International Conference on Space Optics—ICSO 2008

Toulouse, France

14–17 October 2008

Molecular laser stabilization for LISA

Hubert Halloin

Ouali Acef

Berengere Argence

Olivier Jeannin

et al.

MOLECULAR LASER STABILIZATION FOR LISA

Hubert Halloin[(1)]**, Ouali Acef**[(2)]**, Bérengère Argence**[(1)]**, Olivier Jeannin**[(1)]**, Pierre Prat**[(1)]**,
Oscar Turazza**[(1)]**, Eden de Vismes**[(1)]**, Gérard Auger**[(1)]**, Eric Plagnol**[(1)]**, Alain Brillet**[(3)]
Linda Mondin[(4)]**, Jacques Berthon**[(4)]

[(1)] *APC, Université Paris 7 Denis Diderot, 10, rue Alice Domon et Léonie Duquet,
75025 Paris Cedex 13, France, hubert.halloin@apc.univ-paris7.fr*
[(2)] *SYRTE / Obs. de Paris, 61, avenue de l'Observatoire, 75014 Paris,*
[(3)] *ARTEMIS / Obs. de la côte d'Azur, Boulevard de l'Observatoire, 06304 Nice*
[(4)] *CNES, 18 Avenue Edouard Belin, 31401 Toulouse*

ABSTRACT

The expected performance of LISA relies on two main technical challenges: the ability for the spacecrafts to precisely follow the free-flying masses and the outstanding precision of the phase shift measurement. This latter constraint requires frequency stabilized lasers and efficient numerical algorithms to account for the redundant, delayed noise propagation, thus cancelling laser phase noise by many orders of magnitude (TDI methods). Recently involved in the technical developments for LISA, the goal of our team at APC (France) is to contribute on these two subjects: frequency reference for laser stabilization and benchtop simulation of the interferometer. In the present design of LISA, two stages of laser stabilization are used (not accounting for the "post-processed" TDI algorithm): laser pre-stabilization on a frequency reference and lock on the ultra stable distance between spacecrafts (arm-locking). While the foreseen (and deeply studied) laser reference consists of a Fabry-Perot cavity, other techniques may be suitable for LISA or future metrology missions. In particular, locking to a molecular reference (namely iodine in the case of the LISA Nd:YAG laser) is an interesting alternative. It offers the required performance with very good long-term stability (absolute frequency reference) though the reference can be slightly tuned to account for arm-locking. This technique is currently being investigated by our team and optimized for LISA (compactness, vacuum compatibility, ease of use and initialization, etc.). A collaboration with a French laboratory (the SYRTE) had been started aiming to study a second improved technique consisting in inserting the iodine cell in a Fabry-Perot cavity. Ongoing results and prospects to increase the performance of the system are presented in the present article.

1 INTRODUCTION

The LISA mission is a joint ESA-NASA spaceborne project, aiming at detecting gravitational waves in the frequency range $10^{-4} - 1$ Hz [1]. It consists of 3 spacecrafts in a nearly equilateral configuration orbiting around the sun, about 20 degrees behind the Earth.

The satellites are separated by 5×10^6 km, constantly following free-flying masses located at their center. On each spacecraft, two laser beams are emitted towards the other satellites, resulting in six laser links.

These interferometric measurements are used to precisely monitor the distance between the inertial masses and, hence, to detect the tiny variation due to the pass of a gravitational wave.

The goal of LISA is to detect gravitational deformation as small as $\Delta L/L \approx 7 \times 10^{-21}/\sqrt{Hz}$ (i.e 7 pm per million of km) around 5 mHz. Contrary to a classical Michelson interferometer, the optical signal is obtained from two different laser sources. As a consequence the beam phase noise does not vanish and the relative frequency stability of the lasers must be at the same level as the expected sensitivity ($\Delta L/L = \Delta\nu/\nu$). This requirement is far beyond any standard stabilization technique developed on ground and foreseeable for a future space mission.

