Q-switched Nd:YAG lasers for high average-power and high peak-power operation

Mike Poulter*[a], Nick Hay[a], Ben Fulford[a], Paul Campton[a], Mike Mason[a], David Burns[b]
[a]Powerlase Ltd, Imperial House, Link 10, Napier Way, Crawley, W. Sussex, UK, RH10 9RA
[b]Institute of Photonics, University of Strathclyde, 106 Rottenrow, Glasgow, UK, G4 0NW

ABSTRACT

The direct side-pumping of Nd:YAG rods with laser diodes has been shown to be a cost effective scheme for scaling to simultaneous high average and high peak power operation. Careful control of the parameters that govern the performance of a multi-spatial mode MOPA system has led to the demonstration of reliable Q-switched average powers of up to 1600 W and peak powers in excess of 18 MW at the 1064 nm fundamental wavelength. The techniques used to refine the properties of an infrared stable resonator in order to optimise intra-cavity second harmonic generation are discussed. Average powers of up to 290 W and peak powers of up to 0.45 MW at 532 nm have been demonstrated from a single cavity. By polarisation multiplexing the outputs of two cavities emitting at 532 nm, we have achieved single-beam average and peak powers of up to 580 W and 0.9 MW respectively and gained flexible control of pulse duration and temporal shape.

Keywords: Laser, high power, diode-pumped, Q-switched, intra-cavity harmonic generation, Nd:YAG.

1. INTRODUCTION

In recent years a number of materials processing applications have emerged that require lasers capable of producing sufficiently high pulsed peak powers (MW) for ablation of large surface areas, as well as increasingly high average powers (kW) for enhanced throughput. Several of these applications, qualified for operation at 1064 nm wavelength, involve illumination of a mask for the projection etching of thin films, as used in the rapid laser patterning of flat panel displays[1] or the edge deletion techniques integral to photovoltaic cell production. Moreover, applications that require high average and peak powers at 532 nm have also been identified, such as polysilicon annealing[2] and hard materials processing. Importantly, these applications are differentiated in terms of laser performance in that they do not require near diffraction limited beam quality. They do however demand that the scaling to high average and peak power is done at minimum cost and with an industrial standard of reliability and repeatability.

Removing the requirement for operation near the diffraction limit allows for the efficient and scaleable extraction of gain from relatively low complexity and therefore low cost laser geometries. However, this can prove troublesome when attempting to generate the optimum conditions for non-linear conversion to the second and third harmonic wavelengths. Industrial solid-state laser resonators designed to operate at or near the fundamental spatial mode (TEM_{00}) are largely limited to tens of watts at the visible and near infra-red due to factors such as the onset of aberrations at higher pump powers. Directly side-pumping Nd:YAG rods with high power laser diodes and operating at approximately 15 to 25 times the diffraction limit is shown to enable resonator powers of several hundred watts. By using master-oscillator power-amplifier (MOPA) architectures, average powers of up to 1600 W have been demonstrated with peak powers in excess of 18 MW when acousto-optically Q-switched to generate nanosecond pulse durations at kilohertz repetition frequencies.

This paper outlines the laser design principles used in the development of such high average and high peak power laser systems and highlights the differences in the approach required for optimisation at multi-spatial mode operation. Further consideration is given to the refinement of the infrared resonator for the promotion of intra-cavity second harmonic generation, leading to average and peak powers of 580 W and 0.9 MW respectively at 532 nm. Control over temporal pulse shape and duration is gained by combining the outputs from two green resonators in a flexible multiplexing arrangement.

*michael.poulter@powerlase.com; Phone +44 (0)1293 456238; www.powerlase.com

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2. INFRARED LASER DEVELOPMENT

The spatial mode structure generated in a stable resonator has a significant effect on important performance characteristics such as beam quality, mode volume to gain volume overlap, total gain extraction and output power. Spatial mode structure can also affect Q-switched pulse build-up and stability, and CW leakage (pre-lasing). In order to control the spatial modes generated in a transversely pumped solid-state rod geometry, attention must first be given to the design and characterisation of the gain-module (gain medium and pump source), which will determine the spatial variation of gain and thermal lensing in the resonator.

2.1 Gain-module optimisation

The Powerlase HAP200 gain-module uses a straightforward geometry comprising a water cooled Nd:YAG rod transversely pumped with high power CW laser diodes. The diode light is directly coupled without the use of expensive delivery fibres, micro-lenses or optical ducts into a pump chamber that has been designed to maximise absorption efficiency and promote homogeneous thermal loading and gain distribution. At high pump levels there can be a trade-off to make between the fabrication of a less homogeneous gain profile for increased extraction efficiency and increased risk of thermal fracture in the Nd:YAG rod. Non-sequential ray-trace simulations of the HAP200 gain-module indicate a total pump absorption efficiency of up to 80%. For long-term reliable operation the pump diodes are typically operated below their rated current and the pump power per unit length is limited to a predetermined safety factor below the rod thermal fracture limit. In this example, the optimum total pump power is 800 W shared equally with 5-fold symmetry.

The first order aberration that arises when a solid-state rod is heavily pumped and cooled at its periphery is a positive lensing. This occurs due to the formation of radial thermal gradients and the dependence of the refractive index on temperature[3,4,5]. The variation in refractive index with distance along the radius of the rod, x is described by $n(x) = n_o - (1/2)n_2x^2$ where n_2 is a second order refractive index coefficient. The pump power increases linearly with laser diode current from a threshold of ~15 A. This in turn leads to a rise in the gain available to the resonator and an increase in the thermal lens power. The thermal lens power at 632 nm was measured by passing the collimated output of a helium neon laser through a standard HAP200 gain-module[6] and was observed to vary linearly with pump power, as illustrated in figure 1(a). From this we may obtain an approximation for n_2 at 1064 nm as a function of the total pump power such that, $n_2 \approx 1.63\text{x}10^{-7}\ P$, where P is the pump power in watts.

