Piezo-Tunable High Finesse Cavity

Katharina Möhle, Klaus Döringshoff, Moritz Nagel, Evgeny V. Kovalchuk, Achim Peters

Humboldt-Universität zu Berlin, Institut für Physik, AG Optische Metrologie
Hausvogteiplatz 5-7, 10117 Berlin, GERMANY
Email: kmoehle@physik.hu-berlin.de

ABSTRACT

We present the results of our investigations on the performance of a tunable high finesse optical cavity incorporating a piezoelectric actuator. Such a piezo-tunable cavity could find application in the space-borne gravitational wave detector LISA, which needs a tunable prestabilization in order to accommodate slow Doppler-shifts caused by yearly variation of the triangular satellite configuration. The measured laser frequency noise is below 10 Hz/√Hz at Fourier frequencies above 0.1 Hz fulfilling the LISA requirements on laser system frequency noise for a tunable prestabilization. To demonstrate the feasibility of the integration within the LISA arm locking concept, we included the piezo-cavity in an outer feedback loop. Thus the stability of an ultra stable reference cavity could be transferred to the piezo-tunable cavity by stabilizing the cavity length (bandwidth 5 kHz).

I. INTRODUCTION

The need for highly stable lasers in optical metrology and precision measurements has led to a continuous development of optical cavities. With the best high finesse cavities a relative frequency stability < $1\cdot 10^{-15}$ [1] can nowadays be obtained. The frequency of a laser stabilized to such a cavity can ordinarily only be adjusted in multiples of the free spectral range of the cavity, which is determined by the cavity length ($\nu_0 = c/2L$). In order to tune the laser to an arbitrary frequency, the use of e.g. AOMs, EOMs or additional heterodyning lasers is usually necessary. Another approach is to make the cavity itself tunable by adding a piezoelectric actuator and thus be able to tune the cavity length ($\Delta\nu/\nu = -\Delta L/L$). This simple approach is a widely-used technique for low finesse laser resonators, but has not been thoroughly investigated with high finesse cavities yet. For the integration in high finesse cavities the higher thermal expansion coefficient (CTE) and other properties of the piezoelectric material like creep, aging and hysteresis have to be taken into account.

The use of a piezo-tunable cavity has been discussed for the spaceborne gravitational wave detector LISA (Laser Interferometer Space Antenna, [2]). LISA is a planned joint NASA-ESA mission to observe astrophysical and cosmological sources of gravitational waves of low frequencies. It will consist of three space crafts flying in a triangular constellation with an arm length of 5 million km. To measure gravitational waves with a strain < 10^{-21}, an extraordinary frequency stability of the same order of magnitude is necessary in order to perform an interferometric read out of the satellite distance. To achieve such a high stability, a scheme with three steps of noise reduction is proposed. First, a free running Nd:YAG laser has to be prestabilized to a Fabry-Pérot cavity. In a second step, it is intended to transfer the relative length stability of the long LISA arms to the laser frequency stability with a self interference technique called arm-locking [3, 4]. The last step will be provided by post processing of the recorded phase data with a technique called Time-Delay-Interferometry (TDI, [5]), in which the arm length difference of the interferometer is formally canceled. Since the length of the LISA arms will change slowly over time, the prestabilization has to be tunable to accommodate slow Doppler shifts. This tunability could be achieved with a fixed cavity and an extended locking scheme like sideband locking [6, 7] or with a piezo-tunable cavity.

II. SETUP

The piezo-tunable cavity consists of a cylindrical Zerodur spacer with a length of 10 cm and 5 cm diameter. A fused silica mirror with a curvature of 0.5 m is optically contacted to the spacer. A commercial multilayer stack piezo actuator with a length of 7 mm and 1 inch diameter is attached to the other side with a three point glue joint. A second, plane fused silica mirror is attached to the piezo in the same way (see Fig. 1 left). For gluing an adhesive (Eccobond 285) with a low outgasing rate and a low CTE of $3\cdot 10^{-5}$ 1/K is used. A second cavity without piezo but with both mirrors

