International Conference on Space Optics—ICSO 2014

La Caleta, Tenerife, Canary Islands

7–10 October 2014

Edited by Zoran Sodnik, Bruno Cugny, and Nikos Karafolas

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International Conference on Space Optics — ICSO 2014, edited by Zoran Sodnik, Nikos Karafolas, Bruno Cugny, Proc. of SPIE Vol. 10563, 105632S · © 2014 ESA and CNES
CCC code: 0277-786X/17/$18 · doi: 10.1117/12.2304103

AN ULTRA-STABLE OPTICAL FREQUENCY REFERENCE FOR SPACE

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ABSTRACT

We realized ultra-stable optical frequency references on elegant breadboard (EBB) and engineering model (EM) level utilizing Doppler-free spectroscopy of molecular iodine near 532nm. A frequency stability of about $1 \cdot 10^{-14}$ at an integration time of 1 s and below $5 \cdot 10^{-15}$ at integration times between 10 s and 100 s was achieved. These values are comparable to the currently best laboratory setups.

Both setups use a baseplate made of glass material where the optical components are joint using a specific assembly-integration technology. Compared to the EBB setup, the EM setup is further developed with respect to compactness and mechanical and thermal stability. The EM setup uses a baseplate made of fused silica with dimensions of 380 x 180 x 40 mm^3 and a specifically designed 100 x 100 x 30 mm^3 rectangular iodine cell in nine-pass configuration with a specific robust cold finger design. The EM setup was subjected to thermal cycling and vibrational testing.

Applications of such an optical frequency reference in space can be found in fundamental physics, geoscience, Earth observation, and navigation & ranging. One example is the proposed mSTAR (mini SpaceTime Asymmetry Research) mission, dedicated to perform a Kennedy-Thorndike experiment on a satellite in a sun-synchronous low-Earth orbit. By comparing an iodine standard to a cavity-based frequency reference and integration over 2 year mission lifetime, the Kennedy-Thorndike coefficient will be determined with up to two orders of magnitude higher accuracy than the current best ground experiment. In a current study, the compatibility of the payload with the SaudiSat-4 host vehicle is investigated.

I. INTRODUCTION

Optical frequency references based on Doppler-free spectroscopy of molecular iodine near 532 nm are a state-of-the-art technology developed in several laboratories for many years [1-4]. With such systems, a frequency stability at the low 10^{-15} level can be achieved [4,5]. Current efforts aim at a space compatible realization of such a frequency reference with potential applications in science, Earth observation and navigation & ranging. Example missions are the gravitational wave detector eLISA (Evolved Laser Interferometer Space Antenna), the Next Generation Gravity Mission (NGGM) and mSTAR (mini SpaceTime Asymmetry Research), a mission dedicated to perform a space-based test of special relativity.

A schematic of a typical laboratory setup of an iodine frequency reference using modulation transfer spectroscopy (MTS) is shown in Fig. 1, left (as realized at the Humboldt-University Berlin). A Nd:YAG solid state laser with an output wavelength of 1064 nm, internally frequency doubled to 532 nm, is used as light source. The output laser beam is split into pump and probe for spectroscopy, both passing an acousto-optic modulator (AOM) used for intensity stabilization and for generating a frequency shift between pump and probe. Both beams are fiber coupled and sent to the spectroscopy unit. The pump beam is phase modulated using a fiber-coupled electro-optic modulator (EOM). Pump and probe beam are counter-propagating through an 80 cm long iodine cell used in single-pass configuration. A balanced detection is implemented where part of the probe beam laser light is split off before the iodine cell and the detected intensity is subtracted from the detected spectroscopy signal after the cell, eliminating common-mode intensity noise of the laser beam. The spectroscopy signal is mixed down with the EOM driving frequency and appropriately filtered. The resulting error signal is input 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).

