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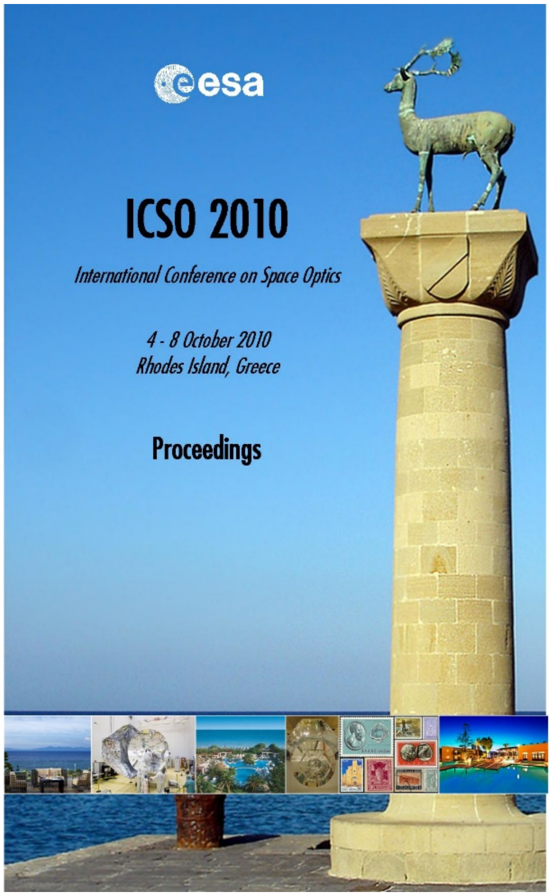

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Nd: YAG LASER FREQUENCY STABILIZED FOR SPACE APPLICATIONS

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I. INTRODUCTION

Nowadays, wide range of space missions including space interferometry laser, fundamental physic tests, ranging measurement, distance changes between space aircraft and optical communication with each other or with ground reference, etc … require powerful lasers in a compact set-up configuration with highly intrinsic frequency stability. The couple "frequency doubled Nd:YAG laser and iodine molecular transition" in the green range of the optical domain, is one of the most promising candidate with superior frequency stability for various applications. *LISA* (Laser Interferometer Space Antenna), DECIGO (DECI-Hertz Interferometer Gravitational wave Observatory), *STAR* (Space Time Asymmetry Research), Post-*GRACE* (Gravity Recovery and Climate Experiment) are few examples of space missions based on ultra stable laser use.

We report on our ongoing development of Nd:YAG stabilized laser using an original and reliable experimental configuration with expected frequency stability in the 10^{-15} range over thousands of seconds of integration time.

II. MOTIVATION OF THIS WORK

The iodine molecule exhibits dense absorption spectrum ranging from 900 nm to the dissociation limit of the molecule near 500 nm [1] and has been frequently used as frequency reference for laser spectroscopy and/or optical frequency metrology purposes [2]. For instance, the frequency doubled Nd:YAG laser stabilized on the hyperfine component a_{10} of the iodine transition R(56)32-0 at 532.245 nm is one of the most stable frequency standard thanks to the intrinsic laser phase noise associated to the high quality factor ($\sim 10^9$) of the iodine hyperfine line. The analysis of various experiments devoted to the Nd:YAG lasers frequency stabilization on iodine hyperfine line at 532 nm shows that the short term stability clearly increases with the interaction length of the laser beam with the iodine vapor [3,4]. A larger interaction length allows a lower pressure and lower optical power in the cell yielding in this way to a small linewidth. Then, the sensitivity to the experimental parameters is decreased opening the way to better long term frequency stability. To our knowledge, the best result in term of long term frequency stability of 4×10^{-15} over 10^4 s integration time is reported in [5] using 180 cm interaction length between Nd:YAG laser beams and iodine vapor.

For space applications, in addition to a high degree of frequency stability, the compactness and the reliability are essential features of the laser source. Instead of the use of long interaction length between the laser radiation and the iodine molecular vapor ("delicate use" in space mission), we propose to insert a very short iodine cell in a low finesse optical cavity (OC). This approach has been proposed in early 1970's by Cole [6], and demonstrated in 1980's by A. Brillet [7] and A. Clairon [8]. Frequency stabilities in the range 10^{-14}-10^{-16} have been demonstrated in the IR domain [9, 10]. Later, this approach has been extended for various atoms or molecules ([11-14] and references therein).

The finesse factor of the cavity allows a significant signal to noise ratio enhancement of the detected signals in a reduced volume. Moreover, the cavity provides a stable and well defined beam geometry which leads to strongly reduce the frequency stability limitations due to wave front curvature, second order Doppler effect, beam diameter fluctuations, … At last, the interaction with the fundamental mode of the optical cavity insures efficient stabilization of the intensity of the laser beams interacting with the molecular vapor.