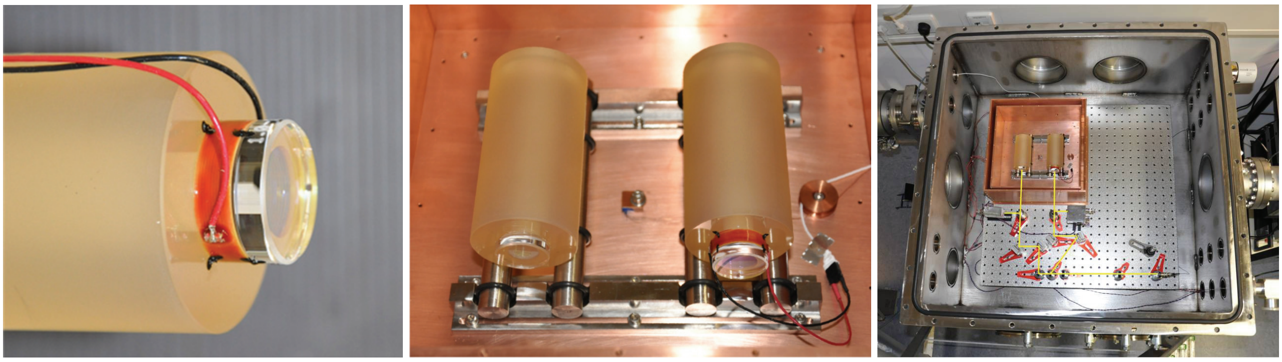

Fig. 1: (left) Cavity with piezo-electric actuator attached via a three point glue joint. (center) Fixed and tunable cavity in same test environment. (right) Whole setup in vacuum chamber (750 x 750 x 350 mm^3)

optically contacted is available for comparison. Both cavities are mounted in their Airy points on Viton O-rings to minimize spacer bending due to vibrations. They are enclosed by thermal shields, an outer actively temperature stabilized shield and an inner passive shield. This assembly, together with coupling optics and photo detectors, is located on an optical bread board inside a 750 x 750 x 350 mm^3 vacuum chamber (Fig. 1 right). The vacuum chamber is placed on pneumatic vibration isolators (Newport PL 2000).

Two Nd:YAG laser used for stabilization to the cavities are located on a separate optical table. Their beams enter the vacuum chamber through the same optical fiber and can each be stabilized to either resonator using the Pound-Drever-Hall technique. For performing a beat measurement and characterization of the Zerodur cavities, several optical references such as a fused silica (FS) cavity [8], a vertical ultra low expansion glass (ULE) cavity and an iodine reference [9] are available in our lab.

III. RESULTS

Frequency Stability

The frequency stability of the piezo-tunable cavity was determined with a beat note measurement between a laser stabilized to the piezo-tunable cavity and the ULE reference. The frequency noise spectral density (ASD) and the Allan deviation (RAV) are shown in Fig. 2. Since the ULE reference cavity shows a much better stability (grey line), the frequency noise can be assigned to the piezo-tunable cavity. The piezo actuator was short circuited during this measurement. For comparison, the frequency noise of the fixed resonator in the same chamber is shown as well.

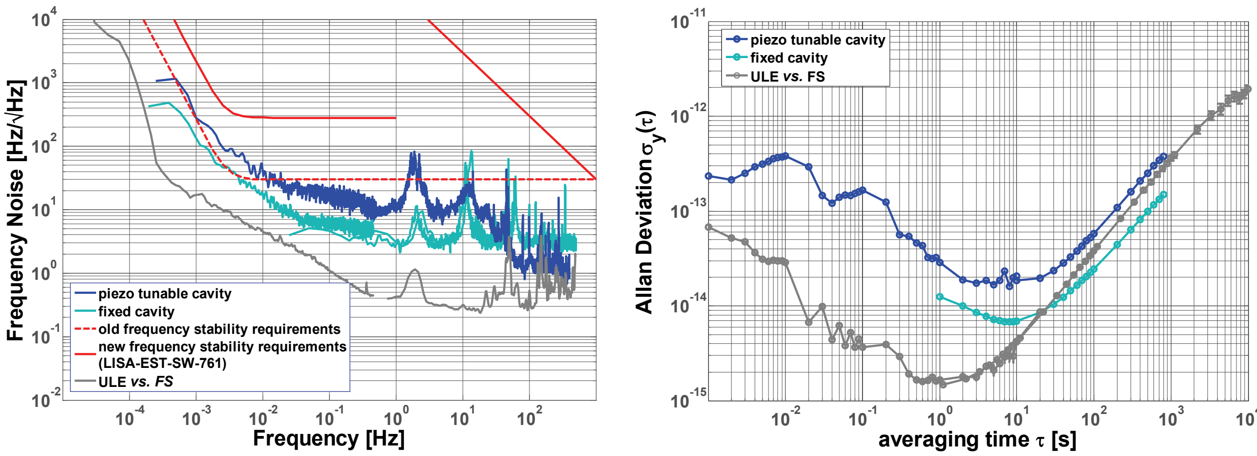

Fig. 2: Performance of the piezo tunable cavity and the fixed cavity in the same environment.
(left) Frequency noise spectral density, (right) Allan deviation. Drifts up to 3rd order are eliminated.

