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High-Performance Optical Frequency References for Space

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Abstract. A variety of future space missions rely on the availability of high-performance optical clocks with applications in fundamental physics, geoscience, Earth observation and navigation and ranging. Examples are the gravitational wave detector eLISA (evolved Laser Interferometer Space Antenna), the Earth gravity mission NGGM (Next Generation Gravity Mission) and missions, dedicated to tests of Special Relativity, e.g. by performing a Kennedy-Thorndike experiment testing the boost dependence of the speed of light. In this context we developed optical frequency references based on Doppler-free spectroscopy of molecular iodine; compactness and mechanical and thermal stability are main design criteria. With a setup on engineering model (EM) level we demonstrated a frequency stability of about $2{\cdot}10^{-14}$ at an integration time of 1 s and below $6{\cdot}10^{-15}$ at integration times between 100 s and 1000 s, determined from a beat-note measurement with a cavity stabilized laser where a linear drift was removed from the data. A cavity-based frequency reference with focus on improved long-term frequency stability is currently under development. A specific sixfold thermal shield design based on analytical methods and numerical calculations is presented.

1. Introduction

High-performance optical frequency references are an essential tool for many applications in metrology, spectroscopy and fundamental physics. Besides on-going improvement with respect to frequency stability, also technology development for future operation in space is currently carried out where crucial design parameters are compactness and rigidity.

Application areas in space include Earth observation, fundamental science as well as navigation and ranging. Thereby, the frequency reference is either needed as laser source for a high-sensitivity inter-spacecraft optical metrology system, as part of a payload enabling tests of fundamental physics or as a high accuracy timebase for global navigation satellite systems (GNSS). Examples are eLISA (evolved Laser Interferometer Space Antenna) [1], a gravitational wave detector using picometer-sensitivity laser interferometric relative distance measurement between spacecraft with a distance of approximately 1 million kilometers; NGGM (Next Generation Gravity Mission) [2], i.e. future missions measuring the Earth's gravitational field requiring a relative distance measurement with nanometer sensitivity between two satellites which are typically 200 km apart; BOOST (BOOst Symmetry Test) [3] / mSTAR (mini SpaceTime Asymmetry Research) [4], a space-based test of Special Relativity carrying out a Kennedy-Thorndike (KT) type experiment, i.e. a test of the boost dependence of the speed of light with an aimed 10 to 100 fold improvement over currently best ground-based determination of the KT coefficient [5] using optical frequency references with frequency instabilities at or below the $1 \cdot 10^{-15}$ level at orbit time.

In the current baseline design, the proposed missions mSTAR and BOOST utilize an optical absolute frequency reference based on molecular iodine and a length reference based on a high-finesse optical cavity, whose resonance frequency is sensitive to the speed of light. The beat-frequency between these two references is measured and analyzed with respect to variations at orbit time of approximately 90 min for the determination of the KT coefficient. While atomic and molecular clocks intrinsically offer high long-term frequency stability, such time scales are challenging for cavity-based frequency references and especially require a specific thermal design. While the frequency references detailed in the following are in particular developed with respect to this application, they are also the basis for many other applications in space as detailed above.

2. Iodine-based frequency references

Optical frequency references based on Doppler-free spectroscopy of molecular iodine near 532 nm are a well-proven technology developed in several laboratories for many years [6, 7, 8], also in compact setups [9, 10, 11, 12]. With setups on laboratory level, frequency stabilities at low 10^{-15} level were demonstrated using modulation transfer spectroscopy (MTS) [8, 13]. For space applications, such systems need to be further developed with respect to compactness and mechanical and thermal stability. In a collaboration of the German Aerospace Center (DLR Institute of Space Systems, Bremen), the Center of Applied Space Technology and Microgravity (ZARM, University of Bremen), the Humboldt-University Berlin and the space company Airbus Defence & Space (Friedrichshafen) two setups on elegant breadboard (EBB) and engineering model (EM) level, respectively, were realized during the last years. These setups are detailed in the following sections.

2.1. Setup on Elegant Breadboard (EBB) level

In a first activity, a spectroscopy setup on elegant breadboard level was realized, based on a laboratory setup at the Humboldt-University Berlin. The light source is a Nd:YAG solid state laser with an output wavelength of 1064 nm, internally frequency doubled to 532 nm (model Prometheus by Coherent, Inc.). The 532 nm output laser beam is split into pump and probe for spectroscopy, both beams pass acousto-optic modulators (AOM) used for intensity stabilization and to generate a frequency shift between pump and probe. Both beams are fiber coupled to the EBB spectroscopy unit. The pump beam is either phase modulated using a fiber-coupled electro-optic modulator (EOM) or frequency modulated using the corresponding AOM.

