# A Compact High-Performance Frequency Reference for Space Applications

By Thilo SCHULDT[1),2)], Klaus DÖRINGSHOFF[3)], Johannes STÜHLER[1)], Evgeny KOVALCHUK[3)], Matthias FRANZ[1)], Martin GOHLKE[2)], Dennis WEISE[4)], Ulrich JOHANN[4)], Achim PETERS[3)], and Claus BRAXMAIER[2),5)]

[1)]*University of Applied Sciences Konstanz, Konstanz, Germany*
[2)]*DLR Institute of Space Systems, Bremen, Germany*
[3)]*Humboldt-University Berlin, Berlin, Germany*
[4)]*Astrium GmbH – Satellites, Friedrichshafen, Germany*
[5)]*University of Bremen, Center of Applied Space Technology and Microgravity, Bremen, Germany*

We present the development of a space-compatible laser frequency stabilization to a hyperfine transition in molecular iodine with a frequency stability in the $10^{-15}$ domain at longer integration times. A setup on elegant breadboard (EBB) level was successfully implemented and verified. Using modulation-transfer spectroscopy, a frequency stability of $4\cdot10^{-15}$ at an integration time of 1.000 s was demonstrated in a beat measurement with a laboratory ULE cavity setup. The spectroscopy setup is realized using a 550mm x 250mm x 50mm baseplate made of a thermally highly stable glass ceramics in combination with adhesive bonding technology for integration of the optical components. The EBB setup is the basis for a setup on engineering model (EM) level that is currently developed using the same assembly-integration technology. A compact design of the EM setup is achieved using a compact multi-pass gas cell.

**Key Words:** Optical Frequency Reference, Iodine Frequency Reference, Modulation Transfer Spectroscopy, Optical Metrology, Tests of Fundamental Physics

## 1. Introduction

Future space missions related to fundamental science, geoscience, Earth observation, navigation and ranging require ultra-stable frequency references, especially in the optical domain. Examples are the gravitational wave detectors LISA/eLISA/NGO (Laser Interferometer Space Antenna, New Gravitational Wave Observatory), the aperture-synthesis telescope Darwin, the GRACE (Gravity Recovery and Climate Experiment) follow on mission exploring Earth's gravity, and missions dedicated to test special relativity by performing clock-to-clock comparison experiments.

Lasers stabilized to atomic or molecular transitions are preferred as they offer an absolute frequency reference with high long-term frequency stability. 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.

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)[3-7)] and are also developed in compact setups[8-9)] and for space applications[10-13)]. Theses setups typically use as light source a Nd:YAG laser at a fundamental wavelength of 1064 nm which is also available in a space qualified version (by Tesat-Spacecom GmbH).

In this paper we report on the realization of ultra-stable optical frequency references (on elegant breadboard (EBB) and engineering model (EM) level) for applications in space. They utilize modulation-transfer spectroscopy of molecular iodine near 532 nm. With the goal of a space qualifiable frequency reference, a compact and ruggedized setup was realized using a baseplate made of Clearceram-HS®, a glass ceramics with an ultra-low coefficient of thermal expansion of $2\cdot10^{-8}$ $K^{-1}$. 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, MAIVT and robustness with respect to shock, vibration and thermal stress. It utilizes a 30 cm long iodine cell in triple-pass configuration. With this setup a frequency stability of $7\cdot10^{-15}$ at an integration time of 1 s and below $5\cdot10^{-15}$ at integration times between 10 s and 5.000 s, was demonstrated in a beat measurement with a ULE cavity setup (after subtraction of a $2^{nd}$ order polynomial). This frequency stability is similar to the one of current state-of-the-art laboratory iodine-based frequency references.

In a current activity, the setup is further developed with respect to mechanical and thermal stability as well as compactness. This setup utilizes a very compact multi-pass gas cell and will undergo environmental testing, including vibration tests and thermal cycling.

