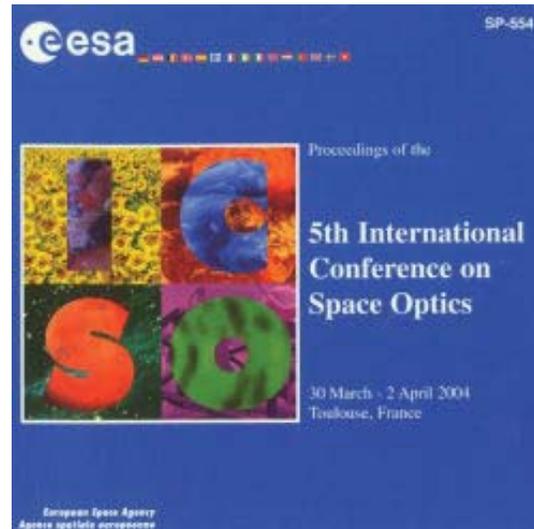


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FREQUENCY STABILIZED ND:YAG LASER FOR SPACE APPLICATIONS

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ABSTRACT

Future space missions rely on the availability of space qualified high precision optical metrology instruments like ultra stable laser sources. Here, we present a compact, frequency-doubled, monolithic Nd:YAG laser (non planar ring-oscillator, NPRO), frequency stabilized to a hyperfine transition in molecular iodine, based on the method of modulation transfer spectroscopy. Using a 10 cm long iodine cell cooled to 1°C and a total light power of ~ 5 mW a frequency stability of $1 \cdot 10^{-12}$ for an integration time of $\tau = 1$ s and $3 \cdot 10^{-13}$ for $\tau > 100$ s was achieved. By use of an active offset compensation (offset compensation by amplitude modulated sidebands, OCAMS), the frequency stability of this setup was furthermore improved to $4 \cdot 10^{-14}$ for $\tau > 5000$ s. This setup therefore fulfills the basic metrological requirements for the LISA and Darwin missions (with potential beyond). Due to very compact construction, it serves as a study and demonstrator for a future space qualified iodine standard.

1. INTRODUCTION

High precision optical frequency standards are a basis for many applications in fundamental science and technology including future space missions. Besides, tests of fundamental physics – which are also planned to be performed in space – are based on highly frequency stable lasers.

The infrared interferometric space telescope Darwin [1] – a cornerstone candidate for the ESA Horizons 2000+ program which is projected to be launched in 2014 with its major objective the detection and characterization of Earth-like planets in other sunsystems – relies on a high accuracy formation flying technique. The seven spacecraft (six with telescopes on board, one central hub for recombining the inter-

ferometric signals of the telescopes) must therefore be placed in space with a relative accuracy of 5 nm and an absolute accuracy of 70 μ m while the baseline between two nearby telescopes is proposed to be 25 – 1000 m. In order to measure distances with this high accuracy laser metrology, i.e. laser interferometers in combination with highly frequency stable light sources, is absolutely necessary.

Planned to be launched in 2012, the ESA/NASA cornerstone mission LISA (Laser Interferometer Space Antenna) consists of 3 satellites forming an equilateral triangle with a baseline of 5 million km. A gravitational wave passing this formation changes the distance between nearby satellites in the order of 10 pm. These changes therefore contain the scientific result of the mission and are measured by use of laser interferometry where the light sources are highly frequency stabilized lasers.

Missions investigating the Earth's gravity field like GRACE (Gravity Research and Climate Explorer) are based on a satellite-satellite-tracking (SST) technology which in an enhanced version relies on high precision optical metrology. The gain in the accuracy of spacecraft distance metrology control here directly corresponds to a gain of the Earth's gravity gradient measurement accuracy.

