Femtosecond Seeded 150nm-Bandwidth Optical Parametric Amplifier for Active Imaging Applications at 1550nm

Karl A. Tillman and Derryck T. Reid

Ultrafast Optics Group, School of Engineering and Physical Sciences (Physics)
Heriot-Watt University, Edinburgh, EH14 4AS, UK
http://www.phy.hw.ac.uk/resrev/ufast/
Tel: +44(0)131 451 3046 Fax: +44(0)131 451 3136

Abstract

Laser ranging and imaging in the atmospheric transmission window at 1.5µm are made difficult by speckle effects which are observed when a rough surface is illuminated by a laser beam with a coherence length greater than the characteristic surface feature size. For the narrowband pulsed lasers currently used for imaging this length is of the order of a few millimetres which leads to observable speckle effects for many surfaces. In this context we describe progress towards the development a short-coherence length laser source operating at 1.5µm and based on optical parametric amplification of broadband seed pulses from a modelocked femtosecond erbium-doped fibre laser. Details regarding a continuous-wave-seeded device based on quasi-phasematched MgO:PPLN developed as a scientific control will be discussed in addition to a femtosecond-seeded device using an aperiodically poled MgO:PPLN crystal for bandwidth enhancement. Results from the 1.5µm optical parametric amplifier using an aperiodically poled crystal design and seeded by a femtosecond Er:fibre laser are presented showing 2.55µJ energies and a single-pass gain ~51dB.

Keywords: Burst illumination imaging, optical parametric amplification, aperiodically poled, quasi-phasematching, MgO:PPLN.

Introduction

Lasers suitable for efficient free-space ranging must possess high pulse energies and repetition rates and operate at a wavelength compatible with efficient propagation in the atmosphere. The beam quality of sources used for long-range free-space propagation should also be very close to diffraction limited and this is only possible by using a diffraction limited pump source. This project is concerned with the development of an optical parametric amplifier (OPA) that meets these criteria and is based on an actively Q-switched configuration operated at 1.5µm capable of achieving microjoule energy pulses at high repetition rates. The OPA is based on quasi-phasematched (QPM) MgO:PPLN which can be operated at room temperature and therefore offers a wider temperature tuning range than PPLN and higher resistance to photorefractive effects [1]. MgO-doped lithium niobate has previously been used in a birefringently phasematched OPA [2] but to our knowledge periodically-poled MgO-doped lithium niobate (MgO:PPLN) has not been applied in an OPA. One important criterion for sources intended for free-space propagation is often the need for optical pulses with a short coherence length because this leads to more accurate ranging and in imaging applications can also minimise the problem of laser speckle effects.

In an OPA the bandwidth of the amplified output signal is determined by the spectrum of the seed laser and the conversion bandwidth of the QPM nonlinear crystal. Conventionally narrowband seeds are used to produce a narrowband OPA output with a relatively long coherence length (~1mm) and millijoule pulse energies. The inverse relationship between the coherence length and the spectral bandwidth of the output pulse means that to produce a short coherence length source the output requires a broadband spectrum. Therefore, to achieve a broadband output from the OPA a broadband seed source is necessary which can be readily found in femtosecond lasers such as an erbium-doped fibre laser. In earlier work (Tillman et al [3]) we demonstrated a new method of optical parametric amplification in which a chirped-period crystal of a quasi-phasematched material was used to obtain broadband optical parametric oscillation using stretched pump pulses from a femtosecond laser. The same approach can be used to construct an optical parametric amplifier (OPA) seeded by broadband highly chirped femtosecond pulses and pumped by narrowband high-energy Q-switched pulses. The chirped-crystal technology uniquely makes it possible to simultaneously maintain a broad conversion bandwidth and high gain which are both key requirements for BIL imaging with low speckle distortion.

Chirped-pulse OPA

Conventional OPAs using either birefringently phasematched or periodically-poled quasi-phasematched (QPM) crystals have a gain bandwidth that varies inversely with the length of the crystal used. This fact means that with conventional approaches it is difficult to simultaneously achieve high gain (implying a long crystal) and broad conversion bandwidth (implying a short crystal). These mutually exclusive conditions can fortunately be met simultaneously by using a quasi-phasematched crystal whose grating period has been chirped along the length of the crystal by using an aperiodic grating structure. Figure 1 illustrates how, in contrast to a conventional unchirped crystal (a), a narrow bandwidth pump can amplify a broadband seed using a chirped QPM crystal (b).

