Control of pulse duration and shape in a 400-W Q-switched 532-nm laser

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ABSTRACT

We present a 400 W Q-switched 532 nm laser using several techniques to control the pulse duration and shape. The laser consists of two separate intracavity frequency-doubled cavities, incoherently combined to give 50 mJ total pulse energy. By extending the cavity length the pulse duration can be increased from 66 ns to 140 ns at 8 kHz with no significant power reduction. Varying the repetition rate and the triggering delay for each cavity's Q-switch allows further adjustment of the pulse duration. The pulse shape can be controlled by adjusting this delay and attenuating the individual cavities.
Keywords: High power, nanosecond, machining, SHG, Nd:YAG

1. INTRODUCTION

Pulse duration is very often a critical parameter for nanosecond lasers used in drilling and surface modification applications [1]. Many processes require a specific pulse duration in order to exceed or avoid various material thresholds, or as determined by the speed of thermal diffusion [2] or the evolution of generated plasma and ejected material [3]. Pulse duration is an important parameter in the hybrid water jet laser machining process developed by Synova S.A. that is the motivation for this work. For this application it is beneficial to have a pulse duration in the range of hundreds of ns [3], with tunability to allow the process to be optimised for each particular machining task.

While Q-switched diode-pumped solid state (DPSS) systems are particularly suited to applications such as these due to the high energy and average power that can be achieved, they are at a disadvantage when it comes to tuning the pulse duration. Since this is determined by the laser dynamics of the Q-switching process, controlling the pulse duration is not trivial. The pulse duration of a laser depends primarily on the net laser gain and the round trip time of the cavity; the higher the gain, the fewer round trips required for the pulse to build up and extract the energy stored in the amplifier. Laser gain is itself a function of many parameters such as pump power, choice of laser medium and pump geometry, most of which cannot be grossly changed without major alterations to the laser design. The pulse repetition period directly affects the amount of stored energy (and hence gain) that is present when the Q-switch pulse begins, so this provides a simple way to vary the pulse duration on the fly without physical changes to the laser. However, this is of limited utility as it also affects pulse energy, which is a critical parameter for most pulsed laser machining applications.

Another means of adjusting pulse duration is to combine multiple lasers and introduce a delay between the Q-switch pulses of each laser. This has been demonstrated previously with Powerlase green lasers in which two lasers were combined [4,5]. The pulse duration can be tuned continuously on the fly over a limited range, although it becomes multi-peaked as the delay approaches the pulse duration.

In a previous paper [4] we demonstrated a high power 532 nm laser that generated Q-switched pulses from 70 ns to 400 ns duration. In this work we demonstrate further control over the pulse duration by extending the cavity length, in addition to other techniques. Our initial impressions were that longer pulses would cause the SHG efficiency to drop dramatically, so here we investigated the effect that these different changes had on the laser performance.

2. LASER DESIGN

The laser described here was based on Powerlase's existing *Rigel g200* laser design, which is shown in fig. 1. This is built around an Nd:YAG rod in a plane-plane resonator, Q-switched by an acousto-optic modulator (AOM). The laser rod was side-pumped by multiple 808 nm diode bar arrays arranged radially around the rod. The end faces of the rod were concave to partially compensate for the effect of thermal lensing. Intracavity frequency doubling was performed by a type II phase-matched LBO crystal, with an output coupler (M_3) that was highly reflective at 1064 nm wavelength and anti-reflective at 532 nm. A dichroic mirror (M_2) served to reflect any green light generated in the backwards direction.

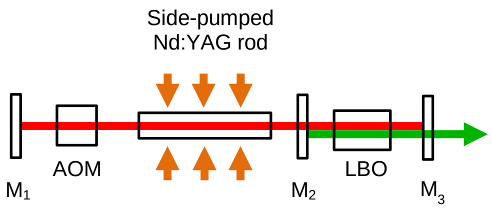

Figure 1. Layout of g200 laser

For long term robustness the cavity arm lengths and rod end face curvature were chosen such that the laser could be operated near the point on the stability curve where the M^2 is highest, as this is where laser performance is least sensitive to perturbations in the pump power. At this point the M^2 is around 30, the high number of modes providing efficient extraction of inversion from the rod as well as high power stability over a wide range of operating conditions and a smooth beam profile despite the strong thermal lens and thermally-induced birefringence present in the rod. The cavity arm lengths are also nearly symmetric to maximise the width of the stability zones. This cavity design has been proven to be well suited to repeatable production, relatively insensitive to problems such as contamination and optical damage, and has been validated with many units in the field.

