One-Watt level mid-IR output, singly resonant, continuous-wave optical parametric oscillator pumped by a monolithic diode laser

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Abstract: We report more than 1.1 Watt of idler power at 3373 nm in a singly resonant optical parametric oscillator (SRO), directly pumped by a single-frequency monolithic tapered diode laser. The SRO is based on a periodically poled MgO:$LiNbO_3$ crystal in a four mirror cavity and is excited by 8.05 W of 1062 nm radiation. The SRO pump power at threshold is 4 W. The internal slope-efficiency and conversion efficiency reach 89% and 44% respectively. The signal and idler waves are temperature tuned in the range of 1541 to 1600 nm and 3154 to 3415 nm respectively. To the best of our knowledge, this is the highest output obtained for a diode pumped optical parametric oscillator (OPO), and the first time a SRO is directly pumped by a monolithic tapered diode laser.

OCIS codes: (140.3600) Lasers, tunable; (140.5960) Semiconductor lasers; (190.4410) Nonlinear optics, parametric processes.

References and links

1. M. E. Klein, C. K. Laue, D.-H. Lee, K.-J. Boller, and R. Wallenstein, “Diode-pumped singly resonant continuous-wave optical parametric oscillator with wide continuous tuning of the near-infrared idler wave,” Opt. Lett. **25**(7), 490–492 (2000).
2. I. D. Lindsay, B. Adhimoolam, P. Groß, M. E. Klein, and K.-J. Boller, “110GHz rapid, continuous tuning from an optical parametric oscillator pumped by a fiber-amplified DBR diode laser,” Opt. Express **13**(4), 1234–1239 (2005).
3. W. R. Bosenberg, A. Drobshoff, J. I. Alexander, L. E. Myers, and R. L. Byer, “Continuous-wave singly resonant optical parametric oscillator based on periodically poled LiNbO($_{3}$).,” Opt. Lett. **21**(10), 713–715 (1996).
4. P. E. Powers, T. J. Kulp, and S. E. Bisson, “Continuous tuning of a continuous-wave periodically poled lithium niobate optical parametric oscillator by use of a fan-out grating design,” Opt. Lett. **23**(3), 159–161 (1998).
5. J.-P. Fève, O. Pacaud, B. Boulanger, B. Ménaert, J. Hellström, V. Pasiskevicius, and F. Laurell, “Widely and continuously tunable optical parametric oscillator based on a cylindrical periodically poled KTiOPO($_{4}$) crystal,” Opt. Lett. **26**(23), 1882–1884 (2001).
6. S. T. Yang, and S. P. Velsko, “Frequency-agile kilohertz repetition-rate optical parametric oscillator based on periodically poled lithium niobate,” Opt. Lett. **24**(3), 133–135 (1999).
7. B. A. Paldus, T. G. Spence, R. N. Zare, J. Oomens, F. J. M. Harren, D. H. Parker, C. Gmachl, F. Cappasso, D. L. Sivco, J. N. Baillargeon, A. L. Hutchinson, and A. Y. Cho, “Photoacoustic spectroscopy using quantum-cascade lasers,” Opt. Lett. **24**(3), 178–180 (1999).
8. S. J. Brosnan, and R. L. Byer, “Optical Parametric Oscillator Threshold and Linewidth Studies,” IEEE J. Quantum Electron. **15**(6), 415–431 (1979).
9. F. Träger, *Handbook of Lasers and Optics*, (Springer, 2007), Part C.
10. S. T. Yang, R. C. Eckardt, and R. L. Byer, “Continuous-wave singly resonant optical parametric oscillator pumped by a single-frequency resonantly doubled Nd:YAG laser,” Opt. Lett. **18**(12), 971–973 (1993).
11. W. R. Bosenberg, A. Drobshoff, J. I. Alexander, L. E. Myers, and R. L. Byer, “93% pump depletion, 3.5-W continuous-wave, singly resonant optical parametric oscillator,” Opt. Lett. **21**(17), 1336–1338 (1996).
12. M. E. Klein, D.-H. Lee, J.-P. Meyn, K.-J. Boller, and R. Wallenstein, “Singly resonant continuous-wave optical parametric oscillator pumped by a diode laser,” Opt. Lett. **24**(16), 1142–1144 (1999).