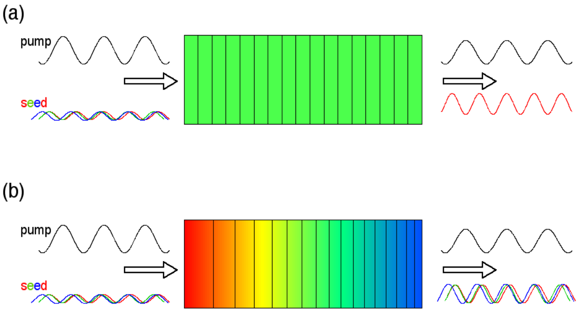

Fig.1: *(a) Conventional and (b) chirped OPAs*

The design of the chirped-pulse OPA is based on a Q-switched 1047nm Nd:YLF laser operating at 1kHz and producing 3.5ns duration pulses with energies of ~130µJ. For broadband operation this laser pumps the OPA in synchronism with low-energy pulses from a femtosecond Er:fibre laser (see Figure 2) centred at ~1.55µm with a bandwidth in excess of 100nm. Prior to amplification the femtosecond seed pulses are stretched from ~150fs to 3.5ns in a 4.5km length of standard SMF28 telecommunications fibre in order to ensure optimum temporal overlap and hence maximum gain. Synchronization between the two lasers is achieved by using a 54MHz radio-frequency oscillator onboard the Q-switched laser as a master oscillator to which the pulse repetition rate of the Er:fibre laser is slaved.

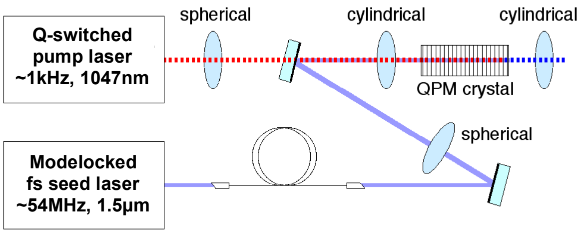

Fig.2: *Schematic of the chirped-pulse OPA*

The OPA crystal is aperiodically-poled MgO:PPLN which has the same high gain of PPLN but exhibits photorefractivity of around 100 times less and can therefore be operated at temperatures as low as room temperature, allowing access to a particularly broad temperature tuning range. In developing the chirped-pulse OPA our approach is to compare the performance of femtosecond seeding with continuous-wave (CW) seeding and so to quantify the advantage of using a broadband femtosecond laser in respect of speckle reduction. For this reason we designed two MgO:PPLN crystals, the first using an unchirped 30.52μm period grating and suitable for CW-seeding and the second with a chirped grating with periods varying from 30.0-30.7μm suitable for femtosecond-seeding. The first experiment using a narrow-line CW fibre laser operating at 1.553μm is briefly summarised in Section 3 (for further details regarding this system refer to the 1st DTC annual conference proceedings). While the results from the second experiment using a broadband modelocked fs-seeded fibre laser are presented in Section 4.

For both the CW-seeded and femtosecond seeded OPAs the optical configurations are identical and the focusing geometry is determined by the need to maintain pump intensities below the (conservative) damage threshold for lithium niobate of 50 MWcm^{-2} (corresponding to a fluence of 0.175Jcm^{-1} for 3.5ns pulse durations) given by Byer et al [4] and simultaneously satisfy the optimum parametric focusing condition (Guha et al [5]). Working within these constraints we designed an elliptical focusing geometry that uses a combination of spherical and cylindrical focusing optics to achieve 1/e^2 spot radii inside the crystal of w_x = 40 μm and w_y = 494 μm. Figure 3 shows the results of an ABCD propagation matrix modelling program used to accurately calculate the required optics.

