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A mezzo cartaceo e elettronico
Al: **Secretariat of the**
Institute of Physics, UMK
Torun, Poland

Report on Mateusz Narożnik, Ultra-stable optical cavities in KL FAMO for metrology and fundamental physics

The thesis explores the design of an ultra-stable optical reference cavity (ORC) exploiting the current state-of-the-art optical and mechanical technology. Its objective is to enhance optical frequency metrology for optical lattice clocks, and to enable high-precision measurements of fundamental physics, including the detection of gravitational waves and spacetime quantum fluctuation.

Despite significant advancements in the development of stable optical resonators, their realization remains a formidable challenge due to several unresolved technical issues. Designing and characterizing such resonators requires expertise in diverse fields such as vacuum technology, material science, finite-element analysis, thermodynamics, acoustics, and laser optics. Mastery of these areas undoubtedly justifies the conferment of a doctoral degree in physical sciences, particularly given the thesis's clear and significant connections to broader research in physics.

The thesis is organized into seven chapters, including an introduction and conclusions. Below is an analysis of its structure and content:

The introductory chapter frames the problem addressed by the thesis and reviews the state of the art for ORCs.

Chapter 2 presents the theoretical framework of optical resonators, including paraxial optics, frequency metrology and statistical methods for characterizing frequency stability. This is descriptive and generally well-executed. The only note that can be made is a missing treatment of the dynamic response of the interferometer, which could play an important role for determining the characteristics of the GW detector proposed later in this work.

Chapter 3 is mainly devoted (and also named after) to thermal noise affecting ORCs. However other "fundamental" limitations affecting their performance are briefly discussed. The treatment is very detailed, starting from the general thermodynamic theory based on the fluctuation and dissipation theorem (FDT). A particular attention is devoted to new spacer materials, such as NEXCERA and its possible characteristics as material for an ORC. The discussion is detailed and highly informative

Chapter 4 is devoted to the description of the design of an ultra-stable ORC system based on a ULE spacer and fused silica mirror substrates with dielectric coating. This includes finite element analysis of the mechanical system, the vibration sensitivity reduction and the mechanical support system. The innovative use of half-ring weights to mitigate vibration sensitivity is noteworthy. It presents interesting original solutions, such as the introduction of half-rings weights applied to the spacer to reduce the residual vibration sensitivity due to imperfect alignment of the suspension points with respect to the optimal points. It contains detailed technical characterization of the system regarding acoustic noise, seismic noise and mechanical transfer functions—essential groundwork for achieving the desired stability.

Chapter 5 is dedicated to the study of possible detection of gravitational waves (GW) by means of ORCs. After a brief introduction to the physics of GWs and their sources, in this chapter a new GW detection scheme based on rigid ORCs is presented in detail. The signal-to-noise ratio of proposed Ultra Stable Optical Cavity (USOC) detector, and thus the detector sensitivity, is studied in terms of the mechanical response of the system by making a parallel with resonant bar detectors. This part of the doctoral thesis is also the core of an article published on a peer-review journal (Ref. 15). However, there is almost no discussion about the (resonant) detection of the output signal (namely, a heterodyne Michelson-like interference signal), which is somehow unexpected, while much interest is paid on possible lowering of the noise by cavity geometry and material engineering. Another possible issue is due to the lack of consideration of the cavity frequency response in calculating the detector transfer function $G(f)$, which would result in a further reduction of sensitivity above tens of kHz (according to Fig. 5.7) or below for longer cavities.

Chapter 6 illustrates another possible application of ORCs for fundamental physics, namely spacetime fluctuation limiting the ultimate measurement uncertainty of space due to quantum mechanics. Here state-of-the-art data from best clocks and cavities are used to pose new limits on the power spectral density of spacetime fluctuations.

The thesis makes several significant contributions:

- It demonstrates that a comprehensive understanding of thermal noise can lead to cost-effective optical designs, such as the concave-convex cavity, capable of achieving unprecedented stability without overly complex equipment.
- It highlights the application of ORCs in fundamental physics, particularly GW detection. While this area requires further development, the groundwork laid here is promising.

The overall quality of presentation is commendable. However, at times, the phrasing relies too heavily on technical jargon, omitting some important defining terms. Occasional grammatical errors and typographical slips also affect readability and, in some cases, lead to ambiguity. The above criticism does not diminish the excellent results.

Dissertation assessment

In summary, this doctoral dissertation represents a substantial contribution to laser optics, optical metrology, and experimental gravitational physics. Despite minor shortcomings, its achievements are highly commendable 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:

Introduction

- Pag. 5: "Currently, modern advanced technologies such as precision radar-ranging systems [19] and deep-space navigation [20] also require ultrastable optical resonators." This statement is quite unsupported either by the cited references and by commercially available system. The candidate should briefly state why those technologies would benefit from ultrastable lasers (not clocks!!) and if there exist some proposal/proof-of-principle experiment.

