High-power quasi-cw laser pulses via high-gain diode-pumped bulk amplifiers.

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Abstract

By pulse-slicing from a cw laser output and then providing high gain amplification, one can obtain quasi-cw pulses at powers well in excess of those available from cw lasers. The use of this is demonstrated with a cw, additive-pulse-mode-locked Nd:YLF laser. Mode-locked pulse trains with an envelope of ~10μsec duration and repetition rate of 2kHz are amplified in a x20 gain, double-pass Nd:YLF bulk amplifier pumped by a 4W diode. Amplified power levels allow efficient single-pass frequency doubling in LBO followed by efficient synchronous pumping of an LBO optical parametric oscillator.

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 pulses is not suitable, either due to their excessive intensity or due to their pulse duration being too short for the intended application. Pulse durations in the microsecond regime can provide the required compromise. For example, a laser source producing such long pulses can provide quasi-cw pumping conditions for Ti:sapphire lasers and can provide sufficient time for frequency selection to be effective, say in Ti:sapphire lasers, or optical parametric oscillators (OPO). In principle, narrowing down to ~MHz linewidths can be achieved in these long pulses. By operating the laser source at pulse repetition rates equal to the inverse of the laser lifetime, efficient power extraction and maximum energy per pulse is achieved. So, for example, with Nd:YLF, having a 450μsec lifetime, operation at a 2kHz repetition rate, with pulses of, say, 10μsec duration would allow pulse powers with up to ~50 times the power that could be extracted cw, but without the thermal penalties that such high power generation cw would entail. In many cases such a power enhancement would be sufficient to allow efficient nonlinear frequency conversion (OPO, SHG) without resorting to Q-switching. Thus with kilohertz repetition rates and microsecond pulse durations, many of the benefits of cw operation can be retained, at much higher power levels, without incurring the thermal penalties of high cw power.

Several workers have reported achieving long-pulse operation of lasers via Q-switching in a long resonator or by using a modified form of Q-switching where the intra-cavity loss is varied actively [1], or passively, for example by intracavity SHG [2]. However, given the possibility of high-gain amplification, a more convenient route is now available, in which the output from a cw laser is pulse-sliced and this pulse then amplified to high power levels. High-gain amplifiers have been demonstrated with a tightly-folded resonator [3], and with multipass amplifier arrangements [4]. However, both of these have rather complex beam paths. In this paper we show that relatively high small-signal gain can be achieved, ~34 times in our case, in a simple double-pass amplifier end-pumped by a diode laser of modest (4Watts) power. We have used this to amplify 10μs pulse envelopes sliced from the output of a cw, additive-pulse-mode-locked (APM) Nd:YLF laser. The amplified pulses then have sufficient power for efficient single-pass SHG in lithium triborate (LBO), followed by efficient synchronous pumping of an OPO based on LBO. Thus, an immediate benefit we have obtained from this arrangement is the ability to dispense with an SHG resonant enhancement cavity, previously necessary for efficient SHG of the mode-locked source when operated cw [5] .

So, even for this non-optimised set-up, significant benefit is achieved. Much more benefit will be achieved in future, with higher gain amplification and increased average power extraction from amplifiers pumped by higher power diode lasers, using, for example, diode lasers whose beam has been optimally shaped into a well-confined circular beam [6].

This amplification scheme offers great flexibility in the choice of pulse repetition rate, pulse duration and shape of the pulse envelope, with quasi-cw power levels in the kW region being achievable in principle from diode-pumped systems. For mode-locked pulse trains peak powers in the megawatt range are feasible. A further area of flexibility in the mode-locked case is in the mode-locked pulse duration, since a Fabry-Perot filter could be used as a convenient means to temporally broaden the pulses to any desired duration, before restoring the desired power level via subsequent amplification.

