International Conference on Space Optics—ICSO 2014

La Caleta, Tenerife, Canary Islands

7–10 October 2014

Edited by Zoran Sodnik, Bruno Cugny, and Nikos Karafolas

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International Conference on Space Optics — ICSO 2014, edited by Zoran Sodnik, Nikos Karafolas, Bruno Cugny, Proc. of SPIE Vol. 10563, 105633S · © 2014 ESA and CNES
CCC code: 0277-786X/17/$18 · doi: 10.1117/12.2304157

PROGRESS ON HIGH ENERGY OPTICAL PARAMETRIC TRANSMITTER FOR MULTIPLE GREENHOUSE GASES DIAL

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Abstract - **We report on a DIAL emitter for remote sensing of greenhouse gases, capable of addressing the three species of interest (CO_2, CH_4 and H_2O) for space applications with a single optical source. It is based on an amplified Nested Cavities Optical Parametric Oscillator (NesCOPO) around 2 µm. The source is single frequency over a wide range of tuneability between 2.05 – 2.3 µm, and shows a typical energy conversion efficiency of 20 % toward the signal wave. Spectral analysis shows a linewidth better than 100 MHz. These performances are measured in the vicinity of absorption lines of interest for space remote sensing of the three gases.**

I. INTRODUCTION

Active sensing of global greenhouse gases distribution is expected to significantly increase the understanding of their influence on climate changes. For this purpose, differential absorption lidar (DIAL) instruments are being actively developed in order to measure atmospheric CO_2, CH_4, and H_2O concentrations with unprecedented precision. For space integrated-path DIAL (IP-DIAL) applications, several sounding frequencies in the mid-infrared have been identified as good candidates especially in the 1.5 µm – 1.65 µm region as well as in the 2.0 µm – 2.3 µm, where the target molecules display absorption lines with appropriate compromises between weighting function, optical density, small dependency on temperature variations, and small cross sensitivity with interfering lines from other species [1, 2]. Consequently, powerful mid-infrared DIAL emitters with stringent spectral properties are being developed with different approaches in an effort to reach the highly demanding specification for spaceborne IP-DIAL applications in terms of emitted wavelengths, output energy, frequency purity and stability, as well as beam quality. In this perspective, we previously reported on the development of a high energy transmitter in the vicinity of the R30 CO_2 absorption line (2051 nm) based on frequency conversion in a Nested Cavities Doubly Resonant Optical Parametric Oscillator (NesCOPO) followed by parametric amplification [3, 4]. With this configuration high energy (> 10 mJ) nanosecond pulses were generated, while maintaining a high spectral (single frequency with 3 MHz rms fluctuations) and spatial quality ($M^2 < 1.5$). Additionally, with the versatile NesCOPO architecture, adjustable multiple wavelengths around 2051 nm as well as shot by shot wavelength switching were demonstrated [3]. In this paper we report on further improvements brought in terms of wavelength coverage for multiple-species applications, output energy extraction, and optical frequency active stabilization.

II. CONTEXT AND ELEMENTS OF BIBLIOGRAPHY

A laser transmitter for greenhouse gas IP-DIAL from space must provide single frequency high energy pulses (tens of mJ), a narrow spectral linewidth (transform limited nanosecond pulses with a linewitdh better than 100 MHz are aimed for), as well as the ability to generate two or more wavelengths in the target gas absorption line. For this kind of application several solid state laser approaches are being investigated, which are mainly based on injection seeded Ho or Ho:Tm laser oscillators at 2 µm for CO_2 concentration measurement [5,6], or based on injection seeded optical parametric devices [7-11]. Optical parametric devices are well suited since they provide wide potential tuning ranges and sufficient output energy especially in the mid-IR where laser options are scarce. Moreover high power architectures (OPO-OPA), benefit from the availability and reliability of high energy Neodymium lasers at 1 µm, which are mature for spatialization. This is especially the case in the frame of the French German MERLIN (Methane Remote Sensing LIdar Mission) project [12, 13]. One interesting aspect to be developed is also the ability to produce several wavelengths in the lines of interest. For spaceborne IP-DIAL application, applying several wavelengths corresponding to multiple weighting functions could provide information in different layers of the atmosphere, and thus give an insight on vertical species distributions [14]. Multiple wavelengths sampling is also expected to provide useful information on the measurement itself, especially regarding systematic errors such as baseline structures that may affect the precision and averaging time [15-17].