- Pag. 5: "an upcoming redefinition of a second will be based on the optical narrow atomic transition where atoms are interrogated by a laser locked to the ultra-stable cavity [21–24]." I would suggest the following changes:
  - after "redefinition" put reference [24];
  - change "on the optical" with "on an optical";
  - Ref. 23 should be cited in the context of the possible applications of ultrastable lasers based on passive optical resonators, which is the core of this thesis, remarking the fact the it is "already possible" to use ultrastable cavities as free-wheels for timescales because of their low drift level.
- Pag.5: "fundamental thermal limit" → thermal noise limit. Regarding the attribute "fundamental", this is debatable because thermal noise is considered a "technical" limit in light interferometry, since it should vanish at the thermodynamic limit T → 0.
- Pag. 5-6: the candidate should mention the effort to reduce mirror thermal noises by changing the beam shape geometry. Notable examples are mesa beams [arXiv:gr-qc/0409075, Appl. Opt. 46 6648 (2007)], conical beams [Phys. Rev. D 78, 082002 (2008)], and higher-order Laguerre-Gauss (LG) beams [Classical Quantum Gravity 23, 5777 (2006), Phys. Rev. Lett. 105 231102 (2010)], and possibly mention why such approaches are difficult to be realized in table-top ultrastable cavities.
- Pag. 6: "new technical challenges related to heat extraction from the cavity's mirrors. [48]." Probably here a reference discussing or experimenting these technical issues should be preferred with respect to the website of a research project.
- Pag. 6: "detect high-frequency gravitational waves and low-frequency space-time fluctuations" → detect … waves and search for. Indeed, it is not verified that such effects exist.
- Pag. 6: "laser frequency locking, mainly Pound-Drever-Hall (PDH)" → laser frequency stabilization, mainly Pound-Drever-Hall (PDH) technique.
- Pag. 7: "I use the best available…" Here there is a switch from a generally impersonal phrasing to a first person. Please correct the statement according to the style used in the rest of the section.

Chapter 2

- Pag. 8: "Assume that light with the complex … the simplest form of a Fabry-Pérot resonator.". I suggest to reverse the order of the above sentences, first defining what a FP is and then specifying the basic assumptions on the electric field in order to calculate the circulating, transmitted and reflected fields. Furthermore, Fig. 2.2 is referenced before 2.1: probably here the correct reference is still 2.1.
- Fig. 2.3: SCS acronym not defined.
- Sec. 2.3: "Laser frequency narrowing and locking": although the name of this section suggests the treatment of the problem of reducing the spectral emission of a laser source, it is actually a brief introduction to the Pound-Drever-Hall frequency stabilization technique. I suggest either to change the name of this section, or to profoundly enlarge it by introducing and explaining the problem of the spectral broadening of the laser emission and its active "narrowing" by servo locking to a passive resonator. For reference, see the seminal work in Zhu, M. & Hall, J. L. JOSA B 10, 802 (1993).

Chapter 3

- Pag. 27: "with a velocity-like dumping force $f\dot{x}$" Probably (and also for consistency with Eq. 3.2) f should be replaced by λ
- Pag. 31, Eq. 3.17: The factor $1/\pi r^2$ is wrong, please replace with $1/\pi w^2$ according to Ref. [109], eq. 13

- Pag. 34-37, Sec. 3.2.3: Regarding the TE noise, it should be noticed that the geometric dependence of the power spectral density is proportional to the inverse third power of the beam size on the mirror surface, i.e., $S \propto w^{-3}$. For reference, see Ref. [128].
- Pag. 37, Sec. 3.2.4: Ref. [128], as it is cited in the text, seems to threat the TE noise of the spacer. Please revise this sentence in order to avoid this misunderstanding. Ref. [128] can be cited earlier, see previous correction.
- Pag. 51: "In [27] δ value was simulated by FEM" I guess the value of δ was estimated from FEM simulation. Please correct the sentence. Furthermore, the acronym FEM is not defined here but later. Please correct it too.

Chapter 4

- Pag. 70, Sec 4.3.3: There is a typo: "Transfer function measurements using 689 nm and 698 cavities" → Transfer function measurements using 689 and 698 nm cavities
- Pag. 74: The initial part of Sec. 4.4.1 is probably more appropriate in Ch. 2.

Chapter 5

- Pag. 93, Eq. 5.16: The right-hand side of this inequality is the formula for the so-called cavity decay time (see for instance W. Nagourney, "Quantum Electronics for Atomic Physics", or Ref. [50], Ch. 4.). The dynamic response of the ORC should play a major role in determining the detection bandwidth of the USOC detector. This frequency cannot be considered an hard-wall constraint, since it just indicates, roughly, the linearity region for the frequency response of a Fabry-Perot. Probably the ORC frequency response should be included and discussed in this work.
- Pag. 93, Fig. 5.7: There is a typo: "and the blue-shaded area is the exclude region." → excluded region
- Pag. 109: "Further advancements in reducing shot noise can be achieved by increasing the finesse and utilizing phase-squeezed light. Further improvement in reducing shot noise can also be reached by increasing the finesse and using phase-squeezed light." These two sentences are basically the same. Please remove one of your choice.

Chapter 6

- Pag. 111: $\delta l \geq \mathrm{sqrt}(l\, l_P^2 /d)$ → d is undefined.
- Pag. 112: $x_{RMS} \sim \sqrt{T_{obs}}$ → While it is clear from the contest what this formula meant, it is formally wrong to use the "similar" symbol, since its dimensionality is wrong. Hence, please change with "proportional" symbol.
- Pag. 114, Fig. 6.1: Please change reference to Fig. 6.1 with "Top panel".

Bibliography

- Ref. [96] and [138] point to the same document. Please unify these two references
- Ref [139]: There is a typo: "RiccardoEditors DeSalvo." → and Riccardo DeSalvo Editors (??). Please check and correct it.

Dr. Marco G. Tarallo