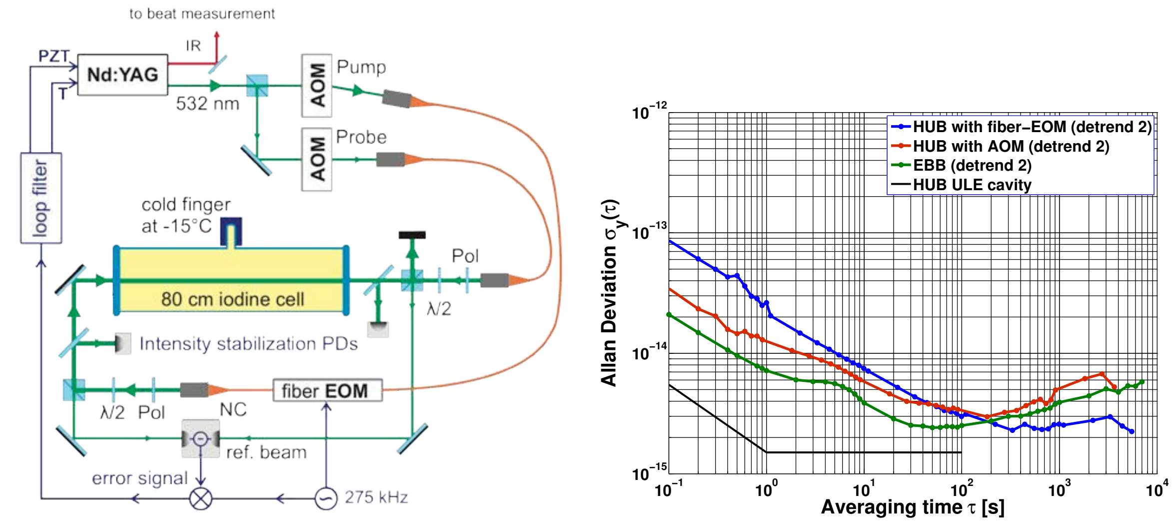

Fig. 1. Left: Schematic of the laboratory setup of the iodine frequency reference at the Humboldt-University Berlin [6]. Right: Frequency stability of iodine-based frequency references [6]. The blue curve corresponds to the HUB laboratory setup as presented in section I using a fiber EOM for phase modulation. The red curve corresponds to a similar setup using an AOM for phase modulation. The green curve shows the frequency stability of the EBB setup as detailed n section II.

With this setup, a frequency stability below $3*10^{-15}$ at integration times between 100 s and 5000 s was achieved, cf. the Allan deviation shown in Fig. 1, right. For this measurement, the iodine reference was beated with a ULE cavity setup. Residual amplitude modulation (RAM) is most probably limiting the frequency stability at longer integration times.

For space applications, this setup needs 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 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.

II. SETUP ON ELEGANT BREADBOARD (EBB) LEVEL

In a first activity, a spectroscopy setup on elegant breadboard level was realized, based on the laboratory setup as described in section I. The laser system is similar to the one detailed above using an internally frequency doubled Nd:YAG laser (by Innolight GmbH, model 'Prometheus') in combination with two AOMs and a fiber EOM. Pump and probe beam are fiber-coupled and sent to the spectroscopy board.

A schematic and a photograph of the spectroscopy unit is shown in Fig. 2. It utilizes a 550 mm x 250 mm x 50 mm baseplate made of OHARA Clearceram-Z HS with a coefficient of thermal expansion (CTE) of $2*10^{-8}$ K^{-1}. The optics (i.e. mirrors, thin film polarizers, glass plates) are made of fused silica and integrated on the board using adhesive bonding technology with a space-qualified two-component epoxy [7,8]. 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 mode of Invar for CTE matching. For integration, the same assembly-integration technology is used. 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 Optics) which is mounted in a specific mount. Using shims, the tilt of the collimator can be adjusted. Polarizers are placed directly behind fiber outcoupling in order to guarantee clean polarization. In the setup, intensity stabilization of pump and probe beam is implemented. Additionally, RAM caused by the EOM is detected at a specific noise-cancelling (NC) detector and removed by feedback to the corresponding AOM in the pump beam. A second noise-cancelling detector is used for generating the error signal, similar to the laboratory setup described above.

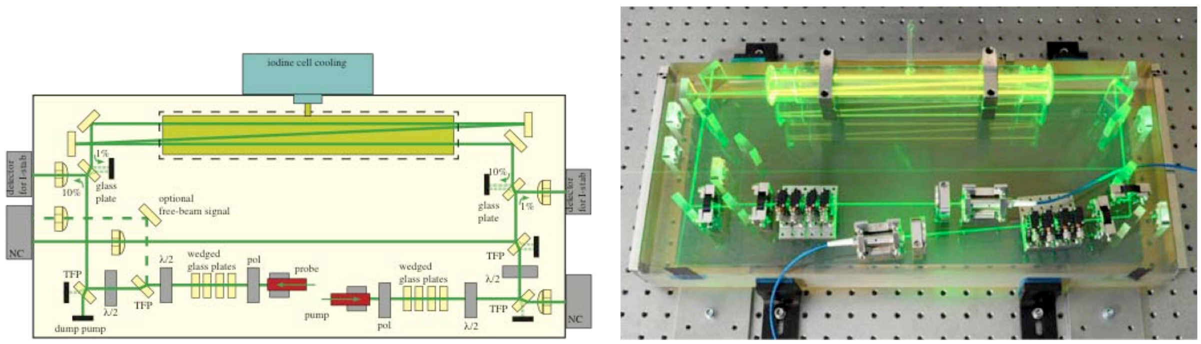

Fig. 2. Schematic and photograph of the spectroscopy setup developed on elegant breadboard level. The baseplate has dimensions of 25 cm x 55 cm [6].

