Efficient, low-threshold synchronously-pumped parametric oscillation in periodically-poled lithium niobate over the 1.3µm to 5.3µm range

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Abstract

Using periodically-poled lithium niobate (PPLN), synchronously pumped by a Nd:YLF laser at 1047nm, optical parametric oscillation is achieved with a mean threshold power as low as 7.5mW, nearly an order of magnitude lower than previously reported. Output slope efficiencies (signal plus idler), at a signal wavelength of ~ 1.7µm (idler 2.7µm), of up to 160% are observed. Efficient operation has been observed out to 5.3µm, well into the infrared absorption edge of lithium niobate.

The high parametric gain available in PPLN based, synchronously pumped, OPOs means that a large idler absorption loss in the PPLN can be tolerated, and oscillation can be achieved with idler wavelengths well into the IR absorption edge of the material [1]. In a previous demonstration of singly-resonant synchronously-pumped optical parametric oscillation in a 6mm long PPLN sample, using a 1047nm pump, a minimum threshold of 54mW was observed and a tuning range of 1.67µm to 2.81µm was covered [2]. In that report it was noted that, in principle, by using a longer crystal (~20mm), with an extended range of grating periods, and appropriate mirror coatings to provide high reflectivity over the required signal tuning range, a major extension in performance should be possible. Here we report the results of making these improvements. These include : (i) a threshold power as low as 7.5mW (average) indicating the possibility, in the near future, for direct diode pumping and pumping by mode-locked optical fibre lasers; (ii) a tuning range (signal plus idler) from 1.3µm to 5.3µm. Even at this long wavelength limit (imposed by the available grating periods rather than idler absorption) strong pump depletion (~60 %) is seen despite the large absorption coefficient at the idler wavelength (~3cm^{-1} at 5.3µm). With the available pump power (~1W average), high parametric gain is observed, allowing oscillation to occur even with an uncoated flat, eg. ZnS with R = 14%, as the output mirror. Under these conditions of high-gain/high-output transmission, initial slope efficiencies (signal plus idler power) up to 160% have been observed. Strong pulse compression is also observed, details of which will be reported in a separate paper.

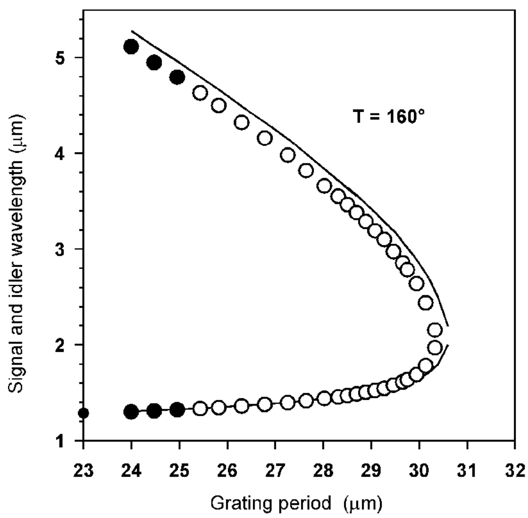


Fig. 1. Calculated tuning curve for a PPLN based OPO pumped at 1047nm [2]. Circles - experimentally determined tuning curve.

According to group velocity dispersion considerations, for the 2.8ps pulses of the pump laser used in ref.2, a 20mm length of PPLN is optimal for low threshold operation. Three PPLN crystals, each of length 19mm were fabricated at Crystal Technology intended for use with that laser. The results reported here made use of these crystals, but pumped by a different laser having 4ps pulses. Each crystal had eight gratings, covering the range of periods from 25.5µm to 31.2µm, in ~0.2µm steps (~0.5µm steps in the range 25.5-28.7µm). The corresponding signal and idler wavelengths, for a 1047nm pump, calculated using the Sellmeier equations of D. H. Jundt [3], are shown in fig. 1. A temperature of 160°C is assumed in the calculation. This corresponds to the temperature the experiments were performed at in order to reduce photorefractive effects. Also plotted in fig. 1 are the corresponding data points (open circles) for the experimentally observed signal and idler wavelengths, showing reasonable

