Development of a Frequency Stabilized Nd: YAG Laser for Space Applications

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INTRODUCTION

Developments of compact, powerful and ultra stable lasers offer a significant opportunity to support a wide range of space applications, including space interferometry lasers (like the ***LISA*** mission), Fundamental Physics tests, ranging measurements in the optical domain, distance changes between spacecraft, optical communications with each other and/or with ground reference etc …

We are investigating the possibility of using a Nd: YAG laser frequency doubled and locked to a hyperfine iodine transition around 532 nm, in an original and reliable experimental configuration, for space applications. In order to insure both high short and long term frequency stability, we combine the use of an optical cavity for molecular absorption signal enhancement and high frequency modulation techniques to operate in the shot noise limited detection regime. The whole experimental optical setup volume, under development in our laboratory (demonstrator), occupies less than 0.1 m^3. The targeted frequency stability is $\leq 1 \times 10^{-14}\ \tau^{-1/2}$. We expect to maintain long term frequency stability in the 10^{-15} range over more than 10^4 s.

MOTIVATION OF THIS WORK

Iodine molecular lines exhibit a high quality factor in the visible range [1] and have been already used successfully to stabilize Nd: YAG lasers in the 10^{-15} range around 532 nm in early 1990's [2]. One particular hyperfine iodine component at 532.245 nm plays an important role in optical frequency metrology. Nd: YAG lasers stabilized on this iodine line is one of the most popular frequency standards, developed by several laboratories for the "*mise en pratique de la definition du mètre*" ([3] and references therein).

Various experimental setups have been developed during the two last decades with achieved frequency stabilities ranging from 10^{-12} to 10^{-15} levels depending on experimental setup complexity and/or motivation of the development. Nevertheless, the space application of these frequency standards was limited by the difficulty to insure compactness, reliability and high degree of frequency stability at the same time. The best results obtained in laboratories are based on long iodine cells (up to 120 cm), or by using multipass in shorter cells [3]. In this last case, optical alignment arrangements seem to be a serious limitation for the long term frequency stability.

We have synthesized on Fig. 1 the obtained short term stability (@ 1s) versus optical length in iodine cells (extract from [3]). The increase of the short term frequency stability depends on the interaction length with iodine vapour, in various configurations in terms of single or multipass in the cells.

