Optical Cavity Setup for Future Hybrid Lock Concept

Timm Wegehaupt[1,2], Josep Sanjuan[1], Martin Gohlke[3], Thilo Schuldt[1] and Claus Braxmaier[1,4]

[1]German Aerospace Center (DLR), Institute of Quantum Technologies, Ulm, Germany
[2]University of Bremen, Center of Applied Space Technology and Microgravity (ZARM), Bremen, Germany
[3]German Aerospace Center (DLR), Institute of Space Systems, Bremen, Germany
[4]University of Ulm, Institute of Microelectronics, Ulm, Germany

***Summary*—We present the ongoing development of a compact and robust optical cavity setup developed with an emphasis on space compatibility and based on a 5 cm ULE cavity with fused silica substrates and crystalline mirrors. A detailed design description is followed by a noise prediction of the final setup. The expected frequency stability is on the order of 5×10^{-16} for $0.1\text{s} < \tau < 10$ s. Designed with the background of combining the cavity setup with a molecular iodine spectroscopy unit into a hybrid lock, both are briefly explained and followed up with a simulation of the hybrid-lock's expected performance. The short-term stability of the hybrid lock is shown to be comparable to the standalone performance of the cavity while having long-term stability on the order of current passive H-Masers.**

Keywords—optical cavity, optical metrology, iodine spectroscopy, hybrid lock

I. Introduction

Precise measurement applications for time or distance, either performed on earth or in space, will benefit from the ever-advancing transition from microwave-based to optical-based technologies. This includes next generation gravity missions (NGGM), as well as proposed future global navigation satellite systems (GNSS), tests of fundamental physics in space or on earth, and earth applications like optomechanical inertial sensors or optical lattice clocks. Crucial for all these measurements are optical frequency references, which can be distinguished into two categories: relative and absolute references. Both technologies offer different advantages. The former, which includes optical cavity technology, offers high short-term stability and low power consumption. The latter, based on atom or molecule transitions, offers excellent long-term stability, low environmental sensitivity and absolute frequency knowledge. With the so-called hybrid lock approach, advantages of both techniques can be combined to create a frequency reference with a goal frequency stability on the order of 10^{-15} between 0.1 s and 10 000 s. At the DLR Institute of Quantum Technologies, a hybrid lock setup is under investigation, which is based on a compact optical cavity setup and an absolute Doppler free iodine spectroscopy unit. The optical cavity setup itself should be designed in a way that it suits applications in future GNSS architectures, as well as future NGGM missions. To bring the former to a new level of performance, we aim for a fractional frequency stability on the order of 1×10^{-15} for $1\text{ Hz} < f < 10$ Hz, while still meeting the NGGM requirement at sub-Hz frequencies. Implemented in the hybrid lock, the system should demonstrate next generations GNSS short term stability as well as the current long-term stability of passive H-Masers. Both setups are under development with emphasis on space compatibility.

II. Compact Cavity-based frequency reference

The new compact optical cavity setup is based on a 5 cm long optical cube cavity with the National Physical Laboratory (NPL) design. It utilizes a spacer made of ultra-low expansion glass (ULE) with fused silica mirrors and ULE compensation rings to provide a zero-crossing CTE near room temperature, while room temperature in previous experiments corresponds to 20°C up to 23.5°C. For reducing the thermal noise limit of the setup, crystalline coated mirrors are used providing a finesse of about 200 000. Crystalline coatings offer up to a 10-fold reduction of coating thermal noise [1]. Considering the thermal noise caused by Brownian motion in the spacer, substrate and coating together with substrate thermo-elastic and coating thermo-optic noises, the fundamental noise level $S_{th}^{1/2}$ of our 5cm setup is expected to be around

$$S_{th}^{1/2} = 4.5 \times 10^{-16} \text{ at } 1s,$$

well below the self-defined requirements for this setup. To

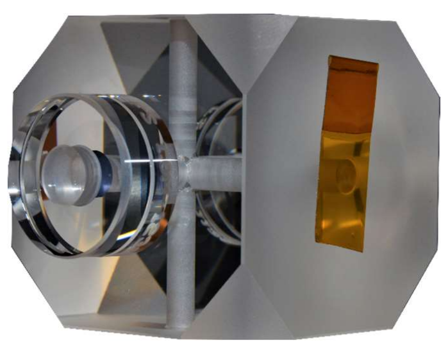

Fig. 1. Optical cube cavity with the National Physical Laboratory (NPL) design and 5cm optical path length.