Nevertheless, this stability can be achieved for LISA thanks to three successive stabilization stages :

1. **Pre-stabilization** : Even with TDI and arm-locking (see below), the light emitted by the laser sources need to be very stable, at the level of 10^{-13} relative frequency change. Up to now, pre-stabilization on a Fabry-Perot cavity has been considered [2]. The work presented here aims at proposing an alternate technique, based on molecular spectroscopy.

2. **Arm-locking [3, 4, 5]** : In the interesting frequency

range of LISA ($10^{-4} - 1$ Hz), the distance between the free-falling masses is very stable. Consequently, it can be used as a length (i.e. frequency) reference. This technique requires the frequency reference of the pre-stabilization to be slightly tunable.

3. **Time Delay Interferometry [6]** : While each optical signals is the combination of two laser sources, the frequency noise of each source is also propagating on two laser links. Thus, by correctly combining the interferometric signals, taking into account the propagation delays (around 16 s between two spacecrafts), it is possible to cancel the laser noises (and, so, recover a 'Michelson-like' signal). However, due to the finite precision of the time stamps (drifts of the ultra stable clocks), this method is not perfect and the noise reduction factor is of the order of 10^8.

2 IODINE STABILIZATION FOR LISA

As mentioned above, the pre-stabilization technique considered for LISA is based on a fixed-length, ultra stable optical resonator. This technique proved to meet the LISA requirement in terms of intrinsic frequency stability [2] by means of the well-known Pound-Drever-Hall stabilization method. Its tunability had been recently demonstrated using an additional electro-optic modulator and side band locking.

Nevertheless, some limitations can be identified for this technique. First, the performance of the FP cavity is very sensitive to mechanical and mainly thermal disturbance. For example, the thermal stability of the tanks housing the cavities must of the order of 10 μK/$\sqrt{\text{Hz}}$ at 1 mHz. On very long time ranges (days), they can even exhibit frequency drifts of many MHz. Additionally, they do not provide an absolute frequency reference. When locking to a single FP cavity, the laser frequency is known *modulo the free spectral range*. Consequently, at the initialization stage of the interferometer, two lasers locked on different cavities are likely to beat at a frequency out of the range of the photodiode (typ. 100 MHz). It will therefore be necessary to scan the frequency of one of the systems to get the correct locking point. Finally, the performance of arm-locking algorithm can be increased with the precise knowledge of the Doppler frequency shift (consequence of the relative drift of one spacecraft w.r.t another one). Without an absolute reference on board, this measurement requires the knowledge of the beat frequencies for all the six links and, hence, must be post-processed and send back to the spacecrafts locking systems.

Locking to a molecular transition (hyperfine resonance line) can circumvent these issues. It offers an absolute frequency reference. The knowledge of the Doppler shift is therefore directly measured from the beat frequency. With a reasonably simple setup, the repeatability of the locking frequency has a long term drift of about a few kHz or less. Therefore, a beat frequency well within the detector bandwidth will immediately be obtained while mixing two molecular stabilized lasers. The position of a molecular transition is also much less sensitive to thermal perturbations than an cavity, the constraints being typically relaxed by about 3 order of magnitudes.

LISA makes use of Nd:YAG, NPRO lasers, known for their good intrinsic power and frequency stability. Unfortunately, there is no known strong molecular resonance around their wavelength of 1064 nm. However, iodine provides strong, narrow hyperfine transitions around 532 nm (2nd harmonic of Nd:YAG laser), that are often used on ground as frequency or length reference (e.g. see [7]). Previous experiments using iodine stabilization for LISA have already been done [8, 9] and showed promising results.

The goal of our experiment is to demonstrate that this technique can be used for space applications (i.e. robust, simple and compact) and meet the LISA requirements of $30 \times \sqrt{1 + (3 \cdot 10^{-3}/f)^4}$ Hz/$\sqrt{\text{Hz}}$. The frequency reference should also be slightly tunable to comply with the arm-locking stabilization.

