Broadband output from OPOs through birefringent and quasi-phasematched schemes

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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, or gain, 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.

The previous paper [1] described the concept of NCPM and the configuration of a device based on 532 nm pumping of the NLO material β*-*Ba_2BO_4 *(BBO). That device has now been characterised, with an optical-optical efficiency of 10 % achieved and with a bandwidth (full-width half-maximum, fwhm) up to 300 nm centred on 1.5* μ*m.*

Higher average powers can be achieved through cw pumping of the pump laser. The construction of a diode-pumped, high repetition rate (HRR) Q-switched Nd:YVO_4 *laser is described. Preliminary results are presented here for the use of this laser to pump an OPO based on PPLN (periodically-poled lithium niobate), also with output at ~1.5* μ*m.*

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 second 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.

Broadband output at 1.5 μm through NCPM operation of a 532 nm pumped BBO OPO

The concepts of phasematching, both non-collinear and quasi, were introduced in the previous paper [1] and are not repeated here due to paper length restrictions. Following a review of possible approaches, the architecture chosen for experimental investigation was that of 532 nm pumping of the NLO material BBO. The tuning curve calculated for the case where the relation between pump and signal wavevectors is

$$\theta_p = \theta_s - 2.5^o$$

is shown in fig. 1, where θ is the angle with respect to the crystal optic axis. The non-collinear angle, α, of 2.5^o is that which gives the point of inflexion in the tuning curve.

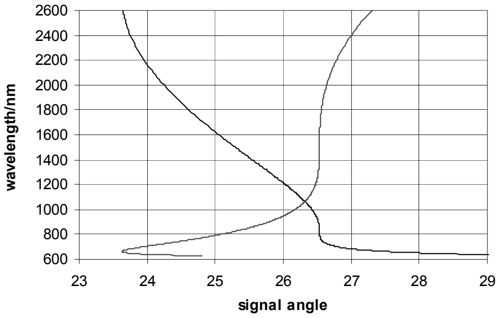

Fig. 1: Calculated tuning curve for NCPM of 532 nm pumping of BBO

It can be seen that resonating a signal wavelength band centred on ~820 nm will also produce broadband phasematching for an idler wavelength centred at ~1.5 μm.

The initial experimental set-up and pump laser characteristics were described in the previous paper [1] so only modifications and extensions to that are described here. To ease following the descriptions, a schematic of the set-up is given in fig. 2.

Observation of the transition from ‘normal’ narrowband operation to the regime which allows instantaneous broadband operation was best achieved by coupling the idler beam into a monochromator (Chromex IS500) operated in spectrograph mode i.e. the output slit was removed and the dispersed image of the input slit was observed with an IR vidicon (Electro-Physics 7290) coupled to an image analysis system. The difference in bandwidth, and angular dispersion, is seen by comparison of a ‘narrowband’ output at ~1.37 μm with broadband output centred on ~1.5 μm, as shown in fig. 3. The broadband condition is achieved through selection of the correct pump angle, θ_p~24^o, in the crystal (through rotation of the crystal) and the required non-collinear angle, α~2.5^o, by rotation of the signal cavity axis (with the signal mirrors attached to a common arm).

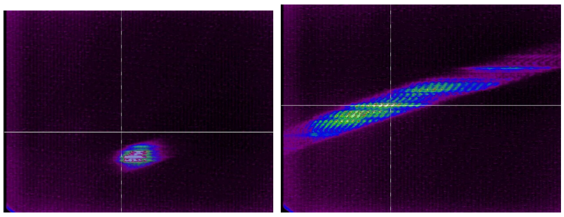

Fig. 3: Spectrograph images of the NCPM OPO; left -‘narrowband’ at ~1.37 μm; right - broadband at ~1.5 μm

Characterization of the idler angular dispersion, which is inherent to this scheme, is described later, along with methods for its compensation.

