Combined wide pump tuning and high power of a continuous-wave, singly resonant optical parametric oscillator

M.M.J.W. VAN HERPEN†, S.E. BISSON, A.K.Y. NGAI, F.J.M. HARREN

1 Life Science Trace Gas Facility, Department of Molecular and Laser Physics, University of Nijmegen, P.O. Box 9010, 6500 GL, Nijmegen, The Netherlands
2 Combustion Research Facility, Sandia National Laboratories, Livermore, California, 94550, USA

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ABSTRACT A new singly resonant, single-frequency optical parametric oscillator (OPO) has been developed for the 2.6–4.7 µm infrared wavelength region, using a high power (> 20 W), widely tunable (1024–1034 nm) Yb : YAG pump source. With the OPO frequency stabilized with an intracavity etalon, the OPO achieved an idler output power of 3 W at 2.954 µm. Tuning of the idler frequency was achieved by longitudinal mode-hop tuning of the pump source (FSR 100 MHz). In this way an idler frequency scan of 100–150 GHz could be obtained, after which the signal frequency hops ahead over the FSR of the intracavity etalon of the OPO (207 GHz). Due to unoptimized mirror coatings for the OPO cavity and PPLN crystal, the frequency stability was limited to 90 MHz over 1 s, with an unaffected long-term frequency stability of 250 MHz over 200 seconds.

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1 Introduction

In a typical optical parametric oscillator (OPO) a fixed frequency or tunable pump source is used to convert one laser frequency into two new tunable frequencies, with the restriction that energy conservation and phase matching (momentum) conditions are fulfilled. The generated frequency with the highest energy per photon is termed the signal, while the other is termed the idler with their sum equaling the pump energy. Since the performance and design of the OPO depend heavily on the pump specifications, some of the most determining factors for an OPO are the specifications of the pump source and its power.

For low pump powers, a pump-enhanced [1–3], doubly resonant [4], or triply resonant [5] OPO cavity is a good choice since the nonlinear conversion process can be enhanced by resonating one or more of the waves. The advantage of such a setup is that the oscillation threshold is reduced significantly, allowing OPO operation at miliWatt power levels. The main disadvantage of such a design is that wide continuous tuning is limited, because not one, but two or three frequencies need to be kept in resonance with the OPO cavity during tuning. In addition low idler output power limits the field of applications for such a system.

The use of quasi-phase matched materials such as periodically poled lithium niobate (PPLN) coupled with higher power pump sources (multi-Watt) allow the practical use of singly resonant OPOs (SROs) [6–12]. This is an important advantage in that wide continuous tuning is relatively easy, because the OPO cavity only needs to be resonant for a single wavelength. Bosenberg et al. [6, 7] demonstrated the first PPLN based SRO, which yielded up to 3.6 Watt of cw idler radiation in the wavelength range of 3.3–3.9 µm. However, due to the linewidth of their pump source, the idler linewidth was approximately 2.2 GHz, which is too broad for many spectroscopic applications. Tuning with SROs can be achieved by (mode-hop) tuning the signal frequency [8, 9], or by tuning the pump source while keeping the signal frequency fixed [10–12]. With pump-tuning, very wide tuning ranges can be achieved, because well developed tuning methods for the pump sources can be transferred to the generated idler frequency. A good example of this is a single-frequency SRO directly pumped by a tunable diode laser at 925 nm, with 56 GHz continuous pump-tuning for the idler wave [10, 11]. This system had a relatively low output power of 200 mW and covered the 2.01–2.19 µm wavelength region, which is easier to operate on compared to the widely used 3 µm idler region. Recently, a single frequency SRO pumped by a Nd : YAG source yielded 24 GHz of pump-tuning at wavelengths between 3.0 and 3.8 µm with 2.2 Watt of idler output power (line width 3 MHz/s) [12, 13]. Up to now, this was the highest idler output power and continuous tunability reported for a single frequency OPO in this wavelength range.

