DIODE SEEDED PARAMETRIC AMPLIFIER PUMPED BY A PICOSECOND ALL-FIBRE SYSTEM

P.E. Britton, N.G.R. Broderick, D.J. Richardson, P.G.R. Smith, G.W. Ross and D.C. Hanna

Introduction

Several recent advances in fibre source development have greatly increased the output powers and energies available from compact fibre laser systems,[1,2,3]. Suitable levels are now achievable for pumping of parametric devices that use highly nonlinear materials such as periodically poled lithium niobate (PPLN). This powerful combination of fibre sources and PPLN promises a whole range of efficient, widely tunable, practical, all solid state optical sources and devices [4,5,6,7]. Fibre-laser-pumped optical parametric amplifiers (OPAs) constitute one such nonlinear device type offering gains in excess of 80dB. With such high gains OPAs can be used to amplify parametric noise to appreciable power levels so as to efficiently provide high power, broadband parametric fluorescence. An OPA operated in such a fashion is called an Optical Parametric Generator (OPG), [8]. A fibre-laser-pumped OPG has already been demonstrated by Galvanauskas et al. [7] who used a femtosecond erbium-fibre-based chirped based amplification (CPA) system with bulk gratings combined with PPLN to obtain broadband emission on a femtosecond timescale tunable in the wavelength range 1.05-2.9µm. However, due to the noise initiated nature of the process and broad gain bandwidth the generated pulses were far from transform-limited. The same authors also demonstrated a high gain OPA, using millijoule energy pump pulses from a bulk amplifier and a chirped nanosecond pulsed seed [9].

In the following we describe PPLN-based OPA (and OPG) experiments performed using a picosecond all-fibre CPA system as a pump source, i.e. achieving pulse compression using fibre gratings rather than the bulk gratings of Ref[7]. We have demonstrated the high gain achievable with OPA systems using engineered quasi-phase-matched PPLN. Additionally we show that seeding of a high gain OPA with a low-power, continuous-wave beam (e.g. from a laser diode) provides a convenient means to obtain near transform-limited high power pulses at the seed wavelength, thus greatly enhancing the pulse quality relative to that achievable using a simple OPG. Our approach, assuming a PPLN sample of suitable period and an appropriate temperature allows one to use established fibre laser technology to obtain high-quality, high-power pulsed output at any signal /idler wavelengths for which a seed laser, (e.g. a semiconductor diode laser), is available.

Experimental details

Our experimental configuration is shown in Fig.1. and comprises four discrete sections; the fibre pump source, two PPLN crystals, one for frequency doubling and the other for parametric- amplification using the frequency-doubled output, and a low power semiconductor diode laser operating at 1.31µm for seeding the OPA. The fibre pump source was an-all fibre CPA system constructed from specially designed large mode area, single transverse-mode (LMA-) fibre components, [10,11] as described in the following presentation. Pulses of duration ~2.0ps, and energy of 10 pJ at a wavelength of 1.534µm are firstly stretched to ~600ps duration using a 20cm linearly chirped fibre Bragg grating (CFBG). These pulses are then amplified in a series of EDFAs with a final LMA fibre amplifier (mode area ~300μm^2) to a peak energy of ~5µJ. The amplified stretched pulses are then recompressed in a second 10cm CFBG with a LMA (~400μm^2) . This created significantly higher peak powers than previously attainable with conventional FBGs (typically ~ 500kW, [10,11] compared to the previously reported highest powers of 150kW, [12]) before detrimental nonlinear effects within the compressor become significant. At the system output we obtained 4ps pulses (all pulse durations in this article assume a sech^2 shape) with an energy of ~ 1.8µJ, sufficient

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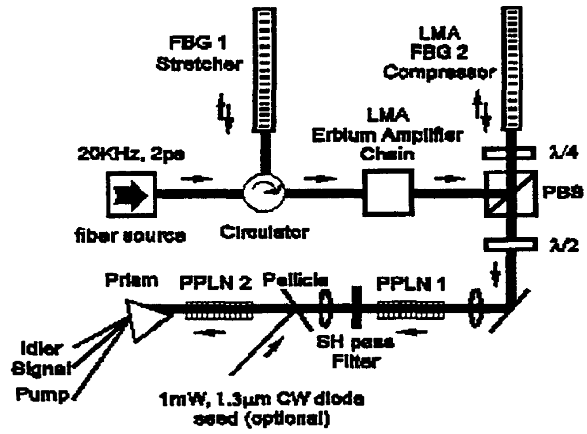

Figure 1 Schematic of laser pump source and parametric amplifier experiment

to allow the high gain OPA to be readily achieved. The time-bandwidth product of these pulses is approximately twice the transform limit, due to a slight mismatch in the dispersion slope of the pulse-stretching and recompression gratings.