3. EXTENDED LASER

The laser was modified to increase its length without changing the fundamental aspects of this cavity design. Figure 2 shows the layout of the extended cavity, with the position of the rear mirror in the g200 laser drawn with a dashed line. The cavity was extended by moving M_1 further from the rod, approximately doubling the total length. A pair of spherical lenses was added to the cavity to image the previous position of the mirror to the new position. Thus despite the cavity being much longer and highly asymmetric, it behaved in as if the rear mirror was close to the original position, i.e. the laser had the cavity stability parameters of a shorter resonator and remained stable over the full range of pump power.

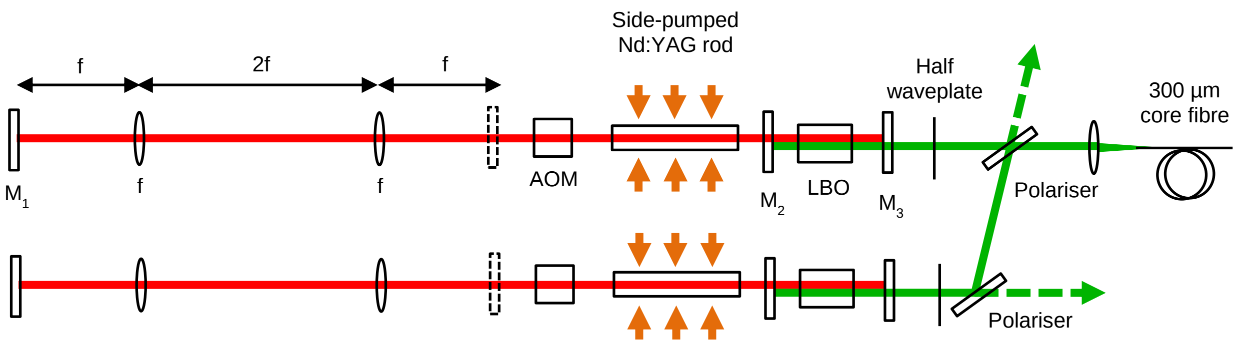

Figure 2. Layout of intracavity frequency-doubled laser showing optimised position of high reflector as dashed line and extended position as solid line.

Although not shown in the diagram, the cavity was folded using a pair of turning mirrors between the AOM and the lenses. The folding enabled the cavity to fit into an existing laser enclosure. Two such identical lasers were incoherently combined into a single beam using a pair of thin film polarisers, then focused into a delivery fibre with a 300 µm diameter core. A rotating half waveplate was placed at the output of each laser, which together with the polarisers acted as a variable attenuator, with independent control for each laser.

Both cavities produced highly stable Q-switched pulses with intensity jitter standard deviation < 1 % over a range of repetition rates from 8 – 35 kHz. The combined laser had a beam quality of $M^2 < 33$, and was smooth in both the near and far field with circularity of 0.88. The beam quality of the laser allows for efficient coupling into a 20 m long, 300 µm core delivery fibre of 0.2 NA, allowing the laser to be remote from the machining process. The spot size at the input to the fibre was maximised in order to reduce the risk of damage, but the beam did not fill the numerical aperture of the fibre. The output NA was measured at 0.054 (54 mrad), meaning $M^2 < 48$, thus the beam quality was mostly preserved through the fibre despite the long propagation length.