3 EXPERIMENT AT THE APC

3.1 General layout

Resonance transitions are usually broadened by the Doppler effect due to the thermal movements of the molecules. In order to get rid of this effect and lock on an hyperfine (roto-vibrational) line, two beams counter propagates within the iodine cell. One of this beam (the pump) is strong enough to 'saturate' the line (i.e. a large part of the molecules on its path are in a excited state). The other beam (the probe), of much weaker intensity, is used to scan the absorption profile. The molecules that have already been excited by the pump beam cannot absorb the probe and then cause a dip in the absorption profile [10]. The two beams being of the same wavelength (or shifted by a constant value, see below), only molecules with a given velocity (projected on the light path) are simultaneously saturated by the pump and scanned by the probe beams. This technique is a standard method of Doppler-free spectroscopy and is used in our experiment.

The general layout of the experiment is shown on fig. 1. Since there is no better frequency reference available in the laboratory, two identical systems have to be built, and their joint performance (i.e. the stability of the beat between the two infrared beams) measured.

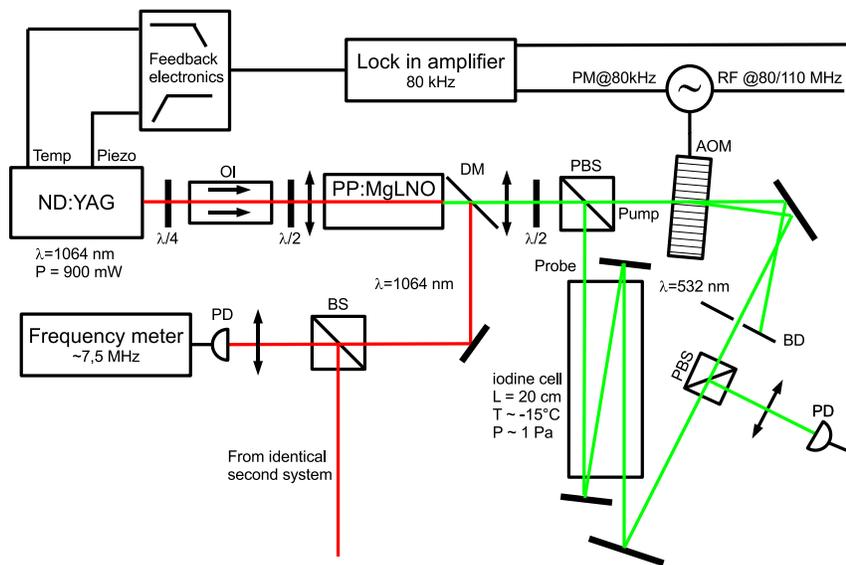About 900 mW of infrared light is emitted from the

Figure 1: Experimental layout of the iodine laser stabilization.

laser source (Innolight Mephisto 1000). Its frequency is then doubled by passing through a non-linear crystal of PP:MgLNO ($3 \times 0.5 \times 20$ mm). This material had been chosen because of its good efficiency and it can stand high power density and space radiations [9]. These crystals are put in a oven and their temperature stabilized at 64.9 °C (system 1, 66.2 °C for system 2).

For an input power of about 830 mW, about 10 mW of green light (at 532 nm) is produced. A dichroic mirror is then used to separate the two wavelength. The frequency noise of the beat between the infrared parts of the two systems is then assumed to be the sum of the frequency noises (quadratic sum) of each of them.

The green beam is divided into a pump (about 5 mW) beam and a probe (about 0.5 mW) beam. The method used here is the modulation transfer spectroscopy (MTS), which already demonstrated very good results on similar experiments [11]. The pump beam is frequency shifted and modulated by an acousto-optic modulator. The modulation frequency is at 80 kHz with a constant frequency shift of 80 and 110 MHz. As the central frequency of the probe beam differs from the one of the pump beam, the position of the locking position is translated by half of the offset (i.e. 40 and 55 MHz). Since the carrier frequency of an AOM can be tuned up to about 20 % of its central value, the locked frequency could be tuned to accommodate the arm-locking requirements.

