Compact and efficient nanosecond pulsed tuneable OPO in the mid-IR spectral range

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ABSTRACT

A compact, robust and efficient nanosecond pulsed optical parametric oscillator (OPO) generating radiation in the mid-IR spectral range is reported. The OPO is based on periodically poled material for the efficient non-linear processes of up-converting 1064 nm radiation to 1538 and 3450 nm respectively. Pulsed emission exceeding 130 mW average power at the idler (3450 nm) with a total conversion efficiency of 30%, including both signal and idler, has been reached. The maximum pulse energy of the idler is 11 µJ, pulse duration around 4 ns and peak power close to 3 kW. The results are achieved for an optical pump power of 1.4 W at the entrance of the OPO and an electrical pump power of 14 W. The total size of the OPO device is only 125x70x45 mm^3 (LxWxH) including the pump laser at 1064 nm. The idler output radiation is narrowed by spectral filtering to < 1.5nm and temperature tuneable over > 50 nm. The OPO has a robust design and withstands shocks up to 60g at 8 ms and the storage temperature is -20 °C to + 60 °C.

The compact size and low power consumption make this OPO device suitable for many kinds of molecular spectroscopy applications in the areas of environmental monitoring and pollution control as well as in combustion physics and process control. Integration of the OPO source into compact equipment for Photo Acoustic Spectroscopy (PAS) allowing fast and highly sensitive detection of methane and ethanol at ppb-levels is also described.

Keywords: Mid-infrared radiation, diode-pumped solid state lasers, optical parametric oscillator, periodically poled materials, nanosecond pulsed, gas detection, environmental monitoring

1. INTRODUCTION

There is a substantial interest to develop tuneable coherent light sources in the mid-infrared spectral range. Such light sources are ideal for fast, accurate and sensitive molecular gas detection applications in environmental monitoring as well as for control and limitation of pollution emissions in petro-chemical, automotive and energy production industries. There are several laser technologies available that are capable of providing emission in the mid-infrared region of interest for molecular gas detection. However, each of them is associated with certain technical limitations that inhibit full market adoption. An optical parametric oscillator (OPO) can provide high enough output power in the spectral region 1.5 to 5 µm, continuous tuning and sufficiently narrow bandwidth to meet the requirements of many scientific and industrial applications. However, OPOs are usually bulky and not robust enough for industrial use. Diode-pumped lasers based on crystalline materials such as Ho:YAG can provide high output powers at 2.1 µm and Tm-doped fiber lasers at 1.9 µm, however with no or very limited tunability. Direct diode lasers based on GaSb and related III – IV compounds are available with fast tuning capability in the spectral region between 1.9 to 3.5 µm but with limited power if in diffraction limited beams. Finally, Quantum Cascade Lasers (QCLs) are available in the range of around 4 to 12 µm, but have difficulties to cover the 3-4 µm region where many gas molecules of interest have their most pronounced finger-prints and they are also relatively power consuming.

In this article we aim at demonstrating a mid-infrared source that possesses all important technical performance features needed to serve in a large variety of industrial and scientific applications, simultaneously combining compactness, robustness, broad spectral coverage, low power consumption and low life-cycle costs.

2. EXPERIMENTAL SET-UP

2.1 Technical background

We have assembled several OPOs during this study, covering the range around 3.3 and 3.45 µm. The main analysis in section 2 and 3 of this paper is concerning an OPO generating coherent radiation in the spectral region 3405 – 3463 nm (the idler region) and 1536 – 1548 nm (the signal region). However, the output data is very similar regardless of the exact spectral region and repeatable from unit to unit. The OPO is pumped by a single frequency nanosecond laser at 1064 nm and both the pump laser and OPO is housed in the same compact laser box. To our knowledge this is the first commercially available OPO capable of delivering > 130 mW average power at the idler wavelength from a compact package.

There are many challenges in designing and producing an OPO that is able to generate in the mid-infrared spectral region. Parametric generation relies on the interplay between three coherent fields of radiation: the pump, the signal and the idler field, see figure 1.

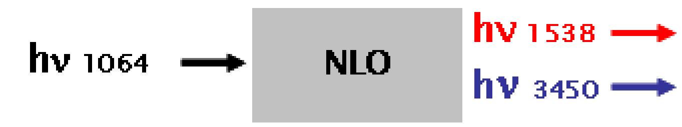


Figure 1. Schematic description of the non-linear processes utilized in parametric generation.

The growth of the signal and idler fields are derived from the non-linear wave equation and is expressed as follows:

$$\begin{aligned} I_s(L) &= I_s(0)(1+G) \\ I_i(L) &= I_i(0)G \end{aligned} \tag{1}$$

L denotes the length of the non-linear medium, *I* the intensity and *G* the gain factor. The subscripts *p*, *s* and i stands for pump, signal and idler respectively. The expression for *G* is written:

$$G = (gL)^2 \frac{\sinh^2\left(\sqrt{x}\right)}{x} \tag{2}$$

And the factors *g* and *x* are expressed as:

$$g^2 = \frac{2\omega_s\omega_i d_{eff}^2 I_p}{\varepsilon_0 c^3 n_p n_s n_i} \tag{3}$$

$$x = (gL)^2 - \left(\frac{\Delta k_{tot} L}{2}\right)^2 \tag{4}$$

angular frequency is denoted ω, d_{eff} denotes the effective non-linear coefficient, *n* is refractive index and Δk_{tot} is the total phase-mismatch.