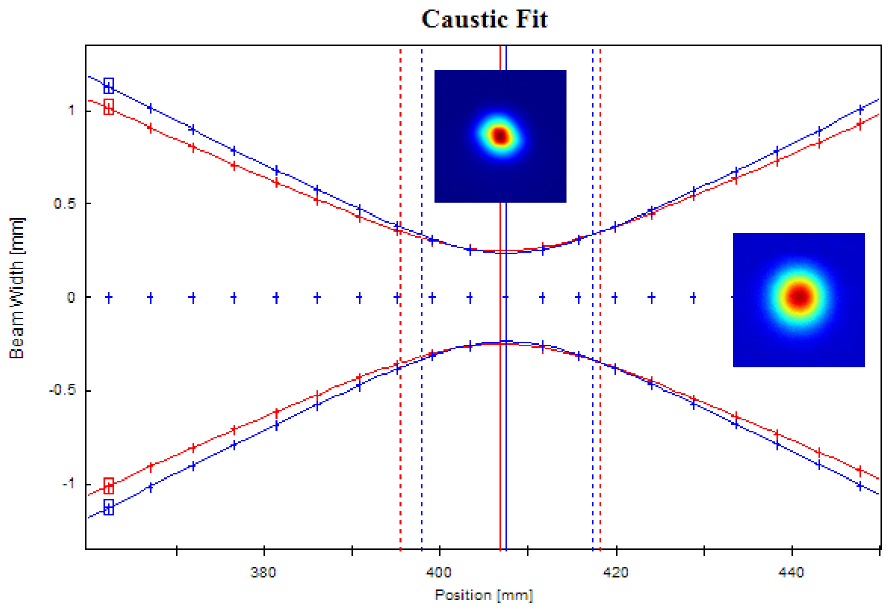

Figure 3. Caustic plot for single laser cavity showing beam profiles in near and far field at 10 kHz.

Pump power

Figure 4 (a) shows the power curve for an individual green laser resonator at 10 kHz, demonstrating over 230 W average power in a single polarised beam. The curve shows that the laser is stable over almost the same range as the short cavity. At each point the power was approx. 20 – 40 W lower, for reasons which are discussed in the following section. There is a difference in the current at which the two curves roll over; this is because the position of the virtual mirror M_1 was slightly closer than its original position. This shifted the stability curve to the right and allowed the laser to be pumped harder, compensating for the lower efficiency but increasing the M^2 (33 compared with 28 for the short cavity). The second curve (b) shows how pulse duration varies with pump current, from 243 ns to 142 ns over the range.

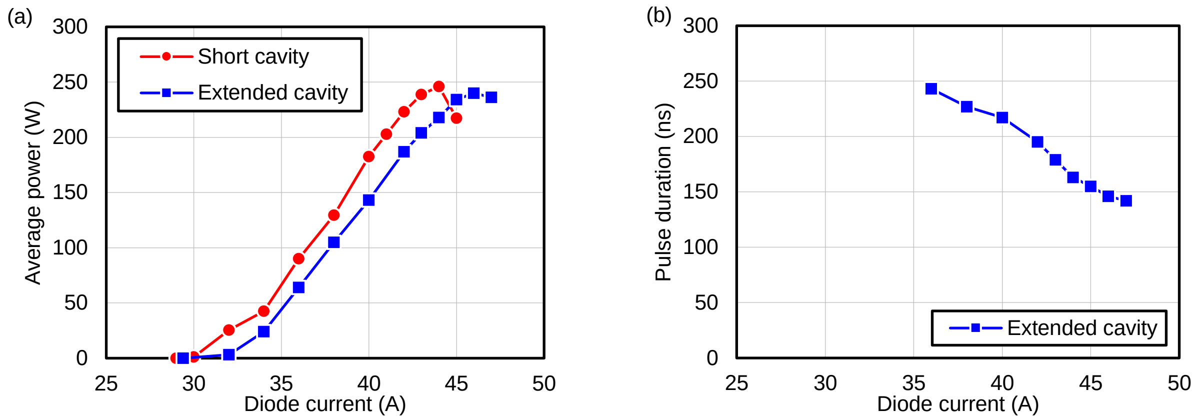

Figure 4. Single cavity power curve for single and extended cavity (a) and pulse duration vs diode current or extended cavity (b) at 10 kHz.

Cavity length and repetition rate

Figure 5 shows the performance of a single cavity as a function of repetition rate, with average power on the left and pulse duration on the right. Pulse duration was approximately twice as long in the extended cavity as the short cavity, and it also varies strongly with repetition rate. Also plotted are modelling results for the extended cavity, and comparison data for the short cavity. Modelling was performed using GLAD prior to the experiment, using the original g200 cavity to calibrate the model.

