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Iodine frequency references for space

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Abstract. Optical frequency references are a key element for the realization of future space missions. They are needed for missions related to tests of fundamental physics, gravitational wave detection, Earth observation and navigation and ranging. In missions such as GRACE follow-on or LISA the optical frequency reference is used as light source for high-sensitivity inter-satellite distance metrology. While cavity-based systems are current baseline e.g. for LISA, frequency stabilization on a hyperfine transition in molecular iodine near 532 nm is a promising alternative. Due to its absolute frequency, iodine standards crucially simplify the initial spacecraft acquisition procedures. Current setups fulfill the GRACE-FO and LISA frequency stability requirements and are realized near Engineering Model level. We present the current status of our developments on Elegant Breadboard (EBB) and Engineering Model (EM) level taking into account specific design criteria for space compatibility such as compactness (size iodine spectroscopy EM: $38 \times 18 \times 10\,\mathrm{cm}^3$) and robustness. Both setups achieved similar frequency stabilities of $\sim 1 \cdot 10^{-14}$ at an integration time of 1 s and below $5 \cdot 10^{-15}$ at integration times between 10 s and 1000 s. Furthermore, we present an even more compact design currently developed for a sounding rocket mission with launch in 2017.

1. Introduction

Future space missions rely on the availability of high performance optical frequency references. They are either used as laser source for high-sensitivity inter-spacecraft optical metrology, as part of a payload enabling tests of fundamental physics or as a high accuracy timebase e.g. for global navigation satellite systems. While different methods for laser frequency stabilization are conceivable including stabilization to an optical resonator and an atomic or molecular transition, Iodine-based frequency references using modulation transfer spectroscopy (MTS) at a wavelength near 532 nm is a well-known technology used in laboratories for many years. Such systems offer high long-term stability and the provision of an absolute frequency reference. With respect to future applications in space, two setups on elegant breadboard and engineering model level, respectively, were realized during the last years.

2. Compact and Ruggedized Iodine Spectroscopy Setups for Space

A specific assembly-integration technology is applied where the optical components are bonded onto a glass baseplate using a space-qualified two-component epoxy. This results in a compact and ruggedized semi-monolithic optical assembly. Two spectroscopy setups have been realized using a Nd:YAG solid state laser with an output wavelength of 1064 nm as light source, frequency doubled to 532 nm. The 532 nm output laser beam is split into pump and probe for iodine spectroscopy and both beams are fiber coupled to the spectroscopy units. Phase/frequency modulation is either carried out by an acousto-optic or an electro-optic modulator.

The EBB spectroscopy unit uses a 550 mm x 250 mm x 50 mm low thermal expansion baseplate made of OHARA Clearceram-Z HS [2]. The optics are made of fused silica and integrated on the baseplate using adhesive bonding technology. A commercial 30 cm long iodine cell is used in triple-pass configuration. Mechanical mounts for fiber outcoupler, waveplates and polarizers are made of Invar. Four pairs of wedged glass plates enable an alignment of the beam overlap in the gas cell after integration of the optical setup. Noise cancelling detection is implemented for residual amplitude modulation (RAM) stabilization and MTS signal detection.

In a subsequent activity on EM level, the design of the EBB setup was further optimized with respect to compactness and mechanical and thermal stability, cf. Figure 1. For realizing a compact and ruggedized setup, a special designed 10 cm x 10 cm x 3 cm fused silica multi-pass gas cell was developed. 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.

The frequency stabilities of the two setups were determined from a beat-note measurement with a ULE cavity stabilized laser. The Allan deviation shows a frequency stability of $1 \cdot 10^{-14}$ at an integration time of 1 s and below $5 \cdot 10^{-15}$ for integration times between 10 s and 1000 s where a linear drift was removed from the beat time record. The frequency stabilities of both setups fulfill the LISA and GRACE follow-on requirements.

Within the project JOKARUS (Jod-Kammresonator unter Schwerelosigkeit), a spectroscopy setup for use on a sounding rocket mission is currently implemented using micro-integrated external cavity diode lasers (ECDLs) as light source. An iodine-based reference is compared to a microwave reference via an optical frequency comb, resulting in a test of local position invariance (LPI).

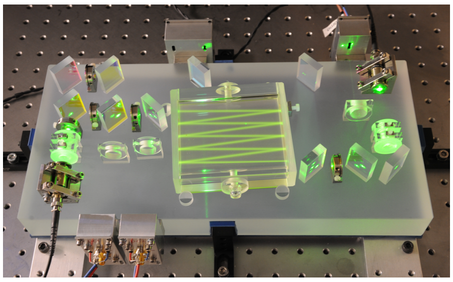

Figure 1. Iodine spectroscopy unit on engineering model (EM) level: the optical components are integrated on a 18 cm x 38 cm x 4 cm fused silica baseplate [1].

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