ICSO 2016

International Conference on Space Optics

Biarritz, France

18–21 October 2016

Edited by Bruno Cugny, Nikos Karafolas and Zoran Sodnik

A compact frequency stabilized telecom laser diode for space applications

C. Philippe

D. Holleville

R. Le Targat

P. Wolf

et al.

icso proceedings

International Conference on Space Optics — ICSO 2016, edited by Bruno Cugny, Nikos Karafolas,
Zoran Sodnik, Proc. of SPIE Vol. 10562, 1056253 · © 2016 ESA and CNES
CCC code: 0277-786X/17/\$18 · doi: 10.1117/12.2296121

Proc. of SPIE Vol. 10562 1056253-1

A COMPACT FREQUENCY STABILIZED TELECOM LASER DIODE FOR SPACE APPLICATIONS

C. Philippe¹, D. Holleville¹, R. Le Targat¹, P. Wolf¹, T. Leveque², R. Le Goff³, E. Martaud³ and O. Acef¹

¹ LNE-SYRTE, Observatoire de Paris, PSL Research Univ., CNRS, Sorbonne Univ. UPMC Univ. Paris 06,

² Centre National d'Etudes Spatiales, 18 avenue Edouard Belin, F-31400 Toulouse, France

³ SODERN (Airbus Group), 20 Av. Descartes, F-94451 Limeil-Brévannes, France

Charles.philippe@obspm.fr

ABSTRACT

We report on a Telecom laser diode (LD) frequency stabilization to a narrow iodine hyperfine line in the green range, after frequency tripling process using fibered nonlinear waveguide PPLN crystals. We have generated up to 300 mW optical power in the green range (~514 nm) from 800 mW of infrared power (~1542 nm), corresponding to a nonlinear conversion efficiency $\eta = P_{3\omega}/P_{\omega} \sim 36\%$. Less than 10 mW of the generated green power are used for Doppler-free spectroscopy of $^{127}\text{I}_2$ molecular iodine, and –therefore– for the frequency stabilization purpose. The frequency tripling optical setup is very compact (< 5 l), fully fibered, and could operate over the full C-band of the Telecom range (1530 nm – 1565 nm). Several thousands of hyperfine iodine lines may thus be interrogated in the 510 nm – 521 nm range. We build up an optical bench used at first in free space configuration, using the well-known modulation transfer spectroscopy technique (MTS), in order to test the potential of this new frequency standard based on the couple “1.5 μm laser / iodine molecule”. We have already demonstrated a preliminary frequency stability of $4.8 \times 10^{-14} \tau^{-1/2}$ with a minimum value of 6×10^{-15} reached after 50 s of integration time, conferred to a laser diode operating at 1542.1 nm.

We focus now our efforts to expand the frequency stability to a longer integration time in order to meet requirements of many space experiments, such earth gravity missions, intersatellites links or space to ground communications.

Furthermore, we investigate the potential of a new approach based on frequency modulation technique (FM), associated to a 3rd harmonic detection of iodine lines to increase the compactness of the optical setup.

I. INTRODUCTION

Nowadays, several couples IR laser / hyperfine iodine lines have already been used to build up optical frequency standards, with demonstrated stabilities in the 10^{-15} range: Frequency doubled Nd: YAG / I_2 (532 nm) [1-3], frequency doubled Yb doped fiber laser / I_2 (515 nm) [4], frequency tripled LD / I_2 (514 nm) [5]. The well-known modulation transfer spectroscopy (MTS) technique is used in all mentioned works to detect very narrow Doppler-free hyperfine iodine lines. The emergence of high efficient non-linear waveguide crystals, combined with the existence of infrared (IR) laser sources with high technological maturity, issued from Telecom development, offer real opportunities to implement reliable and very compact stabilized laser devices of great relevance for space applications. Our proposed frequency tripling process opens the way to link in easy way very performant Telecom laser sources in terms of compactness, high level of emitted optical power and impressive intrinsic phase noise, to high quality factor Doppler-free saturated iodine hyperfine lines existing in the green range.

