Optical parametric oscillation in periodically-poled lithium niobate driven by a diode pumped, Q-switched erbium fibre laser

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Abstract

We describe the first nanosecond PPLN OPO driven by a fibre laser. The source was frequency doubled by a PPLN sample, before pumping a second 20mm long PPLN crystal. The OPO threshold was <10 µJ, with pump depletions of up to 45% and a tunable signal range of 945-1450nm, (1690-4450nm idler range). We demonstrated 130nm signal tuning by varying the pump wavelength and doubling crystal's temperature. Also, we achieved 15nm tuning with all crystals at a constant temperature. The results demonstrate the potential of the fibre laser: PPLN combination for practical, versatile and tunable sources.

Over recent years considerable progress has been made in increasing the output powers from single transverse-mode rare-earth-doped optical fibre systems [1]. The development of power scaling techniques such as cladding-pumping, coupled with advances in both the power and brightness of semiconductor pump lasers, has extended the average powers from robust, compact fiber systems up into the multi-10 W regime, with output powers as high as 35W already reported for a cladding-pumped Yb fiber laser system. In addition, new fiber designs such as large mode-area doped fibres [2] and ring-doping [3], also compatible with the cladding pump concept, have extended the range of pulse energies attainable directly from simple fiber laser systems. Pulse energies of ~0.2mJ and peak powers in excess of 100 kW are reported for nanosecond pulses from simple erbium doped fiber systems. Further advances towards the mJ regime are expected.

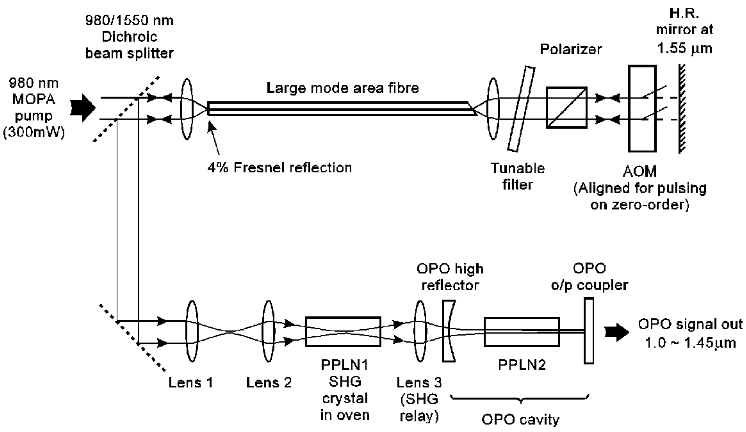

Fig.1 OPO schematic

At these powers and energies fibre laser systems become attractive as pump sources for nonlinear parametric devices such as Optical Parametric Oscillators and Amplifiers (OPO and OPAs). Fibre lasers offer performance advantages over alternative pump laser technologies, e.g. in terms of beam quality; immunity to thermally induced effects; wavelength tunability; and from the practical perspective, robustness, size and cost of the system. Also, the use of engineered, Quasi-Phase Matched materials such as highly nonlinear Periodically-poled Lithium Niobate (PPLN) with the correct choice of grating period, allows any wavelength to be non-critically phase-matched within the material's transparency window [4].To date, efficient (>60%) frequency doubling and mixing of fibre laser output has been demonstrated in the nanosecond [5] and femtosecond [6] regimes using practical fibre laser systems. In addition, a fibre laser pumped OPA has been demonstrated using high power femtosecond pulses from a fibre-based chirped pulse amplification system [7]. In this paper we present what we believe to be the first demonstration of a fibre laser driven OPO which illustrates many of the attractive features of fibre laser pumping of parametric PPLN devices. In particular we wish to emphasise the advantages to be derived from the broad tuning ranges of fibre laser systems (typically 3-40 nm) which allow, through the use of OPO pump tuning [8], very practical and agile wavelength tuning of the OPO.