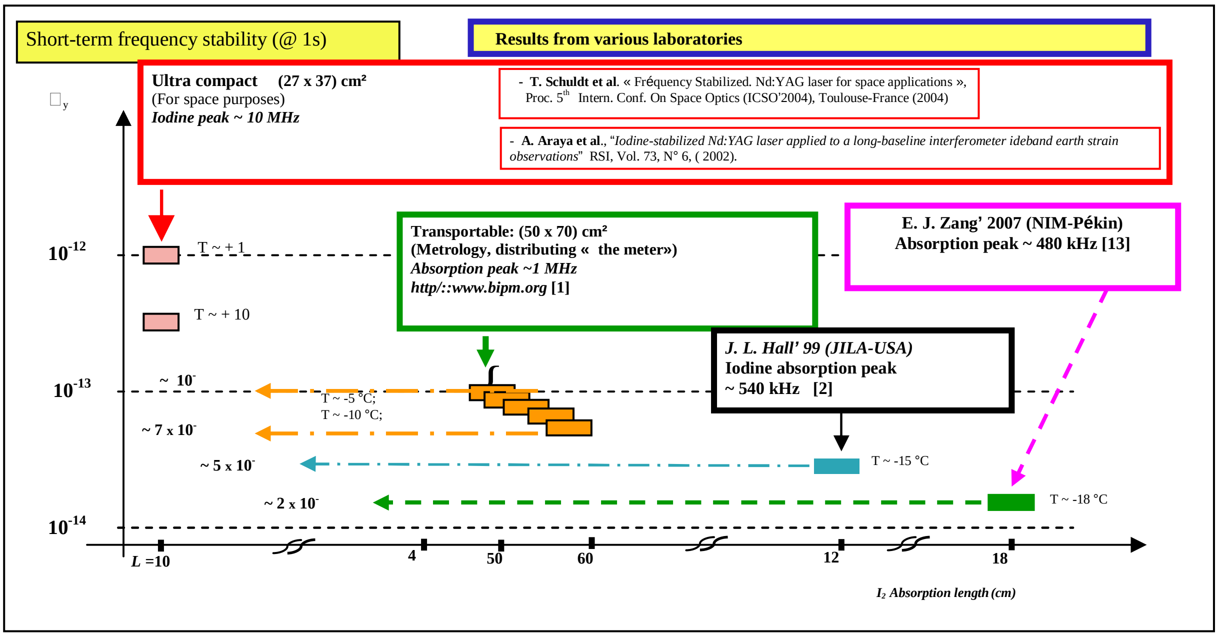

Fig. 1: Short term frequency stability (@ 1s)
versus optical interaction length in iodine cells (in cm) (from [3]).

The use of an optical cavity around a short cell was proposed in early 1970's by Cole [4], to achieve the best performances for the stabilized lasers. From our point of view, this is the best way to overcome the pitfall due to the use of a iodine cell in space. For ground applications, this approach has been first developed in early 1980's [5, 6], with successfully demonstrated frequency stability in the 10^{-14} to 10^{-16} range [6-8] in the infrared domain of the electromagnetic spectrum. Later, it has been extended to the visible domain for various atoms or molecular species (I_2 [9, 10], Rb [11], C_2H_2 [12] …).

The finesse factor of the optical cavity leads to a significant signal to noise ratio enhancement of the saturated signals. On the other hand, the cavity allows achievement of a well defined standing wave interacting with the molecular or atomic vapour. Thus, frequency stability limitations due the beam geometry are strongly reduced (wave front curvature, second order Doppler effect, beam diameter fluctuations etc…). Moreover, the interaction with the fundamental mode of the optical cavity insures the efficient stabilization of intensity of the beam interacting with the molecular vapour.

EXPERIMENTAL SETUP & RESULTS

The project under development at LNE-SYRTE laboratory in the frame of a scientific collaboration involving several laboratories is devoted to develop a compact and ultra stable laser for space applications. It is based on the use of a short iodine cell (10 cm) inserted in a temperature regulated low finesse ring optical cavity (loaded finesse ***F*** ~ 25), and cooled down to -17°C (sidearm of the cell). This approach yields a significant enhancement of the signal to noise ratio of the molecular saturated absorption signal and consequently the short term frequency stability [6]. The very compact optical setup, less than 0.1 m^3 demonstrates the capability and interest for space development. We take care to precisely control several physical parameters which influence the long term frequency stability (temperatures, optical powers, beam shape, residual amplitude modulation, Zeeman effect, etc …). Preliminary results recently obtained show the contribution to the long term frequency stability below $1x10^{-15}$.

High frequency modulation techniques, (NICE-OHMS [13] and Pound-Drever-Hall [14]), are used is our project for the frequency stabilization purpose of the laser and of the optical cavity (OC) respectively (Fig. 2). This approach allows reaching the shot noise limited detection regime. The probe beam is phase modulated simultaneously at 540 MHz and 80 MHz using two independent electro optic modulators (EOM) to achieve the Nd: YAG laser frequency stabilization. The OC is stabilized with respect to the laser frequency which is in turn locked to the hyperfine iodine transition. The 540 MHz frequency modulation is chosen equal to the free spectral range (FSR) of the optical cavity (L_{OC} ~ 0.5 m).