In case of very strong gain and perfect phase-matching the signal and idler fields will experience exponential gain according to the following equations:

$$\begin{aligned} I_s(L) &= I_s(0)\cosh^2(gL) \\ I_i(L) &= I_i(0)\sinh^2(gL) \end{aligned} \tag{5}$$

The parametric generation starts out by borrowing photons from the vacuum state at start, i.e. there are no photons in the signal and idler field at the moment when the pump pulse reach the non-linear medium mediating the frequency conversion. But if the gain factor is large enough then the signal and idler fields will experience exponential growth. A large output from parametric generation is reached in case of high pump intensity, large non-linear coefficient and a long non-linear crystal. This led to the design of a pulsed pump laser to achieve high intensity and a resonant cavity around the non-linear crystal to form an OPO to virtually increase the length of the crystal to enhance the output. Finally periodically poled material has been chosen for efficient and walk-off free conversion.

2.2 Choice of non-linear material

In the scope of choosing non-linear material for efficient conversion several parameters have to be taken into account. First a choice between birefringent phase matching (BPM) and quasi phase matching (QPM) [1] has to be made. QPM offers several benefits such as walk-off free interaction between the interacting electro-magnetic fields leading to long interaction lengths and simultaneously preserving the transversal mode quality. The largest non-linear tensor element of the non-linear process is often also possible to access; something that usually is not the case for BPM processes. The engineering of the QPM material must on the other hand be mastered to get sufficient quality of the periodically poled material.

In case of the presented OPO in this paper we have chosen PPCLN as non-linear material due to its high non-linear coefficient d_{eff} = 15.9 pm/V [2] and apertures of 1 mm thickness as standard. The transparency is excellent up to 5500 nm and the damage threshold is sufficiently high.

Table 1. Material parameters for possible OPO crystal [2,3,4].

	KTP	LiNbO3	LiTaO3	BBO	LBO
Transparency range [nm]	350 - 4500	330 – 5500	280 - 5500	185 – 3500	160 - 2800
Refractive index*	1.8	2.2	2.2	1.6	1.6
Effective non-linearity (deff) [pm/V]	9.8	15.9	8.8	1.8**	NA**
Walk-off** [mrad]	0	0	0	60**	NA**
Phase-matching technique	QPM	QPM	QPM	BPM	BPM

* Values given at 1064 nm. ** Values for phase-matching 1064 nm = 1540.5 nm + 3440 nm

The engineering of the QPM grating inside of the material is done by electric field poling [5]. The dimensions of the non-linear crystal is 20x2x1 mm^3 and the poled period Λ = 30.4 µm.

2.3 Cavity design

The OPO consist of two cavities; the cavity of the pump laser and the OPO itself. Both cavities together with routing and beam shaping optics fit inside an area of 70x50 mm^2. The cavity design of the pump laser is depicted in figure 2 below.

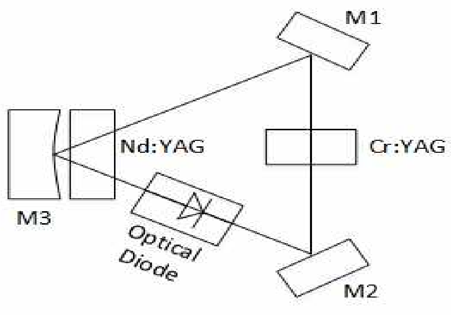
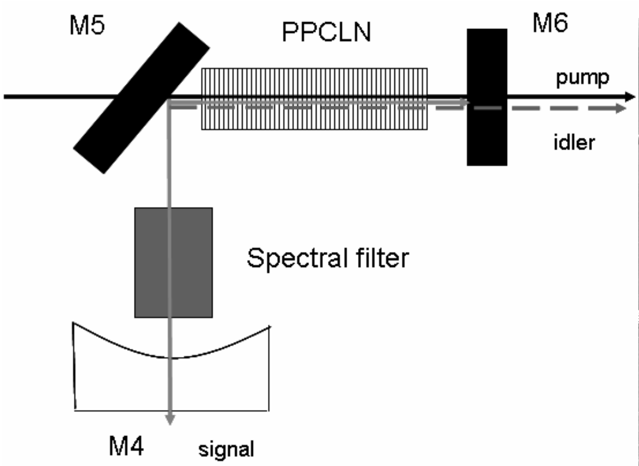


Figure 2. Schematic drawing of pump laser cavity.

The high finesse laser cavity is a unidirectional ring cavity with three cavity mirrors. The three mirrors constitute a triangle with two sides of equal length. Two of the mirrors (M1, M2) are flat but the one at the top of the triangle (M3) is curved. The intra-cavity field at 1064 nm is rotating anti-clockwise around the cavity perimeter; the cavity length is approximately 50 mm. The cavity is pumped through the mirror M3 by one or two laser diodes at 808 nm. The maximum attainable output power level of the diodes is up to 4 W each. The pump focus is approximately 200 µm diameter in the laser crystal (LC). The laser crystal is Nd:YAG with a dopant level of 1% and a length of 3 mm. An optical isolator is inserted in the cavity to force the laser to run uni-directional. A Cr:YAG crystal is inserted acting as a passive Q-switch.