The EBB spectroscopy unit is assembled on a 550 mm x 250 mm x 50 mm baseplate made of OHARA Clearceram-Z HS with a thermal expansion coefficient (CTE) of $2 \cdot 10^{-8}\,\mathrm{K}^{-1}$. The optics (i.e. mirrors, thin film polarizers, glass plates) are made of fused silica and integrated on the baseplate using adhesive bonding technology with a space-qualified two-component epoxy resulting in a semi-monolithic optical assembly [14], see figure 1. A commercial 30 cm long iodine cell (provided by the Institute of Scientific Instruments of the Academy of Sciences of the Czech Republic, Brno) is used in triple-pass configuration.

Mechanical mounts for fiber outcoupler, waveplates and polarizers are made of Invar for CTE matching between baseplate, mount and optics. Four pairs of AR-coated wedged glass plates (Risley prisms) in pump and probe beam, mounted in precision rotation mounts, enable an alignment of the beam overlap in the gas cell after integration of the optical setup. A commercial pigtailed fiber collimator with an output laser beam diameter of 3 mm is used (provided by OZ

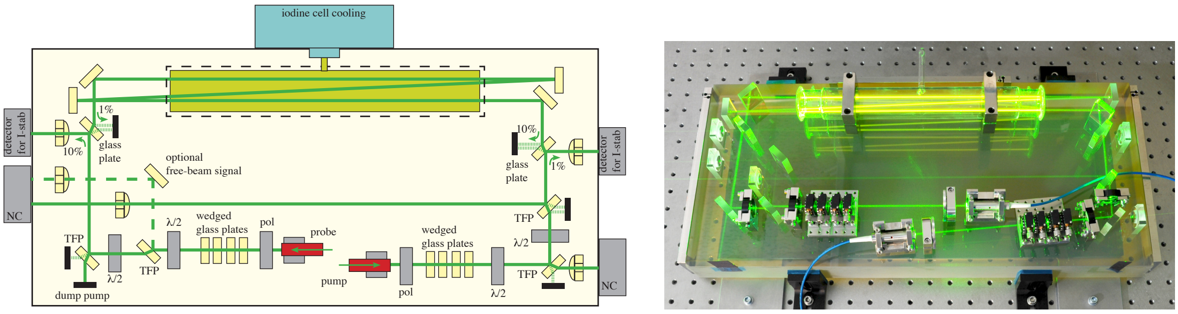


Figure 1. Schematic and photograph of the EBB setup using a commercial 30 cm long iodine cell in triple-pass configuration [15]. The optical components are integrated on a highly stable glass ceramics baseplate using adhesive bonding technology.

Optics). Polarizers are placed directly behind the fiber outcoupling in order to guarantee clean polarization. Additionally, RAM caused by the EOM is detected at a noise-cancelling (NC) detector and removed by feedback to the corresponding AOM in the pump beam. A second noise-cancelling detector is used to detect the MTS signal. Therefor, part of the probe beam is split off before the iodine cell and guided to the NC for balanced detection which allows for shot-noise limited detection. The spectroscopy signal is mixed down with the modulation frequency of about 300 kHz and appropriately filtered. The resulting error signal is fed to a servo control loop actuating the laser frequency via the laser crystal temperature for slow actuation and a PZT mounted to the laser crystal for fast actuation with control bandwidth of about 10 kHz.

The frequency stability of this setup was determined from a beat-note measurement with a ULE cavity stabilized laser. The Allan deviation shows a frequency stability below $1 \cdot 10^{-14}$ at an integration time of 1 s and below $4 \cdot 10^{-15}$ for integration times between 10 s and 1000 s where a linear drift was removed from the beat time record, see figure 2. Residual amplitude modulation (RAM) and residual temperature variations of the iodine cell cooling finger are most probably limiting the frequency stability at longer integration times.

2.2. Setup on Engineering Model (EM) level

In a subsequent activity, the design of the EBB setup was further optimized with respect to compactness and mechanical and thermal stability. A spectroscopy setup on engineering model was developed, based on the experience gained with the EBB setup. The 18 cm x 38 cm x 4 cm baseplate as well as the optics and the iodine gas cell are made of fused silica in order to match the CTE, yielding high dimensional stability under thermal cycling. The optical components are integrated using the same assembly-integration technology (adhesive bonding) as for the EBB setup. A schematic and a photograph of the integrated EM spectroscopy unit are shown in figure 3.

