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Review of the doctoral dissertation of Mateusz Jakub Narożnik, M.Sc. Ing. „Ultra-stable optical cavities in KL FAMO for metrology and fundamental physics”

This dissertation of M.Sc. Ing. Mateusz Jakub Narożnik is devoted to the design of ultra-stable optical cavities (Fabry-Pérot interferometer) from the point of view of its use for the detection of gravitational waves and measurements of the occurrence of quantum space-time fluctuations predicted by one of the models of the quantum theory of gravitation. The range of applications of measurement devices in which ultra-stable cavities are used is very wide, ranging from the verification of hypotheses, e.g. the existence of dark matter, the search for exotic particles outside the standard model, determination of the amplitude of space-time fluctuations, through the detection of gravitational waves, studies of violation of invariance of the Lorentz transformation, to metrological aspects, e.g. determination of the optical time and frequency standard. To perform this type of research, cavities with a resonant frequency stability of $\Delta f/f < 10^{-15}$ are required. Achieving such frequency stability implies that the effective distance stability between the cavity mirrors must be at the same level. This required that the Author of the dissertation, who was faced with the task of designing such an optical cavity, identify and take into account a number of physical phenomena affecting frequency stability, perform quantitative and qualitative simulations in order to select optimal materials and construction solutions. The first part of M.Sc. Mateusz Narożnik's dissertation is devoted to these problems. The results of the work presented in the first part of the dissertation are comprehensive designs of ultra-stable optical cavities: the first with a spacer made of ULE, and the second with a spacer made of the NEXCERA material. In the second part of the dissertation, the author proposed the use of ultra-stable optical cavities to test fundamental physics subjects, i.e. as resonant probes of gravitational waves and to determine the amplitude limits of space-time fluctuations, in the so-called ‘foam’ model of space-time.

The structure of the thesis is as follows: it begins with an introduction in which the author presents the motivation for the research and discusses the arrangement of the dissertation. Chapters two to four are devoted to the design of an ultra-stable optical cavity, and the next two chapters are devoted to a description of the possibility of using the cavity to detect gravitational waves and to determine the constrains od the quantum space-time amplitude fluctuations. The last two chapters are conclusions and bibliography.

Chapter two covers the basic concepts related to the operation of resonant optical cavities. These include the mathematical description of the resonance conditions and its width, the topic of resonator stability for a Gaussian light beam profile, the distribution of cavity mods. In the next part of this chapter, the Pound-Drever-Hall method of laser light frequency stabilisation using a cavity is discussed, as well as the influence of cavity parameters on the frequency stability of laser light coupled to an optical cavity. In the last part of the chapter, the quantities describing the stability of the cavity resonant frequency, and the frequency and phase domain noise are discussed together with their time scales. In this chapter, Figure 2.9 p. 22, showing the progression of the frequency stability of successive cavity generations, the author fitted two straight lines to the data set to illustrate the rate of increase in cavity stability. It is not clear from the text of the thesis what parameters were taken into account in assigning the data to the two groups, and whether there are any general conclusions to be drawn from this fitting for the way cavities are designed or built?

In chapter three, the fundamental sources of optical cavity frequency instability related to thermal noise are addressed. This chapter provides the basics of thermal noise theory with a quantitative description of the effects of individual phenomena on the stability of the optical cavity resonant frequency. The analysis performed by the author includes: temperature expansion of materials, length fluctuations caused by vibrations of the material structure at non-zero temperature (Brownian noise), thermoplastic processes, changes in the refractive index of mirror coatings and the medium in which light propagates inside the cavity. The quantitative thermal noise simulations are carried out for a range of spacer materials, mirror substrates and reflective coatings. The author focused special interest on two materials, ULE and NEXCERA, which were considered for the spacer of the new cavity. The choice of these materials is motivated, among other things, by the fact that their coefficient of linear thermal expansion (CET) is zero in the room temperature range. By setting the operating temperature of the cavity at a level for which the CET coefficient is zero, the thermal noise of the mirrors makes a dominant contribution to the fundamental limitation of the cavity stability. In order to reduce the thermal noise of the mirrors, the author proposed a solution utilizing the fact that the thermal noise of the substrate and reflective coating depends inversely proportional to the diameter of the incident laser beam (as $\sim 1/\omega$ and $\sim 1/\omega^2$, respectively). It involves changing the configuration of the resonator mirrors from plano-concave to convex-concave, which makes it possible to increase the diameter of the incident beam on the mirrors at a fixed spacer length. In the standard plano-convex configuration of the mirrors in the resonator, the limitation of the beam diameter is mainly due to the limitations of the technology of making a concave mirror with a large radius of curvature. As a result of the simulations, the Author determined that it would be most efficient in terms of increasing the diameter of the incident beam on the mirrors to use mirrors with a curvature of R_1 = -10 m and R_2 = 20 m, respectively, for the planned 30 cm long cavity spacer. However for this configuration the resonator is close to being geometrically unstable. The question is, how does this result in practical use of such a configuration, e.g. in the process of laser beam adjusting to the fundamental cavity mode?