In this paper, we describe a new approach combining the use of frequency tripled Telecom laser diode (TLD) operating in the 1.5 μm range and one from thousands of narrow iodine hyperfine lines existing in the green part of the visible spectrum for the frequency stabilization purpose. This all fibered system emits simultaneously three cw-coherent and stabilized radiations. Compared to other IR laser sources, the TLD exhibit unprecedented intrinsic phase noise (linewidth < kHz), before any electronic feedback, associated to an extremely small volume (~ few cm^3) and optically fibered mode operation. Furthermore, iodine lines around 515 nm have remarkable quality factor ($Q > 2 \times 10^9$) [6], achievable with simple and compact experimental interrogation configurations using the well-known MTS technique.

II. FREQUENCY TRIPLING PROCESS

Third harmonic generation (THG) of continuous wave (CW) infrared lasers has been demonstrated in only few cases, with very poor efficiency $P_{3\omega}/P_{\omega}$ [7, 8]. In early 2002, a first attempt to observe iodine lines via a THG of a telecom laser has been described using two second order nonlinear processes in a unique crystal [9]. The two processes were operated in a single periodically poled Lithium Niobate crystal (PPLN) allowing a green power generation at level of few tens of nW. The associated optical conversion from IR to green $\eta = P_{3\omega}/P_{\omega}$ is in the range of 10^{-5} %. The main limitation is due to the difficulty to fulfill the quasi phase matching conditions for second harmonic generation (SHG) and sum frequency generation (SFG) simultaneously in the same nonlinear crystal. Recently, higher efficiency has been demonstrated at level of $\eta = P_{3\omega}/P_{\omega} = 0.25$ %, corresponding to 1.5 mW generated green light, with two cascaded crystals used to fulfill two second order steps: $(\omega + \omega \rightarrow 2\omega)$ followed by $(\omega + 2\omega \rightarrow 3\omega)$ [10].

Following this demonstration, we propose a new optical architecture using two fibered ridge waveguide PPLN nonlinear crystals [11]. We utilize two optically fibered ridge waveguide Zn doped PPLN crystals to achieve a SHG process followed by a SFG process in an original optical arrangement as depicted in Fig. 1. We generate up to $P_{3\omega} = 300$ mW at 514 nm using $P_{\omega} = 200$ mW associated to red power $P_{2\omega} = 330$ mW achieved independently from PPLN1 with 600 mW at ω . Consequently, this maximum output green power was obtained from 0.8 W total IR power at $1.542 \mu\text{m}$, corresponding to an optical conversion efficiency $\eta = P_{3\omega} / P_{\omega} \sim 36$ %. During our measurements, synthesized in Fig. 3, the total optical power incident onto the SFG crystal was intentionally limited to ~ 0.55 W ($P_{\omega} + P_{2\omega}$) in order to avoid possible optical damage.

Fig. 1: Principle of the THG setup: $(\omega + \omega \rightarrow 2\omega) + (\omega + 2\omega \rightarrow 3\omega)$.

A= Erbium Doped Optical Fibre Amplifier, PPLN1 = Optical fibered PPLN crystal for SHG operation, PPLN2=optical fibered PPLN crystal for SFG operation, DM: Dichroic mirror.

The IR laser source used in this work is a butterfly type narrow linewidth laser diode (linewidth ~ 1 kHz, power ~ 10 mW) followed by an erbium doped optical amplifier (EDFA) delivering up to 1 W over the full C band of the telecom range. All optical fibers, splitters and optical isolators used in this setup are polarization maintaining devices (Fig. 2).

Fig. 2: Frequency tripled Telecom laser diode

Fig. 3: Evolution of the measured third harmonic power Versus input optical powers at 1542 nm and 771 nm.

III. FREQUENCY STABILIZATION SETUP

We use the well-known saturated absorption approach associated to the MTS technique to frequency stabilize the 1.542 μm laser diode against an iodine hyperfine line in the green (Fig. 4). We have used the a_1 hyperfine component of the R 35 (44-0) $^{127}\text{I}_2$ line [12] at ~ 514.017 nm for a preliminary frequency stabilization evaluation. The pump beam (respectively probe beam) is frequency shifted by 79 MHz (resp. 80 MHz) with acousto-optic modulators. A low frequency modulation (220 kHz) is applied to the pump beam thanks to an electro-optic modulator to detect the atomic saturation signal. The two optical laser beams of diameter ~ 2 mm are carefully collimated and overlapped in the 20 cm long iodine cell. The interaction length is extended up to 1.2 m thanks to 6 successive optical passes in the cell. Both internal and external faces of the cell windows are antireflection coated in the green [13]. The quartz cell is filled with highly pure iodine in Institute of Scientific Instruments in Czech Republic.

