Efficient third harmonic generation of a CW-fibered 1.5 μm laser diode

Charles Philippe, Erick Chea, Yoshiki Nishida, Frédéric Du Burck, Ouali Acef

Efficient third harmonic generation of a CW-fibered 1.5 µm laser diode

Charles Philippe[1], Erick Chea[1, 2], Yoshiki Nishida[3], Frédéric du Burck[4] and Ouali Acef [1,*]

[1]LNE-SYRTE, Observatoire de Paris, PSL Research University, CNRS, Sorbonne Universités, UPMC Univ. Paris 06, 61, avenue de l'Observatoire, 75014 Paris, France
[2]SATT-Lutech, 24, boulevard de l'Hôpital 75005 Paris, France
[3]NTT Electronics Corporation 6700-2 To, Naka-shi, Ibaraki 311-0122 Japan
[4] LPL- Laboratoire de Physique des Lasers, Université Paris 13, Sorbonne Paris Cité, 99, avenue Jean Baptiste Clément 93430 Villetaneuse, France

**Corresponding author: Ouali.acef@obspm.fr*

ABSTRACT

We report on frequency tripling of CW-Telecom laser diode using two cascaded PPLN ridge nonlinear crystals, both used in single-pass configuration. All optical components used for this development are fibered, leading to a very compact and easy to use optical setup. We have generated up to 290 mW optical power in the green range, from 800 mW only of infrared power around 1.54 µm. This result corresponds to an optical conversion efficiency $P_{3\omega}/P_{\omega} > 36$ %. To our knowledge, this is best value ever demonstrated up today for a CW-third harmonic generation in single-pass configuration. This frequency tripling experimental setup was tested over more than two years of continuous operation, without any interruption.
The compactness and the reliability of our device make it very suitable as a transportable optical oscillator. In particular, it paves the way for embedded applications thanks to the high level of long term stability of the optical alignments.

1 INTRODUCTION

Narrow linewidth and powerful continuous wave (CW) lasers in the visible/UV spectral ranges are widely needed for various applications such as laser cooling, medical diagnostics, underwater optical communications, high resolution spectroscopy, gravitational wave detection, earth etc. [1-7]. So far, the green range was covered mainly by dye or Ar^+ lasers which have high optical power. Besides, narrow spectral linewidths can be achieved by pre-stabilization systems. Others sources based on frequency doubled infrared (IR) lasers like Nd: YAG or Yb: YAG in the vicinity of 1 µm, are also used in various configurations depending on the required level of green power. Usually, when only few tens of mW green power are needed from a watt-level laser source, a single-pass second harmonic generation (SHG) is a convenient solution. However, SHG efficiencies reported in the literature are limited to few percent [8]. When much higher harmonic power is required with the same low IR optical power, intra-cavity SHG process is commonly used. Very impressive levels of optical conversion efficiencies (up to 95 %) are demonstrated in various developments [9-11]. In this case, the increase of the doubling efficiency is associated to a more complex setup, resulting from the necessity to lock the optical cavity length to the laser frequency via an electronic feedback loop.

Of course, this additional step can be avoided when the fundamental power is sufficient. Several watts of green power are thus reported, obtained from more than ten watts of IR radiation [12, 13].

In this paper, we describe an original approach for green radiation generation based on the frequency tripling of a narrow laser source emitting in the C band of Telecom range. The third harmonic generation (THG) process is achieved using waveguide periodically poled Lithium Niobate (PPLN) nonlinear crystals in single-pass configuration. From 800 mW of IR power, we demonstrate a conversion efficiency $P_{3\omega}/P_{\omega} > 36\%$. Our setup which does not involve any optical cavity is based on fully fibred optical components, and consequently leads to a compact and reliable green laser source. The interest of the Telecom lasers lies in their unprecedented intrinsic phase noise (linewidth <1 kHz) associated to extremely small volume (~ cm^3) and fibered mode operation. Moreover, when long term frequency stability is needed, thousands of intense and narrow iodine lines in the 510 nm – 521 nm green range, with high quality factor (> $2x10^9$) [14, 15] could be used as reference in simple and compact experimental configuration, for frequency stabilization purpose. Besides, let us mention that in addition to the third harmonic radiation (3ω), our device delivers the first (ω) and second harmonic radiations (2ω). Thereby, the whole setup acts as generator of three powerful and coherent radiations in the IR and visible domain, and could be usefully used for the realization of accurate telemetry systems.

