Singly resonant cw OPO with simple wavelength tuning

Markku Vainio,[1] Jari Peltola,[1] Stefan Persijn,[2,3] Frans J. M. Harren[2] and Lauri Halonen[1,*]

[1]*Laboratory of Physical Chemistry, P.O. Box 55 (A.I. Virtasen aukio 1), FIN-00014 University of Helsinki, Finland*
[2]*Life Science Trace Gas Facility, Molecular and Laser Physics, Institute for Molecules and Materials, Radboud University, P.O. Box 9010, NL-6500 GL Nijmegen, The Netherlands*
[3]*Current address: Nederlands Meetinstituut, Thijsseweg 11, 2629 JA Delft, the Netherlands*
[*]*Corresponding author: lauri.halonen@helsinki.fi*

Abstract: A singly resonant continuous-wave optical parametric oscillator (cw OPO) is described. The OPO contains no intracavity etalon, which makes its wavelength tuning simple and straightforward, including only temperature tuning of the nonlinear crystal and wavelength tuning of the pump laser. The OPO provides watt-level output in the mid-infrared region and operates reliably without mode hops for several hours.

OCIS codes: (190.4970) Parametric oscillators and amplifiers; (140.3600) Lasers, tunable.

References and links

1. A. Henderson and R. Stafford, "Low threshold, singly-resonant CW OPO pumped by an all-fiber pump source," Opt. Express **14**, 767-772 (2006).
2. A. K. Y. Ngai, S. T. Persijn, G. von Basum, and F. J. M. Harren, "Automatically tunable continuous-wave optical parametric oscillator for high-resolution spectroscopy and sensitive trace-gas detection," Appl. Phys. B **85**, 173-180 (2006).
3. I. Lindsay, B. Adhimoolam, P. Groß, M. Klein, and K. Boller, "110GHz rapid, continuous tuning from an optical parametric oscillator pumped by a fiber-amplified DBR diode laser," Opt. Express **13**, 1234-1239 (2005).
4. S. E. Bisson, K. M. Armstrong, T. J. Kulp, and M. Hartings, "Broadly tunable, mode-hop-tuned, cw optical parametric oscillator based on periodically poled lithium niobate," Appl. Opt. **40**, 6049-6055 (2001).
5. T. Ikegami, S. Slyusarev, and S. I. Ohshima, "Long-term, mode-hop-free operation of a continuous-wave, doubly resonant, monolithic optical parametric oscillator," Opt. Commun. **184**, 13-17 (2000).
6. G. Boyd and D. Kleinman, "Parametric interaction of focused Gaussian light beams," J. Appl. Phys. **39**, 3597-3639 (1968).
7. A. V. Smith, SNLO software, 4.0 edn. (2005).
8. A. V. Okishev and J. D. Zuegel, "Intracavity-pumped Raman laser action in a mid IR, continuous-wave (cw) MgO:PPLN optical parametric oscillator," Opt. Express **14**, 12169-12173 (2006).
9. A. Henderson and R. Stafford, "Spectral broadening and stimulated Raman conversion in a continuous-wave optical parametric oscillator," Opt. Lett. **32**, 1281-1283 (2007).

1. Introduction

Continuous-wave optical parametric oscillators (cw OPOs) have become important spectroscopic tools in the mid-infrared region, where the availability of tunable laser sources is otherwise limited. Singly resonant OPOs are of particular interest because of their large output powers of up to several watts [1,2]. In the 3-μm-band OPOs, the most commonly used nonlinear crystal is MgO-doped, periodically poled lithium niobate (MgO:PPLN). Coarse wavelength tuning of several hundred cm^{-1} can be attained by selecting appropriate crystal poling period and by tuning the crystal temperature for the desired phase-matching wavelength. Mode-hop free fine tuning, however, is more difficult to obtain over a frequency range that would be large enough for practical applications. Apparently the most promising method is pump-tuning, in which the OPO signal wavelength is kept fixed while the pump laser is tuned. Recent advances with the widely tunable high-power pump lasers have made it possible to obtain mode-hop free idler tuning of more than 100 GHz [1,3].

