Mode Number Determination of Optical Cavities for Next Generations of Gravity Missions

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Summary— Next generations of gravity missions require new technologies for an absolute frequency determination of cavity stabilized lasers. One proposed technology uses a readout of the free spectral range of the cavity to process it along with the mode number to the absolute frequency. This technology would require only a small amount of hardware but presupposes a stable mode number. In a laboratory experiment, this technology is analyzed for an existing high finesse cavity setup and the mode number is determined with an accuracy up to three digits. These measurements carry out a non-negligible fractional offset of $\alpha = 0.786 \pm 0.003$, where a part of $\gamma = 0.69$ is probably caused by the mirror coatings. For further investigation of how external influences can affect this offset, the plans for a new compact cavity setup which is designed precisely for these studies are presented here.

Keywords—optical cavity, optical metrology, absolute frequency, next generation gravity missions

I. Introduction

Space-based gravimetry is one of the most important methods for observing natural processes on Earth and monitoring the effects of climate change. Thinning of ice sheets, sea level rises, droughts and many other phenomena have been detected by the popular GRACE-Missions.

GRACE-FO launched in 2018 is the first and only gravity recovery mission with a Laser intersatellite interferometer (LRI) onboard till the date. Planned as a technology demonstrator, it exceeded the expectations and thus the LRI will become the primary instrument for future gravity missions. With this instrument, the relative distance between the two satellites is measured and will be post-processed to create a relative gravity field map of the Earth. Here, precise knowledge of the absolute frequency of the stabilized laser used for interferometry is one of the crucial parameters for post-processing.

Similar to GRACE-FO, for future gravity missions an optical cavity is foreseen as frequency reference. Cavity based references offer high frequency stabilities on short timescales while requiring small laser power and having a comparatively small volume and mass. The drawback is that optical cavities are relative references. This essentially means the laser frequency is stabilized to the length of a macroscopic resonator, so the absolute frequency of an optical cavity varies over time, which makes a pre-characterization impossible. While GRACE-FO uses cross-correlation measurements between the Microwave Ranging Instrument (MWI) and the LRI for calculating the absolute frequency, new methods have to be developed for future missions where MWI will be no longer part of the mission

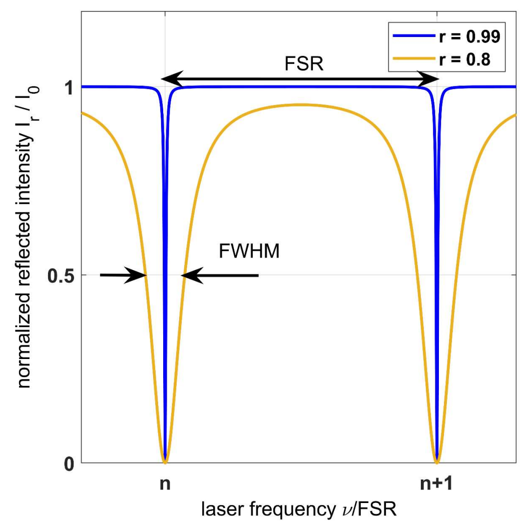

Fig. 1. Reflected intensity of an optical cavity shown for different mirror reflectivity. The distance between two cavity resonances is the free spectral range (FSR).

II. Cavity Mode number Determination

For solving this problem, a technique has now been proposed that is capable to measure the absolute frequency of an optical cavity reference in space with only a small amount of additional hardware. [1,2]

This technique would use an in-orbit measurement of the free spectral range (FSR) of the optical cavity which is the frequency spacing between two intensity minima in the reflected intensity of an optical cavity, shown in Fig. 1. The FSR can then be post-processed with the integer mode number n and the fractional offset α to the absolute frequency ν_{cav} by

$$\nu_{\text{cav}} = (n + \alpha) \cdot FSR$$

Here, α is a sum of the gouy phase shift β_{gouy} and an offset γ which is probably predominantly caused by the mirror coatings. The gouy phase shift β_{gouy} is dependent on mirror curvature r and the transverse electromagnetic mode (TEM) orders p, l. The FSR is dependent on the effective optical path length of the optical cavity. As this principle would measure the FSR only, it presupposes both, β_{gouy} and γ to be stable over the whole mission's lifetime.

For a further investigation within the Collaborative Research Center TerraQ, where frequency references for future gravity missions are studied, a cavity setup based on an 87 mm crossed-cavity with a cube design of the National Physical Laboratory (NPL) operating at 1064 nm is used. The cavity setup is shown in Fig. 2 and explained in more detail in [3].