2 DESCRIPTION

CW-THG of 1.5 µm lasers has been attempted in only few cases, with very poor generated visible light due to the weakness of the third harmonic nonlinear conversion efficiency [16, 17]. In early 2002, a first attempt to observe iodine lines with THG of a Telecom laser has been reported, but the nanowatt level of generated green power was not sufficient to saturate the iodine vapor [18]. Later, a second experiment has been tested using a combination of SHG followed by a sum frequency generation (SFG) [19]. The two second order nonlinear processes were operated in a unique PPLN allowing a green power generation at level of few tens of nW. These two approaches of optical conversion from IR to green range, led to an optical conversion factor ($\eta = P_{3\omega}/P_{\omega}$) in the range of 10^{-5} %. The main limitation was the difficulty to fulfill the phase matching conditions for SHG and SFG simultaneously, while it can be realized much more easily using two cascaded and independent nonlinear crystals. More recently, a higher optical conversion η = 8% has been demonstrated in [13] using three cascaded nonlinear crystals associated to a high IR optical power (15 W at 1.5 µm).

In a previous, we have reported 1.5 mW of green light generated from 0.6 W of 1.5 µm amplified Telecom laser, using two cascaded bulk PPLN crystals, yielding to an optical conversion $\eta \sim 0.25$ % [20]. This result was achieved by superimposing in an 50 mm long SFG crystal, the second harmonic beam (2ω) with the residual fundamental beam (ω), both emerging from the same SHG crystal. The efficiency of this "classical" approach already demonstrated for producing UV radiation with IR lasers (see for example [21]) is limited by the difficulty of optimizing independently several experimental parameters associated to the optical beams at first and second harmonics. The most critical of them are the overlapping between optical beams (at ω and 2ω), polarization orientations, power ratio, beam shapes, focusing in the SFG crystal, etc.

To overcome these limitations, we have proposed an original optical architecture using two independent Lithium Niobate nonlinear crystals [22]. In this new approach depicted in figure 1, the residual fundamental IR beam (ω) issued from the SHG crystal is blocked with an appropriate short-pass optical filter. Thereby, the harmonic beam (2ω) is sent to the SFG crystal and mixed with a portion of the IR beam (ω), extracted upstream the SHG process. This architecture improves strongly the efficiency of green generation (3ω) by giving the possibility to optimize independently the experimental parameters mentioned above. This innovative development has been validated firstly using a Zn doped PPLN ridge waveguide crystal for the SHG process (PPLN1), and a free space bulk MgO: doped PPLN crystal (PPLN2) for the SFG process [23]. A conversion factor $\eta \sim 2.9$ % was obtained from 1 W of total IR power. We describe in the present paper a more compact and more reliable setup based on fully fibred Zn doped ridge waveguide PPLN crystals.

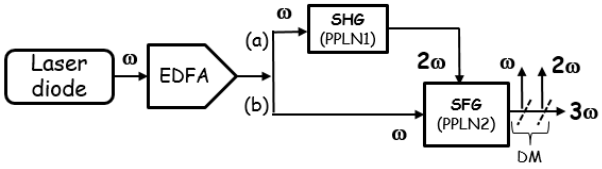

Fig. 1: Principle of the third harmonic generation setup using two cascaded steps: $(\omega + \omega \rightarrow 2\omega)$ and $(\omega + 2\omega \rightarrow 3\omega)$
EDFA = Erbium Doped Optical Fibre Amplifier, PPLN1 = optical fibered crystal for SHG operation, PPLN2= optical fibered crystal for SFG operation, DM = Dichroic mirror.