The non-linear frequency conversion takes place in the OPO cavity, figure 3. The cavity consists of three mirrors, the idler is coupled out through mirror M6. The mirrors M5 and M6 are highly reflective at the signal wavelength and the mirror M4 is transmitting 5 % of the signal. The pump energy is single pass. A spectral filter is inserted to reduce the bandwidth of this OPO. The idler radiation is then beam shaped to desired divergence and diameter and routed to the exit hole of the laser. A fraction of the beam is also tapped off to the feed-back loop for output power control. The pump cavity fits within an area of 30x20 mm^2 and the OPO cavity 25 x 15 mm^2 which must be considered to be very compact. The laser including electronic boards for the laser head takes a volume of 125x70x45 mm^3.



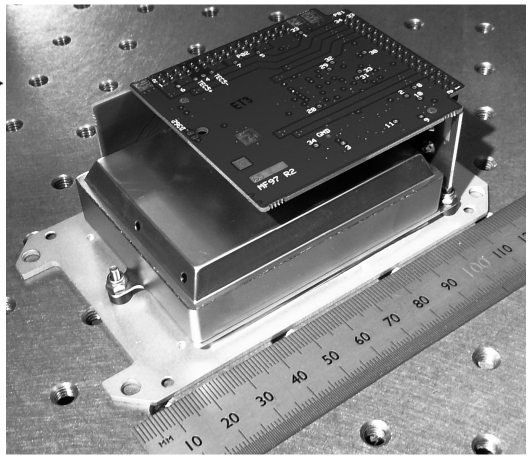


Figure 3. Left: Schematic description of the OPO cavity. Right: Picture of the laser head with removed outer lid. The hermetically sealed sub-package containing pump laser, OPO and routing optics is visible underneath the electronics board. The scale on the ruler is in mm.

2.4 HTCure™ technology

The output parameters of the ring laser described here is strongly dependant on a very stable platform. Therefore Cobolt AB has developed the HTCure™ technology [6]. The HTCure™ technology is based on building the lasers into a hermetically sealed sub-package in a planar configuration. The material and design of each component in the architecture has been carefully chosen for extremely high overall thermo-mechanical stability. This is foremost done through matching the thermal expansion coefficient of all included parts to each other. As a result, the design is so thermo-mechanically stable that the whole laser can be baked at >100 °C for several hours and at multiple phases as part of the manufacturing process without the laser going out of alignment or any damage being caused.

This extra-ordinary capability of the design has enabled the use of an advanced type of adhesive for the fixation of cavity components that cures at high temperatures, instead of the traditional UV curing fixation methods. Thermal curing yields a very stiff and reliable fixation joint, free from outgassing and the long-term drifts sometimes associated with after curing using UV light only.

3. EXPERIMENTAL RESULTS

3.1 Pump laser

The average power from the 1064 nm pump laser was measured with a Melles Griot 13PEM01 power meter. The maximum average pump power reached 1.5W at 3.5A of laser diode pump current. The pulse duration and repetition rate was measured with a fast InGaAsP photodiode model UPD-70-IR2-P with 70 ps rise time from Alphalas. This diode was connected to 1 GHz oscilloscope from Tektronix. The pulse energy was calculated by dividing the average power with the pulse repetition rate. The pump laser reached 115 uJ pulse energy at full power and the repetition rate was then 13 kHz, see figure 4. The pulse duration varied between 4 - 5 ns depending on the pump current, see figure 5. The peak power was calculated from the pulse energy divided by the pulse duration, with the assumption that the pulse shape was a top-hat profile for simplicity, also figure 5. The actual pulse shape in the time domain is shown in figure 6. The peak power is the most interesting parameter for driving the OPO. The pump laser reached 29 kW of peak power at full pump power.

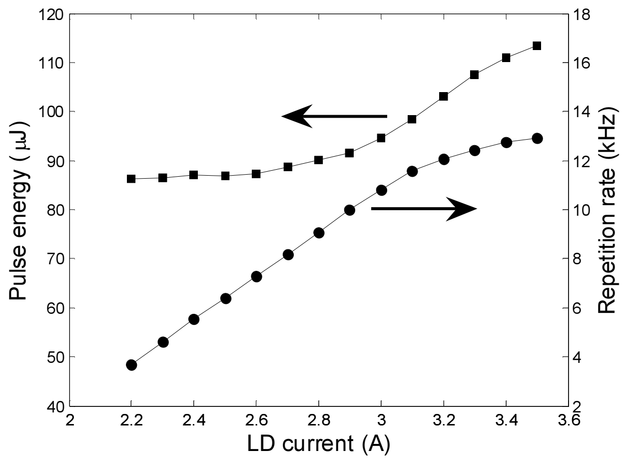


Figure 4. Pulse energy and repetition rate of the pump laser with dependence of laser diode current.