#126973 - $15.00 USD Received 13 Apr 2010; revised 4 May 2010; accepted 5 May 2010; published 11 May 2010

13. H. Verbraak, A. K. Y. Ngai, S. T. Persijn, F. J. M. Harren, and H. Linnartz, "Mid-infrared continuous wave cavity ring down spectroscopy of molecular ions using an optical parametric oscillator," Chem. Phys. Lett. **442**(1-3), 145–149 (2007).
14. A. K. Y. Ngai, S. T. Persijn, F. J. M. Harren, H. Verbraak, and H. Linnartz, "Selective trace gas detection of complex molecules with a continuous wave optical parametric oscillator using a planar jet expansion," Appl. Phys. Lett. **90**(8), 081109 (2007).
15. B. Sumpf, K.-H. Hasler, P. Adamiec, F. Bugge, J. Fricke, P. Ressel, H. Wenzel, G. Erbert, and G. Tränkle, "1060 nm DBR tapered lasers with 12 W output power and a nearly diffraction limited beam quality," Proc. SPIE **7230**, 72301E (2009).
16. B. Sumpf, K.-H. Hasler, P. Adamiec, F. Bugge, F. Dittmar, J. Fricke, H. Wenzel, M. Zorn, G. Erbert, and G. Tränkle, "High-Brightness Quantum Well Tapered Lasers," IEEE J. Sel. Top. Quantum Electron. **15**(3), 1009–1020 (2009).
17. K. Paschke, J. Behrendt, M. Maiwald, J. Fricke, H. Wenzel, and G. Erbert, "High power, single mode 980 nm DBR tapered diode lasers with integrated 6th order surface gratings based on simplified fabrication process," Proc. SPIE **6184**, 618401 (2006).
18. B. Sumpf, K.-H. Hasler, P. Adamiec, F. Bugge, J. Fricke, H. Wenzel, G. Erbert, and G. Tränkle, "12.2 W output power from 1060 nm DBR tapered lasers with narrow spectral line width and nearly diffraction limited beam quality," in *European Conference on Lasers and Electro-Optics 2009 and the European Quantum Electronics Conference.* CLEO Europe - EQEC 2009, DOI 10.1109/CLEOE-EQEC.2009.5192718.
19. J. N. Walpole, "Semiconductor amplifiers and lasers with tapered gain regions," Opt. Quantum Electron. **28**(6), 623–645 (1996).
20. I. D. Lindsay, P. Groß, C. J. Lee, B. Adhimoolam, and K.-J. Boller, "Mid-infrared wavelength- and frequency-modulation spectroscopy with a pump-modulated singly-resonant optical parametric oscillator," Opt. Express **14**(25), 12341–12346 (2006).
21. J. E. Bjorkholm, "Some Effects of Spatially Nonuniform Pumping in Pulsed Optical Parametric Oscillators," IEEE J. Quantum Electron. **7**(3), 109–118 (1971).
22. H. Odriozola, J. M. G. Tijero, L. Borruel, I. Esquivias, H. Wenzel, F. Dittmar, K. Paschke, B. Sumpf, and G. Erbert, "Beam Properties of 980-nm Tapered Lasers With Separate Contacts: Experiments and Simulations," IEEE J. Quantum Electron. **45**(1), 42–50 (2009).
23. ISO 11146–1:2005," Lasers and laser-related equipment–Test methods for laser beam widths, divergence angles and beam propagation ratios–Part 1: Stigmatic and simple astigmatic beams," *http://www.iso.org/iso/iso_catalogue/catalogue_tc/catalogue_detail.htm?csnumber=33625*.
24. M. Ostermeyer, P. Kappe, R. Menzel, and V. Wulfmeyer, "Diode-pumped Nd:YAG master oscillator power amplifier with high pulse energy, excellent beam quality, and frequency-stabilized master oscillator as a basis for a next-generation lidar system," Appl. Opt. **44**(4), 582–590 (2005).