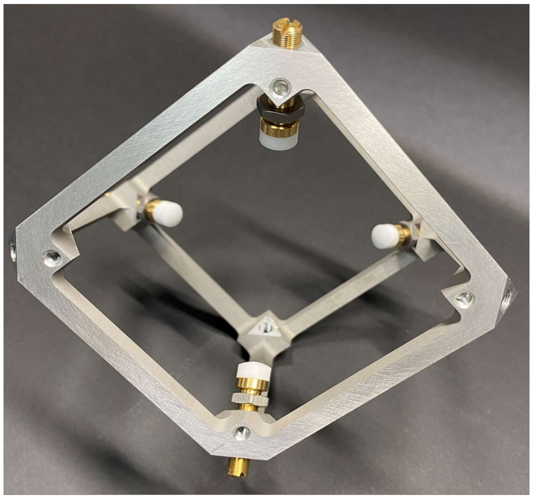

Fig. 2. Cubic mounting frame with tetrahedral arranged posts for a highly vibration insensitive cavity mounting.

achieve the highest vibration insensitivity, the optical cavity will be mounted in a tetrahedral configuration with a well-defined compression force applied by four posts [2]. For frequency stability reasons the optimal force F should be equal to 100 N, but should be at least half of the maximum of an outer force applied to the system to insure continued contact. The contact surface between these posts and the optical cavity is a weighting between thermal conduction and stress that will be applied by the compression force towards the ULE spacer. The contact can be described as a Hertzian contact and has been analyzed in detail revealing brass posts with PTFE endcaps as a promising option.

Two thermal shields of 3mm thick aluminum will enclose the cubic mounting frame, with the outer one actively stabilized. According to [3] the passive attenuation of the shields in combination with the active stabilization, which is assumed to be

$$\mathrm{S}_{\mathrm{T,out}}^{1/2} \leq 1\ \mathrm{mK\ Hz}^{-1/2}\ ,$$

would suppress temperature caused frequency changes for $f > 0.01$ Hz below the thermal noise limit. Here, a thermal expansion coefficient $\alpha < 4\ \times 10^{-8}$ is assumed, which allows working in a temperature range of four degrees around the zero-crossing point [Fig. 3].

A direct in-coupling mount with a 6-axis translation stage made out of TI6Al-4V is attached to one of the thermal shields and allows for a mechanically stable and compact alignment solution [Fig 4]. The in-coupling itself is done with a

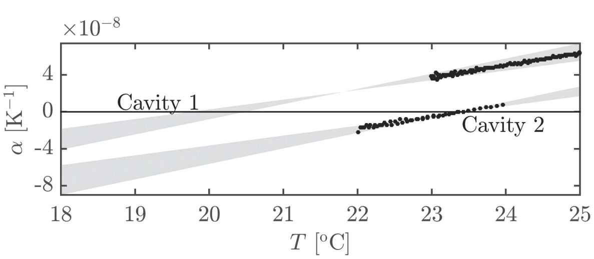

Fig. 3. Coefficient of thermal expansion for two 8.7cm cube cavities over temperature [4].

Fig. 4. Model of a 5 cm cube cavity mounted in a tetrahedral configuration with parts of the two-layer thermal shield. Attached to the top one is a 6-axis translation stage for direct in-coupling.

Schäfter+Kirchhoff collimator in combination with an additional lens to match the cavity's mode. On the opposite outer shield, a beam splitter in combination with an InGaAs photodiode is mounted for active intensity stabilization. According to a prior-experiment the transfer function between intensity fluctuations and frequency fluctuations follow a low-pass behavior estimated as $H_I = 90\ \mathrm{Hz}/\mu\mathrm{W}$ with a cut-off frequency of $f_c = 40$ mHz [4]. Intensity fluctuations are modeled as 1/f noise with

$$RIN \approx 5 \times 10^{-5}\ Hz^{-1/2} \text{ at } 10 \text{ mHz}$$

and a local maximum at $f = 10^{-3}$Hz according to experiences of previous-projects. With such a system, intensity caused frequency fluctuations will dominate only for a frequency span of $1\ \mathrm{mHz} < f < 5\ \mathrm{mHz}$. Though this is already at least one order of magnitude better than the NGGM frequency requirement. The active stabilization is done by a MEMS-based voltage-controlled attenuator placed between laser and EOM [Fig. 5]. The DC voltage is generated by a FPGA based compact digital electronics-board. This board also drives the

