521

# Synchronous pumping of an optical parametric oscillator using an amplified quasi-cw pump envelope.

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**Abstract**

Pulse-slicing from a cw laser output followed by high gain amplification can produce quasi-cw pulses at power levels well in excess of those available from large frame cw lasers. Mode-locked pulse trains with an envelope of 10μs duration and at 2kHz repetition rate are amplified by a factor of 20 to give 5Watts of envelope average power. These power levels allow efficient single-pass frequency doubling and subsequent pumping of a lithium triborate optical parametric oscillator.

**Key Words**

Mode locked lasers, Optical amplifiers, Parametric oscillators and amplifiers

## Introduction

There are many experimental situations where laser power requirements are well in excess of those available from cw lasers, but where the alternative of Q-switched lasers is not suitable, due to the excessive intensity or the pulse duration being too short for the intended application. As an example, a laser producing pulses in the μsec regime can provide quasi-cw pumping conditions for short lifetime laser transitions, eg. Ti:sapphire. The long quasi-cw pump pulse can provide sufficient time for frequency selection to be effective in Ti:sapphire or in optical parametric oscillators (OPO's), with MHz linewidths achievable in principle. Thus with long pulses many of the benefits of cw operation can be retained, but at higher powers

By pulse-slicing the laser at pulse repetition rates equal to the inverse fluorescence lifetime, and then subsequent amplification, high power extraction and maximum pulse energy in the amplified pulse are achieved. Thus for example by using Nd:YLF ($\tau_f \approx 450\mu sec$), operation at 2kHz with say 10μsec pulses allows pulse power with up to 50 times that which could be extracted cw but without the associated thermal penalties that such high power cw generation would incur.

In our present system we use a simple end-pumped double-pass amplifier to achieve small signal gains of ~34 for a modest pump power of 4Watts. We have used this arrangement to amplify 10μsec pulse envelopes from a cw additive-pulse mode-locked (APM) Nd:YLF laser. These amplified pulses then have sufficient peak power to allow efficient single-pass harmonic generation in lithium triborate (LBO), whereas previously when operating cw efficient SHG required the extra complexity of a resonant enhancement cavity.

This amplification scheme offers considerable flexibility in the choice of operating parameters such as repetition rate, pulse duration and the shape of the pulse envelope.

## Nd:YLF double-pass amplifier

The experimental arrangement used for this demonstration is shown in figure 1.

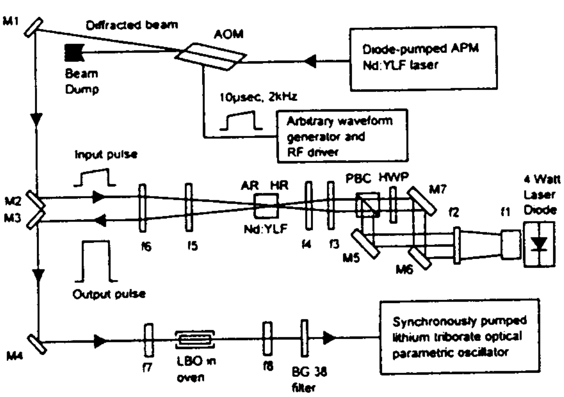


Figure 1. Schematic layout of the experiment. AOM-acousto-optic modulator, HWP-half-wave plate, PBC-polarizing beam-splitter cube, M1-M4, HR@1.047μm, f1-f8, lenses, M5-M7, HR@0.8μm.

The output of the APM laser consisted of 2.4psec pulses at 105MHz with average cw power of 540mW. The cw beam was pulse-sliced by an acousto-optic modulator (AOM), with the diffracted beam being then



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amplified. A maximum diffraction efficiency of 70% was measured with this device. The pulse shape, length and repetition rate were all freely adjustable by modulation of the RF drive to the AOM. An area of increased flexibility was provided by the use of an arbitrary waveform generator, AWG (Tektronix AWG 2005). This allowed control of the pulse envelope shape to the amplifier, so that gain saturation during the pulse could be offset by a corresponding increase in the input signal thus enabling flat-topped output pulse envelopes to be produced (see figure 6 for a comparison).