By four waves mixing [12], the modulation is transfered on the probe beam. The carrier-side bands interference produce a beat on the probe beam whose amplitude is roughly proportional to the derivative of line profile

and can then be used as an error signal for the feedback electronics. One of the main advantages of the MTS technique is that it is insensitive, at first order, to the residual amplitude noise of the pump (as long as it 'saturates' the molecules) that could be induced by the modulation process.

We chose to lock on the a_{10} R(56)-32-0 line [13], which is intrinsically narrow and sufficiently isolated from other lines. The iodine cells are 20 cm long, 25 mm in diameter and have been provided by the BIPM (Bureau International des Poids et Mesures). The beam is folded three times in the cell, increasing the effective interaction length to 60 cm. T he cold finger of the cell is stabilized at a temperature of -15.1 °C (-15.7 °C) with a precision better than $\pm\, 0.01$°C (see section 3.2.2). The iodine pressure is then regulated at 0.75 Pa (0.80 Pa) [14].

After demodulation with a lock-in amplifier, the error signal is fed through the feedback electronics, acting on the temperature and piezo-electric actuator of the laser crystal. The temperature is used for correction on long timescales (corner frequency at about 70 mHz). The piezo-electric actuator handles higher frequencies, up to about 1 kHz.

3.2 Results

3.2.1 Frequency stability

Assuming that the two stabilization setups have the same performance, the power spectrum of the infrared beat is twice the power spectrum of one system. The linear spectral density for a single laser is plotted on fig. 2.
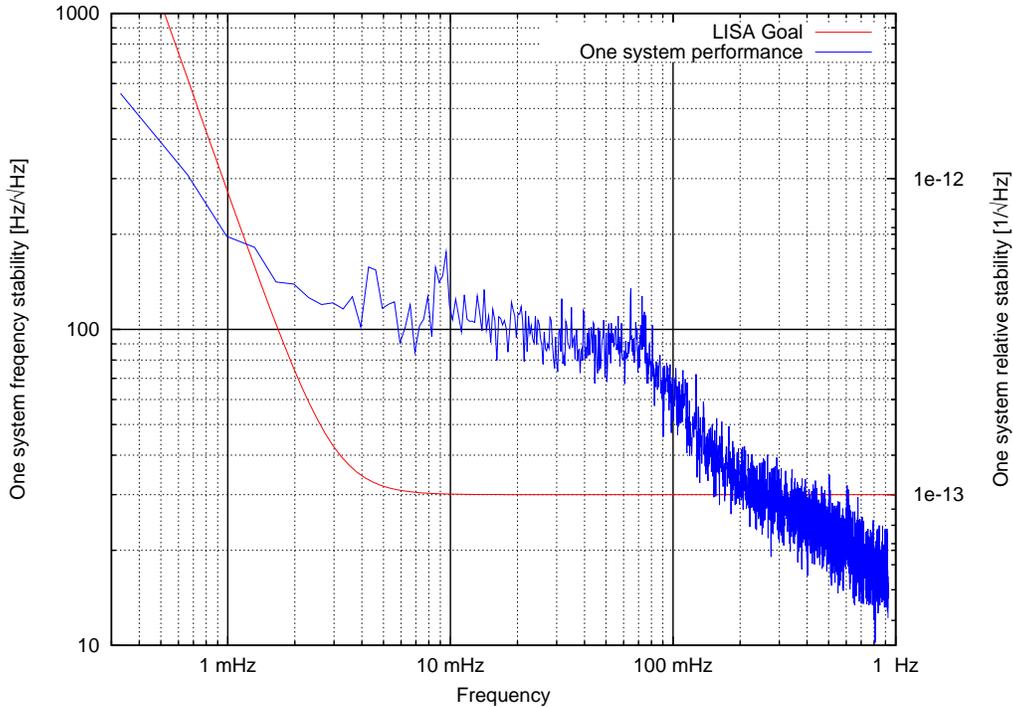
Figure 2: Frequency stability of one system.

