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A Low-Cost Approach to Diode-Pumped Ti:Sapphire Lasers With Watt-Level Output

Niall Simpson, Martin Lee, Alan J. Kemp

***Abstract*- We report a continuous-wave Ti:sapphire laser with an output power of 1.03 W, achieved with two low-cost single-emitter diode pumps, both of blue wavelength (448 and 468 nm). Using a novel strategy of combining blue-wavelength pumping with a long, low-doping Ti:sapphire crystal, we maximise the available pump power while minimising deleterious effects associated with blue pump wavelengths, demonstrating Watt-level output powers.**

***Index terms*—Diode-pumped lasers, solid state lasers, laser crystals.**

I. INTRODUCTION

Diode-pumping has enabled Ti:sapphire lasers to be designed for applications outside of laboratory environments [1], [2], [3], [4]. Despite the low cost per Watt of diode lasers relative to their diode-pumped solid-state counterparts, power-scaling of diode-pumped Ti:sapphire (dpTiS) is difficult to implement, and has primarily been driven by improvements in diode manufacturing rather than by substantive changes in the way that diode-pumping is utilised. Higher resonator powers are typically obtained by increasing the number of diodes per resonator. This can be easily implemented for two diodes via dichroic beam-combining, though higher numbers of diodes require increasingly complex strategies of beam combination.

Blue laser diodes (~445-470 nm) are more easily produced than GaN laser diodes of longer wavelength [4], [5], [6], [7], [8], offer higher output powers, longer operating lifetimes [9], higher wall-plug efficiency [9] and the lowest cost per Watt of visible-light laser diodes. However, with respect to Ti:sapphire, the advantages of blue laser diodes are weighed against the lower absorption coefficient and higher quantum defect of blue-pumping relative to green. Further, considerations such as reduced pump fraction [10] and pump-induced loss (PIL) [11], [12] can place additional limits on the output powers of blue-pumped systems. As blue diode powers are currently the highest available, and may remain so for the foreseeable future, it is advantageous to develop means of utilising blue wavelengths without compromising laser efficiency unnecessarily.

In our recent study into pump-induced loss in Ti:sapphire [13] we suggested that the deleterious effects associated with blue-pumping can be minimised or eliminated in low-doping samples, as both pump fraction and PIL are consequences of the increased residual band absorption strength in more highly doped crystals. Here, we continue to investigate the viability of blue-pumping for longer, low-doping Ti:sapphire crystals. We achieve Watt-level resonator power despite using pump wavelengths and crystal doping levels that have previously been considered undesirable for diode-pumped Ti:sapphire lasers. Though this output power is not the highest obtained from diode-pumped Tisapphire[14], it does not rely on a complex pump setup, and is, to the best of our knowledge, the highest power output obtained for two single-emitter diode pumps.

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II. EXPERIMENTAL SETUP

We used the setup shown in Figure (1), a simple 3-mirror cavity comprising of a plane 2% transmission output coupler, and two highly reflective (HR) mirrors with radius of curvature (ROC) 100 mm and 50 mm.

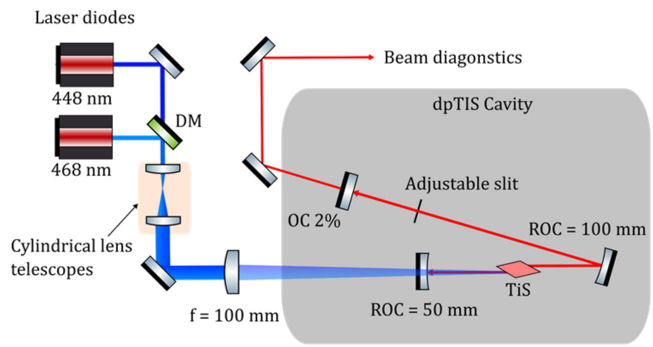

Fig. 1. Schematic diagram of the laser cavity and pump paths.

