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Extended operation of synchronously pumped optical parametric oscillators to longer idler wavelengths

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A synchronously pumped optical parametric oscillator, based on periodically poled lithium niobate, has operated at idler wavelengths out to 7.3 μm. Directly measured idler output powers (average) are 4.2 mW at 6.1 μm, 0.5 mW at 7.0 μm, and 0.04 mW at 7.25 μm. Characterization of the idler output indicates essentially bandwidth-limited and diffraction-limited operation.

OCIS codes: 160.3730, 190.4970, 320.7120

In a number of experiments demonstrating optical parametric oscillation (OPO) in periodically-poled lithium niobate (PPLN), it was observed that oscillation could be achieved at long idler wavelengths, falling within the infrared absorption band-edge, where the idler experiences strong absorption. Synchronously pumped OPOs (SPOPOs), with their high gain as a result of high-power pulsed pumping, give a good demonstration of this extended infrared tuning [1-4]. In Ref. 3, the longest idler wavelength achieved was 6.3 μm, limited by mirror reflectivity roll-off for the signal wave, and it was concluded from the analysis in that paper that oscillation out to 7 μm would be feasible. In Ref. 4, using shorter pump pulses (100 fs rather than the 4 ps of Ref. 3), the tuning range was extended to 6.8 μm and powers enhanced (e.g. to 0.2 mW average at 6.5 μm). Here we report a further significant extension in performance, both in power (by ~ an order of magnitude for wavelengths beyond 6.5 μm) and tuning range (to ~ 7.3 μm), again using pump pulses of 4-ps duration. Measured average output powers range from 4.2 mW at 6.1 μm to 0.5 mW at 7.0 μm, and 0.04 mW at 7.25 μm. We note in passing that operation to ~ 7.3 μm has been recently reported for an OPO with a Q-switched pump [5], although the idler power level was not measured. With our power levels we were able to make measurements of the spatial and spectral characteristics, indicating near diffraction-limited performance and bandwidth-limited performance. These results show that the conventional notion of ~ 5 μm as the mid-infrared wavelength limit for practical devices in lithium niobate needs some revision. In this letter we give details of the performance, drawing attention to a number of less familiar aspects that need consideration in an optimized long wavelength OPO device. We also discuss the scope for further significant enhancement.

An analysis of the effect of idler loss on parametric gain, and hence on pump threshold, has been made by Lefort *et al* [3] and by Lowenthal [6]. The two analyses have different emphases, and so start with different assumptions. Lowenthal's analysis emphasizes cw-pumped operation, hence low gain, so his starting assumption is that the signal can be treated as constant throughout the crystal. The analysis of Lefort *et al*, emphasizes the case of very large idler absorption, $\alpha L > \Gamma L$, accessible in SPOPOs via their high gain capability. Here α is the idler absorption coefficient, L the crystal length, and Γ the usual parametric gain term, $\Gamma^2 = (2\, \omega_i \omega_s d^2 I_p) / (n_i n_s n_p \varepsilon_0 c^3)$, where d is the effective nonlinearity and I_p the pump intensity (see e.g. [7]).

From Lowenthal's analysis the fractional signal power gain per pass through the crystal is (after correction of a typographical error in [6]), $\Gamma^2 L^2 \{(2\,[\exp(-\alpha L / 2) - 1] + \alpha L) / (\alpha L / 2)^2\}$. This expression is valid for any $\Gamma^2 L^2$, including large values (which would result in large parametric gain in the absence of idler loss), provided that the presence of idler loss in fact makes the actual parametric gain small. For large αL, the expression in curly brackets becomes $4/\alpha L$, agreeing with the result from Lefort *et al*, that for large αL and small parametric gain, the effect of the idler absorption is to increase the threshold by $\alpha L/4$ (originally misprinted in [3] as αL). Given that a large threshold increase may be involved (we have worked with αL as large as 100), it is important to minimize the signal losses since, as can be seen by equating the above gain expression to signal round-trip loss, the threshold pump-power is still proportional to signal loss, as in the usual case of low gain and no idler loss. For this reason we have used our OPO in a ring configuration, since this involves fewer mirror reflections per round trip and only a single pass through the crystal per round trip. The low signal loss also helps to increase the intra-cavity circulating signal power, as required to optimize the efficiency of idler generation. In fact the analysis of Lefort *et al* confirms that, as expected, the idler output power is essentially that generated within an idler extinction-length of the crystal exit face. The strategy for optimizing idler output is therefore to ensure that a maximum product of signal and pump intensities is present at the exit end of the crystal.

