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Abstract—**We present the development of a compact optical frequency reference with a stability in the 10^{-15} domain at longer integration times utilizing Doppler-free spectroscopy based on molecular iodine. With respect to its future application in space, a setup on elegant breadboard (EBB) level was realized and successfully implemented and tested. A frequency stability of $5 \cdot 10^{-15}$ at an integration time of 200 s was verified in a beat measurement with a ULE cavity setup. For ensuring high thermal and mechanical stability, the EBB utilizes a baseplate made of ultra-low CTE glass ceramics. The optical components are fixed to the baseplate using an adhesive bonding technology. In a current activity, a setup on engineering model (EM) level will be realized with increased compactness and stability compared to the EBB setup utilizing a very compact multipass gas cell.**

I. INTRODUCTION

Future space missions related to fundamental science, geoscience, Earth observation, navigation and ranging require ultra-stable frequency references, especially in the optical domain. Lasers stabilized to atomic or molecular transitions offer an absolute frequency reference with high long-term frequency stability. While single-ion clocks and neutral atom lattice clocks have the potential of ultimate frequency stability down to the 10^{-18} level, their complexity prevent their immediate development for space compatibility. Setups based on Doppler-free spectroscopy offer frequency stabilities in the 10^{-15} domain at longer integration times and have the potential to be developed space compatible on a relatively short time scale. They feature a better frequency stability than (space) hydrogen masers in the microwave domain.

We realized an ultra-stable optical frequency reference on elegant breadboard (EBB) level, which utilizes modulation-transfer spectroscopy of molecular iodine near 532 nm. With the goal of a space qualifiable iodine frequency reference, a compact and ruggedized setup was realized using a 30 cm long iodine cell in triple-pass configuration and a 550 mm × 250 mm baseplate made of Clearceram-HS, a glass

ceramics with an ultra-low coefficient of thermal expansion of $2 \cdot 10^{-8}$ K^{-1}. The optical components are joint to the baseplate using adhesive bonding technology in combination with a space-qualified two-component epoxy. This technique allows for higher long-term frequency stability due to enhanced pointing stability. The setup also takes into account space mission related criteria such as compactness, the process of MAIVT (manufacturing, assembly, integration, verification and testing) and robustness with respect to shock, vibration and thermal stress. With this setup a frequency stability of $3 \cdot 10^{-14}$ at an integration time of 1 s and $5 \cdot 10^{-15}$ at an integration time of 200 s was verified in a first beat measurement with a ULE cavity-based setup. We present design, implementation and characterization of the EBB-level setup, the current performance status of the enhanced iodine frequency reference on laboratory level and the current status of a setup on engineering model (EM) level utilizing a specifically designed compact multi-pass gas cell.

II. IODINE-BASED OPTICAL FREQUENCY REFERENCES

Frequency references based on Doppler-free spectroscopy of molecular iodine at a wavelength near 532 nm are commonly used laboratory equipment since many years. They use either frequency modulation spectroscopy (FMS) [1], [2] or modulation transfer spectroscopy (MTS) [3], [4], [5], [6], and are also developed in compact setups [7], [8], [9], [10], [11]. State-of-the-art setups reach noise levels of $2 \cdot 10^{-14}$ at an integration time of 1 s and below $3 \cdot 10^{-15}$ at integration times between 100 s and 1000 s using an 80 cm long iodine cell in single-pass configuration in combination with a frequency-doubled Nd:YAG laser [12], [13] (also cf. Fig. 3).