The amplifier consisted of a 6mm long by 4mm dia. Nd:YLF rod with 1.1% doping. The crystal was AR coated at 1.047μm on one face, with the other face coated to be HR@1.047μm and HT @~0.8μm through which end-pumping took place. The signal beam entered the crystal with a small angle to the face normal allowing a double pass and separation of the input and amplified beams. The pump diode was a 4W device (SDL 2382-P1), operating at 796nm. The two output lobes of the diode are superimposed in the rod by first separating them and then after polarisation rotation of one half, re-combining via a polarising beam splitter cube (PBC). This arrangement shown in figure 1 and described elsewhere[1] allows enhancement of the pump beam brightness, an important step in maximising the gain.

The basic approach for achieving largest gain is to minimise the pumped volume within the absorption length of the crystal. Circularity of the pump beam is not required and as such the signal beam was shaped to match the elliptical pump beam. Through a combination of crossed cylindrical lenses (f3 and f4 in figure 1) of focal length 100mm and 60mm respectively we achieved a pump beam at the laser rod with $1/e^2$ intensity radii of 175μm by 44μm. To ensure maximum gain the input signal beam was focussed with a pair of cylindrical lenses, f5 and f6 of respective focal lengths 150mm and 250mm to produce an elliptical spot of size 176μm by 57μm, such that the signal beam overlapped the most intensely pumped region of the gain medium.

Using this arrangement, a double-pass cw gain of 4.4 was obtained for an input power of 270mW. This value was considerably reduced by saturation from the small signal gain (SSG) value of 34, see figure2. By using the AOM to provide pulse envelopes from the cw mode-locked pulse train with short envelope lengths and low enough repetition rates, it would be possible to access essentially the full of the small signal gain. In practice, we opted for an envelope length of 10μs at 2KHz repetition frequency, which gave an envelope energy gain of 20, reduced from the SSG by saturation. Using square input pulses we achieved a maximum amplified power of 5W

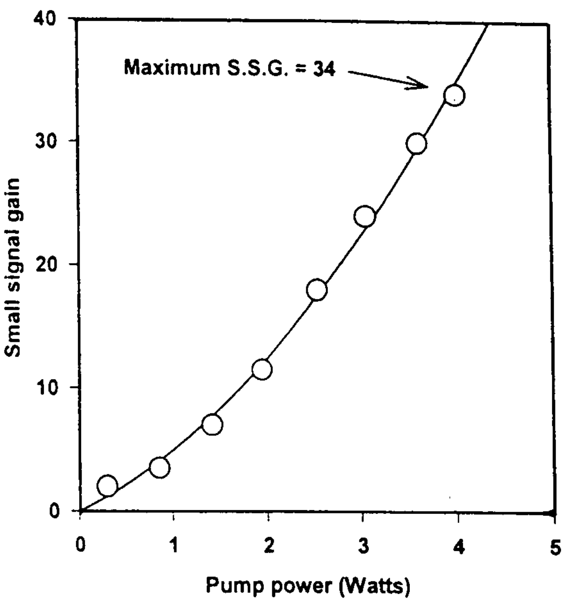



Figure 2. Small signal gain (1mW input) versus diode pump power.

(averaged over the sliced-pulse envelope), a factor of 5 greater than was available from this system under cw conditions [1]

The $M^2$ beam quality factor of the output beam was measured to be ~1.05, confirming that amplification did not introduce significant beam distortion.

**Second harmonic generation in LBO**

Further confirmation of the beam quality was provided by harmonic generation. A 15mm long LBO crystal, temperature-tuned non critical phase matching, was used for single-pass doubling with the fundamental beam focussed to a spot size of 30μm. A maximum generated single-pass second harmonic power of 2.5W was measured (envelope average), this is significantly greater than that achieved under cw conditions, where a resonant enhancement cavity was needed to achieve 0.65W. The pulse duration was measured to be 2.3psec ($sech^2$ pulse assumed). The autocorrelation is shown in figure 3. It should be noted that autocorrelation of the individual pulses ~1000 within one amplified envelope was not feasible since this would involve scanning a mirror over approx 1.5mm in <10μs, a speed of 150m/sec which is about half the speed of sound in air. Instead we chose to slowly scan the mirror (2mm in 20sec) and use an integrator to look at the harmonic signal with an integration time of 10msec (or 20 individual pulse envelopes).

