Research Article
Vol. 4, No. 4 / 15 Apr 2025 / *Optics Continuum* 704
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Multi-watt diode-pumped Ti:sapphire laser

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Abstract: We present a diode-pumped Ti:sapphire laser with 2.9 W output power and M^2 of 1.2×1.1. This is the highest output power reported for a near-TEM_{00} ($M^2 \leq 1.2$) diode-pumped Ti:sapphire. The laser is pumped by a commercially available diode-laser module designed for cutting and engraving applications, in a configuration that reduces the complexity of the optical setup relative to other diode-pumped systems.

1. Introduction

With the suite of successful demonstrations across a range of applications [1–7], diode-pumped Titanium:sapphire (dpTiS) systems show significant potential, not only in extending Ti:sapphire functionality beyond lab environments, but in offering cheaper, smaller-footprint alternatives to lab-based Ti:sapphire lasers, often without significantly compromising performance. There remains a gap in the attainable output powers of dpTiS systems relative to conventional, DPSS-pumped Ti:sapphire systems, however. To this end, successful power-scaling of dpTiS remains an important avenue of investigation.

DpTiS lasers have recently achieved Watt-level outputs in both green-pumped [8,9] and blue-pumped [10,11] configurations. Wang *et al.* [9] achieved 1.24 W of resonator power with excellent beam quality (1.08×1.02) using 2 green pump modules, each comprised of 2 spatially-combined ~1.7 W green diodes. Miao *et al.* [8] also developed a green pump module by combining and coupling the outputs of 40×1 W green diodes into an optical fibre. They obtained 1.4 W of resonator power using one such ~22 W module, and 3.8 W by adding a second module in a double-sided pumping configuration. In the case of two-sided pumping, however, the beam quality was low, with reported M^2 values of 1.9×1.8 for the resonator beam. Backus *et al.* [10] reached 11 W of resonator power when operating their regenerative amplifier system as a CW resonator. Backus *et al.* also used 2 fibre-coupled pump modules, each giving 50 W of pump power at 450 nm. This result was only obtainable through cryo-pumping of the Ti:sapphire, without which the fluorescent yield of the crystal was not high enough to enable lasing. We [11] recently demonstrated Watt-level (1.03 W) power through the use of 2 low-cost blue diodes in a single-sided pumping configuration, obtaining M^2 values of 1.03×1.02, at room-temperature.

Our recent work [11] outlined a means of utilising blue diode pumps in a way that does not incur the deleterious performance effect of pump-induced loss [12–14], or result in a significant reduction in pump fraction [15]. This approach gives reasonable (11.6%) optical-optical conversion efficiencies that allow blue-pumped Ti:sapphire systems to reach Watt-level output. In this earlier publication [11] we also discussed the advantages of blue laser diodes over green with respect to the manufacturability, cost, and the prospect of future development [16–19]. Though longer-wavelength pumping is favoured in recent dpTiS studies [4,6,9,20], we believe blue diode technology currently offers a clearer route to higher power.

The relative advantages of blue laser diodes are epitomised in low-cost, commercially available laser-cutting and engraving modules. Such modules can emit up to ~80 W of optical power at

#555027
Journal © 2025
https://doi.org/10.1364/OPTCON.555027
Received 7 Jan 2025; revised 13 Feb 2025; accepted 15 Feb 2025; published 20 Mar 2025

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~450 nm through combination of 5 W diodes into an array of beams *via* polarisation-combining and beam-stacking, i.e., the stacking of beams along the fast axis direction, shown in (Fig. 1). Due to the nature of their application, these modules are designed to produce a small spot size through a high degree of alignment between beams in the array, as well as small spatial separation between the beams. Though this results in a reduction of beam-quality in the fast axis relative to a single diode output, it also gives rise to a scenario where the beam widths and beam quality in the fast and slow axes can be equalised, reducing the need for cylindrical lenses, as demonstrated in this paper.