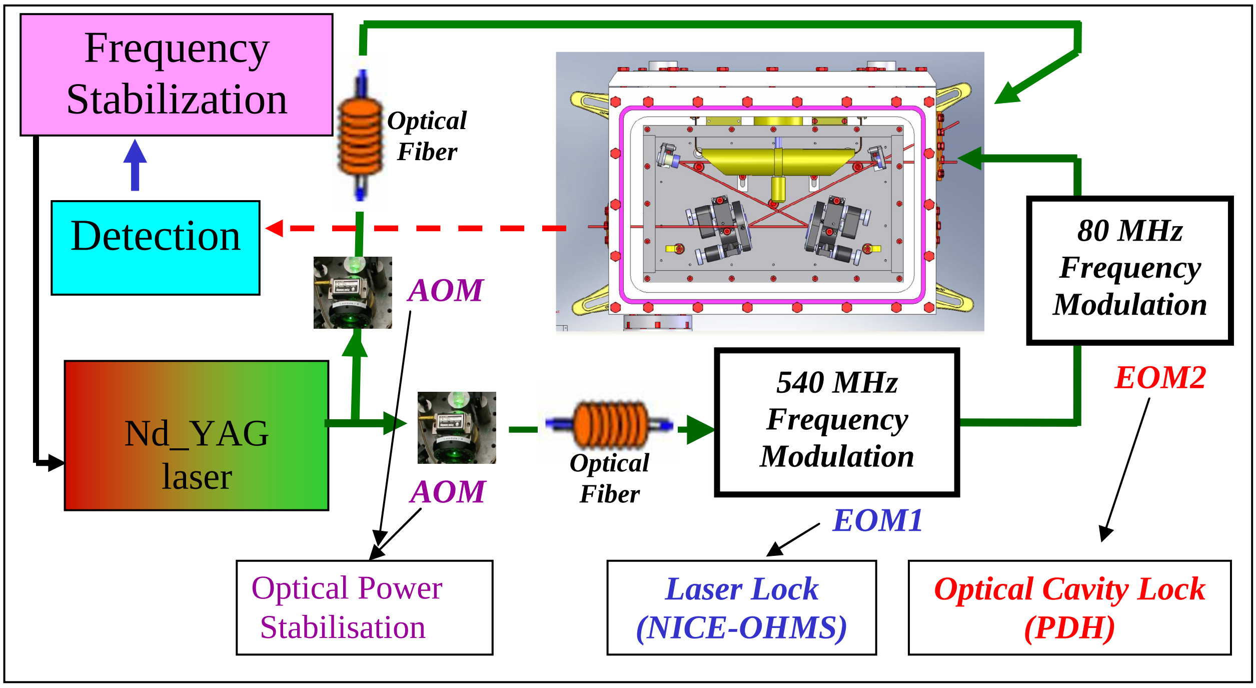

Fig. 2: Schematic experimental setup

The pump and probe beams cross two independent acousto-optic modulators for intensity stabilization before interrogating the iodine transition. The sidearm of the iodine cell is cooled down to -17°C with residual thermal fluctuations below 1 mK over 10^4 s (see Fig. 4). At the same time, the temperature of the iodine cell body is stabilized around + 5°C with the same performances. The iodine cell is inserted in a bow tie optical cavity, both placed in a vacuum tank (residual pressure ~10^{-5} mbar).
The power stabilization is achieved within few parts in 10^6 (Fig. 3), reducing in this way iodine lights shift down to the level of 10^{-15} in terms of iodine relative frequency fluctuations. The electro optic modulators are temperature stabilized below mK level over 10^4 seconds, in order to reduce the residual amplitude modulation (RAM) associated to phase modulation. We have obtained more than 70 dB reduction of this RAM, thanks to the simultaneous and precise control of the beam shape, and its temperature stabilization.
Figure 4 reports the stabilized temperature of the iodine cell sidearm (placed in vacuum), below 1 mK level over 10^4 s. This result leads to an estimated contribution of the iodine pressure fluctuations to the laser frequency stability at the 10^{-15} level.
Fig. 5 shows a preliminary record of the $^{127}I_2$-R(56) 32-0 line saturated absorption profile at 532.245 nm, with the iodine sidearm cooled down to -17 °C. At the associated iodine pressure of ~ 1 Pa, the collision-broadened peak is 500 kHz wide (quality factor Q ~10^9). The finesse of the optical cavity was measured to be 25. The beam diameter in the cell was 1 mm and the probe beam power at the entrance of the cavity is only 20 µW. The peak contrast of the a_{10} hyperfine component is 1.2 % of the linear absorption. This result is in good agreement with the expected S/N of 3 x10^4 in 1 Hz bandwidth (in the shot noise regime detection).