High precision optical frequency standards are also used in tests of fundamental physics: different methods for frequency stabilization have different dependencies on constants, like the fundamental fine structure constant α , the electron-proton mass ratio m_e/m_p or the speed of light c . By comparing the frequencies of two different stabilized lasers, high precision tests of possible variations can be carried out. This includes tests of special relativity (Michelson-Morley experiments (MM), and Kennedy-Thorndike experiments (KT)) as well as general relativity (tests of local position invariance (LPI)). Such tests of fundamental physics can furthermore be improved in spaceborne versions of the experiments. MM, KT

and LPI experiments on board a satellite are proposed for the OPTIS mission [2]. The SUMO mission proposes a spaceborne MM experiment [3].

As a light source for the interferometers and the tests of fundamental physics, a monolithic integrated single-end diode pumped Nd:YAG laser (MISER, also called: non planar ring-oscillator, NPRO) is an appropriate choice. Due to its monolithic design, it provides a high frequency stability. Also, this type of laser already exists in a space qualified version [4].

However, for the applications described above, even the stability of such an NPRO is not sufficient and has to be further improved by means of an active stabilization to an external reference. This can e.g. be an optical resonator or the frequency of an atomic or molecular transition. The laser frequency is steadily compared to the reference and corrected if necessary. For long term frequency stability, in case of the Nd:YAG laser at a fundamental wavelength of 1064 nm, transitions in molecular iodine $^{127}\text{I}_2$ at 532 nm (i.e. at the second harmonic wavelength of the Nd:YAG laser) are a commonly used frequency reference. A frequency stability of $6 \cdot 10^{-15}$ for integration times $100 \text{ s} \leq \tau \leq 1000 \text{ s}$ was achieved in a laboratory setup with a 1.2 m long iodine cell [5]. For future space applications, effort must be put into the development of a *compact* iodine standard. This is the aim of this work.

2. METHOD OF FREQUENCY STABILIZATION

For an active laser frequency stabilization, a frequency reference is needed. Here, two options are (i) an optical resonator and (ii) transitions in atoms (or molecules). In case of an optical resonator (cavity), its resonance condition $\nu = mc/(2L)$ (with $m = 1, 2, 3, \dots$ a constant mode number, the speed of light c , and the length L of the resonator), is defining the frequency reference. The method thus relies on the constancy of the cavity length L (and of c).

In practice, atomic and molecular transitions offer an advanced long term stability. Molecular iodine $^{127}\text{I}_2$ is suitable for this work because it has very strong absorption lines at wavelengths around 532 nm, corresponding to the frequency-doubled emission wavelength of a Nd:YAG laser. For the resulting frequency stability, the ratio of the signal-to-noise ratio SNR and the linewidth $\Delta\nu$ of the transition (i.e. $\text{SNR}/\Delta\nu$) is relevant. In order to maximize this term, Doppler-free spectroscopy resolving the hyperfine structure – with natural linewidths $\Delta\nu_{\text{nat}} \sim 400 \text{ kHz}$ – is needed. The resulting linewidth $\Delta\nu_{\text{res}}$ is given by

$$\Delta\nu_{\text{res}} = (\Delta\nu_{\text{nat}} + \Delta\nu_p + \Delta\nu_{\text{tof}}) \sqrt{1 + S_0}, \quad (1)$$

where $\Delta\nu_p$ represents the broadening of the linewidth

due to pressure broadening, $\Delta\nu_{\text{tof}}$ the time-of-flight broadening, and $\sqrt{1 + S_0}$ the saturation broadening with the saturation parameter $S_0 = I/I_{\text{sat}}$. I_{sat} is the saturation intensity.

2.1. Doppler-free spectroscopy

In order to resolve the hyperfine structure of iodine, Doppler-free spectroscopy is needed where modulation transfer spectroscopy (MTS) and frequency modulation spectroscopy (FMS) are most commonly used in combination with a frequency-doubled Nd:YAG laser. Both methods use two counter-propagating laser beams in the iodine cell. One beam (pump beam) is saturating the transition, causing a dip (the so called Bennet hole) in the population density. The width of this dip is given by Equation 1. This hole in the population density is detected by a second beam with an intensity not causing saturation (probe beam), which is passing the iodine cell in opposite direction to the pump beam. The probe beam is scanned over the Doppler-broadened line. In case of resonance (here, the Bennet hole caused by the pump beam, is present) the probe beam is subject to a smaller absorption (Lamb-dip in the absorption).