The compressed pulses were then focussed into the first PPLN sample (PPLN1, Fig.1) used for frequency doubling the CPA output. PPLN1 was 10mm long, with a period of 18.3μm, chosen for frequency-doubling the fundamental 1.534μm input at a crystal temperature of 150°C. The effective nonlinear coefficient was independently measured to be d_{eff} = 16pm/V. The fundamental spot-diameter ($1/e^2$ intensity width) within PPLN1 was 105 μm. The fundamental was converted to the second-harmonic (SH) with an average efficiency of 40% (external). The duration of the resulting SH pulses was 3.5ps, slightly shorter than the fundamental. The SH pulses were then filtered using a short-wavelength-pass filter with <-30dB transmission at 1.534μm to stop any seeding of the back conversion of the SH to fundamental. The SH was then passed through a pellicle beam splitter (44% SH transmission) before being launched into the second PPLN sample (PPLN2, Fig.1). The pellicle allowed coupling of ~20% of the output of a 1mW CW DFB diode laser operating at 1.31μm collinearly with the SH into PPLN2. This crystal had two 20mm long gratings with periods of 18.3 and 18.7μm, either of which could be accessed by lateral adjustment of the crystal. The SH beam spot diameter within PPLN2 was 80μm and the injected seed beam diameter was 220μm, thus reducing the mode overlap alignment tolerances for the seed beam. By turning the injected laser on or off we were able to investigate the performance in both OPA and OPG regimes for identical SH pump and phase-matching conditions. The device performance was characterised at the system output in both the spectral and time domains (second harmonic autocorrelator). All pulse energy measurements were made via average powers monitored with a calibrated pyroelectric meter.

Optical Parametric Amplifier(OPA)/Generator(OPG) Performance

Fig.2, line a, shows a typical plot of output pulse signal energy for the OPA as a function of input SH energy, maintained at a temperature of 150°C for optimal phase-matching at 1.310μm. The effective threshold (i.e. when the generated pulse energy becomes a significant fraction of the pump energy) occurs at an input pulse energy of ~30 nJ corresponding to a pulse peak power of 9 kW (and corresponding on axis maximum intensity of ~350MWcm^{-2}). This can be compared to the higher threshold, (40nJ) of the OPG, (Fig. 2 line b). The conversion efficiency for the OPA (pump to signal) is ~ 39% with maximum output energy of 50nJ. Note that two times greater pulse energies could have been achieved by replacing the lossy pellicle pump/seed beam combiner with an appropriate dichroic beam splitter. For example with the pellicle removed OPG pulse energies of 75nJ were achieved, (not shown in Fig. 2).

We measured the OPA gain (defined in terms of the number of photons in the output signal relative to the number of seed photons injected within the 3.5ps temporal

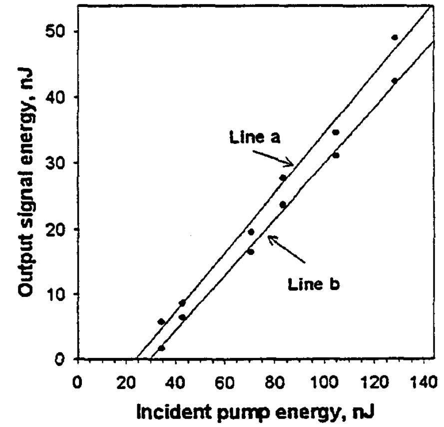

Figure 2 OPA and OPG energy characteristic
Line a represents the OPA signal pulse energy versus pump energy, whilst line b gives corresponding data for the OPG.

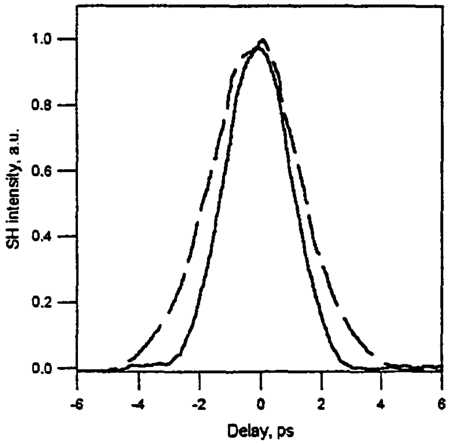

Figure 3 Second-Harmonic autocorrelation of pulses
Solid line represents the OPA, (FWHM ~ 2.7ps), whilst
the dashed line shows the OPG temporal profile, (FWHM ~ 3.5ps)

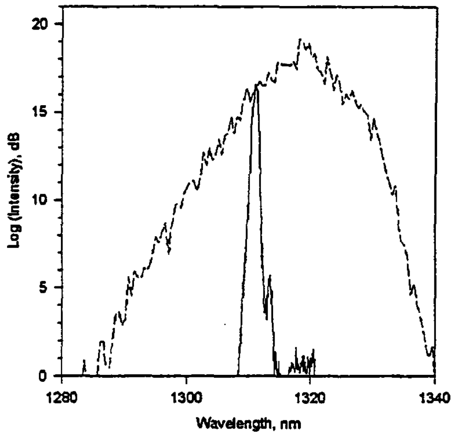

Figure 4 Spectrum of OPA (solid line) and OPG (dashed line)
Δv ~ 20nm for the OPG compared to only Δv ~ 1.5nm
for the OPA.

gain window created by the SH pump pulses) to be 75dB. This resulted in an excellent pulse to cw background ratio for the signal pulses generated in the regions of temporal (and spatial) overlap of the SH pump and seed beams.An even higher gain of 90dB must have been obtained for the OPG in order to obtain large pulse energies from the amplification of zero-point fluctuations.