One highly sought general property is also the capability to provide multiple-gas detection with a single instrument or a generic architecture. In the case of injection seeded sources, the overall tuning capability will depend on the availability and tuning abilities of the seeding system. Moreover, for fast, shot by shot, and stable single frequency operation, these schemes need at least one seeder per emitted wavelength, which can lead to complex systems when multi-wavelengths DIAL or multispecies DIAL operation is desired. Especially, up to now, no demonstration of a generic emitter approach, allowing targeting the three main species of interest for IP-DIAL sensing from space with a single device, was demonstrated.

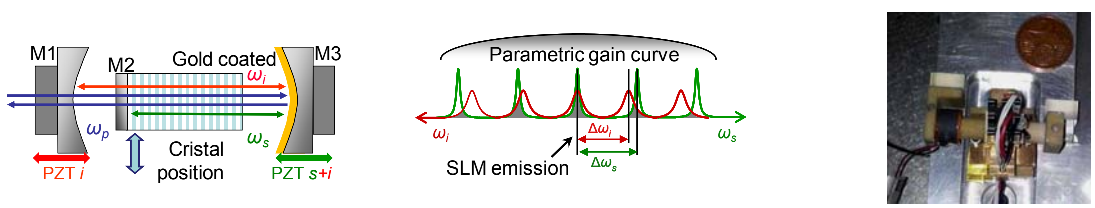
In this context, the Onera/DMPH group has been working on the development of a specific OPO architecture (NesCOPO), enabling the generation single frequency pulses widely tunable in the mid-IR, as well as its implementation for spectrometry applications including short-range IP-DIAL [16, 18, 19].

III. GENERAL ARCHITECTURE AND WAVELENGTH TUNING

A. NesCOPO principle

Taking advantage of the production of two highly correlated fields (signal and idler) through the parametric conversion process, the NesCOPO approach [19] consists in the implementation of two optical cavities separately resonant at the signal and idler radiations; the nonlinear crystal subtending the parametric conversion of the input pump laser radiation is placed inside the common part of the two cavities. Both cavity lengths can be separately adjusted. By correctly adjusting the dissociation of these two cavities by a few %, single frequency operation can be obtained according to the Vernier spectral filtering.

The NesCOPO geometry is described in Fig. 1(a), pairs of mirrors M2-M3 and M1-M3 are related to signal and idler cavities, respectively. A double-pass pump beam is performed thanks to mirror M3, which has a high reflectivity for all wavelengths (pump, signal and idler). Such a configuration is suitable to achieve a low threshold of oscillation. Mirrors M1 and M3 are mounted on piezoelectric transducer (PZT) for fine frequency tuning. Fig. 1(b) illustrates the Vernier spectral filtering that can be achieved with a NesCOPO having two slightly different cavity lengths. The NesCOPO design is compact and can be easily integrated (Fig. 1(c)). Specific tuning procedures can be implemented by making use of the dual-cavity configuration. Discrete mode-hop frequency tuning as well as fine continuous tuning can be obtained by adjusting independently or simultaneously the two cavities length. Both approaches have been demonstrated [18, 20].



(a) (b) (c)

Fig. 1. (a) Schematic representation of the NesCOPO configuration, (b) mode overlapping between signal and idler cavities, SLM emission is achieved for one single exact coincidence within the parametric gain bandwidth, (c) picture of an integrated NesCOPO device.

B. Emitter set-up for high power emission and temperature tuning in the 2.05 – 2.3 µm range

For high energy applications such as DIAL, the NesCOPO can be implemented in a Master Oscillator Power Amplifier set-up (MOPA) with Optical Parametric Amplifiers (OPA) in order to reach tens of mJ in the mid-IR, while maintaining high spatial and spectral quality.