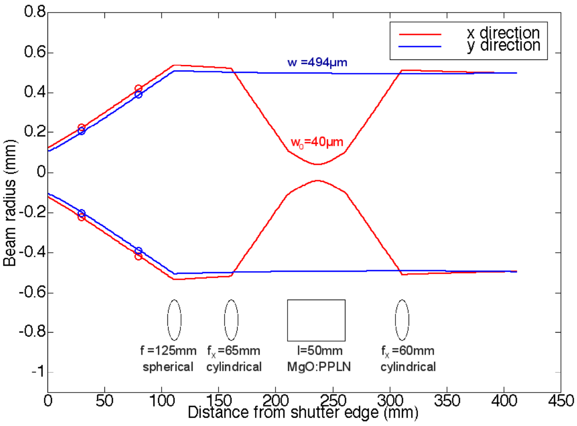

Fig.3: *Modelled pump beam radii for propagation from the laser through the MgO:PPLN crystal*

A similar plot (not shown) exists for the seed beam from the fibre laser.

Continuous-wave-seeded OPA

The CW-seeded OPA was pumped by a Lightwave 110B Nd:YLF laser with results obtained using repetition frequencies ranging from 1-10kHz. The OPA design used spherical 125mm and 200mm lenses respectively to collimate the beams from the pump laser and seed fibre collimator and a 63mm cylindrical lens to focus the pump and seed light into the MgO:PPLN crystal.

Initially a low-level parametric fluorescent signal was detected using an InGaAs photodetector for the pump laser operating at a repetition frequency of 10kHz. Once this signal was located a CW seed beam (λ_{seed}=1553nm) was introduced and parametric amplification was observed with the best conversion obtained at 46°C as illustrated by the temperature tuning data represented in Figure 4.

The same experiment was then repeated several times with the pump laser repetition frequency being reduced each time from 10-1kHz in 1kHz steps increasing pump pulse energies. At the lowest repetition frequency of 1kHz the pump laser produces pulses with a maximum energy of ~130μJ.

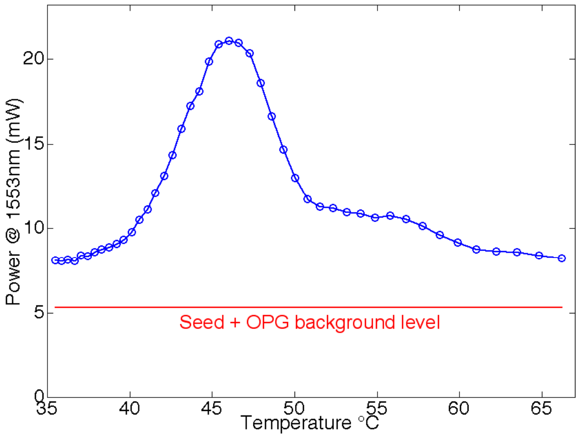

Fig.4: *Temperature dependence of the average output power from the CW-seeded OPA*

At this frequency the 1.553μm amplified output pulses had energies of ~15μJ, corresponding to a conversion efficiency of 12.5% and a single-pass gain of around 10^5 (50dB). Typical pulse bandwidths were around 2.1nm corresponding to a coherence length of ~1.1mm.

These results represent a scientific control against which the operational characteristics of the second OPA, based on femtosecond seeding of a chirped crystal, can be compared once completed.

Femtosecond-seeded OPA

After completion of the CW-seeded system the OPA was reconfigured to include the chirped crystal and the fibre seed laser was set to operate in its modelocked configuration. Figure 5 is a plot of the modelocked seed spectra where a bandwidth in excess of 100nm (1500-1600nm) is clearly shown with the main peak off-centre at 1576nm.

In this mode the seed laser operates at a repetition frequency of 54.25MHz delivering pulses with energies of ~18pJ (~1mW average power) in the horizontal polarisation state. A frequency counter configured to count the seed pulses monitors the exact operating frequency of the seed laser. The frequency counter signal is then mixed with the RF master oscillator signal used to drive the pump laser Q-switch, which also operates ~54MHz, to produce a beat frequency signal. The master oscillator signal is extracted from the pump laser head before it can drive the Q-switch and is later used as an external trigger source.

