Approach for power scaling solid-state lasers with intracavity motion

MATTHEW ECKOLD, JACOB I MACKENZIE, W ANDREW CLARKSON*

Optoelectronics Research Centre, University of Southampton, Southampton, SO17 1BJ, UK
**Corresponding author: wac@orc.soton.ac.uk*

Received XX Month XXXX; revised XX Month, XXXX; accepted XX Month XXXX; posted XX Month XXXX (Doc. ID XXXXX); published XX Month XXXX

Solid-state lasers are typically limited by adverse thermal effects within the gain medium. In this paper we describe a new method for dramatically reducing thermal effects in an end-pumped solid-state laser by incorporating a rotating intracavity periscope in the resonator to spatially separate the lasing and thermal processes. In contrast to previous examples of moving solid-state lasers our approach keeps the gain medium stationary simplifying the heat removal arrangement. This scheme has been applied to a Nd:YAG laser yielding an output power of 120 W at 1.064 µm, limited by available pump power. Analysis suggests that scaling to much higher power is feasible with the appropriate laser design. © 2016 Optical Society of America

OCIS codes: *(140.3580) Lasers, solid-state; (140.3410) Laser resonators; (140.6810) Thermal effects.*

http://dx.doi.org/10.1364/OL.99.099999

In an optically pumped solid-state laser the quantum defect between pump and laser photon creates an unavoidable heating effect, which, in some circumstances may be further exacerbated by parasitic spectroscopic processes such as energy-transfer-upconversion and excited-state absorption. The net result is an increase in temperature and associated thermal effects (lensing, stress-induced birefringence and stress-induced fracture), which become increasingly problematic as pump power is increased, particularly in end-pumped lasers [1]. These deleterious thermal phenomena generally limit the achievable output brightness from a solid-state laser [2]. The laser community has developed a number of different designs to alleviate the problems created by thermal loading. One strategy is to drastically increase the length of the lasing region to reduce the temperature rise; this is best demonstrated by the fiber laser [3]. Alternatively, the direction of heat extraction can be carefully managed to avoid transverse temperature gradients, such as in a thin disk laser [4]. These laser geometries have been particularly successful for scaling power and brightness in the continuous-wave operating regime, but at the expense of needing relatively high brightness diode pump sources, in the case of the fiber laser, or a rather complicated multi-pass pumping scheme for efficient pump absorption, in the case of the disk geometry. Furthermore, scaling average power and pulse energy in pulsed mode is significantly more challenging with these laser geometries due to the low threshold for nonlinear processes and damage in fibre lasers and the low axial gain in disk lasers.

An alternative and very different strategy for scaling laser power exploits the fact that the build-up time for gain (i.e. threshold inversion density) is generally much shorter than the timescale for establishing thermal effects. This feature is exploited to good effect in so-called 'heat capacity' lasers [5] and to some extent in quasi-cw lasers, where laser emission and thermal effects are separated in time by adopting low-repetition-rate pulsed pumping. This approach allows much more flexibility in gain medium geometry and hence is attractive for the generation of laser pulses with high energy and high peak power. However, average powers are rather limited as a significant period of time must elapse between pump pulses to allow the gain medium to cool down.

One attractive way of avoiding this limitation, whilst still exploiting the different build-up times for laser emission and thermal effects is to introduce relative motion between the gain medium and the pumped region of the gain medium. In this way, the laser (stimulated) emission region can be moved away from the heated region of the gain medium before detrimental thermal effects are established. This avoids the low duty-cycle limitations associated with heat capacity lasers opening up a route to high average powers. The concept has been explored before in the context of moving slab lasers [6], rotating hollow cylinder lasers [7] and rotary disk lasers [8,9,10,11], where the gain medium is moved and the pump beam and laser emission region are stationary. However, this approach has a major drawback in that it is extremely difficult to remove the heat that builds up in the gain medium using standard heat-sinking techniques.