Increased pump power is another key factor for extended long-wave tuning. To achieve this we have followed the mode-locked Nd:YLF laser (Microlase DPM-1000-120, $\lambda = 1.047$ μm) with an amplifier stage (Q-Peak MPS-1047 CW-10 with output coupler removed), giving a diffraction-limited beam of typically 3.5 W (average) power incident on the PPLN crystal. The 120-MHz repetition rate and 4-ps pulse duration imply incident peak powers of ~ 7.5 kW. In the absence of a rigorous analysis to guide the optimization, which would require a treatment combining transverse spatial behavior (noting considerable idler diffraction spread on account of its long wavelength), with the temporal/spectral behavior, we have followed the usual practice of treating spatial and temporal effects separately, the latter in a plane wave situation and the former in a cw situation. While this heuristic procedure lacks rigor it does offer some useful insight. Thus, in deciding on the length of crystal to use, one notes that for the cw case, with confocal focusing and no idler loss, the gain for a given pump power has a linear dependence on crystal length (Γ^2 is proportional to intensity and hence to $1/L$). For short pulses however an upper limit on useful (in terms of increased gain) crystal length is set by the length over which the pulses become separated due to their group-velocity-mismatch (GVM). In the presence of idler loss, the overall fractional signal power gain (given again by the above expression) initially increases with L, until becoming independent of L for large αL. This implies that the useful upper limit on length, in terms of reducing the threshold, is not, as might be expected, set by a need to keep αL

small, but by the limit imposed by GVM. In practice we have used a 19-mm long PPLN crystal, this length chosen for convenience rather than on the basis of a GVM limit, which would allow a much longer crystal for our pulse durations. Even so, at an idler wavelength of 7.25 μm, αL exceeds 100 [8].

The OPO ring cavity (see Fig. 1) has four mirrors with high reflectivity (~ 99.8%) for signal wavelengths, and 74% transmission at the pump wavelength. The idler output mirror (CaF_2 substrate) has an overall transmission of > 85% across the range of idler wavelengths. The PPLN crystal, with grating periods in 0.5 μm steps from 18 μm – 23 μm, is held at 165 °C to reduce photorefraction. Oscillation in different wavelength regions is obtained by lateral (vertical) translation of the crystal to access different grating periods. The temperature-dependent Sellmeier equation from Ref. 9 was used for all calculations requiring PPLN refractive indices. Thus Fig. 2 compares the experimentally observed and calculated signal/idler wavelengths showing reasonable agreement despite the idler wavelengths being far removed from the spectral region used to determine the Sellmeier coefficients [9]. The pump beam was focused to a waist of 30 μm at the centre of the PPLN crystal, whilst the resonator gave a signal spot-size of 40 μm also at the crystal centre, hence focusing parameters (defined as the ratio of crystal length to confocal parameter) for pump and signal were 1.6 and 1.1 respectively. Fig. 3(a) shows the average idler output power versus idler wavelength. Sufficient power was available out to 7.25 μm to make direct measurements of idler output power, spectrum, and beam quality (M^2). Above 0.1 mW, idler powers were measured directly on a thermal power meter (Melles Griot 13PEM001) and for lower powers on a calibrated pyroelectric detector. Oscillation threshold versus idler wavelength is shown in Fig. 3(b), with idler absorption coefficient (data from Ref.

10) also shown for comparison. The spot-size, $\overline{w_i}$, of the idler polarisation induced at the output end of the crystal is given by $\overline{w_i}^{-2} = w_p^{-2} + w_s^{-2}$ where w_p, w_s are pump and signal spot sizes at the end of the crystal. The idler polarisation has a rather flat wavefront since its curvature is essentially determined by the difference of the wavefront curvatures of pump and signal. The idler emission can therefore be treated as coming from a waist of spot-size $w_i = \overline{w_i}$, i.e. 53 μm, and thus having a divergence angle (for a TEM_{00} mode at 6 μm) of ~ 36 mrads, with corresponding spot-size (radius) of ~ 4 mm at the surface of the output mirror. Since the extinction length of the idler is typically somewhat shorter than the Rayleigh range ($\pi w_i^2 n / \lambda_i$), the expectation is that the idler output will be essentially a pure TEM_{00} mode. In fact however, our M^2 measurements of the idler beam after the output mirror typically gave a value of ~ 4, despite the fact that the clear aperture diameter (12.7 mm) of the output mirror would truncate any idler component with $M^2 > \sim 1.5$. We ascribe this degradation of beam quality to aberration (in particular, coma) caused by transmission through the tilted curved mirror. A rough measurement of idler spot-size before the output mirror was made by closing a variable aperture at the mirror surface, both confirming that the idler beam was not truncated by the mirror, and indicating $M^2 < 1.5$.

