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ABSTRACT

We report on a compact optical frequency standard (OFS) based on a Telecom laser diode operating at ~ 1542 nm, frequency stabilized to a narrow iodine transition located in the green range of the visible domain (~514 nm), after a highly efficient frequency tripling process. We use two cascaded waveguide Lithium Niobate nonlinear crystals for the third harmonic generation process (THG), resulting in a harmonic power of 300 mW in the green range (@ 3ω) using 800 mW of infrared power (@ ω). This result corresponds to an optical conversion efficiency $P_{3\omega}/P_{\omega} > 36$ % which is -to our knowledge- the best result ever reported for a third harmonic process in continuous wave regime (CW). This process uses only 20 W of total consumption power, which can be drastically reduced, knowing that less than 10% of that green power level is needed for the iodine Doppler free spectroscopy, and consequently for the frequency stabilization purpose. We have already demonstrated a frequency stability of 2.9 x10^{-14} $\tau^{-1/2}$ conferred to a laser diode operating at ~ 1542 nm, using the a_1 hyperfine component of the R34 [44-0] located at ~ 514 nm. This corresponds to an amplitude spectral density of the residual frequency fluctuations < 10 Hz/$\sqrt{Hz}$.

We plan to extend this approach to set up a new OFS by using a narrow linewidth fiber-laser emitting at ~ 1597 nm, which will be used for the phase-locking of a 1064 nm laser. Thus, this OFS, compact and mainly fibered, will perform the same role as that of a rigid optical cavity, widely used to stabilize 1064 nm lasers, involved in various terrestrial applications or space missions. The compact design of the whole setup will make it easily transportable to different sites and could be readily used as an ultra-stable frequency reference.

Keywords: Ultra stable laser, iodine Doppler free spectroscopy, space missions, third harmonic generation, nonlinear crystals, optical frequency standard, frequency reference.

1. INTRODUCTION

Ultra-stable lasers provided in compact optical architecture are an important technological key for many space applications, such as gravitational wave detection in space, Earth observation, ground to space or inter-satellites optical links, accurate laser ranging [1-4], etc. Currently, the requirements in terms of residual laser frequency noise for these space missions are in the range of 10^{-14}-10^{-15}. These performances are usually achieved in simple way in metrological laboratories by the use of the well-known Doppler free spectroscopy technique of atomic gas inserted in sealed cells. Infrared lasers (IR), such as solid state Nd: YAG lasers or Telecom laser diodes, are commonly the basis of numerous space missions, regarding to their high output power, their compactness and their low intrinsic phase noise before any electronic feedback. Unfortunately, the atomic absorption lines located in the vicinity of that lasers suffer from their insufficient metrological qualities to confer the frequency stability required for the space missions mentioned above [5]. Thus, harmonic frequency generation processes are needed to have access to higher frequency ranges, where narrow lines are located with high absorption contrast at the same time.

The iodine molecule has an advantageous position to achieve the targeted frequency stability, due to its wide and strong absorption band in the visible, especially in the green range (510 nm – 520 nm) [6], where experimental signal to noise ratio (S/N) and line quality factor (Q= $\nu/\Delta\nu$) can be easily optimized. Indeed, the frequency instabilities ($\delta\nu$) of a laser locked to an atomic absorption line is estimated by the parameter: $\delta\nu \sim [(\nu/\Delta\nu)*(S/N)]^{-1}$, where $\Delta\nu$ is the experimental absorption linewidth and ν its center (or laser) frequency. Hence the importance of maximizing both parameters at the same time. Intense and narrow hyperfine transitions in the vicinity of 532 nm are already successfully used to frequency stabilize 1064 nm lasers, after a second harmonic generation process (SHG) [7-11].

In this work, we propose to take advantage of numerous strong and much narrow lines located in the 510 nm-520 nm range [6], barely a few GHz apart, to frequency stabilize any Telecom laser source emitting in the C Band of the optical domain, after a frequency tripling process [12]. In such a way, ultra-compact and mainly fibered OFS can be set up, combining superior metrological qualities of iodine transitions in this green range to narrow linewidth lasers and various optical fibered components who exhibit a high technological readiness level (TRL) existing in the Telecom band [13].