1. Introduction

Singly resonant, continuous-wave (cw) optical parametric oscillators (SROs) have the advantage of wider and simpler continuous idler tuning (without mode hops) compared to doubly and triply resonant optical parametric oscillators (OPOs). Continuous, mode-hop free tuning of an SRO over a range as large as 56 GHz and 110 GHz, has been demonstrated by Klein et al. [1], and Lindsay et al. [2] respectively, by using an intracavity etalon and continuously tuning the pump. Tuning via mode-hops, used to increase the total accessible spectrum, can be achieved by multiple mechanisms, including temperature tuning [3], fan out gratings [4], cylindrical poled crystals [5], and acousto-optic deflection [6], among others. In addition, for photoacoustic spectroscopy the sensitivity depends on the radiation intensity: higher powers provide a lower limit of detection [7]. Therefore it is important to develop broadly tunable high power mid-infrared sources.

A disadvantage of an SRO is the higher threshold. Specifically in the so-called 3-5 μm molecular fingerprint region — accessible by broadly tunable OPOs, and important for addressing the absorption features of a wide range of organic molecules—the threshold increases rapidly and is typically between 2 and 4 W [3]. The rising threshold originates from a reduced parametric gain, with increasing wavelength [8], and often also from an increased absorption of the idler wave in the nonlinear crystal, such as in $LiNbO_3$ beyond 5 μm. OPOs in general require an excellent (near diffraction limited) spatial beam quality for the pump [9].

To minimize threshold, the first cw SROs were pumped by Nd:YAG solid state lasers [10] that had good spatial beam quality. Although multi-watt output powers [11] were obtained, these pump-sources could not be tuned, and the overall efficiency was low due to cascaded

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pumping. Direct pumping of an SRO using a diode laser can increase the overall efficiency substantially.

A few directly diode-pumped SROs with improved overall-efficiency have been reported in refs [1,12]. These were pumped with a dedicated master-oscillator power-amplifier system where a bulk optical approach was required to achieve single-frequency and tunable pump radiation of sufficient power and beam quality. For lowering the threshold of the SRO to a few hundred mW and to increase the pump to idler conversion efficiency, relatively short pump wavelengths (around 920 nm) were used in combination with relatively short idler wavelengths of 2.0 to 2.3 µm, near to degenerate operation. A record idler output power of 480 mW idler was demonstrated at 2.1 µm, with only 2.5 W pump power [12]. However, the restriction of the idler tuning to this wavelength range renders this approach of limited use for addressing organic molecules in the fingerprint region, which is one of the main motivations for research on mid-IR OPOs [13,14]. To access this important fingerprint region with diode-pumped SROs, and keep the OPO threshold reasonably low, longer pump wavelengths are required so that the OPO operates closer to degeneracy.

High power diode lasers usually operate on multiple spatial modes, resulting in high divergence and poor spatial beam quality. The poor coupling between such a pump beam and the cavity mode of the resonant signal increases the OPO threshold. To overcome this problem, advanced diode lasers designs are required that show only a moderate spectral and spatial beam quality degradation at high output power.

In this work we use such a design in the form of a compact monolithic DBR tapered diode laser [15,16] as a tunable pump source for an SRO based on a MgO:PPLN crystal. The diode laser produces up to 12 W of power with a narrow spectral bandwidth. The centre wavelength of the laser can be coarsely tuned between 1062.3 and 1063.4 nm by varying the taper current and temperature. Varying the ridge waveguide current provides fine tuning over a range of 0.1 nm.

We obtain more than 1.1 W of idler power at a wavelength of 3400 nm when pumping with 8.05 W at a wavelength of 1062 nm. To our knowledge, this is the highest output power ever achieved with a diode pumped OPO, due to the nearly diffraction limited beam quality of the monolithic DBR tapered laser and its superior output power. Also we observe a high internal conversion efficiency and slope efficiency of 44% and 89% respectively. The pump power at threshold oscillation is 4 W. The signal and idler waves are temperature tuned in the range of 1541 to 1600 nm and 3154 to 3415 nm respectively.

2. Monolithic DBR tapered laser

The pump laser, shown schematically in Fig. 1 consists of a ridge waveguide and a tapered section. The characteristics of similar lasers have been reported in refs. 15, 16 and 18. The 2 mm long and 5 µm wide ridge-waveguide (RW) section carries a 1 mm long DBR section with a sixth-order surface-grating, and a gain section that is 1 mm, long. The DBR section is located at the rear facet, which is antireflection coated ($R_f \approx 10^{-3}$). The 4 mm long taper has a full taper angle of 6°, while the cleaved and polished end facet acts as the output coupler with a reflectivity of 1% and an aperture width of 430 µm. Because the device is soldered p-side up, onto a conductively cooled submount, the ridge waveguide and taper current may be individual controlled. This allows independent control of the output power, laser frequency, beam quality, and direct modulation of the laser frequency simply by variation of ridge-waveguide current alone [17]. The laser submount is attached to a thermoelectric cooler to control the temperature and is typically held at a temperature of 14.7°C.