A typical idler spectrum measured at 6.27 μm via a monochromator (Bentham 300), is shown inset in Fig. 2. This bandwidth is consistent with a bandwidth-limited pulse of the same duration as the signal, measured as 3.8 ps ($\Delta\nu\Delta\tau = 0.44$). No direct measurement of idler pulse duration has been made, e.g. via autocorrelation. However the expectation is of a pulse duration close to that of the pump since any tendency of the idler pulse to broaden due to group velocity mismatch (GVM) with respect to the pump is counteracted by absorption of the idler. In fact the idler output is mainly from the last extinction length and over this length the effect of GVM (~ 1 ps/mm for $\lambda_i = 6.27$ μm) gives little broadening with respect to the pump pulse duration. One should also note here that the calculated signal gain bandwidth in the absence of idler loss would imply a bandwidth too narrow to support the observed signal bandwidths. In fact however, the idler absorption loss leads to a broader gain bandwidth (attenuation of the idler reduces the sensitivity of gain to idler phase, and hence to phase mismatch), and for large idler absorption the parametric gain bandwidth is determined by $\Delta k = \alpha$, which for $\lambda_i = 6.27$ μm implies a signal gain bandwidth of ~ 0.8 nm, thus capable of supporting signal pulses of ~ 3 ps.

In conclusion, we have achieved a significant enhancement in both output power and tuning range for idler wavelengths beyond 6 μm in a PPLN OPO, reaching in fact 7.3 μm. The idler output is essentially diffraction-limited and bandwidth-limited, a consequence of the short region of the crystal from which the idler output originates. The idler power level is sufficient to provide a practical source. Detailed studies of optimisation and scaling, that will be published elsewhere, indicate scope for significant further enhancement of power. Power enhancement will come from increased pump power as heating due to idler absorption does not yet pose a limitation. Also the use of shorter pump pulses can give further enhancement even at the same average pump power. Further reduction of signal losses in the resonator will also be beneficial. Care should also be taken to take the idler output through a plane mirror, to preserve beam quality (see e.g. Ref. 11). Other materials beside PPLN should also, particularly when synchronously pumped, offer significant extension of their useful long-wavelength operating limit.

This work has been supported by the UK Engineering and Physical Sciences Research Council (EPSRC). Malcolm Watson and Paul Lloyd acknowledge the support of EPSRC studentships.

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Fig. 1. Schematic of the SPOPO setup. Pump source provides 4-ps pulses at 120-MHz repetition rate.

Fig. 2. Signal/idler tuning curve - experimental (single points) and theoretical (solid curve). Inset: Idler spectrum (FWHM bandwidth of 15.3nm (115 GHz)).

Fig. 3. (a) Idler average output power as a function of wavelength: 40 μW @ 7.25μm; 300 μW @ 7.1μm; 4.2 mW @ 6.1μm (pump power = 3.4 W).

(b) Threshold average pump power (single points) and attenuation coefficient from [10] (solid curve) as a function of idler wavelength.