By use of phase modulation, an error signal is generated and the detection sensitivity can furthermore be improved. In case of FMS the probe beam is phase modulated with a frequency f_{mod} much larger than the linewidth, producing sidebands on both sides of the carrier frequency in the distance f_{mod} . The phase relationship between the sidebands is disturbed when the probe beam is close to resonance with a transition (and with the corresponding Bennet hole in the population density caused by the pump beam) and therefore a signal, amplitude modulated at the frequency f_{mod} is generated at the detector [6, 7, 8]. In case of FMS, the Doppler background of the signal is still contained in the error signal but can easily be removed by use of lock-in technique.

FMS results in a very good signal-to-noise ratio and therefore in a very good short term frequency stability. On the other hand, the long term stability is limited: As the modulated probe beam is detected, a possible residual amplitude modulation (RAM) caused by imperfections of the modulator is directly converted to an unwanted component of the error signal. Changes in RAM on longer times limit the achievable frequency stability.

The method of MTS achieves a better long term stability by phase modulation of the pump beam as shown in Figure 1. Here, the modulation frequency f_{mod} must be smaller than the linewidth of the transition. This frequency is transferred to the probe beam in case of resonance due to two effects [8]: (i) modulated hole burning and (ii) reflection at an induced population density graticule. Regarding modulated hole burning, sidebands of the modulated pump beam at frequencies $f_{\text{laser}} - f_{\text{mod}}$ and

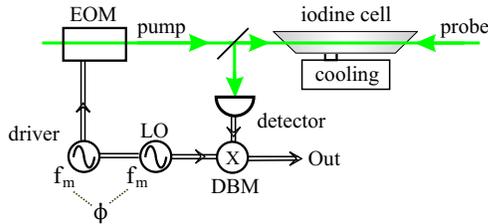


Figure 1. Schematic of MTS (DBM: double balanced mixer, LO: local oscillator, EOM: electro-optic modulator).

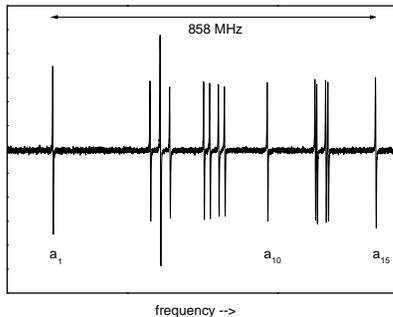


Figure 2. Resolved hyperfine splitting of the 1110 line using modulation transfer spectroscopy. The a_{10} component is taken for frequency stabilization.

$f_{laser} + f_{mod}$ generate modulated holes in the population density. In case the laser frequency f_{laser} is in resonance, the unmodulated probe beam interacts with molecules whose population density is modulated in the way described above. The probe beam therefore underlies a varying absorption and dispersion, corresponding to a frequency modulation of the probe beam which is detected. The second effect is based on reflection. Interference of the two counter-propagating laser beams generates a standing wave structure in the population density which acts as a diffraction grating on which a part of the two beams is reflected backwards. This effect results in an additional signal.

In modulation transfer spectroscopy, the signal does not contain a Doppler background as the (detected) interaction with the molecules takes only part in case of resonance. Also, as the modulated beam is not directly detected, the consequences of RAM of the electro-optic modulator are not as relevant as in case of FMS. Here, MTS results in a better long-term stability. Nevertheless, due to a smaller signal-to-noise ratio, the short-term stability of FMS is superior. For the a_{10} component of the R(56) 32-0 band (also called 1110 line) the resulting linewidth (cf. Equation 1) can be less than 1 MHz. (For comparison: the width of the Doppler-broadened line is ~ 800 MHz. In Figure 2, the sub-Doppler spectra of the 1110 line, resolved by means of MTS in the compact setup is shown.)