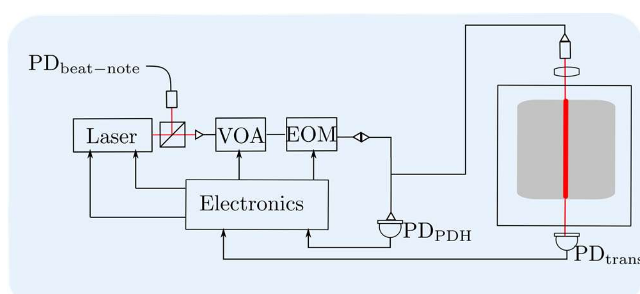

Fig. 5. PDH frequency stabilization scheme. VOA: voltage controlled optical attenuator, PD: Photodetector, EOM: electo-optical modulator.

EOM to create sidebands for the Pound-Drever-Hall (PDH) lock and the corresponding slow and fast modulation of the laser frequency [5].

The cavity, in-coupling optics and modulation electronics will be placed in a vacuum chamber to reduce pressure and temperature caused fluctuations, shown in Fig. 6. For optical path length changes due to pressure changes, a transfer function of $H_P = 50\ \mathrm{Hz/nbar}$ is assumed with a low pass behavior and cut-off frequency of $f_c = 50\ \mathrm{mHz}$. A goal pressure of 10^{-7} mbar along with pressure fluctuations modeled as RW-noise with

$$S_P^{1/2} \approx 5 \times 10^{-9}\ \mathrm{mbar\ Hz^{-1/2}}\ \text{at 1 Hz},$$

would suppress pressure caused frequency fluctuations below the thermal noise limit.

Since the in-coupling optics are entirely fiber coupled, fiber noise needs to be accounted. Fiber noise is mainly driven by temperature fluctuations and follows a high pass behavior. A bench-level assembly of the whole fiber setup was used to estimate the worst-case phase noise in the fiber.

A fit of the phase noise together with all formerly introduced and expected noise sources of the compact setup are plotted as amplitude spectral density in Fig. 7. The overall sum is shown as black trace and indicates that the design will meet the requirements.

III. IODINE-BASED FREQUENCY REFERENCES

Iodine based references are a well proven technique and have undergone an enormous development during the recent years. Multiple iterations on the way to space compatibility without compromising performance have been developed and frequency stabilities at low 10^{-15} level for long integration times are

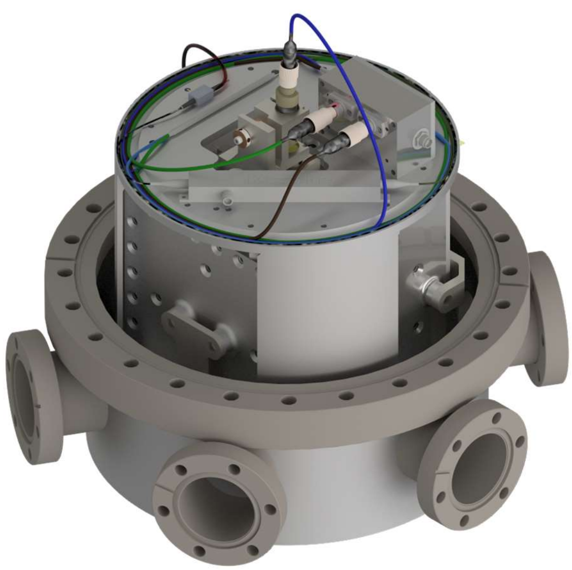

Fig. 6. 3D-Model of the current compact cavity development. The optical cavity is enclosed by two thermal shields and mounted in a two-piece vacuum chamber. On top of the thermal shields the in-coupling optics are mounted.