A schematic of the laboratory setup as realized at the Humboldt-University Berlin is shown in Fig. 1. An NPRO (non-planar ring oscillator) type Nd:YAG laser at a wavelength of 1064 nm, frequency doubled to 532 nm is used as light
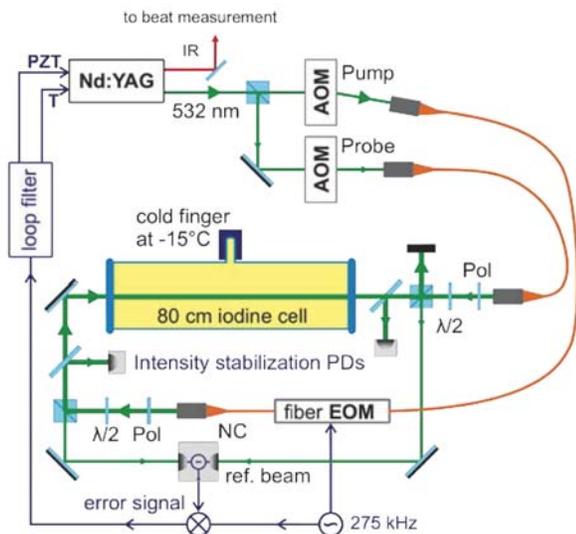
Fig. 1. Schematic of the iodine frequency reference as realized at the Humboldt-University Berlin (AOM: acousto-optic modulator, EOM: electro-optic modulator, NC: noise-cancelling detector, Pol: polarizer, PD: photo diode [14].

source for the iodine spectroscopy. The 532 nm output beam is split into pump and probe beams for realizing modulation transfer spectroscopy. Each beam passes an acousto-optic modulator (AOM) and is coupled into a single-mode polarization-maintaining optical fiber enhancing the pointing stability of the two counter-propagating laser beams in the iodine cell. After fiber outcoupling, part of the probe beam is split off as reference beam for a noise-cancelling (NC) detection of the spectroscopy signal. Part of pump and probe beam are split off for intensity stabilization of the corresponding beam in front of the iodine cell. The intensity is stabilized using feedback to the amplitudes of the RF-driving signals of the AOMs. A fiber electro-optic modulator is used for phase-modulation of the pump beam but in an alternative modulation setup, frequency modulation is carried out by the AOM in the pump beam. The detected signal is mixed with the EOM driving frequency, low-pass filtered and input to a loop filter actuating the laser frequency (via PZT and crystal temperature).

III. ASSEMBLY-INTEGRATION TECHNOLOGY FOR SPACE

To develop optical systems for operation in space includes specific design aspects such as compactness, rigidity and modularity. All components (and the whole system) must fulfill mission specific requirements on vibration, shock and thermal cycling as well as radiation hardness. Therefore, optical components (such as laser, EOM, AOM, fiber collimators) are specifically selected. The assembly-integration (AI) technology for realizing the optical setup must offer high thermal and mechanical stability, high long-term stability, alignment feasibility of the optical components and space-qualification of the AI technology. For realizing optical systems with highest stability, a baseplate made of an ultra-low expansion glass

ceramics, such as Zerodur or Clearceram, with a coefficient of thermal expansion of $2 \cdot 10^{-8}$ K^{-1} is used. For integration of the optical components, two methods are conceivable: hydroxide-catalysis bonding [15] and adhesive bonding [16].

Hydroxide-catalysis bonding is a well proven technology, already demonstrated in the realization of the optical bench of the LISA Technology Package (LTP) aboard LISA Pathfinder. The optical bench includes a heterodyne interferometer with pm/$\sqrt{\text{Hz}}$ and nrad/$\sqrt{\text{Hz}}$ sensitivity in translation and tilt measurement and was successfully subjected to environmental tests (thermal and vibration) [17]. Typical bond thicknesses are between 20 nm to 100 nm, depending on the bonding solution; the settling time (i.e. the time after which the component can not be moved) of the bonding procedure is between 1 min and 10 min (typically 2 min).

Adhesive bonding can be used for optical assemblies with components made of glasslike materials (such as Zerodur, ULE, fused silica) and Invar. In a pre-experiment, a bond layer thickness of a few μm was measured using a space-qualified two-component epoxy (Hysol EA 9313). Vibration, shock and thermal cycling tests were carried out in comparison to hydroxide-catalysis bonding, where no difference between the two integration methods was observed [16]. For adhesive bonding, the settling (i.e. alignment) time can be up to several hours (depending on the ambient temperature) and no clean-room environment is required.