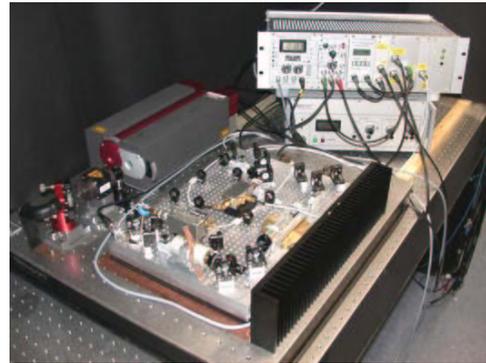


Figure 3. Photo of the compact setup of an iodine stabilized Nd:YAG laser. The aluminum breadboard has a size of 27×37 cm² and contains the optics for modulation transfer spectroscopy. Also shown are the laser controller and the electronics unit for frequency stabilization.

3. OFFSET COMPENSATION

A main problem in frequency standards, limiting the frequency stability, are time-dependent offsets in the error signal. Such offsets are mainly caused by residual amplitude modulation caused by the electro-optic modulator [9], parasitic resonators in the optical setup and electro-magnetic stray fields of HF-components in the setup. In order to minimize these effects, offset compensation by amplitude modulated sidebands ('OCAMS')[10, 11] was implemented in the iodine frequency standard. This method continuously measures and compensates for a potential offset in the error signal.

The laser light is phase modulated with a frequency f_{OCAMS} additionally to the modulation necessary for MTS (resp. FMS). This modulation generates sidebands on the laser light, i.e. a part of the power of the light is transferred into these sidebands. As a consequence, the error signal amplitude is reduced, while in many cases, the offset is unchanged. Thus, the zero crossing (i.e. the lock point for the frequency stabilization) of the error signal is shifted. By periodically turning the extra modulation on and off, a periodic change in error signal amplitude is achieved which causes a periodic change of the locking point. This can be detected via a lock-in technique. A correction voltage is then added to the error signal, in order to annihilate the periodic changes in laser frequency. f_{OCAMS} must be chosen large enough, so that the generated sidebands do not influence the error signal other than in height.

4. COMPACT SETUP

The compact setup of an iodine standard was developed to comply to the following requirements: for a possible space qualification (i) compactness and (ii) utilization of commercial products (if possible already space-qualified). Moreover, it should have (iii)

a frequency stability of $1 \cdot 10^{-12}$ for integration times of 100 s to 1000 s, according to the Darwin mission requirements.

In order to fulfill the long-term stability requirements the method of modulation transfer spectroscopy is chosen for the setup. However, a setup was developed that also allows to change to frequency modulation spectroscopy in a simple way. A photo of the whole setup including laser, laser controller and the electronics unit for frequency stabilization is shown in Figure 3.

The laser is an NPRO-type Nd:YAG laser (laser system 'Prometheus' provided by InnoLight GmbH, Hannover, Germany) at a fundamental wavelength of 1064 nm, internally single-pass frequency-doubled to 532 nm. The laser provides 1 W output power at 1064 nm and 20 mW at 532 nm. It is additionally equipped with a 'noise-eater' stabilizing the intensity of the laser light. The frequency of the laser can be tuned by changing the temperature of the laser crystal as well as by applying a voltage to a piezoelectric transducer (PZT) mounted to the laser crystal, influencing its geometry. By use of these two actuators (and the appropriate electronics), the frequency of the laser is kept at the reference frequency.

4.1. Modulation Transfer Spectroscopy

The optical setup for modulation transfer spectroscopy finds place on a $27 \times 37 \text{ cm}^2$ aluminum breadboard, the whole setup including laser on a $60 \times 60 \text{ cm}^2$ one. A photo of the spectroscopic setup is shown in Figure 4. To control the iodine vapor pressure and thus minimize the pressure broadening and -shift, the temperature of the iodine cell's cold finger is electronically stabilized to $+1^\circ\text{C}$. The cold finger is cooled by use of peltier elements placed in a hermetic brass pot. The temperature of 1°C is chosen in order to prevent ice-formation. At this temperature the pressure broadening is 470 kHz. The coefficient for the dependency of the shift of transition frequency due to a change of pressure in the cell is for our iodine cell -1.2 kHz/Pa .