Using the same Nd : YAG source it was possible to extend the operation of cw, single-frequency PPLN based OPOs to longer wavelengths between 3.9–4.8 µm [14, 15], where absorption by the PPLN crystal is significant. This was the first report of a widely tunable, single frequency laser source within this wavelength region. Due to the strong idler absorption for wavelengths longer than 3.9 µm, OPO operation beyond this point has been a problem [16]. The only other OPO operating up to 4.8 µm was shown by Myers and Bosenberg [17] in 1997, but that system used a multi-mode pump source (linewidth ∼ 2.2 GHz) and was therefore not single frequency.
Here we demonstrate an SRO pumped by a high power (> 20 W) Yb:YAG pump source with wide quasi-continuous tunability (1024–1034 nm), which we have recently used in a pilot experiment for CO2 detection [15]. Due to the high pump power, the OPO could be operated from 2.6 to 4.66 μm, far into the range where absorption of idler wave in the PPLN crystal is significant. An idler output power of 3.0 Watt was achieved at 2.954 μm while using an intracavity etalon to hold the signal frequency constant over a range of 100–150 GHz.

To our knowledge, this is the highest idler output power ever reported for an SRO operating in this wavelength region. Pump tuning was easy and even tuning the pump source by hand gave very good results. The effect of the wide pump tuning on the stability of the signal and idler frequencies was also studied.

2 Experimental setup

The basic OPO setup is similar to that described before [12] and is shown in Fig. 1.

The pump source (Versadisk-1030-30-S, ELS, Gross-Zimmern, Germany) employs a diode-pumped 240 μm thick disk of Yb : YAG material inside an optical resonator, to generate up to 20 W of single-frequency output power in the range of 1024–1034 nm with excellent TEM00 beam quality. An intracavity etalon is placed inside the optical resonator of the Yb : YAG laser to achieve single-frequency operation with a linewidth less than 5 MHz over 1 second. By combining the etalon with an intracavity Lyot filter the system can be tuned from 1020 to 1050 nm, but the system used here applied a different Lyot filter with tuning from 1024–1034 nm. An external chiller was used in a closed loop to cool the Yb : YAG disk with de-ionized water. Even though the output power of the pump laser could be regulated with the driving current, the pump laser was always operated at maximum output power, in order to keep a stable pump power. A combination with a half wave plate (New Focus, Santa Clara, CA, USA) and polarizing beam splitter (OFR, Caldwell, NJ, USA) was used to regulate the laser power delivered to the OPO.

The pump beam was focused into the PPLN crystal through the curved cavity mirror, with a 100 mm focal length lens. The SRO cavity has a bowtie-ring cavity design that was resonant for the signal frequency. The cavity consisted of 2 flat and 2 curved mirrors (radius of curvature 100 mm), coated for maximum reflectivity at the signal wavelength and maximum transmission at the pump wavelength. The reflectivity at the idler wavelength was left as a free parameter and averaged around 10%–20%. This configuration was used previously in our Nd : YAG pumped SRO [12, 14] and hence the mirror coatings were not optimized for pump range of the Yb : YAG (1024–1034 nm). Two different sets of mirrors were used, specified in Table 1, with the first set working at idler wavelengths between 3.0–3.8 μm [12] and the second set operating between 3.65–4.85 μm [14].

The input and output faces of the PPLN crystals were anti-reflection coated for the pump, signal and idler frequencies (see Table 2). As with the cavity mirrors, the PPLN crystal AR coatings were designed for use at 1064 nm, but they should be able to have sufficient anti-reflection properties at 1024–1034 nm.

To prevent photo-refractive damage, crystals were operated at 180–190 °C with a commercially available oven (Super Optronics, Gardena, CA, USA), where they were temperature stabilized to 0.1 °C.

While the OPO tended to operate in a single longitudinal mode (SLM) in the resonated signal wave, SLM operation was enhanced by means of an intracavity, plane parallel (<10 arc seconds) 400-μm thick uncoated YAG etalon (reflectivity 8%, FSR 207 GHz). Combined with the single frequency pump source, this resulted in a single frequency idler beam with tuning characteristics similar to the pump laser. The intracavity etalon could be rotated to mode-hop-tune the OPO [8, 9], but due to the wide tunability of the pump source this was not necessary.