#97335 - $15.00 USD Received 11 Jun 2008; revised 9 Jul 2008; accepted 9 Jul 2008; published 10 Jul 2008

All singly resonant cw OPOs demonstrated so far need an intracavity etalon for long-term single-mode operation and/or frequency tuning. Although the etalon-cavity OPOs can provide stable single-mode operation, they suffer from intracavity losses that depend on the etalon rotation angle. Etalon walk-off losses can increase the OPO threshold, limit the wavelength scan range, and cause large power variations when scanning the wavelength [4]. With an air spaced etalon the problem of varying losses can be overcome, but at the expense of complexity and at risk of residual etaloning in the OPO cavity [4]. A common feature of all etalon-cavity OPOs is the existence of etalon mode hops during wide wavelength scans. This leads to unnecessary spectral overlapping and sometimes to even gaps in the covered wavelength region. In addition, an intracavity etalon inevitably prevents the use of a monolithic OPO cavity. A monolithic cavity would be desirable in many applications because of its compact structure and inherently high stability, as has previously been demonstrated with the doubly resonant OPOs [5].

In this paper, we present the first demonstration of a cw singly resonant OPO that reliably operates in a single longitudinal mode without the need for an intracavity etalon. Good stability and convenient wavelength tuning have been achieved by careful thermal control of the nonlinear crystal, and by taking advantage of the thermal self-locking effect. The experimental setup and its characteristics are described in the following section. In section 3 we discuss the requirements for thermal control of the crystal.

2. Experimental setup

The singly resonant OPO described here produces watt-level cw output in the mid-infrared region of 2.7-3.45 μm. Signal wavelength resonating in the cavity is 1.54-1.76 μm, and pump wavelength is 1.064 μm. Figure 1 shows the two OPO cavity configurations that we have used. Cavity design parameters are summarized in Table 1. In addition to the linear standing-wave cavities, we have tested the commonly used four-mirror ring cavity [1-4]. The ring cavity provides essentially the same OPO performance as the four-mirror linear design.

In both the two- and four-mirror configurations, we have used an output coupler mirror that has a reflectivity of 97 to 98.5%, depending on the signal wavelength. The output coupler is highly transparent for the idler but reflects 9% of the pump wavelength. Nevertheless, the cavities remain purely singly resonant, since all the other mirrors are highly reflective at the signal wavelength and highly transparent for the pump and idler. Rear surfaces of all mirrors are antireflection coated for all three wavelengths in order to avoid residual etalons. For the same reason, the faces of the nonlinear crystal are also antireflection coated and angle (1°) polished. The crystal is a 50-mm long, 1-mm thick MgO:PPLN (HC Photonics), which contains 7 separate gratings with poling periods between 28.5 and 31.5 μm. The crystal temperature is controlled using thermo-electric coolers (Peltier-elements) and a commercial controller (Newport 350B). With our current setup the temperature can be stabilized to within ±6 mK anywhere between 20 and 120 ^{o}C. We have used a Teflon cover on top of the crystal mount for improved thermal isolation and for protection against air currents.

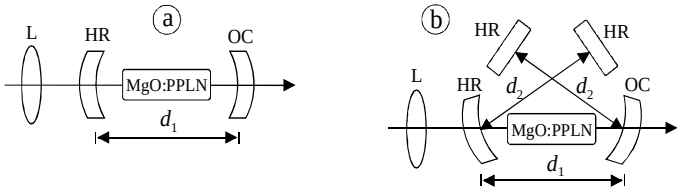

Fig. 1. Schematics of the cavity configurations used in this work. Cavity dimensions d_1 and d_2 are given in Table 1, on the next page. In the figure, L is the pump focusing lens, HR indicates mirrors that are highly reflective (R>99.9%) at the signal wavelength, and OC is the output coupler (R~98%). All mirrors were coated by QTF (Quality Thin Films).