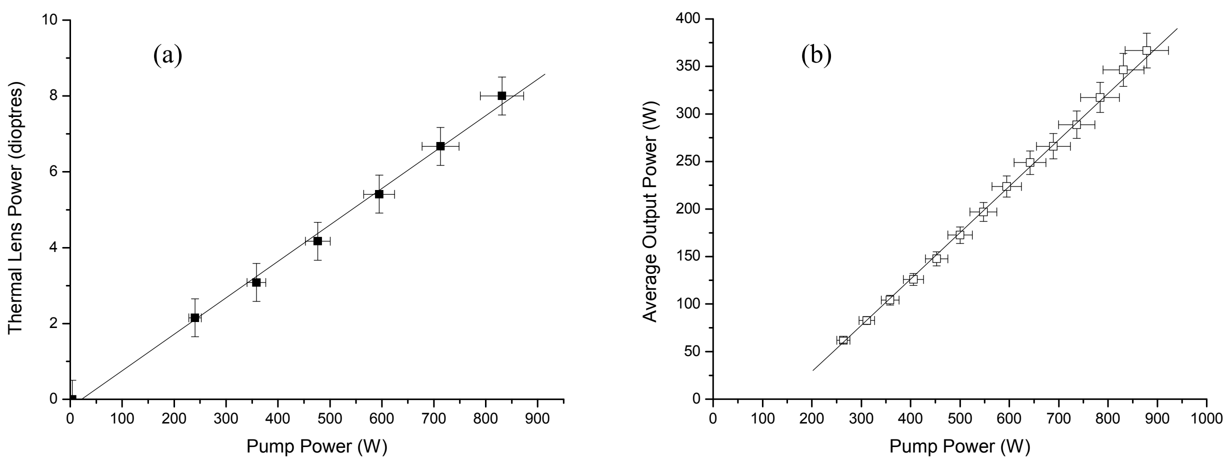

Fig. 1: (a) Thermal lens power and (b) CW output power as a function of optical pump power for a Powerlase HAP200 gain-module based test cavity.

When used in a short test-resonator with plane mirrors positioned near to the rod ends the HAP200 gain-module typically produces 330 W CW output with 800 W pump power using an optimum output coupling of 30%. For the example shown in figure 1(b) the pump threshold was 140 W with a CW slope efficiency of 49%

2.2 Multi-spatial-mode resonator design

When designing a resonator for multi-spatial mode operation it is important to consider stability and how this relates to robust industrial operation. The stability of a resonator constructed using a Powerlase HAP200 gain-module is influenced by the rod diameter (limiting aperture), the resonator length and symmetry and the strength of the thermal lens in the gain module[7]. Given a fixed rod diameter, the resonator length should generally be reduced in order to increase stability but this is limited by beam quality requirements and the need to incorporate acousto-optic modulators for Q-switching, safety shutters, non-linear crystals for frequency conversion and other intra-cavity components. Conventionally, thermal lensing may be compensated for and the resonator stability further controlled by the use of cavity mirrors with spherical curvature[8]. In this case however, the stability of a simple Fabry-Perot resonator is shown to be controlled by applying spherical curvature to the facets of the Nd:YAG rod[9]. This means that the gain module may be considered as a lensing element with both a dynamic, positive thermal lens component and a static, typically negative lens component. The resultant net lens strongly influences the stability of the resonator and can be controlled by altering the rod facet radius of curvature (ROC).

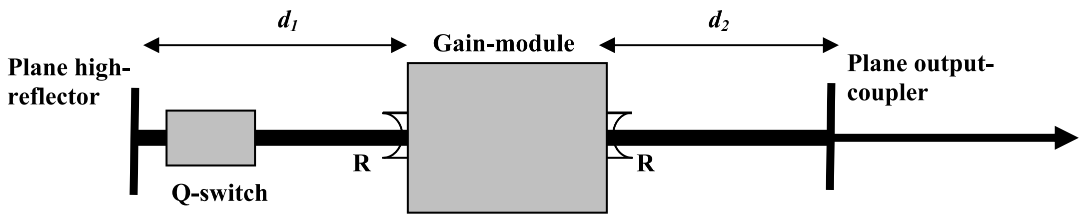

Fig. 2: Typical layout of a single HAP200 gain-module resonator (not to scale).

The g_1 and g_2 stability parameters can be defined for a single gain-module optical system as a function of rod facet radius of curvature, R (in meters), total pump power, P (in watts) and cavity arm length between the rod lens principle planes and the cavity mirrors, d_1 and d_2 (in meters), such that

$$g_1 = 1 - d_2\left(\frac{2(n-1)}{R} + C_t P\right) \quad \text{and} \quad g_2 = 1 - d_1\left(\frac{2(n-1)}{R} + C_t P\right)$$

where n is the refractive index of the rod and C_t is a proportionality constant specific to the thermal lensing characteristics of the Powerlase HAP200 gain-module.

In a resonator designed to support multiple transverse modes, the variation in resonator stability determines the number of stable transverse modes that the laser will operate on given sufficient gain. This is characterized by the beam quality or M^2. For optimum gain extraction and long term reliability of such a multimode cavity it is prudent to run at or near to the maximum achievable M^2. At this point, the cavity is also typically most tolerant to changes in pump absorption (e.g. long term pump diode degradation) and mechanical misalignment or creep. It is therefore advantageous to be able to control the stability of the cavity so that the peak M^2 can be positioned at the optimum pump power for a given design - 800 W in this case. The magnitude of the peak M^2 at this design point is predominantly limited by the Fresnel number of the cavity, which is in turn governed by the rod diameter and cavity arm lengths.

Figure 3 illustrates how the cavity stability and therefore peak M^2 can be tailored to suit the optimum pump condition by changing cavity length and net rod lens strength (through variation of rod facet radius of curvature). For a perfectly symmetrical cavity the M^2 curves would be parabolic with central maxima. However, at this peak M^2 condition the resonator operates amid two regions of instability and is not suitable for reliable operation. By forcing a small degree of asymmetry in the beam propagation code (~5% of the full length) it can be shown that two M^2 maxima can be generated for a given resonator. These maxima are now located away from any regions of resonator instability therefore either may be used as the final design point for robust laser performance. The filled black squares show the optimum solution which in this case corresponds to plane-plane rod ends in a 480 mm long resonator giving operation near the second maximum on the M^2 curve.