In comparison to hydroxide-catalysis bonding technology, adhesive bonding has clear advantages in settling time and required integration process environment and can therefore be carried out faster and with less complexity. Using this AI technology, a heterodyne interferometer was developed at Astrium (Friedrichshafen) in a collaboration with the Humboldt-University Berlin and the University of Applied Sciences Konstanz [18], [19], [20]. This setup is realized as a demonstrator for the optical readout of the LISA gravitational reference sensor. With this setup, noise levels below 5 pm/$\sqrt{\text{Hz}}$ in translation and below 10 nrad/$\sqrt{\text{Hz}}$ in tilt measurement, both for frequencies above 10^{-2} Hz, were demonstrated. For integration of the interferometer, a specific jig was developed which offers the possibility of adjusting the optical component in tilt and translation. The jig also applies a dedicated force to the substrate which is perpendicular to the bonding surface, ensuring a thin and homogenous bonding layer.

IV. IODINE-FREQUENCY REFERENCE ON ELEGANT BREADBOARD LEVEL

With respect to its further application in space, a fiber-coupled spectroscopy setup on elegant breadboard (EBB) level was realized using adhesive bonding technology as described in section III (cf. the schematics and photograph in Fig. 2).

The baseplate is made of OHARA Clearceram-Z HS, a thermally and mechanically highly stable glass ceramics with a CTE of $2 \cdot 10^{-8}$ K^{-1} and has dimensions of 550 mm $\times$ 250 mm $\times$ 50 mm. Plates made of Invar are glued to the sides of the baseplate which are used for integration of
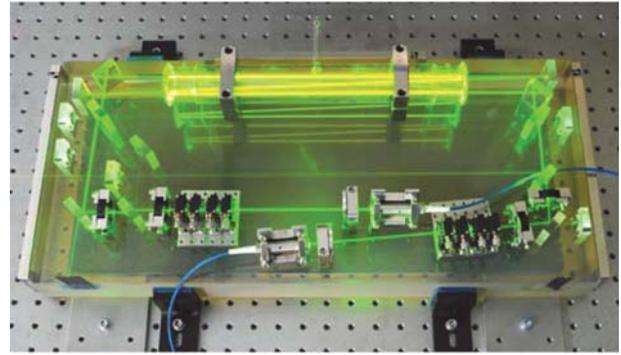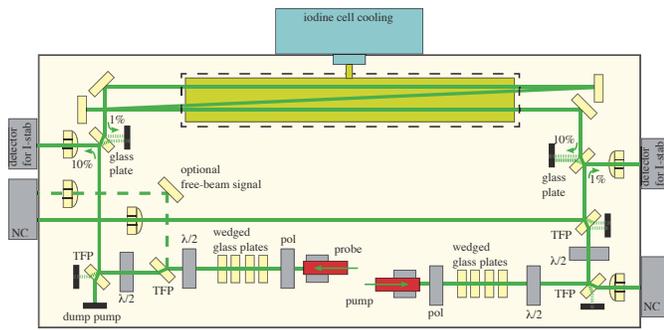
Fig. 2.   Schematic (left) and photograph (right) of the spectroscopy setup on EBB level [14]. This setup utilizes a 30 cm long iodine cell in triple-pass configuration, the baseplate has dimensions of 550 mm × 250 mm × 50 mm. Not shown in the photograph are the detectors and the cell cooling.

detectors and cell cooling. The 30 cm long iodine cell, provided by the Institute of Scientific Instrument of the Academy of Sciences of the Czech Republic (Brno), is used in triple pass-configuration.