The resonator was pumped with two InGaN diode lasers with blue output wavelengths: an OSRAM PLPT9 450LB_E (with 5W output at 448 nm) and a Laser Tree LT-LD-470-4100M (with 4.2 W output at 468 nm). Respectively, these diodes have a cost per Watt of $10 and $44. Both diodes were housed in water-cooled mounts with a water temperature of 13 °C. The angular orientation of the diodes in the mount was set such that the diode slow-axis is parallel with the plane of the optical table.

We used aspheric collimation lenses (f = 4.51 mm) to collimate the fast axis of each diode before combining the diode outputs into a single collinear beam using a Chroma ZT442dcrb-UF1 dichroic mirror. A Keplerian cylindrical lens telescope was then used to expand and collimate the slow axis of the combined beam (f = -50 mm and f = 150 mm). The use of a Keplerian telescope was motivated by availability of lenses, and has no additional significance. Finally, the pump beam was focused through a 100 mm focal length spherical lens

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onto the crystal, a 10 mm path-length Brewster-cut sample (Crystal Systems) with $\alpha = 2.37$ cm^{-1} @ 515 nm. This crystal was selected based on the studies in [13], as we identified this samples as having a low susceptibility to pump-induced loss and thus the potential for more efficient operation under blue diode-pumping. Further details on the crystal specification and the tests undertaken can be found in [13]. We measured the waist radii of the combined 448 nm and 468 nm beam to be 59 µm × 15 µm in air (~103 µm × 15 µm in the crystal), and calculate the resonator waist radii in the crystal to be 56 µm × 17 µm. We measured the pump powers at the crystal to be 4.8 W at 448 nm and 4.1 W at 468 nm, a total of 8.9 W. The low crystal doping gives a single-pass absorption of 76% at 448 nm and 90% at 468 nm.

III. RESULTS

A. Non-TEM$_{00}$ output

In the described configuration we initially obtained high output powers and slope efficiency, though only as a consequence of non-TEM$_{00}$ resonator mode. Optimising this cavity for output power alone, we obtained an output of ~1.4 W (Fig 2.), and measured the beam quality of the resonator as 1.05 × 5.7 (Fig 3.), with the high-M^2 axis of the output beam corresponding to that of the diode slow-axis.

Although this result demonstrated good slope efficiency, approaching that expected from a 532 nm pump [15], most applications of Ti:sapphire demand near-diffraction limited output which we demonstrate in the next section by inserting an intracavity slit.

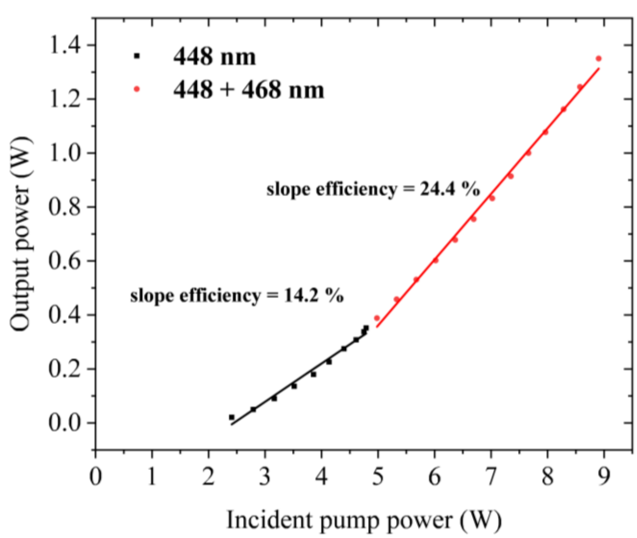

Fig. 2. Power transfer of the Ti:sapphire resonator before the addition the intracavity slits.