A schematic of the optical setup is shown in Figure 5. The green light at 532 nm is first passing an optical isolator before it is split in a polarizing beamsplitter into pump and probe beam, passing the 10 cm long iodine cell (provided by PTB, Braunschweig, Germany) in opposite directions. Pump power was $\sim 3 \text{ mW}$, probe power $\sim 0.12 \text{ mW}$. With a beam cross-section of $\sim 1 \text{ mm}^2$, this leads to a saturation broadening factor $\sqrt{1 + S_0} = \sqrt{5}$. The pump beam is phase modulated at a frequency $f_{mod} = 774 \text{ kHz}$ by use of an electro-optic modulator (EOM). The probe beam is frequency shifted by 80 MHz using an acousto-optic modulator. This shifts any unwanted signal components due to interferences between both beams to a signal frequency of 80 MHz, which can easily be suppressed by low-pass filtering (actually using the limited speed of the detector) [12]. The

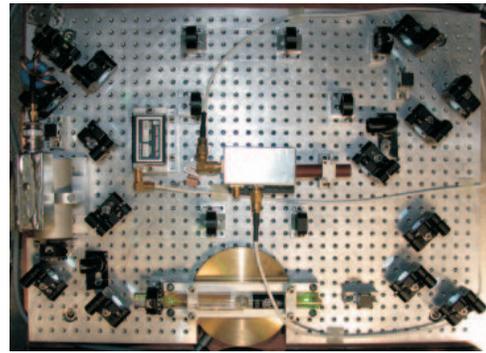


Figure 4. Photo of the aluminum breadboard accommodating the optics for modulation transfer spectroscopy. Below in the center the iodine cell is placed with the appropriate cooling below (brass pot). On the left side, the electro-optic modulator is situated, in the middle the detector; left of the detector the acousto-optic modulator.

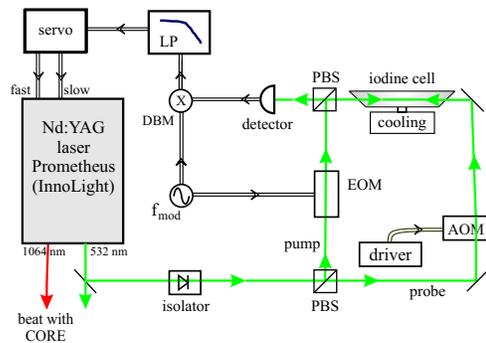


Figure 5. Schematic of the setup for frequency stabilization utilizing MTS. (DBM: double balanced mixer; LO: local oscillator; LP: low pass filter; PBS: polarizing beamsplitter; EOM: electro-optic modulator; AOM: acousto-optic modulator)

detector signal is amplified (2 times Mini Circuits ZFL-500LN), band-pass filtered at 774 kHz, mixed down with a double balanced mixer (Mini Circuits SRA-8) driven by the modulation frequency f_{mod} , and then low-pass filtered with a cut-off frequency of 1 kHz. This error signal is sent to a servo unit (PID controller), providing the signals for frequency stabilization to the two ports of the laser (crystal temperature ('slow') and PZT in the crystal ('fast')). The resulting linewidth in this setup adds up to $\Delta\nu_{res} = 1.9 \text{ MHz}$ where the saturation broadening and the pressure broadening are the substantial – and reducible – contributions.

In order to reduce residual amplitude modulation of the EOM, the polarization of the incoming light is adjusted via a half-wavelength plate in front of the EOM. An additional polarizing beamsplitter behind the EOM guarantees orthogonal polarizations of pump and probe beam in the cell (in order to minimize interferences between them). It was seen that reflections of the pump beam at optical elements behind the iodine cell are a serious problem that limit the frequency stability. This effect was reduced by

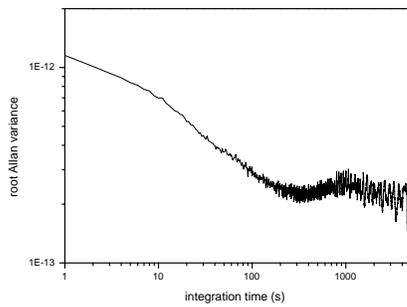


Figure 6. Root Allan variance of the compact setup without offset compensation.

placing a polarizing beamsplitter directly behind the iodine cell which deflects the pump beam.