For realizing a compact and ruggedized setup, a special designed compact multi-pass gas cell was realized. The 10 cm x 10 cm x 3 cm fused silica cell is designed for nine-pass of pump and probe beam, corresponding to an interaction pathlength of 90 cm.

Commercial fiber collimators by Schäfter and Kirchhoff (with 3 mm output beam diameter) in combination with Invar mounts are used. A pair of wedged glass plates are placed after each fiber outcoupling, enabling a beam adjustment after integration similar to the EBB setup. The glass plates are mounted to specific mounts made of fused silica. Polarizers and waveplates are glued to mounts made of titanium for CTE matching. As in the EBB setup, part of pump and probe beams are split off before entering the gas cell for power stabilization.

The Allan deviation of the beat note with the ULE cavity indicates a frequency stability of

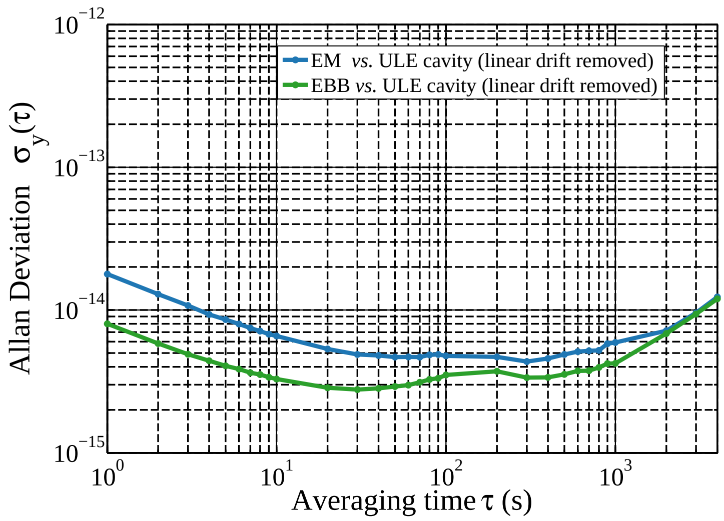
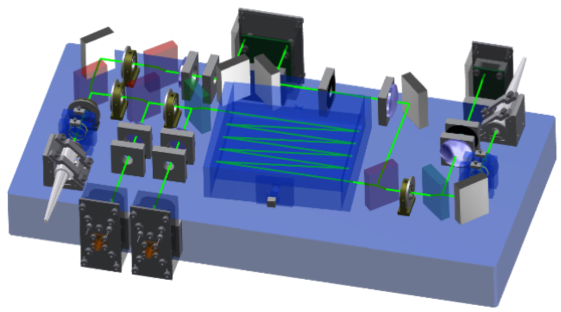


Figure 2. Relative Allan deviation of the beat note frequency between the EBB (green, lower curve) and the EM (blue, upper curve) and a laser locked to a cavity made from ultra-low expansion glass ceramics (ULE). A linear drift of 50 mHz/s, mainly attributed to isothermal creep of the cavity, has been removed from the time record of the beat data. The length of the time record is 76000 s. (colour online)



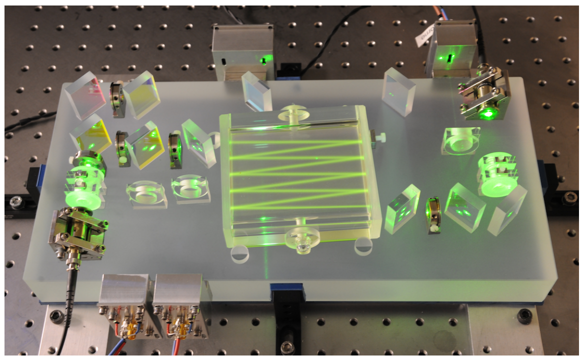


Figure 3. CAD and photograph of the spectroscopy unit on engineering model level using a specifically designed compact gas cell in nine-pass configuration [16].

$5 \cdot 10^{-15}$ for integration times larger than 100 s, similar to the EBB setup, see figure 2. The spectroscopy unit was subjected to thermal cycling from -20°C to +60°C and vibrational loads with sine vibration up to 30 g and random vibration up to 25.1 g_{rms}. The frequency stability was measured before and after the tests where no degradation was observed.