Above 70 mHz, the frequency noise falls as $1/f^{0.5}$ ($1/f$ in terms of power), being at the level of about 15 Hz/$\sqrt{\text{Hz}}$ at 1 Hz. Between 2 and 70 mHz, the spectrum is roughly flat, around 100 Hz/$\sqrt{\text{Hz}}$. The corner frequency at 70 mHz coincides with the thermal feedback loop, leading to suspect a noisy link or a too low thermal gain. The nature of this plateau is currently being investigated. At lower frequency, the frequency amplitude noise rises as $1/f$ (frequency random walk).

This setup already demonstrates good frequency stability, although about 3 times worse than the most conservative stability requirements for LISA. Taking advantages of the improved arm-locking techniques, the present stabilization is nevertheless an possible alternative to the FP cavity foreseen for LISA.

Fig. 3 gives a typical time evolution of the beat frequency. The measured drift is of the order of 300 Hz over 9 hours.

3.2.2   Temperature stability of the elements

In the mHz region, one of the most prominent disturbance is due to thermal fluctuations. Two components requires a dedicated, efficient thermal control : the cold finger of the iodine cell and the doubling crystal.

Within the cell, the vapor is in equilibrium with a solid grain of iodine, i.e. its pressure is equal to the normal vapor pressure of iodine, only depending on the temperature of solid iodine. These 'saturated' cells are used to com-
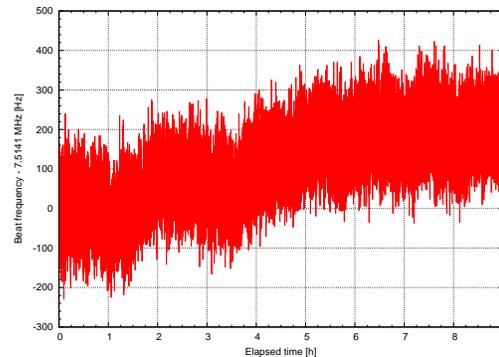

Figure 3: Typical time evolution of the beat frequency.

pensate any loss of iodine vapor within the cell (e.g. due to adsorption on the glass). Therefore, the temperature of the cold finger must be tightly controlled. The linear variation of pressure as a function of temperature [14] is about 0.09 Pa/K at -15°C. In addition to the modification of linear absorption within the cell, a pressure change induces a shift of the position of the transition line ; typical values of 3 kHz/Pa have been reported [11, 7]. Finally, we can estimate a shift of 278 Hz/K due to temperature fluctuations of the cold finger, our goal of 30 Hz/$\sqrt{\text{HZ}}$ meaning a stabilisation better than 0.1 K/$\sqrt{\text{Hz}}$. Fig. 4 (blue curve) shows a typical temperature density spectrum of the cold finger : the thermal stability is limited by

the instrument resolution above 100 mHz (1 mK/$\sqrt{\text{Hz}}$), and below 0.02 K/$\sqrt{\text{Hz}}$ at 1 mHz and below.
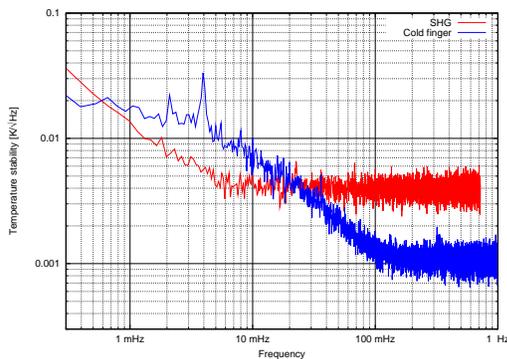

Figure 4: Temperature stabilities of the cell cold finger and doubling crystal (improved feedback electronics).