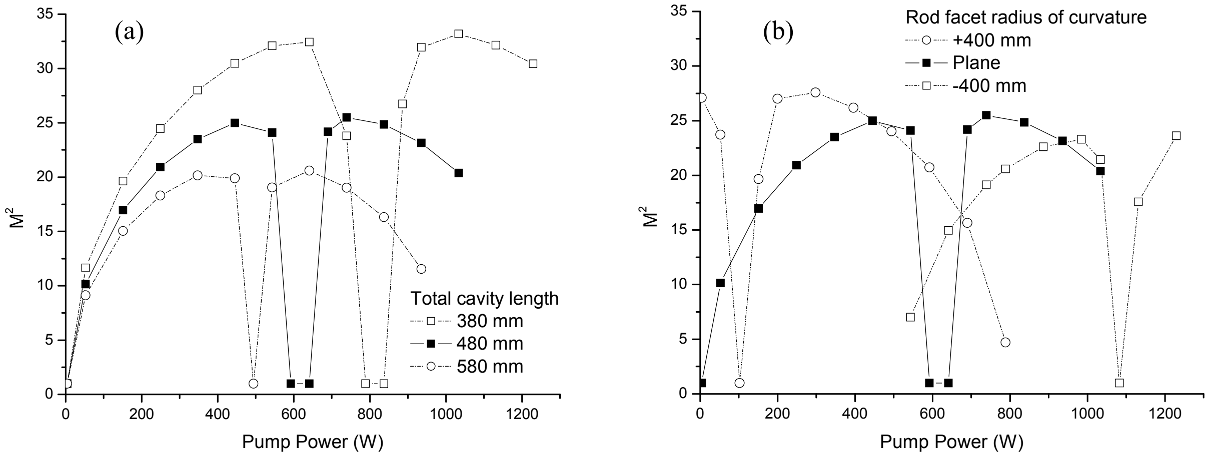

Fig. 3: Simulated plane-plane resonator stability curves showing M^2 as a function of gain-module pump power and the effect of (a) changing total cavity length and (b) changing rod facet radius of curvature. The filled black squares show the optimum solution which in this case corresponds to plane-plane rod ends in a 480 mm long resonator.

2.3 Single gain-module resonator

The design principles outlined above were used to construct a robust resonator optimised for Q-switching at high average power; a schematic of the cavity is shown in figure 2. In this case the Q-switch is made up of a pair of acousto-optic modulators aligned to provide the optimum modulation depth for operation at lower pulse repetition frequencies (<20 kHz). The modulators were aligned to the Bragg condition and rotated with respect to each other in order to affect orthogonal polarisation components. It is possible to optimise for operation at higher PRF ranges by refinement of the Q-switch configuration.

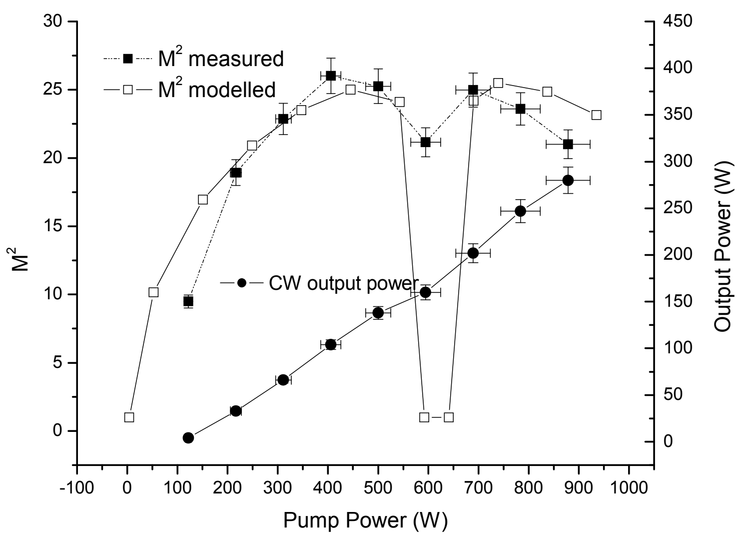

Fig. 4: Experimentally measured and modelled resonator stability curves for a single gain-module cavity optimised for operation at 800W pump power. The resulting CW output power with 34% optimum output coupling is also illustrated.

All of the infrared resonators presented in this paper are unpolarised and are therefore largely unaffected by depolarisation loss, promoting efficient extraction of the stored energy. Moreover, Findlay-Clay analysis[10] indicates internal cavity losses of less than 4%, nearly an order of magnitude lower than the optimum output coupling for this laser resonator at the intended pump level, this further promotes the efficiency of the system.

Figure 4 illustrates the agreement of the experimentally measured data to the resonator model. As expected there are two distinct maxima in M^2, the second of which (at higher pump power) is positioned near to the optimum pump level of 800 W. Although the M^2 decreases in the central region of instability, in practice the cavity does not cease lasing. In fact, other than this small change in beam quality, the instability is only seen as a perturbation in the corresponding output power. This is due to the presence of polarisation bifocusing and higher order aberrations introduced by the thermal lens. Investigations using finite element analysis suggest that the distribution of the gain profile may contribute to spatial mode shape more than the resulting higher order aberrations of the thermal lens[11]. Polarisation bifocusing can be compensated for with the correct use of retarding optics[12] but this often has practical limitations at high powers, is expensive and is often not required at high M^2 operation.

The resonator length selected is near to the minimum required to incorporate Q-switching optics and an intra-cavity shutter. This results in a peak M^2 value of approximately 25 compared to approximately 70 in the short test cavity. One consequence of this is a reduced overlap volume between the spatial mode and the distribution of gain within the rod. This in turn leads to a fall in extraction efficiency and reduces the CW slope efficiency to 34%.