We have already demonstrated the ability to generate a green radiation from a C-band Telecom laser diode, by using an efficient frequency tripling process yielding to the generation of 300 mW in the green from only 800 mW. This result corresponds to an optical conversion from the IR to the green $P_{3\omega} / P_{\omega} > 36$ %**,** in a continuous wave regime [12]. Moreover, this THG process uses only 20 W of total consumption power, which can be drastically reduced knowing that less than 10% of that generated green power is needed for the Doppler free iodine spectroscopy used in this work for the frequency stabilization purpose. We employ the well-known saturated absorption technique associated to phase modulation of the optical radiation to detect narrow and intense iodine lines around 514 nm. We have already demonstrated a repeatable day-to-day frequency stability at the level of 2.9 x 10^{-14} $\tau^{-1/2}$ decreasing down to 5.7 x 10^{-15} after about 100 s of integration time (τ).

On the other hand, we shown in early 2014, the feasibility of the frequency stability transfer achieved around 1.54 µm to the near infrared range (~ 1 µm), in a simple manner, using an additional SHG step, associated to the usual phase looking locking loop (PLL) technique between two lasers [14]. This approach will be used in near future to frequency stabilize a 1064 nm laser against a compact and fibered Telecom ultra-stable OFS at 1597 nm, which performs the same role as that of a rigid optical cavity, widely used to stabilize 1064 nm lasers, involved in various space missions. The compact design of the whole setup will make it easily transportable to different sites and could be readily used as an ultra-stable frequency reference.

2. FREE SPACE OPTICAL FREQUENCY STANDARD DESCRIPTION

We have first developed an OFS based on a fibered laser frequency tripling process setup, associated to a free space optical bench devoted to the iodine Doppler free spectroscopy as shown in Fig. 1a & 1b. The optical volume of the homemade frequency tripled Telecom laser doesn't exceed 5 liters, while the dimensions of the iodine spectroscopy bench is about ~ 40 cm x 40 cm (see Fig. 2).