The erbium fibre laser pumped OPO system, shown in Fig.1, comprises three main components: a Q-switched laser, PPLN sample 1 in which the laser output is doubled to around 780 nm and the OPO cavity containing PPLN sample 2. The Q-switched laser [9] is pumped with light from an isolated 980 nm, 370 mW MOPA semiconductor

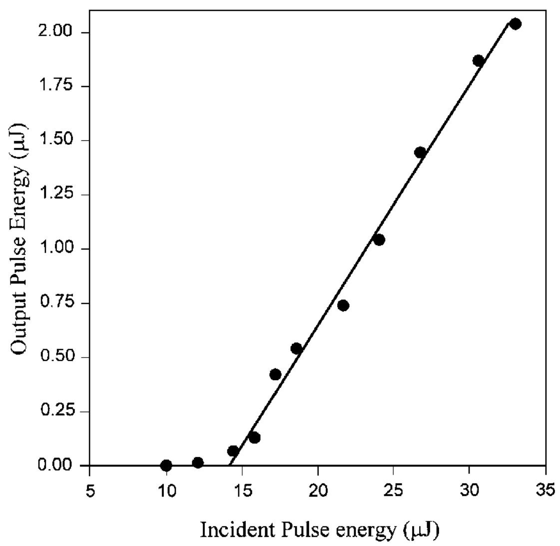

Fig. 2 OPO characteristic

source. About 320 mW is launched into a large mode-area (320 µm^2), erbium doped fibre. The fibre is 4.0m long and doped with 400ppm of Er^{3+}ions. It has an NA of 0.066 with a cut-off wavelength of 1450nm, which ensures a single transverse mode at the operating wavelength. The laser cavity is formed by the 4% Fresnel reflection at the pump launch end and the high reflector mirror. All other surfaces within the cavity are either anti-reflection coated or angle-polished. The laser is configured to run in the zero-order, Q-switched mode. An angle-tuned, dielectric bandpass filter of 1nm spectral width is included within the cavity to allow for laser tuning (between 1530nm and 1560 nm) and to further reduce the loss of energy to ASE. A polariser is also included in the cavity to ensure a linearly polarised output. The slope efficiency for both cw and Q-switched operation was 0.36 with respect to incident power and corresponds to approximately 70% quantum efficiency with respect to launched pump power. When operated at 300 Hz, as it was for the experiments described here the laser produces pulses of up to 150µJ and ~50 ns duration, corresponding to ~ 3kW peak power. The spectral bandwidth of the pulses is typically 0.25nm. Note that the large area mode concept is fully compatible with cladding-pumping, enabling average power scaling of the output to the multi-Watt regime.

The PPLN crystals for these experiments were fabricated in 0.5mm thick z-cut lithium niobate by electrical poling. The samples were mounted in temperature-controlled oven assemblies to allow temperature tuning of the phase-matching condition. Sample 1, designed for second harmonic generation at wavelengths around 1560nm, had a period of 18.7µm, and was 20mm long. Sample 2, also of length 20mm contained a number of different grating periods (19, 19.5, 20, 20.5 µm) suitable for 780nm pumped OPO operation in the signal range 950-1450nm. Sample 1 was Anti-Reflection (AR) coated with single layer silica coatings. Sample 2 had MgF_2 coatings and gave <2.5% reflectivity at 1300nm for each face. Previous measurements on the samples indicated an effective nonlinear coefficient of 16pm/V, approaching the maximum possible value.

The laser output at the fundamental wavelength was collimated and focused to a spot diameter of 80µm within PPLN sample 1. The corresponding intensity was thus 120 MW/cm^2, which was safely below a previously found damage threshold of 350MW/cm^2. The conversion efficiency from fundamental to SH was around 40%, giving SH

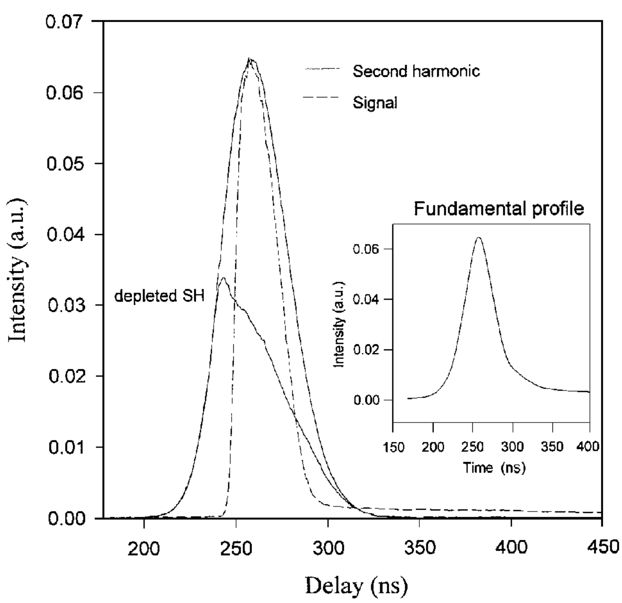

Fig. 3 Fundamental, second harmonic input and depleted output, and signal pulse forms.