In this paper an alternative strategy is reported which exploits the same underlying physics for alleviating the effects of heat loading, but in a radically different way. Rather than moving the gain medium, we adopt a novel rotating cavity laser (RCL) design where the pump beam and laser mode are moved across the gain medium. This yields a significant advantage in that the gain medium can be face-cooled by very simple and effective heat-sinking arrangements. The net result is an architecture that both has the potential to be scaled to very high average powers with flexibility in mode of operation, and in a practical format that should lend itself to low-cost implementation. In the rotating cavity laser (RCL) relative movement between the gain medium and the pumped region in the gain medium is achieved through the use of a rotating intracavity periscope, as illustrated in Fig. 1. The pump beam and intracavity laser beam are re-directed by the periscope so that the pumped region and laser mode both move with a circular trajectory on a fixed disk or slab of gain medium, whereas the output beam exits from a fixed (non-moving) portion of the resonator. The power scaling potential of this approach is ultimately determined by the physical size of the gain medium, since the heat generated is spread over the entire pumped volume. For a given pump power, the resulting temperature rise and associated thermal effects in the gain medium are reduced compared to the static case by a factor roughly equal to the ratio of the total pumped volume for the RCL to the pumped volume for the static laser. The availability of ceramic laser materials (e.g. Nd:YAG, Yb:YAG) in large volumes with very low loss and high uniformity [12] opens the door to a very large improvement in performance compared to the stationary case. Whilst the benefits of the RCL for reduction in thermal effects are clear, it should be noted that movement of the pumped region does mean that a fraction of the inverted ions are left behind and no longer spatially overlap with the laser mode. The main effect is an increase in threshold pump power (or equivalently, a decrease in the effective energy storage time) by a factor, γ, given by the approximate expression:

$$\gamma \approx \frac{1}{1-\beta\left[1-\exp\left(-1/\beta\right)\right]} \qquad (1)$$

where $\beta = v_{\varphi}\tau_f/2w_p$, w_p is the radius of the pump beam in the gain medium, τ_f is the fluorescence lifetime of the upper laser level and v_{φ} is the azimuthal velocity of the pump beam and laser mode. Parameter β can be thought of as the normalised azimuthal velocity in terms of the number of pump beam waists travelled per upper-state lifetime. The above expression assumes top-hat pump beam and laser mode profiles. However, the increase in threshold pump power is more than offset by the beneficial reduction in thermal effects, allowing higher pump power to be used, operation many times above threshold and, when required, increased energy storage for high repetition rate pulsed (Q-switched) mode of operation. Conservative estimates suggest that with the appropriate resonator design, performance levels exceeding two to three orders-of-magnitude compared to the stationary case are achievable. Thus, power levels from RCLs in the multi-kilowatt regime with high efficiency and excellent beam quality are quite realistic. An important feature of the RCL scheme is that it can be applied to much thicker gain media than disk lasers allowing high energy storage and extraction with simple resonator designs.

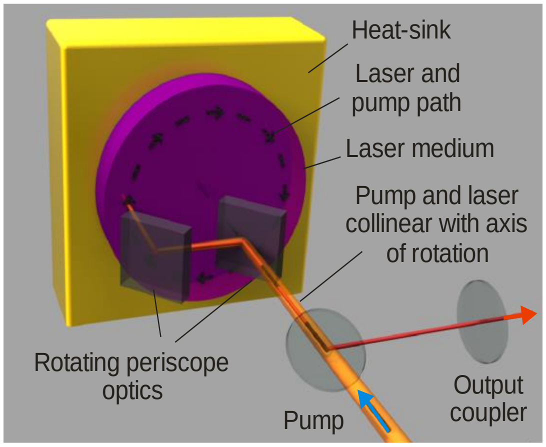

Fig.1. Schematic of rotating cavity laser concept.

In a first demonstration of the RCL approach a simple telescopic resonator was employed together with a rotating fused silica rhomboid prism, as shown in Fig. 2. A 50 mm diameter, 6 mm thick disk-shaped slab of ceramic Nd:YAG with a 1 at.% Nd doping concentration from Baikowski Co. (Japan) was employed as the gain medium. Opposite faces were respectively coated with broadband antireflection (<0.1% reflectivity) and high reflectivity (>99.8%) dielectric coatings at both the lasing wavelength (1.064 μm) and the pump wavelength (~808 nm) allowing double-pass pumping and efficient absorption of pump light. The Nd:YAG slab was mounted using indium foil on a water-cooled copper heat-sink for removal of waste heat. A folded-mirror resonator design was adopted comprising a plane mirror output coupler with 30% transmission at 1.064 μm and antireflection coated plano-concave and plano-convex lenses with respective focal lengths of -75 mm and +150 mm. The latter were positioned as shown in Fig. 2 to yield a calculated TEM_{00} waist radius of 660 μm in the gain medium. Pump light was provided by a fiber-coupled diode laser source at 808 nm with a maximum pump power of 400 W. The latter was collimated and then focussed using a simple telescope (not shown) to yield a beam waist radius in the Nd:YAG slab of 700 μm and hence generating an inversion region that slightly over-filled the TEM_{00} mode volume to minimise any influence of the transverse gain profile on laser beam quality. The pump beam and intracavity laser beam were carefully aligned to propagate collinearly inside the resonator and should be incident at 90° to the Nd:YAG faces after passing through the rhomboid prism to minimise cyclic variation in resonator loss. The rhomboid prism was fabricated from fused silica with broadband antireflection coatings at both the pump and lasing wavelengths on the entrance and exit faces. The prism was designed to give an intracavity beam displacement of 20 mm and was mounted in a rotation stage to perform as a rotating intracavity periscope. The latter was driven by an electric motor via a drive belt to provide isolation against vibration. In this way, both pump beam and laser mode move through the Nd:YAG slab with a circular trajectory. The tolerance on parallelism for opposing faces of the prism is < 10 μrad. This ensures that incident and exiting beams from the prism propagate along paths that are sufficiently parallel to avoid unwanted cyclic