The IR laser source used in this work is a butterfly narrow laser diode emitting at 1542.1 nm (linewidth ~2 kHz, power ~10 mW), followed by an Erbium doped optical fiber amplifier (EDFA) delivering up to 1 watt. All optical fibers involved in this work are polarization maintaining type. This IR power is separated in two parts : the first one is used for the second harmonic generation process (SHG: $\omega + \omega \rightarrow 2\omega$), while the other IR part is combined with the red beam from SHG to realize the sum frequency operation (SFG: $\omega + 2\omega \rightarrow 3\omega$). Two optically fibered Zn-doped PPLN ridge waveguide crystals are used to achieve both SHG and SFG processes. The SHG process is fulfilled in a fully fibered crystal (in & out). The optical coupling in the second one uses two polarization maintaining optical fibers optimized for ω and 2ω radiations. The generated 3ω radiation is extracted in free space way. We generate up to 300 mW of harmonic power in the green at 3ω, using 330 mW of red power at 2ω associated to 200 mW of fundamental power at ω. The more detailed description is given in [12].
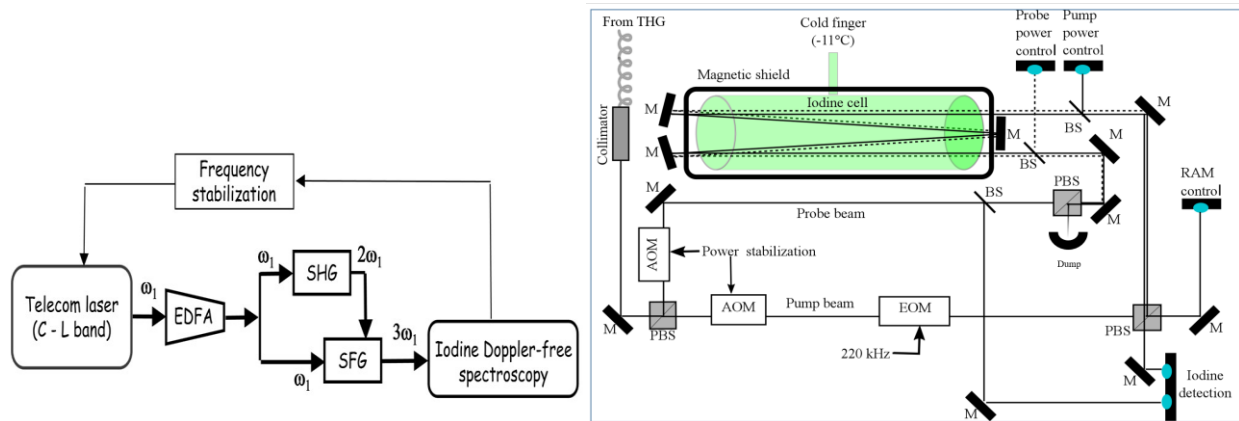
Fig. 1 a): Left. Principle of the frequency tripling process.
Fig. 1. b: Right. Scheme of the iodine stabilization optical setup in free space. BS: beam splitter, M: Mirror, AOM: Acousto-optic modulator, EOM: electro-optic modulator, PBS: polarizing beam splitter.
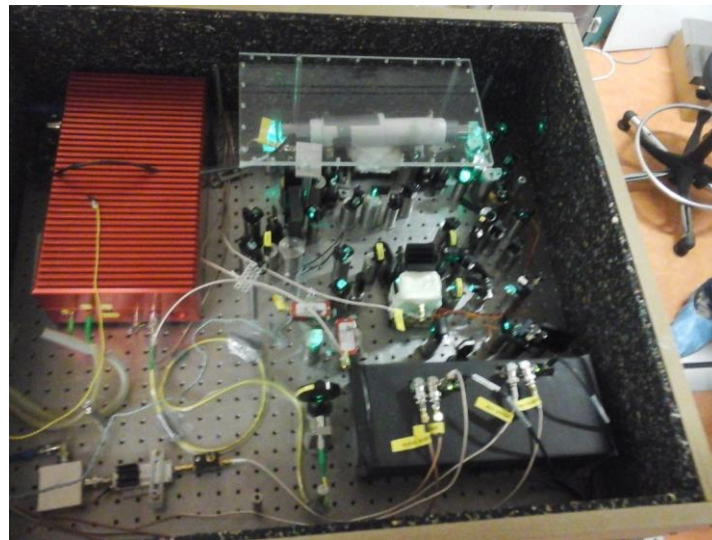

Fig. 2. Photograph of the whole optical setup. The EDFA and the frequency tripling crystals are integrated in the red box at the left (Volume ≈ 5 l). The dimensions of the spectroscopy optical bench are 40 cm x 40 cm. The cooled cell is visible at the top below a Plexiglass plate. At the bottom, the photodiodes are housed in a black box to avoid stray lights. The EOM is inserted in a homemade oven (white) for the temperature regulation.

Well known iodine Doppler free spectroscopy associated to the modulation transfer technique are used to frequency stabilize the 1542 nm laser diode against iodine hyperfine line in the green. The pump beam (respectively probe beam) is frequency shifted by ~ 78 MHz (resp. ~ 82 MHz) with acousto-optic modulators (AOM). A low frequency modulation at 220 kHz is applied to an electro-optic modulator (EOM) to detect the iodine atomic saturation signal. The two optical laser beams of ~3 mm diameter are carefully collimated and overlapped in the 30 cm long iodine cell, inserted in a magnetic shield. The interaction length is extended up to 1.2 m thanks to 4 successive passes. A balanced photodiode is used for the saturation signal detection. A part of the probe beam laser light is split off before the iodine cell and the detected intensity is subtracted from the detected saturation signal after the cell, eliminating common-mode intensity noise of the laser beam (see Fig. 1.b). Then, the saturated absorption signal is sent to a locking amplifier for frequency locking purpose. The incident optical powers into the iodine cell are ~ 4 mW (pump) and ~ 200 µW (probe). Both laser beam powers are stabilized by acting on the RF signal that drive the two AOM's, and the residual fluctuations are thus

controlled within ~ 10^{-4}. An additional photodiode is used for a permanent control of the residual amplitude modulation (RAM) associated to the phase modulation of the pump beam. The EOM operating in the green is inserted in a homemade oven to stabilize its temperature around 24 °C within 10mK. Thus, the undesirable RAM is reduced by about 40 db. The cold finger temperature of the iodine cell is regulated around -11 °C within 2mK, using homemade temperature regulation device. The iodine linewidth is estimated to be ~ 400 kHz (FWHM).