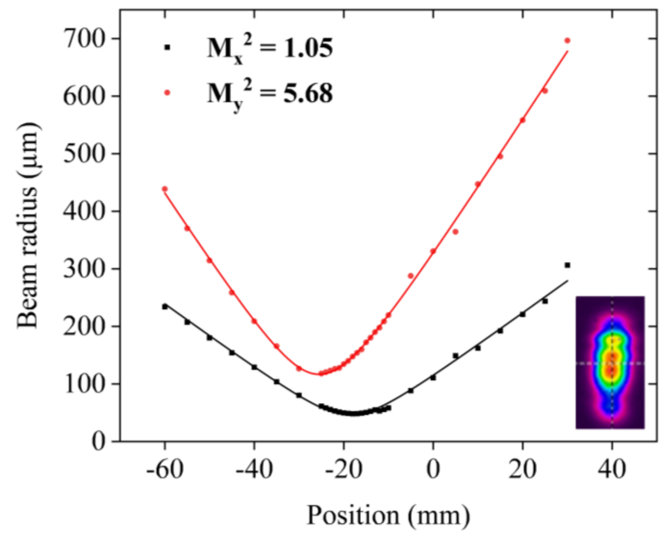

Fig. 3. Measurements of the output beam radius around the focus, for the x (black) and y (red) axes, before addition of the intracavity slits. Solid lines show the hyperbolic fit-function used to derive the annotated M^2 values. A profile of the collimated beam is included for reference.

B. TEM$_{00}$ output

We introduced TEM$_{00}$ operation by incorporating an adjustable slit into the cavity at the position shown in Fig. 1, to act as a spatial filter for the resonator. TEM$_{00}$ operation was obtained at a slit width of 1.16 mm, and was confirmed *via* the beam quality measurement shown in Fig. 2., from which we obtained M^2 values of 1.03 × 1.02. In this configuration, the resonator output power was stable at 1.03 W, and we measured slope efficiencies, with respect to incident pump power, of 11.1% for 448 nm pumping and 16.8% for 468 nm pumping. The resonator operated with an output wavelength of 767 nm, measured using an Avantes AvaSpec-ULS2048CL-EVO-RS spectrometer.

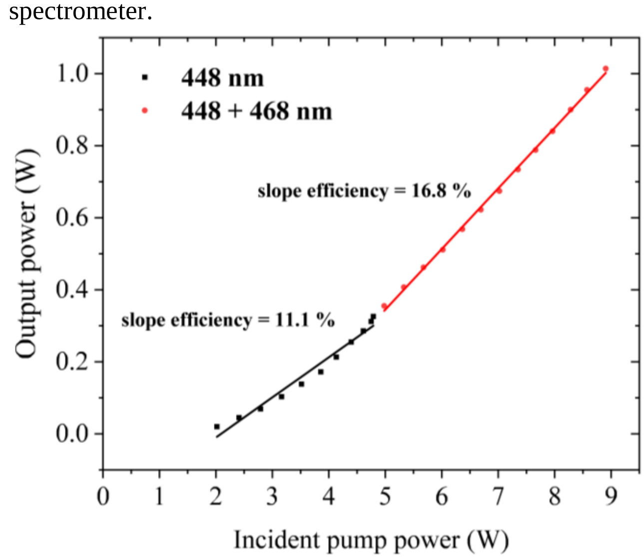

Fig. 4. Power transfer of the Ti:sapphire resonator after the addition of optical slits.