## 2. Iodine-Based Frequency References

A state-of-the-art laboratory setup of an iodine-based frequency reference was developed at the Humboldt-University Berlin (HUB) over the last years[7)]. As light source, a non-planar ring-oscillator (NPRO) type Nd:YAG laser with a wavelength of 1064 nm, frequency-doubled to 532 nm, is used (model 'Prometheus' by InnoLight GmbH). The schematic of the setup using modulation-transfer spectroscopy (MTS) is shown in Fig. 1. The laser output beam is split into pump and probe and both beams are passing AOMs which are used for intensity stabilization. Also, the pump beam is shifted in frequency by 80 MHz. Pump and probe beams are fiber coupled and sent to the spectroscopy unit. A fiber electrooptic modulator (EOM, by Jenoptik GmbH) is used for phase modulation of the pump beam at a frequency of 275 kHz. An 80 cm long iodine cell (provided by ISI Brno, Czech Republic) is used in single-pass configuration. After fiber outcoupling, part of each beam is sent to a monitoring photo diode used for intensity stabilization. For error signal generation, balanced detection is implemented where part of the probe beam, split off before the iodine cell, is used as reference beam. The mixed down error signal is input to a servo control loop actuating the laser frequency via the temperature of the laser crystal (slow actuation) and a PZT mounted to the laser crystal (fast actuation).

With this setup, a frequency stability of $3\cdot10^{-15}$ at integration times between 100 s and 10.000 s was achieved, cf. Fig. 2. The beat measurement was carried out by comparing the iodine setup to a reference ULE cavity setup. It is assumed that the stability of the iodine setup is limited by residual amplitude modulation (RAM) effects at these longer integration times. Also, a measurement using the AOM in the pump beam for phase modulation was performed (cf. Fig. 2). Due to enhanced signal-to-noise ratio (due to higher laser power), the short-term stability was improved. The long-term stability slightly decreased, most probably caused by additional AOM RAM effects.

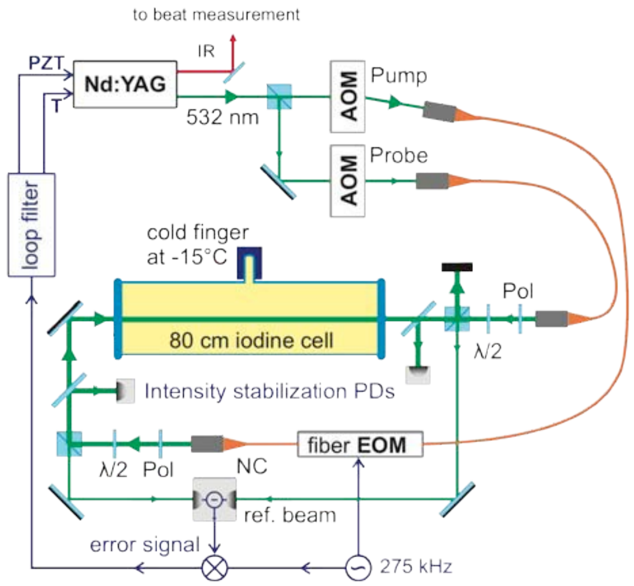


Fig. 1. Schematic of the laboratory setup of an iodine-based frequency reference using modulation transfer spectroscopy and an 80 cm long iodine cell[14].

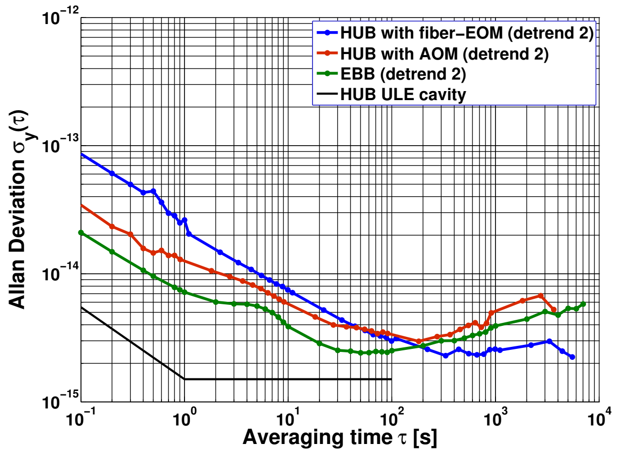


Fig. 2. Frequency stability of different iodine-based frequency references (given in root Allan deviation). Shown are the stability curves for the EBB setup and the laboratory setup at HUB (with fiber-EOM and AOM modulation, respectively). A second order polynomial was subtracted from the beat note time record. Also shown is the stability of the ULE cavity setup at HUB used as reference for the iodine setups.

