OPO Routes to Broadband 1.5 μm Sources for Speckle Reduction in BIL

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Abstract

Advances in active remote sensing systems are often hampered by the lack of suitable coherent sources. This work describes progress in obtaining broadband output through the use of specific phasematching architectures in optical parametric oscillators (OPOs); namely non-collinear phasematching (NCPM) and quasi-phasematched (QPM) structures, the latter consisting of periodically poled non-linear optical (NLO) materials.

Two different approaches are reported, both based on OPOs pumped at 1.064 μm. A 'high energy' approach produced >30 mJ of broadband (~40 nm) output, centred on 1.55 μm. This is more energy and better efficiency than the previous work based on 532 n pumping, but the bandwidth is ~10 % of that produced with 532 nm.

The second approach was based on the use of a diode-pumped, repetitively Q-switched Nd:YVO$_4$ laser to pump an OPO based on a fan-out grating structure in MgO doped periodically poled lithium niobate (PPLN). This system produced an average power of >1.5 W, with a bandwidth of ~20 nm centred on 1.55 μm, at repetition rate of 25 kHz.

Keywords: active sensing, OPO, 1.5 microns, broadband, burst illumination, IR laser

Introduction

Active sensing, where a target is first illuminated by a source controlled by the party undertaking the sensing activity, rather than relying on thermal radiation from the target itself or illumination from ambient sources i.e. passive sensing, is seen increasingly as a tool for detection, and potentially identification, at longer ranges and in more challenging environments. Obviously, such an approach requires the provision of suitable sources. Development of the technology for such sources is the prime aim of this project, and the work reported here covers the final year of a three-year programme of work.

While laser technology is continuing to advance, there are often spectral ranges where no suitable (or even any) lasers operate. In these circumstances, access to these spectral ranges can often be gained via non-linear frequency conversion techniques. This report describes such an approach where the frequency conversion is achieved with a non-linear optical (NLO) device termed an optical parametric oscillator (OPO). In particular, architectures are discussed which allow a broadband spectral output to be obtained.

The previous two conference papers [1,2] reported the work on the use of the 2nd harmonic of a Nd:YAG laser at 532 nm to pump a NCPM OPO using the non-linear material BBO. This produced a broadband output covering the range 1300-1700 nm (300 nm fwhm) with maximum pulse energy of 6.5 mJ at 10 % efficiency from the 532 nm pump. The system efficiency is further reduced by the need to convert to 532 nm initially. With this limited efficiency in mind, and the fact that the broadband output is angularly dispersed, though this can be corrected externally, a new approach was proposed based on pumping at 1.064 µm.

Broadband output at ~1.5 µm through pumping a NCPM KTP OPO at 1.064 µm

The 532 nm pumping scheme allowed for very broadband output at ~1.5 µm through the use of an inflexion point in the tuning curve of the material BBO, accessed through a non-collinear phasematching regime. However, the desired output at ~1.5 µm was the longer wavelength of the two generated in the OPO process, termed the idler, which would always limit the efficiency. An extensive search of materials could find no such equivalent broadband feature (i.e. point of inflexion) for the 1.5 µm output when pumping at 1.064 µm. However, as shown in figure 1, it looked possible to both shift and broaden the tuning 'nose' of a type II scheme in KTP through a non-collinearity of 2.75°.

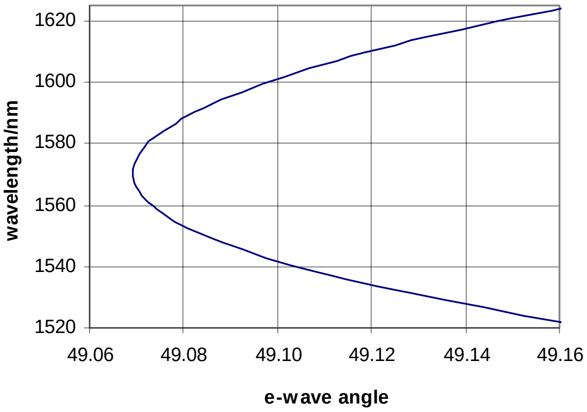


Figure 1: NCPM in ac-plane of KTP, with pump-signal non-collinearity of 2.75° for pumping at 1.064 µm