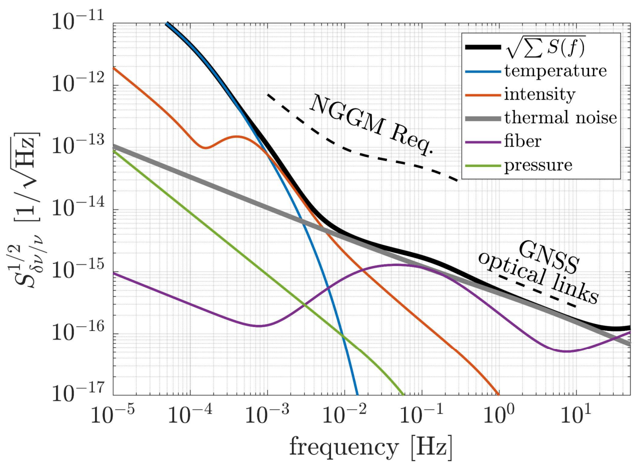

Fig. 7. Noise prediction of the current compact cavity development as the square root of the power spectral density. The overall sum is shown as black trace.

possible [6]. Therefore, a frequency doubled Nd:YAG laser is stabilized via doppler-free modulation transfer spectroscopy (MTS) to a hyperfine transition next to 532nm. Promising strong absorption lines are e.g. R(56)32-0, a_1 and a_{10}. A photograph of a compact and ruggedized setup is shown in Fig. 8. All optical components are mounted on a low CTE fused silica breadboard by adhesive bonding. The molecular iodine is stored in a compact multipass gas cell in the center of the board. Designed for nine-passes of pump and probe beam, corresponding to an interaction pathlength of 90cm. The whole spectroscopy unit was subjected to thermal cycling from -20°C to +60°C and vibrational loads with sine vibration up to 30g and random vibration up to 25.1 g_{rms}.

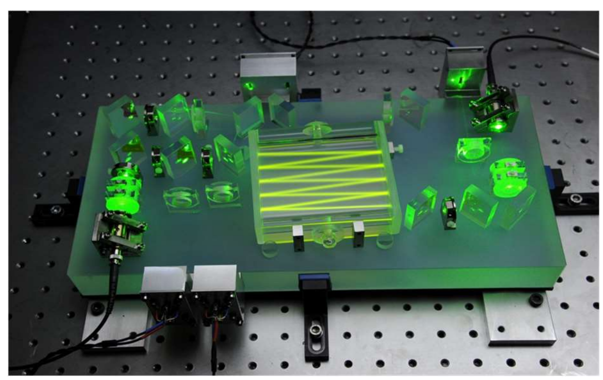

Fig. 8. Photograph of a compact and ruggedized iodine spectroscopy unit [6].

IV. HYBRID-LOCK APPROACH

New proposed architectures for global navigation satellite systems (GNSS) foresee optical frequency references on MEO and LEO satellites to keep the whole system autonomous on mid-timescales and allow for an optical synchronization among themselves. For autonomy, one would require long-term stability as provided by an iodine setup. Laser-link synchronization on the other hand requires high-short term stability due to a round-trip time of less than a second. The hybrid-lock concept provides both since it synergizes the advantages of both individual setups: Short- and long-term stability, low environmental sensitivity and absolute frequency knowledge. In the hybrid-lock concept, a NPRO Nd:YAG laser is stabilized with common MTS to a molecular Iodine spectroscopy unit. One portion of this already stabilized laser is guided to an additional frequency actuator, as shown in Fig. 9.

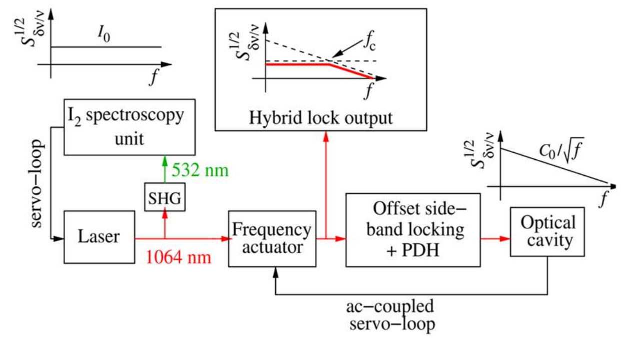

Fig. 9. Schematic of the hybrid-lock combining an optical cavity setup with an iodine spectroscopy unit [7].