As explained in the next section, a good thermal stability was also needed for the non linear crystals. Fig. 4 (red curve) shows the typical achieved stability, almost limited by the instrument resolution.

3.2.3 Effect of the doubling crystal on the frequency stability

The second harmonic generation (frequency doubling) is achieved by passing through a PP:MgLNO (non-linear) crystal. The (quasi-)phase matching requires a constant temperature of the crystal in order to match the length of the periodically poled regions with the laser wavelength. The doubling efficiency curve (as a function of temperature) peaks at the phase-matching temperature, with a width of a few tenths of degrees. Any temperature fluctuation, will therefore induce intensity fluctuations of the pump and probe beams. The reference frequency of our system was found to be sensitive to these power perturbations. Very different shifts (suggesting a role of the wavefront curvature) have already been reported in the literature, up to 2 kHz/mW [11]. Consequently, the temperature of the doubling crystals must be stabilized, at the optimum efficiency temperature, in order to minimize the influence of crystal temperature on the frequency stability.

We first used a commercial temperature controller for the crystal oven. Unfortunately, strong temperature fluctuations, correlated with power stability of the green beam have been measured (see fig. 5). A dedicated temperature controller was then developed, whose performance are shown on fig. 4. With this improved controller, no effect of the fluctuations of the doubling crystal temperature could be measured on the frequency stability of the laser.
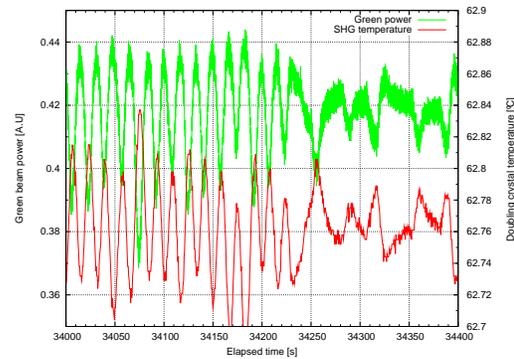

Figure 5: Time evolutions of green beam power and doubling crystal temperature.

4 FUTURE DEVELOPMENT : IODINE CELL IN A FP CAVITY

The best, long term, stabilization performance obtained with iodine, are of the order of a few 10^{-14} of relative frequency stability, but required very long interaction length [11, 15]. These systems are also quite sensitive to alignment and residual intensity noise (e.g. coming from fluctuations of the doubling efficiency). However, in order to be attractive for space application, any system would have to be compact and robust.

Consequently, with collaborators from SYRTE (Obs. de Paris) and ARTEMIS (Obs. de la Côte d'Azur), we are currently designing a new stabilization technique based on iodine in a low finesse resonant cavity. Using a Fabry-Perot cavity increases the effective interaction length, while the geometry and curvature of the beams are fixed. This technique has already been used at others wavelength (and molecules) and demonstrated very good stability results [16, 17].

Experimentally, enclosing a molecular reference inside a Fabry-Perot cavity, seems to have been first demonstrated by Brillet et al. in the early 80's [18]. Its possible application to gravity space missions was also underlined by Bender et al. [19].

Fig. 6 gives the general layout of the foreseen experimental setup. The whole system (excluding the laser source) will fit in a 30×50 cm^2 box.