It must be emphasized that molecular iodine gives the possibility to detect narrower lines in the 520 to 500 nm range, where the quality factor of the iodine lines are much higher [15].

For example, the natural width of the components of transitions P(13)43-0 and R(15)43-0 at 515 nm are in the range of 50 kHz to 150 kHz HWHM (Half Width Half Maximum) [16] and only few tens of kilohertz HWHM at 501 nm [17]. Frequency stabilized lasers for spatial applications could use these lines as frequency references. In particular, frequency doubled diode-pumped Yb:YAG lasers emitting at 515 nm are today available. Fiber laser sources around 500 nm are expected in near future.

Our stabilization set-up described below will give us the possibility to test these transitions for the realization of much more stable sources in near future, with no significant modifications.

III. EXPERIMENTAL SET-UP

The ratio of the experimental iodine linewidth ($\Delta\nu$) to the signal to noise ration (SNR) is the relevant parameter which minimizes the residual laser frequency instability. We use saturated absorption spectroscopy to achieve sub-Doppler detection of the resolved hyperfine structure of iodine line and we take particular care to optimize these two parameters ($\Delta\nu$/ SNR). In our case, the experimental iodine linewidth ($\Delta\nu \sim 500$ kHz, HWHM) is only twice the natural linewidth, using very low iodine vapor pressure (~ 0.7 Pa). The SNR is more than 10^4 (in 1 Hz bandwidth) thanks to the increase of interaction length using optical cavity around the short iodine cell.

The experimental set up (see Fig. 1) is based on the use of a short iodine cell (10 cm) inserted in a temperature regulated low finesse ring optical cavity (loaded finesse $\boldsymbol{F} \sim 35$). In this way, the equivalent interaction length iodine/laser beam is enhanced by ($2^*\boldsymbol{F}/\pi$) factor giving more than 2 m equivalent interrogation length.

This OC including the iodine cell inserted in thermal shield is placed inside a compact tank vacuum ($\sim 10^{-5}$ mbar). The total size of the tank is only 20 x 30 x 17 $cm^{3.}$ The whole optical set-up volume including the laser and all optical components is less than 0.1 m^3 (Fig. 1).

The side arm of the iodine cell is cooled down to -17°C, and temperature stabilized with residual fluctuations below 1mK over 10^4 s (Fig. 2a). In the same time, the temperature of the iodine cell body is also stabilized around + 5°C with the same performances than its sidearm.

The OC is based on two spherical mirrors and two flat mirrors with 55 cm of total optical length. The iodine cell is placed between the flat mirrors, centred at the larger waist of the cavity (diameter of 1-2 mm). The optical cavity length is stabilized to the laser frequency which is in turn locked to the iodine transition. We use two well known modulation/detection techniques for the frequency stabilization purpose: the Pound-Drever-Hall (PDH) [18] for the cavity frequency lock and the Noise-Immune Cavity-Enhanced Optical Heterodyne Molecular Spectroscopy [13] for the laser to iodine frequency lock. In this way, we overcome both intrinsic amplitude laser fluctuations and residual frequency to amplitude conversion by the OC.