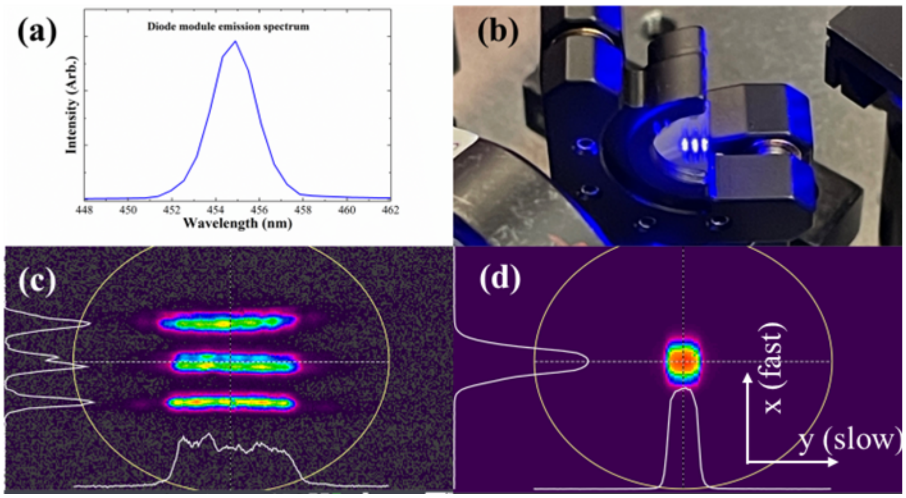

Fig. 1. Characteristics and visualisations of the pump module output: (a) the pump emission spectrum, (b) 3 of 6 pump stripes incident on the pick-off (scraper) mirror, (c) the pump beam profile at the fast axis focus, and (d) the pump beam profile at the slow axis focus.

In this paper, we demonstrate that a relatively low-cost ($900) laser-diode module designed for laser-cutting can be used as a pump for a mutliwatt Ti:sapphire laser.

2. Experimental

The pump source used in this study was a commercially available laser-cutting module, a Lasertree K60, with 60 W of output at ~ 455 nm (Fig. 1(a)). This module comprises twelve 5 W blue diodes that are polarisation-combined in pairs and then spatially stacked to give 6 output stripes with a small spatial separation. Each stripe consists of two diode outputs, with 10 W of power split between two orthogonal polarisation states. The fast and slow axes of the polarisation-combined diodes lie in the same plane, however. In this investigation, we mounted the pump module such that the slow axes of the diodes were vertically aligned. We chose this orientation in order to implement a simple beam pick-off setup using a knife-edge scraper mirror mounted on a single-axis translation stage (Fig. 1(b)). The beam pick-off was used to dump 3 of the 6 beam stripes. The remaining ~30 W was employed to pump the resonator.

The module output is controlled by a supply board with a small footprint (~75×60 mm). However, due to the nature of the module as a subcomponent of a laser-cutting unit, the output power could not be adjusted while operating in CW, though a quasi-CW mode with variable on/off periods could be used for alignment.

We improved the thermal stability of the module by removing the outermost section of the chassis such that two water-cooled blocks could be placed in contact with the module's fan-cooled heat sinks. The module includes a digital display of the diode temperature, and during operation at full power we consistently observed a stable temperature of 30 °C.

The pump module is supplied with a 40 mm focusing lens fitted to the output, resulting a in a spot with radius 60×80 µm, as provided by the manufacturer. We employed a 75 mm spherical lens to collimate the diverging module output, and subsequently expanded the beam using a telescope with -25 mm and 75 mm focal length spherical lenses. Alignment of the telescope is simplified by the ability to use spherical lenses, as no rotational alignment is required, as would be the case for cylindrical lenses. The two polarisations of the beam were then separated using a polarising beamsplitter cube. We implemented a 2-sided pumping configuration with the polarisation-separated beams, with a half-wave plate employed to rotate the polarisation of the component reflected by the beam cube. We employed a 75 mm focussing lens on 1 side of the setup (path A), and an 80 mm lens at the other (path B). The resulting pump waist radii ($1/e^2$) were: path A; 41.8×44.0 µm, and path B; 46.2×85.6 µm, for the fast and slow axes, respectively. A slight mismatch of the focal lengths was employed to reduce feedback into the pump module, and no issues were observed in this configuration.

Though this setup allows us to select any number of beam stripes to pump the resonator, allowing for 10-60 W of pump power to be selected at 10 W intervals, we investigated only the case where 3 stripes are used. We prioritised this case due to the symmetry of the resultant pump spot at the slow axis focus. As a result of astigmatism, the pump module has two distinct foci along the z-axis, corresponding to the fast axis focus (Fig. 1(c)) and slow axis focus (Fig. 1(d)). We observed that, for a configuration with 3 beam stripes, the pump spot at the slow axis focus is reasonably symmetric. Increasing the number of beams increases the pump power, but also increases the waist radius in the fast axis. In our previous work [11] we obtained a multimode resonator beam in the axis aligned with the diode's slow axis, and we achieved TEM_{00} operation by employing optical slits, likely compromising some of the laser efficiency. In the present study we therefore chose to maintain a fast axis beam waist approximately equal to or smaller than that of the slow axis, to reduce the probability of multimode operation in a second axis.

The final pump powers at the crystal were: path A; 12.9 W, and path B; 10.8 W, with a combined power of 23.7 W. We note that the loss of pump power through the setup is high. Immediately after the -20 mm focal length lens of the telescope, the power is 30.8 W, though the total pump power after polarisation-separation is only 28.3 W, composed of 13.7 W in path A and 14.6 W in path B. We attribute the initial loss of pump power to the beamsplitter cube, as, in previous iterations of this setup with a smaller beam size at this optic, the optic-bonding cement separating the cube segments was damaged by the beam over time. Even with a significantly increased beam size, this optic became warm during operation. The significant power loss through path B is ascribable to a mismatch of the beam size to the aperture of the half-wave plate required to rotate the polarisation, leading to clipping of the beam on the optic mount.