When the resonator is Q-switched the pulse stability is governed by the statistical variation in the pulse build-up from optical noise. This is influenced by the available gain and the resonator stability. In this case, the optimum for both of these conditions is seen to occur close to the previously discussed design point. As long as there is sufficient gain, broader resonator stability curves allow for larger ranges of pump power over which stable Q-switching can occur. Empirical data also suggests that resonators with larger Q-switched stability ranges also exhibit improved pulse energy stability at the optimum condition. Peak-to-peak pulse energy stability of <2% has been measured from this resonator at 10 kHz PRF. The Q-switched stability range becomes limited at higher pulse repetition frequencies due to the reduction in gain build-up time between optical pulses.

The resonator illustrated produced a maximum average power of 235 W with 100 ns pulse duration when Q-switched at 20 kHz and at lower PRF has a Q-switched stability range that spans both M^2 maxima, leading to the maintenance of Q-switched stability at pump powers as low as 160W above lasing threshold.

2.4 Dual gain-module resonator

To increase the output power generated by a single resonator, two HAP200 gain-modules have been used to construct a dual-rod configuration. Obvious deviations from the single gain-module case are the requirement for increased overall cavity length and a doubling of the total thermal lens power. In order to reposition the design point at optimum pump power, all of the rod facets are given higher concave spherical curvature. This leads to a narrowing of the resonator stability curve and limits operation to the second stability apex due to restrictions in curvature fabrication. A result of the reduced resonator stability range is a reduction in the pump range over which stable Q-switching is achieved with respect to the single gain-module resonator condition however this is still suitably robust for reliable industrial usage as the design point is not compromised by the observed variation or degradation in component performance.

As with the single gain-module resonator, this laser operates in an unpolarised condition. In this case however, we are able to easily account for the polarisation bifocusing by using mutual compensation between the two gain-modules. This can be done using a number of methods[13] including the simple addition of a 90° quartz rotator placed between the gain modules with the objective to achieve equal phase retardation at each point of the rod cross-section for radially and tangentially polarised radiation[14]. The result of this is a slight further narrowing of the resonator stability curve but with improved gain extraction, leading to an increase in output power of up to 10% and an elevated CW slope efficiency of 49%.

Figure 5 illustrates the simulated and experimentally measured data taken for the dual-rod resonator and highlights the consequential narrowing of the stability curve compared to the single gain-module resonator. Although the total resonator length has increased, the cavity arm lengths (rod facet to end mirror distance) remain similar and as the rod diameter is also unchanged the Fresnel number is largely maintained. This results in a comparable peak M^2 value, but with a factor of two increase in output power leading to an output beam with twice the radiometric brightness of the single gain-module condition. This resonator produced a maximum Q-switched output power of 460 W at 20 kHz PRF giving an optical-to-optical efficiency (pump-to-fundamental) of 29%.

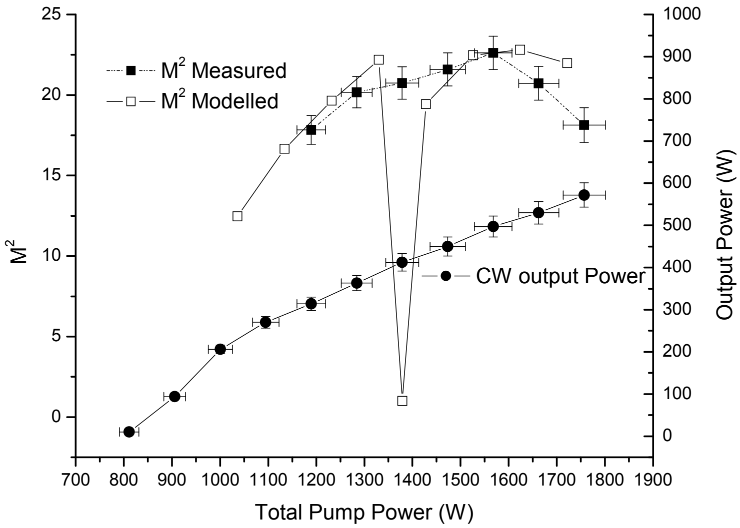

Fig. 5: Experimentally measured and modelled resonator stability curves for a dual gain-module IR cavity optimised for operation at ~800 W pump power per gain-module (~1600 W total pump). The resulting CW output power with 65% optimum output coupling is also illustrated.

2.5 MOPA systems

The scalability of power by the addition of HAP200 gain-modules to a single resonator is limited by the requirement for increased rod facet curvature. Restrictions associated with curvature fabrication limit the number of HAP200 gain-modules to two per cavity. In order to further scale output power additional HAP200 gain-modules were introduced in the form of extra-cavity amplifiers. The CW pumping of these gain-modules leads to a relatively low single pass gain and forces the need for a high power master oscillator in order to achieve efficient energy extraction, although this also means that back reflections are unlikely to be problematic. A HAP200 MOPA system was therefore constructed by implementing 1 and then 2 additional gain-modules as power amplifiers for the high power dual-rod resonator described in section 2.4.