3. Cavity-based frequency reference

Cavity-based frequency references are a very common technology, also already developed in compact and ruggedized setups dedicated to future application in space, see e.g. the JPL cavity development for the Gravity Recovery and Climate Experiment follow-on (GRACE-FO) mission [17] and the ESA project 'High Stability Laser (HSL)' for future Next Generation Gravity Missions (NGGM) [18]. While such systems are usually optimized for highest short-term frequency stability (up to several seconds), improved long-term stability at the low 10^{-15} level at integration times of several 1000 seconds is investigated in a collaboration project of

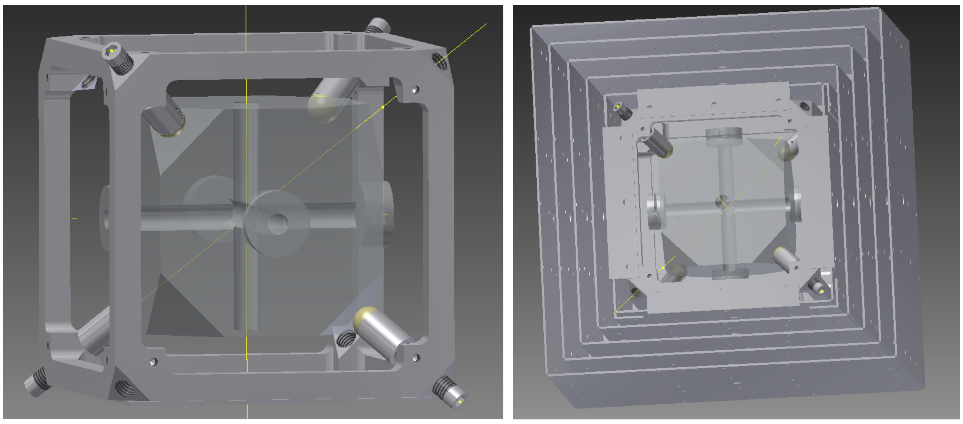


Figure 4. Preliminary cavity mounting and sixfold thermal shielding design. The cubic cavity has a side length of 87 mm and the outermost shield has a length of 242 mm.

the Center of Applied Space Technology and Microgravity (ZARM, University of Bremen), the German Aerospace Center (DLR Institute of Space Systems, Bremen) and the Leibniz-University Hannover to meet the demands of a future KT Mission.

As the frequency stability at longer integration times is mainly limited by residual temperature fluctuations and ultimately by thermal noise, main effort is put on a thermal design of the cavity enclosure. In our experiment, a cubic cavity designed by NPL with a side length of 87 mm [19] is used as it provides highest vibration insensitivity and is already under development for space compatibility within the HSL project. The cavity consists of a spacer made of ultra-low expansion (ULE) glass in combination with fused silica mirror substrates resulting in a theoretical thermal noise limit of $4.5 \cdot 10^{-16}$. The mirrors are equipped with ULE compensation rings in order to obtain a CTE zero crossing temperature of the assembled cavity near room temperature [20].

The cavity mounting is based on experience of NPL in combination with the design of a specific thermal shield. The current baseline foresees a cubic six-stage thermal shield made of 1.5 mm thick highly polished aluminum plates, cf. the CAD shown in figure 4. The temperature stability of the cavity can be further improved by temperature stabilization of the outermost shield at the CTE zero crossing temperature of the cavity. The design of the thermal shield is based on analytical models and numerical simulations, cf. [21, 22]. Different materials such as Teflon, Ultem and Titanium are investigated for the shield supports.

4. Conclusion

We presented our current efforts in realizing compact setups of frequency references based on Doppler-free spectroscopy of molecular iodine and on an optical resonator for future applications in space. Two iodine standards on elegant breadboard and engineering model level were realized, both optimized with respect to dimension, mass and thermal and mechanical stability. A frequency stability below $1 \cdot 10^{-14}$ at an integration time of 1 s and below $4 \cdot 10^{-15}$ for integration times between 10 s and 1000 s was determined in a beat measurement with a ULE cavity setup where the drift attributed to the cavity has been removed. Beside that, we presented first steps on the realization of a cavity setup with enhanced long-term stability. Analytical models were developed for thermal shielding evaluation, resulting in a six-stage thermal shield baseline design. Such optical frequency references are of high interest for a variety of future space missions including the proposed missions mSTAR and BOOST, which require optical frequency references with frequency stabilities at or below the $1 \cdot 10^{-15}$ level at orbit time (90 min). Furthermore, the frequency stability achieved with the iodine references – which in contrast to cavity stabilized systems feature an absolute frequency reference – fulfills the requirements for planned missions like eLISA and NGGM.

Acknowledgments

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