The small bandwidth of the CW diode seed, (<<1GHz) ensured a narrow signal spectral width of 1.5nm, (Fig 3, solid line). This spectral width combined with the 2.7ps signal pulse duration, (Fig 4, solid line) as determined by autocorrelation, gave a time-bandwidth product of 0.66. This is close to transform limited, (0.44 for a Gaussian pulse). In sharp contrast the OPG spectrum was ~10 times broader than the OPA spectrum, (Fig 4, dashed line), clearly demonstrating the major advantage of seeding.

Fig. 5 shows the range of signal wavelengths over which the two PPLN periods could be temperature tuned to achieve phase-matching. Any seed wavelength could theoretically be amplified within this range. The OPG, with no seed wavelength restrictions, could temperature tune over the signal(idler) range of 1.2-1.44 (1.65-2.15)μm. With an increased range of grating periods operation over the extended range ~0.9-5μm should prove possible, [5]

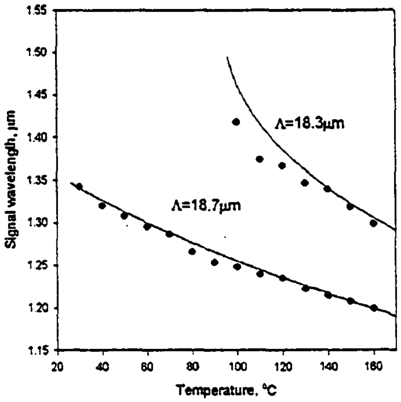

Figure 5 Temperature tuning curves for the gratings, (periods indicated).

Interestingly we found that the peak wavelength of the amplified signal pulses was offset (redder by about 1nm) from the wavelength of the injected seed. This strange effect is shown in Fig. 6, where the amplified pulse is asymmetric about the unamplified narrow CW diode peak. Note that previously in Fig. 4 the remaining unamplified pulse diode was not visible since we pulsed the diode seed (~1ns) in synchronous with the pump pulses. This greatly decreased the contribution of the remaining seed to the spectrum. The magnitude of this offset did not appear to be pump power dependent, nor was it dependent on the signal and pump wavelengths, (at least over their restricted tuning ranges, +/- 0.5nm). The wavelength offset was also independent of the PPLN temperature, (a peak phase-matching wavelength tuning range of ~ 10nm). The offset was sensitive to the chirp of the fundamental, which was varied by creating a temperature gradient on the pulse stretching fibre grating. However, without some means of directly determining the chirp, and pulse shaping effect of tuning the grating dispersion on the SH pump pulses, we were unable to satisfactorily quantify this sensitivity. We currently do not fully understand these observations, with both experimental and theoretical investigations ongoing.

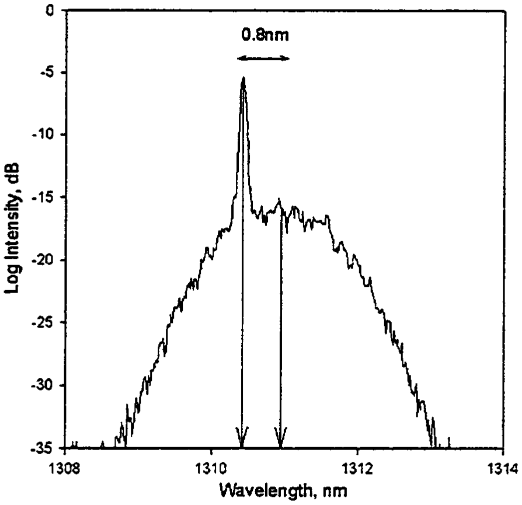

Figure 6 Amplified signal pulse offset

Conclusion

In summary, we have described a picosecond OPA, pumped by an all-fibre source, and generating 50nJ pulses. We have demonstrated OPA gains in excess of 75dB for these ps pulses, and confirmed that significant improvements in the pulse's spectrum relative to an OPG, can be conveniently achieved by seeding with a low power CW seed beam. With such an approach one can use robust and established fibre and PPLN technologies together with CW diode lasers in the range 0.9-5µm, to obtain high power pulses. These results provide further evidence of the compatibility between PPLN and fibre devices which should lead to the development of a wide range of versatile all-solid state laser sources.

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