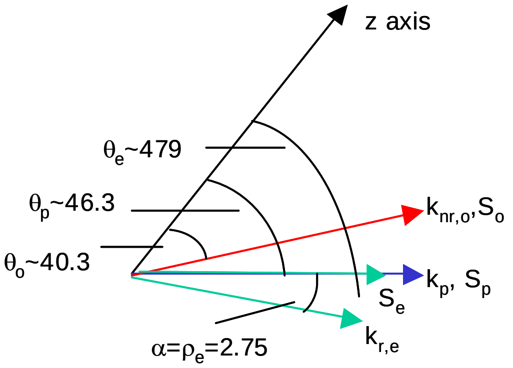


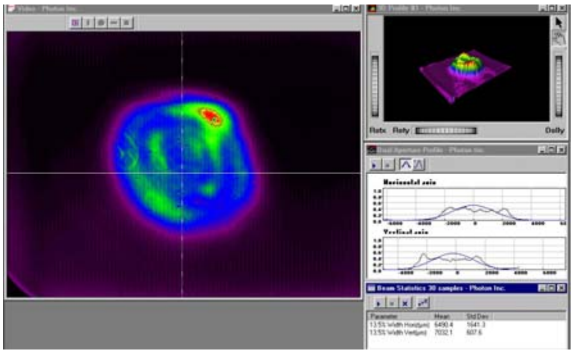
Figure 2: Vector diagram showing overlap of signal (e-wave) Poynting vector with pump vectors (o-wave) when the signal wave angle is larger than that of the pump by the signal walk-off angle of 2.75°

Here the resonant signal wave is e-pol, and figure 2 shows that this magnitude and sign of non-collinearity produces both a nose at ~1.57 µm, and maps the signal Poynting vector onto that of the pump, so maximizing the pump-signal interaction length.

Thus, it was expected that such a scheme would be capable of producing a broadband output at ~1.57 µm with higher efficiency and energy than 532 nm pumping, and in a non-angularly dispersed beam. The compromise was that the bandwidth would be reduced.

Broadband KTP OPO experiments

The pump source was the same as that used previously [2], i.e. Spectra-Physics DCR-11, except here, the fundamental would be used rather than the second harmonic. Unfortunately, this laser uses diffraction round a hard-edged aperture to extract large energy; with the result that the beam profile in near and mid-field contains diffraction rings, as shown in figure 3. It can also be seen that the beam appeared to contain a hot-spot, which may have been the cause of some optical damage experienced in the experiments.



Parameter	Mean	Std Dev
13.5% Width Horiz(µm)	6490.4	1641.3
13.5% Width Vert(µm)	7032.1	607.6

Figure 3: Pump beam profile at OPO plane

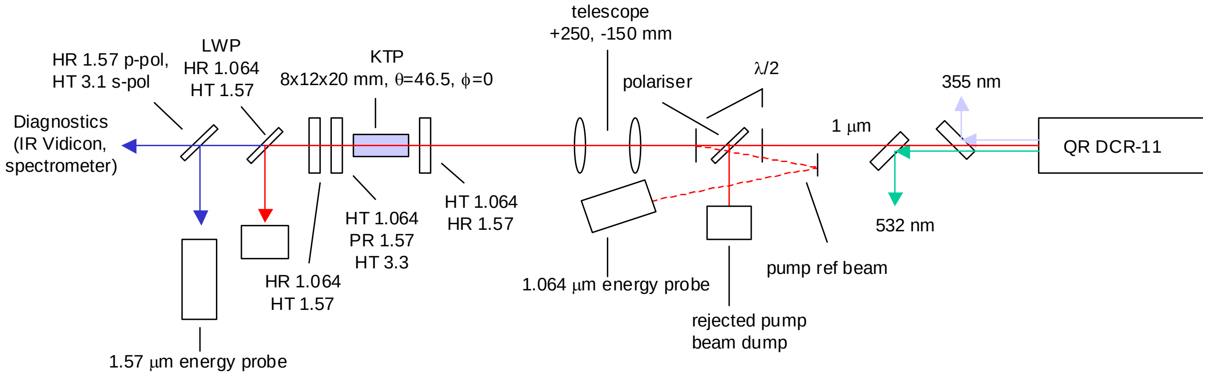


Figure 4: Experimental set-up for 'high energy' KTP OPO

A schematic of the experimental set-up is shown in figure 4. The maximum pump energy, after control optics, was ~250 mJ, which, with a ~5 mm diameter pump, resulted in a pump fluence of ~2.5 Jcm^{-2} (assuming a Gaussian profile). Calculations had shown that double-passing of the pump would be required to operate at least a few times threshold, though these also assumed a Gaussian profile. Initial experiments resulted in damage both to the crystal coating and internal to the crystal, with suspicion that the latter may have been due to the pump hot-spot. As the damage marks were off-centre, the crystal was re-polished and re-coated with a higher specification AR coating.