We now describe an experimental set-up (see fig.1) which we have chosen to demonstrate this pulse-slicing and amplification, followed by frequency-conversion. The diode-laser-pumped Nd:YLF APM laser, operating at 1.047μm has been described elsewhere [7]. Its TEM_{00} output consisted of 2.0ps pulses, at 105MHz repetition rate, with an average power of 540mW. This input beam was pulse-sliced by an acousto-optic modulator (AOM), using the diffracted beam as the output to be subsequently amplified. A maximum diffraction efficiency of ~ 70% was achieved with this AOM (Gooch & Housego, Model QS0802BRCG), so that typically the maximum diffracted cw power of the pulses was ~360mW, and adjustable simply by varying the RF drive power to the AOM. Pulse duration and repetition rate of the sliced-out envelope were also freely adjustable by using a pulse generator to modulate the RF drive. Additional versatility was provided by the use of an arbitrary waveform generator (Tektronix AWG 2005). This allowed control of the input pulse envelope 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 2 for comparison).

The amplifier consisted of a 6mm long Nd:YLF rod (ϕ, 4 mm), of 1.1% Nd doping, with plane faces, AR coated on one face and having high reflectivity for 1.047μm and high transmission at ~0.8μm on the other face, through which longitudinal pumping took place. The signal beam entered and left the AR coated face, undergoing double-pass amplification, with a small angle (1.5°) to the face normal to allow separation of the input and output beams. The diode laser pump was a 4W broad-stripe (SDL-2382-P1), operated at 796nm, and with the two halves of its output beam superimposed in the rod, by first splitting the beam, then polarisation rotating one half, and superimposing it on the other half by means of a polarising beam splitter cube. This arrangement, shown in figure 1 and described elsewhere [5],[8] allows enhancement of the pump beam brightness, an important feature in enhancing the gain.

The basic aim here is to minimise the pumped volume within the absorption length of the pump. Circularity of the pump beam is not required, and the signal beam was shaped to match the elliptical pump beam. The plane of the diode junction is the (horizontal) plane of figure 1. The beam from the diode laser is conditioned as shown in figure 1. First the beam is collected and collimated in the fast divergence direction (vertical plane) by a 6.5mm focal length, 0.6NA lens f1 (Melles Griot, Part 06GLC001/D). The residual divergence in the slow direction (horizontal plane) is compensated for by a 200mm focal length cylindrical lens, f2. After recombining the two lobes of the diode laser beam, they are subsequently focussed into the gain medium by a pair of crossed cylindrical lenses (f3 and f4 in fig1) of respectively 100mm focal length (vertical) and 60mm (horizontal). This arrangement produced a pump beam at the laser rod with $^1/e^2$ intensity radii of 175μm (in the plane of the array) and 44μm (in the orthogonal plane) with corresponding half-angle beam divergences of 3.6° and 1.2°. To ensure maximum gain the input signal beam was focused using a pair of cylindrical lenses, f5 and f6 of respective focal lengths 150mm and 250mm, to an elliptical shape with spot sizes of 176μm and 57μm, so that the signal beam overlapped the most intensely pumped region of the gain medium.

With the above arrangement, a double-pass gain of 4.4 was obtained for a cw signal input of 270mW. This gain was considerably reduced, by saturation, from the small signal value of 34. By using the AOM to chop the signal beam, with short enough pulses and low enough repetition rates, it would be possible to access essentially the full small-signal gain. In practice we opted for a pulse duration of 10μsec and a repetition rate of 2kHz, giving a gain of 20, reduced from the small signal value by saturation in the amplifier. A maximum amplified power of 5.0W (averaged over the envelope of the sliced pulse) was obtained, a factor of five greater than was available from this system under cw conditions [5].