4.2. Offset Compensation

For implementing OCAMS in this setup, a second EOM and its driver electronics could be avoided which contributes to the compactness of the setup. The additional phase modulation for OCAMS at f_{OCAMS} was generated using the PZT mounted to the laser crystal. This limited f_{OCAMS} to 4.05 MHz, which was generated by a function generator. The same function generator also generated the amplitude modulating square wave at 61 Hz.

If offset voltages are present in the error signal, this amplitude modulation now causes a signal component in the error signal that oscillates at this frequency. Using a commercial lock-in amplifier (time constant set to 100 s with a 6 dB/oct rolloff) referenced to the 61 Hz AM waveform, these components (and thus, the offsets) are detected. The lock-in amplifier's output is added to the MTS error signal to compensate for the offsets.

5. MEASUREMENTS

For measuring the frequency stability of the iodine stabilized laser system, the stabilized laser frequency was compared to a laser stabilized to a cryogenic optical resonator (CORE) [13] whose frequency stability of $7 \cdot 10^{-16}$ for $\tau = 200$ s does not limit this measurement. The beat frequency between these two oscillators is recorded over several hours and this data is taken to calculate the (relative) root Allan variance (RAV). A typical RAV measurement (compact setup without offset compensation) is shown in Figure 6, showing a frequency stability of 1×10^{-12} for 1 s integration time and 3×10^{-13} for $\tau > 100$ s.

A measured beat frequency and the calculated RAV for the compact setup with offset compensation is shown in Figure 7. During this measurement, the

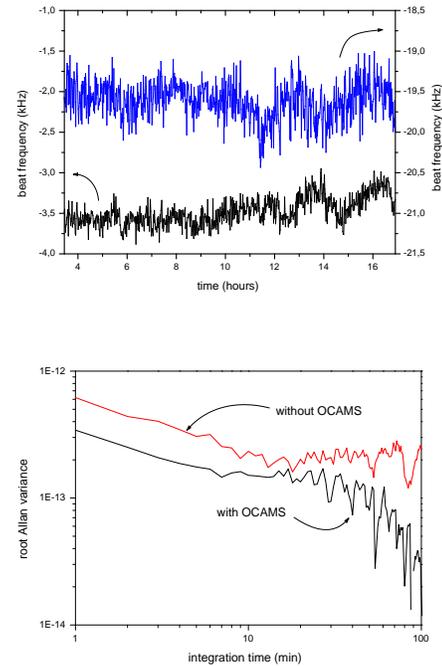


Figure 7. Top: measured beat frequency between the iodine stabilized laser with OCAMS and a CORE stabilized laser. The lower curve represents the measured data, the upper curve shows the reconstructed measurement without OCAMS; Bottom: calculated RAV from the ~ 8 h of these data.

output signal of the lock-in amplifier was recorded. The lower curve represents the measured data. Here, a frequency stability of $4 \cdot 10^{-14}$ for $\tau > 5000$ s is achieved. For comparison, the beat frequency without OCAMS was reconstructed from this measurement and the recorded correction signals (upper curve). It shows a frequency offset of about -16 kHz.

In order to demonstrate the effectiveness of OCAMS, the change in beat frequency due to a change in the polarization of the light at the input to the EOM (i.e. rotating the half-waveplate in front of the EOM) was measured once with OCAMS and once without. Without OCAMS, residual amplitude modulation generated in the EOM has a strong impact on the beat frequency. The measured beat data is shown in Figure 8.

In this measurement the polarization was changed in steps of 10° and the mean value of ~ 200 s of data was taken. With OCAMS, the sensitivity of the setup to changes in polarization is reduced by about one order of magnitude: The fit in Figure 8, right, shows a change of $\delta\nu_{beat} \sim -(13.5 \pm 0.3)$ MHz $\times \phi^4$ without offset compensation and $\delta\nu_{beat} \sim (0.0 \pm 0.3)$ MHz $\times \phi^4$ with offset compensation.