## 3. Assembly-Integration Technology

Important factors for operation of optical systems in space are design aspects such as compactness, rigidity and modularity. Also, all components (and the whole system) must fulfill mission specific requirements on vibration, shock and thermal cycling as well as radiation hardness. 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 $2\cdot10^{-8}\,K^{-1}$ 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/√Hz and nrad/√Hz sensitivity in translation and tilt measurement and was successfully subjected to environmental tests (thermal and vibration). 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[15]. For adhesive bonding, the settling (i.e. alignment)

time can be up to several hours (depending on the ambient temperature) and no cleanroom 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 collaboration with the Humboldt-University Berlin and the University of Applied Sciences Konstanz[17)], cf. Fig. 3. 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/√Hz in translation and below 10 nrad/√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 that is perpendicular to the bonding surface, ensuring a thin and homogenous bonding layer.

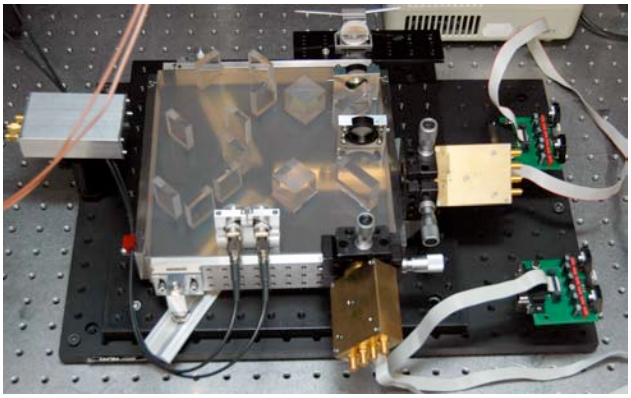

Fig. 3. Photograph of the integrated heterodyne interferometer using adhesive bonding technology. The baseplate is made of Zerodur with dimensions of 200mm x 200mm. For noise characterization, a single mirror acting as reference and measurement mirror was implemented (shown on top side of the photograph). Two quadrant photo detectors are used for tilt measurement.

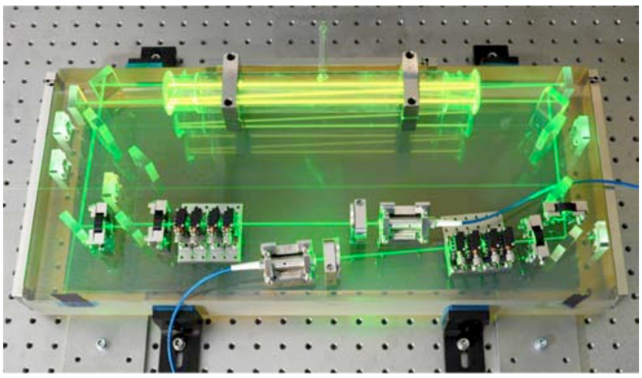

Fig. 4. Photograph of the spectroscopy unit realized on elegant breadboard level. The baseplate is made of Clearceram-HS with dimensions of 550mm x 250mm. The optical components are integrated using adhesive bonding technology[14)].

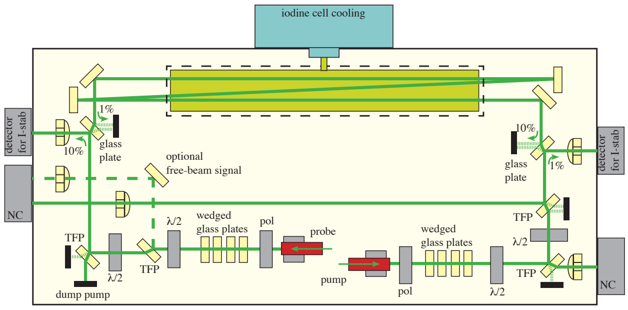


Fig. 5. Schematic of the EBB setup. The two laser beams for pump and probe are fibre-coupled to the spectroscopy board. Wedged glass plates are used for beam adjustment after integration. This setup uses a 30 cm long iodine cell in triple-pass configuration[14)].

## 4. Setup on Elegant Breadboard (EBB) 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 above, cf. Fig. 4 and Fig. 5. 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 550mm x 250mm x 50mm. Plates made of Invar are glued to the sides of the baseplate which are used for integration of 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 35mm x 25mm x 8mm 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 $10^{-6}$ $K^{-1}$. 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. Similar 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 focusing the beams onto the photo diodes. The lenses are bond to fused silica substrates that 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 beat measurement with a ULE cavity setup was performed, resulting in a frequency stability of $4 \cdot 10^{-15}$ at an integration time of 1.000 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 and a free-beam AOM, respectively.