We use an independent ultra-stable stable optical frequency reference (OFR) laser to evaluate the frequency stability of our 1542 nm iodine-OFS. This ultra-stable OFR is based on a similar IR laser source frequency locked to an ultra-stable optical cavity described elsewhere [15]. This OFR is located in a separate building and is connected to our experiment by a 200 meters optical fiber link. During this measurement the frequency noise of this optical link was not compensated, because its contribution together with the reference cavity instabilities exhibit an Allan deviation at level of ~10^{-15} over the full integration time measurement (Fig. 3.b). Subsequently, the frequency stability evaluation of our iodine stabilized laser is not affected [13]. The linewidth of the optical beat note between the two infrared laser beams (OFR and Iodine-OFS) is less than 10 kHz, detected using a large bandwidth InGaAs photodetector. The Allan deviation associated to the iodine-OFS frequency instabilities is reported on Fig. 3.a. This curve corresponds to the raw data from the frequency measurement, without any post processing being applied (no any frequency drift has been removed). This Allan deviation exhibits a slope of ~ 2.9 x10^{-14} $\tau^{-1/2}$ with a minimum value of 5.7 x10^{-15} for 100 s of integration time.

A new iodine-OFS under development, and described below, will permit us to overcome the optical cavity frequency drift, and thus to evaluate in near future the iodine stabilized laser frequency stability for longer integration times.
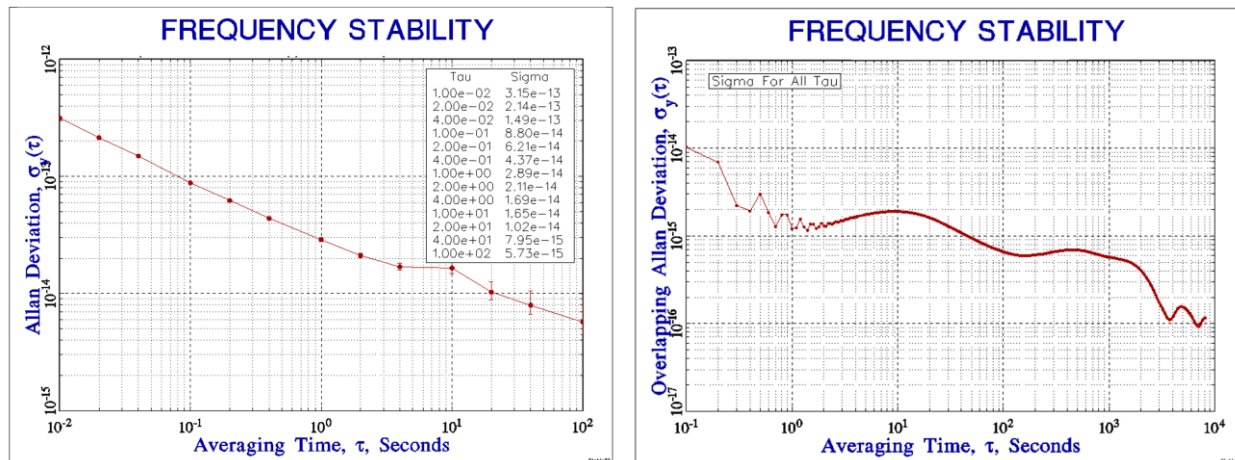

Fig. 3.a: Left. Typical Allan variance associated to the iodine-OFS frequency instabilities.
Fig. 3.b: Right. Allan variance associated to the frequency noise of the uncompensated 200 m-long fiber link connecting the iodine-OFS and an independent frequency reference.