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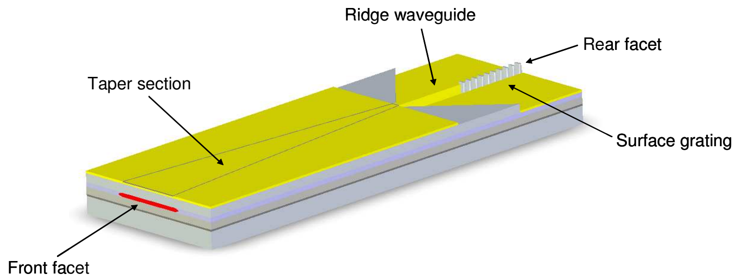

Fig. 1. Schematic view of the monolithic DBR tapered laser with a surface grating.

The laser emits p-polarized light with a power of up to 12.2 W at a ridge waveguide and taper current of 450 mA and 17 A respectively, at 25°C. The divergence of the beam along the fast axis at FWHM is 15°. At 9 W of output power the central lobe of the beam waist contains 76% of the total power. The specifications state a M^2 value (using a $1/e^2$ method) of smaller than 1.2 for powers up to 10 W [18]. During most of our experimental work, the output power of the laser, measured in front of the OPO, was kept constant at 8.05 W. OPO oscillation was possible from threshold to pump powers beyond 8.05 W (see Fig. 4), however, changing the input power via the drive currents resulted in changes to the beam profile due to filamentation [19], requiring re-optimization of the OPO cavity alignment.

The spectrum of the laser (measured with the optical spectrum analyzer (Ando AQ6317)), operating at 14.7°C, with waveguide and taper currents of 350 mA and 12.5 A, respectively, is shown in Fig. 2. The side mode suppression is more than 35 dB. Since the linewidth of the laser could not be resolved by the optical spectrum analyzer (OSA), it was measured with a high finesse Fabry-Perot interferometer with a free-spectral range of 3 GHz and a spectral resolution of 34 MHz. The measured linewidth at FWHM is 87 MHz, and is shown in the inset of Fig. 2.

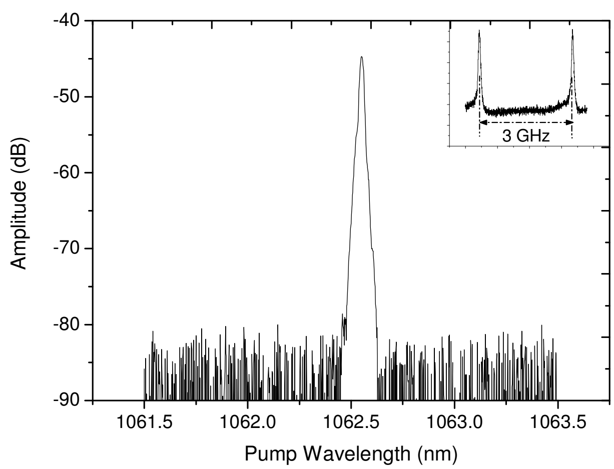

Fig. 2. Spectrum of the pump wave. The ridge waveguide and taper current are 347.7 mA and 12.5A respectively. The temperature of the laser was 14.7°C. Inset: Linewidth of the pump measured with a Fabry Perot interferometer with a FSR of 3 GHz.

The wavelength of the tapered laser can be set independently by the temperature of the laser, the ridge waveguide current, and the taper current. The laser may be tuned over ~0.35 nm by varying the taper current at a fixed temperature, while combined temperature and current tuning provides more than 1.1 nm of tuning.