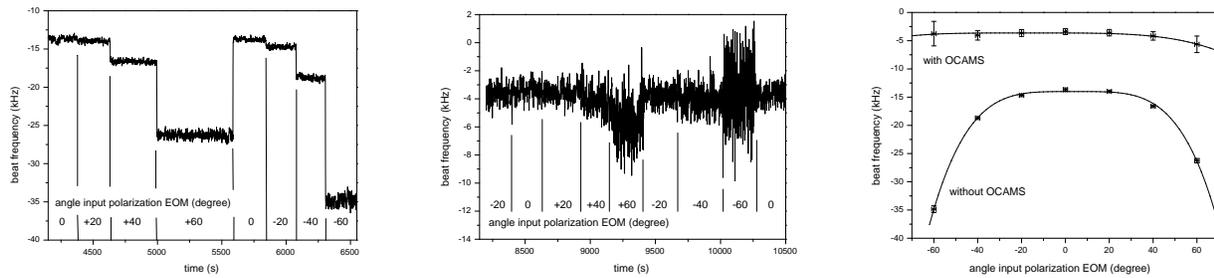


Figure 8. Change of the beat frequency due to a rotation in the linear input polarization to the EOM. Left: without OCAMS; Middle: with OCAMS; Right: plotted results.

6. OUTLOOK

This compact iodine standard can be further improved w.r.t. compactness and frequency stability. Transitions in molecular iodine at wavelengths below 532 nm have natural linewidths of around 40 kHz [14, 15], one order of magnitude smaller than the natural linewidth of the transition at 532 nm taken as frequency reference in this work. With a frequency doubled Yb:YAG laser (with a fundamental wavelength of 1030 nm) a light source at the wavelengths of interest near 514 nm is available. Further improvement in frequency stability can be obtained by cooling the gas to a lower temperature (in order to decrease the pressure broadening) and by increasing the interaction between the laser light and the iodine molecules (e.g. by use of a longer iodine cell, multipath configuration through the iodine cell, cavity around the cell).

In order to improve the short-term stability of the setup, it might also be useful to pre-stabilize the laser to an optical resonator for short times (ms to s).

An improved absolute frequency standard offers the opportunity of improved tests of relativity like Kennedy-Thorndike experiments or tests of local position invariance. By comparing a laser stabilized to an optical resonator and a laser stabilized to an atomic (or molecular) transition, the independency of the speed of light w.r.t. the speed of the laboratory system can be tested (KT experiment). In the best current test at optical frequencies, the speed variation of the Earth during its way around the sun was taken into consideration [16]. The most accurate KT-experiment measured the frequency difference between a cryogenic microwave oscillator and an H-maser, taking into account the variation in speed due to the Earth's rotation [17]. The local position invariance is tested by comparing two clocks which are based on different physical principles. The best test compared the frequencies of a Mg-frequency standard and a Cs-frequency standard over a time of 430 days [18]. The single test using an electronic transition was based on a comparison of an iodine stabilized system to a CORE stabilized system [16].

Further improvement is achieved with a spaceborne

version of these tests as proposed e.g. in the OPTIS or the SUMO mission.

7. SUMMARY

In this work we presented a compact setup of an iodine stabilized frequency-doubled Nd:YAG laser at a wavelength of 532 nm. By use of modulation transfer spectroscopy a resulting linewidth of ~ 1.9 MHz for the a_{10} component of the 1110 line is obtained. In this setup an active offset compensation method (OCAMS) was implemented resulting in a frequency stability of $4 \cdot 10^{-14}$ for integration times larger than 5000 s.

This frequency standard represents a compact setup of a highly frequency stable laser system, which in the future will be more compact and ruggedized w.r.t. a future space qualified iodine standard. Such space qualified laser systems are of interest for several future missions and also subject of investigation in other groups [19].

8. ACKNOWLEDGEMENTS

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