3 Output power

Since the OPO was intended to serve as a broadly tunable, high power mid-IR source for an ultra-sensitive photo acoustic spectrometer, it was important to achieve the highest possible idler power. We investigated the OPO performance...
with both mirror sets throughout the tuning range of the OPO. For mirror set 1 and PPLN crystal 1 (periods ranging from 28.5–29.9 µm) we achieved an idler output power of 3 W with a pump power of 18 Watt (measured behind the OPO cavity with OPO operation blocked). Figure 2 shows the OPO idler output power versus pump power for a PPLN period of 29.3 µm. For a PPLN crystal temperature of 189.5 °C, this resulted in signal and idler frequencies of 1584 nm and 2954 nm, respectively. For frequency stability, the OPO was operated with the intracavity YAG etalon which increased the oscillation threshold to 8 Watt. However, this caused almost no loss of output power at full pump power levels. More important was the loss of performance due to the non-optimized pump coatings on the input mirror and PPLN crystal. Pump reflectivity losses at the output face of the PPLN crystal and output mirror are less important as they do not effect the power reaching the PPLN crystal. For these optics, the pump power that was available at the PPLN crystal was reduced by about 15%. Since the OPO was operated substantially above threshold, we estimate that for optimized coatings the idler output power would have increased to 3.5 Watt.

With 18 W pump power reaching the exit of the OPO cavity an idler output of 3.0 Watt was achieved with a pump depletion of 67%. The high threshold and low pump depletion again can be attributed to the non-optimized coatings. Despite this, the 3.0 W idler output power of this system is the highest output power ever reported for a cw single-frequency PPLN OPO at this wavelength. Using proper coating for the optics, this can be easily improved in future.

4 Tunability

The Yb : YAG pump source can be frequency tuned with the intracavity etalon or with an intra-cavity Lyot filter. By tuning the intracavity etalon (FSR 25 GHz) the Yb : YAG laser showed quasi-continuous mode-hop tuning over its cavity modes (FSR 100 MHz). For scans longer than 25 GHz, the Lyot filter could be used to tune the laser over its entire range (1024–1034 nm) via 25 GHz mode hops from the intracavity etalon. The effect of Lyot filter tuning on the signal and idler frequencies was studied by monitoring these frequencies with a wavemeter (Burleigh WA1000 IR, NY, USA) while tuning the Lyot filter manually with a fine pitch adjustment screw. The effect of tuning on the signal frequency is shown in Fig. 3.

The figure compares the measured signal frequencies with the frequencies calculated with the Sellmeier equations of Jundt [18]. Due to the intra-cavity etalon of the OPO the signal frequency initially doesn’t change when the pump wavelength is tuned up. However, after about 100–150 GHz of pump-tuning, the difference between the calculated and the measured signal frequency is greater than the free spectral range of the intra-cavity etalon (207 GHz). At that point, a mode-hop occurs in the OPO cavity, which can be observed as a 207 GHz mode-hop in the signal frequency. This effect is important for the generated idler frequencies, as is shown in Fig. 4.

When the pump frequency was tuned and the signal frequency remained fixed, the idler frequency could be mode-hop tuned with steps of 25 GHz, caused by the intracavity etalon within the pump laser. The signal frequency makes 207 GHz mode-hops after about 100–150 GHz of tuning in the pump and idler frequencies. When the signal frequency makes its mode-hop, the idler wavelength hops back over 207 GHz. This is a problem, because the direction of the idler mode-hop is in the same direction as the idler tuning, which means that not all idler frequencies are covered within the scan (see also Fig. 4). To compensate for this, the etalon within the OPO cavity can be tuned. Alternatively, the temperature of the crystal can be increased or decreased in order to prevent the signal frequency from mode hopping.

By tuning the intra-cavity etalon of the pump laser, quasi-continuous mode-hop tuning can be achieved over its free spectral range of 25 GHz. Very wide scans can be made when this is combined with tuning of the Lyot filter. This was demonstrated by recording a 190 GHz wide absorption spectrum of a mixture of 20-ppm ethane in nitrogen with photo acoustic spectroscopy [19, 20]. The photo acoustic cell was
the same as described earlier [21] and has an open-ended cylindrical acoustic resonator (length 300 mm, radius 2 mm) excited in its first acoustical longitudinal mode at a resonance frequency of 560 Hz. The photo acoustic signal was detected by 3 Knowles IK3024 electret microphones and amplified with a lock-in amplifier.