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3. Experimental configuration

The experimental configuration is shown schematically in Fig. 3. The output of the laser is collimated along the fast axis by an aspherical lens (F1) with a focal length of 8 mm and a numerical aperture of 0.5. A second, cylindrical lens (F2), with a focal length of 100 mm, is used to collimate the beam along the slow axis, and compensates for astigmatism in the tapered laser to obtain a nearly symmetrical beam profile at the focus, however, far away from the focus, the beam profile remain asymmetrical. A half wave plate (H) combined with a polarizing beam splitter (PBS) was used to control the pump power rather than changing the currents of the ridged waveguide and tapered section, because the beam quality, astigmatism and filamentation depend on the current density in the laser.

A spherical mode matching lens (F3) with a focal length of 150 mm creates a beam waist (radius) of 70 µm (measured at the 4σ level in both transverse directions) in the periodically poled $MgO:LiNbO_3$ nonlinear crystal. The lenses and PBS are AR-coated for 1064 nm. The 50 mm long $MgO:LiNbO_3$ crystal is poled with multiple periods between 28.5 and 31.0 µm, however, unless otherwise stated, only the 30.5 µm period is used. The crystal is AR-coated for the pump, signal and idler. In order to control phase-matching conditions, the crystal temperature is maintained at a set temperature using a thermoelectric cooler and a resistive heater.

The signal resonant OPO cavity is a symmetric bow-tie ring resonator, formed by two 50 mm radius of curvature mirrors (M1, M2), and two plane mirrors (M3, M4). The mirrors (M1 to M4) are coated for high reflectivity (R>99% between 1450 and 1650 nm) for the signal wave. The mirrors (M1, M2) are anti-reflection coated for the pump wave, preventing resonant enhancement of the pump. Mirror (M2) is highly transmissive for the idler wave (T = 90%), while M3 and M4 (BK7 substrates) are anti-reflection coated for the residual idler (R = 10%), preventing doubly resonant oscillation. The rear surfaces of the mirrors (M1, M3, M4) are anti-reflection coated for the pump and signal wave, but posses a small residual reflectance for the idler wave. This combination of optics results in highly stable singly resonant oscillation at the signal wavelength. The curved and plane mirrors are separated by 80 mm and 20 mm respectively. The angle of incidence at all mirrors is 13.3°. The optical length of a single roundtrip in the resonator is 272 mm, resulting in a free spectral range of 1.1 GHz. The calculated cavity mode size (radius) is 55 µm. In addition, the symmetric bow-tie configuration avoids astigmatism.

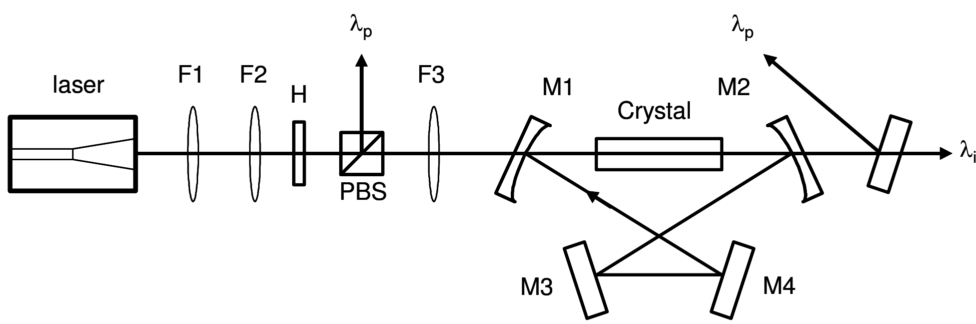

Fig. 3. Experimental setup. laser: Monolithic DBR laser, F1: aspherical lens with 8 mm focal length, F2: cylindrical lens with 100 mm focal length, H: half wave plate, PBS: polarizing beam splitter, F3: mode matching spherical lens with 150 mm focal length, M1-M4: cavity mirrors HR for the signal wave, M5: dichroic mirror to separate the residual pump from the idler.

A dichroic mirror (M5), behind the SRO, separates the pump and idler. The pump and idler power are measured with optical power meters (Newport 841PE, with a 818P-010-12 head, and Thorlabs PM100 with a D3MM head). The spectra of the pump and signal are

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measured with an optical spectrum analyzer (Ando AQ6317). To determine the linewidth of the pump, a home-built confocal Fabry-Perot interferometer with a free spectral range of 3 GHz is used. The beam profiles of the pump and idler are measured with a Thorlabs BP104IR beam profiler. The beam profile of the idler is measured with an Electrophysics PV320-L2ZE camera using an uncooled focal plane array detector.

