An Absolute Optical Frequency Reference Based on Doppler-Free Spectroscopy of Molecular Iodine Developed for Future Applications in Space

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We present the development of a high performance optical frequency reference using Doppler-free spectroscopy of molecular iodine near 532 nm. For future applications in space, special emphasis is put on compactness and robustness of the spectroscopy setup using a specific custom-made design of a multi-pass gas cell in combination with a dedicated assembly-integration technology.

1 Introduction

Optical frequency references are a key technology for a variety of future space missions dedicated to fundamental physics, Earth observation and navigation & ranging. Frequency stabilized lasers are e.g. needed as light source for high-sensitivity distance metrology between distant spacecraft. Example missions are the gravitational wave detector eLISA (Evolved Laser Interferometer Space Antenna) and missions dedicated to measure the Earth's gravitational field such as GRACE follow-on (Gravity Recovery and Climate Explorer) and NGGM (Next Generation Gravity Mission). Proposed missions such as mSTAR (mini Space-Time Asymmetry Research) and BOOST (BOOst Symmetry Test) will test Special Relativity by performing clock comparison experiments using optical frequency references.

Laser frequency stabilization to an atomic or molecular transition is a commonly applied technology providing an absolute frequency reference with excellent long-term stability.

2 Iodine-Based Frequency References

Fig. 1 shows a typical laboratory setup of an iodine based frequency reference using modulation transfer spectroscopy (MTS). A frequency doubled Nd:YAG solid state laser at a wavelength of 532 nm is used as input for the iodine spectroscopy. The setup includes intensity stabilization of pump and probe beams using acousto-optic modulators for intensity actuation and balanced detection for error signal generation [1].

Based on the laboratory frequency reference, two modular fiber coupled setups on elegant breadboard (EBB) and engineering model (EM) level were realized, taking into account specific design criteria for space compatibility such as compactness and robustness. They use a baseplate made of glass material in combination with a dedicated easy-to-handle assembly-integration technology for the optical components (adhesive bonding using a space-qualified two component epoxy) ensuring high pointing stability of the two counter-propagating laser beams in the iodine cell and therefore high long-term stability [2].

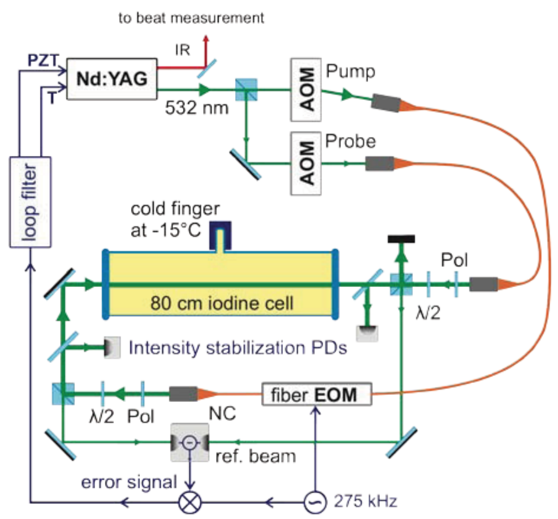

Fig. 1 *Schematic of the laboratory setup (HU Berlin): modulation transfer spectroscopy using a frequency-doubled Nd:YAG laser near 532 nm [1].*

The EBB spectroscopy setup is shown in Fig. 2. It utilizes a baseplate made of OHARA Clearceram-Z HS glass-ceramic with a coefficient of thermal expansion (CTE) of $2*10^{-8}$ K^{-1} and a commercial off-the-shelf 30 cm long iodine cell in triple-pass configuration. The mechanical mounts are made of Invar in order to minimize CTE mismatch with the baseplate for enhanced thermal stability.

The EM setup was further developed with respect to compactness and uses a specifically designed and manufactured compact iodine cell made of fused silica in a nine-pass configuration with a specific robust cold finger design (see Fig. 3).

Both setups were characterized in beat measurements with a ULE cavity setup. Similar frequency stabilities 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 were demonstrated. These values are comparable to the currently best laboratory setups [1],[3].

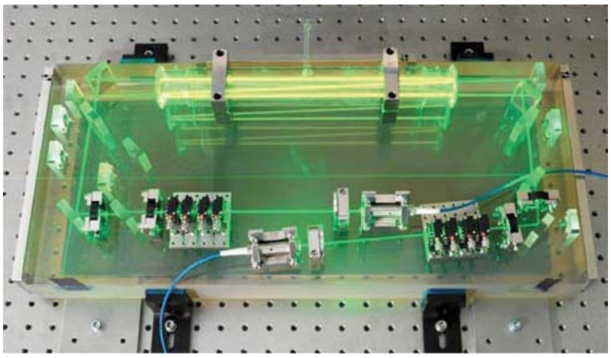

Fig. 2 *Photograph of the iodine spectroscopy unit on elegant breadboard level. This setup utilizes a commercial 30 cm long iodine cell in triple pass configuration. The baseplate is made of Clearceram-HS with dimensions of 550 x 250 x 50 mm^3.*

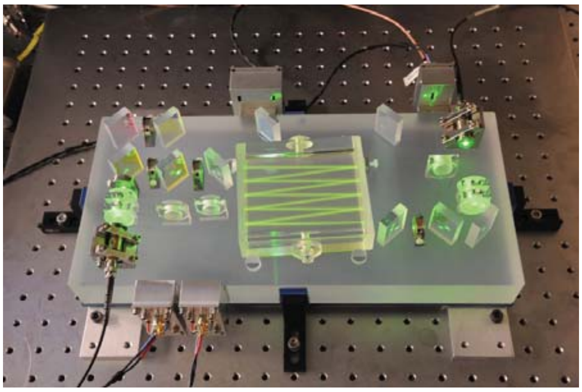

Fig. 3 *Photograph of the iodine spectroscopy unit on engineering model level utilizing a compact multipass gas cell in nine pass configuration. The optics are joint to a 380 x 180 x 40 mm^3 baseplate made of fused silica.*

The EM 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.

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