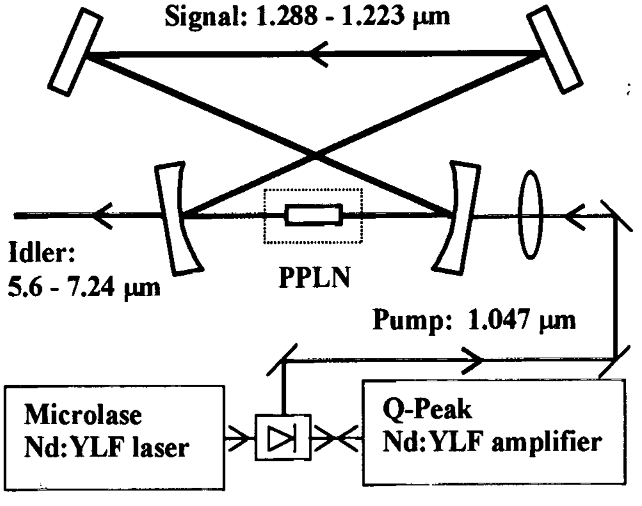
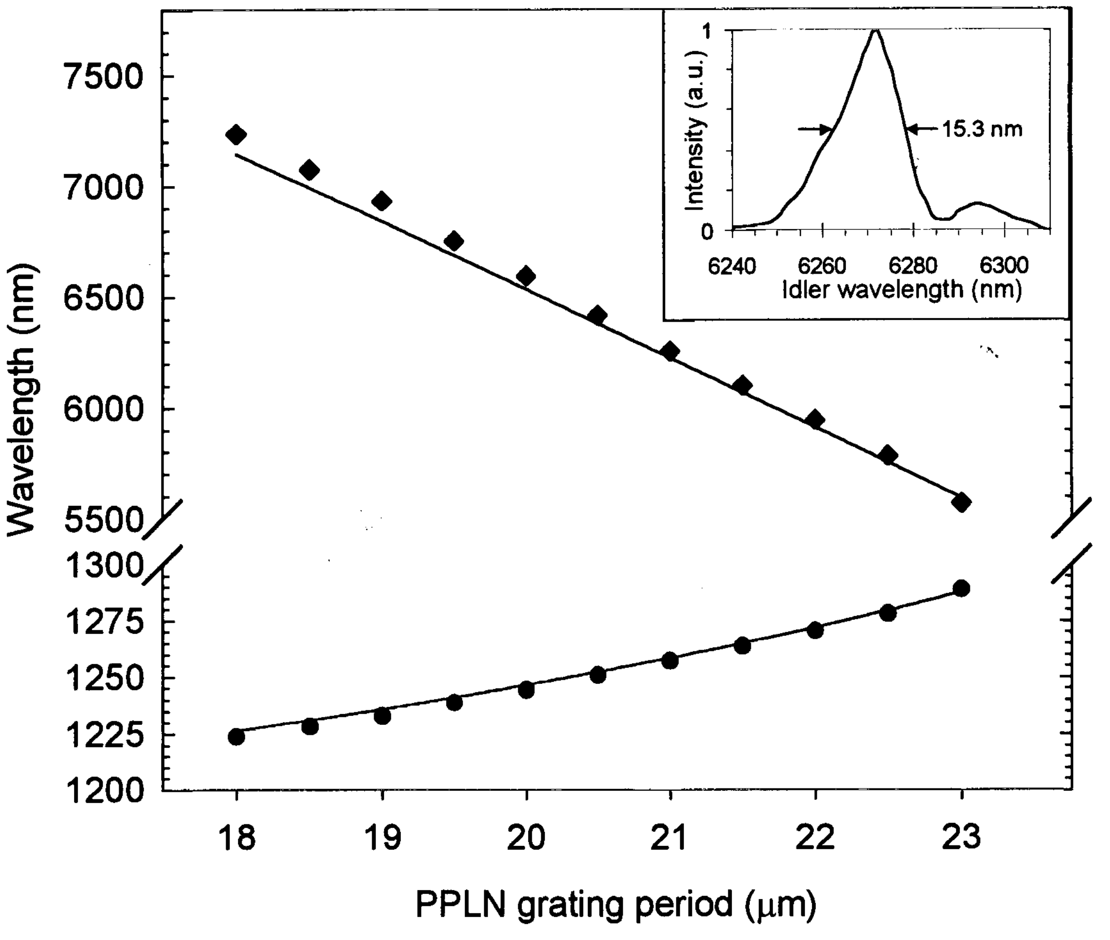

Signal: 1.288 - 1.223 μm
Idler:
5.6 - 7.24 μm
PPLN
Pump: 1.047 μm
Microlase
Nd:YLF laser
Q-Peak
Nd:YLF amplifier