Tuning of the idler frequency was performed by hand, using one fine pitch adjustment screw on the Lyot filter and one on the intra-cavity etalon of the pump laser. Tuning was accomplished in two steps. First, the pump intracavity etalon was used to tune the idler frequency over 25 GHz with 100 MHz mode hops in the pump laser. Then the Lyot filter was tuned slightly in order to induce an intracavity pump-etalon mode-hop of 25 GHz, after which the pump-etalon could be tuned again. This process was repeated several times in order to cover a 190 GHz region containing several absorption lines of ethane (Fig. 5). This shows two strong absorption peaks in the recorded ethane spectrum, which agrees very well with an ethane spectrum measured previously with an FTIR spectrometer [22].

The peak to the left was recorded by relatively fast tuning of the pump laser, whereas the peak to the right was recorded when tuning the pump laser more carefully. In the future, a stepper motor could be used to make tuning easier and more controllable resulting in a much higher quality of the recorded spectrum than the current hand-tuned result. However, the manual tuning demonstrates the simplicity by which the pump laser and the OPO can be tuned. The strongest recorded ethane absorption line (Fig. 5) has a maximum strength of 950 mV/Watt, which is in agreement with previously reported results using a continuously-tunable Nd : YAG pumped OPO [21]. In that report an ethane detection limit of 0.01 ppb was achieved with 1.2 W of power, whereas this system has an output power of 2.15 Watt at the same idler frequency. This means that this OPO system has the potential to improve the ethane detection limit by a factor of two, because the photo acoustic signal scales linearly with the applied laser power.

5 Frequency stability

For the current setup unwanted etalon and resonance effects are expected, as the coatings of the cavity mirrors and PPLN crystals are not optimized for the current combination of pump, signal and idler frequencies. In order to ensure singly resonant operation of the OPO it is important to suppress residual reflectivity of the mirrors at the pump and idler frequencies, otherwise the OPO can become slightly doubly resonant [9, 23]. Similarly, the AR coatings on the PPLN crystal must be of good quality otherwise etalon effects will be observed. In the present case this is mitigated through the use of an angled cut of 1° on the PPLN crystal face. Both of these effects (double resonance and etaloning) can have adverse effects on the frequency stability and tuning of the OPO [23]. As shown, pump tuning of the idler frequency was not affected significantly. The wavelength stability and high-resolution performance of the OPO were examined using a photo-acoustic recording of a low-pressure (77 mbar) absorption line of the same 20-ppm ethane mixture that was used for the tuning experiments. The strongest peak of Fig. 5 at 2996.9 cm⁻¹ was used for this experiment. The laser emission was placed at the half maximum of this absorption line in order to estimate the frequency stability of the idler wavelength by the change of the photo acoustic signal over time [13].

Figure 6a shows a fairly good overlap between the recorded photo acoustic spectrum and the calculated absorption line with 670 MHz full width at half maximum. When tuning the intra-cavity etalon of the pump laser, the output frequency was mode-hop tuning over the free spectral range of the pump laser cavity (100 MHz). Fortunately, the mode-hops were small enough to be able to record an absorption at this low pressure. However, a continuously tunable laser source would achieve a much better resolution and would therefore be more suited to measure such an absorption.

The frequency stability of the system is shown in Fig. 6b, which shows the recorded photo-acoustic signal with all
tuning elements stationary. The signal shows many random power oscillations at high frequencies, combined with an oscillation at a lower frequency. These oscillations are caused by detuning of the idler frequency, resulting in a different photo acoustic signal. The slow oscillations have been identified before as originating from oscillations in the temperature of the PPLN crystal [13]. In 200 seconds the slow oscillations caused an idler frequency drift of 250 MHz, which is similar to the stability of a Nd : YAG pumped OPO [13]. However, the fast frequency drift has not been observed with that OPO system, but here this can be as high as 90 MHz per second. It is likely that the not-optimized coatings of the optics used in this setup cause these oscillations through resonance and etaloning effects. In this case the mirror transmission was about 15% for the pump light. The idler frequency was well within the specified range of the anti-reflection coatings, with the signal frequency at the edge of these coatings at 1.5 µm. Another explanation for the bad short-term frequency stability could be the fact that the OPO cavity was not covered with a box, so air currents could have caused instabilities. If this is solved with properly optimized coatings and a cover around the cavity, the OPO frequency stability can be below 3 MHz/s [13], limiting the idler stability to the frequency stability of the pump source (less than 5 MHz in 1 second).