The re-worked crystal was then used in the OPO to produce the output spectrum shown in figure 5, where the non-collinear angle was ~1.3^{o}.

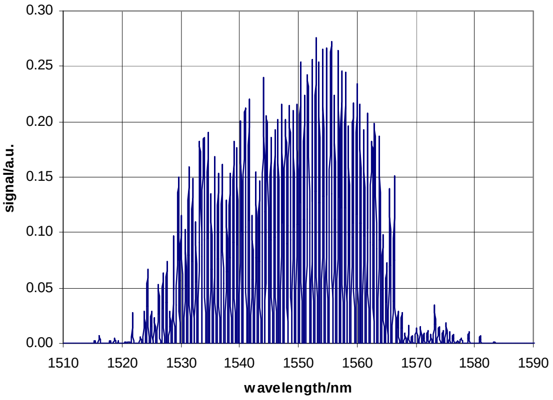


Figure 5: Broadband output for a non-collinear angle of ~1.3^{o}.

This is not the design point, but when the angle was increased to the ~2.75^{o}, angle, there was no significant increase in bandwidth, but the device became more unstable, presumably due to an increase in threshold. Also the signal wavelength was at ~1.55 µm, which is higher than expected from the tuning calculations. In fact, the tuning nose for collinear operation was found to be ~1525 nm, rather than the calculated ~1480 nm, suggesting inaccuracies in the Sellmeier equations. The beam quality was also poor, as typified by the beam profile shown in figure 6.

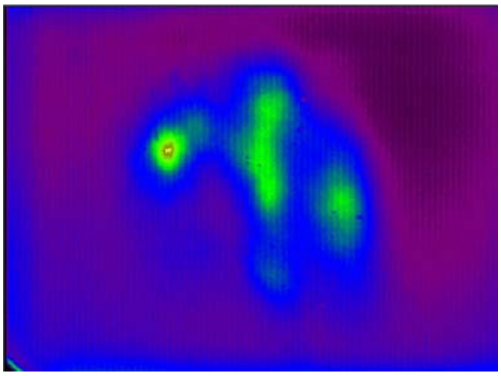


Figure 6: Typical signal beam profile

The maximum measured signal output from the device was ~30 mJ for 250 mJ pump, which is an efficiency of 12 %. This is higher than with 532 nm pumping, but lower than expected. The poor performance of the device, i.e. efficiency, bandwidth, stability and beam profile, is attributed to the poor pump beam and the consequently poor gain guiding.

>1.5 W average power, broadband output at ~1.5 μm through pumping a fan-out MgO:PPLN OPO at 1.064 μm

Initial experiments on high repetition rate (HRR) pumping of an OPO based on MgO doped PPLN possessing a fan-out grating structure were described at the previous conference [2], where it transpired that the PPLN sample supplied didn't, in fact, contain such a structure.

The pump laser was an in-house diode-pumped, repetitively Q-switched Nd:YVO_4 laser. When operated cw, the laser produced ~7.5 W in a near TEM_{00} mode for ~15 W from the fibre-coupled diode laser. Q-switched operation was achieved with an acousto-optic modulator, with maximum average power obtained for high rep rates i.e. >50 kHz. However, operating at lower rep rates (minimum achievable without break-through was ~20 kHz due to the high gain) produces more energy per pulse, but the reduction in extracted power results in harsher thermal aberrations in the YVO_4. The best compromise achieved with YVO_4 gave 5.5 W at 25 kHz with the beam quality estimated as M^2~2.

An OPO based on PPLN (MgO doping allows operation at room temperature without photorefractive damage) with a single period along its length would typically produce a narrowband output, <1 nm, well away from degeneracy. Broadband output can be achieved by 'chirping' the grating, or varying the periodicity along its length. The downside of this approach is that the gain-bandwidth is fixed once the sample has been patterned, and if narrowband operation is desired, only a small fraction of the length of the chirped grating provides gain. We chose to investigate the use of a so-called fan-out grating, where the period of poling varies transversely to the direction of propagation rather than along it, a schematic of which is shown in figure 7.

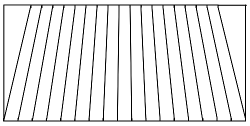


Figure 7: Schematic of fan-out PPLN

Fan-out gratings have been investigated previously, where the main interest was in achieving wide tunability through translation of the sample across the pump beam and so varying the period interacted with, and hence the signal and idler wavelengths generated.