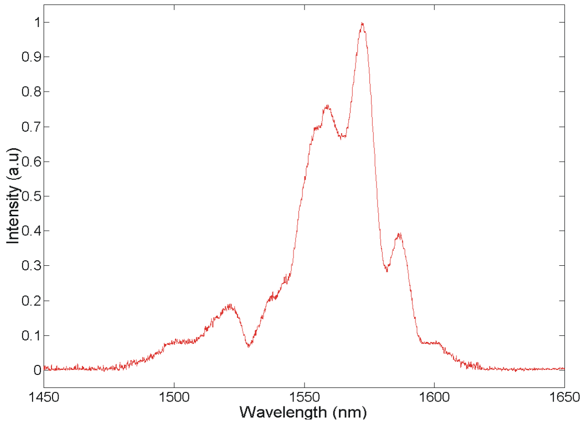

Fig.5: *Normalised plot of the modelocked Er:fibre seed laser spectrum*

Piezoelectric control of a free-space section of the seed laser cavity allows the exact repetition frequency of the seed laser cavity length to be carefully controlled. This allows the beat frequency of the two mixed signals to be monitored and minimised using a piezoelectric offset actuator. As a result the repetition rates of the two lasers can be locked together achieving high-quality synchronisation. The pump laser Q-switch master oscillator signal is then frequency divided down to 981Hz before being used as an external trigger source for the pump laser. Optical path length adjustments were then made to the seed pulses to ensure temporal overlapping between the two trains. Figure 6 shows a temporal measurement of the two laser signals recorded simultaneously on a fast (<175ps) InGaAs photodetector using a highly attenuated pump beam.

After synchronising the pump and seed pulse trains the chirped crystal (held at ~75°C) was inserted into the combined beam and a parametric signal detected and extensively optimised. With the main peak of the seed spectrum now located at 1576nm (rather than 1553nm as for the

CW-seeded OPA) phasematching conditions require a higher operating temperature for the crystal. By varying the crystal operating temperature over a range of 45-115°C a low power output was detected at a crystal temperature of ~75°C implying pulses with energies ~100nJ and indicating a gain of ~37dB. This suggested a conversion efficiency of ~0.08%, which was very low in comparison to the 12.5% observed for the CW-seeded unchirped OPA described in Section 3.

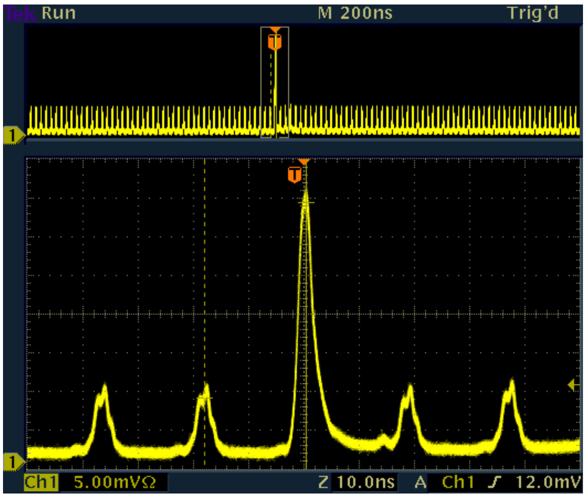

Fig.6: *Simultaneous measure of the pump and seed beams using a fast InGaAs photodetector showing the temporal overlap of the seed pulses (54MHz) and the pump pulses (981Hz).*

Spectral measurements where then made of the OPA and OPG signals over a 45-115°C temperature range using a lock-in amplifier and a slow scanning-mirror assembly. This enabled the spectral bandwidth of the parametric signal to be evaluated. Figure 7 shows the spectra that were recorded over this temperature range however unexpectedly no temperature variation was observed. These spectra, although corresponding to low-energy pulses, indicate a full-width-half-maximum (FWHM) spectral bandwidth in excess of 80nm although a more representative measure would be at the $1/e^2$ (13.5%) intensity point where a bandwidth of the order of 130nm can be measured. Based on the FWHM spectral bandwidth and a peak wavelength of 1576nm a coherence length of ~31μm can be calculated. This is a decrease in coherence length over the CW-seeded unchirped OPA by a factor of ~35.