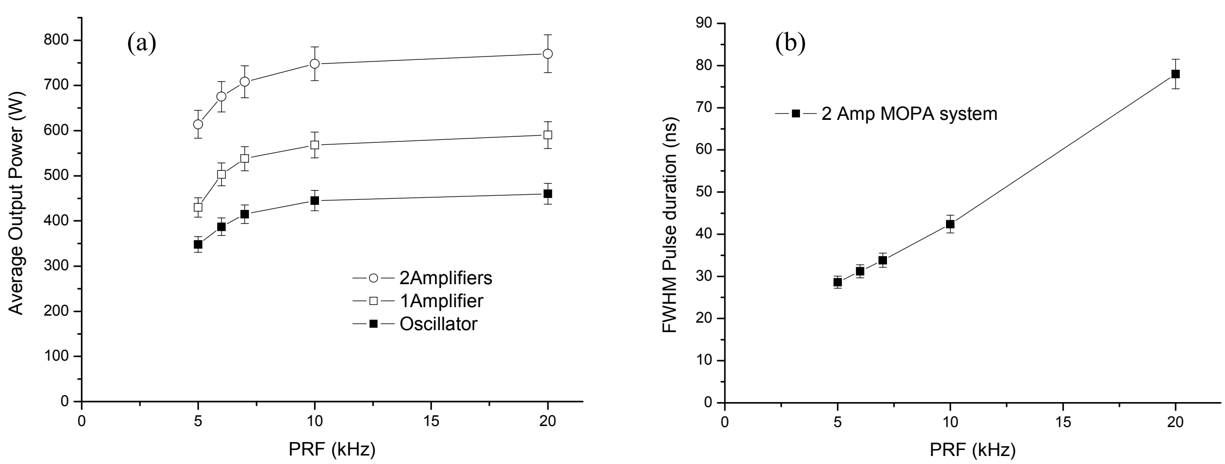

Fig. 6: (a) Average output power and (b) full-width half-maximum (FWHM) pulse duration as a function of pulse repetition frequency (PRF) for the dual gain-module master oscillator, and with the addition of 1 and 2 amplifying HAP200 gain-modules.

The amplifier gain-modules were given the same rod facet ROC as those inside the resonator and placed such that optimum coupling was achieved between the master oscillator and the amplifier pair, reflecting the position of those inside the master oscillator[15]. This geometry effectively maximises the laser-mode to gain-distribution overlap in the amplifiers to the benefit of energy extraction and maintenance of output divergence (with both amplifiers installed).

Figure 6 shows the average output power and pulse duration as a function of pulse repetition frequency for the master oscillator and with the addition of one and two amplifier gain-modules. The first amplifier demonstrated a gain of ~1.3 resulting in average output powers of up to 600 W. The second amplifier also provided a gain of ~1.3 increasing the maximum output power to around 800W, giving 25% total optical-to-optical efficiency (pump-to-fundamental).

The aberrations present in the amplifier pair increased the beam propagation factor by around 3 to M^2~26. If required, this increase can be reduced to ~1 by the implementation of the same birefringence compensation between the amplifier rod pair as used inside the resonator (see section 2.4).

2.6 Power scaling at the fundamental wavelength

To scale the average power beyond 1 kW it is possible in principle to simply add further HAP200 amplifier pairs in an extension of the MOPA design described above. In practice there are several reasons why this is not a desirable approach for an industrial design: system size and complexity are increased, component tolerances are tightened and robustness is reduced. An important limitation is optical damage. At the exit of the second HAP200 amplifier the peak irradiance on the rod facet is similar to that in the resonator but the addition of further HAP200 amplifiers increases the peak irradiance and so the amplifier chain begins to limit rather than increase the peak power of the system. To achieve our design goals of scaling high average power with high peak power an alternative approach is required.

Figure 7 shows the average and peak powers obtained from a four gain module MOPA design using HAP400 gain modules which have approximately twice the pump power of the HAP200. Beam quality in the resonator is maintained by using a single HAP400 gain module with a rod diameter matching the HAP200 gain module. Using HAP400 gain modules with larger diameter rods in the amplifier chain gives a thermal lens power similar to the HAP200 and allows peak irradiance on the rod facets to be maintained at a safe level as the peak power is increased. The results shown in figure 7 are taken from a MOPA design which has been further optimized for reduced M^2 and reduced pulse duration to give M^2~17 with peak power of 18 MW and average power of 1250 W at 4 kHz PRF. At 20 kHz PRF an average power of 1600 W was produced giving ~25% overall optical-to-optical efficiency.

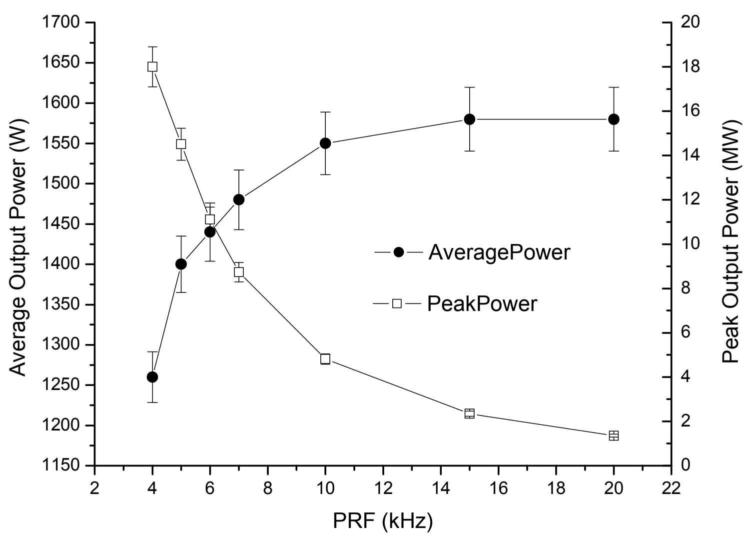

Fig. 7: Average and peak output power as a function of PRF for the power scaled (HAP400 based) infrared MOPA laser system.

3. INTRA-CAVITY SECOND HARMONIC GENERATION

There are many commercially available lasers that employ non-linear conversion to generate shorter wavelengths. Most of these lasers are however designed to operate at or near to the diffraction limit. This facilitates generation of the small beam sizes and low angles of divergence that are advantageous for efficient non-linear coupling. These systems are still however limited to tens of watts by the low power at the fundamental wavelength. A number of higher power, higher M^2 green lasers have been reported including a 73 W oscillator by S. Lee et al[16] and a 100W system by J. Yi et al[17]. More recently, other commercially available multi-spatial mode oscillators operating at or around 532 nm have also become available up to 100 W.

The challenge at high M^2 operation is to generate the intensities required for non-linear conversion while maintaining divergences low enough to stay within the acceptance angle for the converting media used. In an extra-cavity configuration the fundamental must be focused in order to reach the intensities required for efficient non-linear conversion. However, at higher M^2 values the minimum focus size for a given f-number is increased, thus reducing the intensity and conversion to the second harmonic. Compensating by focusing to a smaller spot to give higher intensity tends to increase the beam divergence beyond the acceptance angle of the non-linear medium, again leading to reduced conversion efficiency. One solution to this problem is to use intra-cavity harmonic generation where the non-linear medium can take advantage of larger spots with lower angles of divergence while maintaining sufficient intensity for efficient conversion. Moreover, intra-cavity harmonic generation does not require the single-pass conversion to be high as any unconverted fundamental is 'recycled' for potential conversion on later passes.