The approach adopted here is to use a pump beam that is expanded in the 'tuning-plane', i.e. the plane containing the fan. In this way the beam will interact with a wide range of grating periods and therefore be able to generate broadband output. The bandwidth will be controllable by adjusting the width of the pump beam in the tuning plane.

HRR fan-out MgO:PPLN OPO experiments

A schematic of the experimental set-up is shown in figure 8. For initial experiments, a single lens, f=+175 mm, was used to spherically focus the pump beam into the OPO. Later, cylindrical lens telescopes were used to control the pump in the horizontal (tuning) plane, and so vary the width of the pump spot. The vertical plane was focussed with an f=150 mm cylindrical lens, producing a pump diameter of ~150 µm.

For the spherically focussed case (pump diameter ~180 µm), an OPO input mirror was used where the reflectivity varied rapidly with signal wavelength. This allowed for the optimum output coupling to be determined, as the rear mirror was highly reflecting for both pump and signal. The output signal was then extracted using the first of three mirrors that were ~98 % reflecting for the signal, and highly transmitting for the pump. The other two steered the output to the diagnostic equipment. For a pump power of 1 W, maximum output power was ~250 mW at a signal wavelength of 1525 nm and input mirror reflection of 70 %. Maximum pump depletion of ~50 % was achieved with operation at ~4 times threshold. The output linewidth was ~1 nm (measured with the fibre- coupled OSA) and the beam quality determined to be ~3.3 x 2.6. However, all signal beam profiles were determined with an IR vidicon, which is thermally noisy and not ideal for second moment beam analysis.

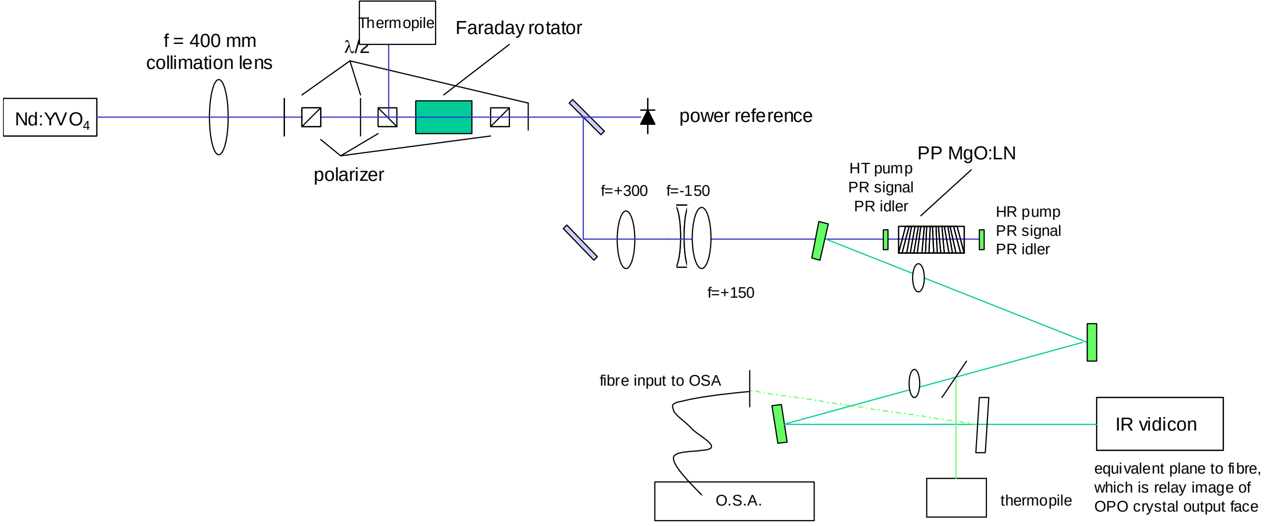


Figure 8: Experimental set-up for fan-out PPLN OPO experiments.

By simply translating the PPLN across the pump beam, the signal was tuned from 1450 to 1675 nm, with corresponding idlers of ~2.9 to 4.0 µm, covering the so-called molecular fingerprint region.

The pump beam diameter was subsequently expanded, using different cylindrical lens pairs, in the horizontal plane in a series of steps; ~260 µm, ~500 µm and finally ~1.05 mm. In each case the maximum pump power used was limited to ~5 times the OPO threshold. Typically, this is near the optimum efficiency for a pulsed OPO, without substantial back-conversion degrading the beam quality, and also mitigates against the risk of damage. No damage to the PPLN was observed in these experiments (the MgO:PPLN was held on a mount heated to 35°C).