Mirrors, beam splitters and thin film polarizers are based on 35 mm ×25 mm ×8 mm rectangular substrates made of fused silica. Optics such as waveplates, fiber collimators, wedged glass plates and polarizers are placed in specific mounts made of Invar with a CTE of $10^{-6}\,\mathrm{K}^{-1}$. Substrates and Invar mounts are joint to the baseplate using adhesive bonding technology as described above. Four AR-coated wedged glass plates mounted to precision rotation mounts are placed in each, pump and probe beam, enabling an alignment of the two counter-propagating beams in the iodine cell after integration.

Pump and probe beams are fiber coupled to the spectroscopy baseplate using pig-tailed fiber collimators with an output laser beam diameter of 3 mm. Using shims in the collimator mount, the tilt of the collimator can be adjusted ensuring an output beam parallel to the baseplate. Polarizers directly after fiber output ensure a clean (and linear) polarization.

Part of the pump beam is transmitted at the first thin film polarizer (TFP) impinging on a noise-cancelling detector (NC). Its signal is used for residual amplitude modulation (RAM) stabilization using feedback to the RF-amplitude of the corresponding AOM. At a glass plate (with uncoated front surface and AR-coated back surface), part of the pump beam is split off and sent to a monitor photo diode whose signal is used for intensity stabilization (carried out by feedback to the corresponding AOM or, alternatively, to the temperature of the frequency doubling crystal).

The probe beam is split at a first TFP, the reflected beam can be taken as a (free-beam) reference signal for the noise-cancelling detection of the spectroscopy signal. Analog to the pump beam, part of the probe beam is split off at a glass plate for intensity stabilization (using feedback to the RF-amplitude of the corresponding AOM). After passing thrice the iodine cell, the probe beam is out-coupled towards a noise-cancelling detector yielding to the spectroscopy signal. Lenses are mounted in front of each detector focussing the beams onto the photo diodes. The lenses are bond to fused silica substrates

which are adhesive bonded to the baseplate.

For a first characterization of the EBB spectroscopy setup, the laser system (Nd:YAG laser model 'Prometheus' provided by InnoLight GmbH, internally frequency doubled) and electronics of the laboratory setup at the Humboldt-University Berlin were used. An alternative modulation scheme was implemented allowing for higher optical powers than the fiber EOM. The pump beam modulation was carried out by frequency modulating the corresponding RF-driving frequency of the AOM. The resulting amplitude modulation was suppressed using the RAM stabilization as detailed before.

A first beat measurement with a ULE cavity setup was performed, resulting in a frequency stability of $5\cdot10^{-15}$ at an integration time of 200 s (cf. the root Allan deviation shown in Fig. 3). The frequency stability of the compact EBB setup is slightly degraded, compared to the laboratory setup. This is most likely caused by a not yet optimized RAM stabilization in the AOM modulation scheme. Also shown in Fig. 3 are the frequency stabilities of the HUB laboratory setups with modulation carried out using a fiber-EOM or a free-beam AOM. For comparison, the frequency stability of the best reported iodine standard [6] is included.

V. IODINE-BASED FREQUENCY REFERENCE ON ENGINEERING MODEL LEVEL

Based on the experience with the EBB setup, a more compact and ruggedized setup on engineering model (EM) level – with similar performance – is currently designed and realized. Compared to the EBB setup, it will feature reduced mass and dimension and higher mechanical and thermal stability. This setup will be subjected to environmental tests such as vibration tests and thermal cycling. A first schematic of the EBB setup is shown in Fig. 4. It uses the same baseplate material and integration technology as the EBB setup.