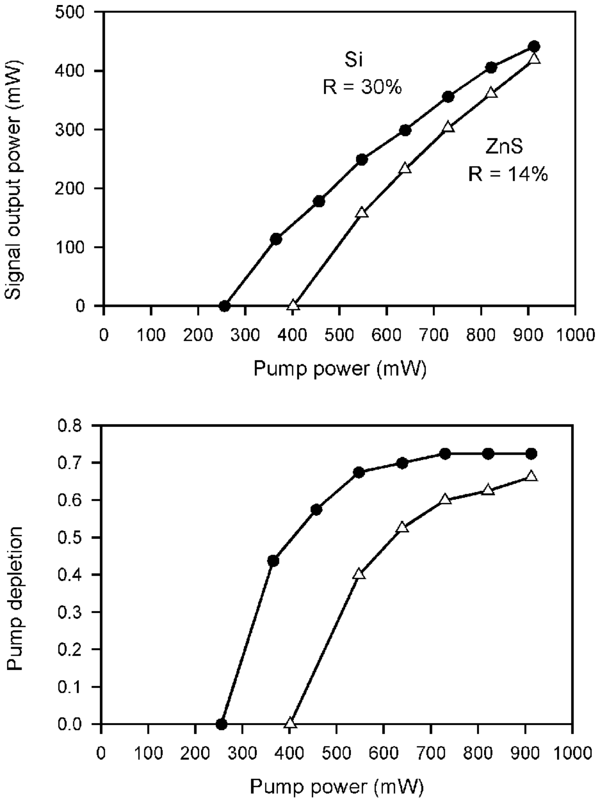


Fig. 2a. Signal output powers versus pump power for various reflectivities of the output coupler. For very high output coupling (R = 14%) the signal slope efficiency is initially ~100%.
Fig. 2b. Pump depletion versus incident pump power.

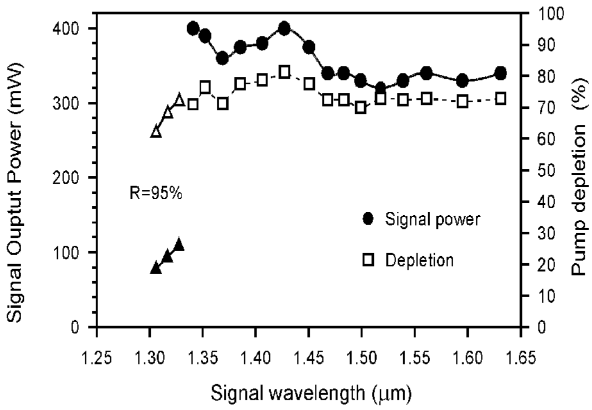
agreement with predictions. On finding that the parametric oscillator operated very effectively at 4.8µm, the longest wavelength allowed (by the shortest period grating), a further PPLN sample of 19 mm length was fabricated (at Southampton) with shorter periods, 24µm - 25µm, (in 0.5µm steps) which permitted extension of the oscillation to an idler wavelength of 5.3µm. The experimental data for these gratings is shown as solid circles. The crystal is AR coated with a single layer of MgF_2 centred at 1.3µm.

The pump source is a commercial diode-pumped APM Nd:YLF laser (Microlase DPM-1000-120). This gives a mean output power of 1W in a diffraction limited TEM_{00} mode at 120MHz pulse repetition rate, with bandwidth limited pulses of 4 psec duration. These slightly longer pulses would, in principle, allow a longer PPLN crystal to be used, which should result in a corresponding reduction in observed threshold powers. The OPO cavity is operated as a ring resonator in the bowtie configuration. The advantage of a ring resonator, over a standing wave one, is reduced loss per round trip, plus the ability to dispense with an isolator as none of the mirror reflections retro-reflect to the pump laser. However, it makes for more complexity in alignment.

With all high reflectors for the signal, the lowest threshold (ring resonator with the pump beam focussed to ~26µm in the crystal and a signal cavity mode size of ~38 µm) obtained is 7.5mW, corresponding to a peak power of 16W. From this we estimate a round trip loss of ~5%. Since pumping at ~ two orders of magnitude higher power is possible, very high parametric gain is achievable, confirmed by the ability to achieve oscillation using Fresnel reflections from the surface of uncoated flats (ZnS, R = 14%, Si, R = 30% were used).

A typical set of curves for signal output powers (for a signal wavelength of 1.7µm, idler 2.7 µm) versus pump power is shown in fig. 2, for various reflectivities of the output coupler. Note that for very high output coupling (R = 14%) the signal slope efficiency is initially ~100%, so that the total slope efficiency, which is $(1 + \omega_i/\omega_s)$ times greater, actually reaches a value of ~160%. This can be understood on the basis that a given increase in input pump power, would require roughly a corresponding decrease in the emerging (depleted) pump power, if net gain over the crystal length is to remain fixed (*i.e* essentially 200% slope efficiency). These slope efficiencies of greater than 100% are clearly not sustainable as the pump power increases, and the decreasing slope is very evident in fig.2.

Fig. 3 shows a typical plot of signal and idler output power versus wavelength for a fixed incident pump power of 0.8W. These results were obtained by translating the PPLN crystal to a grating of different period for each data point. Corresponding pump depletions are also indicated. Continuous fine wavelength tuning would be achievable either by temperature tuning (as in ref. 2) or via pump tuning (as in ref 4). The dip in idler power at ~4.3µm, for which there is no corresponding dip in the signal, is attributed to CO_2 absorption in the air path between the PPLN crystal and the detector. Fig. 4 shows the corresponding signal and idler spectra. CO_2 absorption lines are clearly visible in the idler spectrum whereas the signal profile remains smooth. The temporal profile ($sech^2$) was determined by an intensity autocorrelation of the