With different techniques the fractional offset is measured to

$$\alpha = 0.786 \pm 0.003$$

while the gouy phase shift β_{gouy} is calculated to:

$$\beta_{\text{gouy}} = 0.094$$

This results in an offset of $\gamma = 0.69$, which can have a large impact on the absolute frequency determination as 1% variation of γ would already create an absolute frequency change of more than 10 MHz. It is also important to note that the measured offset is different from the one published in [2], although it should be noted that a triangular cavity with three mirrors was used there.

(a)

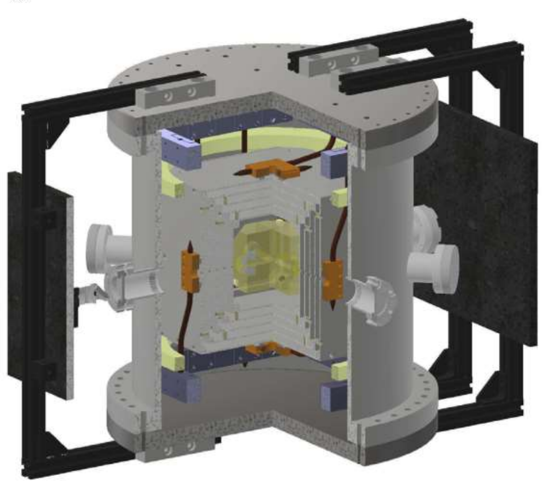

Fig. 2. Model of the used cavity setup with an 8.7 cm cubic cavity in the center, it is enclosed by five thermal shields actively stabilized and placed in a vacuum chamber. The optical components are placed on breadboards that are vertical mounted to the chamber. [3]

III. CAVITY SETUP FOR DETAILD INVESTIGATION

For a more profound study and a better understanding of the origin and stability of the offset, a new cavity setup is under development. It is focused on providing the opportunity to vary different factors like temperature or pressure as the offset is assumed to be a phase shift at the coating. At the same time, the setup should be a modular system that is compact and transportable, though it can be used for many different measurement campaigns. The requirements for this setup regarding frequency stability are low compared to the state-of-the-art systems and should be at the order of 10^{-15} at 1 s.

Derived from these requirements, the system is based on a 50 mm cubic cavity with NPL cube design, with spacer and substrates made out of Ultra Low Expansion (ULE) glass. The coating is a standard IBS coating providing a finesse of about 100 000. To keep the system flexible and simple, it should rely mainly on standard components. The only exception is the cavity mounting and thermal shielding shown in Fig. 3. A schematic overview of the whole system is shown in Fig. 4

To mount the cavity, an aluminum frame is designed that fixes the cavity with four posts by applying a force of about 100 N in a tetrahedral configuration to it. According to [6], the vibration sensitivity should be at an order of 10^{-11} 1/g with this mounting structure. At the same time, the mounting frame acts as interface for a one-layer thermal shield. The shields are made of aluminum and have peltier-elements bonded to all six sides by thermal conducting adhesive. This design was chosen to guarantee a homogenous temperature distribution and have short thermalization times, which is not possible if only two shields are controlled as in many commercial setups. The

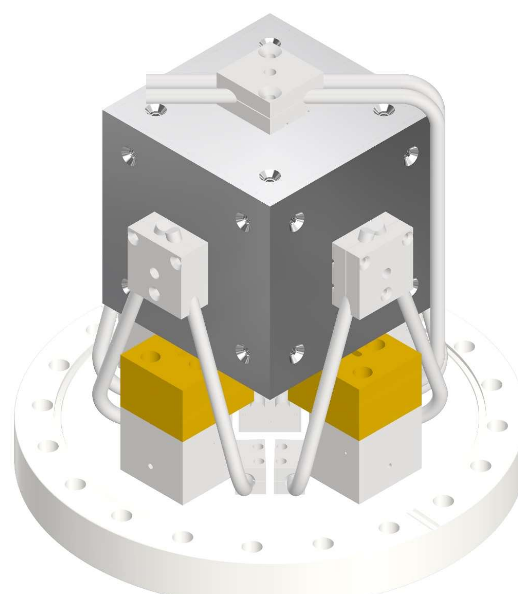

Fig. 3. CAD-Model of the mounting and thermal shielding concept of an optical cube cavity. The spacers, shown in yellow, provide a good thermally isolated connection between the thermal shield and the base plate, a CF160 blind flange that also serves as a heat sink for active temperature control of the shields.