For the slightly expanded pump beam of ~260 µm diameter, the bandwidth increased slightly to ~2 nm for operation with a signal wavelength of ~1550 nm (the central wavelength for all the results with expanded pump). For a pump of ~1 W, maximum output power was ~260 mW, very similar to the spherically focussed case. Expanding the pump to ~500 µm, the threshold increased to ~430 mW (c.f. ~200 mW for 260 µm pump), giving an output power of ~700 mW through a 33 % slope efficiency, when pumped with 2.5 W. Pump depletion approached 60 %. The bandwidth increased to ~5 nm (fwhm), and the beam quality was estimated as 2.1 x 1 (horizontal x vertical), bearing in mind accuracy issues stated previously.

The pump was finally expanded to ~1 mm in the tuning plane, whereupon the threshold doubled to ~900 mW, and the output power increased to ~1.2 W for ~4.8 W of pump, an efficiency of 25 %. The bandwidth increased to ~10 nm (fwhm), as can be see in figure 9.

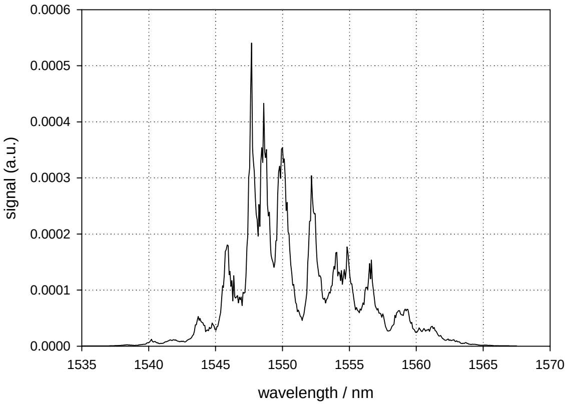


Figure 9: Output spectrum for 1 mm elliptical pump

What is really evident here, and was also noticed for the 500 µm pump size, is that the spectrum consists of peaks separated by ~2 nm. Combining this with the observation that the beam quality in the horizontal field was ~6 times that in the vertical, it was hypothesised that the signal could consist of an array of beamlets, brought about through some form of transverse spectral hole-burning. To verify this hypothesis required a detailed measurement of the spectral v spatial content of the OPO output. This was attempted, but initially led to confusing results (as will be discussed in the presentation).

The latter aspect was revisited and revealed an unexpected outcome. It was discovered that the input mirror was in fact a meniscus optic (equal radii of curvature of two surfaces) rather than the plane mirror supposed. This was an in-house optic that had been characterised for its spectral transmission, and assumed to be plano as it had no discernible focusing power.

This discovery explained the presence of an unexpected dual-lobed structure for the beam profile in the vertical plane, and appears to have been the cause of the confusing spatial v spectral measurements previously undertaken (lack of space prevents explanation here). Replacing the meniscus optic with a genuine plane mirror with the same 1550 nm reflectivity of ~70 % allowed for the generation of ~1.6 W of signal for ~5.2 W of pump, an efficiency of ~30 %. The bandwidth, measured after reflection from a ground-glass screen to ensure all wavelengths entered the OSA input fibre, increased to ~12 nm fwhm, or ~21 nm fw1/e^2, as shown in figure 10.

The beam quality was also substantially improved, at ~2.3 x 1.3, implying the previous issues were down to highly multi-mode operation due to the small signal mode with a stable cavity.

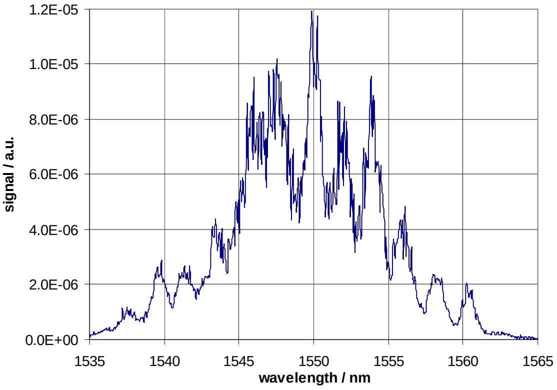


Figure 10: Output spectrum at full power

The 2 nm structure appears to be a feature of the fan-out grating, as the wavelength peaks don’t tune with translation. It may be that the structure is stepped on a fine scale, rather then continuously varying.

Future Work

This project has now finished, but a key issue yet to be addressed is what bandwidth is required to suppress speckle in BIL, and similar imaging applications.

References

1 Terry, J A C et al, EMRS DTC 1st Ann. Conf., Edinburgh May 2004, paper B2
2 Terry, J A C et al, EMRS DTC 2nd Ann. Conf., Edinburgh June 2005, paper B2

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