Initial experiments were performed with

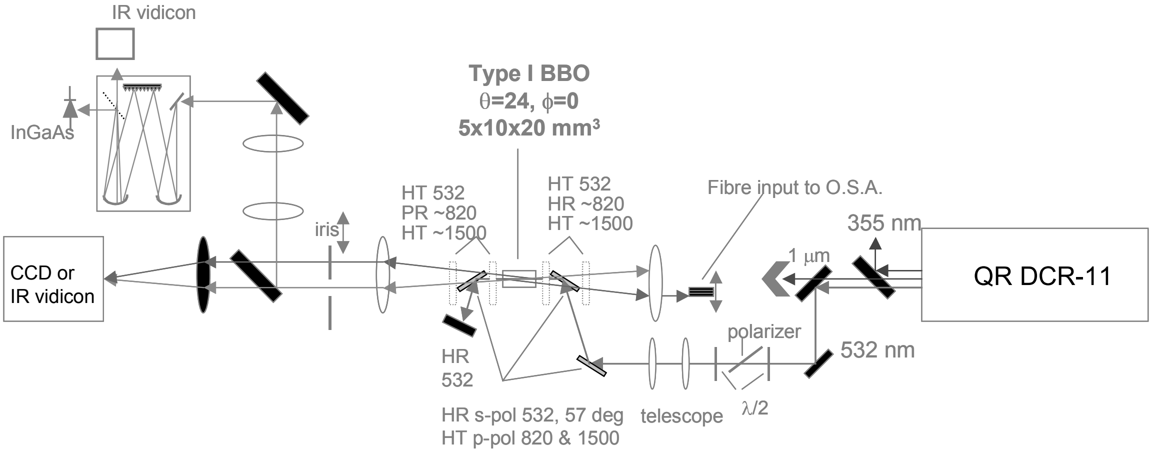

Fig. 2: Schematic of experimental set-up for NCPM OPOs

existing in-house optics. The poor transmission of the pump (1.064 μm) by these signal mirrors necessitated the use of 'pump-steerers' intra-cavity, to bring the pump into the signal cavity, and take-it out again. These signal mirrors were non-ideal in that their reflectivity varied over the required signal range (770-900 nm), and the inclusion of the pump-steerers presented loss to both signal and idler. This limited the bandwidth achievable with this configuration. Still, a full-width half-max (fwhm) idler bandwidth of ~150 nm was measured (with scanned monochromator rather than spectrograph), with extremes of ~1380 and 1650 nm. Almost 3 mJ of useful broadband 1.5 μm output was obtained for ~58 mJ of 532 nm pump. In addition, >2 mJ of signal (centred on ~820 nm) was extracted, as was additional signal and idler in the reverse direction due to double passing the pump and identical signal mirrors being used at either end. The idler slope efficiency was ~18.5 %, but the high threshold (>40 mJ) ultimately limited the efficiency for this level of pumping.

Roughly a doubling of this efficiency was achieved when the in-house signal mirrors were replaced with new mirrors with signal reflectivity centred at ~830 nm. The input/output curve for this configuration (with the signal reflectivity of the output coupler of ~90 %) is shown in fig. 4.

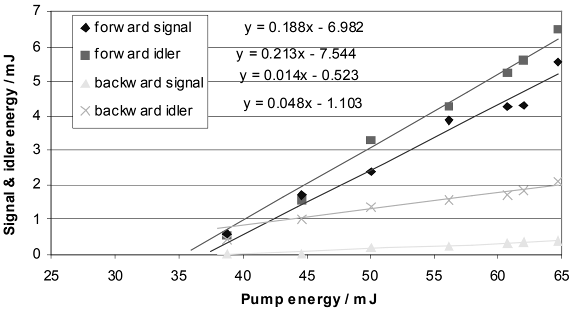

Fig. 4: Input-output curves for intra-cavity pump steerers & 90% R signal output coupler.

With improved output from the pump laser, ~6.5 mJ of broadband 1.5 μm was achieved for 65 mJ, an efficiency of 10%. This comes about through reduced threshold and improved slope efficiency. The fwhm bandwidth of the 1.5 μm idler increased to ~200 nm.

The beam quality of signal and idler was assessed by measuring the beam profiles, with CCD camera for signal and IR vidicon for idler, through a focus. The resulting beam quality figures are given in table 1.

Beam/plane	Horizontal	Vertical
Signal	13.2	5.2
Idler	12.8	14.1

Table 1: M^2 values for $\theta_s>\theta_p$, intra-cavity pump steerers and 830 nm mirrors

All results quoted above are for the case $\theta_s>\theta_p$ i.e. θ_s~26.5°. Due to the symmetry of the type I scheme, there is a complementary case for $\theta_s<\theta_p$, i.e. θ_s~21.5°. Although the energy conversion figures were similar for the two schemes, improved beam quality was exhibited for the $\theta_s>\theta_p$ case, and so only those values are quoted here.