Fig. 4 : Iodine stabilization optical setup.

BS: beam splitter, M: Mirror, AOM: Acousto-optic modulator, EOM: electro-optic modulator, PBS: polarizing beam splitter.

The saturated absorption signal is detected by a balanced silicon photodiode. A part of the probe beam is split off before propagating in the cell in order to eliminate common noise of the laser probe beam. The probe and pump powers are stabilized with signals detected with two independent photodiodes. An additional photodiode (not shown in fig. 4) is used for a permanent control of the residual amplitude modulation (RAM) associated to the phase modulation of the pump beam. The cold finger temperature of the cell is regulated around -15°C within 1.5 mK, using an homemade electronic PID controller. The corresponding vapor pressure in the cell is estimated about 1 Pa.

An independent stable frequency reference laser (FRL) is utilized to fulfill the frequency stability measurement of our 1.5 μm iodine optical frequency standard. The FRL is based on another IR laser source frequency locked to an ultra-stable optical cavity described elsewhere [14]. It is located in a separate building and is connected to our experiment by a 200 meters long fiber link. During this preliminary measurement the frequency noise of this optical link was not compensated, because its contribution together with the reference cavity instability exhibit an Allan deviation at level of $\sim 10^{-15}$ over the full integration time measurement. Subsequently, the frequency stability evaluation of our iodine stabilized laser is not affected.

Fig. 5: Frequency stability of the iodine stabilized 1542 nm laser diode using MTS technique.

Figure 5 reports the preliminary short term frequency stability measurement of the iodine stabilized laser diode. It shows an Allan deviation decreasing with a slope of $4.8 \times 10^{-14} \tau^{-1/2}$ with a minimum value of 6×10^{-15} for 50 s of integration time. During these preliminary measurements the residual amplitude modulation (RAM) was not compensated and could explain the behavior of the frequency stability observed for $\tau > 50$ s. The Allan deviation shown in Fig. 5 is associated to the measured frequency beat note between the iodine stabilized laser and the cavity reference laser. Hence, none frequency drift has been subtracted.

The corresponding frequency noise in terms of linear spectral density shown in Fig. 6 is compared to the LISA requirement: $30 * \sqrt{1 + \frac{3 \text{ mHz}}{f}} \text{ Hz}/\sqrt{\text{Hz}}$ between 0.1 mHz and 1 Hz.

Fig. 6: Frequency noise of the iodine stabilized 1542 nm laser diode

Red line: LISA requirement

Proc. of SPIE Vol. 10562 1056253-5

This frequency stability reported above is achieved using the usual MTS technique, where only the pump beam is frequency modulated (Fig. 4). We are investigating the potential of a new approach based on frequency modulation technique (FM), associated to a 3rd harmonic detection of iodine lines. Thus, we build up a preliminary optical setup based upon this concept, directly connected to our THG laser setup (Fig. 2). We start measurement with this new approach and achieve a very preliminary short term frequency stability measurement at the level of 2×10^{-13} at 1s (Fig. 7). This new approach currently under evaluation - and improvement- could be highly relevant for space applications. A final very compact optical setup design (volume < 3 l) based on this approach is under development (Fig. 8).

Fig. 7: Preliminary frequency stability of the iodine stabilized 1542 nm laser diode
Using FM technique and 3rd harmonic iodine line detection

Fig. 8: New optical bench using frequency modulation technique
Under development in the frame of SYRTE-SODERN collaboration

IV: CONCLUSION

We have presented our ongoing developments in realizing a frequency-stabilized-compact and fibered frequency reference laser source in the optical Telecom domain. We have already demonstrated frequency stability in the 10^{-15} range, using a compact tripled IR laser associated to a “conventional” free space optical bench for the iodine Doppler-free spectroscopy. This result shows a great potential for obtaining high stability laser reference for future space mission requiring together accuracy and frequency stability.