As in the 'standard' experiment, the laser source is an Nd:YAG laser emitting at 1064 nm. The beam is then frequency doubled by passing through a non linear, PP:MgLNO crystal. The first AOM (acousto-optic modulator) is used to stabilize the intensity of the green beam. It can also be used to offset the reference frequency (of the green beam w.r.t the infrared one), and therefore is compatible with a slight tuning of the stabilization frequency, as needed by the arm-locking technique.
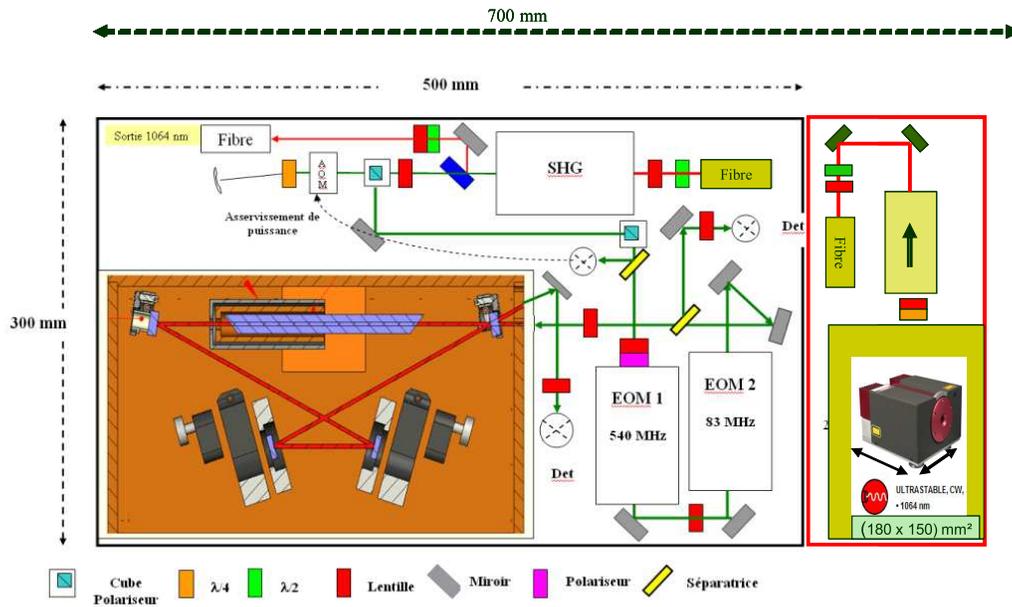
Figure 6: Experimental layout of the laser stabilization with iodine in cavity.

The core of the system is based on a 10 cm long iodine cell (12 mm in diameter), with windows at Brewster angle to minimize losses. The cold finger of the cell will be maintained at -18°C (± 1 mK), for which the width of the iodine line is estimated to be about 500 kHz. The cell will also be magnetically and thermally shielded and put into a small vacuum chamber (20×30 cm). The iodine is enclosed in a resonant cavity. The iodine absorption drives the losses of the cavity and consequently its low finesse (34).

Two modulation stages of the pump are needed : one used to stabilize the laser frequency, the other one to control the length of the cavity.

The first EOM (electro-optic modulator) has a modulation frequency equal to the free spectral rage of the cavity (540 MHz), according to the NICE-OHMS (Noise Immune Cavity-Enhanced Optical Heterodyne Modulation Spectroscopy) technique [17]. In that way, both the carrier and the side bands are transmitted by the cavity and their beat signal is used for frequency stabilization of the source.

The second EOM provides a modulation at 80 MHz. The length of the cavity is then tuned so that it is resonant with the laser frequency, according to the Pound-Drever-Hall technique [20].

According to previous experiments and our own calculation, the achievable frequency stability could be as low as 2 Hz/$\sqrt{\text{Hz}}$, i.e. one order of magnitude better than LISA requirements between 10^{-3} and 1 Hz. Such a performance, would greatly relax the constraints on second stage stabilization techniques, such as arm-locking and

TDI (Time Delay Interferometry).

5 CONCLUSION

Iodine laser stabilization had been investigated in the context of LISA. The standard stabilization scheme does not yet meet the most stringent requirements for LISA (30 Hz/$\sqrt{\text{Hz}}$) but the achieved performance (less than 150 Hz/$\sqrt{\text{Hz}}$ above 3 mHz) would be enough with the foreseen, improved versions of arm-locking and TDI.

Nevertheless, it would be of great interest to relax the constraints of the second and third stages of stabilization and rely on a single, excellent absolute frequency reference. For this reason, our team developed a new concept of stabilization based on a iodine cell within a low finesse cavity. This setup, expected to achieve stability of the order of 2 Hz/$\sqrt{\text{Hz}}$ above a few mHz, is currently being designed and built.

