweezers system, targeting applications in quantum computing and simulation at the University of Amsterdam. The developed auto-relocking algorithm demonstrated versatility and effectiveness across various lasers and cold atom experiments. Extensive cavity and laser characterizations were performed. Finally, Rydberg spectroscopy on strontium atoms at $n = 61$ energy levels, confirming the enhanced robustness and reliability of the experimental systems post-automation, were done.

The Appendices A-D offer valuable supplementary information, providing practical guidance and resources related to the automation and control systems developed in this research.

While the candidate's achievements are commendable, there are areas where the dissertation could have been further strengthened. A more thorough discussion of alternative stabilization techniques, along with a deeper comparison to the systems used by other research groups, would have enriched the context of the presented work. Although the candidate compares the performance of the Sr optical clock across different campaigns, a further exploration of the limitations of the current automation systems and potential areas for future improvements would add valuable depth to the conclusion.

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The PhD thesis is written in very good, correct, and professional language, which reflects the author's high level of language skills. The writing style is clear, precise, and tailored to academic standards, making it easier to understand the technical and scientific issues presented. However, the author has not entirely avoided a few imperfections:

- *Abstract (p. iv) and Summary and conclusions (p.115)*: The expression '(...) to make these complicated experiments more robust and easy to operate (...)' could be better phrased as '(...) to make these complex experiments more robust and easier to operate (...)';
- *Outline (p. 11)*: A PhD student should avoid industry slang and consistently replace it with proper specialist language. Thus, the following phrases:
    a. 'I have performed many clock spectroscopy (...)',
    b. '(...) the system is complicated to operate (...)',
    c. '(...) the clock needs to operate non-stop (...)',

  should have been expressed as:
    a. 'I have performed extensive clock spectroscopy measurements (...)',
    b. '(...) the system is challenging to operate (...)',
    c. '(...) a continuous clock operation is required (...)';
- *Acknowledgments (p. ii)*: The expression '(...) carry out to test my developed program (...)' would benefit from the improved structures '(...) carry out tests of my developed program (...)'.

The above-mentioned shortcomings of the reviewed dissertation do not in any way detract from its excellent quality.

Summary

Mehrdad Zarei's doctoral thesis is a comprehensive and well-organized document that addresses complex and important challenges in the field of quantum metrology. The presented results will certainly contribute to the development of this branch of science, making the extremely complex experiments of optical atomic clocks and optical tweezers machines more resistant to many destabilizing factors and easier to conduct. **The doctoral candidate's work demonstrates originality by tackling a fundamental scientific challenge regarding the long-term stability and functionality of quantum experimental setups through innovative automation techniques. The candidate's ability to design, implement, and validate novel solutions to this complex problem reflects a profound understanding of atomic physics, laser spectroscopy, quantum technologies, and programming languages. These qualities not only highlight the scientific significance of the candidate's work but also suggest his ability to conduct independent scientific research.**

Recommendation

The presented dissertation fully meets the formal requirements for a PhD thesis as outlined in the *Act of 20 July 2018 - Law on Higher Education and Science* (section 187, p. 1-4). Therefore, I strongly recommend the admission of Mr. Mehrdad Zarei to the subsequent stages of the doctoral procedure.

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