#97335 - $15.00 USD Received 11 Jun 2008; revised 9 Jul 2008; accepted 9 Jul 2008; published 10 Jul 2008

Table 1. Parameters of the OPO cavities shown in Fig. 1

		2-mirror cavity	4-mirror cavity
Spacing between curved mirrors	d_1 (mm)	222	138
Distance from curved to flat mirror	d_2 (mm)	-	262
Longitudinal mode spacing	FSR (MHz)	~ 530	~ 210
Radius of curvature, curved mirrors	ROC (mm)	100	100
Pump focusing lens focal length	f_p (mm)	300	250
Focusing parameter of signal	ξ_s	0.7	2.0
Focusing parameter of pump	ξ_p	1.6	2.3

Cavity dimensions given in the table are physical distances. Focusing parameter is defined as $\xi_x = L\lambda_x/2\pi w_x n_x$, where L=50 mm is the MgO:PPLN crystal length, λ_x is wavelength, w_x is the beam waist size, and n_x is the crystal refractive index seen by the beam. Beam waist sizes are calculated diffraction limited values for a cold cavity; the effect of thermal lensing has not been taken into account.

The OPO is pumped with a narrow-linewidth (70 kHz), polarization maintaining fiber laser (IPG YLR-20-1064-LP-SF). The laser consists of a fiber seed laser and a two-stage fiber amplifier that can deliver up to 20 W of output power. Laser wavelength is 1064 nm and it can be continuously tuned over 140 GHz by changing the laser temperature. The pump laser light is coupled out through an optical isolator and focused into the crystal using a single lens.

Figure 2 shows the OPO output power versus pump power for the two cavity configurations. Both OPOs oscillate in a single longitudinal mode within the plotted power regimes. For the four-mirror cavity, the pump depletion was also measured. Compared to the two-mirror cavity, the four-mirror configuration provides better conversion efficiency because its dimensions can be designed for an optimum focusing parameter of $1 < \xi < 7$ [6].

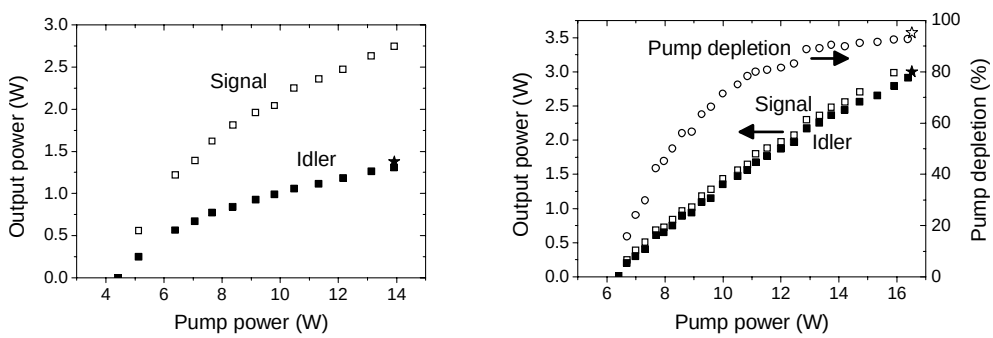

Fig. 2. Output power of the two-mirror OPO (left) and of the four-mirror OPO (right). Pump power was measured before the OPO cavity. For the four-mirror OPO, pump depletion is also shown. Stars indicate the idler power and pump depletion measured after realigning the cavity at the highest pump power – optimum cavity alignment slightly depends on the power level. Idler wavelength is 3130 nm.

2.1 Spectral characteristics and stability

To achieve high spectral resolution and selectivity in laser spectroscopy, the laser source should operate in a single longitudinal mode without mode hops. To confirm single-mode operation of our OPO, we used a wavelength meter (EXFO WA-1500-NIR/IR-89) equipped with a laser spectrum analyzer (EXFO WA-650). These devices together allow us to measure the optical spectrum and wavelength of the OPO pump, signal, and idler. Resolution of the wavelength meter is high enough to resolve adjacent longitudinal modes of the OPO cavity.