The experimental set-up is depicted in Fig. 2. The pump laser is a 100 mJ single frequency Nd:YAG laser, delivering 15 ns pulses at a 30 Hz repetition rate. The NesCOPO oscillator is based on a type II periodically poled lithium niobate (PPLN) nonlinear crystal, pumped by a few hundreds of µJ, and emitting up to 30 µJ of idler to be further amplified. Amplification is realized in a two steps amplifier architecture. The first stage is a 25 mm long, 2 mm thick, type 0 PPLN booster amplifier leading to an energy gain of 40. It is followed by high energy amplifiers, based on high aperture KTP crystals, whose damage threshold is higher than the PPLN booster stage. KTP crystals are oriented in a walk-off compensation configuration in order to maximize conversion efficiency and beam quality. A 10 ns delay line is inserted in the pump path before amplification in order to compensate for the OPO build-up time.

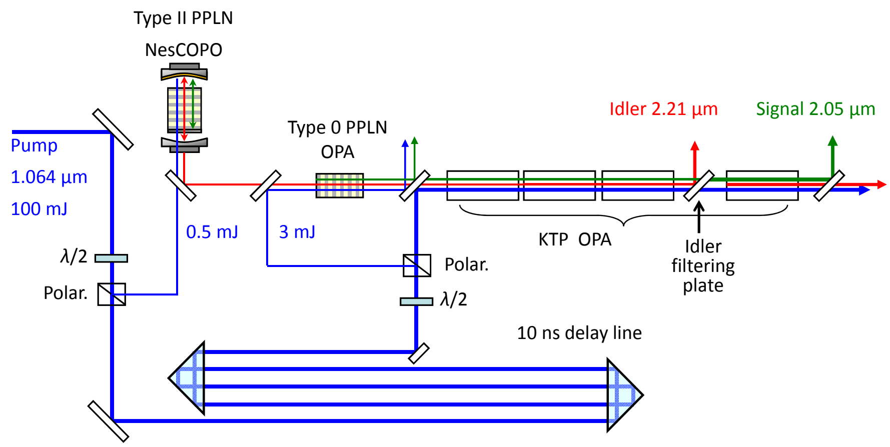
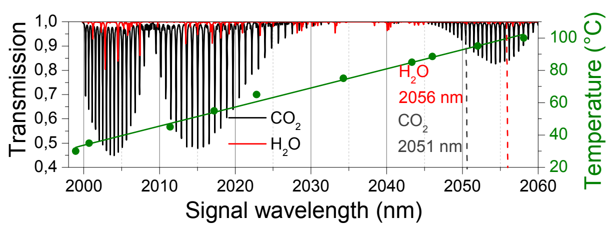


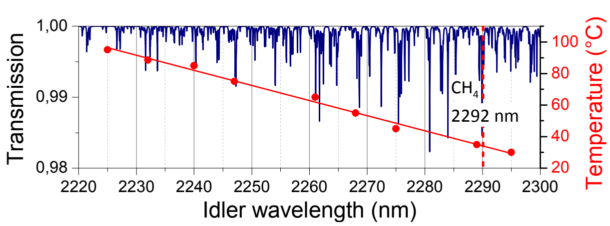
Fig. 2. Experimental set-up for the high energy MOPA. The wavelengths represented correspond to the case where the signal is emitted in the CO_2 R30 line around 2051 nm.

For broad tunability of the bench, quasi-phase matching conditions inside the OPO cavity are first to be modified. This can be done essentially by temperature tuning of the nonlinear crystal, or mechanically by switching from one quasi-phase matching period to another, which is possible with multiple tracks PPLN crystals. With our experimental set-up we modify both parameters. As can be seen on **Fig. 3** temperature tuning of the crystal on two different grating poling periods enabled to tune the signal wave from 2.00 µm to 2.06 µm, and the idler wave from 2.22 µm to 2.29 µm. In particular some absorption lines of interest for space application can be addressed either with the signal wave or the idler wave, which leads to our knowledge to the first emitter capable to address the three main greenhouse gases with a single device. The specific phase matching-parameters applied to reach those lines are summarized hereafter.



