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Referee report on the doctoral thesis „Ultra-stable optical cavities in KL FAMO for metrology and fundamental physics" by mgr inż. Mateusz Narożnik

The dissertation was prepared on the basis of the work done at the National Laboratory FAMO in Toruń (Poland). The supervisors of the thesis are Prof. Dr. Habil. Michał Zawada and Dr. Marcin Bober from Nicolaus Copernicus University in Toruń (Poland). The main scientific activity was focused on the design of an ultra-stable, relatively long (0.3 m) optical cavity. Careful optimization of its parameters allowed the author to propose to use the cavity as a detector of the gravitational waves and to discuss application of the cavity to observe space-time quantum fluctuations.

Structure and contents of the thesis:

The doctoral dissertation consists of 152 pages and is divided into seven chapters. The main chapters cover the following topics:

Chapter 2: The physical principles of optical cavities, their characterization, and methods of utilizing them for spectral narrowing and laser stabilization

The main part of the dissertation begins with an introduction to the physical description of Fabry-Perot interferometers and the parameters that characterize them. The issue of resonator stability is addressed, along with a basic description of Gaussian beams and transverse modes in a Cartesian coordinate system. A brief description of the PDH technique is provided, as well as measures of resonator stability, including Allan variance, modified Allan variance, and power spectral density. Fig. 2.9, presented at the end of the chapter, is a valuable summary of the stability of various optical cavities with different designs.

Chapter 3: The theory of thermal noise and methods for its reduction

A clear yet in-depth introduction to the theoretical description of thermal noise and thermal noise floor is presented. The mechanical and thermal properties of various materials used for spacers, anti-reflective mirror coatings, and mirror substrates are described. The author focuses on Brownian thermal noise in the spacer, substrates, and reflective coatings, as well as thermoelastic noise in the substrates and thermo-optic noise in the coatings. This section concludes with a calculation of the total thermal noise floor for room-temperature cavities. I particularly appreciate Fig. 3.8 for its didactic value.

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The author also discusses the loss angle, photon statistics, and briefly, radiation pressure. A significant portion of this chapter is devoted to methods for reducing thermal noise. The author introduces the idea of increasing the beam radius inside the cavity to mitigate Brownian thermal noise in the coatings and proposes a convex-concave cavity configuration for this purpose.

Another valuable contribution described in this chapter is the analysis of the promising NEXCERA material for spacers, along with an investigation into zero-crossing point shifts for combinations of NEXCERA and ULE, fused silica, and single-crystal silicon substrates.

Chapter 4: The optical and mechanical design of a 30 cm cavity, including vacuum and thermal shielding, as well as a description of vibration tests conducted at the cavity's installation site

The author presents a very careful design of the ultra-stable cavity, including: numerical simulations of its mechanical distortions, optimization of the position of the support points, analysis of displacements and tilts of the mirrors under the influence of the gravity, reduction of the acoustic and seismic noises, and design of the UHV system. Also, the preliminary measurements are described, where using two cavities and a frequency comb, the frequency response of the cavity under test to the mechanical noise was investigated.

Chapter 5: The fundamentals of gravitational wave theory and a proposal to use ultra-stable optical cavities as resonant detectors for these waves in the high and ultrahigh-frequency range (from kHz upwards)

The author provides a very clear introduction to the fundamental concepts of gravitational waves. In Fig. 5.3, he presents the capabilities of current and proposed detectors, categorized by the frequency of the detected waves. Following the introduction of the characteristic strain, amplitude spectral density, and energy density of gravitational waves, the author proposes the innovative idea of using ultra-stable cavities as resonant detectors for high- and ultrahigh-frequency gravitational waves. This nontrivial concept is supported by a thorough analysis of the thermal limits of cavities with various designs, including different materials, lengths, temperatures, and spacer radii.

Chapter 6: The basics of spacetime fluctuation theory and a new perspective on existing concepts for using ultra-stable cavities to detect these fluctuations, along with an analysis of detection limits based on data from the best cavities in the world

The author presents a more comprehensive analysis of the constraints on spacetime fluctuations than what has been published so far, based on measurements conducted with ultra-stable cavities by other research groups. The author claims a reduction in the limits by one to three orders of magnitude compared to previously reported results.

