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To **Secretariat of the Institute of Physics, UMK, Torun, Poland**

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Report Topic: Towards Autonomous Operation of Optical Atomic Clocks and Tweezers Machine

Dead time limits the estimated instability and uncertainty in optical clocks. Additionally, for field deployable quantum devices, hands-off operability is highly desirable. The thesis work exactly tries to overcome both the issues, i.e. deadtime and hands-off operation. In particular, the thesis is about integrating the idea of autonomous operation in setups for optical lattice clocks and tweezer setups for quantum computing using Rydberg atoms. The idea of autonomy in these setups is very new and timely. The thesis employs ultra cold strontium atoms for both the optical lattice and tweezer setups. Automation system is developed through controlling direct digital synthesiser (DDS), locking and relocking lasers and control of magnetic fields in compensation coils. The developed system has been tested and validated through the following tasks in a lattice clock setup- i) clock spectroscopy on the $^1S_0$-$^3P_0$ transition in strontium in order to measure linewidth to be 3 Hz and Rabi oscillations to be ~106 Hz; ii) measurement of the temperature of strontium (Sr) atoms in the ground state, $^1S_0$; iii) measurement of Zeeman shift (98.7 Hz) and probe light shift (0.3 (0.5) Hz). The temperature measurements are aimed at understanding the heating of atoms while they are trapped in a lattice at a magic wavelength, in case of Sr at 813.4 nm for red detuned and at 390 nm for blue detuned. The measurements with 390nm laser could not be carried out due to the laser being out of order. In case of the tweezer setup, autonomy character of the system is tested through performing Rydberg spectroscopy while the Rydberg laser remains locked at 316.5 nm. Additionally, the stability of the atom-cavity is measured during a campaign in 2022. The results of the campaign are compared with an earlier campaign in 2015. After the automation in 2022, the active working time could be increased from 27.85% in 2015 to 59.98% in 2022.

The thesis consists of 7 chapters, followed by the 'summary and conclusions' section. The chapter 1 introduces the topic of lasers in cold atoms. Particularly, external cavity diode lasers (ECDL) and their stabilisation, strontium clock setup in KL FAMO, Torun and optical tweezers in Amsterdam. It finally outlines the structure of the thesis. The chapter 2 is dedicated to the theoretical concepts associated with the work carried out in the thesis. It describes trapping of atoms in a magneto-optical trap (MOT), why strontium for the work, dipole trap, magic lattice and precision spectroscopy using Rabi method and the evaluation of systematic shifts in a clock setup. It further discusses the measurement of temperature in the thesis. The chapter 3 is on the design of automation for the compensation coils in the clock setup. It describes hardware and software, flowchart and testing of the design. The Chapter 4 consists of the description of the control system for direct digital synthesis. Like in the chapter 3, it introduces the idea, describes hardware and software, flowchart and algorithms and finally ends with test. The Chapter 5 is dedicated to relocking of lasers stabilised to cavities and wavemeters. It describes the implementation of the graphical user interface (GUI) in two versions. The Chapter 6 focuses on the optical lattice clock setup in Torun. It starts with the introduction of the setup, laser cooling, optical lattice and clock transition interrogation, followed by the description of lattice lifetime measurements (1.6 s), clock spectroscopy (3 Hz) and evaluation of systematic shifts e.g. Zeeman and probe light shifts. It also describes the measurement campaign carried out with other clocks. The final technical chapter, i.e. the chapter 7 describes the optical tweezer experiment in Amsterdam. The idea of automation developed in the chapter 5 is implemented in the setup, including the web application of auto relocking of the Rydberg laser at 316.5 nm. It finally reports on the Rydberg spectroscopy in an automated setup.

Additionally, there are appendices containing technical work relevant to the thesis work. I have also noted that the work carried out in the thesis has resulted in publications, as mentioned below. Given the nature as well as amount of the work, I am glad to recommend the thesis for a PhD degree.

Dissertation assessment
In summary, this doctoral dissertation represents a timely and significant contribution to optical metrology and quantum computing using neutral atoms. Despite minor shortcomings, its achievements are highly timely and certainly meet the conditions specified in Art. 187 of the Law on Higher Education and Science, thus warrant the awarding of a doctoral degree in physics.

Some minor issues:

Abstract
- The language coherence of the abstract could be improved. It also lacks mentioning some of the main results of the thesis, e.g. efficiency of the optical clock setup achieved after the automation.

Introduction
- Page 1, section 1.1, the last line of the third paragraph- the figure of 8.6x 10^{-18} for the inaccuracy of optical clocks needs update. Optical clocks have already reached into ~$10^{-19.}$ I would suggest updating the number and the associated references.
- Page 3, figure 1.3- slow feedback part is missing in the figure.
-Page 17, figure 2.2- Most of the neutral Sr optical clocks are based on Sr^{87}. I would suggest changing the caption to ‘relevant energy level diagram of strontium.’

Chapter 6
- Page 80, section 6.1.2: Laser cooling- briefly explain how frequency comb provides long term stability to the 689nm laser.
- Page 97, section 6.4.3: clock line measurement, figure 6.30- reader will benefit if direct values of magnetic field (in units of Tesla or Gauss) is mentioned in the panels/caption. At the moment, it is written in ‘volts’ requiring the knowledge of conversion and calibration.
-Page 98, figure 6.31- the figure caption needs some tweaking to correctly correspond to the panels of the figure.

Chapter 7
-Page 107, figure 7.4- The figure lacks the stabilisation of the ECDL 1070nm. I assume that it is also required to get a stable output of the SFG module. It would be good to include that in the figure.
-Page 108, figure 7.5- I assume that the figure caption is written in the reverse order.
-Page 108, figure 7.6- I would suggest changing the caption to, ‘Optical setup for transferring the stability of 689nm laser to 633nm laser via a transfer cavity. The cavity is PDH locked to the 689nm laser whilst the 633nm laser is locked to the cavity.’
-Page 113, figure 7.15- ‘Rydberg spectroscopy with 100 percent power of the UV laser and 500 µs duration of UV light. The measurement has been repeated only once’-→ ‘Rydberg spectroscopy with 100 percent power (*xx write the value of the power*) of the UV laser for 500 µs. The y-axis shows the atoms survived in the ground state $3P_0$. The measurement has been repeated only once.’

Publications
Below are the publications resulting from the thesis work-

1) M Zarei, I Knottnerus, A Urech, F Schreck, M Zawada, P Morzyński, "Autonomous Frequency Stabilization in Cold Atom Experiments" 2023 Joint Conference of the European Frequency and Time Forum and IEEE International Frequency Control Symposium (EFTF/IFCS)

2) Piotr Morzyński, Sławomir Bilicki, Marcin Bober, Adam Ledziński, Marcin Witkowski, Mehrdad Zarei, Michał Zawada, "Open-source electronics ecosystem for optical atomic clocks" 2023 Measurement Science and Technology, **34,** 075022.

3) M Zarei, I Knottnerus, A Urech, F Schreck, M Zawada, P Morzyński, "Automatic Relocking ECDL in Optical Tweezer Machine for Quantum Computing and Simulation" 2023 Conference on Lasers and Electro-Optics Europe & European Quantum Electronics Conference (CLEO/Europe-EQEC)

4) M Zarei, A Ledziński, M Bober, M Zawada, P Morzyński, “Automatic real-time control of magnetic field in an optical atomic clock” 2022 Joint Conference of the European Frequency and Time Forum and IEEE International Frequency Control Symposium (EFTF/IFCS)

Yours Sincerely,
Yeshpal Singh

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(Signature)