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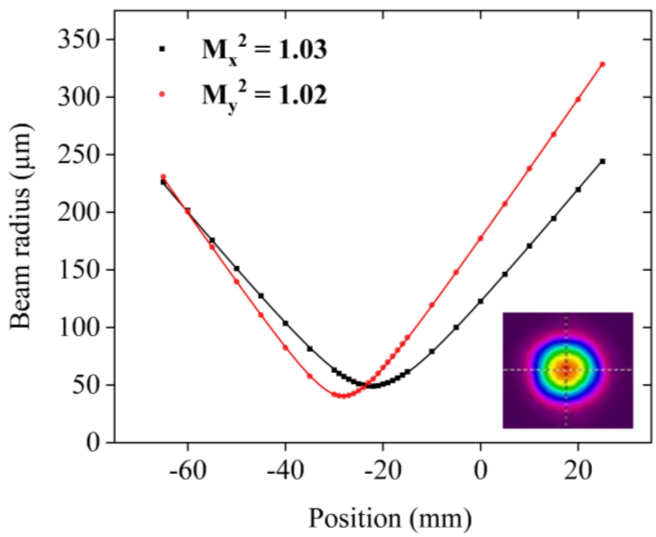

Fig. 5. Measurements of the output beam radius around the focus, for the x (black) and y (red) axes, after addition of optical slits to the cavity. Solid lines show the hyperbolic fit-function used to derive the annotated M^2 values. A profile of the collimated beam is included for reference.

For both the TEM_{00} and non-TEM_{00} cases, we obtained data using different output coupler transmission; 1%, 2% and 3%, but include only the results with 2% transmission. The output coupling optimises at the relatively low value of around 2% because the pump mode area is relatively large (around twice that in [22], for example) and so the threshold is comparatively high as a fraction of the available pump power. It was not possible to rigorously analyse the passive losses using Findlay-Clay or Caird analysis from this dataset, but such data as we do have suggests a round trip passive loss in the region of 1.5%, but with a large error bound: the losses sit between about 1% and 3% with 1.5% the most probable value.

Additionally, we investigated double-sided pumping of the system by adding a second, similar dual-pump path through the 100 mm ROC mirror. Though we employed mismatching of the lens focal lengths (150 mm for the focusing lens, -19 mm and 50 mm for the cylindrical lens telescope), the feedback between OSRAM diodes remained significant owing to the ~1.2W of 448 nm light transmitted through the crystal. The double-sided system was thus prone to damage to the 448 nm diodes. As such, we were unable to achieve a sufficiently long period of operation of the system to confirm TEM_{00} output. However, for this system we recorded a maximum output power of 2.38 W without the intracavity slits, and 2.05 W with the slits, using a 3% transmission output coupler. Although this issue can be resolved with the use of optical isolators, this will increase system cost and complexity.

IV. DISCUSSION

We attribute the high power output of this resonator design to the pairing of blue pump wavelengths with a low-doping Ti:sapphire crystal; this yields comparatively high optical-to-optical efficiencies for blue-pumping [16]. From work by Moulton *et al.* [10], [17], higher doping is expected to give rise to lower pump fraction for short-wavelength pumping. From our own work on pump-induced loss [13], we also expect that a highly doped crystal will exhibit greater PIL. A reduction in doping therefore circumvents two deleterious effects associated with blue-pumping, though the crystal length must be increased to compensate for the longer absorption length resulting from the reduced Ti^{3+} concentration. It might be expected that an increase of the crystal path length contributes to a significant increase in parasitic absorption at the laser wavelength; however, reducing the doping-level has the additional effect of reducing the NIR absorption strength in Ti:sapphire, assuming a fixed figure of merit (FOM) [18], [19]. Further, higher FOM samples are typically available at lower doping. We acknowledge that longer crystals are not desirable for ultrafast systems, however, owing to the extra dispersion introduced.

In order to investigate the repeatability and broader applicability of our approach, we examined the resonator performance with two further crystals of similarly low-doping: (i) a 10 mm, Brewster-cut, Northrop Grumman sample with $\alpha = 1.98\ cm^{-1}$ @ 515 nm and (ii) 12 mm, Brewster-cut, Crystal Systems sample with $\alpha = 2.13\ cm^{-1}$ @ 515 nm. We obtained maximum power outputs of 0.91 W for crystal (i) and 0.90 W for crystal (ii), both with 2% transmission output couplers. In each case, TEM_{00} output was confirmed *via* beam quality measurement. Though additional samples would be desirable, we were limited by the availability of materials.