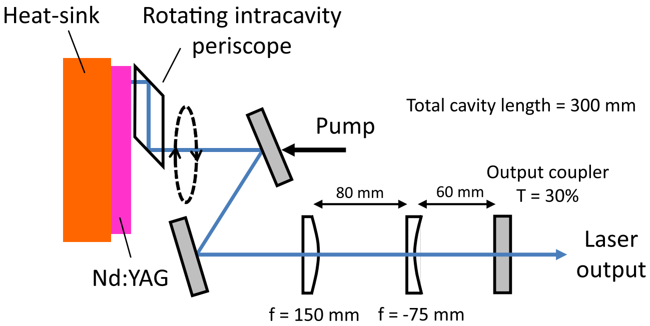

Fig.2. Schematic of rotating cavity laser concept.

variation in beam alignment which might otherwise cause temporal variation in output power and beam quality.

Before operating the laser at high pump power, a preliminary experiment using a lower power diode pump source and a slightly modified resonator design was performed to see how threshold pump power varies with the azimuthal velocity of the pump beam and verify the validity of equation (1). For these experiments the pump spot size was focussed to a waist radius of 330 μm inside the Nd:YAG slab and the resonator was designed to yield a TEM$_{00}$ radius approximately equal to the pump beam size inside the slab. Fig.3 shows the fractional increase in threshold pump power, γ as a function of normalised azimuthal velocity β. As expected, the threshold pump power increases with azimuthal velocity reaching a value of ∼2.4 times the stationary threshold pump power at normalised velocity of ∼0.85, corresponding to a value of v_φ of 2.4 ms^{-1}. Moreover, the predicted fractional increase in threshold pump power is in close agreement with experimental data.

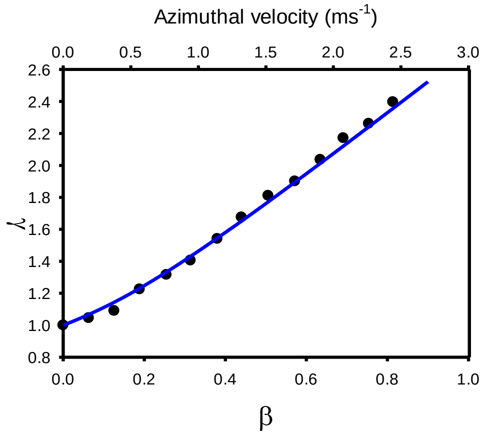

Fig.3. Fractional increase in threshold pump power γ as a function of normalized azimuthal velocity β. The solid line shows the predicted fractional increase in threshold according to equation (1) and the dots represent experimental data.

Figure 4 shows the output power produced by the telescopic resonator in Fig.2 as a function of incident pump power for azimuthal velocities of 0.75 ms^{-1} (β=0.124), 1.51 ms^{-1} (β=0.25) and 2.64 ms^{-1} (β=0.43). For the lower azimuthal velocities the output power begins to roll over, due to thermal lensing, at pump powers well below the maximum available pump power. However, in the latter situation thermal lensing is further reduced by using a higher azimuthal velocity allowing scaling to 121 W output power at 1.064 μm for 352 W of pump power with no roll over. The slope efficiency with respect to incident pump power was ∼37%. It is worth pointing out that in an earlier experiment without rotation the Nd:YAG disc was damaged due to thermally-induced fracture at a pump power of only 85 W.