ACKNOWLEDGMENTS

References

[1] , Danzmann K., LISA Mission Overview, *Adv. Space Res.*, Vol. 25, 1129, 2000

[2] LISA Technology Status Report - DRAFT, *ESA-NASA*, Dec. 2006

[3] Sheard B.S. et al., Laser Frequency Stabilization by Locking to a LISA Arm, *Physics Letters A*, Vol. 320, 9, 2003.

[4] Tinto M. and Rakhmanov M., On the Laser Frequency Stabilization by Locking to a LISA Arm, *gr-qc/0408076v1*, Dec. 2007

[5] Sylvestre J., Simulations of Laser Locking to a LISA Arm, *Phys. Rev. D*, Vol. 70, 102002, 2004.

[6] Tinto M. et al., Implementation of Time-Delay Interferometry for LISA, *Phys. Rev. D*, Vol. 67, 122003, 2003.

[7] Picard S. et al., Results from International Comparisons at the BIPM Providing a World-Wide Reference Network of $^{127}I_2$ Stabilized Frequency-Doubled Nd:YAG Lasers, *IEEE Trans. on Instr. and Meas.*, Vol. 52, 236, 2003.

[8] Mondin L., Stabilisation de Fréquence de Laser Nd:YAG pour Applications Spatiales, *Thse de l'Universit de Nice-Sophia Antipolis*, 2005

[9] Leonhardt V. and Camp J.B., Space Interferometry Application of Laser Frequency Stabilization with Molecular Iodine, *Applied Optics*, Vol. 45, 4142, 2006.

[10] Demtröder W., *Laser Spectroscopy 3rd Ed.*, Springer-Verlag, Berlin Heidelberg, 2003

[11] Hall J.L. et al., Stabilization and Frequency Measurement of the I_2-Stabilized Nd:YAG Laser, *IEEE Trans. on Instr. and Meas.*, Vol. 48, 583, 1999.

[12] Raj R.K. et al., High-Frequency Optically Heterodyned Saturation Spectroscopy via Resonant Degenerate Four-Wave Mixing, *Physical Review Letters*, Vol. 44, 1251, 1980.

[13] Ye J. et al., Absolute Frequency Atlas of Molecular I_2 Lines at 532 nm, *IEEE Trans. on Instr. and Meas.*, Vol. 48, 544, 1999.

[14] Gillepsie L.J. and Fraser L.H.D., Normal Vapor Pressure of Crystalline Iodine, *Journal Of the American Chemical Society*, Vol. 58, 2260, 1936.

[15] Zang E.J. et al., Realization of Four-Pass I_2 Absorption Cell in 532-nm Optical Frequency Standard, *IEEE Trans. on Instr. and Meas.*, Vol. 56, 673, 2007.

[16] Clairon A. et al., State-of-the-Art for High Accuracy Frequency Standards in the 28 THz Range Using Saturated Absorption Resonances of OsO_4 and CO_2, *Frequency Standards and Metrology*, Ed. A. de March, Springer-Verlag, 212, Heidelberg 1989

[17] Sheng M.L. and Hall J.L., Optical Heterodyne Spectroscopy Enhanced by an External Cavity: Toward Improved Working Standards, *IEEE Journal of Quantum Electronics*, Vol. 26, 1990

[18] Brillet A. et al., Recent Work on 612 nm He-Ne Stabilized Lasers, *Precision Measurement and Fundamental Constants, Proceedings of the Second International Conference*, Ed. by B.N. Taylor and W.D. Philips, June 1981

[19] Bender P.L. et al., Satellite-Satellite Laserlinks for Future Gravity Missions, *Space Science Reviews*, Vol. 108, 377, 2002

[20] Drever R.W.P. et al., Laser Phase and Frequency Stabilization using an Optical Resonator, *Appl. Phys. B : Photophys. Laser Chem.*, Vol. 31, 97, 1983.