On the other hand, we investigate a new approach based on a different frequency modulation/detection technique in order to develop a more compact optical setup.

FUNDING

Agence Nationale de la Recherche (ASTRID program ANR 11 ASTR 001 01), Labex FIRST-T, SATT Lutech and AS-GRAM (CNRS/INSU). C. Philippe thesis is co-funded by CNES and SODERN.

ACKNOWLEDGMENTS

We are grateful to M. Lours and B. Venon for assistance in the frame of this development. O. A. is deeply indebted to Dr. Y. Nishida (NTT Co.) for the helpful and continuous discussions on the nonlinear crystals developments. We thanks Jan Hrabina from the Institute of Scientific Instruments of the Academy of Sciences of the Czech Republic (Brno) for helpful discussions on the realization of the multi-pass gas cell.

V: REFERENCES

- [1] John L. Hall et al., "Stabilization and Frequency Measurement of the I2-Stabilized Nd: YAG Laser », IEEE Trans. On Instrum. And Meas., Vol. 48, N°2, April 1999, pp. 583-586.
- [2] E. J. Zang, et al., « 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.
- [3] T. Schuldt et al., « An ultra-stable optical frequency reference for space », ICSO 2014, International Conference on Space Optics, Tenerife, Canary Islands, Spain, 7 - 10 October 2014.
- [4] A. Suemasa, A. Shimo-oku, M. Musha, « Developments of highly frequency stabilized lasers for space gravitational wave detector DECIGO/pre-DECIGO », ICSO 2016, Biarritz France, 18-21 October 2016.
- [5] C. Philippe et al., "Frequency tripled 1.5 μm telecom laser diode stabilized to iodine hyperfine line in the 10^{-15} range", 30th European Frequency and Time Forum, EFTF 2016, 4th – 7th April 2016, York, United Kingdom.
- [6] W.-Y. Cheng, L. Chen, T. H. Yoon, J. L. Hall, and J. Ye, "Sub-Doppler molecular-iodine transitions near the dissociation limit (523–498 nm)", *Opt. Lett.* 27(8), 571-573 (2002).
- [7] B. Corcoran, C. Monat, C. Grillet, D. J. Moss, B. J. Eggleton, T. P. White, L. O'Faolain, and T. F. Krauss, "Green light emission in silicon through slow-light enhanced third harmonic generation in photonic-crystal waveguides", *Nat. Photonics* 3, 206 (2009).
- [8] S. Sederberg and A. Y. Elezzabi, "Coherent Visible-Light-Generation Enhancement in Silicon-Based Nanoplasmonic Waveguides via Third-Harmonic Conversion", *Phys. Rev. Lett.* 114, 227401 –June 2015
- [9] R. Klein and A. Arie, "Observation of iodine transitions using the second and third harmonics of a 1.5- μm laser", *Appl. Phys. B* 75, 79-83 (2002).
- [10] N. Chiodo, F. Du-Burck, J. Hrabina, M. Lours, E. Chea, and O. Acef, "Optical phase locking of two infrared continuous wave lasers separated by 100 THz", *Opt. Lett.*, 39(10), 2936-2939 (2014).
- [11] C. Philippe, E. Chea, Y. Nishida, F Du-Burck and O.Acef, "Efficient third harmonic generation of a CW-fibered 1.5 μm laser diode", To be published.
- [12] S. Gerstenkorn, and P. Luc, « Atlas du spectre d'absorption de la molécule d'iode », Editions du C.N.R.S., Paris, France, 1978.
- [13] J. Hrabina, M. Šarbort, O. Acef, F. Du Burck, N. Chiodo, M. Holá, O. Číp O, J. Lazar, "Spectral properties of molecular iodine in absorption cells filled to specified saturation pressure", *Appl Opt.* 53(31):7435-7441, Nov. 2014.
- [14] B. Argence, E. Prevost, T. Leveque, R. Le Goff, P. Lemonde, S. Bize and G. Santarelli, "Prototype of an ultra-stable optical cavity for space applications » *Optics Express* 20 (23) pp. 25409-25420 (2012).