The measured Allan deviation, in comparison with a ULE cavity setup, is shown in Fig. 1, right (green curve). A frequency stability of $4*10^{-15}$ at an integration time of 1000 s was obtained.

III. SETUP ON ENGINEERING MODEL (EM) LEVEL

In a further activity, the setup on EBB level was 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 baseplate as well as the optics and the gas cell are made of fused silica in order to match the CTE and therefor yielding to high thermal stability. As in the EBB setup, the optical components are integrated using adhesive bonding technology. A schematic and a photograph of the EM spectroscopy unit are shown in Fig. 3. This setup was subjected to environmental tests (vibration, thermal cycling).

A specific compact multi-pass gas cell was realized with a specific robust cold finger design. The 10 cm x 10 cm x 3 cm fused cell was designed for nine-pass operation using internal high-reflectivity coatings, cf. Fig. 3. Commercial fiber collimators by Schäfter and Kirchhoff (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. 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. Details are shown in the photographs in Fig. 4. As the EBB setup, part of pump and probe beam is split off before entering the gas cell for power monitoring. By actuating the amplitude of the corresponding AOM, the beam intensity is stabilized. Noise-cancelling detection is implemented for error signal generation.

With this setup, a frequency stability of $5*10^{-15}$ for integration times > 1000 s was achieved, similar to the EBB setup. The spectroscopy unit was subjected to thermal cycling (-20°C to +60°C) and vibrational testing (sine vibration up to 30 g; random vibration up to 25.1 g). The frequency stability was measured before and after the tests where no degradation was observed.

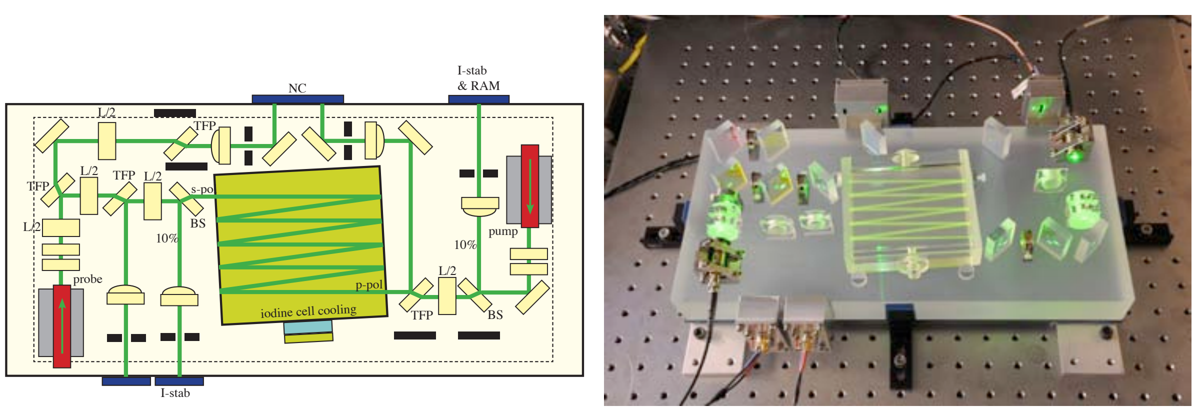

Fig. 3. Schematic and photograph of the spectroscopy setup developed on engineering model level using an 18 cm x 38 cm baseplate made of fused silica.

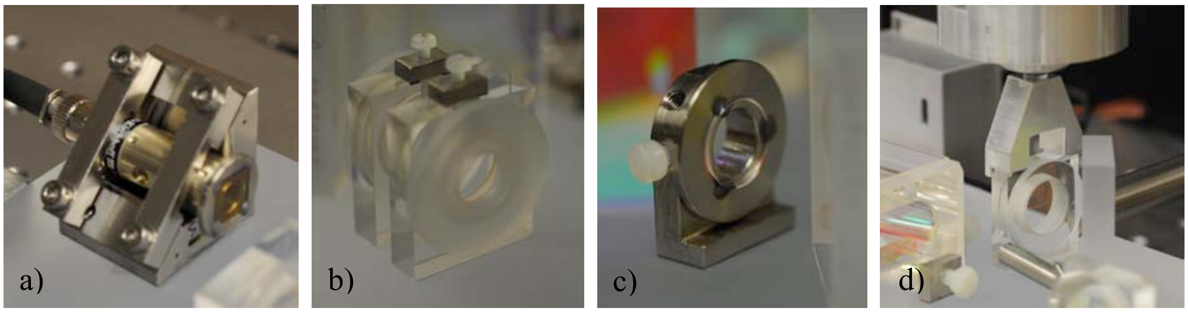

Fig. 4. Detail photographs of the fiber collimator with Invar mount and polarizer (a), the pair of wedged glass plates (Risley prism pair) with all-glass mounts (b), the waveplate with titanium mount (c), and a lense mounting during integration process (d).