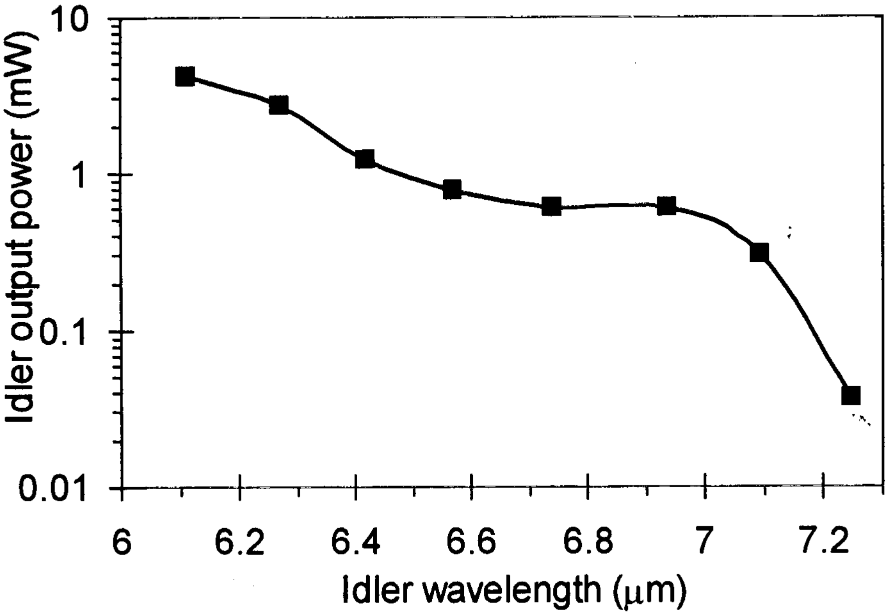
Figure 1



Wavelength (nm)
7500
7000
6500
6000
5500
1300
1275
1250
1225
1200
18
19
20
21
22
23
PPLN grating period (μm)
Intensity (a.u.)
1
0
15.3 nm
6240
6260
6280
6300
Idler wavelength (nm)

Figure 2

(a)



(b)

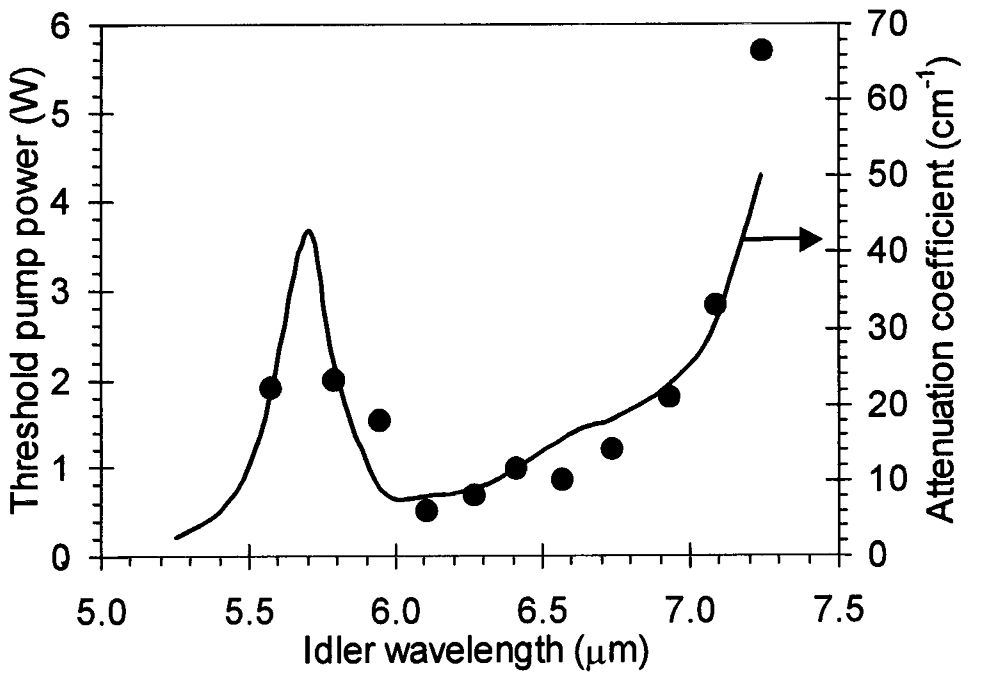


Figure 3 (a) & (b)