International Conference on Space Optics—ICSO 2018

Chania, Greece

9–12 October 2018

Edited by Zoran Sodnik, Nikos Karafolas, and Bruno Cugny

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icso proceedings

International Conference on Space Optics — ICSO 2018, edited by Zoran Sodnik,
Nikos Karafolas, Bruno Cugny, Proc. of SPIE Vol. 11180, 111807X · © 2018 ESA
and CNES · CCC code: 0277-786X/18/$18 · doi: 10.1117/12.2536204

An absolute optical frequency reference for space

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ABSTRACT

A variety of future space missions rely on the availability of high-performance optical frequency references with applications in fundamental physics, geoscience, Earth observation and global satellite navigation systems (GNSS). Examples are the gravitational wave detector LISA (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 where compactness and mechanical and thermal stability are main design criteria. We demonstrated a frequency instability of $6{\cdot}10^{-15}$ at 1 s integration time and $3{\cdot}10^{-15}$ for integration times between 100 s and 1.000 s. Furthermore, a very compact spectroscopy setup was realized for the sounding rocket mission JOKARUS which was successfully flown in May 2018. In a current activity, an integrated high-performance iodine-based frequency reference is developed which serves as a demonstrator for future GNSS using optical technologies.

Keywords: optical clock, space instrumentation, satellite navigation, tests of fundamental physics, modulation transfer spectroscopy, laser frequency stabilization

1. INTRODUCTION

Optical frequency references are required by space missions in various applications. They are needed as stable light source for long distance inter-satellite metrology as foreseen within missions to measure the Earth's gravity field (e.g. GRACE (Gravity Recovery and Climate Explorer) follow-on, NGGM) and space-based gravitational wave detection (e.g. LISA). Optical frequency references are also proposed for tests of fundamental physics such as General and Special Relativity performing clock-clock-comparison experiments (e.g. ACES (Atomic Clock Ensemble in Space), BOOST (Boost Symmetry Test)). Satellite navigation systems (e.g. GPS (Global Positioning Service), Galileo, Glonass) currently use microwave clocks. Future generations could benefit by optical clock technologies (including a space optical frequency comb) promising higher frequency stabilities and the potential to be easily combined with optical link technologies e.g. for communication and ranging between the satellites.

In the past years, we realized several setups of absolute frequency references based on Doppler-free spectroscopy of molecular iodine [1,2,3,4]. The light source is a 1064 nm solid-state Nd:YAG laser, which is available space-qualified used e.g. aboard GRACE follow-on, LISA Pathfinder and the Laser Communication Terminals (LCTs). For iodine spectroscopy, the laser output is frequency doubled to 532 nm where iodine shows strong absorption lines. The second harmonic generation is based on Periodically-Poled Lithium Niobate (PPLN) waveguide technology. Spectroscopy setups on elegant breadboard (EBB) and engineering model (EM) level, respectively, were realized using a baseplate made of glass material in combination with a dedicated easy-to-handle assembly-integration technology for the optical components. This ensures high pointing stability of the two counter-propagating laser beams in the iodine cell and therefore high long-term stability. A frequency instability of $6{\cdot}10^{-15}$ at 1 s integration time and a noise floor below $3{\cdot}10^{-15}$ for integration times between 100 and 1000 s was demonstrated [1]. The EM 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}.

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The frequency stability was measured before and after the tests where no degradation was observed [2]. A very compact spectroscopy setup for use on a sounding rocket mission, successfully launched in May 2018, was implemented using micro-integrated external cavity diode lasers (ECDLs) as light source [3]. An iodine-based reference was compared to a microwave reference via an optical frequency comb, resulting in a test of local position invariance (LPI).

Within the current project ADVANTAGE (Advanced Technologies for Navigation and Geodesy), optical clock technologies based on Doppler-free spectroscopy of molecular iodine are investigated experimentally with respect to applications in GNSS, also – in collaboration with the DLR Institute of Communications and Navigation – in combination with optical link technology at 1064 nm. An advanced iodine setup is currently implemented based on the setups mentioned above.