Species	NesCOPO crystal temperature	Emitted wavelength (signal λs)
CO_2	88.5 °C	λs = 2051 nm
H_2O	94.5 °C	λs = 2057 nm

(a)



Species	NesCOPO crystal temperature	Emitted wavelength (idler λi)
CH_4	90 °C 30 °C	λi = 2211 nm λi = 2292 nm

(b)

Fig. 3. Temperature tuning of the signal wave emitted by the NesCOPO for a quasi-phase matching period of 14.369 µm *(a)*. Temperature tuning of the idler wave for a quasi-phase matching period of 14.380 µm *(b)*. Dots correspond to experimental wavelength measurements. Solid lines HITRAN simulation for CO_2 (black), H_2O (red), and CH_4 (blue) absorption lines calculated for typical atmospheric concentration and absorption length of 100 m. Dashed lines locate the absorption lines of interest for spatial applications.

IV. OUTPUT ENERGY AND SPECTRAL CHARACTERIZATIONS

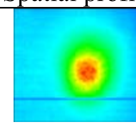
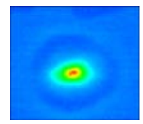
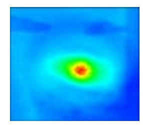
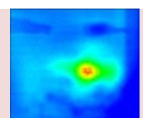
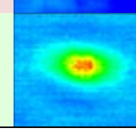
All energetic and spectral characterizations detailed hereafter are carried out after the amplification stages.

A. Energy extraction and conversion efficiency

In terms of energy amplification and extraction, improvements compared to our previous work have been achieved. These could be established essentially by using a longer pre-amplifier PPLN booster of 25 mm, and idler wave rejection inside the KTP amplification line in order to reduce saturation and back-conversion defects.

This latter function is realized by inserting a filtering plate between the last two KTP amplifiers as described Fig. 2. As illustrated in Tab. 1 below, the filtering plate significantly reduces back conversion effects in the last KTP crystal, and enables to reach 20 mJ on the signal wave at 2051 nm. This back-conversion reduction is accompanied by an improvement of the spatial quality. By use of the 16% - 84% knife-edge method after focalization of the signal, the M² propagation factor was measured to be < 1.5 in both horizontal and vertical directions. These results are thus very encouraging in the perspective of further energy scaling.

Tab. 1. Energy and near field spatial profile measurement at the output of the KTP amplifiers for the signal wave at 2051 nm.

Number of KTPs	Idler filtering	Signal output energy	Spatial profile
1	no	3.3 mJ	
2	no	9.6 mJ	
3	no	18.3 mJ	
4	no	13.8 mJ	
4	yes	20 mJ	

The performances of the emitter were measured for different wavelengths of emission corresponding to the absorption lines for spatial application, and are reported in Tab. 2 below. At the output of the amplifiers stages we measure a typical 40 % pump depletion. After extraction and filtering optics in order to remove the residual 1 µm radiation, the typical extracted energy is 20 mJ in the signal beam and 16 mJ in the idler beam, which is compliant with ground based lidar demonstration experiments. Regarding amplification stages, further improvements are being investigated with the use of high aperture PPKTP crystals in order to improve energy extraction while increasing the compactness or the overall set-up.

Tab. 2. Output energy and conversion efficiency of the MOPA for different tuning wavelengths

Targeted species	Wavelength (nm)	Signal output energy	Idler output energy	Total output energy	Total optical to optical extraction efficiency
CO_2	$\lambda_s = 2051$	20 mJ	17 mJ	37 mJ	37 %
H_2O	$\lambda_s = 2057$	20 mJ	16 mJ	36 mJ	36 %
CH_4	$\lambda_i = 2211$	20 mJ	16 mJ	36 mJ	36 %
	$\lambda_i = 2292$	20 mJ	17 mJ	37 mJ	37 %

B. Frequency stability, spectral linewidth, and side modes suppression

The central wavelengths emitted by the parametric source are measured shot by shot, after second harmonic generation, with a WSU 10 High Finesse wavemeter (operating range up to 1.1 µm). This experimental set-up enables to measure the optical frequency stability over time on a wide spectral range. In order to assess the precision of the wavemeter, the instrument's performances were characterized with a frequency double laser diode locked on a Rb atomic transition at 780 nm. The Allan deviation of the wavemeter itself is far better than 1 MHz up to 100 s averaging time (see Fig. 4).