3 EXPERIMENTAL SETUP

The IR laser source used in this work is a narrow laser diode emitting at 1542.1 nm (linewidth <1 kHz, power ~10 mW [24]) 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 (a) is used for the second harmonic generation process (SHG: $\omega + \omega \rightarrow 2\omega$), while the other IR part (b) is combined with the red beam from SHG for the sum frequency operation (SFG: $\omega + 2\omega \rightarrow 3\omega$). Two optically fibered Zn doped PPLN ridge waveguide crystals manufactured by NTT electronics are used to achieve both SHG and SFG processes. The first one 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 (Fig. 2).

The SHG crystal length is 34 mm and its transverse dimensions are 7.6 µm x 8.3 µm. The grating period is Λ = 17.71 µm. The phase matching temperature set point was measured to be ~ 28 °C for frequency doubling of the 1542.1 nm fundamental radiation. Concerning the SFG crystal, its length is 22 mm and its transverse dimensions are 9.4 µm x 10.2 µm. Its grating period is Λ = 6.66 µm. The phase matching temperature set point was found to be ~ 15.2 °C at 1542.1 nm. Two homemade electronic control devices are used to fulfill the phase matching temperature conditions within less than 5 mK. The setup including the laser diode, the EDFA and all needed optical components occupies a total volume of 4.5 liters.

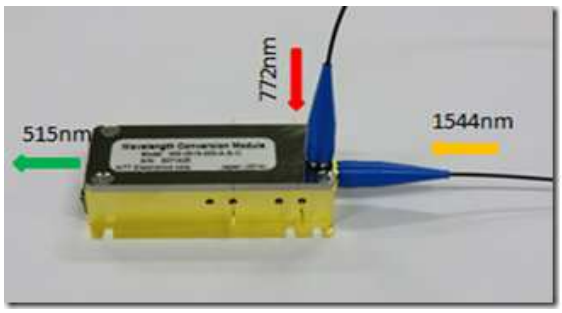

Fig. 2. Photograph of the SFG – PPLN waveguide module

Fig. 3 shows the evolution of the output green power (3ω) as a function of input powers at ω and 2ω. This preliminary characterization of the green generation is realized with two independent EDFA's used to amplify separately the two IR radiations coupled to the PPLN1 and PPLN2 crystals (Fig. 1). During these measurements, the total optical power incident onto the SFG crystal (P_ω + $P_{2\omega}$) was intentionally limited to 0.55 W in order to avoid possible optical damage. From Fig. 3, we deduce that the optical powers which optimize the green power are P_ω = 200 mW associated to $P_{2\omega}$ = 330 mW. Consequently, in the final experimental setup (Center inset in Fig. 4), we have implemented a 70/30 optical coupler associated to a single EDFA for both SHG and SFG processes to fulfill this optimal situation. Then, 290 mW maximum green power is generated at 514 nm (3ω) using 800 mW total IR power at ω (600 mW at the input (a) and 200 mW at the input (b), in Fig. 1).

This arrangement maximizes the optical conversion efficiency η > 36 %. The detailed evolution of the green harmonic power versus the product P_ω x $P_{2\omega}$, measured in this configuration is reported in Fig. 4. The nonlinear optical conversion of the SFG waveguide crystal is deduced to be $\Gamma = P_{3\omega} / (P_\omega \times P_{2\omega}) \sim 440\ \%.W^{-1}$. The temperature and the wavelength acceptances associated to the SFG process were measured to be 1°C and 0.16 nm respectively.

To characterize the optical efficiency of the THG setup, we have used a short-pass optical filter at the output of SFG crystal to block completely the residual transmitted IR and red powers. This optical filter, carefully calibrated at 514 nm, introduces 13 % optical losses in the green. Thereby, the experimental data in the green reported in Fig. 3 and 4 are corrected by this value.