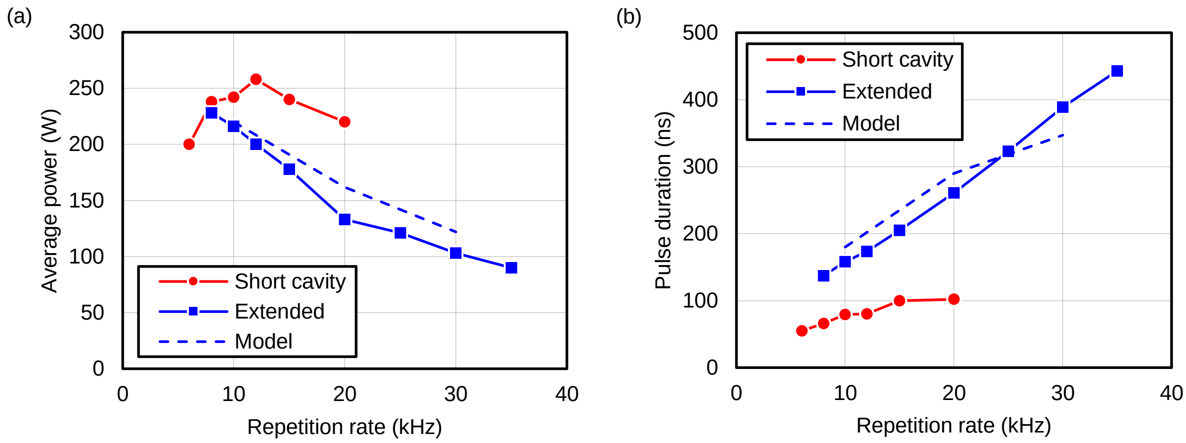

Figure 5. Single cavity average power (a) and pulse duration (b) as a function of pump current for short and extended cavity at 10 kHz, compared with GLAD model for extended cavity

Before this work it had been suspected that extending the cavity would lead to a dramatic decrease in output power because of the longer pulse duration. The conversion efficiency of the SHG crystal is a function of peak power, so a longer pulse duration or lower energy would lead to less green conversion per pass. However, since the conversion takes place inside the cavity, the effect of this on the actual output power is more complicated. The SHG crystal together with the dichroic mirror can be thought of as a nonlinear output coupler, whose transmission is a function of intracavity peak power. Maximum power will occur when the output coupler reflectivity reaches the optimum value for the cavity, as determined by the balance of gain and loss.

In the case of the compact cavity, the output power reached a maximum at 12 kHz, with the power decreasing for either higher or lower repetition rates (see fig 5(a), red curve). This suggests that optimum output coupling was achieved at 12 kHz for the compact cavity. In the case of the extended cavity (fig. 5(a), blue curve) it never reached a peak value over the range of tested parameters, so clearly the optimum output coupling condition was not fulfilled. Nevertheless at 8 kHz output coupling appears to be close enough to the optimum value that reasonably high power is obtained. What this shows is that extending the cavity does not necessarily reduce the laser's efficiency dramatically, but the power drops off with repetition rate more quickly than for the shorter cavity.

Alignment sensitivity was also examined using the model. There had been a concern that the cavity extension could increase the laser's sensitivity to misalignment of the mirrors. This was modelled here by angling one of the cavity mirrors and evaluating the reduction in output power. The model showed that the extended cavity was no more sensitive to misalignment than the original cavity. Indeed in practice the laser did not prove to be unduly sensitive to misalignment of the mirrors. The addition of two lenses as well as the folding mirrors did increase the number of optical elements to be aligned, but the laser has shown the same long-term stability as Powerlase's standard g200 product, demonstrating maintenance-free operation during extended trials at Synova S.A. in Switzerland.

Combination delay

With the outputs of the two laser cavities combined into one beam, further tuning of the pulse duration was possible by adding a delay between the trigger signals to the two Q-switches. Figure 6 shows the average power and pulse duration vs repetition rate for the incoherently combined dual-cavity laser with the delay set to equal one single pulse duration. Over 400 W average power was obtained between 8 – 10 kHz. These data were measured before coupling into the fibre.

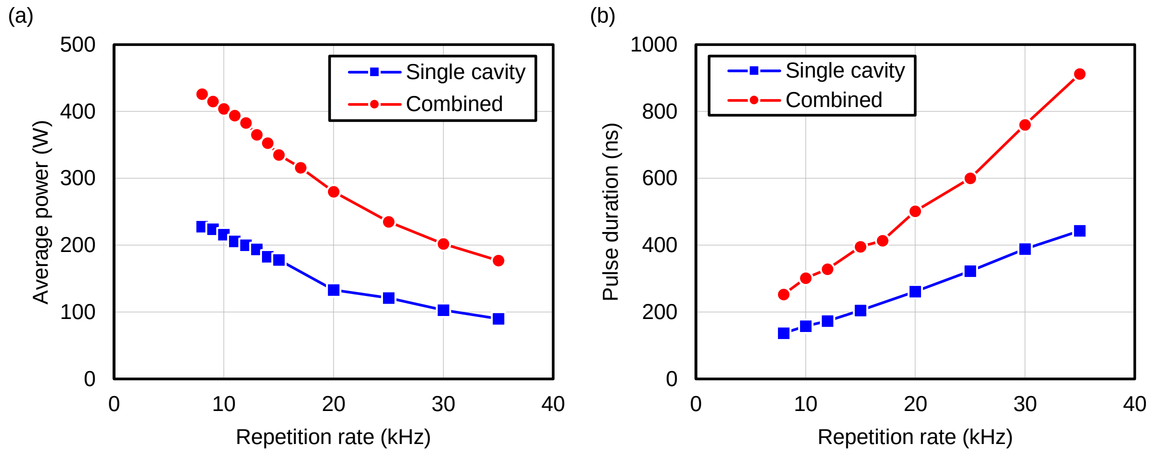

Figure 6. Average power (a) and pulse duration (b) vs pulse repetition rate for single and combined cavities with the delay set to equal one single cavity pulse duration.