pulse energies of up to 60µJ at the OPO input. This conversion efficiency, although sufficient for these experiments was lower than previous measurements (due to previous damage to the crystal's surface), when conversion efficiencies of 63% and pulse energies approaching 90µJ had been obtained [5]. The pulses shortened in the SHG process to 45ns duration, as shown in Fig.3. The acceptance bandwidth for efficient SHG (3dB halfwidth) at fixed PPLN temperature was ~1nm. The 25-180 deg C temperature range of the doubling crystal allowed 7nm of SH tuning.

The OPO cavity, (see Fig. 1) had a concave input coupler with a radius of curvature of 10 cm, and reflectivity of 15% at 780nm. 99.5% of the signal band (920-1450nm) was reflected and <15% over the idler band (1690-5100nm). The output coupler had a reflectivity of ~75% over the signal band and

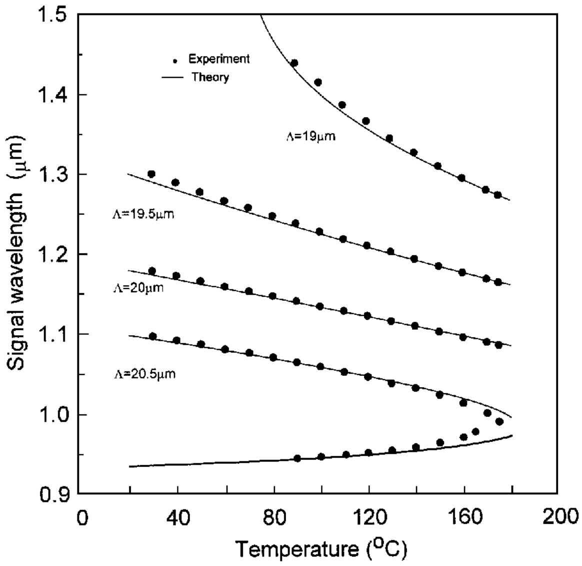

Fig. 4 Tuning curves for different gratings.

<15% over the idler band. The 780nm pump beam was focused to a spot diameter of 80μm within PPLN sample 2. The total cavity length was ~11cm resulting in a cavity round trip time of 900ps, hence approximately 50 cavity round trips were made within the pulse half width.

A typical OPO power characteristic plotted in terms of output pulse signal energy versus incident SH pump energy is shown in Fig.2. For this measurement the 20μm grating was used at 150°C, generating a signal wavelength of 1150nm. The SH pump wavelength was 780nm. From Fig.2 it is seen that a threshold of ~10 μJ is obtained. This threshold value is close to that expected for the system parameters and comparable to values obtained with Nd:YAG pumped nanosecond OPOs [4]. A slope efficiency of ~10% was observed at 1150nm, (Fig. 2). Significantly higher slope efficiencies should be possible with reduced losses of the AR coatings. Fig.3 shows plots of the fundamental pulse, the input and output SH pump pulses, and the signal pulse shape for a launched SH pulse energy of 40 μJ. These indicate an average pump depletion of 44 % with peak depletions in excess of 60%, from which simple theory predicts a 13% slope efficiency, in good agreement with the measured value.