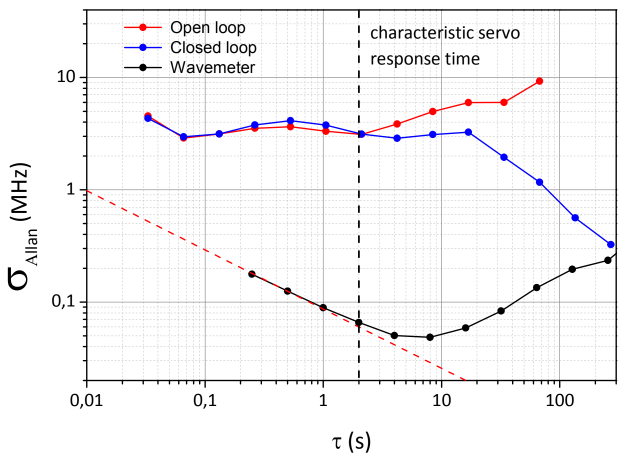


Fig. 4. Allan deviation of the signal frequency emitted by the MOPA set-up in free-running and with active stabilization of the OPO cavity. The Allan deviation the wavemeter is shown in black.

In free-running configuration, the signal frequency emitted shows short term fluctuations of a few MHz which are mainly attributed to the residual electronic noise of the PZT driver, whose contribution to frequency instability was measured to be around 2 MHz. The long term frequency drifts could be corrected with active control of mirror M1 position. The control loop is fed with an error signal given by the wavemeter's measurement, and counter acts to frequency drifts with a typical response time of 1 s. As show on Fig. 4 the implementation of feedback loop enabled to maintain the emitted signal frequency with sub-MHz stability over 100 s. Regarding frequency stability, future developments will focus on the reduction of intrinsic sources of instability such as thermo-mechanical design, pump laser frequency fluctuations, and PZT driver noise in order to decrease short term frequency fluctuations. Faster servo loop control of the OPO cavity is also expected to improve the overall stability.

Finally, in order to assess the linewidth and the side modes suppression ratio (SMSR) at the output of the MOPA, preliminary beat note experiments were carried out by mixing the signal radiation with DFB laser diode at 2051 nm (Fig. 5) on a fast InGaAs photodiode (12 GHz, which limit the overall detection bandwidth). The OPO radiation is set around 3 GHz from the diode. The experimental beating signal is analysed with a 13 GHz bandwidth oscilloscope (see Fig. 6) and with an 18 GHz bandwidth electronic spectral analyzer (ESA) (see Fig. 7).

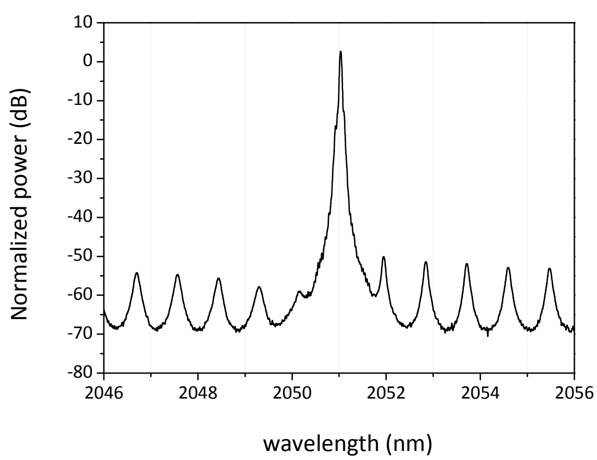


Fig. 5. Emission spectrum of the diode laser used as a spectral reference for beat note mixing and analysis. The measurement realized with an optical spectrum analyser.