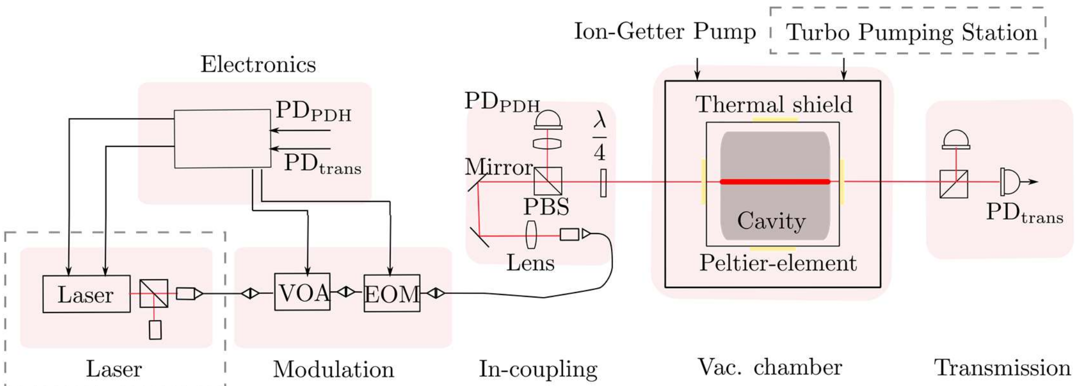

Fig. 4. Schematic of the experimental setup with the laser board and electronics, the modulation board with a voltage-controlled attenuator (VOA) and a phase modulator (EOM), and the optical cavity housed in a vacuum chamber where the coupling and transmission board are rigidly mounted.

bottom side of the thermal shield is mounted to an aluminum CF160 flange. Therefore, spacers made out of PEEK are used for a good thermal isolation. At the same time the aluminum flange is used as heat sink for the active controlled six sides of the thermal shield. Heat pipes are used to ensure adequate heat transport between the peltier-elements and the heat sink.

The active temperature stabilization in combination with a passive attenuation and an operation point around the zero-crossing point will allow for a frequency stability at the order of 10^{-14} for up to 100 s.

This assembly is then inserted into an aluminum vacuum chamber with a cube design and CF160 flanges on each side. One side is used for an electrical feedthrough to power the peltier-elements and read out thermal sensors. A second CF160 flange is used for the vacuum systems, which consists of an ion-getter pump, a turbo pumping station, and an additional valve for a controlled pressure modulation. The two CF160 flanges on the cavity mirror sides are used for wedged windows with AR coating that are installed for an optical access to the chamber.

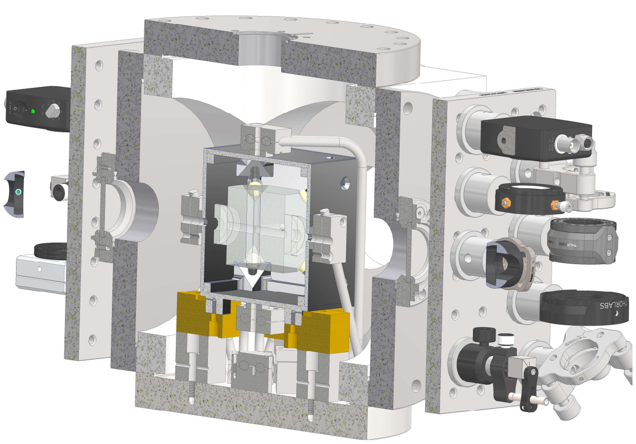

Fig. 5. Half section of the experimental setup with the optical cavity in its center. Breadboards are mounted vertically on both sides of the vacuum chamber to provide in-coupling optics on one side and beam analysis components on the other side.

The optical assembly outside the chamber is realized on two breadboards rigidly mounted to the vacuum chamber providing in-coupling optics with detection for Pound-Drever-Hall (PDH) laser stabilization, as well as beam analyses on the transmission side, Fig. 5. The latter consist of a CCD-camera and a photodetector for power stabilization of the used External Cavity Diode Laser (ECDL). Here, a *DLC DL pro* from *TOPTICA* with a wavelength of 1064 nm is used. The linewidth for the un-stabilized laser is about 20 kHz. For the PDH-control electronic, a *DLC pro* Controller from *TOPTICA* in combination with an analog PID-controller with a high bandwidth of 50 MHz is used.

All components will be mounted into a 19" rack, already providing a minimum amount of shock absorption, which then results in a compact transportable system.

IV. Conclusion

We have shown our first results for a mode number determination of a high finesse optical cavity. The mode number is measured with up to three digits accuracy and has a fractional offset of $\alpha = 0.786 \pm 0.003$. A fraction of $\gamma = 0.69$ is probably predominantly caused by the mirror coatings and must be investigated further, as it can have an influence on the accuracy of the determination of the absolute frequency in future missions. The here described new cavity setup will be used for a more profound study of the long-term stability, as external influences like pressure or temperature can be studied.

Acknowledgments

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