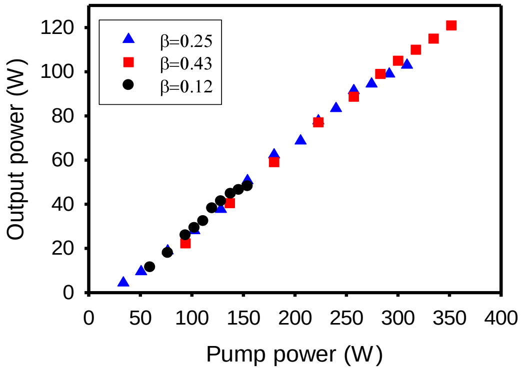

Fig.4. RCL output power versus incident pump power for three different rotation rates corresponding to β=0.12, 0.25 and 0.43.

The presence of moving intracavity components can impact on the output power stability due temporal variation in alignment. However, with careful design, this can be made very small. Figure 5 shows output power fluctuations for the RCL over a time scale corresponding to three rotation periods of 51 ms when operating with an average output power of 72 W and azimuthal velocity of 2.49 ms^{-1}. The standard deviation over a rotation period was calculated to be 2.8%. Close inspection of the measured power fluctuations reveals that there is a significant cyclic component. The origin of this is the subject of further investigation, but is believed to be due to imperfect parallelism of the periscope faces and defects in the ceramic Nd:YAG gain medium. Improved manufacturing tolerances and better uniformity of these components should yield a decrease in power fluctuations. Alternatively, due to the cyclic nature of the power fluctuations, it should be possible to compensate for these via active control of the pump power or intracavity loss. Fig.6 shows the resultant power fluctuations after the cyclic component is removed by subtracting the measured power as a function of time for single successive rotation periods. It can be seen that there is a dramatic reduction in the power fluctuations to ∼1.3% (standard deviation).

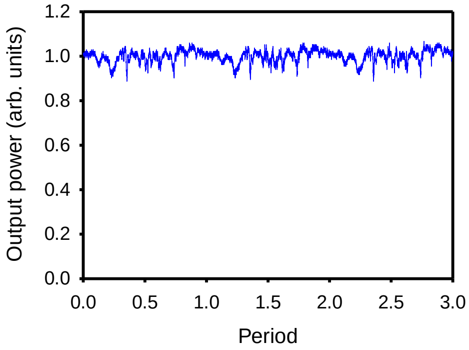

Fig.5. Temporal variation in output power.

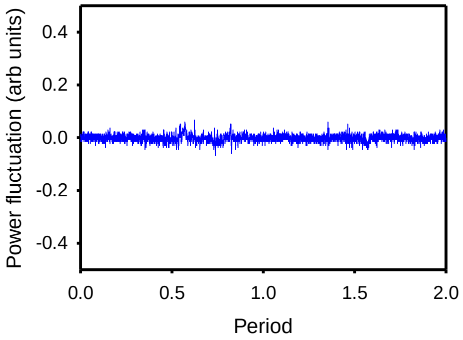

Fig.6. Temporal variation in output power with cyclic component removed.

The beam propagation factor (M^2) for the RCL output averaged over a rotation period was measured for the case where β=0.43 and is plotted as a function of output power in Fig.7. At low output power the RCL yields a diffraction-limited TEM$_{00}$ output with M^2=1.1, but the beam quality degrades with increasing output power reaching a value for M^2≈11 at ~100 W. The origin of this degradation in beam quality has yet to be confirmed, but is believed to be due to two contributing factors: Firstly, in the adiabatic limit, heat loading arising from quantum defect heating produces a more or less linear variation in temperature across the pumped region and hence the laser mode. This, in turn, results in a thermally-induced wedge in optical path difference in the gain medium which moves with the pump beam. The net effect is misalignment which increases with pump power and degrades the pointing stability, which was measured to be ~3.6 mrad (rms) at ~100 W output power. This can be remedied by increasing the azimuthal velocity, albeit at the expense of a higher threshold pump power. However, our rotation speed was limited by mechanical factors and hence an improved design for the rotating periscope is needed to explore this option. Another important factor is the inversion (and hence gain) distribution across the pump beam and laser mode, which becomes increasingly non-uniform and broader in spatial extent at higher rotation speeds. Fig.8 shows calculated inversion distributions for a top-hat shaped pump beam as a function of azimuthal distance at a particular time for different normalised azimuthal velocities (β=0, 0.4, 0.85). One striking feature is that the position for the inversion maxima moves towards the trailing edge of the pump beam. Moreover, the difference in gain between the trailing edge and centre of the pump beam increases with rotation speed. The net effect will be a lower threshold for the TEM$_{01}$ mode (rather than the fundamental TEM$_{00}$ mode) and increased spatial overlap of the inversion with multiple higher order modes. The result will be that higher order modes are excited in preference to the fundamental mode as rotation speed increases leading to a degradation in beam quality. This problem could be remedied using an aperture or by tailoring the pump beam profile to pre-compensate for effect of rotation.