The red curves show the frequency stability requirements for the LISA prestabilization in order to ensure the feasibility of arm-locking in the next step. The dashed line describes the requirements as given at the beginning of this work, which are almost completely fulfilled. In the meantime the requirements were relaxed as described by the solid red line. These relaxed requirements are entirely fulfilled by the piezo-tunable cavity.

Both cavities show a relatively high white noise floor, which can be attributed to a poor signal-to-noise ratio, caused by a low coupling efficiency (less than 10 %) into the cavities. This is due to a bad impedance match of the cavity mirrors, as the mirrors were unfortunately polluted during the optical contacting process. In the ASD of the piezo cavity the white noise floor is only visible for Fourier frequencies higher than 100 Hz. For lower Fourier frequencies a correlation with the seismic noise in the laboratory is obvious. The peaks at 2 Hz and 15 Hz arise from movements of the building (the laboratories are located on the 8th floor) and the 2 Hz peak is additionally enhanced by the vibration isolators, which exhibit a resonance at this frequency. At Fourier frequencies between 10 mHz and 1 Hz the ASD rises with a slope of $f^{1/4}$, which is also supposed to be caused by seismic noise. Due to the asymmetric design of the piezo cavity and the attachment of the piezo actuator with small glue joints, the piezo cavity shows a higher sensitivity to seismic noise. To minimize the resulting frequency noise in the future, the mounting of the piezo cavity will be optimized by simulating the system and a better vibration isolation system will be installed.

Concerning the long term stability, the beat measurement reveals a drift of the piezo-tunable cavity of about 50 Hz/s. Due to the integration of the piezo actuator, the piezo cavity has a CTE of $3\cdot10^{-7}$ 1/K in comparison to $2\cdot10^{-8}$ 1/K of pure Zerodur. The calculated thermal noise floor of the piezo cavity in the RAV is $7\cdot10^{-16}$ in contrast to $5\cdot10^{-16}$ for the fixed cavity, since the quality factor of the piezo material is relatively low (Q ~ 100). However, for both cavities other noise contributions have to be reduced to reach this floor.

Tunability

In order to tune the piezo cavity a voltage has to be applied to the piezo actuator. One thus has to take into account that voltage noise transforms directly to length noise of the cavity and consequently to frequency noise. With the used 7 mm piezo actuator a displacement of ~ 3 µm can be achieved by applying 1000 V, which corresponds to a frequency shift of 7.5 GHz. To tune a free spectral range of 1.4 GHz a voltage of 188 V is necessary. This high voltage is provided by a PA45 operation amplifier from Apex. Although having an excellent noise performance for a high voltage amplifier ($10\ \mu V/\sqrt{Hz} \cdot (1\ Hz / f)^{1/2}$ for $f < 10$ Hz, derived from beat measurement), the amplifier noise is still too high to fulfill the requirements. Therefore a low pass filter with a cut-off frequency below 1 mHz is employed. Using this filtered control voltage the cavity can be tuned more than one free spectral range maintaining the frequency stability performance, but only slow laser frequency tuning is possible. To combine high bandwidth and wide tuning range by high voltage, a frequency separating filter is employed to implement an additional ‘fast’ path. Before passing the high voltage amplifier the control signal is split and additionally AC coupled to the piezoelectric actuator (Fig. 3 left). This circuit allows for a fast frequency control (bandwidth ~ 5 kHz) and a high dynamic range > 1 FSR.