The OPO signal wavelength can be tuned by adjusting the temperature of sample 2 and selecting different grating periods within the sample, whilst keeping all other system parameters fixed. In Fig.4 we show temperature tuning curves for grating periods 19, 19.5, 20, 20.5 μm showing operation of the OPO over >500 nm of signal wavelength from 945-1450nm. The corresponding idler tuning range was 1690-4450nm. The wavelength tuning of a single grating is typically 100nm for 100°C tuning range. These tuning ranges were limited only by the reflectivity of the mirror sets and different mirrors should significantly extend the tuning range. The short wavelength 945-975nm signal branch obtained using the 20.5μm grating, (see Fig. 4) required a change of output coupler to one that was highly transmitting above 1μm but highly reflecting below. The lower losses of the sub-micron wavelength branch now favoured operation in this new regime. Note that even when operating the OPO at temperatures as low as 30°C there was no evidence of photorefractive damage effects due to the intense 780nm pump. The observed tuning ranges are seen to agree well with our theoretical expectations based on the improved Sellmeier equations due to Jundt, [11].

A major advantage of using a fibre laser as a pump

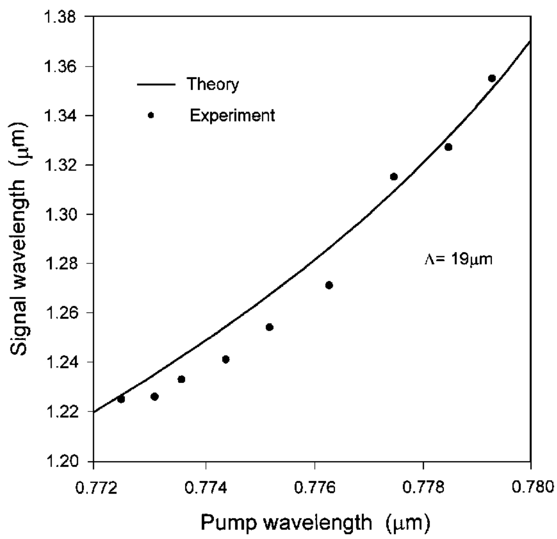

Fig. 5 Pump tuning curve

source is that one can readily tune the input pump wavelength to obtain significant tuning of the signal output, all other parameters of the OPO e.g. temperature/grating pitch remaining constant. The high gain of the laser allows significant spectral width in the tuning element to be tolerated. This is an extremely attractive feature from a practical standpoint and should allow for rapid wavelength tuning of the OPO output. Calculations show that large differential rates of wavelength tuning can be obtained. For example, using a 19µm pitch grating one can obtain differential tuning factors of 25, by using a 780nm pump wavelength and signal wavelengths around 1400nm i.e. 1nm of pump tuning causes 25nm tuning of the signal, and ~ 50 nm tunability in the idler. In order to demonstrate the pump tuning capability of our current system we examined the output signal wavelength versus the input fundamental wavelength under two conditions. Firstly keeping both PPLN sample temperatures and periods fixed whilst only varying the fundamental wavelength (around 1559nm, giving ~1nm tunability). Secondly allowing the temperature of the SHG PPLN sample to be tuned for optimum SH efficiency as the fundamental wavelength was tuned over 14nm. In the first instance we obtained 9nm tuning for 0.3nm tuning of the fundamental. This was extended to 15nm for a 0.6nm pump change by using a 10.5mm long PPLN sample for the SHG but otherwise identical experiments, corresponding to a differential tuning factor of 25 with respect to SH wavelength. In the second instance we obtained 130nm of signal tuning for 7nm of SH tuning ,(see Fig. 5) corresponding to an average differential tuning factor of 19. The results illustrate the advantages of using a readily tunable fibre laser as a pump. In our current system the range over which we can pump-tune the OPO signal wavelength is restricted by the SHG acceptance bandwidth (~1nm) of the frequency doubling process rather than by the tuning limitations of the fibre laser itself. With an appropriate set of grating periods in the SH PPLN sample, (not available in this experiment), efficient SHG could be possible without temperature tuning. Using a grating of 19 µm period at fixed temperature within the OPO, signal tunability of >300nm would be achievable. Note also that our results suggest that a nanosecond OPO directly pumped by a fibre source at a wavelength of 1.55µm (expected threshold ~80µJ) should also be possible, thus simplifying the overall system.

In conclusion, we have reported, what we believe to be the first demonstration of a practical diode pumped, fibre laser driven OPO illustrating the compatibility of fibre and PPLN technologies. Such a combination promises practical parametric devices of great flexibility and simplicity.

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