The M^2 beam quality factor of the amplified beam was measured to be $\simeq$1.05, confirming that the amplification did not cause significant beam distortion. However, there was some slight astigmatism introduced to the amplified beam (w_{ox}/w_{oy}=1.25) due to the anisotropic thermal lens in the Nd:YLF amplifier. Further confirmation of the beam quality was provided by frequency doubling. An LBO crystal of 15mm length was used, and with the amplified beam focused to a spot-size of 28μm, internal single-pass conversion efficiencies of 57% and 53% were obtained for the two types of pulse envelope (ie. non-uniform output envelope and flat-topped envelope respectively), in close agreement with the calculated values. This calculation was based on an assumed duration of the mode-locked pulses of 3.2ps, a value calculated from the known spectral narrowing, and hence temporal broadening that the amplifier would impose on the initial 2ps of the unamplified pulses. The generated single-pass second harmonic (SH) powers of 2.5W and 1.7W (envelope average of the pulses) were significantly greater than that achieved under cw conditions, where a resonant enhancement cavity had been used to achieve a SH power of 0.65W [5].

The SH beam from the LBO was then used to synchronously pump an OPO based on LBO. This singly-resonant oscillator was basically the same as described elsewhere [5], which for cw pumping conditions had shown a threshold power of 170mW for operation with signal/idler wavelengths of 950nm/1164nm, with a signal output mirror transmission of 2.5%.

With this same OPO resonator and signal/idler wavelengths, the pulsed threshold power was 475mW (envelope average). Figure 2 shows typical temporal behaviour of the OPO for a full pump power of 1.7W in a flat-topped pulse. Also shown as an inset in figure 2 is the behaviour without the pulse-shaping via the AWG. Here, the pump pulse shows a drop in power as saturation of the Nd:YLF amplifier occurs during the pulse. It should be noted that a price is paid when shaping the pulse envelope in that significantly higher pump powers were available with the unshaped pulses (a 32% reduction of available green power when utilising the pulse-shaping). A build-up delay of ~2μsec occurs before a significant OPO output is reached. This delay is consistent with a calculated net gain for 1.7W of pump of ~12% per round trip with 210 round trips (≡ 2μsec) needed to provide a gain of ~e^{25}. Once oscillation commences, the pump depletion is large, figure 2 indicating ~50% depletion. The output powers obtained for 1.7W of pump are (envelope averages), 250mW for the signal (950nm) and 150mW for the idler (1164nm). These are consistent with the observed pump depletion. These results indicate performance, in terms of threshold and efficiency, close to that observed with the cw oscillator, so the expectation is that, with further optimisation of the setup, the full performance of the cw system will be reproduced in this pulsed fashion. Thus for example one expects the full tunability, 0.65μm to 2.65μm as demonstrated for the cw device [5].

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. This quasi-cw pump source has proved effective for pumping an OPO. Quasi-cw pumping of Ti:sapphire and Cr^{4+} lasers are other possibilities. There is much scope for extending the capabilities of such quasi-cw sources, particularly by going to higher power diode pumps. Frequency conversion will benefit very much from this approach, with UV generation being an obvious candidate. Indeed using a BBO crystal (2mm thick) we have easily generated ~50mW (envelope average) of output at 261.5nm from 1.1W of green light. The advantage demonstrated here, even in our non-optimised arrangement, and using modest diode pump power, has been the ability to achieve efficient single-pass doubling for a long quasi-cw pulse, dispensing with the complexity of a SHG resonant enhancement cavity, which was necessary under cw operation.

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Figure Captions

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

Figure 2: 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. Inset is the same behaviour but using a square input pulse to the Nd:YLF amplifier.