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Advantages of the dissertation:

The topic undertaken by Mr. Narożnik is very interesting, advanced, ambitious, and timely. Optical cavities are an essential component of optical atomic clocks – advanced devices that have the potential to become, at least in part, the foundation of a new definition of the second. In these clocks, optical cavities are responsible for maintaining the short-term stability of clock lasers during intervals between frequency measurements of the reference standard. There are more applications for high-finesse cavities, such as in highly precise measurements of molecular line shapes.

In this doctoral dissertation, one could say that optical cavities gain a new life. They are no longer merely the workhorses of optical clocks but emerge as standalone detectors for testing hypotheses in modern physics, including physics beyond the Standard Model.

I must admit that I am a big fan of compact and relatively inexpensive solutions developed from atomic and optical physics, which are used to verify fundamental hypotheses of modern physics. On the opposite end of the spectrum are, of course, large, extremely costly infrastructures that require extensive teams of people to operate – whether on Earth, underground, or in space.

Regarding the main part of the thesis, the reader benefits from a clear overview of the optical cavities and the theory of thermal limits of their stability. Fig. 3.8 (and 2.9 earlier) is of particular didactical value.

In Chapter 4 the author shows his extensive work on the design and modelling of the new cavity, of a relatively large length. As far as I know, the realization of the whole setup is being finalized now. I must stress that the design of an ultra-stable cavity is very demanding and requires a deep knowledge in the field of physics and engineering.

In the next chapter the author deeply analyses the capabilities of the current and proposed detectors of the gravitational waves and confronts them with his idea of using the optimized ultra-stable optical cavity for this purpose. The gravitational waves are clearly described in terms of their frequency and their potential sources – both astrophysical and beyond the Standard Model.

In the final chapter, the author proposes a modified analysis of the existing data from other groups to attack an ambitious problem of observation of space-time quantum fluctuations.

Last but not least, the dissertation includes an impressive bibliography consisting of 312 entries, spanning a total of 30 pages.

Criticism:

It is my duty to point out some weaknesses of the dissertation. I want to focus on two main aspects here:

1) During reading the thesis I had a feeling that I miss some important aspects of the general philosophy of the thesis. The introduction should serve as a guide to the dissertation – and to some extent, it does. However, the introduction states that the main part of the work focuses on designing a cavity operating at room temperature, with additional theoretical

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calculations aimed at improving the cavity for use as a detector of gravitational waves or spacetime fluctuations. The problem is that such an improvement requires operating at cryogenic temperatures. I am afraid that the designed cavity is not suitable for this purpose.

Moreover, I miss a clear justification for choosing ULE as the spacer material, especially since the new material, NEXCERA, was previously praised as promising in the context of long-term stability.

2) To be honest, I am not a big fan of Chapter 6. While the introduction to the theory of quantum spacetime fluctuations is undoubtedly very clear and comprehensible, the explanation of the author's calculations is not entirely clear – at least to me. I find the lack of justification for the choice of the parameter β particularly problematic. Including only references to the literature is insufficient, given that this parameter is crucial for the calculations. Furthermore, while the use of a specific model (here, power functions) is, of course, permissible, drawing concrete conclusions should be supported by some form of hypothesis testing or a deeper analysis of the impact of introducing the given power dependence on the final results.

List of some of the specific issues (please do not address these issues except answering questions or if you think I missed the point)**:**