### 5. Setup on Engineering Model (EM) Level

Based on the experience with the EBB setup, a more compact and ruggedized setup on engineering model (EM) level – with an aimed similar performance as the EBB – 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. The CAD model of the EM setup is shown in Fig. 6 and Fig. 7. The setup uses a baseplate made of fused silica with CTE matched optical components. The components are fixed to the baseplate using adhesive bonding technology using a space qualified two-component epoxy.

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 100mm x 100mm x 30mm fused silica spacer with wedged windows. The cell is designed for a nine-pass configuration (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.

The fiber launchers are adapted from the EBB design using commercial Schäfter+Kirchhoff collimators with a beam diameter of approximately 3mm. The collimator is using an Invar mount with shims for coarse adjustment of the beam output parameters. Risley pairs of two wedged glass plates are used for adjustment of the beam overlap in the gas cell. The corresponding mounts are made of fused silica. Waveplates and polarizers are mounted to holders made of titanium for CTE matching. The detection is similar to the EBB setup using noise cancelling detection for the spectroscopy signal. Also, pump and probe beam are stabilized in intensity in front of the gas cell using a beam sampler pick-up. After passing the cell, the pump beam is sent to a photodiode for power monitoring.

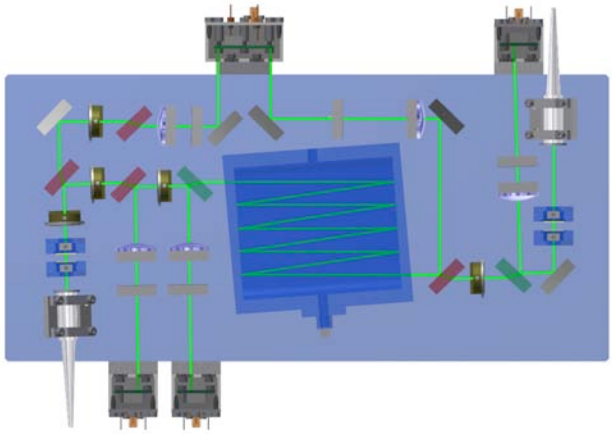

Fig. 6. Top view of the CAD model of the spectroscopy unit (engineering model level). The baseplate has dimensions of 380mm x 180mm x 40mm. The laser beam launched on the left side corresponds to the probe beam, the laser beam launched on the right side to the pump beam.

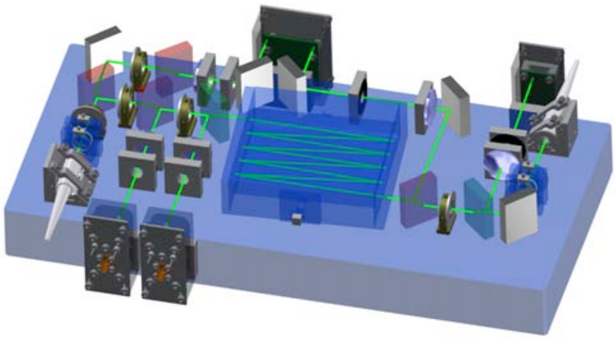

Fig. 7. 3D view of the CAD model of the EM setup. The electronics is mounted to the sides of the fused silica baseplate.

### 6. Conclusions

We presented the efforts carried out in order to realize a space compatible frequency reference based on molecular iodine. A setup on elegant breadboard level was successfully realized and its performance verified. A frequency stability of $4 \cdot 10^{-15}$ at an integration time of 1.000 s was demonstrated. Currently, a setup on engineering model level is being realized based on the experience with the EBB setup. The EM setup will undergo vibration tests and thermal cycling. As a result, a high-performance optical frequency reference with a frequency stability at the $10^{-15}$ level with a high technology readiness level (TRL) is available which can then be easily and with small effort further developed for specific applications in space.


## Acknowledgments

Financial support by the German Space Agency DLR with funds provided by the Federal Ministry of Economics and Technology (BMWi) under grant numbers 50QT1102 and 50QT1201 is highly appreciated. The authors thank Jozef Lazar and Jan Hrabina from the Institute of Scientific Instrument of the Academy of Sciences of the Czech Republic (Brno) and their colleagues from Meopta (Czech Republic) for many fruitful discussions on the realization of the multipass cell.