The OPO operates in a single mode with a side-mode suppression ratio (SMSR) of better than 23 dB. The high spectral purity is useful in many spectroscopic applications that require precise measurement of the sample absorption – if the SMSR is poor, accidental overlap of an

#97335 - $15.00 USD Received 11 Jun 2008; revised 9 Jul 2008; accepted 9 Jul 2008; published 10 Jul 2008

OPO side mode with an absorbing feature may cause significant error in the measurement. As the idler frequency ω_i is determined by the energy conservation condition $\omega_i = \omega_p - \omega_s$, it is affected by any drift of either the pump laser or the OPO cavity that resonates the signal frequency. To identify the sources of idler frequency drifts, we separately measured the pump laser and signal frequency stability. It was observed that, during the first hour, the pump laser warm-up caused a major effect on the idler drift. During this period there are often some mode-hops in signal frequency, which are believed to be due to changes in pump laser power. After the warm-up period, the pump laser wavelength typically stays within 50...100 MHz and power stability is better than 1%. The OPO runs without mode hops for several hours, which is demonstrated in Fig. 3 for the two-mirror cavity configuration.

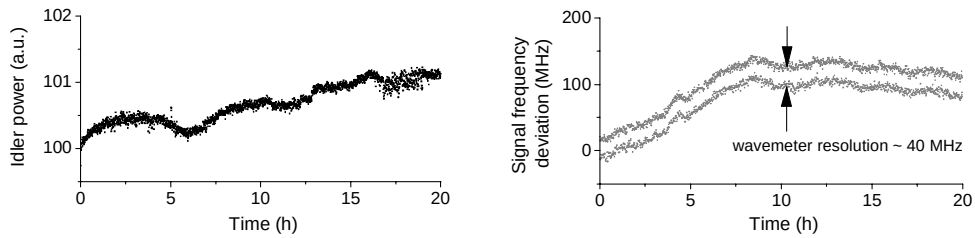

Fig. 3. Normalized idler power (left), and deviation of the signal frequency from its original value (right) over 20 hours. The actual idler power is 0.52 W and the idler wavelength is 3033 nm. Sample interval is 1 s. Power and frequency drifts observed during the measurement are < 1.2% and < 150 MHz, respectively.

Stability of the four-mirror cavity was observed to be similar to that of the two-mirror cavity. In our current setup, the cavity baseplate is not temperature stabilized and the largest effect on signal frequency drift was caused by thermal expansion of the baseplate. This was confirmed by monitoring the baseplate temperature during the measurements. Short-term stability of the open OPO cavity was limited by air currents, which would cause signal frequency fluctuations as large as 100 MHz. To avoid these fluctuations, the cavity was shielded with a plexiglass cover during the measurement presented in Fig. 3. Elimination of the air currents reduced the short-term fluctuations to below the wavemeter resolution.

2.2 Wavelength tuning

Coarse tuning of the OPO wavelength is done in the same way as with most cw OPOs: by selecting a crystal poling period and temperature that provide phase matching for the desired signal-idler pair. Our setup differs from the other ones reported in that no etalon is needed, which means that we avoid the problems related to etalon mode hopping and varying walk-off losses. Using the crystal poling periods 30.5, 31, and 31.5 μm and by tuning the crystal temperature between 20 and 120 ^{o}C, it is possible to cover signal and idler wavelength regions of 1.54–1.76 μm and 2.7–3.45 μm, respectively.

Within the wavelength region supported by a single poling period, the idler wavelength can be tuned without gaps by combining stepwise crystal temperature scanning with mode-hop free pump scanning. After changing the crystal temperature (signal and idler wavelengths), one has to wait for the crystal temperature to stabilize. This takes 30 to 60 s, after which the pump laser frequency can be scanned. If the step size in signal frequency is kept smaller than the tuning range (140 GHz) of the pump laser, successive pump scans will overlap and continuous high-resolution scan of the idler wavelength can be obtained. In our present system, the pump laser is tuned by adjusting its temperature, which makes the tuning slow. When tuning faster than 10 GHz/min was attempted, the laser temperature could not follow the scan signal anymore. This resulted in instabilities in the pump laser, causing occasional OPO-cavity mode hops and reduction of the SMRS. There is also some dead time at the end of each scanning cycle because the pump frequency has to be restored to its initial value before the next scan. These problems could be remedied by using a rapidly tunable pump laser, such as those described in references [1,2].