Integration in an outer Feedback Loop

One approach for the integration of the tunable prestabilization in the LISA frequency concept is to feed the error signal, produced by arm-locking, not directly to the laser but to the piezo-tunable cavity (Fig.4 left). In this way the

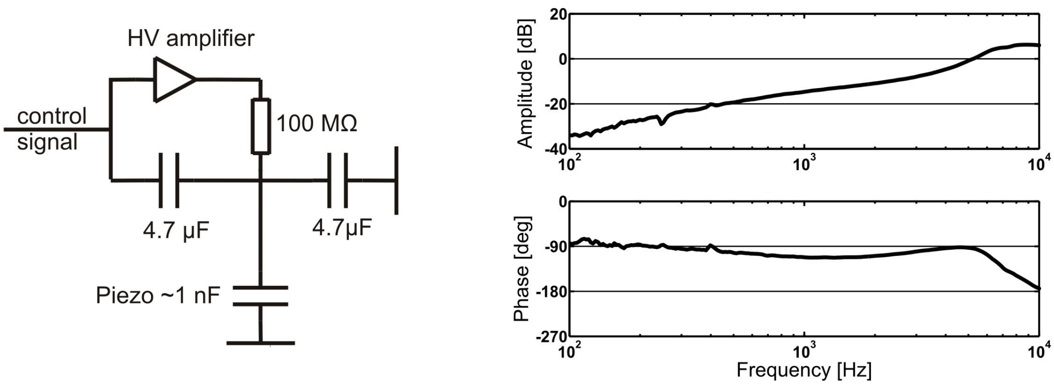

Fig. 3: (left) Scheme of frequency separating filter. (right) Transfer function closed loop.

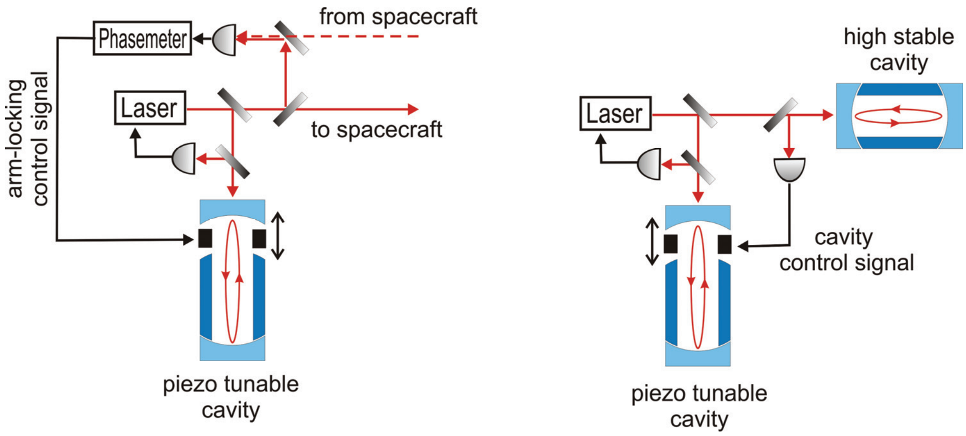

Fig. 4: (left) Integration of the piezo-tunable cavity in the LISA frequency plan feeding the arm-locking error signal to the piezo actuator. (right) Arm-locking signal replaced by a second cavity error signal.

length stability of the LISA arms can be transferred to the piezo cavity. This leads to the requirement that the prestabilization has not only to be able to follow the slow Doppler shifts, but also to provide a bandwidth of more than 1 kHz. To demonstrate the feasibility of this approach, we tried to transfer the length stability of a fused silica reference cavity to the piezo cavity in the following way: A Nd:YAG laser was stabilized to the piezo cavity. Then, via applying an appropriate voltage, the resonance frequency of the piezo cavity and thus the laser frequency was tuned to a resonance frequency of the fused silica resonator. The resulting error signal was used to regulate the length of the piezo actuator and consequently the frequency of the piezo cavity. The obtained stability is shown in Fig. 5, as well as the stability measured directly between the FS cavity and the ULE cavity. It can be seen that the stability of the fused silica resonator was almost completely transferred to the piezo cavity. The bandwidth of the piezo control loop was ~ 5 kHz (Fig. 3 right) exceeding the 1 kHz required for the LISA arm locking concept. The measurements were done with the frequency separating filter described above.