3. FIBERED OPTICAL FREQUENCY STANDARD DESCRIPTION

Following this first step, we are developing a new OFS which will be optimized with respect to more compactness and reliability and less power consumption, in order to meet transportability requirements. We report in this section preliminary results achieved with this approach.

The targeted whole optical volume of that new OFS is less than 10 l. To maximize the compactness of the setup we operate the phase modulation in the infrared (1544 nm) using fibered EOM. A scheme and a photograph of this new OFS under development are reported in Fig. 4 and 5.a respectively.
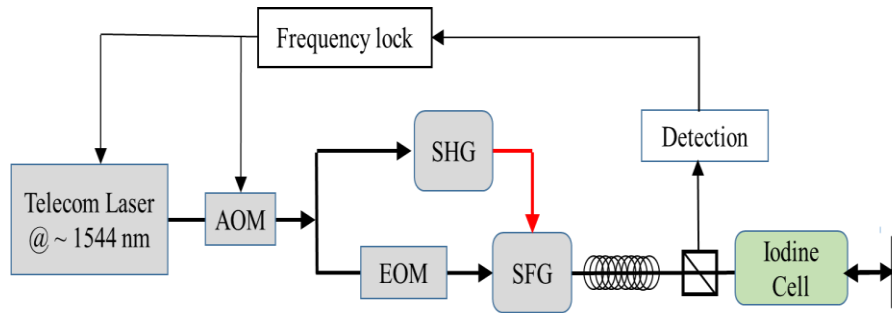
Fig. 4. Scheme of the new fibered iodine OFS-under development. The phase modulation is done before the frequency tripling process.

The phase modulation applied to an EOM operating in the IR implies that it's no more possible to use the usual transfer modulation technique. To overcome the impact of the phase modulation of both green beams counter-propagating in the iodine cell, which lead to the presence of a linear absorption background on which is detected the saturated absorption iodine line, we detect simultaneously the first and the third derivative of iodine absorption response. The 1st derivative is used to correct the fast frequency fluctuations (acting on an AOM), while the 3rd one is applied on the fiber laser PZT to correct the long term variations (Fig. 4). We have already detected both signals with excellent signal to noise ratios as shown in Fig. 5.b). The frequency stability evaluation using this approach is ongoing and will be published soon.
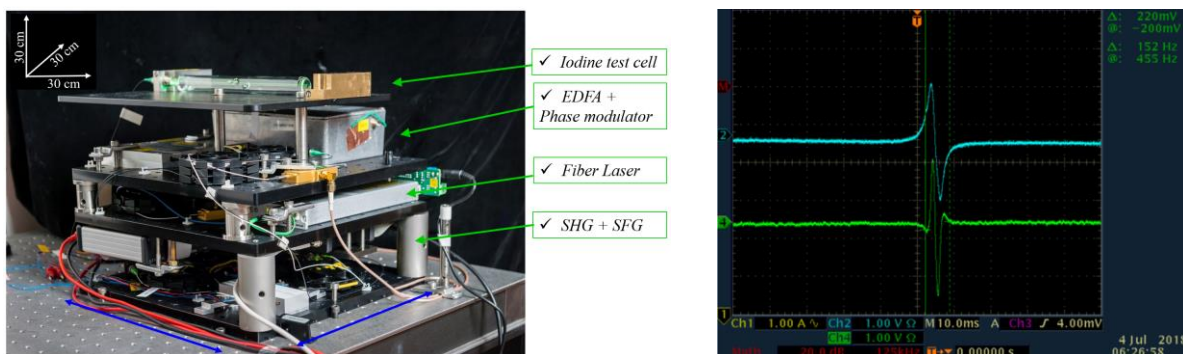

Fig. 5. a: Left. Photography of the fully fibered optical setup under development. This multi-storey structure allows to hold the whole optical setup in a compact architecture (30 cm on each side).
Fig. 5.b: Right. First and third derivative of the a_1 hyperfine component of the P46 (44-0) line at 514.5 nm recorded simultaneously. The Doppler background is no more visible with the third derivation. Although the amplitude of the signal is smaller, the line shape is narrower than in the first derivative case.