2. IODINE-BASED FREQUENCY REFERENCES FOR SPACE APPLICATIONS

Optical frequency references based on Doppler-free spectroscopy of molecular iodine near 532nm are a well-proven technology developed in several laboratories for many years, also in compact setups [5,6,7,8,9]. Development for applications in space is ongoing, resulting in compact and ruggedized setups [1,2,3,10,11]. In a collaboration of the German Aerospace Center (DLR Institute of Space Systems, Bremen), the University Bremen (Center of Applied Space Technology and Microgravity, ZARM), the Humboldt-University Berlin and the space company Airbus Defence & Space (Friedrichshafen), several setups for space applications have been developed in the last years, including a setup on Elegant Breadboard (EBB) and Engineering Model (EM) level. A very compact setup has been realized for the sounding rocket mission JOKARUS, which was successfully flown in May 2018. These setups are detailed in the following.

2.1 Setup on Elegant Breadboard level

Based on a laboratory setup, a spectroscopy setup on elegant breadboard level was realized. The light source is a Nd:YAG solid state laser with an output wavelength of 1064 nm, internally frequency doubled to 532 nm. 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. For modulation transfer spectroscopy (MTS), the pump beam is frequency modulated using the corresponding AOM. The layout of the EBB laser system is shown in Figure 1, left, together with the corresponding control electronics.

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 very low coefficient of thermal expansion (CTE) of $2\cdot10^{-8}$ 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 [12]. 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 (i.e. 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. Polarizers are placed directly behind fiber outcoupling in order to guarantee clean polarization. A photograph of the integrated spectroscopy setup is shown in Figure 1, right.

Residual amplitude modulation (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. Therefore, part of the probe beam is split of before the iodine cell and guided to the NC for balanced detection which allows for shotnoise 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 of $6\cdot10^{-15}$ at an integration time of 1 s and below $4\cdot10^{-15}$ for integration times between 10 s and 1000 s. RAM and residual temperature variations of the iodine cell cooling finger are most probably limiting the frequency stability at longer integration times.

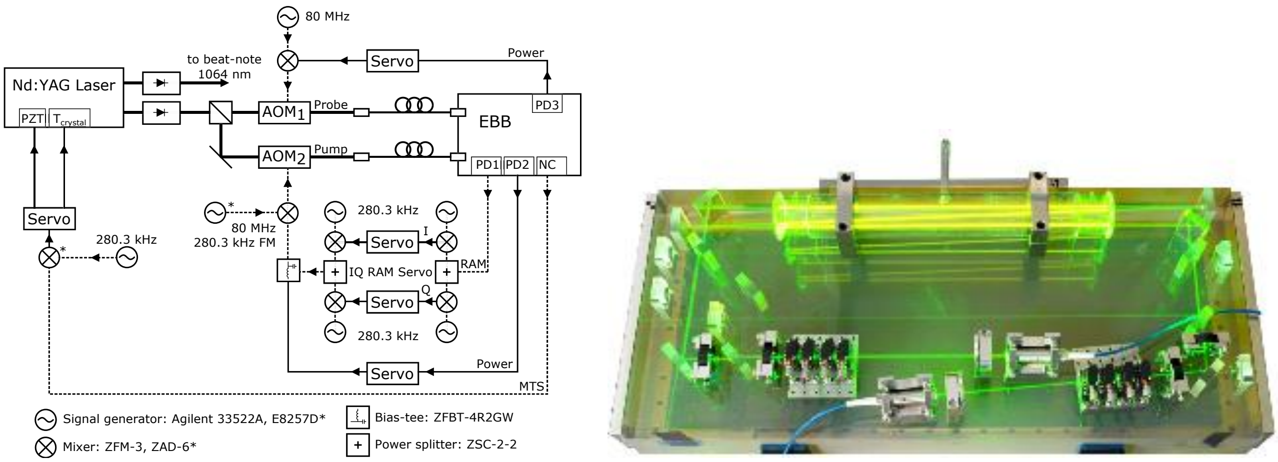

Figure 1. Schematic of the laser system for modulation transfer spectroscopy (left) and photograph of the integrated EBB iodine spectroscopy setup (right) [1].