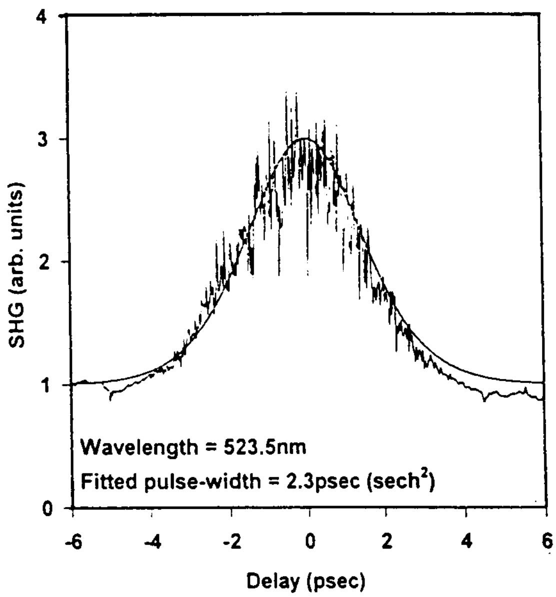



Figure 3. Quasi-cw autocorrelation of the second harmonic amplified pulses at 523.5nm.

**LBO optical parametric oscillator**

The SH beam was subsequently used to drive a synchronously-pumped OPO again based on LBO.

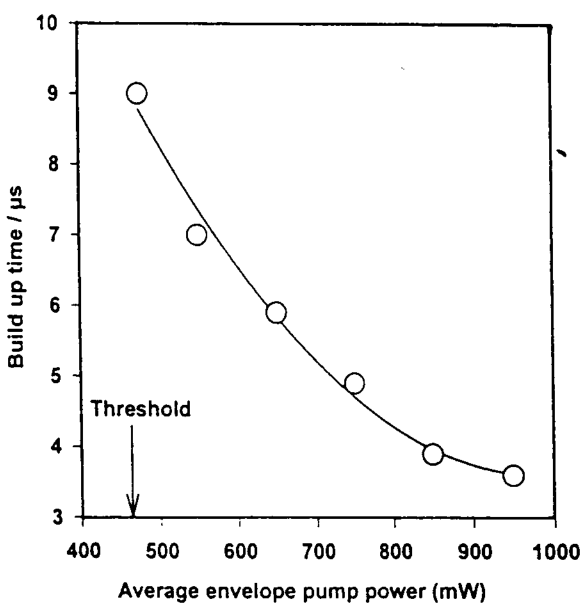



Figure 4. 10% output build up time versus incident pump power.

The singly resonant OPO was basically the same as that described elsewhere [1], which had a threshold of 170mW under cw pumping conditions, for a signal wave of 950nm and an output coupling of 2.5%. The corresponding pulsed threshold was 475mW (envelope average). This threshold was surprisingly high at first given the much reduced power levels required for cw operation. The turn on time or build up time for oscillation was investigated by measuring the delay between the onset of pumping and the OPO reaching 10% of its final level. The reason for this is that the lower gain in the OPO requires more round trips to reach threshold for lower pump power levels. This dependence is shown in figure 4.

Typical values for the output powers of the signal and idler are shown in figure 5, with slope efficiencies for the signal and idler pairs of 29% and 16% respectively.

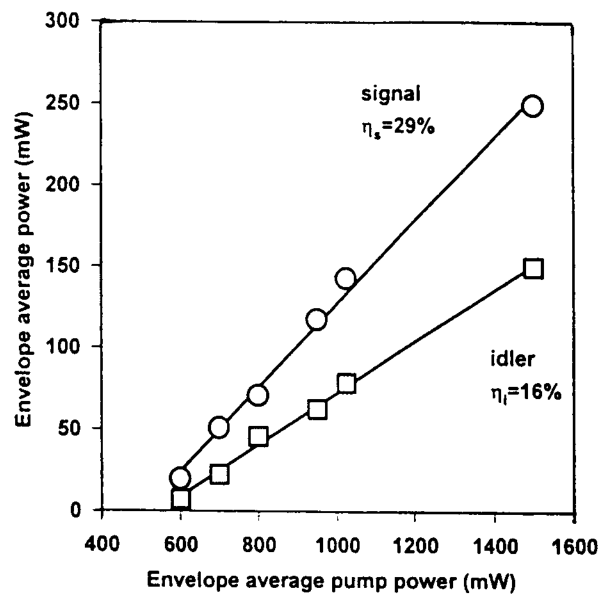
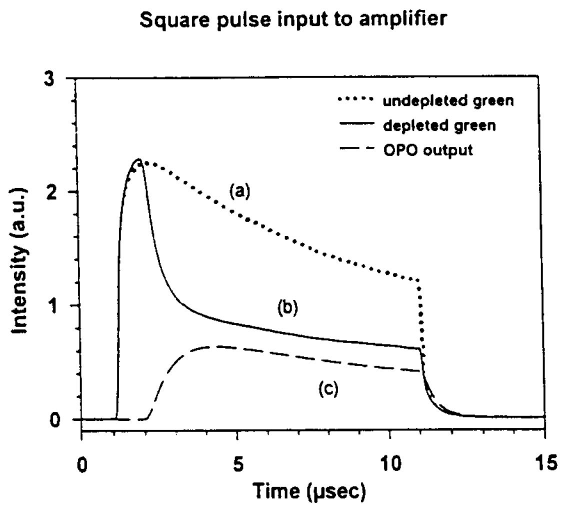