As in the previous setup, we use two similar non-linear waveguide crystals for the SHG and SFG processes, with aimed optical power less than 5 mW at 514.5 nm. This level of harmonic power is sufficient for the iodine saturation line detection. Figures 6.a & 6.b show the evolution of the output red power at 2ω (resp. green power at 3ω) as function of fundamental IR power at ω (respectively with fixed 240 mW of red power at 2ω). A polarization maintaining optical fiber is used to extract the green radiation and sent onto the iodine cell. The non-linear optical conversion of the SHG crystal (resp. SFG crystal) is deduced to be $\Gamma_{SHG} = P_{2\omega}/(P_\omega^2) \sim 108$ % W^{-1} (resp. $\Gamma_{SFG} = P_{3\omega}/P_\omega$ x $P_{2\omega} \sim 225$ % W^{-1}).
In current operation mode, for the frequency stabilization operation of the IR laser (@ ~ 1544 nm), less than 4 mW of harmonic power (@ ~ 514.5 nm) is sent into the iodine cell. Therefore, IR optical power is decreased down to 160 mW (respectively to100 mW) at the input of the SHG crystal (respectively of the SFG crystal).
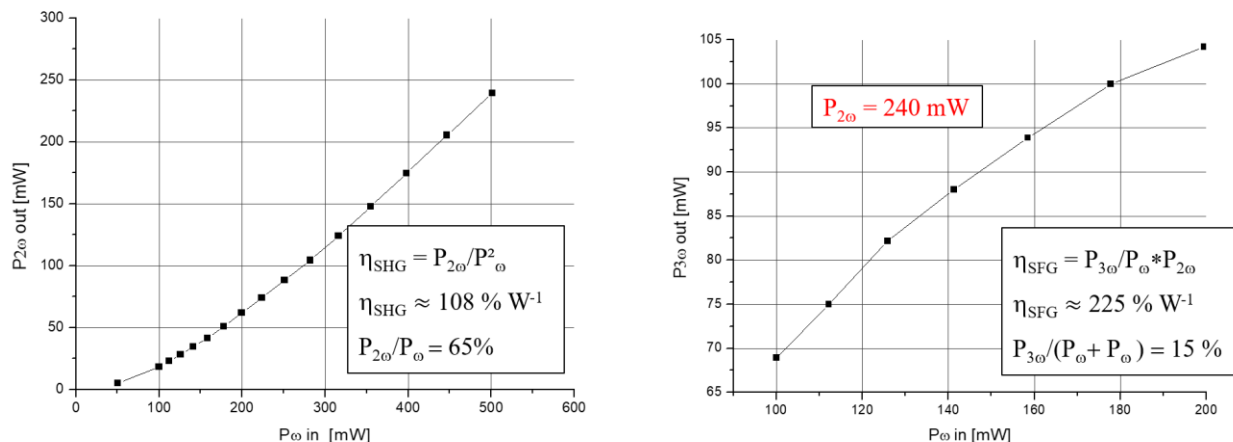
Fig. 6. a: Left. Evolution of the harmonic power ($P_{2\omega}$) versus the fundamental power P_ω.
Fig. 6. b: Right. Evolution of the harmonic power ($P_{3\omega}$) versus the fundamental power P_ω for a fixed red power $P_{2\omega} = 240$ mW.

4. CONCLUSION

We have developed compact optical frequency standards based on a frequency tripling of Telecom lasers. Nonlinear optical conversion from the infrared to the green ranges at the level of 36 % is reported. We have demonstrated a frequency stability conferred to a Telecom laser in the 10^{-15} range. These pioneer results open the way to develop -in near future- very compact setups which could match space mission requirements.

We plan to extend this approach to set up an OFS based on a frequency tripled -narrow linewidth- fibered laser operating at ~ 1597 nm, to provide an ultra-stable frequency reference for the phase-locking of a 1064 nm laser. Thus, this OFS will perform the same role as a rigid optical cavity, widely used to stabilize 1064 nm lasers, involved in various terrestrial applications or space missions.

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