4. Tuning range and output power

Unless stated otherwise, the results reported here are obtained for a pump wavelength of 1062 nm. The SRO exhibits a threshold of 4 W, which is slightly more compared to a similar SRO pumped by a fiber-amplified, multi section DBR diode laser [20]. A maximum idler output of 1110 mW is obtained at an idler wavelength of 3373 nm and 8.05 W of pump power (see Fig. 4), the pump power being measured in front of mirror M1. This represents an external power efficiency of 13.8%. The internal conversion and slope efficiency of pump photons into signal and idler photons is 44% and 89%, respectively. The linear fit (see Fig. 4) indicates that saturation has not been reached. It has been shown that the maximum internal conversion efficiency for an OPO pumped by a Gaussian beam at twice the threshold is ~35% [21]. In contrast, we measure an internal conversion efficiency in excess of this limit indicating that the pump mode is somewhat more like a plane wave at these power levels.

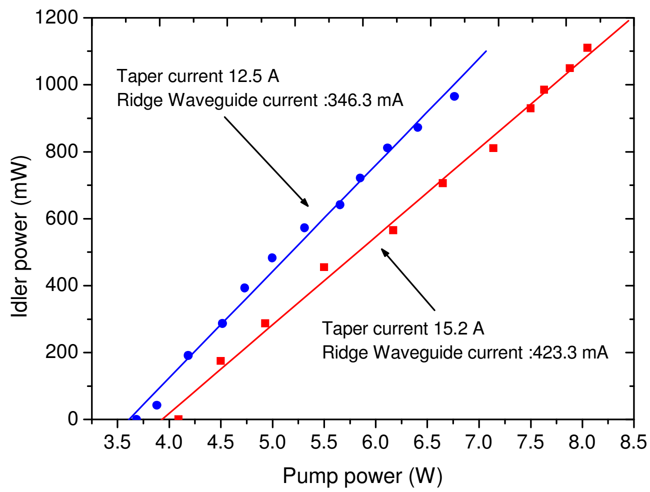

Fig. 4. Idler output power measured with respect to the pump power for taper currents of 12.5 A (blue dots) and 15.2 A (red squares). The solid lines are linear fits to the data. The wavelengths of pump, signal, and idler were 1062 nm, 1549 nm, and 3373 nm respectively.

Increasing the diode laser's output power above 8 W did not result in more efficient SRO oscillation. We found that this can be addressed to a change of the spatial quality of the pump beam, such that the power contained in the central lobe of the beam waist is reduced to less than 80%, indicating an increase of the M^2 value [19]. For wavelength tuning of the SRO, the temperature of the MgO:PPLN crystal is varied between 20°C and 160°C. Figure 5. shows the measured signal and idler output wavelengths and the idler output power as a function of crystal temperature as obtained with a pump power of 6.8 W. It can be seen that the signal tunes from 1530 to 1600 nm and the idler tunes from 3150 to 3400 nm. Over this tuning range the reflectivity of the mirrors changes by approximately 0.2% for the signal and by 10% for the non-resonant idler. Furthermore, the changes to the idler reflectivity are uncorrelated to the changes of the OPO output power.

It should be noted that other tuning mechanisms, such as pump-tuning are also available. The diode emission can be tuned over approximately 1.1 nm. However, changing the ridge

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waveguide and taper currents changes the pump spatial mode and reduces the OPO output power.