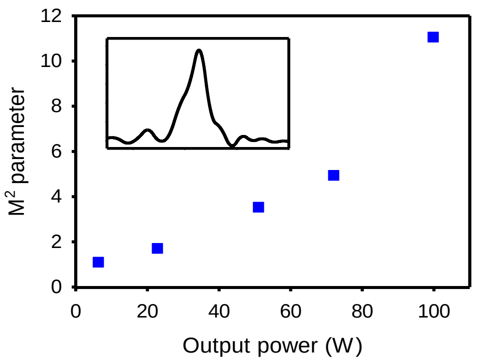

Fig.7. Beam propagation factor (M^2) versus output power. Inset shows a typical near-field transverse beam profile at 100W output power.

In summary, we have presented a novel approach for alleviating the detrimental effects of thermal loading in a solid-state laser using a rotating intracavity periscope to physically separate the heated region of the gain medium from the emission region. In contrast to other schemes that exploit intracavity motion to reduce thermal effects, the RCL scheme has the attraction that the gain medium remains stationary and hence can be cooled efficiently by conventional means, thereby simplifying the laser design and facilitating implementation. In preliminary experiments, ~120 W of output from a RCL based on Nd:YAG has been achieved, limited by available pump power. Further improvements in the RCL design to allow the use of increased rotation speed and tailoring of the pump beam profile to improve mode selection promise higher power and improved beam quality.

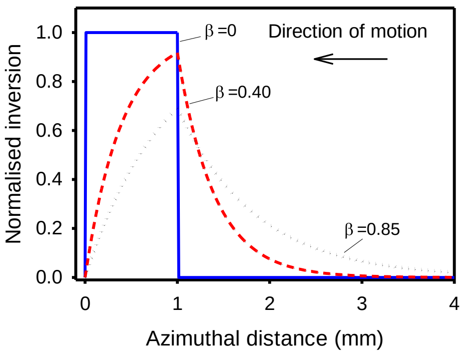

Fig.8. Normalized steady-state inversion density versus distance along the pump beam trajectory for a 'top-hat' pump beam with w_p=0.5mm and β=0 (solid-line), 0.4 (dashed), 0.85 (dotted).

Supplementary Material:

The data from this paper can be obtained from University of Southampton e-Prints repository (http://dx.doi.org/10.5258/SOTON/401291).

Funding:

Engineering Physical Sciences Research Council (EPSRC) studentship (EP/P505739/1). EPSRC Centre for Innovative Manufacturing in Photonics (EP/H02607X/1).

References

1. W. Koechner, Solid State Laser Engineering (Springer, New York, 2006), 6th ed.
2. W. A. Clarkson, Journal of Physics D: Applied Physics 34, 2381 (2001).
3. J. W. Dawson, M. J. Messerly, R. J. Beach, M. Y. Shverdin, E. a. Stappaerts, A. K. Sridharan, P. H. Pax, J. E. Heebner, C. W. Siders, and C. P. J. Barty, Optics Express 16, 13240 (2008).
4. A. Giesen and J. Speiser, IEEE Journal of Selected Topics in Quantum Electronics 13, 598 (2007).
5. G. F. Albrecht, S. Sutton, E. George, W. Sooy, and W. Krupke, Laser and Particle Beams 16, 605 (1998).
6. S. Basu and R. L. Byer, Optics Letters 11, 617 (1986).
7. F. Zhou, G. Huang, and S. Gu, Applied Physics B 591, 585 (1996).
8. S. Basu and A. Sridharan, Optics Express 12, 3114 (2004).
9. S. M. Massey, J. B. McKay, T. H. Russell, A. H. Paxton, H. C. Miller, and S. Basu, Journal of the Optical Society of America B 22, 1003 (2005).
10. S. Basu, IEEE Journal of Quantum Electronics 11, 626 (2005).
11. A. P. Ongstad, M. Guy and J. R. Chavez, Optics Express, vol. 24 (1), 108 (2016).
12. A. Ikesue, Nature Photonics 19, 430 (2008).