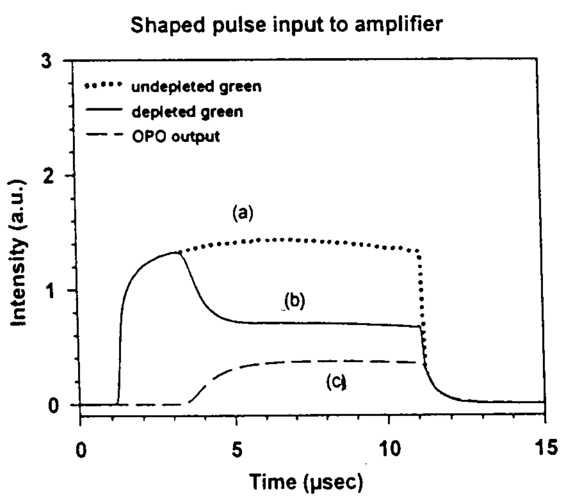

Figure 5. Output versus pump power for the signal and idler pairs at 950nm and 1164nm respectively.

The typical temporal behaviour of the OPO for a pump power of 1.7W in a flat-topped pulse is shown in figures 6 (a.b) Figure 6(a) is the behaviour without the pulse-shaping via the AWG. Here, the amplified pulse shows a drop in power as saturation of the amplifier occurs during the pulse envelope.

It should be noted that a penalty is paid when using the shaped envelope in that significantly higher power was available with the unshaped pulse (2.5 W cf. 1.7W flat-topped). After a build-up time of ~2µsec, oscillation occurs with a large depletion of the pump (50%) as shown in figures 6(a,b). The output powers obtained for 1.7W of pump were 250mW for the signal at

950nm and 150mW for the idler at 1164nm. These results indicate performance close to that observed for the cw pumped oscillator, so the expectation is that, with further optimisation of the setup, the performance of the cw oscillator will be fully reproduced in this pulsed fashion, with tuning from 0.65μm to 2.65μm [1].




Figures 6 (a,b). Temporal behaviour of the synchronously pumped quasi-cw OPO. The traces shown are a) the undepleted pump pulse, b)the depleted pump pulse and c) the OPO output. Figure 6(a) shows how using a square input envelope to the amplifier saturation occurs over the duration of the amplified pulse envelope.

## Conclusions

The experiment described here was chosen as a demonstration of the concept for using high gain amplification of long pulses to create a quasi-cw pump source with power substantially greater than would be available in cw operation. There is much scope for extending the capabilities of such a source, by moving to higher power diode pumps, particularly in the form of a diode bar with output beam shaped for longitudinal pumping [2]. An advantage demonstrated here even in our non-optimised arrangement, and with modest pump power, has been the ability to achieve efficient single-pass doubling for a long, quasi-cw pulse, without the complexity of a resonant enhancement cavity as needed for cw operation.

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## References.

1. S. D. Butterworth, S. Girard and D. C. Hanna, "High-power, broadly tunable all-solid-state synchronously pumped lithium triborate optical parametric oscillator", J. Opt. Soc. Am. B, **12**, p.2158-2167 (1995)
2. W. A. Clarkson, A. B. Neilson and D. C. Hanna, "Diode laser bar beam shaping technique" CLEO Europe technical digest, Paper CFH6, p.410-41 (1994)