No more corrections have been applied to draw these figures. Concerning IR power determination, we have used an independent optically fibered power meter optimized for Telecom wavelengths to measure the true IR power values on the channels (a) & (b) in Fig. 1. The same procedure was applied for the red power measurements with a dedicated optical filter.

The collimated output green beam exhibits a well Gaussian shape (top inset in Fig. 4) with a polarization ratio higher than 3000:1.

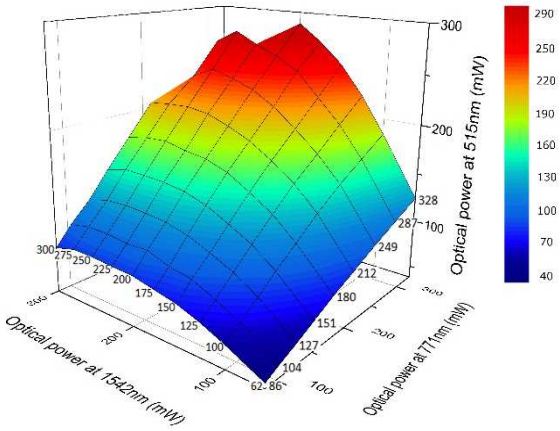

Fig. 3. Evolution of the measured third harmonic power as a function of the input optical powers at 1542 nm and 771 nm.

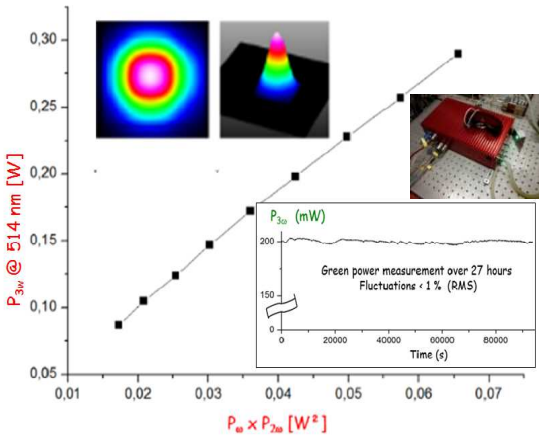

Fig. 4. Conversion efficiency of the third harmonic process.
Top inset: Gaussian beam profile at the output of the SFG crystal.
Center inset: Photograph of the new optical setup.
Bottom inset: green power fluctuations measured over 27 hours.

The spectral purity of the green radiation after THG process has been investigated by comparison to the green radiation generated in the previous partially free space setup mentioned above (Sect. 2). The beat note between both green radiations exhibits a linewidth smaller than 10 kHz. The long term power stability was tested during 27 hours, with a green power fixed at $P_{3\omega}$ = 200 mW (bottom inset of Fig. 4).

The observed relative fluctuations are lower than 1% RMS. The setup has run continuously for more than 2 years during which only the temperature stabilization set point of the two nonlinear crystals were adjusted. Only a slight degradation of a few percent of the output power at 514 nm has been observed. Fig. 5 and Fig. 6 report the dependence of the generated green power to the temperature fluctuations of both PPLN1 and PPLN2 crystals respectively. The full width at half maximum of these curves is found to be 1°C for a temperature variation of PPLN1 and 0.9°C for a temperature variation of PPLN2.

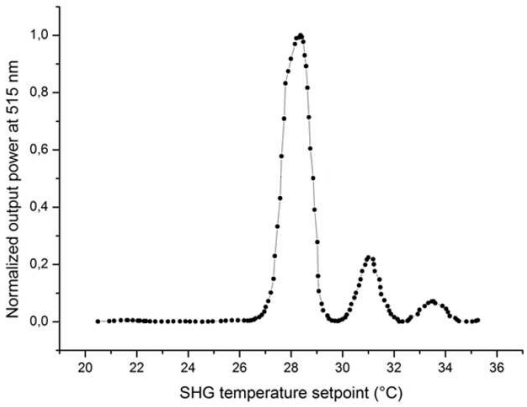

Fig. 5: Sensitivity of the harmonic power at 3ω to the SHG temperature variation.