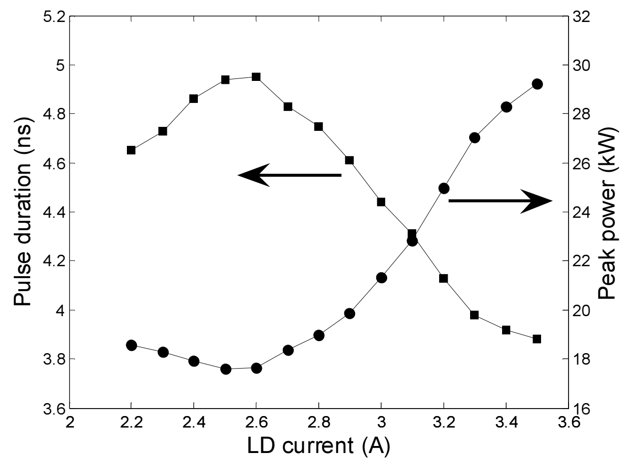


Figure 5. Pulse duration and peak power of the pump laser with dependence of laser diode current.

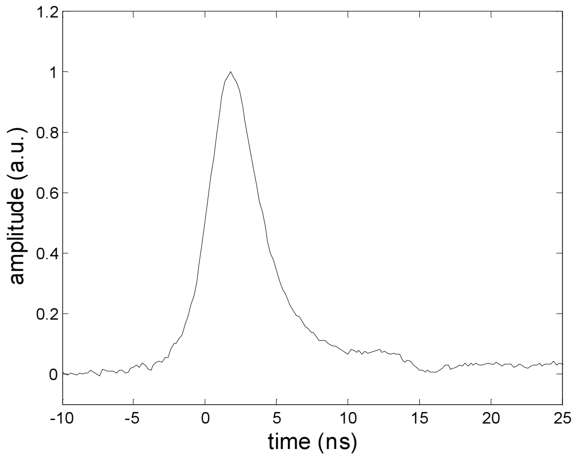


Figure 6. Pulse shape in time domain of the pump laser at 1064 nm.

The laser was running with a stable pulse train where the pulse to pulse amplitude fluctuations were less than 5% at constant current operation. No double pulse behavior was observed. The spectral properties were characterized by an optical spectrum analyzer, Yokogawa AQ6370C. The spectrum showed a resolution limed peak with a bandwidth of 0.02 nm FWHM. This resolution was on the low side for satisfyingly proving single frequency operation. However, the combination of the high stability of the pulse train and the narrow bandwidth strongly supports the assumption that every single pulse was spectrally single mode. If several longitudinal modes would have been running simultaneously a highly unstable pulse train would have be seen.

The laser is passively Q-switched with the use of Cr:YAG. This implies a certain uncertainty in the buildup time of the pulse which starts from noise and gradually bleaches the saturable absorber as the intensity builds up. In Nd:YAG the energy storage time of the upper laser level is 230 µs, this limits the lower frequencies that practically can be used in CW pumping of passively Q-switched systems. Below the 3-4 kHz "cut-off" frequency, which correspond to ~2.3A of pump current the pulse-to-pulse jitter becomes very large. At higher repetition rates the pulse-to-pulse jitter reduces to below 0.5 µs, see figure 7

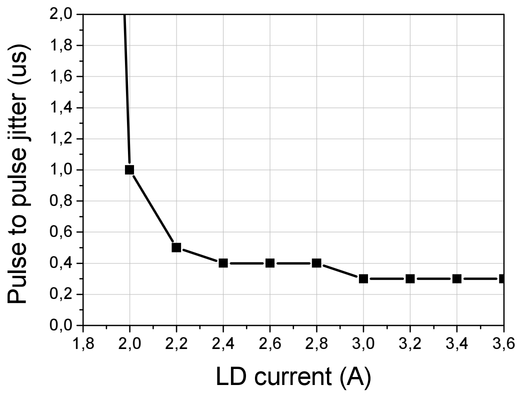


Figure 7. Pulse-to-pulse jitter measured on the pump laser.

The transversal mode is highly symmetrical with an ellipticity > 0.95:1. This was measured with a camera from Spiricon, model SP503U. The M2-value was measured with a Spiricon M2-meter, model M2-200S-FW. The M^2 -value given as geometrical mean $M^2 = \sqrt{M_x^2 M_y^2}$ was better then 1.2 through out the full pump range, see figure 8.

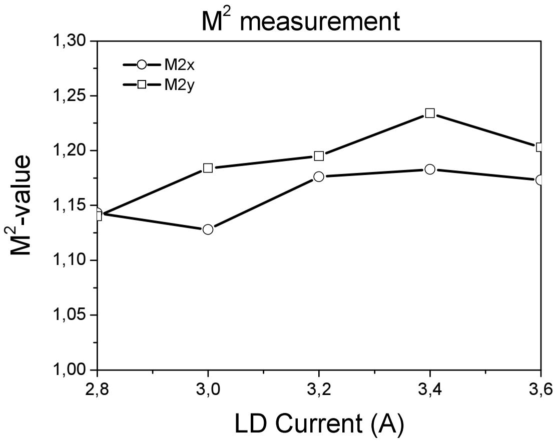


Figure 8. M^2-value of the pump laser at different pump diode currents.