2.2 Setup on Engineering Model level

A spectroscopy setup on engineering model level was developed, based on the experience gained with the EBB setup. It is further optimized with respect to compactness and mechanical and thermal stability. 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 2.

Light source is a Nd:YAG laser with an output wavelength of 1064 nm. Pump and probe beams pass AOMs and are then frequency doubled using fiber coupled, temperature stabilized, PPLN waveguide modules. In contrast to the EBB setup, beam preparation is carried out in the infrared where space proven hardware including fiber beam splitters and fiber pigtailed AOMs is available. Intensity and RAM stabilization as well as MTS signal generation are done in a similar fashion as in the EBB setup.

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. The beams are reflected at the inner surface of the cell windows (with AR coating at the outer surface). Commercial fiber collimators 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 before entering the gas cell for power stabilization.

The Allan deviation of the beat note with the ULE cavity indicates a frequency stability of $5 \cdot 10^{-15}$ for integration times larger than 100 s, similar to the EBB setup. 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.

Current iodine setups use gas cells with a cooling finger where ~mK temperature stability is required. Within the EM spectroscopy setup, first tests with a gas cell filled with an unsaturated vapor pressure were carried out, showing very similar frequency stabilities to the measurements with a cell using a cooling finger [2]. The use of an unsaturated cell simplifies the system as no cooling finger and no thermal control is required. This is especially an advantage with respect to space implementation.

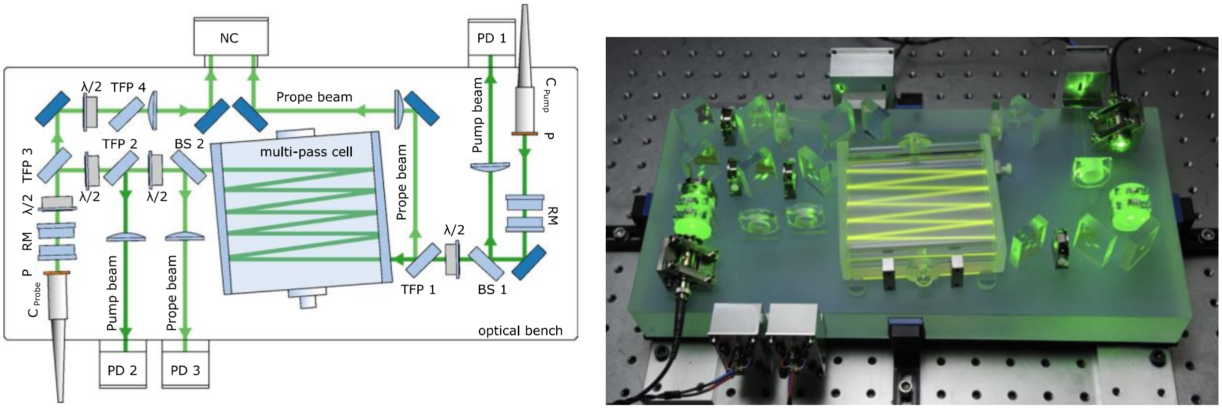

Figure 2. Schematic and photograph of the EM spectroscopy setup using a compact rectangular multi-pass gas cell [2].

2.3 Spectroscopy setup for the sounding rocket mission JOKARUS

A very compact iodine spectroscopy unit for use on a sounding rocket was recently developed [3]. It was successfully flown in May 2018. Compared to the EBB and EM setups detailed above, the dimensions and the mass of the module are further reduced in order to fit to the sounding rocket interface requirements. The optical layout is similar to the EM setup using a fused silica baseplate with a footprint of 24.6 cm x 14.5 cm and a 15 cm long unsaturated iodine cell in double-pass configuration, cf. Figure 3.