TABLE I
COLLECTED CW RESONATOR DATA FROM DPTIS GROUPS

Author [Ref]	Pump power breakdown	Ti:S absorption coefficient @ 515 nm (cm^{-1})	Total incident pump power (W)	Maximum resonator output power (W)	Optical-to-optical efficiency	Beam quality (M^2)	Total electrical-to-optical efficiency
Gürel [20]	2 × 1.5 W (520 nm)	4.4	3.0	0.65	21.6 %	1.0 × 1.2	2.8%
Rohrbacher [21]	2 × 3 W (450 nm)	(0.25 wt.%)	5.8	0.47	8.0 %	1.12 × 1.08	2.6 %
Coyle [22]	2 × 3.5 W (450 nm)	3.3	6.5	0.72	11.1 %	-	3.4 %
Sugiyama [23]	2 × 1 W (478 nm) 2 × 1 W (520 nm)	-	3.15	0.66	21.0 %	-	3.1 %
Lagatsky [2]	1 × 5 W (470 nm) 1 × 2 W (490 nm)	4.8	6.7	0.70	10.5 %	< 1.15 × 1.15	3.2 %
Wang [14]	4 × 1.7 W (520 nm)	4.6	6.7	1.24	18.5 %	1.08 × 1.02	2.8 %
This work	1 × 5 W (448 nm) 1 × 4.2 W (468 nm)	2.37	8.9	1.03	11.6 %	1.03 × 1.02	3.2 %

We now compare our results to those of other dpTiS groups that have utilised few (≤ 4) single-emitter pumps to obtain particularly high average powers, high optical-to-optical efficiencies, or both (Table 1.). We also include an estimate of the total electrical-to-optical efficiencies, calculated by comparing the maximum Ti:sapphire output power to the diode electrical power, the latter of which we estimate using the "typical" values for operating current and voltage stated on corresponding product datasheets, or specific values where provided by the authors. We also provide the reported absorption coefficients for the Ti:sapphire crystals used in this study, approximately converted to the corresponding absorption @515 nm. Where an absorption coefficient is not specifically given, we estimate this from other given parameters, or provide the wt. % instead.

It is evident that the highest optical-to-optical efficiencies (~20%) are obtained under green-pumping. This is expected, as the lower quantum defect of green-pumping makes it fundamentally more favourable in this metric. Additionally, the higher absorption coefficient of Ti:sapphire at green wavelengths, relative to blue, Finally, the typically lower output power of green diode lasers means they have higher beam quality in the slow axis, allowing smaller pump waist radii than are obtainable with blue pumps. Despite these factors, resonator output powers (using two diode-pumps) have previously been comparable between blue and green-wavelength pumping, as the greater optical powers of blue pumps are able to compensate for the disadvantages discussed. Though Wang et al. were able to exceed 1 W in output power, they achieved this through the use of three or more diodes; using two diodes, they obtained 0.725 W output power [14]. While this is still a remarkable result from only 3.4 W pump power, the total resonator output remains similar to that obtained by Coyle *et al.* [22] with two blue diodes. It should also be noted that, as illustrated in Table I., the overall efficiency of blue-pumped systems is typically 10-15% higher than green-pumped systems because the lower optical-to-optical efficiency of the Ti:sapphire resonator is more than offset by the higher electrical-to-optical efficiency of the pump diodes.

This work substantially improves the resonator power output that can be achieved with two diodes by ~40% (from 0.73 W to 1.03 W). Use of a low-doping crystal is key to accessing the highest pump powers available from single-emitter diodes, as these powers are only available at blue wavelengths. Without considerations such as PIL or pump fraction, we expect that the performance of blue-pumped resonators would otherwise continue to improve as the doping-level increases. Interestingly Coyle et al. were able to obtain excellent resonator output under blue-pumping, also using a crystal with reasonably low doping (~3.3cm^{-1} @ 515 nm), despite noting a small deterioration in output power typical of PIL [22]. This suggests that there still remains scope to increase the crystal doping without compromising performance under blue-pumping. Our use of a crystal with α = 2.37 cm^{-1} @ 515 nm is primarily based on availability of material and a demonstrable lack of PIL [13]. A systematic survey to identify the optimal doping for blue-pumping would be beneficial to improving this approach, and similarly, the optimal crystal length also remains to be determined.