3.2 Mid-infrared threshold and output power and energy

According to [7], the threshold pump pulse energy of a nanosecond singly resonant OPO can be calculated from

$$I_{th} = \frac{1.8 I_p}{g^2 g_s L_{eff}^2 (1+\gamma)^2} \left(\frac{25 L_{cav}}{c\tau} + 2\alpha_p L + \ln\frac{1}{\sqrt{R}} + \ln 2 \right)^2, \tag{6}$$

where L_{cav} is the cavity length, $R=R_{in}R_{out}(1-R_c)^4$, τ is the FWHM of the pulse duration and g_s is the mode-coupling coefficient of the pump and signal beams. Inserting the parameters of the pump beam and cavity configuration results in a pump threshold intensity of 110 MW/cm^2. In terms of pump pulse energy, this corresponds to a threshold of 21 μJ for a 4 ns pulse with a beam diameter of 120μm. Due to the compact lay-out of the pump laser and OPO it is not possible to introduce an additional optical element between the pump laser and OPO. Consequently it is not possible to perform a measurement of the idler pulse energy where we only vary the pump pulse energy by changing the loss in such an additional optical element. Instead we can vary the pump pulse energy by changing the laser diode current. This, however, means that also the pulse length is varied slightly, figure 5 above. Furthermore, since the laser can not produce pulse energies much below 90 μJ, in such a measurement we can not measure at low pump pulse energies close to the threshold, see figure 4. Still, it allows for an approximation of the pump threshold and the result is presented in figure 9 where the pump pulse energy was tuned by varying the laser diode current between 3 and 3.5 A. The extrapolated linear fit yields pump threshold energy of 11 μJ.

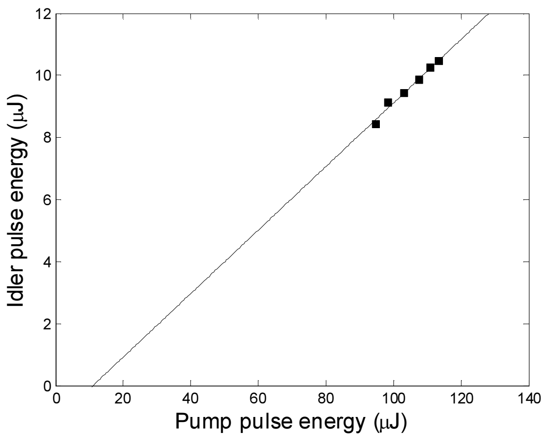
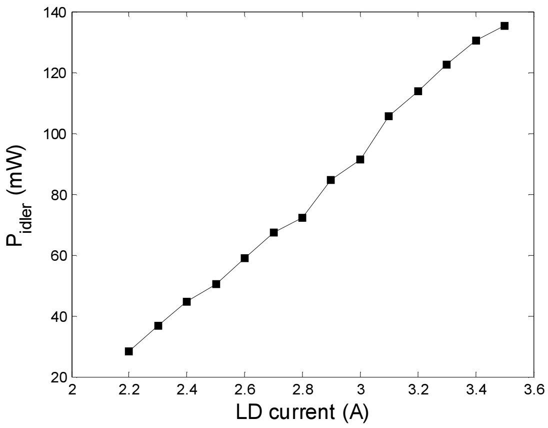


Figure 9. Idler pulse energy as function of pump pulse energy. The line represents a linear fit.

For this device, the maximum measured output power of the idler was 135 mW, figure 10 measured at a pump diode current of 3.5A. As seen in the plot, the OPO is likely to be able to deliver even higher output powers but will ultimately be limited by the damage threshold of the coatings and/or crystal material. The conversion efficiency, defined as ratio of total signal and idler output power and the pump power, was found to be 30% throughout the attainable pump powers.



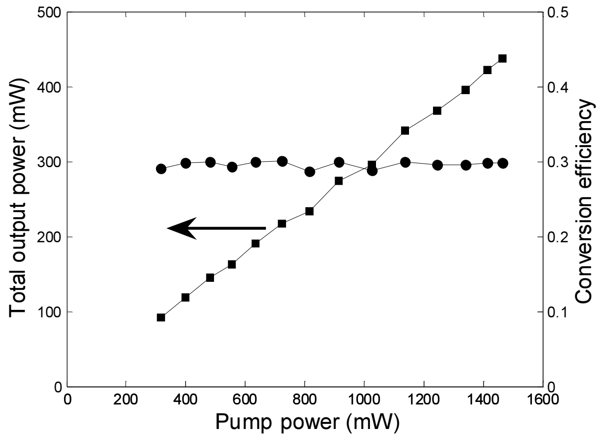


Figure 10 Left: Idler power as function of laser diode current. Right: Total output power of signal and idler as function of pump power and the corresponding conversion efficiency.

The collimated output idler beam was measured using a DataRay WinCamD-FIR2-16 (Figure 11) and the 13.5% beam diameter was 2.5 mm at the exit and the ellipticity 0.96:1.