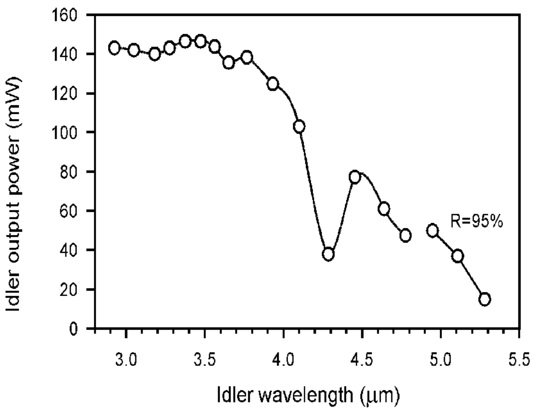
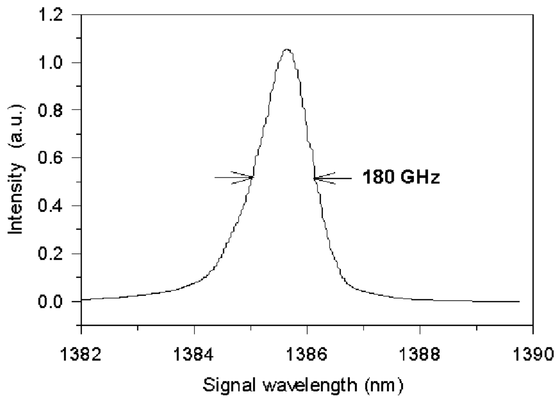


Fig. 3a. Signal output power versus wavelength. Corresponding pump depletions are also indicated. The Circles and squares were obtained with 35% output coupling whereas the triangles correspond to 5% output coupling.
Fig. 3b. Idler output power versus wavelength.

signal pulse. The time-bandwidth product is ~0.33, indicating chirp free, almost transform-limited pulses. This is maintained across the entire tuning range.

It is interesting to note that even at an idler wavelength of 5.3μm, which lies well within the IR absorption band of PPLN, efficient oscillation is observed with a threshold power of less than 300mW and over 60% pump depletion. From the observed depletion it is estimated that ~ 100mW of idler is generated. As the detected output is only 10mW, it implies that ~90% of the idler is absorbed. Estimates of the consequent heating of the PPLN confirm our finding that there was no observable change in the phase matching behaviour. A more detailed treatment of OPO operation, in the limit of strong idler absorption, will appear in another paper, including some more recent results leading to oscillation at an idler wavelength of 6.3μm.

The low threshold and high parametric gain achievable in our OPO led to an unexpected observation when using the appropriate grating for 4.8μm generation. It was found that at the highest available pump power, the signal output (at 1.34μm) was accompanied by satellite emissions on either side of it (at 1.35μm and 1.33μm). At the same time a strong red emission was visible, corresponding to the second harmonic of the signal wavelength. The explanation for this behaviour is that the strong intracavity signal wave (high reflectors for the signal were used to maximise the output at longer idler wavelengths) leads to second harmonic generation via second-order quasi-phase-matching. This process depends on there being a sufficient departure from exact 50:50 mark-to-space ratio for the grating domain. The second harmonic light was sufficient to pump near-degenerate optical parametric oscillation (doubly-resonant), which gave rise to the observed satellite emissions. This behaviour can be suppressed, as we found with the additional PPLN crystal fabricated for the longer wavelength range (4.8 - 5.3μm), by paying particular attention to achieving a good 50:50 mark to space ratio, thus discriminating against second-order quasi-phase-matching effects. The results do however provide



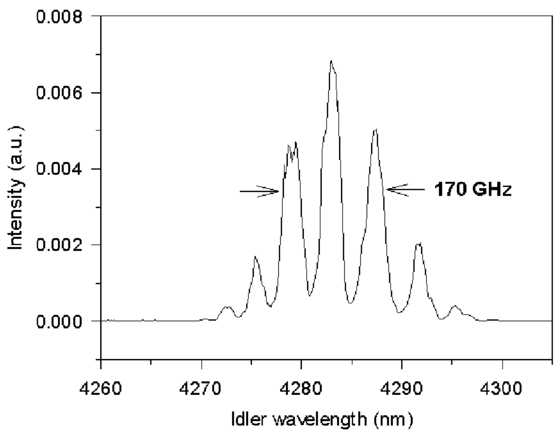


Fig. 4a. Signal spectral profile.
Fig. 4b. Idler spectral profile. The absorption lines in the spectrum are attributed to CO_2.

a reminder that PPLN allows parasitic process to occur, rather easily, if precautions are not taken.

In conclusion, we have demonstrated very high efficiency/low threshold oscillation in a synchronously pumped PPLN based OPO at wavelengths well into the IR absorption band of the crystal. Further improvements in operation can be obtained by use of a longer crystal. These results indicate quite clearly the possibility of diode-pumping or fibre laser pumping, the latter giving the added benefit of easy OPO tunability through pump tunability. Additionally, the very high gains that are possible from synchronously pumped OPOs based on PPLN, allow strong pulse compression if the OPO cavity is detuned from synchronism. A factor of 20 compression, giving rise to ~200fs signal pulses with a corresponding increase in spectral bandwidth, (not described in this paper), from 4ps pump pulses, is observed, details of which will be published in a subsequent paper.

Acknowledgements

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