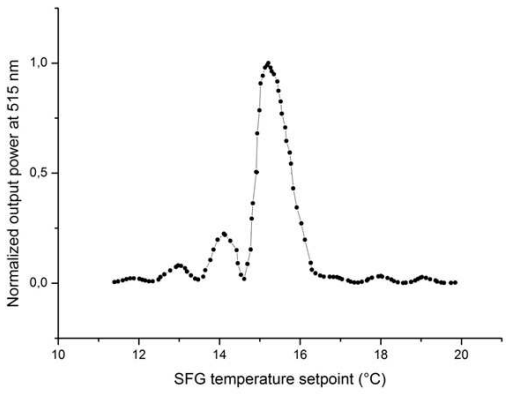

Fig. 6: Sensitivity of the harmonic power at 3ω to the SFG temperature variation.

Similarly, the sensitivity to the IR wavelength variations is shown in Fig. 7. The full width at half maximum of this curve is 160 pm. As it is often reported elsewhere, experimental data deviate from the theoretical squared sine cardinal ($sinc^2$) shape and show a strong asymmetry [20, 25-27]. This results from inhomogeneity of the polling period or of the geometry or the index of the guide (thermal distribution, doping concentration inhomogeneity, etc.) [28 - 30].

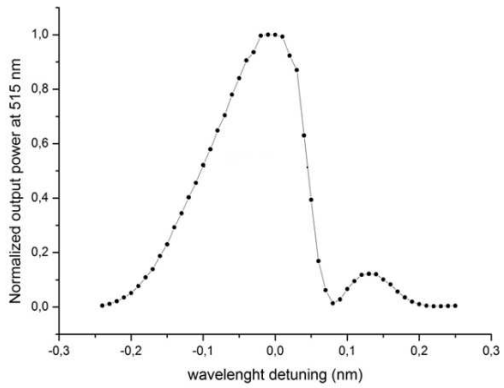

Fig. 7: Sensitivity of the harmonic power at 3ω to the IR laser wavelength variation.

4 CONCLUSION

We have demonstrated an unprecedented efficiency in the generation of CW green radiation from Telecom band laser source thanks to the implementation of Zn doped PPLN ridge waveguide crystals for both SHG and SFG processes combined in an original architecture. An output power of 290 mW of green radiation is generated from only 800 mW of fundamental power at 1542.1 nm, corresponding to a maximum nonlinear optical conversion $\eta > 36$ %. Moreover, the fundamental radiation (IR) and second harmonic radiation (red) are also available on independent outputs of our experimental setup. Thereby, the whole setup acts as a generator of three powerful and coherent radiations in the IR and visible domain. This fully fibred optical setup is very compact (4.5 liters) and shows an excellent stability of the optical alignments. A high level of long-term stability of the output power has been demonstrated. Those features make our experimental setup particularly suitable for achieving transportable devices.

This intense, spectrally narrow and stable green source could be useful for many applications in the field of high resolution spectroscopy and atom cooling. Moreover, the available green power allows efficient UV radiations synthesis by additional harmonic steps. Due to its compactness, it can also be used in embedded devices for telemetry, satellite or underwater communications, or by stabilization onto molecular iodine transitions, for the realization of transportable optical clocks.

FUNDING

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

ACKNOWELGMENTS

We are grateful to D. Holleville, M. Lours, J. Pinto, B. Venon, J. P. Aoustin and S. Ravily for their assistance in the frame of this development. We thank E. Declercq for helpful discussions and critical reading of this manuscript.