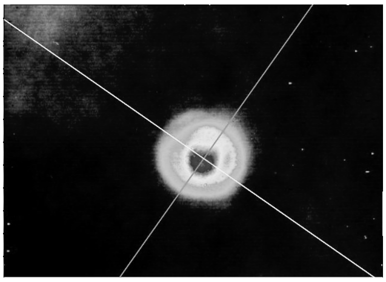


Figure 11. Beam profile of the idler beam measured at exit.

The temporal width of the idler pulse is estimated to be the same as for the pump pulse since the OPO cavity is only resonant for the signal energy. This gives a pulse length of about 4 ns at full power as seen in figure 5 and hence a maximum peak power of close to 3 kW. The electrical power to the laser diodes was then approximately 14 W.

3.3 Narrow bandwidth

Using equations 2, 3 and 4, the FWHM idler bandwidth of the gain, expressed in wavelength, was calculated to 30nm using the Sellmeier coefficients in [8]. To estimate the bandwidth of the OPO, we used the relation between gain bandwidth and the OPO bandwidth presented in [9],

$$\Delta\omega_{OPO} = \frac{1}{\sqrt{p_N}}\Delta\omega_{gain}, \tag{7}$$

where p_N is the number of round trips of the signal pulse in the cavity. In terms of wavelength, the idler bandwidth for our OPO, without the spectral filtering present, was calculated to 9 nm. Although many parameters in calculations are associated with uncertainties, this theoretically calculated value agrees well with the measured spectrum shown to the left in figure 12 where the FWHM of the idler spectrum is approximately 8nm. Since no spectrum analyzer covering the

3-3.5 um regime was available, the idler spectrum was calculated from the measured signal spectrum and assuming energy conservation, i.e. $\omega_p=\omega_s+\omega_i$.

Since many applications benefit from a narrow (and tunable) spectrum, an optical tunable filter was placed in the cavity as shown in figure 3 above. Note that only the signal is resonant in the cavity, hence only the signal passes through the filter. The result on the spectrum width is shown to the right in figure 12 below where it is seen that the bandwidth is reduced to approximately 1.1 nm.

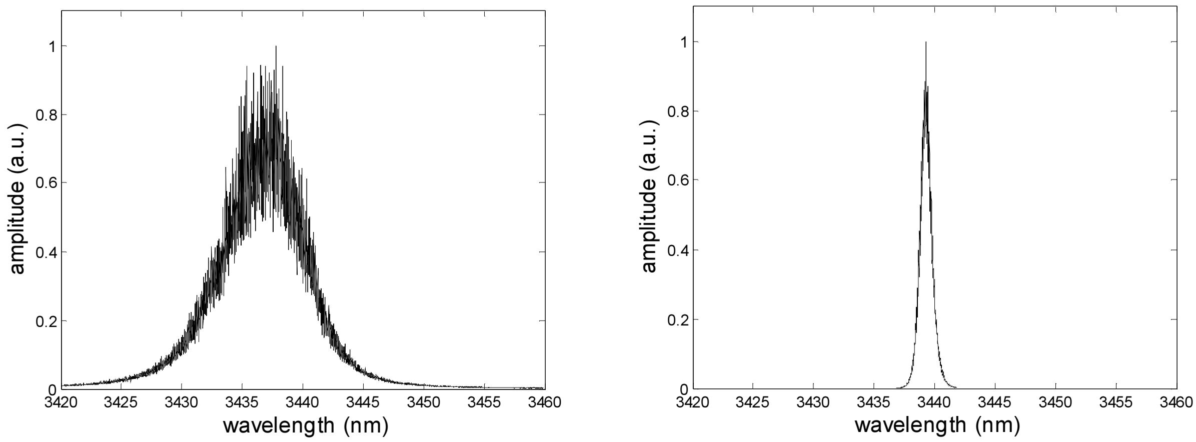


Figure 12. Idler spectrum of the OPO without the spectral filtering (left) and with spectral filter (right).

3.4 Wavelength tuning

In addition to spectral narrowing, the presence of the filter allows for a smooth tuning of the wavelength. The total tuning range of the idler covers 58 nm from 3405 nm to 3463 nm. In figure 13 an example of four spectra is plotted. The idler output power variation across the entire tuning range was found to be approximately 4% when operating the device at a constant laser diode current. This value can be improved substantially by introducing a constant power feed-back loop.

The central wavelength of the tuning range can be controlled by tailoring the QPM period of the PPLN crystal, and devices operating in other wavelength ranges have been evaluated with similar performance as the data presented in this paper. In the application described in section 4 below, an OPO with a tunable idler wavelength range of 3237-3297 nm was used.