This system is operated with laser diode technology developed by the Ferdinand-Braun Institute Berlin [13,14] A micro-integrated 1064 nm master-oscillator power-amplifier (MOPA) module consisting of a narrow line-width extended cavity diode laser (ECDL) master oscillator and a power amplifier are used as light source for spectroscopy, providing a fiber coupled 500 mW output power [15]. While EBB and EM setups use AOMs for phase modulation, an EOM is used here because the corresponding driver electronics has lower power consumption and is less complex and easier to implement. An ARM based embedded system for autonomous control of the experiment is used (provided by Menlo Systems GmbH) and an automatic frequency locking and relocking is implemented (developed at the Humboldt-University Berlin) [3].

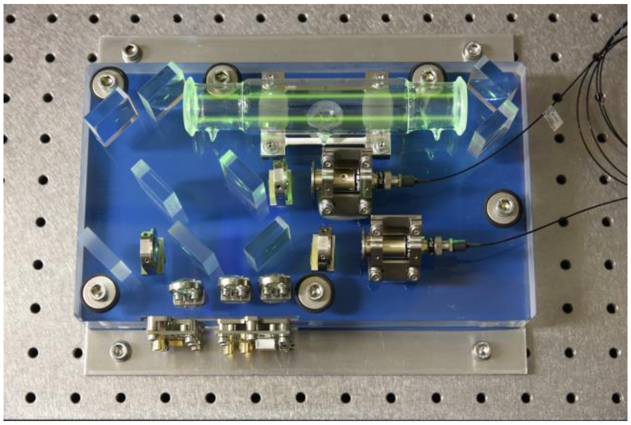

Figure 3. Photograph of the iodine spectroscopy setup for use on the sounding rocket mission JOKARUS. It uses a 15 cm long iodine cell in double-pass configuration [3].

3. ADVANCED IODINE REFERENCE DESIGN

Within the project ADVANTAGE, an advanced iodine reference is currently developed, based on the setups presented above. It is designed for highest frequency stability, i.e. the design is based on the EBB and EM setups using a solid-state Nd:YAG laser as current baseline. It includes a system design including dedicated interface definitions needed for space instrumentation. The system design includes two physical boxes: the iodine spectroscopy unit (with beam preparation optics) and the instrument electronics unit, cf. Figure 4. For a modular and flexible design, the laser source is fiber coupled to the iodine spectroscopy unit.

The spectroscopy setup is similar to the JOKARUS design but includes a 22 cm long iodine cell in four-pass configuration, Risley prisms for beam steering and intensity and RAM stabilization control loops. A schematic of the spectroscopy unit is shown in Figure 5, left. Currently, a stacked design within the iodine spectroscopy unit is foreseen where the lower level includes the fiber optical components for beam preparation including AOMs, EOM and second harmonic generators (SHGs). The upper level includes the spectroscopy unit integrated on a Zerodur baseplate within a temperature shielding, cf. Figure 5, right.