#97335 - $15.00 USD Received 11 Jun 2008; revised 9 Jul 2008; accepted 9 Jul 2008; published 10 Jul 2008

Figure 4(a) shows a stepwise scan over 6 THz (200 cm^{-1}). Crystal temperature was changed by 1.25 ^{o}C after every 7 minutes, which resulted in discrete and fairly well-controlled steps in signal and idler frequencies. Due to the dispersion of MgO:PPLN, the frequency change versus temperature change is different for the short and long wavelength ends of the wavelength scan: -45 GHz/K and -85 GHz/K, respectively. There is also some variation in the sizes of adjacent steps [Fig. 4(b)], which is caused by frequency dependent losses, such as residual etalon effects and irregularities in the crystal. Continuous wavelength tuning range is currently limited by the maximum temperature rating (120 ^{o}C) of the Peltier elements. With different type of Peltier elements, the crystal temperature tuning range could be extended to above 200 ^{o}C [5]. This should provide a wavelength tuning range of 450 cm^{-1}, which has been previously reported for a temperature tunable OPO that contains an intracavity etalon [2]. Compared to the previous work, our setup provides simplified wavelength tuning and avoids the problems related to etalon walk-off losses. Despite of this, the output power variation can be significant when performing wide wavelength scans (Fig. 4). This was caused by a small change in the optical alignment of the OPO cavity as the crystal temperature is varied. Power variation can be reduced to below 20% by aligning the cavity for the temperature that corresponds to the center of the tuning range.

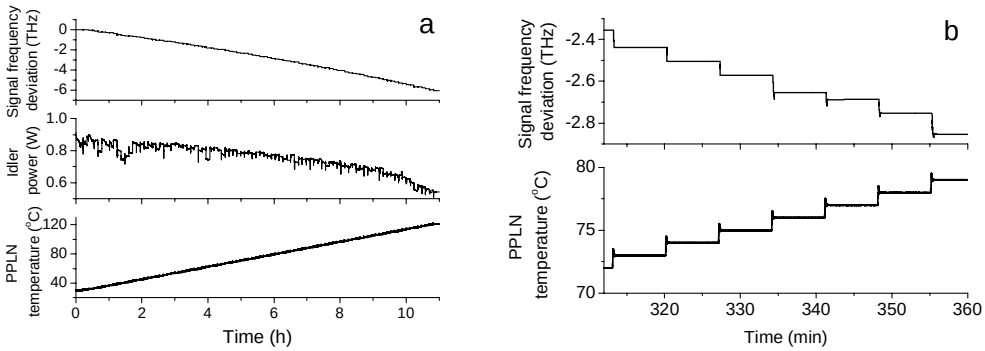

Fig. 4. (a). Stepwise wavelength scan over 6 THz with the two-mirror OPO. Crystal poling period of 31 μm was used. Signal frequency was scanned from 1597 nm to 1639 nm, which corresponds to an idler scan from 3188 nm to 3033 nm. Figure (b) shows a detail of the scan.

In most cases, the signal wavelength quickly settles down to a new value after a temperature step. Occasionally, we observe mode hops or weak side modes still few minutes after stepping the temperature. Such behavior is rare at modest OPO power levels, but becomes more frequent when the pump level is increased above 2–2.5 times the threshold, depending on cavity configuration. For this reason, a pump level of two times the threshold was used in the scan shown in Fig. 4. Mode hops are often triggered by acoustic disturbances. It is thus expected that more reliable operation at high power levels could be attained if the cavity was better isolated from such disturbances. Probability of the mode hops can also be reduced by using a shorter cavity, mainly because that increases the cavity mode spacing. Drawback of this approach is reduced nonlinear conversion efficiency if one has to go for focusing parameters of smaller than 1 [6].