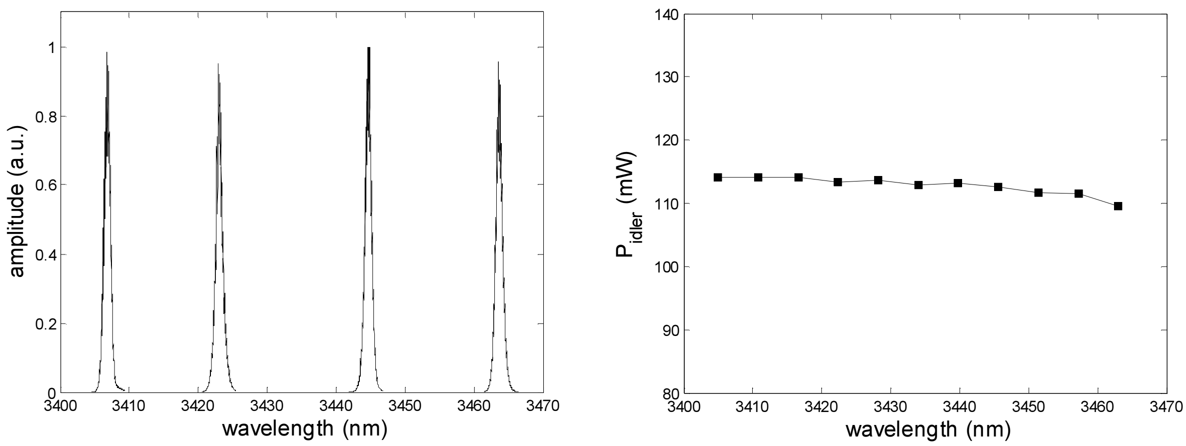


Figure 13, Left: Example of four idler spectra attained when tuning the OPO. The spectra is generated from the measured signal spectrum and assuming energy conservation i.e. $\omega_p=\omega_s+\omega_i$. Right: Power of the idler as function of wavelength measured at a constant laser diode current. The power variation across the tuning range is approximately 4%.

3.5 Stability

The device shows excellent power stability with variations below 2% at constant ambient temperature as well as when cycling the baseplate temperature between 20°C and 50°C. The repeatability of idler power when turning the device on/off is also well within these 2%, figure 14. Also the wavelength is stable with a variation of less than 50 pm over 6h at constant temperature. The wavelength repeatability when tuning the device up and down in wavelength is better than 0.3 nm.

This robustness is very much a result of the manufacturing technology HTCure^{TM} described above.

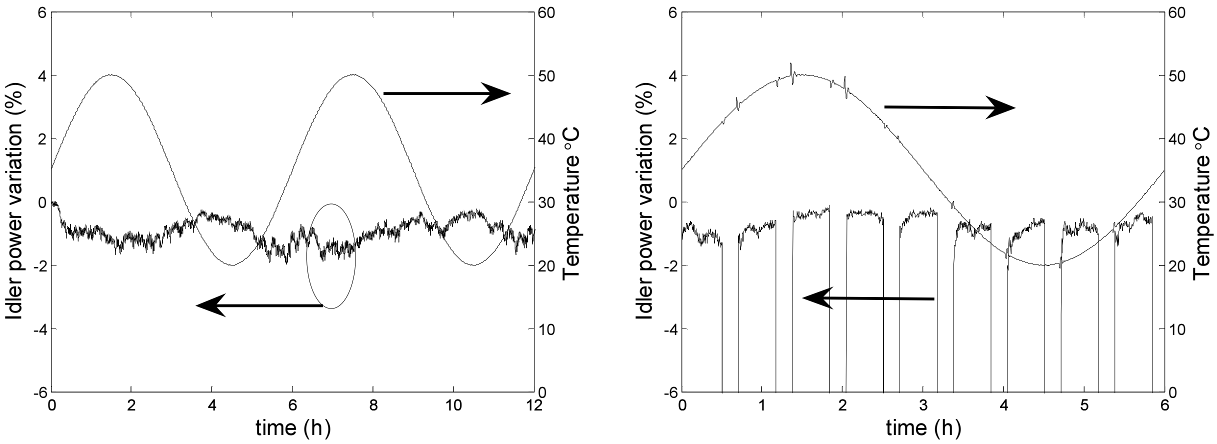


Figure 14. Left: Idler power variation when temperature cycling the baseplate between 20°C and 50°C. Right: Idler power variation when temperature cycling the baseplate and simultaneously turning the device on/off.

3.6 Robustness

The OPO and pump laser has been assembled following the HTCure^{TM} manufacturing process. A laser built in exactly the same package has been tested for robustness in shock and vibration tests following the IEC standard, IEC 60068. The package has proven to sustain shock up to 60g during 8 ms. The OPO will undergo the same type of tests in the near future. The OPO has in addition also passed storage testing between – 20 °C and + 60 °C.

4. APPLICATION

4.1 Introduction

Collaboration between the companies Gasera Ltd [10] and Cobolt AB was set-up to demonstrate the usefulness of the mid-infrared source. In this case another OPO unit was used emitting between 3237 – 3296 nm and with output characteristics very similar to the one described in section 2 and 3. This example shows a low ppb level gas measurement using an extremely sensitive cantilever enhanced photo-acoustic detector combined with the OPO. Target molecule in the demonstration was methane whose detection limit was determined to be 4 ppb using 1 second observation time.

4.2 Measurement set-up

The measurements were performed at Gasera using the photo-acoustic detector PA201 [11] with an optical cantilever microphone and the OPO. The collimated coherent beam at 3.3 µm was directed through the gas cell to a power meter. The OPO idler power was modulated at 135 Hz using a mechanical tuning fork chopper. Gas was sampled using an internal pump inside the photo-acoustic detector. The gas cell was sealed during the measurement and the sample gas pressure was set to 953 mbar. Table 2 contains the OPO parameters during the measurement and table 3 the parameters of the photo-acoustic detector.