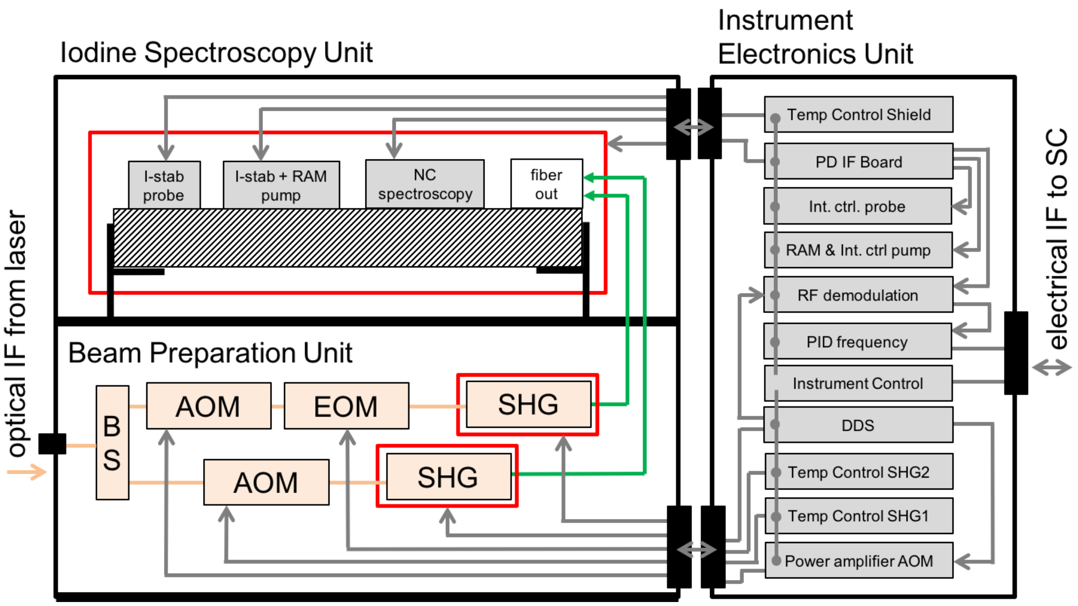

Figure 4. Functional diagram of the iodine reference developed within the ADVANTAGE project. It consists of two physical boxes with clear interfaces: the iodine spectroscopy unit and the instrument electronics unit.

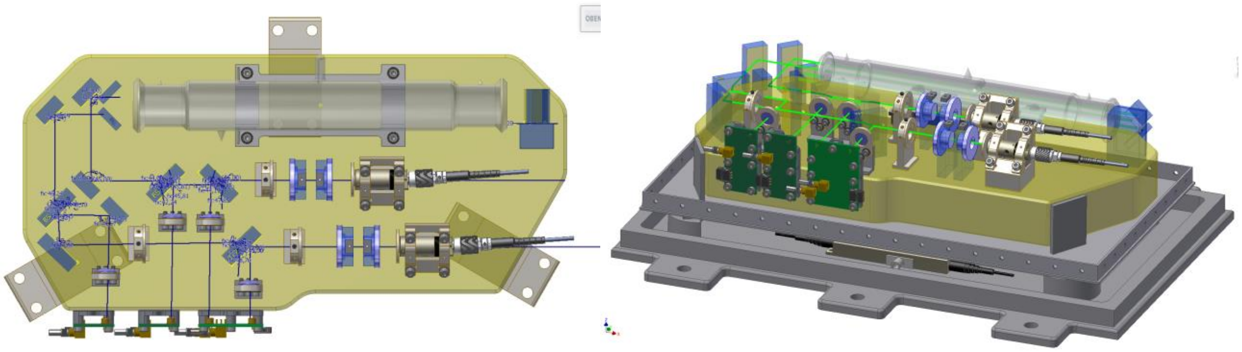

Figure 5. Preliminary design of the iodine spectroscopy unit and the overall system integration together with the beam preparation unit at the lower level. Not shown are the top part of the thermal shield around the spectroscopy unit and the housing.

ACKNOWLEDGEMENTS

The integration of the iodine spectroscopy setups took place at the Laboratory for Enabling Technologies at Airbus Defence & Space (Friedrichshafen). The authors thank Ulrich Johann, Dennis Weise and Alexander Sell from Airbus for their support. Realization of the iodine cells was carried out by the Institute of Scientific Instruments of the Czech Academy of Sciences. The authors thank Jan Hrabina and Josef Lazar for their cooperation and many fruitful discussions on possible cell designs.

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 Agency DLR with funds provided by the Federal Ministry of Economic Affairs and Energy (BMWi) under grant numbers 50QT1102, 50QT1201 and 50WM1646. The project ADVANTAGE is a joint project of DLR and the GFZ German Research Centre for Geosciences. It aims at defining a future system for navigation, geodesy and metrology.

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