3. Discussion

We have shown that it is possible to obtain reliable single-mode operation of a singly resonant cw OPO without any etalon or other frequency selective intracavity elements. In order to avoid longitudinal mode hops, the relative frequency fluctuations between the parametric gain curve and the cavity frequency should not exceed FSR/2, on average. In the case of our four-mirror cavity, this corresponds to frequency fluctuations of approximately 100 MHz. Such fluctuations can arise due to acoustic noise if the OPO cavity is open to air. Another possible reason for such frequency fluctuations is a shift of the parametric gain curve due to fluctuations of the crystal temperature. The sensitivity to crystal temperature can be calculated

#97335 - $15.00 USD Received 11 Jun 2008; revised 9 Jul 2008; accepted 9 Jul 2008; published 10 Jul 2008

from the available data for crystal refractive index [7], or it can be measured. An example of such measurement is the wavelength scan shown in Fig. 4. In the worst case, at the low-frequency end of the signal tuning range (1760 nm), the parametric gain curve shift versus temperature is -150 GHz/K. This means that, in order to avoid mode hops, the crystal temperature variations should be smaller than 0.65 mK. (Crystal temperature variations shift the cavity modes as well, but this effect is small enough (-5 GHz/K) to be ignored).

Although stabilization of the crystal temperature to better than 1-mK level could be possible, it requires some special attention. Luckily, the stability requirement is relaxed by a self-locking effect, which is believed to be of thermal origin. Thermal locking has previously been observed in doubly and triply resonant cw OPOs, in which it has helped to attain mode-hop free operation of up to several hours [5]. Locking owes to small temperature variation in the nonlinear crystal due to the absorption of optical power. If the cavity frequency drifts relative to the parametric gain curve, there will be a small change in the circulating intracavity field and hence also in the absorbed power. Within a certain locking range the corresponding optical path length variation can partly compensate for the drift. In practice we found that the OPO can, depending on the operation point, tolerate crystal temperature changes larger than 0.1 K without a mode hop. The observed mode-hop-free temperature tuning range is thus two orders of magnitude larger than what could be expected without the thermal locking effect. The strength of the thermal lock depends on the slope of the parametric gain curve at the frequency of OPO oscillation. The locking effect is hence enhanced by any residual effects that modify the otherwise wide and flat parametric gain curve. According to our calculations, even a small (1-2%) modulation of the parametric gain due to residual etalon effects etc. can explain the experimentally observed increase of the mode-hop-free tuning range.

Although signal absorption in the crystal is necessary for self-locked operation of the OPO, it can also lead to significant thermal lensing at high power levels. High intracavity power can lead to other problems, too. At high pump levels of 3.3–4.5 times the threshold (depending on the cavity configuration), we have observed the same kind of broadband multi-mode oscillation and Raman lasing that have recently been reported by two other groups [8,9]. At pump levels close to, but below the transition to broadband oscillation, the OPO often has increased tendency for side modes and mode hopping. In this case, the side modes are typically weak (few % of the main mode) and there are only two of them. In singly resonant OPOs, the intracavity signal power is significantly larger than the pump and idler power. To be able to use tight focusing (ξ>1) for efficient OPO operation, we have followed the example of Henderson and Stafford [9] and decreased the circulating signal power level by using a partly transmitting (T~2%) output coupler instead of a mirror that is highly reflective (R>99.9%). The output coupler reflectivity can be optimized so that high idler output power can be obtained without the problem of broadband multimode oscillation [9].

4. Conclusion

In this paper, we have demonstrated, for the first time, a singly resonant cw OPO design that does not require any intracavity optical elements for frequency selection. The OPO can be operated without mode hops for several hours. Due to the lack of an intracavity etalon, wavelength tuning of the OPO is simple and straightforward, including only temperature tuning of the nonlinear crystal and wavelength tuning of the pump laser.

The high OPO performance has been achieved mainly due to good thermal control of the MgO:PPLN crystal. This includes (1) Good stabilization of the crystal temperature to within 12 mK, (2) limiting of the intracavity power level by using suitable output coupling optics for the resonating signal beam, and (3) thermal self-locking effect that relaxes the requirements for thermal and mechanical stability of the crystal and the cavity.

Acknowledgments

The financial support of the Academy of Finland is gratefully acknowledged. University of Helsinki is acknowledged for funding the laboratory equipment needed in this work.

#97335 - $15.00 USD Received 11 Jun 2008; revised 9 Jul 2008; accepted 9 Jul 2008; published 10 Jul 2008