This will take over the fast control of an additional cavity stabilization scheme. Behind the frequency actuator, a wideband EOM is implemented which closes the gap between the absolute frequency of the molecular iodine absorption line and the closest cavity resonance by offset sideband locking. This part takes over the slow frequency control loop of the cavity reference. As shown in Fig. 9, the last component, here named the “Optical cavity”, describes the common setup including the PDH-EOM and active intensity stabilization as fully explained in II. Using the model from [7] and including the new compact optical cavity setup, a fractional frequency stability is expected that suits both the requirements of GNSS optical links as well as the current requirements on long-term stability. An Allan deviation plot of the expected performance is plotted in Fig. 10. On short timescales, the hybrid lock has almost the same performance as the single optical cavity setup. Designed in a way for an optimum crossover between cavity and iodine spectroscopy, the spectroscopy unit will take over once its stability flattens on long time scales. This allows for an optimization of the cavity size, complexity and weight, without reducing performance. On long time scales, the hybrid lock performance is at the level of the

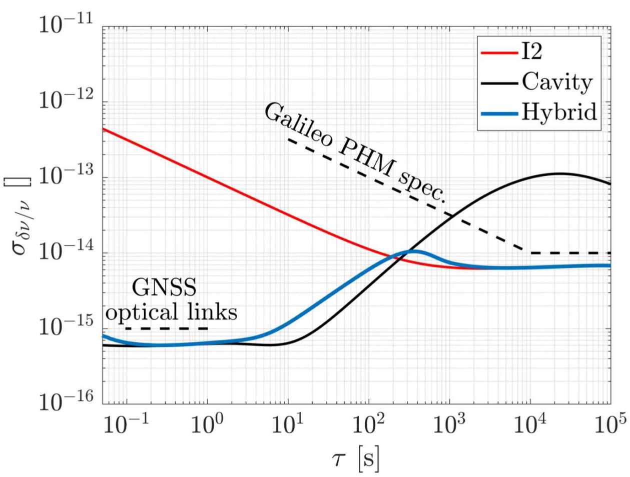

Fig. 10. Simulation of the expected relative frequency stability in Allan Deviation consisting of the new developed compact robust cavity setup with an Iodine spectroscopy unit.

iodine spectroscopy which is still better than the current requirements of Galileo’s passive H-masers (PHM).

V. Conclusion

We presented the efforts carried out on the ongoing development of a compact and robust cavity setup that is developed with emphasis on space compatibility. The expected frequency stability is predicted with 5×10^{-16} for $0.1\text{s} < \tau < 10$ s limited by thermal noise after which for long time-scales, it is mainly limited by temperature fluctuations. It would fulfill the requirements of NGGM on long timescales as well as these of future GNSS-architectures and their optical links on short-timescales. This estimation is based on a detailed noise prediction, including the knowledge and experiences of a former cavity project on elegant breadboard design. With this predicted frequency stability, the setup is well suited for the planned hybrid lock, which is a combination with a molecular iodine spectroscopy unit. Such a hybrid lock allowing for a wide range of applications.

Acknowledgments

This work is supported by the Helmholtz-Gemeinschaft Deutscher Forschungszentren e.V. under grant number ZT-0007 (ADVANTAGE, Advanced Technologies for Navigation and Geodesy) and by the German Space Center (DLR e.V.), with funds provided by the Federal Ministry of Economic Affairs and Climate Action, within the project COMPASSO.

References

[1] G. Cole, W. Zhang , M. Martin, J. Ye and M. Aspelmeyer,”Tenfold reduction of Brownian noise in optical interferometry”, Nat. Photonics 7, pp. 644–650, 2013.

[2] S. Webster and P. Gill, "Force-insensitive optical cavity," Opt. Lett. 36, pp. 3572-3574, 2011

[3] J. Sanjuan, N. Gürlebeck, and C. Braxmaier, "Mathematical model of thermal shields for long-term stability optical resonators," Opt. Express 23, pp. 17892-17908, 2015

[4] J. Sanjuan, K. Abich, M. Gohlke, A. Resch, T. Schuldt, T. Wegehaupt, G-P. Barwood, P. Gill, and C. Braxmaier, "Long-term stable optical cavity for special relativity tests in space," Opt. Express 27, pp. 36206-36220, 2019

[5] E. D. Black , "An introduction to Pound–Drever–Hall laser frequency stabilization", American Journal of Physics 69, pp. 79-87, 2001

[6] K. Döringshoff, T. Schuldt, E.V. Kovalchuk, J. Stühler, C. Braxmaier and A. Peters, „A flight-like absolute optical frequency reference based on iodine for laser systems at 1064 nm”, Appl. Phys. B, pp. 123: 183, 2017

[7] J. Sanjuan, K. Abich, L. Blümel, M. Gohlke, V. Gualani, M. Oswald, T. Wegehaupt, T. Schuldt, and C. Braxmaier, "Simultaneous laser frequency stabilization to an optical cavity and an iodine frequency reference," Opt. Lett. 46, pp. 360-363, 2021