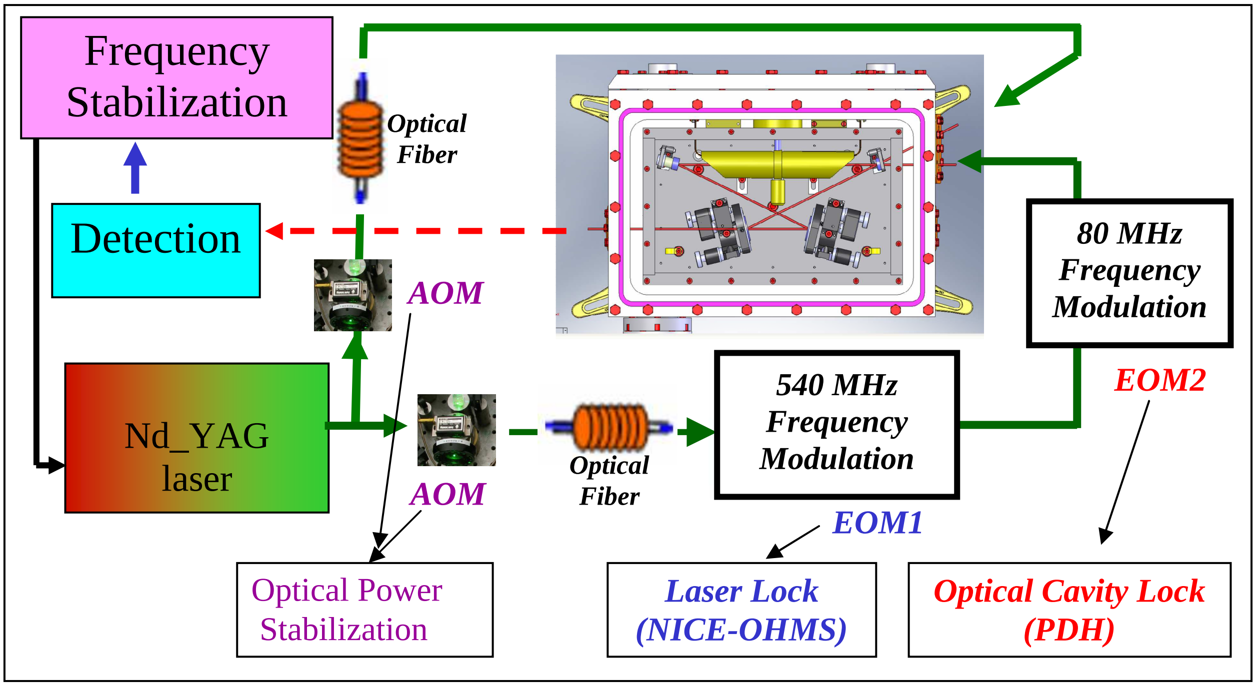

Fig. 1: Experimental set-up

Two independent frequency modulations are used via two separate electro optic modulators (EOM in Fig. 1). The EOM’s are temperature stabilized to reduce the residual amplitude modulation (RAM) which is well known to be a serious limitation to the long term frequency stability [5, 19].

We have already achieved 70 dB reduction of this RAM thanks to a severe control of the EOM’s temperature stability (< 0.1 mK). We estimate the contribution to the relative laser frequency instability below 10^{-15}.

On the other hand, the pump and probe beams cross two independent acousto-optic modulators (AOM in Fig. 1) for intensity stabilization before interrogating the iodine transition. The power stabilization is achieved within few parts in 10^{6} (Fig. 2b), reducing in this way iodine lights shift at level of 10^{-15} in terms of contribution to the relative frequency instability.

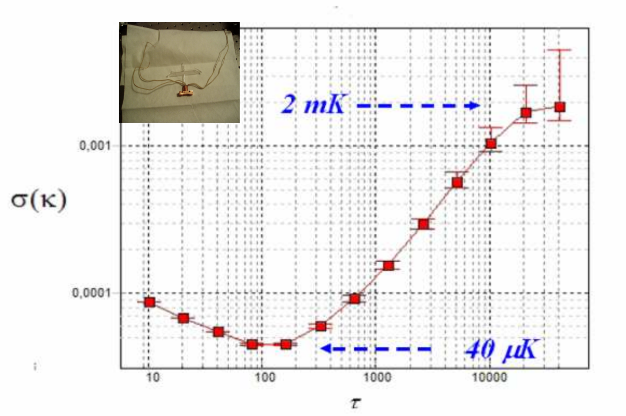

Fig. 2a: Temperature stabilization of the side arm of iodine cell.

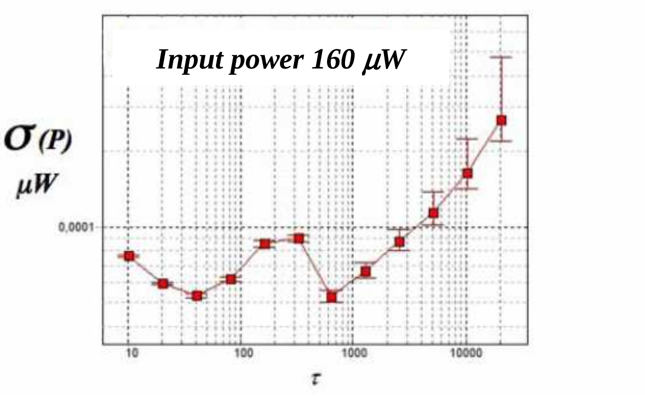

Fig. 2b: Laser power stabilization in the optical cavity

Fig. 3 reports the R(56) 32-0 hyperfine structure of the $^{127}I_2$ at 532, 245 nm, as obtained in our set-up. The peak contrast is impressive with values up to 10 % of the linear absorption depending on the chosen hyperfine component. The NICE-OHMS technique used in this project allows optical detection in the shot noise limited regime. Using the a_{10} hyperfine component for laser frequency stabilisation, we estimate the short term frequency stability at level of 10^{-14} @ 1s.