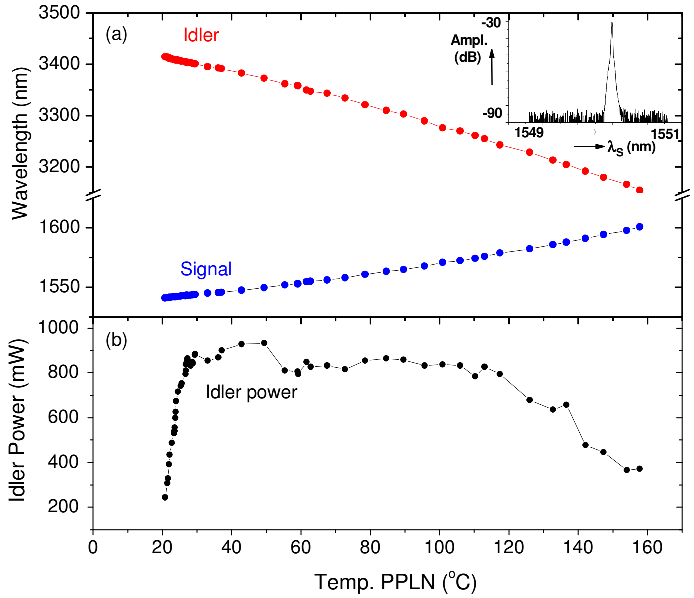

Fig. 5. Signal and idler wavelength (a) and OPO output power (b). Inset is the spectrum of the signal.

In the range between 3200 and 3400 nm the idler power is approximately constant and in excess of 800 mW, showing an approximately constant conversion efficiency of the SRO over a wide tuning range. The bandwidth of the signal at 1550 nm was smaller than the resolution of the optical spectrum analyzer (1.7 GHz). The longitudinal mode separation was 1.1 GHz, thus, if more than a single mode is oscillating, the linewidth is resolvable, therefore we can conclude that the OPO is oscillating on a single longitudinal mode. We also measure a side mode suppression of more that 50 dB, as shown in the inset of Fig. 5.

To determine the output stability of the SRO, we have measured the idler power during a one-hour period and find that the RMS amplitude-stability is 1.2%. Amplitude instability is usually caused by the resonating signal hopping between longitudinal modes. This can be caused by, amongst others, temperature and pump instabilities, which are overcome by the use of intra cavity etalons and other stabilization measures. In contrast, we have taken no special measures to improve the stability of the idler output of this SRO. Hence, we believe that the SRO pumped by a monolithic DBR laser has potential to be a very stable mid-infrared source for high resolution, high accuracy spectroscopy in the important molecular finger print region.

5. Beam quality

To successfully use the diode laser as a pump source for an SRO, the brightness of the pump beam is an important issue in exciting SROs. It is well known that tapered diode lasers at high power show the tendency to form filaments limiting their maximum brightness. Filaments are formed by self focusing and poor spatial filtering, resulting in multiple lobes in the near and far field. The filtering capability of the RW section can be improved by using a tapered laser with electrically isolated RW and tapered sections. The advantage of this type of laser is the improvement of the backward optical field intensity profile at the interface between the RW and taper section. Odriozola et. al. [22] have shown, both experimentally and by simulations, that beam quality can be improved simply by increasing the current through the RW section.

Increased gain in the RW section reduces the gain in the taper section. Consequently, the backwards reflected wave in the taper section is not amplified as strongly, and, thus, decreases unwanted optical pumping of the cladding along the sides of the RW section. The filtering of the RW is improved, and, as a result, the side lobes of the forward field in the taper section are reduced. However, this improvement is not general, and, especially at high powers, the tendency to form filaments is most likely.

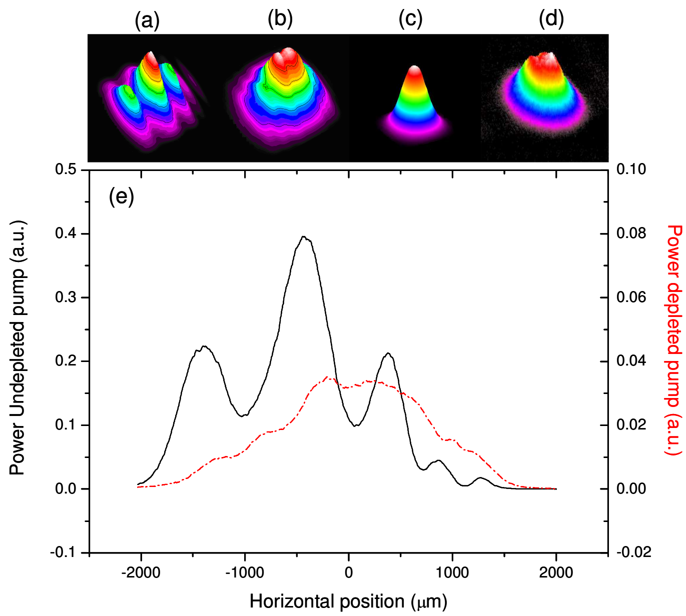

Fig. 6. Examples of the beam profiles measured for the undepleted pump (a), the depleted pump (b), the signal (c), and the idler (d). (a) through (c) are measured with the Thorlabs BP104IR beam profiler, while (d) is measured using the Electrophysics PV320-LZZE camera. (e) shows the cross section of the undepleted pump (solid trace) and the depleted pump (dashed trace) along the slow axis.