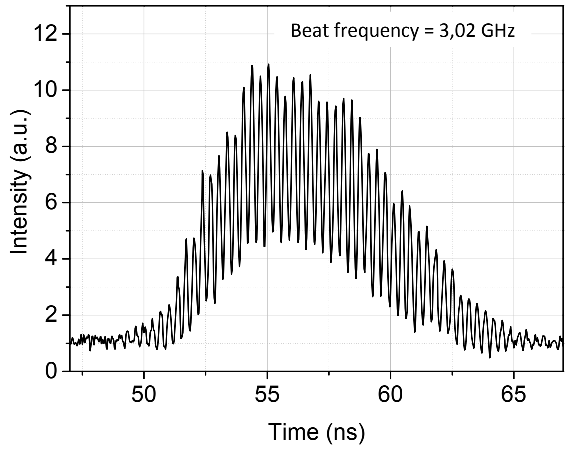
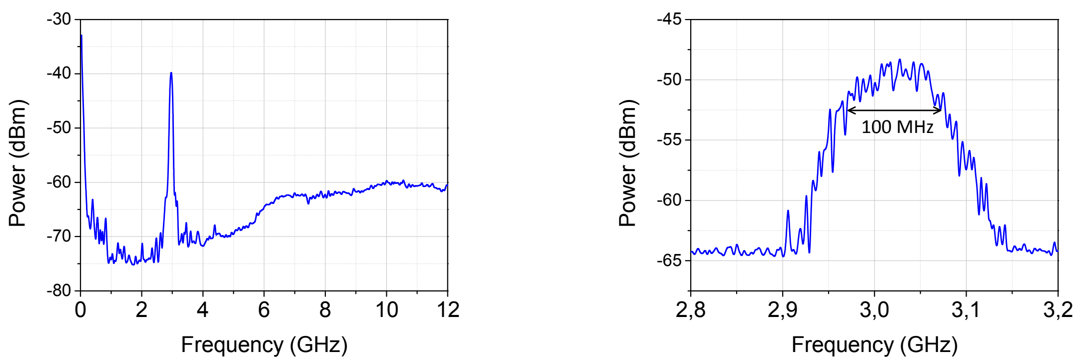


Fig. 6. Visualization of the instantaneous beat note between output pulses from the emitter and a DFB laser diode at 2051 nm on a fast oscilloscope.



(a) *(b)*

Fig. 7. Beat note analysis with an 18 GHz electronic spectrum analyser. The spectra shown are envelope of multiple scans accumulated over 20 s.

Beat note analysis gives an insight on the SMSR and the mean linewidth of the pulses emitted by the MOPA. In particular no additional peak separated from the free spectral range of the cavity could be detected which assesses single mode operation with an extinction better than 20 dB, the measurement being currently limited by the noise level of the photodiode and ESA. The full width at half maximum of the beat note linewidth is measured to be better around 100 MHz. Given that the beat note spectrum is the result of convolution between the laser diode and the emitter (including their respective fluctuations during the acquisition process), it can be assessed that the output linewidth of the emitter is better than 100 MHz.

V. CONCLUSION

We have thus demonstrated an emitter able to address the CO_2, CH_4 and H_2O lines of interest for IPDIAL monitoring from space. The output performances of the emitter are consistent on a wide spectral range from 2.05 µm to 2.3 µm, with an overall optical efficiency close to 40 %. Up to 20 mJ in the signal wave could be extracted and spectral characterization show a frequency stability of 2 MHz over 10s, a SMSR better than 20 dB and a linewidth better than 100 MHz at FWHM. Future work will be dedicated to the improvement of the frequency stabilization and tuning scheme, the improvement of the source technical readiness level through proper thermo-optical design and environment testing, multi-species multi-line sampling DIAL experiments, and energy scaling up to the levels required for space applications.

This work has been partially supported by contract 115606/00, “Source paramétrique multi-longueurs d’onde pour Lidar DIAL”, of the CNES Research and Technology programme

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