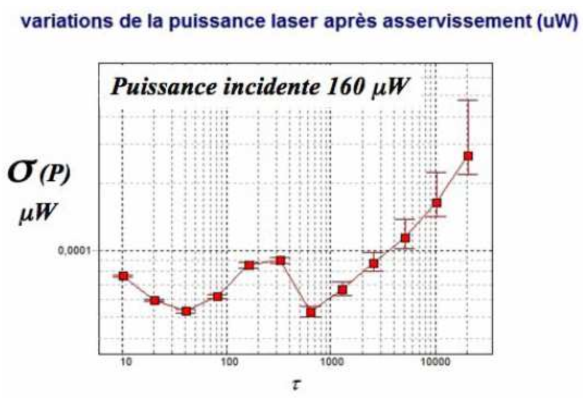

Fig. 3: Laser power stabilisation using Acousto-optic modulator

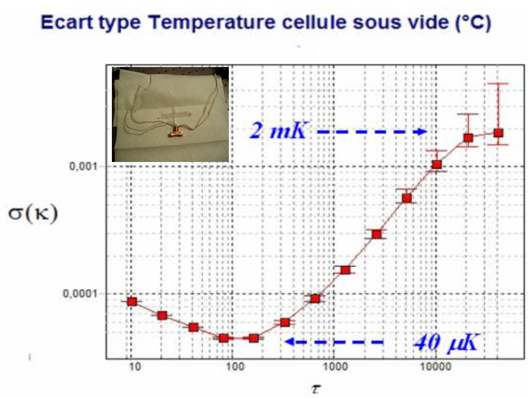

Fig. 4: Sidearm temperature (T ~ -17 °C) stability of the iodine cell in vacuum.

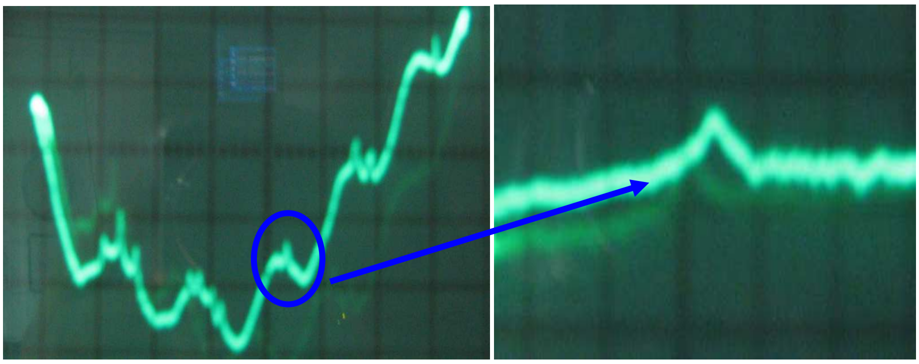

Fig. 5: Peak absorption of the $^{127}I_2$ - R(56) 32-0 transition at 532.245 nm (left)
The a_{10} component contrast is ~ 1.2 % of the linear absorption @ T = -17 °C (right)

CONCLUSION

The preliminary detected saturated absorption signal exhibits a S/N ratio (3 x 10^4 in 1 Hz) in good agreement with the expected value. In case of a shot noise detection limited regime, the estimated short term frequency stability is 3 ~ 4 x 10^{-14} @ 1s. We aim at increasing the stability below 1 x 10^{-14} in a near future.
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 reduced to the 10^{-15} level in terms of long term frequency instability. Our preliminary results already satisfy the LISA mission requirements.

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