- Inconsistent use of singular and plural forms in the first person ("I" versus "we") and impersonal forms.
- Three very strange curves in Fig. 2.2 (bottom left).
- Eq. 2.5 is correct but in reality it is an approximation for R large enough (very good approximation for good cavities).
- Comment to Eq. 2.7: for me, the A, B, C, D elements characterize the optical elements and not "the final state of the light's round trip".
- Incorrect orientation of the polarizing cube in Fig. 2.7. I'll risk hypothesizing that this was a test of the reviewers' attentiveness 😊.
- Page 19, footnote 4: $T = \tau$ is clear to me but might not be to a more general audience.
- Page 35, bottom: I miss a very brief description of the method for canceling thermo-optic noise.
- Page 37: It is stated that some types of noise are ignored. It would be helpful for the reader to include numerical values to justify this approach.
- Fig. 3.11: (snippy comment) The wavefronts are depicted incorrectly for this particular divergence of the beam. The smallest radius of curvature should be around $z = \pm 0.5$ m (Rayleigh length).
- Page 48: Just to clarify – in the sentence "more significant thermal drift," do you mean "thermal drift" or is it actually structural aging?
- Page 53: the description of the mechanical design of the post is very brief.
- Fig. 5.1: the coordinate system is missing.
- Page 82: a very brief definition of the chirp mass is missing.
- Page 87: the sentence "the vertical distance between the curves" is unclear to me.
- A duplicated sentence appears on page 109 (upper half).

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Editorial and language side of the thesis:

The number of mistakes, such as common typos, is very low. I also noticed a small number of editorial errors; however, it does not make sense to list them here, as they are clearly the result of oversight rather than a lack of knowledge of linguistic rules or the LaTeX environment. The only exception is the incorrect use of straight quotation marks instead of typographic ones.

The language of the dissertation is clear, and aside from a few minor grammar and spelling errors, it is correct. These mistakes do not hinder readability in any way. Reading the dissertation was a pleasure for me.

Some of the questions I would like to ask during the defense:

1) What is the current status of the development of the 30 cm cavity in KL FAMO?
2) Is there any opportunity to build new setups and to perform the proposed detections of the gravitational waves and searches for the signs of the existence of a quantum foam (space-time fluctuations)?
3) What was the basis of the calculations whose results are presented in Fig. 6.3? Are they purely theoretical (as I assume), or do they take into account any realistic constraints? In other words, to what extent could the calculated sensitivities (thermal limits) be weakened in a real-world cavity?
4) Why was the NEXCERA material not used for constructing the spacer? Is this decision related to its cost, availability, incomplete data about its properties, and consequently, the high risk of investing in it?
5) Why the solid red curve in Fig. 5.12 (bottom) suggests better sensitivity than the black dashed one in left panel and worse sensitivity in the right panel?
6) What is the target pressure in the designed cavity? Is it really at 2×10^{-10} mbar level? (page 74)
7) I am not sure if the beat-note signal (page 89) will benefit from decoupling the light from the main beam. The transmitted beam is weak but fully “engaged” in the process. The back-reflected beam is relatively strong but a significant part of the light just forms the background.

Conclusions:

Despite the criticisms mentioned above, I believe the Ph.D. candidate has demonstrated an excellent understanding of the underlying theory and computational methods, particularly the numerical ones. His knowledge of the current state of the art in modern physics is undeniable. Furthermore, the thesis provides clear evidence that Mr. Narożnik has mastered the skills required to develop highly advanced experimental setups in the field of ultra-precise measurements. Additionally, he possesses strong data analysis skills essential for formulating scientific conclusions. The thesis also demonstrates that the author has a solid understanding of both the strengths and limitations of the experimental setup he designed.

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Formal statements:

In my opinion, the presented thesis demonstrates that mgr inż. Mateusz Narożnik satisfies the requirements laid down by the Polish law (ustawa Prawo o szkolnictwie wyższym i nauce 2018, art. 187, ust. 1 i 2, z późniejszymi zmianami) for candidates for the doctoral degree. In particular, the doctoral dissertation definitely demonstrates the general theoretical knowledge of the Ph.D. candidate in physics and the ability to carry out research independently. The latter is also supported by the fact that he is first author of one scientific peer-reviewed article and co-author of four published conference materials. Also, the subject matter of the doctoral dissertation is an original solution to a scientific problem (complete design of a 0.3 m ultra-stable optical cavity, proposal and analysis of a new type of the gravitational waves detector, extension of the interpretation of the searches for the indications of space-time fluctuations).

I recommend the admission of mgr inż. Mateusz Narożnik for the subsequent stages of the procedure, including the public defense.

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