At high average and peak power operation we are predominantly limited in our choice of non-linear crystal by the laser induced damage threshold and optical transmission properties at 1064 nm and 532 nm. In this case, lithium triborate (LBO) was selected as a suitable SHG medium due to its relatively high damage threshold, low absorption, high optical homogeneity and large acceptance angles[18].

The single gain-module based IR cavity detailed in section 2.3 was used to investigate intra-cavity harmonic generation at higher M^2. This cavity generates random polarisation at the fundamental wavelength so in order to utilise more than one polarisation component for non-linear conversion, LBO cut for type II critical phase matching at 25 °C was chosen and thermally managed using a thermo-electric cooler and thermistor control loop. This technique uses a beam polarised parallel to the ordinary axis of the LBO crystal and an orthogonal beam polarised parallel to the extra-ordinary axis to generate a second harmonic ordinary beam. Although LBO cut for type I critical phase matching has a larger non-linear coefficient, it also has a smaller acceptance angle and would only utilise one polarisation component of the fundamental, thus greatly restricting the number of photons available for conversion to the second harmonic. In the other extreme, the larger angles of acceptance seen with non-critical phase matching may provide a further increase in non-linear coupling but would require the implementation of a crystal oven, resulting in additional expense and undesirably lengthy system warm-up periods.

3.1 IR resonator refinement for SHG

In order to liberate the green light generated and ensure that little IR is emitted the cavity output coupler was replaced by a dichroic optic coated for high reflection (HR) at 1064 nm and anti-reflection (AR) at 532 nm (see figure 8). This also increases the fundamental intra-cavity power and the intensity at the LBO crystal, thus promoting conversion to the second harmonic. However, as a consequence the peak fluence at the resonator waists, located at the cavity end mirrors, readily exceeds the limit for laser induced damage. This intra-cavity fluence can be reduced by applying a partial reflectivity to the rear cavity mirror, thus discarding excess IR. For reliable operation the peak operating fluence at the cavity mirrors was not permitted to exceed a pre-determined safety factor below the damage threshold. A dichroic optic is also installed to reflect 532 nm light that is propagating toward the gain module back in the direction of the green output, while allowing the resonating IR to be transmitted with negligible loss. The non-linear coupling was observed to be unaffected by the overlap of the two green beams in the LBO crystal.

Using the method of spatial mode control outlined in section 2.2 it is possible to select an alternative design point that will maintain maximum resonator stability but also lead to a spatial mode shape that has larger beam waists at the cavity mirrors. This will occur at the first apex of the stability curve (the left most of the M^2 maxima, illustrated in figure 3). The larger mode waists allow for an increase in rear cavity mirror reflectivity while maintaining a safe peak intra-cavity fluence and permit the generation of higher intra-cavity powers for a given pump level. Furthermore, for the same peak M^2, the larger waists induce lower divergences, which force a larger proportion of light into the acceptance angle of the LBO crystal leading to increased conversion to the second harmonic.

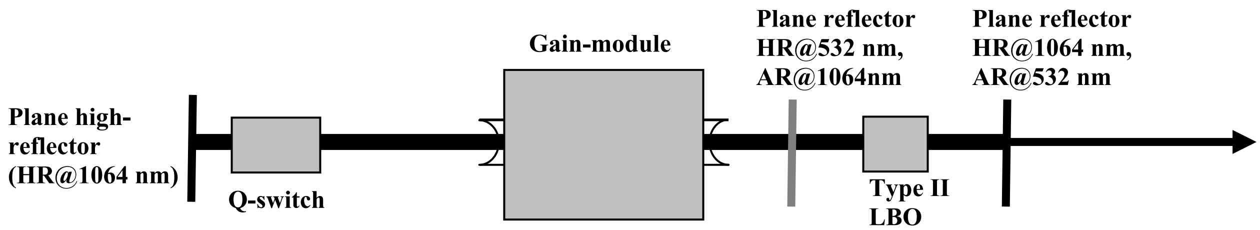

Fig. 8: Layout of the single HAP200 gain-module resonator with intra-cavity second harmonic generation (not to scale).

In addition to the enhanced non-linear coupling observed with operation at the first resonator stability apex we can increase the overall efficiency of the green laser by attempting to match the harmonic conversion efficiency to the optimum output coupling for the fundamental resonator. There are three interrelating parameters that need to be considered here, the first and second make up the total output coupling and are given by the rear cavity mirror reflectivity and the non-linear coupling. Changing the rear cavity mirror reflectivity will alter the intra-cavity power and therefore influence the non-linear coupling. The rear cavity mirror reflectivity will also govern the amount of IR light discarded at the rear of the cavity, which should be reduced where possible. The third parameter is the gain at the fundamental wavelength. This can be controlled by changing the pump level, which will in turn alter the optimum output coupling for the resonator. Changing the gain will also affect the intra-cavity power and therefore the non-linear coupling. It is therefore advantageous to select a suitable combination of pump level and rear cavity mirror reflectivity in order to match the total output coupling to the optimum for the fundamental resonator. For operation at high PRF (30 – 50 kHz) we can tend toward this condition by decreasing the pump level to 650 W and increasing the rear cavity mirror reflectivity to 99% (the resonator stability design point must be re-optimised to accommodate for this new optimum pump level by a change in rod facet ROC). This reduces the amount of wasted IR at the rear of the cavity (while maintaining a safe intra-cavity working fluence), conserves intra-cavity power, sustains non-linear coupling and increases overall efficiency by closer matching the total output coupling to the optimum for the refined fundamental resonator.

Figure 9 shows the theoretical and experimentally measured M^2 as a function of pump power for the infrared resonator optimised for second harmonic generation. At 650 W pump power the optimum total output coupling is 15% which gives a maximum IR Q-switched output power of 240 W (at 15 kHz PRF). Implementation of intra-cavity SHG described above produces a maximum Q-switched green output power of 121 W (at 30 kHz PRF), which corresponds to 19% optical-to-optical efficiency (pump-to-green).