The resonator employed was a simple 3-mirror cavity, similar to that used in our previous study [11]. We used a 2% transmission output coupler, and a Brewster-cut Crystal Systems Ti:sapphire crystal with a 10 mm path length and an absorption coefficient, α, of $2.37 cm^{-1}$ @ 515 nm. The complete optical setup is depicted in (Fig. 2). As in our previous work, we used a long, low-doping crystal to mitigate pump-induced loss [12,14] from blue-pumping, and to maximise the pump fraction [15]. Approximately 4 W of the total pump power is not absorbed by the crystal, giving an average single-pass absorption of ~83% for the two pumps.

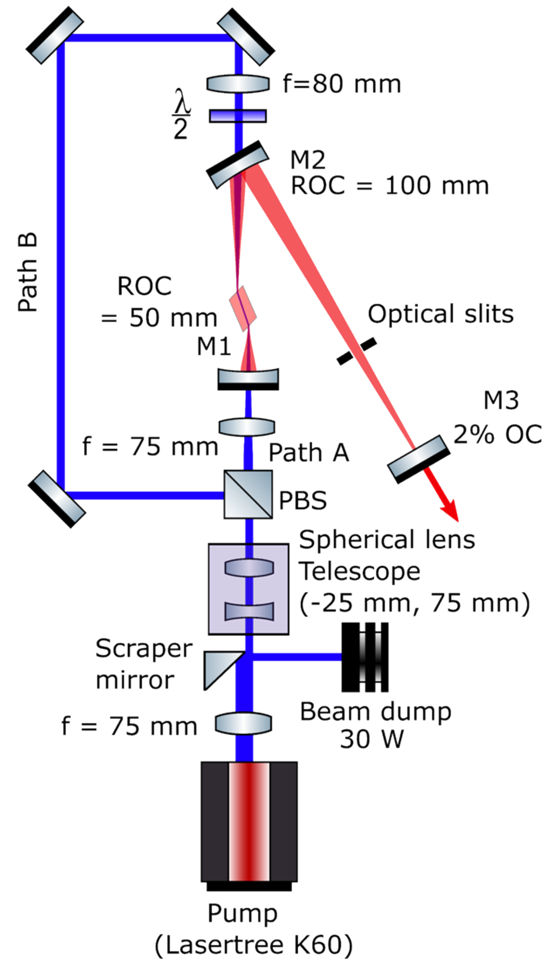

Fig. 2. Schematic diagram of the pump and resonator setup.

3. Results

As previously [11], when optimised for power, the resonator mode was observed to have poor quality in the equivalent of the diode slow-axis (vertical-axis), with M^2 of ~9. The maximum power recorded under these conditions was ~3.4 W, with a 2% transmission output coupler. Though the beam quality could be improved somewhat through adjustment of the cavity, TEM_{00} operation was not obtained by this approach alone. As per our previous work, we used optical slits to reach TEM_{00} operation. The slits were placed ~50 mm from the output coupler, and near-TEM_{00} operation was confirmed at a slit width of 1.05 mm. Figure 3 displays our measurement of the resonator beam quality, from which we extracted M^2 values of 1.2×1.1 for the horizontal and vertical axis, respectively. We note a slight astigmatism in the laser output.

Under near-TEM_{00} operation, the maximum output power obtained was 2.9 W. As previously mentioned, the output power of the module could not be adjusted while operating in CW. Variation in pump power, required to capture the resonator transfer, was implemented *via* an additional half-wave plate and polarising beamsplitter cube. The attenuation optics were employed first on pump path A without path B, then the power was attenuated in path B while path A was operating at full power. The resulting transfer plot is shown in (Fig. 4).

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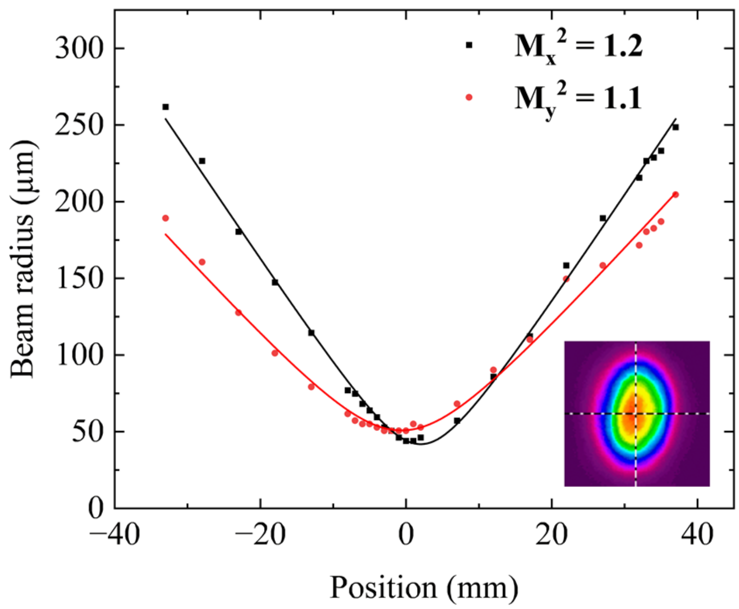