In our experiments, we are not able to remove the filaments in the pump beam at the laser power required to pump the OPO. However, by adjusting the RW current we are able to improve the beam quality, simply by making the structure more symmetrical along the slow axis. To quantify the pump beam quality, we measure the beam quality parameter M^2 using the second moment of the beams intensity profile [23], which is more appropriate for beams with a non-Gaussian spatial profile. The M^2 value is measured behind the cylindrical lens F2 (see Fig. 3). We use a spherical CaF_2 lens with a focal length of 150 mm, and measure the beam radii along the beam propagation path after the focusing lens. The propagation of a non-ideal Gaussian beam is then fitted to the measured spot size as a function of position. We find an M^2 value of 5.5 ± 0.5 along the slow axis. Despite this large M^2 value, more than 80% of the pump power is contained in the central lobe. If one considers only the central lobe, then the M^2 reduces to less than 1.3. The M^2 for the signal and the idler is also measured using the same technique. The signal is found to be very close the Gaussian diffraction limit (M^2 = 1.0 ± 0.1) as expected since it is generated in resonance with a high-finesse cavity. The measured beam quality of the idler is slightly better than that of the pump, namely 3.8 ± 0.4 along the slow axis. Figure 6 shows examples of the beam profiles for the pump (a), the depleted pump (b), the signal (c) and the idler wave (d). By comparing (b) with (a) it can be seen that the pump is highly depleted at its centre and also depleted at one of the two side lobes [see Fig. 6(b)]. Figure 6(e) shows the cross sections of the non-depleted (solid line) and depleted pump (dashed line) measured along the slow axis.

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6. Summary

In summary, we have demonstrated a continuous wave, singly resonant optical parametric oscillator directly pumped, for the first time, by a monolithic diode laser. The improved spectral and spatial brightness of the monolithic DBR tapered diode laser at high output power results in the highest reported idler power produced by such an SRO in the important molecular fingerprint region.

We are able to produce more than 1 W of output power at 3373 nm and we demonstrate wide tunability in the 3100 to 3400 nm region with appreciable power (more than 0.8W from 3200 to 3400 nm) as single frequency radiation with a narrow spectral bandwidth (80 MHz). Although no intracavity etalon was used to obtain long term single mode operation, the SROs rms amplitude-stability was 1.2% over one hour. The internal conversion and slope efficiency were 44% and 89% respectively. Due to the high internal conversion efficiency, we find an electrical-to-optical (signal plus idler) efficiency of 14.9% for our diode laser pumped SRO. This is about 7 times higher than electrical-to-optical efficiencies [24] of an OPO that is pumped by a diode laser pumped solid state laser. Furthermore, the combined features such as a small overall size, high brightness, and high wall-plug efficiency are an important step towards a compact SRO setup in view of possible applications.

The high-finesse resonator produces a high quality signal wave ($M^2 = 1.0$). The measured idler beam quality-parameter is $M^2 = 3.8$, slightly better than for the pump beam ($M^2 = 5.5$). Although filamentation, apparent as side lobes in the near and far field of the pump laser, limits the beam quality parameter to ~5-times the diffraction limit, disadvantageous effects on the performance of the SRO are found to be limited. We attribute this to the observation that more than 80% of the pump power remains in the nearly-diffraction-limited central lobe, for operation of the pump diode to output powers of up to 8 W.

Since this type of laser is the subject of intensive investigation and further development, we expect that the central lobe powers at higher drive currents can be further increased, which should enable a further reduced pump threshold of the SRO, and which should yield even higher conversion efficiencies. In the short-term, we expect to improve threshold and efficiencies by installing a laser with a somewhat larger RW-width (6 microns), which provides more power in its central lobe. The resulting reduction in overall size and complexity of the setup is an important precondition for a more widespread application, such as for gas analysis within the 3-5 µm molecular fingerprint region.

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