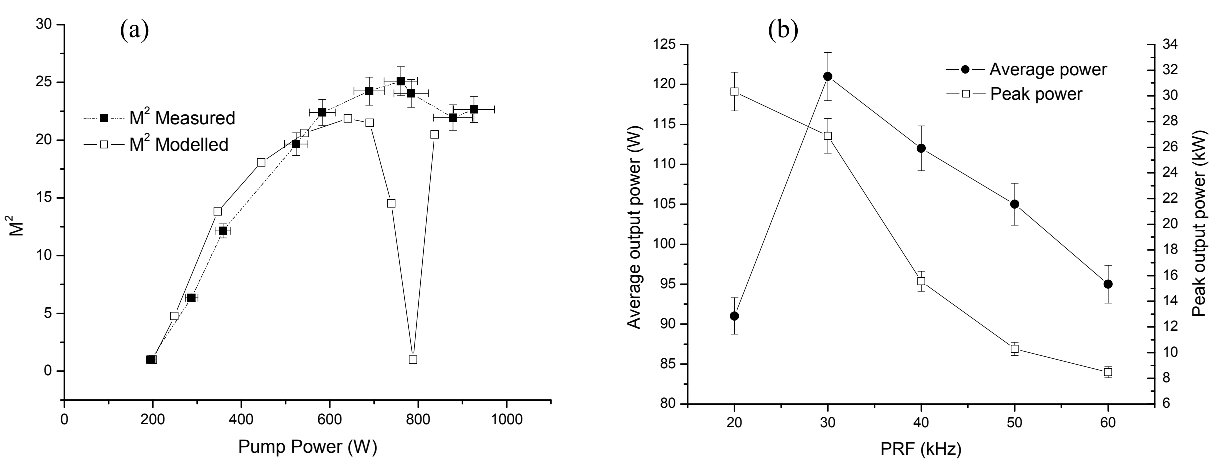

Fig. 9: (a) Experimentally measured and modelled IR resonator stability curves for a single gain-module cavity optimised for intra-cavity second harmonic generation and (b) the subsequent average and peak green output powers as a function of PRF (optimised for 30 – 50 kHz).

3.2 Dual-resonator green system

The output power from a green laser system can be scaled by the simple combination of two independent linearly polarised green oscillators. The two beams are made co-linear by multiplexing orthogonal polarisations from each oscillator at a thin film polariser. This gives the possibility of flexible control of the pulse duration and temporal shape at the joint output.

A method of temporal pulse shape control has been developed that involves the independent manipulation of the Q-switched pulses generated from two beam combined oscillators such that the relative timing and amplitude (energy) of the pulses can be altered via the laser user interface. This allows the oscillators to be either synchronously pulsed together (with no delay) or fully interlaced, which will effectively produce double the pulse repetition frequency at the combined output (up to 100 kHz). A fine delay allows the user to separate the pulses by between 0 and 1000 ns with a resolution of 5 ns. Separating the timing of the pulses by sub-pulse length durations and altering the relative amplitude from each resonator enables control of the temporal pulse shape and therefore duration of the combined output.

The optical multiplexing has been combined with an attenuation technique to allow individual control of the power that each oscillator contributes to the combined output. The basic principle involves the variable transmission of the laser beams through a thin film polariser with change in incident polarisation, which is rotated using a half-wave plate in front of each resonator. In this case the half-wave plates are held in bespoke motorised opto-mechanical mounts that allow rotation, and therefore attenuation to be controlled via the laser control interface. By using this means of optical attenuation, instead of pump level reduction, it is possible to sustain the optimum conditions for stable Q-switched operation while maintaining M^2 and divergence, which are important for reliable coupling into an optical fibre for delivery of the beam to a machine tool or work piece.

These techniques have enabled the development of a HAP200 gain-module based laser system capable of generating average powers over 240 W (at 30 kHz PRF and 130 ns pulse duration) which has been reliably fibre delivered using a 10 m long step-index multi-mode fibre with 200 μm core diameter. Figure 10 illustrates the flexible pulse shape control available from this system.

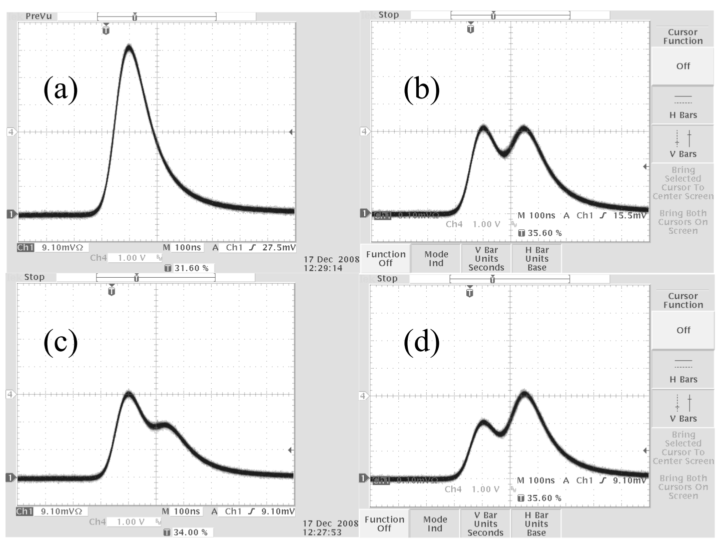

Fig. 10: Pulse waveforms from a beam combined dual-resonator green laser system showing (a) addition of pulses 1 and 2, (b) separation of pulses 1 and 2 by 150 ns and their amplitudes set equal, (c) pulse 2 delayed and attenuated relative to pulse 1, and (d) pulse 2 delayed with pulse 1 attenuated relative to pulse 2.