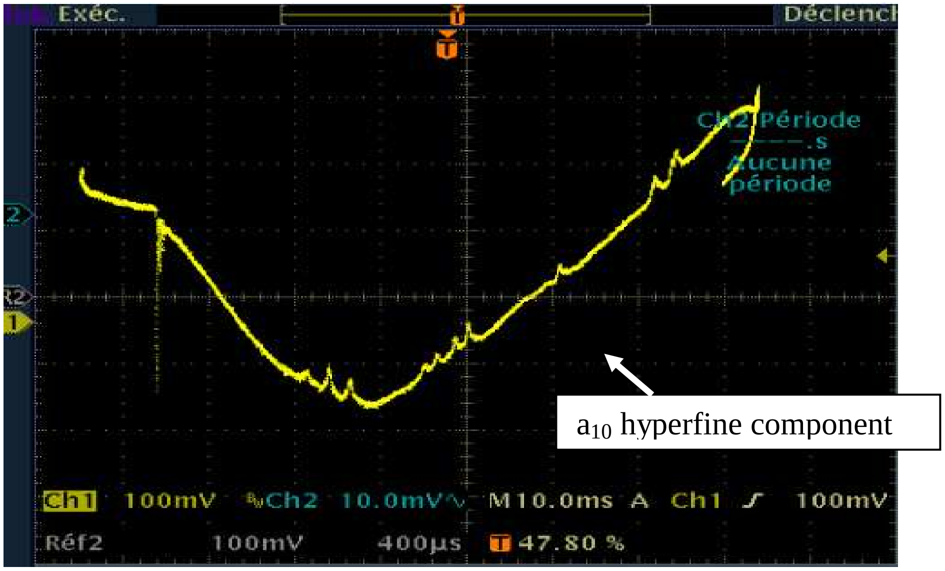

Fig. 3: R(56) 32-0 iodine hyperfine structure at 532.245 nm

This estimation is in good agreement with the measured SNR deduced from the relative intensity noise (RIN) versus Fourier frequency of the Nd:YAG laser when frequency locked on the a_{10} hyperfine component (Fig. 3), with a FFT spectrum analyser.
We plan to measure directly the frequency stability of our one-off project via a frequency comparison with a much more stable optical clock operating at SYRTE laboratory. For this purpose, we are developing a phase compensated optical fiber (150 m length) to connect our stabilized laser to optical atomic clocks located in a separate building.

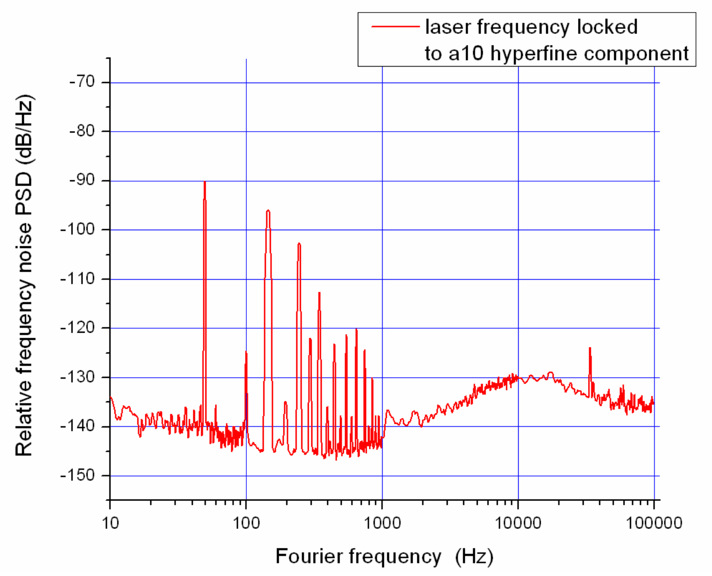

Fig. 4: Relative intensity noise measurement versus the Fourier frequency of the stabilized Nd:YAG laser to the a_{10} hyperfine component of $^{127}I_2$ at 532.245 nm.

From various developments of iodine stabilized Nd:YAG laser reported in [2, 5] and references therein, we have estimated the contribution of the major experimental parameters liable to limit the long term frequency stability to 1 x10^{-15} level in term of laser relative frequency noise.
These contributions are summarized in table 1.

	Laser power fluctuations	Cold finger Temperature stabilization	EOM temperature stabilization	Laser beams overlapping	RAM reduction	Residual magnetic field
Requirement	$< 10^{-3}$	< mK	~10 mK	~mRad	60 dB	~mG
This work	$< 10^{-5}$	< 0.1 mK	< 0.1 mK	Insured by the OC	70 dB	< 0.1 mG

Table1: Contributions of major experimental parameters to the long term frequency stability.

IV CONCLUSION

We have developed a compact experimental set-up devoted to stabilize Nd:YAG laser on iodine line at 532 nm which could fulfil several space missions requirements. Our preliminary measurements show potential short term frequency stability at level of 10^{-14} $\tau^{-1/2}$ expressed in terms of Allan variance. We have carefully investigated the contributions of the major parameters which influence the long term frequency stability (dependence with the laser power, the temperature, the iodine pressure fluctuations, the RAM, Zeeman effect, etc …). All contributions have been estimated at 10^{-15} level for the long term frequency instability.

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