REFERENCES

1 A. Hemmerich, D.H. McIntyre, D. Schropp Jr., D. Meschede, T.W. Hänsch: Optics Comm. 75, 118 (1990)
2 J. G. Fujimoto, C. Pitris, S. A. Boppart and M. E. Brezinski: Neoplasia 2, 9 (2000)
3 F. Hanson, and St. Radic: Appl. Opt. 47, 277 (2008)
4 J. L. Hall: Rev. Mod. Phys. 78, 1279 (2006)
5 B. Woodward, H. Sari: Appl. Phys. B 91, 189 (2008)
6 P. L. Bender, J. L. Hall, J. Ye, W.M. Klipstein: Space Science Reviews 108, 377(2003)
7 T. Schuldt et al.: ICSO 2014, International Conference on Space Optics, Tenerife, Canary Islands, Spain, 7 - 10 October 2014.
8 V. Pruneri, R. Koch, P. G. Kazansky, W. A. Clarkson, P. St. J. Russell, and D. C. Hanna: Optics Lett. 20, 2375 (1995) and references therein
9 Y. Hadjar, F. Ducos, and O. Acef**:** Optics Lett. 25 ,1367 (2000)
10 Z. Y. Ou, S. E Pereira, E. S. Polzik, and H. J. Kimble: Optics Lett. 17, 640 (1992)
11 S. Ast, et al**:** Optics Lett. 36, 3467 (2011)
12 S. C. Kumar, G. K. Samanta, K. Devi, and M. Ebrahim-Zadeh**:** Optics Express 19, (2011)
13 S. Vasilyev, A. Nevsky, I. Ernsting, M. Hansen, J. Shen and S. Schiller**:** Appl. Phys B 103, 27 (2011)
14 S. Gerstenkorn, and P. Luc **:** Editions du C.N.R.S., Paris, France, 1978.
15 W.-Y. Cheng, L. Chen, T. H. Yoon, J. L. Hall, and J. Ye: Optics Lett. 27, 571 (2002)
16 B. Corcoran, et al: Nat. Photonics 3, 206 (2009).
17 S. Sederberg and A. Y. Elezzabi: Phys. Rev. Lett. 114, 227401 (2015)
18 R. Klein and A. Arie: Appl. Phys. B 75, 79 (2002)
19 M. Marangoni, M. Lobino, and R. Ramponi: Optics Lett. 31, 2707 (2006)
20 N. Chiodo, F. Du-Burck, J. Hrabina, M. Lours, E. Chea, and O. Acef: Optics Lett. 39, 2936(2014)
21 I. Ricciardi, M. De Rosa, A. Rocco, P. Ferraro, A. Vannucci, P. Spano, and P. De Natale: Optics Lett. 34, 1348 (2009) and References therein
22 Proposal is subject to patent (PCT: EP2014/057633).
23 C. Philippe et al.: 30th European Frequency and Time Forum, EFTF 2016, 4th – 7th April 2016, York, United Kingdom
24 We use a fibered external cavity laser diode (Planex type from RIO Co). This information is given only for complete technical description, it does not constitute an endorsement by SYRTE.
25 M. Achtenhagen, W.D. Bragg, J. O'Daniel and P. Young**:** Electronics Lett. 44 (2008)
26 T. Nishikawa, A. Ozawa, Y. Nishida, M. Asobe, Feng-Lei Hong, and T. W. Hänsch: Optics Express 17, 17792 (2009)
27 T. Kobayashi, D. Akamatsu, Y. Nishida, T. Tanabe, M. Yasuda, Feng-Lei Hong, and K. Hosaka**:** Optics Express 24, 12142 (2016)
28 Y. L. Lee, Y.-C. Noh, C. Jung, T. J. Yu, D.-K. Ko, J. Lee: Optics Express 11, 2813 (2003)
29 D. Jedrzejczyk, R. Guther, K. Paschke, G. Erbert, and G. Trankle: Applied Phys. B109, 33 (2012)
30 S. Guo, Y. Ge, Y. Han, J. He and J. Wang: Optics Communications 326, 114 (2014)