## References


1) Bjorklund, G.: Frequency-modulation spectroscopy: A new method for measuring weak absorptions and dispersions, Opt. Lett., vol. 5 (1980), no. 1, pp. 15–17.
2) Arie, A. and Byer, R.: Laser heterodyne spectroscopy of 127I2 hyperfine structure near 532 nm, J. Opt. Soc. Am. B, vol. 10 (1993), no. 11, pp. 1990–1997.
3) Shirley, J.: Modulation transfer process in optical heterodyne saturation spectroscopy, Opt. Lett., vol. 7 (1982), no. 11, pp. 537–539.
4) Ye, J., Robertsson, L., Picard, S., Ma, L.-S. and Hall, J. H.: Absolute frequency atlas of molecular I2 lines at 532nm, IEEE Transactions on Instrumentation and Measurement, vol. 48 (2008), pp. 544–549.
5) Ye, J., Ma, L.-S. and J. L. Hall: Molecular iodine clock, Phys. Rev. Letters, vol. 87 (2001), p. 270801.
6) Zang, E. J., Ciao, J. P., Li, C. Y., Deng, Y. K. and Gao, C. Q.: Realization of Four-Pass I2 Absorption Cell in 532-nm Optical Frequency Standard, IEEE Transactions on Instruments and Measurement, vol. 56 (2007), no. 2, pp. 673–676.
7) Döringshoff, K., Reggentin, M., Nagel, M., Kovalchuk, E., Keetman, A., Schuldt, T., Braxmaier, C. and Peters, A.: Iodine based optical frequency reference with $10^{-15}$ stability, Proceedings of the 26th European Frequency and Time Forum (2012), 2012.
8) Hong, F.-L., Ishikawa, J., Bi, Z.-Y., Zhang, J., Seta, K., Onae, A., Yoda, J. and Matsumoto, H.: Portable I2-Stabilized Nd:YAG Laser for International Comparisons, IEEE Trans. Instrum. Measur., vol. 50 (2001), no. 2, pp. 486–489.
9) Nyholm, K., Merimaa, M., Ahola, T. and Lassila, A.: Frequency stabilization of a diode-pumped Nd:YAG laser at 532 nm to iodine by using third-harmonic technique, IEEE Transactions on Instrumentation and Measurement, vol. 52 (2003), pp. 284–287.
10) Schuldt, T., Braxmaier, C., Müller, H., Huber, G., Peters, A. and Johann, U.: Frequency stabilized Nd:YAG laser for space applications, Proceedings of the 5th International Conference on Space Optics (ICSO 2004), ESA Publications, 2004, pp. 611–617.
11) Argence, B., Halloin, H., Jeannin, O., Prat, P., Turazza, O., de Vismes, E., Auger, G. and Plagnol, E.: Molecular laser stabilization at low frequencies for the LISA mission, Phys. Rev. D, vol. 81 (2010), p. 082002.
12) Acef, O., Clairon, A., Du Burck, F., Turazza, O., Djerroud, K., Holleville, D., Lours, M., Auger, G., Brillet, A. and Lemonde, P.: Nd:YAG Laser Frequency Stabilized for Space Applications, Proceedings of the International Conference on Space Optics, ICSO 2012, 2012.
13) Musha, M., Nakagawa, K. and Ueda, K.: Developments of the light source for DECIGO and DPF, Proceedings of the International Conference on Space Optical Systems and Applications, ICSOS 2011, 2011
14) Schuldt, T., Keetman, A., Döringshoff, K., Reggentin, M., Kovalchuk, E., Nagel, M., Gohlke, M., Johann, U., Weise, D., Peters, A. and Braxmaier, C.: An ultra-stable optical frequency reference for space applications, Proceedings of the 26th European Frequency and Time Forum, EFTF 2012, 2012.
15) Ellife, E. J., Bogenstahl, J., Deshpande, A., Hough, J., Killow, C., Reid S., Robertson, D., Rowan, S., Ward, H. and Cagnoli, G.: Hydroxide-catalysis bonding for stable optical systems for space, Class. Quantum Grav., vol. 22 (2005), pp. S257–S267.
16) Ressel, S., Gohlke, M., Rauen, D., Schuldt, T., Kronast, W., Mescheder, U., Johann, U., Weise, D. and Braxmaier, C.: Ultrastable assembly and integration technology for ground- and space-based optical systems, Appl. Opt., vol. 49 (2010), no. 22, pp. 4296–4303.
17) Schuldt, T., Gohlke, M., Kögel, H., Spannagel, R., Peters, A., Johann, U., Weise, D. and Braxmaier, C.: Picometre and nanoradian heterodyne interferometry and its application in dilatometry and surface metrology, Meas. Sci. Technol., vol. 23 (2012), p. 054008.