6 OPO operation between 4 and 5 µm

As there are many species of interest that absorb at wavelengths longer than 4.0 µm, there is considerable interest in extending OPO operation beyond 4.0 µm. Continuous wave OPO operation beyond 3.9 µm has proved difficult in lithium niobate as intrinsic absorption becomes significant at longer wavelengths [14, 16, 17]. However, there is considerable interest in PPLN OPOs operating above this wavelength, as there are currently no powerful, widely tunable, single-frequency laser sources available in this range. Recently, the first single-frequency OPO operating in this range was presented [14]. This was a Nd : YAG (1064 nm) pumped SRO, operating at idler wavelengths between 3.9 and 4.7 µm. Here, we extend operation of this OPO using the same optics that were used for the previous OPO demonstration but with a tunable Yb : YAG pump laser.

Using the wide pump-tuning range combined with the 8 poling periods of the PPLN crystal, an idler wavelength range between 3.3 and 4.6 µm could be achieved. This means that the OPO can be aligned with the default procedure at 3.9 µm, after which the crystal can be tuned to generate wavelengths above 3.9 µm. Figure 7 shows the output power of the system with a pump power of 11.5 W (measured behind the OPO cavity with OPO operation blocked), which is the same output power used with the Nd : YAG pumped system [14].

As expected, the output power drops quickly for idler wavelengths longer than 3.9 µm. At 3.8 µm the output power (without the intra-cavity etalon) was 1.5 W, which dropped to 90 mW at 4.66 µm. From 3.8 to 4.66 µm the oscillation threshold and pump depletion went from 3.5 W to 7.5 W and from 65% to 17%, respectively. This is similar to the previous results with the Nd : YAG pump source, but since this system can be pumped with much more power than 11.5 W, the maximum output power can be much higher. With full pump power this system was able to produce 200 mW output power at 4.235 µm (2361.47 cm⁻¹), where the strongest absorption line of gaseous CO₂ is located. This is an order of magnitude higher than the Nd : YAG pumped OPO system [15]. In a pilot experiment we have shown that this system can potentially be used to monitor the CO₂ release of single plant cells [15].

7 Conclusion

The Yb : YAG Versadisk laser has proved to be very well suited as pump source for a widely tunable OPO at idler wavelength between 3 and 5 µm. One advantage of the Versadisk is its high output power, resulting in a high idler output power for the OPO. In addition, the wide tunability of the pump laser can be used to tune the OPO with little effort with steps of 100 MHz. Tuning of the pump source is easy, and even with manual tuning very accurate and detailed
spectra can be recorded. When tuning the pump source, the OPO intra-cavity etalon or the PPLN temperature needs to be adjusted to prevent or compensate for mode-hops in the signal frequency. A possible drawback of the system is that the ability to tune the pump source means that a wavemeter or spectrum analyzer is required in order to measure the pump or idler wavelengths. With a fixed-frequency pump source, a rough indication of the idler frequency can be derived from the PPLN period and its temperature [14]. The performance of the OPO setup was limited due to un-optimized coatings on the cavity mirrors and PPLN crystal, which were designed for use with a 1064 nm pump source. This caused instabilities in the generated idler frequency of 90 MHz/s. The stability of the idler frequency was 250 MHz over 200 s, caused primarily by fluctuations in the temperature of the PPLN crystal. Despite the use of un-optimized coatings, an output power of 3 W was achieved at 2954 nm idler wavelength. The system also operated at wavelengths between 3.9 and 4.66 µm, where crystal absorption at the idler wavelengths makes OPO operation difficult. Due to its wide tunability, the system could potentially cover the full idler wavelength region from 2.5 to 5 µm with just one single multi-period PPLN crystal.

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