3.3 Power scaling at the second harmonic

At the pump levels used the magnitude of the thermal lensing and the requirement to control resonator stability using rod profiling allows up to two gain-modules to be used per resonator. However, in order to take advantage of the enhanced intra-cavity non-linear coupling observed with operation at the first resonator stability apex it is possible to apply the single gain module resonator optimisation principles (outlined in section 3.1) to the power scaled HAP400 gain module, detailed in section 2.6.

In order to promote peak power, this single gain module resonator was optimised for use at 8 - 30 kHz PRF and given a suitable combination of pump level and rear cavity mirror reflectivity in order to prevent optical damage and match the total output coupling to the optimum for the fundamental resonator. This led to a maximum average power of over 290 W at 532 nm operating at 15 kHz PRF, again resulting in an optical-to-optical efficiency of 19% (pump-to-green). A reduction in pulse duration to around 65 ns at 8 kHz PRF provided a maximum operating peak-power of 0.45 MW.

Further power scaling was achieved with the implementation of a dual-resonator system by polarisation multiplexing, as detailed in section 3.2. This led to a maximum average power in excess of 580 W and a maximum peak power of 0.9 MW at 532 nm. Figure 11 shows the average and peak output power as a function of PRF for this system.

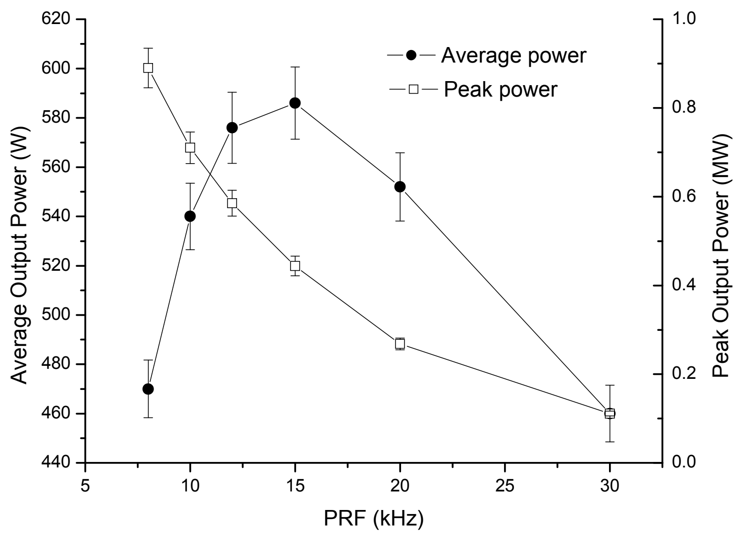

Fig. 11: Average and peak output power as a function of PRF for the power scaled dual green resonator laser system.

4. CONCLUSIONS

Cost effective scaling to simultaneous high average and peak powers has been demonstrated through the development of multi-spatial-mode Q-switched Nd:YAG lasers designed for reliable performance in a range of 24/7 manufacturing environments. Average powers at 1064 nm of up to 1600 W have been achieved with peak powers in excess of 18 MW using a power scaled 4 gain-module MOPA system. Refinement of an infrared resonator for the promotion of intra-cavity second harmonic generation has led to an optical-to-optical efficiency of 19% (pump-to-green). Average and peak powers of 580 W and 0.9 MW respectively have been demonstrated at 532 nm with the beam combining of two single gain module resonators by polarisation multiplexing. Control over temporal pulse shape and duration has also been demonstrated using this flexible multiplexing arrangement.

REFERENCES

[1] M. Henry et al, “Rapid laser patterning versus wet-etch lithography for flat panel display manufacture: A technical and commercial comparison”, Proc. ICALEO (2007), paper M505.

[2] T. Okamoto et al, “Development of line-shaped optical system for green laser annealing used in the manufacture of low-temperature poly-Si thin-film transistors”, Appl. Opt., 45 (19), 4711 (2006).

[3] W. Koechner, “Thermal lensing in a Nd:YAG laser rod“, Appl. Opt., 9 (11), 2548 (1970).

[4] J. D. Foster and L. M. Osterink, "Thermal Effects in a Nd:YAG Laser", J. Appl. Phys., 41 (9), 3656-3663 (1970).
[5] R. Weber et al, "Thermal Effects in Solid-State Laser Materials", Opt. Materials II, 245-354 (1999).
[6] T. J. Gleason et al, "Thermally induced focusing in an Nd:YAG laser rod at low input powers", Appl.Opt., 12 (12), 2942 (1973).
[7] S. De Silvestri et al, "Novel Stability Diagrams for Continuous-Wave Solid-State Laser Resonators", Opt. Lett., 11 (8), 513-515 (1986).
[8] H. Kogelnik and T. Li, "Laser Beams and Resonators", Appl. Opt., 5 (10), 1550-1566 (1966).
[9] Powerlase patent # P36611TW "A Laser Apparatus".
[10] D. Findlay, R. A. Clay, "The measurement of internal losses in 4-level lasers", Phys. Lett. 20, 277 (1966).
[11] Unpublished work carried out by W. Lubeigt and D. Burns at the University of Strathclyde.
[12] R. Kandasami et al., "Analysis of Birefringence Compensation Using a Quarter-Wave Plate in Solid-State Lasers", Opt. Rev. 7 (2), 149 (2000).
[13] Q. Lu et al, "A Novel Approach for Compensation of Birefringence in Cylindrical Nd:YAG Rods", Opt. Quantum Elec., 28, 57-69 (1996).
[14] I. Moshe and S. Jackel, "Correction of Thermally Induced Birefringence in Double Rod Laser Resonators – Comparison of various methods", Opt. Comms., 214, 315-325 (2002).
[15] Powerlase patent # P36612GB "Laser Amplifier".
[16] S. Lee et al, "A diode-pumped linear intracavity frequency doubled Nd:YAG rod laser with 40 ns pulse width and 73 W green output power", Optics & Laser Tech. (36), 265-271 (2004).
[17] J. Yi et al, "Diode pumped 100W green Nd:YAG rod laser", Appl. Opt., 43 (18), 3732 (2004).
[18] S. P. Velsko et al, "Phase Matched Harmonic Generation in Lithium Tiborate (LBO)", J. Quantum. Elec., 27 (9), 2182 (1991).