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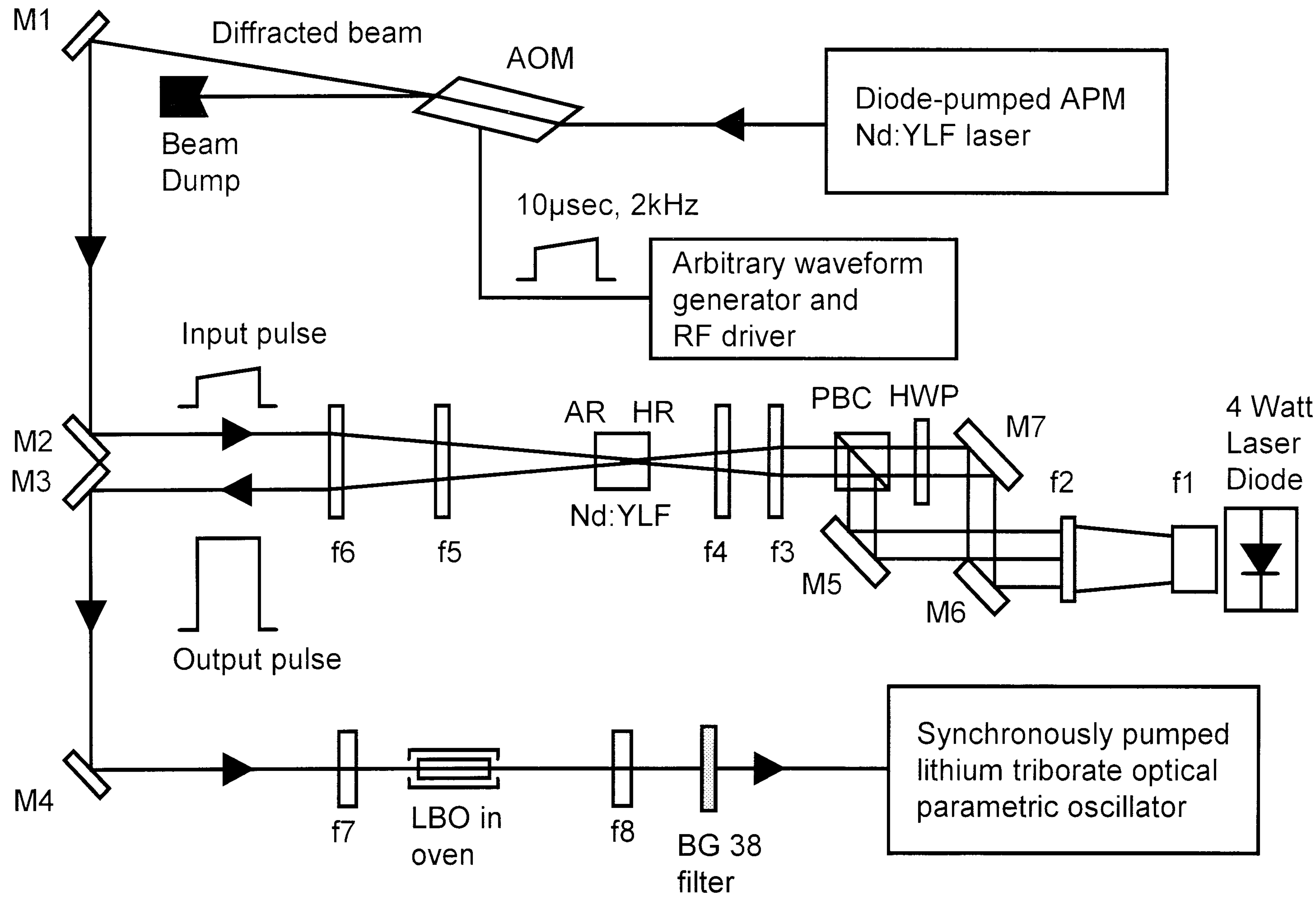
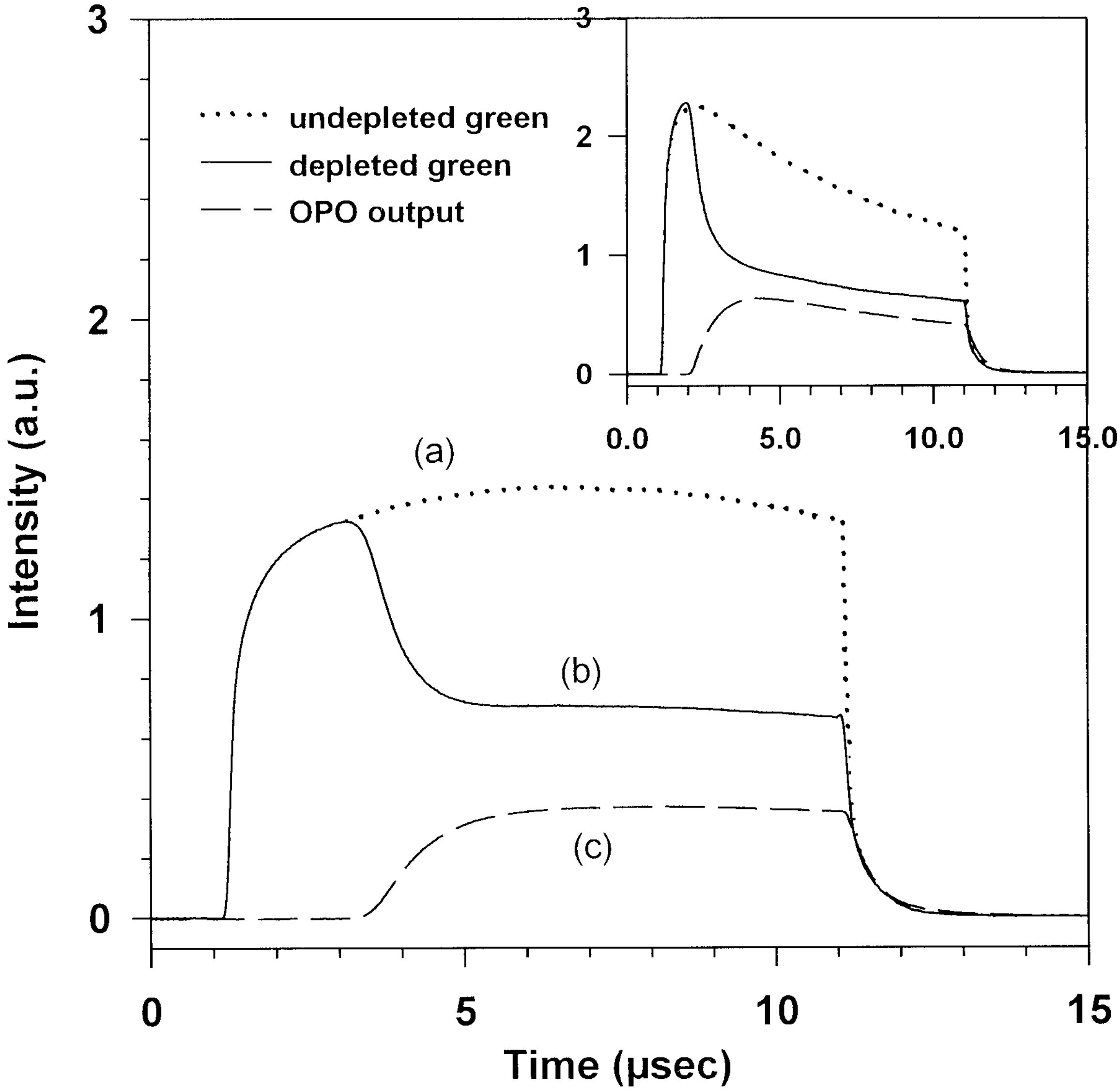

M1
Diffracted beam
AOM
Diode-pumped APM
Nd:YLF laser
Beam
Dump
10µsec, 2kHz
Arbitrary waveform
generator and
RF driver
Input pulse
AR
HR
PBC
HWP
4 Watt
Laser
Diode
M2
M3
M7
f2
f1
Nd:YLF
f6
f5
f4
f3
M5
M6
Output pulse
Synchronously pumped
lithium triborate optical
parametric oscillator
M4
f7
LBO in
oven
f8
BG 38
filter



undepleted green
depleted green
OPO output
(a)
(b)
(c)
Intensity (a.u.)
Time (µsec)
0
1
2
3
0
5
10
15
0.0
5.0
10.0
15.0