The high pump transmission of the 830 nm mirrors allowed for pumping through the ends. The pump steerers were then used extra-cavity to separate the pump from the generated beams. This allowed the OPO cavity to be made shorter, reducing the build-up time loss and hence threshold. The efficiency of this configuration was improved over the case of the intra-cavity steerers (idler slope efficiency 30% for $\theta_s<\theta_p$), but the beam quality was worse (likely due to the increased Fresnel number of the shorter cavity). The maximum 1.5 μm output was 4.5 mJ for 58 mJ of pump. The slope efficiency was only slightly improved (over intra-cavity pump steerers) for $\theta_s>\theta_p$ (~22%) and the beam quality was very poor, though this has now been attributed to slight aperturing of the idler by the extra-cavity pump steerers. However, the reduced threshold allowed for a much broader bandwidth to be achieved – as high as 300 nm fwhm when the output coupler was 95% reflecting, as show in fig. 5.

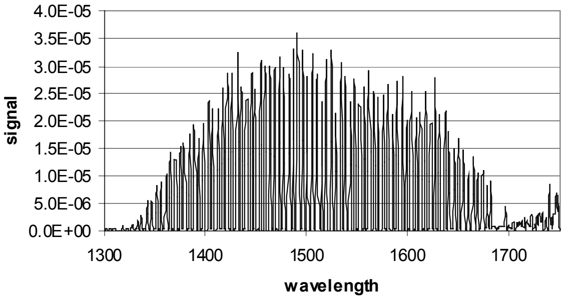

Fig. 5: Broadband 1.5 μm output for extra-cavity pump steerers & R=95% signal coupler

The angular dispersion was measured by translating the input fibre of an optical spectrum analyser (OSA) in the focal plane of a collection lens. The idler dispersion was thus determined to be ~140 nm/deg, in close agreement to the calculated value, based on crystal dispersion.

Whilst compensation of this dispersion was not attempted experimentally, calculations showed that this could be achieved with either a diffraction grating or a prism. Image relaying would provide for spatial overlap of the spectral components in both near and far-fields.

NCPM of type II phasematching

While external compensation of the idler dispersion can be achieved, this adds cost and complexity. An alternative route was sought.

Calculations showed that NCPM utilizing type II phasematching, again in BBO, could transfer the angular dispersion from the desired idler to the unused signal, as shown in fig. 6.

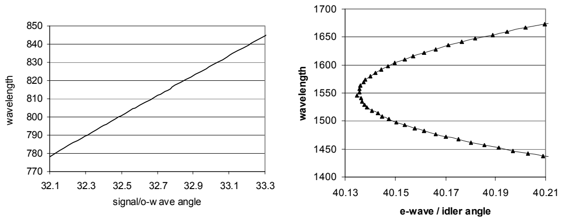

Fig. 6: Signal and idler tuning curves for type II NCPM in BBO with a 2.5° non-collinearity

Operation of such a scheme was demonstrated [2], for the first time to our knowledge, with a BBO crystal cut for $\theta=35^{\circ}$ and $\phi=30^{\circ}$. Otherwise the experimental configuration was essentially the same as for type I.

An output at 1.5 μm was observed, but so were other wavebands, as shown in fig. 7.

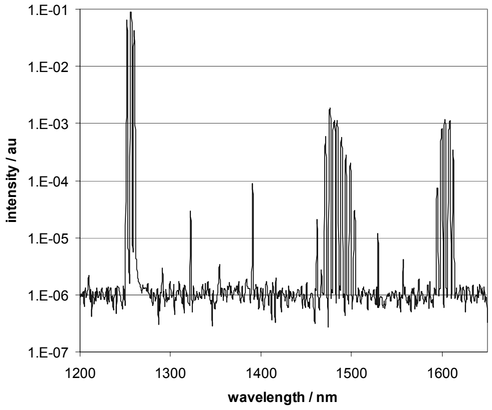

Fig. 7: Multi-spectral output from type II NCPM in 532 nm pumped BBO

There is a dominant feature at ~1250 nm, which is due to a competing process where the resonated signal wave is an e-wave at ~920 nm instead of the desired o-wave at ~800 nm. Consideration of the directions of the Poynting vectors shows that for the undesired, narrowband process, the vectors are spread over a smaller range of angles resulting in a longer interaction length than for the desired, broadband process.

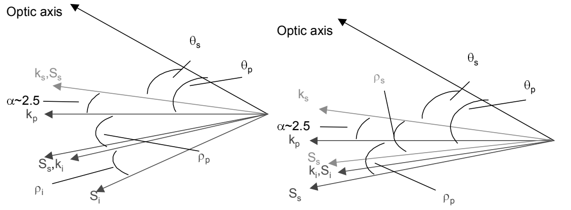

Fig. 8: Competing resonant e- and o-wave processes for 532 nm pumped type II BBO

Although operation with the intra-cavity pump steerers, which were partial polarizers, was insufficient to kill the unwanted process, it should be possible to suppress the e-wave resonance with suitable polarizers, or by resonating the idler, but none of these were available at the time of this work. However, the efficiency is likely to be limited by the short interaction length.