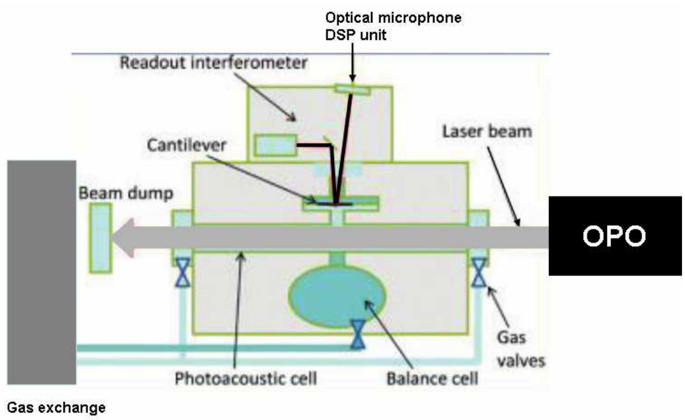


Figure 15. Schematic picture of the photo-acoustic detector set-up.

Table 2. OPO parameters during the measurement

Average power	100	mW
Repetition rate	10	kHz
Pulse width	4	ns
Pulse energy	10	µJ
Linewidth	1.3	nm
Beam diameter	1.6	mm
Wavelength	3237 – 3296	nm

Table 3. Measurement parameters of the gas cell:

Cell pressure	953	mbar
Measurement frequency	135	Hz
Methane concentration	10	ppm
Observation time	0.957	s
Photo-acoustic cell length	95	mm
Photo-acoustic cell diam.	4	mm
Cantilever dimensions	5 x 1.2 x 0.01	mm

4.3 Results

The OPO wavelength was scanned from 3236.45 nm to 3295.95 nm in steps of 0.1 nm. Data was integrated over 0.957 seconds at each measurement point. The resulting spectrum of methane is shown in figure 16 below.

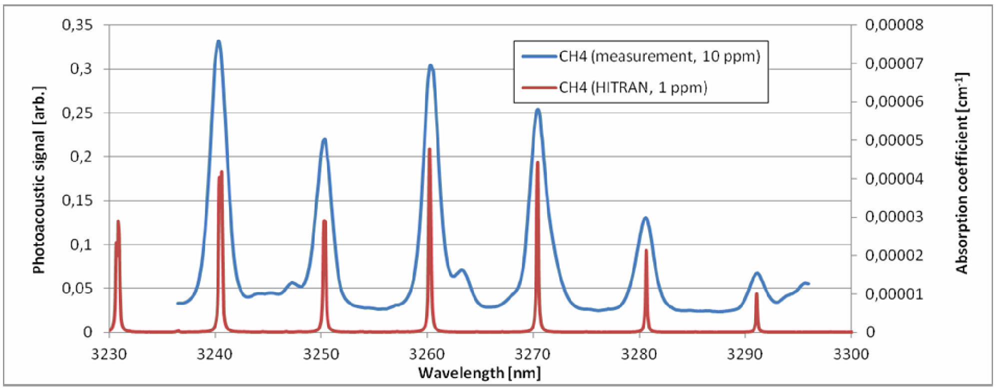


Figure 16. Methane spectrum taken by the OPO and HITRAn spectrum as reference.

The background signal and the noise level at different wavelengths were measured by introducing dry nitrogen into the cell. The noise followed the background signal level since amplitude modulation was used. This means that the main sources of the noise in the experiment are the fluctuations of the parametric power and the optical microphone. In both cases estimated to be below 0.2 %. The detection limit was calculated by dividing the concentration by the signal-to-noise ratio (2 x RMS). The detection limit was calculated to 3.3 ppb see table 4.

Table 4. Calculation of the detection limit

Methane concentration	10	ppm	Methane signal	0.307	
Wavelength	3240.3	nm	Noise	5.00 x 10-5	
Signal	0.331		SNR	6140	
Background signal	0.024		Detection limit (2 x RMS)	3.3	ppb

5. CONCLUSION

In this paper we have presented very compact nanosecond pulsed mid-infrared OPOs operating in the range at around 3.3 µm and 3.45 µm. The OPOs have excellent transversal and spectral properties, running stable with a narrow bandwidth. They are power efficient and capable of delivering more than 130 mW of average power and pulse energies up to 11 µJ at the idler. The OPO and pump laser design is compact and built according the HTCure^{TM} technology for robustness and reliability.

The combination of the sensitive cantilever microphone and the tuneable mid-infrared OPO source was a good match for rapid and selective trace gas analysis. Relatively high output power from the OPO at the fundamental vibration bands of many hydrocarbons and high sensitivity of the photo-acoustic detector results in the low ppb sensitivity. High selectively between the trace gas molecules are ensured due to the large tuning range and narrow bandwidth of the OPO. Both the coherent source and the photo-acoustic cell are already very compact and fit easily to a table top size analyzer.

6. ACKNOWLEDGEMENTS

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