The main issue for a compact setup is the realization of a compact multipass cell. While different geometries are conceivable, a layout with internally reflected beams was worked out and is currently realized. The cell uses a 100 mm × 100 mm × 30 mm fused silica spacer with wedged windows. The cell is designed for a nine-pass configuration
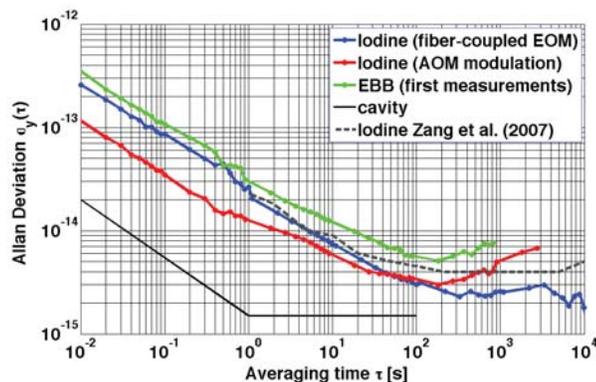
Fig. 3. Frequency stability of different iodine-based frequency references, given in root Allan deviation. Shown are the stability curves for the EBB setup, the single- and triple-pass laboratory setup at HUB, the best published iodine system by Zang et al [6] and the stability of the ULE cavity setup at HUB used as reference for the HUB iodine setups [12].
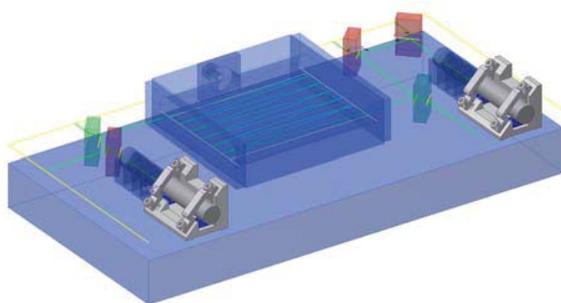

Fig. 4. Possible design of an iodine spectroscopy setup on engineering model (EM) level using a compact multipass iodine cell with internal reflection.

(corresponding to 90 cm interaction length) but can easily be adapted for other interaction lengths by tilting the cell with respect to the incoming laser beam. For ensuring high mechanical stability, the conventional cooling finger is replaced by a mechanically more stable alternative cell cooling design.

VI. LASER SYSTEM AT 532 NM

The EBB spectroscopy setup is currently tested with a laboratory laser system consisting of an internally frequency-doubled Nd:YAG laser (model 'Prometheus' by InnoLight GmbH, Germany) in combination with free beam AOMs. With respect to future applications in space, work was already carried out in the context of other projects. The frequency-doubled InnoLight laser is used in an airborne Lidar experiment [21] but not available space-qualified. The Nd:YAG laser at the fundamental wavelength of 1064 nm is provided in a space-qualified version by Tesat Spacecom GmbH (Germany) with an output power up to 100 mW. This type of laser is used e.g. in the ADM Aeolus mission and the LISA precursor mission LISA Pathfinder. A waveguide PPLN frequency doubler was investigated in the framework of NASA's Space Interferometry Mission (SIM), where vibration and thermal-vacuum tests but no test on radiation hardness were performed [22]. For the laser transmitter for the CALIPSO mission, a

KTP doubling crystal for pulsed beams with a wavelength of 1064 nm was subjected to vibration and thermal-vacuum tests [23]. Radiation hardness of PPKTP and PPMgOLN doubling crystals was successfully tested taking the LISA radiation dose as basis [24].

AOMs using a TeO_2 crystal for a laser wavelength of 1064 nm were space qualified for LISA Pathfinder in a pig-tailed version [25]. Except the AR-coating of the crystal, a similar design should also work out at 532 nm. EOMs at a wavelength of 1064 nm are investigated in the context of the LISA mission, also addressing space relevant criteria [26], [27].

VII. OUTLOOK

The EBB setup is currently operated with the HU laboratory setup laser system and electronics. Its performance is verified in a beat measurement with a ULE cavity setup and currently optimized. For obtaining an independent and transportable frequency reference, the EBB setup will be combined with a dedicated laser system and corresponding electronics. This also enables a direct comparison of the EBB setup and the HU laboratory setup eliminating possible limitations of the cavity setup at longer integration times. In a current activity, the EBB and the laboratory setups are further optimized and analyzed with respect to possible limitations in frequency stability.

ACKNOWLEDGMENT

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