We must acknowledge that the resonator discussed here is a test system with no additional elements that add to the cavity loss, such as etalons, birefringent filters, etc. However, we expect that higher output powers can be readily obtained by further optimisation of this approach, such as a small increase to crystal doping.

In this study we also sought to maintain low cost per Watt; if this was not a consideration, resonator power could be increased relatively simply by replacing the 4.2 W LaserTree diode operating at 468 nm with a 5 W Nichia diode operating at the same wavelength. Performance could also be improved by reflecting and refocusing the unabsorbed pump light (~ 1.6 W; ~18%) back into the crystal, at the cost of increasing system complexity.

Additionally, if single transverse-mode resonator operation can be achieved through improved mode-matching rather than the incorporation of an optical slit, loss in the cavity will be reduced; a plane-cut crystal may be advantageous in this regard, as the Brewster surface, while superior for minimising the pump power lost through Fresnel reflection, causes significant expansion of the pump beam in one axis. As the slow-axis pump radii of blue diodes is already large due to their high M^2 values, expansion of the pump beam creates a scenario where mode-matching of pump and resonator is optimised for a larger resonator mode, which in turn increases the lasing threshold. The high slope efficiency we obtained in the non-TEM_{00} system demonstrates that mode overlap may be significantly limiting the efficiency of high beam-quality operation.

It is noteworthy that, in previous studies where multiple lower-power blue diodes have been employed, such as those of Roth and Coyle, smaller pump waist radii are possible owing to the lower slow-axis M^2 of lower-power diodes. The mode-matching efficiencies of these systems is likely to be higher than those obtained here, resulting in higher optical-optical conversion efficiency. This is similarly true of studies that utilise green or “skyblue” (~490 nm) diode pumps. It is likely that lower-power, longer wavelength diodes will maintain this advantage in mode-matching over blue diodes, even as diode technology continues to advance. We must then underline that the approach presented in this paper is not suggested as a replacement to the strategy of combining higher-doping crystals with green diode-pumps, but as a viable alternate approach to Watt-level output that makes different trade-offs that may be more desirable under certain circumstances. Broadly, we have exchanged mode-matching efficiency and higher crystal absorption for higher pump power and a cheaper, less-complex pump setup. Critically, this trade-off relies on low-doping Ti:sapphire crystals; without circumventing the deleterious effects of blue-pumping, the advantages of this approach are lost.

V. CONCLUSION

Here we demonstrate a CW, diode-pumped Ti:Sapphire with Watt-level output using two low-cost blue laser diodes and a long, low-doping Ti:sapphire crystal (10mm path length and α = 2.37 cm^{-1} @ 515 nm). We obtained 1.03 W, TEM_{00} output at 767 nm from 8.9 W incident pump power (4.8 W @ 448 nm and 4.1 @ 468 nm) with an optical-to-optical efficiency of 11.6% and, more significantly from a systems perspective, an electrical-to-optical efficiency of 3.2%. We also identify several ways to improve upon this result. We demonstrate for the first time that through judicious crystal choice it is possible to eliminate pump-induced loss in a blue-diode-laser pumped Ti:sapphire resonator while simultaneously achieving efficient operation with good beam quality.

This previously overlooked approach shows potential for reducing the size, weight, power and cost (SWaP-C) for Watt-level Ti:sapphire lasers. Further, this approach is well-placed to benefit from the more rapid advances in blue laser diode development relative to longer-wavelength counterparts.

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