Figure 7(a) shows the combined pulse shape for four different delays. The shape evolved as expected; as the delay approached the single pulse duration, the pulse split into a dual-peaked pulse, and separated out into two pulses for very large delay. Since each laser was fitted with a variable attenuator, further pulse shaping was possible by attenuating the two cavities by different amounts (see fig. 7(b)). The ability to change the shape has potential benefits for some laser material interactions where different physical processes occur on different timescales.

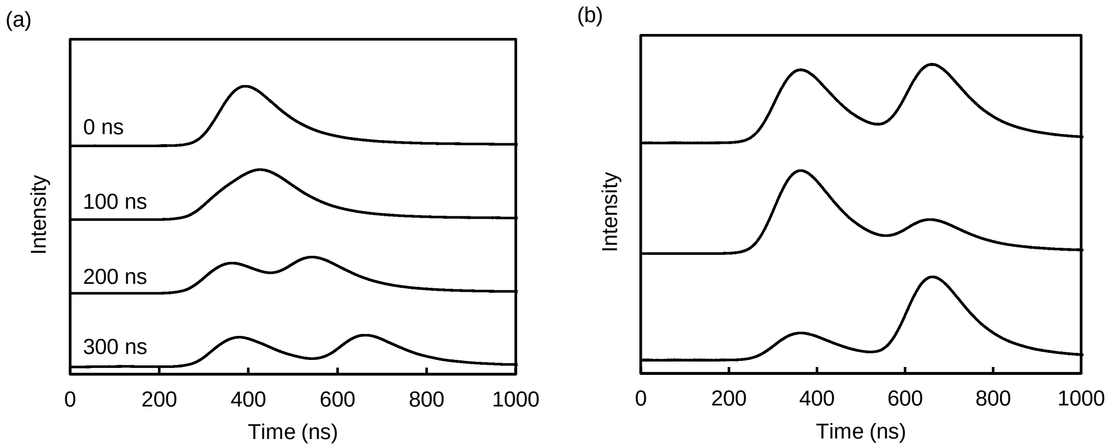

Figure 7. Shape of combined pulse for different delays (a) and shape of combined pulse with 300 ns delay and changing the attenuator values for the two lasers (b).

Finally, the delay can be increased up to half the pulse repetition period so that the two cavities are combined in an interleaved manner. With this, it is possible to obtain pulses at double the repetition rate (e.g. up to 70 kHz with 450 ns pulses) but with a pulse duration and SHG conversion efficiency that is characteristic of the actual (lower) repetition rate of the individual lasers. It is also possible to operate one cavity in long pulse mode and one in short pulse mode by having different cavity lengths in the two oscillators should the application demand such pulse shapes. Since the laser is fibre coupled both pulses emerge in an unpolarised state and in a practical sense should be indistinguishable if configured to have equal energy and duration.

4. CONCLUSION

In this work we demonstrated a variety of practical methods for adjusting pulse duration in a high-power solid-state 532 nm laser. By varying cavity length and combining multiple lasers, in addition to pulse repetition rate and current, the laser can be engineered to operate within a certain range of pulse durations. Over 400 W average power with 50 mJ pulse energy was obtained from a frequency-doubled diode-pumped Nd:YAG laser, with Q-switched pulse durations from 66 to 912 ns.

In principle the cavity lengthening technique could be extended further. SHG conversion efficiency appears to be the fundamental limit on cavity extension. While the second harmonic conversion efficiency can probably be improved in our design, some limit will exist where any further increase in the pulse duration would result in lower energy. In this experiment we were limited by size of the enclosure in which the laser was built.

The techniques here could also be applied to UV systems such as Andritz Powerlase’s 180 W dual cavity UV laser. Powerlase is continuing to push the boundaries of pulse flexibility in our laser systems, and with this work and with other gain media and laser mechanisms being developed we plan to continue development of high energy, pulse and PRF agile green laser systems.

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