In chapter four, design solutions for the cavity and its surroundings are presented in order to achieve the stability of the cavity at $\Delta f/f \sim 10^{-16}$ level, i.e. close to the fundamental limits described in chapter three. Achieving this level of stability requires reducing the influences of vibration, pressure and temperature fluctuations on the cavity. The Author approaches this problem comprehensively using both passive and active methods to stabilise the operating conditions of the cavity. In order to minimise the impact of pressure and temperature fluctuations, the cavity will be placed in a box-in-box enclosure under high vacuum. This solution eliminates convection, which could lead to uneven temperature distribution within the cavity, as well as fluctuations in the refractive index. In order to stabilise the temperature of the cavity inside the vacuum enclosure, three thermally and mechanically isolated enclosures are placed, one inside the other. The temperature of the outer one is actively controlled using Peltier modules and temperature sensors. Remaining two inner enclosures, in the proposed layout, act as a low-pass filter for the temperature. They thus ensure a uniform temperature distribution and limit the temperature fluctuations in the cavity area. An extensive section of the chapter is devoted to minimising the influence of vibrations. Firstly, by performing a series of simulations, the Author determined the position of the support points of the spacer, in such a way that its vibrations have the smallest possible impact on the change in the position of the mirrors relative to each other (distance and tilt). In the analyses, the author also considered ways to compensate for deviations in the actual position of the support points from the calculated ones, as well as the effect of deformation of the elastic supports under the pressure of the spacer. Furthermore, the deformation rates were determined empirically and included in the modelling. Another element of the project intended to minimise the impact of vibrations on the cavity was the vibro-acoustic adaptation of the cavity's room. This included soundproofing the room with appropriate acoustic structures, separating the platform on which the cavity will finally be placed from the building by placing it on an independent foundation. In addition, a composite pedestal made of materials with different mechanical properties (lead, granite, concrete) was placed on the platform to minimise the transmission of low-frequency vibrations. Finally, the vacuum enclosure of the cavity will rest on a TS-300 platform placed on this pedestal. The TS-300 will actively stabilise the vibrations on the basis of readings from a seismographs placed on the cavity enclosure. At each stage, the efficiency of the implemented solutions was confirmed by measurements. In Section 4.3.3, an interesting concept for active frequency compensation of a cavity-coupled laser based on vibration measurement with an external sensor and a predetermined transfer function is presented. The Author performed measurements of the transfer function, i.e. the influence of the cavity vibration on its stability with respect to the vibration amplitude measured with the accelerometer. However, a demonstration of the efficiency of this solution is missing in the thesis.

In chapter five, the author proposes the application of an ultra-stable optical cavity (USOC) as a resonant gravitational wave detector. The first part of this chapter covers the basics of the theoretical characterisation of gravitational waves and an overview of gravitational wave detectors classified according to the frequency range of the measured gravitational waves. The chapter also provides an overview of the types of gravitational wave sources according to the frequency band of the generated gravitational waves. The next part of the chapter covers the principle of operation of a resonant gravitational wave detector using an optical cavity and a detection scheme based on ultra-stable cavity system or a single cavity in combination with an atomic clock. Based on simulations, the author identified possible fundamental sensitivity limitations of such detectors depending on the design and operating conditions of the UOSC. To determine the sensitivity requirements of a USOC-based detection system, the author simulated the spectrum of gravitational waves generated by three types of astrophysical sources and two potential types of nonastrophysical sources (black holes with masses smaller than the mass of the Sun and axions). Finally, the author has shown that in the emission band of the analysed gravitational wave sources it is possible to use cavities with a spacer length below 2 metres as detectors. Nevertheless, to achieve sufficient sensitivity of such USOC-based detectors, it is required to solve a number of technical and material problems, which are described in the last section of this chapter.

The chapter sixth is devoted to an application of the ultra-stable optical cavity as a detector of space-time fluctuations. The chapter begins with a theoretical description of the space-time fluctuations predicted by so called “foam” model and the method of their determination. In the followed part of chapter Author proposes improving existing limits using data from a set of two cavities aligned both perpendicular and parallel The author has analysed the instability measurement data available in the literature for the three currently best optical cavities. This approach allows to improve the literature constraints by an order of magnitude. Author proposed also two methods of using a single cavity to determine limit space-time fluctuations. The first one is a based on the data set obtained from the three-cornered hat method, which gives two orders of magnitude improvement respect to literature constraints. The second approach, which involves data from a single cavity compared with strontium atoms, sets limits that are an order of magnitude more stringent than those achieved using the single cavity with the three-cornered hat method.

In summary, this dissertation provides a comprehensive approach to the design of an ultra-stable optical cavity and its application to the detection of gravitational waves and the determination of the constraints on space-time fluctuations predicted by one of the models of the quantum theory of gravity. The Author designed and partly built the ultra-stable cavity based on the analyses presented in this dissertation. The results presented in this dissertation are relevant not only for metrological research, but also for fundamental physics and astrophysics hypothesis testing.

In my opinion, the presented work meets the legal requirements for doctoral dissertations specified in Article 187 of the Law on Higher Education and Science of 20 July, 2018 (with subsequent amendments). I recommend that M.Sc. Mateusz Narożnik be admitted to the next steps in the procedure for awarding the doctoral degree.

W mojej opinii przedstawiona praca spełnia ustawowe wymogi stawiane rozprawom doktorskim określone w art. 187 ustawy Prawo o szkolnictwie wyższym i nauce z dnia 20 lipca 2018r. (z późniejszymi zmianami). Wnoszę więc o dopuszczenie mgr. Mateusza Narożnika do dalszych czynności przewodu doktorskiego.

J. Szczepkowski
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