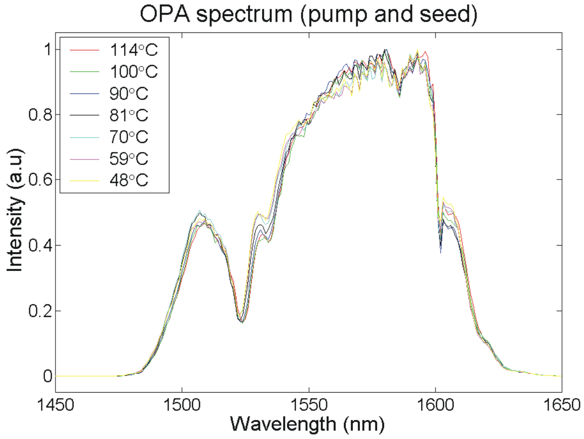

Fig.7: *Seven separate OPA spectra recorded over a 45-115°C temperature range*

The low efficiency of this configuration led to the development of alternative beam focusing arrangements to increase the pump fluencies and the conversion efficiency. The original damage threshold value of 0.175Jcm^{-2} (50MWcm^{-2}) was considered to be too conservative and an alternative range of 1-2Jcm^{-2} was suggested [6] to be more realistic. Several progressively tighter spherical focusing arrangements were simulated using an ABCD propagation matrix modelling program to investigate the potential increases in pump fluence they would offer. Two configurations, using 100mm and 80mm lenses, were identified as potential candidates for experimental investigation. These arrangements were separately configured and investigated to identify the focal arrangement giving the best operational performance. Of the two arrangements the 100mm configuration demonstrated the best performance producing pulses with energies of 2.55μJ at 981Hz. This corresponded to a gain of 51dB and a conversion efficiency of ~2% and was a significant improvement on the elliptical focusing configuration. These pulse energies are compatible with levels needed for use in BIL systems.

Preliminary indications are that the FWHM bandwidth of the OPA signal using the spherical focusing configuration has a similar bandwidth to that measured using the elliptical focusing arrangement, however issues regarding the mode overlap of the three signals (seed, OPG and OPA) have not enabled a definite spectral measurement of the OPA signal to be made before this submission. A full analysis of this system will be completed shortly and results will be presented at the conference.

Future directions and summary

Basic investigations of the seed laser have indicated that due to the available gain pulse energies were likely to be too low for efficient amplification. This suggested that a small but noticeable increase in seed power could significantly increase in OPA pulse energies. To this end the next stage of the project is to integrate an EDFA into the seed delivery stage of the device boosting the seed powers from ~1mW to several tens of milliwatts. This should enable the device to produce an amplified output with pulse energies of the order of tens of microjoules. Optimisation of this setup would be expected to increase conversion efficiencies to similar levels as those seen in the CW-seeded unchirped OPA, i.e. ~12%.

A second point currently under consideration is the limited parametric gain length offered by a laterally chirped crystal, i.e. a period that varies along the crystal length. Individual wavelengths generated by the individual grating periods only see gain in a small section of the crystal. After completion of the current investigation a fs-seeded chirped OPA will be developed that incorporates an MgO:PPLN crystal with a fan-grating structure. This would enable an elliptically focused pump beam to increase the gain section seen by the generated wavelengths and in principle noticeably increase the parametric gain per unit wavelength. It is hoped that this system will further improve on the current system with and without an EDFA incorporated into the seed delivery section of the device.

In conclusion we have demonstrated a parametrically amplified output signal at 1576nm with a bandwidth in excess of 80nm using a fs-seeded chirped crystal configuration. Although currently demonstrating limited conversion efficiency (2%) and low pulse energies (2.55μJ), work is underway to significantly increase these values.

References

1. D. A. Bryan, et al., *Increased Optical-Damage Resistance in Lithium-Niobate.* Appl. Phys. Lett., 1984. **44**(9): p. 847-849.
2. F. Rotermund, et al., *Femtosecond noncollinear parametric amplification in the mid- infrared.* Opt. Comm., 1999. **169**(1-6): p. 183-188.
3. K. A. Tillman, et al., *Low-threshold, high-repetition-frequency femtosecond optical parametric oscillator based on chirped-pulse frequency conversion.* J. Opt. Soc. Am. B-Opt. Phys., 2003. **20**(6): p. 1309-1316.
4. R. L. Byer, et al., *Efficient 2nd-Harmonic Generation of Nd-YAG Laser-Radiation Using Warm Phasematching* $LiNbO_3$*.* Appl. Phys. Lett., 1981. **39**(1): p. 17-19.
5. S. Guha, et al., *The Effects of Focusing on Parametric Oscillation.* IEEE J. Quantum Electron., 1982. **18**(5): p. 907-912.
6. J. A. C. Terry and S. Duncan., *Damage Threshold in MgO:PPLN.* Personal Communication, DTC progress meeting, Edinburgh, December 2004.