IV. THE MSTAR MISSION

The mSTAR (mini SpaceTime Asymmetry Research) mission is a proposed mission dedicated to perform a space-based test of special relativity. By comparing an absolute frequency reference to a length-based frequency reference, the boost dependency of the speed of light can be tested (Kennedy-Thorndike experiment). Using clocks with a frequency stability at the 10^{-15} level at the relevant integration time (i.e. the orbit time of approximately 90 min), the Kennedy-Thorndike coefficient can be determined with an up to two orders of magnitude higher accuracy that the current best ground-based experiment [9]. A space-based experiment offers a number of advantages including a vibration free environment, elimination of large DC gravity forces and optimized experimental conditions (especially of the velocity modulation, with impact on the instrument requirements).

The mSTAR payload is depicted in the functional diagram shown in Fig. 5. It consists of an iodine-based frequency reference (clock 1) with laser source and second harmonic generator (SHG), a cavity-based frequency reference (clock 2) with thermal enclosure and frequency shifter (acousto-optic modulator, AOM), the corresponding control electronics for the clocks and the laser and a data management unit (DMU). For the Kennedy-Thorndike experiment, the signal from the reference clock is compared to the signal from the cavity reference and analyzed with respect to variations at the orbit frequency. In a current study, the feasibilility of the payload within the SaudiSat 4 satellite bus is evaluated.

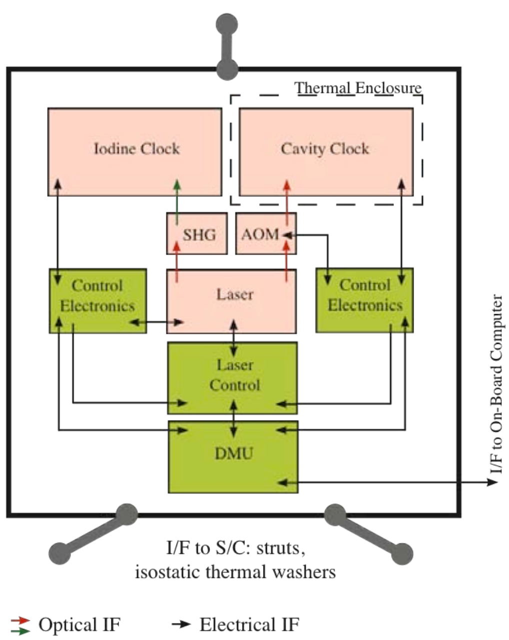

Fig. 5. Functional diagram of the mSTAR scientific payload.

V. CONCLUSION

We presented two setups of an iodine-based frequency reference, developed with respect to future applications in space. These setups are optimized with respect to dimension, mass and thermal and mechanical stability. The setup on engineering model level was subjected to environmental testing (vibration, thermal cycling). A frequency stability of $4*10^{-15}$ at an integration time of 1000 s was demonstrated. Such a setup can be used in a variety of future space missions, i.e. as light source for high sensitivity inter- and intra-spacecraft laser metrology or as payload for space-based tests of fundamental physics. One example is the proposed mSTAR mission, dedicated to perform a Kennedy-Thorndike experiment.

ACKNOWLEDGEMENTS

Financial support by the German Space Agency DLR with funds provided by the Federal Ministry of Economics and Technology (BMWi) under grant numbers 50 QT 1102 and 50 QT 1201 is highly appreciated. The authors thank Jan Hrabina and Josef Lazar from the Institute of Scientific Instruments of the Academy of Sciences of the Czech Republic, Brno, for fruitful discussions on the realization of the multipass iodine cell.

The mSTAR mission is investigated in an international collaboration including the King Abdulaziz City for Science and Technology (KACST, Riyadh, Saudi-Arabia), Stanford University (USA), NASA Ames (USA) and a German Team consisting of the German Aerospace Center (DLR Institute of Space Systems, Bremen), the Center of Applied Space Technology and Microgravity (ZARM, University Bremen) and the Humboldt-University Berlin. The authors thank all team partners for many fruitful discussions.

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