The output bandwidth was ~20 nm, though this should be improved with idler resonance, and the angular dispersion was un-resolvable using the technique employed for characterising the type I case.

A HRR Nd:YVO_4 laser

The above work was based on the 10 Hz operation of a flashlamp pumped Nd:YAG. For other applications, operation at high repetition rate (HRR) is desirable. No such laser was available to the project, so one was constructed, shown schematically in fig. 9.

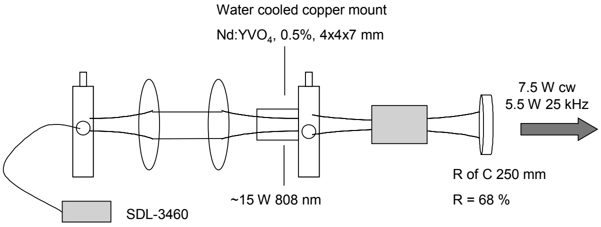

Fig. 9: Schematic of diode-pumped HRR Q-switched Nd:YVO_4 laser

When operated cw, the laser produces ~7.5 W in a near TEM_{00} mode for ~15 W from the fibre-coupled diode laser. Q-switched operation is achieved with a fused silica acousto-optic modulator (AOM), which combines low insertion loss and high damage threshold. When running Q-switched, maximum average power is obtained for high rep rates i.e. >50 kHz, but this results in individual pulses of low energy (<130 μJ). Operating at lower repetition 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 worsened thermal aberrations in the YVO_4.

The host YVO_4 was utilised as the laser was originally only intended to be operated cw. Its large emission cross-section and natural birefringence are well suited to this. However, its short upper state lifetime is not well suited to (relatively) low rep rate operation, due to a reduction in storage efficiency. For operation at <20 kHz the YVO_4 will be replaced with YAG (the emission being 1.064 μm in both cases), though this brings its own difficulties through thermally-induced birefringence.

The best compromise achieved with YVO_4 gave 5.5 W at 25 kHz with the beam quality estimated as M^2~2.

Fan-out grating PPLN OPO

This pump laser, allowing for losses in control optics, resulted in ~200 μJ per pulse for pumping an OPO. This is insufficient for pumping the type of OPO previously described, but is well suited to pumping an OPO based on the material periodically-poled lithium niobate (PPLN), which has a high non-linear coefficient.

An OPO based on PPLN 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 [3], where the period of poling varies transversely to the direct of propagation rather than along it, a schematic of which is shown in fig. 10.

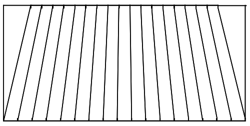

Fig. 10: Schematic of fan-out PPLN

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.

A sample of fan-out PPLN (MgO doped to allow room temperature operation without the risk of photorefractive damage) was obtained for preliminary experiments to allow verification of these ideas and to inform on exactly what range of periods would be optimum. An OPO was constructed where the 0.5 mm thick PPLN was pumped with a beam waist of ~130 μm diameter. In a plane/plane cavity the threshold for operation was ~7 μJ (or ~0.1 Jcm^{-2}). Optimum operation for a pulsed OPO typically occurs for ~5 times threshold, giving confidence that this approach will work without operating too close to the LN damage threshold of ~1 Jcm^{-2}.

Unfortunately, attempts at tuning the device showed that the supplier had shipped the wrong crystal so no attempt could be made at broadband operation. A replacement was being shipped at the time of writing.

In addition, a scheme has been devised which would allow very rapid tuning of narrowband operation of such an OPO, potentially with no moving parts. When pumping at 1 μm and with a signal near 1.5 μm, the corresponding idler could be tuned over the 3-3.5 μm region where many molecules contain characteristic spectra, allowing for their identification.

Future Work

The next phase of the work involves broadband operation of the fan-out PPLN. Preliminary experiments suggest that this should work with a simple plane/plane cavity rather than requiring the use of cylindrical mirrors to confine the mode in the non-tuning plane.

Subsequent to this, the NCPM approach will be re-investigated to look at improvements to efficiency through the use of 1 μm pumping, at the expense of some of the bandwidth. It is still expected to generate many 10s of nm, and in a non-angularly dispersed beam.

References

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