IV. CONCLUSION AND OUTLOOK

The performance of a piezo-tunable high finesse cavity developed for LISA was investigated. The Allan deviation shows a flicker floor of $2 \cdot 10^{-14}$ between 2 s and 20 s and the frequency noise is below 10 Hz/√Hz at Fourier frequencies higher than 0.1 Hz. The setup can be further improved by optimizing the cavity mounting and by installing a better vibration isolation system. With the improved setup different piezoelectric materials will be tested and systematically

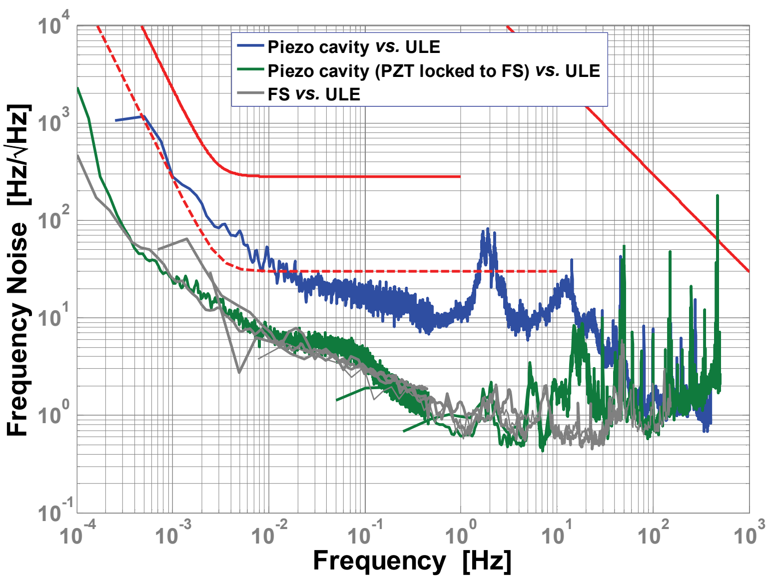

Fig. 5: Stability of the piezo-tunable cavity with piezo actuator locked to fused silica cavity.

investigated. For the long term frequency stability it is planned to implement a temperature stabilized design with two nested piezo actuators of the same length.

The laboratory tests show that a piezo-tunable cavity is in principal compliant with the LISA requirements for a tunable prestabilization concerning frequency stability and tunability. For the application in a space mission, components such as the piezo actuator still have to be tested concerning their space qualification and the cavity design, especially the mounting of the cavity, has to be adapted to the conditions during the launch and operation in space.

ACKNOWLEDGMENTS

This work is supported by the German Space Agency DLR with funds provided by the Federal Ministry of Economics and Technology (BMWi) under grant number DLR 50 OQ 0601.

REFERENCES

[1] J. Millo, D. V. Magalhães, C. Mandache, Y. Le Coq, E. M. L. English, P. G. Westergaard, J. Lodewyck, S. Bize, P. Lemonde, and G. Santarelli, "Ultrastable lasers based on vibration insensitive cavities," *PRA* **79,** 053829 (2009).

[2] K. Danzmann, LISA "Laser Interferometer Space Antenna for the detection and observation of gravitational waves," *Pre-Phase A Report, Second Edition*, *Tech. Rep*. (Max-Planck-Institut für Quantenoptik, 1998).

[3] B. S. Sheard, M. B. Gray, D. E. McClelland, and D. A. Shaddock, "Laser frequency stabilization by locking to a LISA arm," *Ph.Lett. A* **320**, 921 (2003).

[4] Sutton, A. & Shaddock, D. A., "Laser frequency stabilization by dual arm locking for LISA" *PRD* **78**, 082001 (2008).

[5] M. Tinto, F. B. Estabrook, and J. W. Armstrong, "Time-delay interferometry for LISA," *PRD* **65**, 082003 (2002).

[6] J. I. Thorpe, K. Numata, and J. Livas, "Laser frequency stabilization and control through offset sideband locking to optical cavities," *Opt. Express* **16**, 15980 (2008).

[7] J. C. Livas, J. I. Thorpe, K. Numata, S. Mitryk, G. Mueller, and V. Wand, "Frequency-tunable pre-stabilized lasers for LISA via sideband locking," *CQG* **26**, 094016 (2009).

[8] S. Herrmann, A. Senger, K. Möhle, M. Nagel, E. V. Kovalchuk, and A. Peters, "Rotating optical cavity experiment testing Lorentz invariance at the 10^{-17} level," *PRD* **80**, 105011 (2009).

[9] K. Döringshoff, K. Möhle, M. Nagel, E. V. Kovalchuk and A. Peters, "High performance iodine frequency reference for tests of the Lisa laser system," within these proceedings.