Fig. 3. Measurements of the output beam radius around the focus, for the x (black) and y (red) axes, after addition of optical slits to the cavity. Solid lines show the hyperbolic fit-function used to derive the annotated M^2 values. A profile of the collimated beam is included for reference.

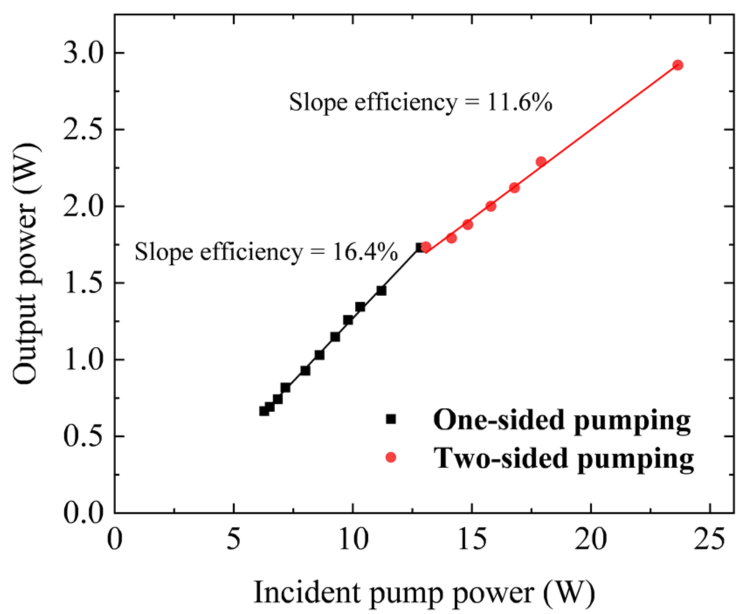

Fig. 4. Power transfer of the resonator using a 2% transmission output coupler, with optical slits in place to achieve TEM_{00} operation.

We obtained a slope efficiency of 16.4% from one-sided pumping with path A, and a slope efficiency of 11.6% from two-sided pumping with path B as the second pump. The optical-optical conversion efficiency was 12.2% for the combined pumps. The efficiencies in each case are calculated with respect to the incident pump power, rather than the absorbed power. Since the incident pump power was measured at the crystal position for both beam paths, the comparatively high loss of pump power through path B is already accounted for in (Fig. 4), indicating that the lower slope efficiency for this path is caused by other factors. We have noted a smaller beam size for path A relative to path B: A; 41.8 × 44.0 µm, and B; 46.2 × 85.6 µm. Though this is broadly expected, given the longer focal length employed in path B, the differences in beam waist radii in the slow axis are excessively large. This is likely the result of poorer collimation in the slow axis combined with the longer propagation length of path B, contributing to a larger pump spot and lower slope efficiency. Another potential explanation for the low slope efficiency for pump path B is the resonator beam waist location inside the crystal. Though it is a speculative observation, we noted from the visible path of the beams through the Ti:sapphire crystal that, at an optimised power level, the focus of pump path A lies close to the face of the crystal onto which it is incident, resulting in an essentially minimised beam spot on this face. When incorporating path B for 2-sided pumping, the optimal resonator power output occurs when the pump foci coincide along the optical axis of the Ti:sapphire crystal. Since the focus of path A lies closer to the 50 mm ROC mirror, pump B must propagate through additional Ti:sapphire before reaching a focus, resulting in lower power at the focus.

We observed significant thermal lensing in the crystal, which we infer from the extent of re-optimisation needed when switching the pump module from quasi-CW to CW. When the system is fully optimised under quasi-CW operation of the pump, the switch to CW mode with 30 W initially results in an output power similar to the maximum obtained, though this power level drops to 100s of mW in a period of 10-20 s. The majority of this power can be recovered easily through adjustment of the pump lenses, specifically by translating these in z-direction. The position of the curved resonator mirrors, with respect to the crystal, must also be adjusted to optimise the system, further suggesting that the resonator waist location varies with pump power to a non-negligible degree.

Though we acquired data with various output couplers (1, 2, 3 and 5% transmission), the highest output power was recorded using a 2% OC.

4. Discussion

We have demonstrated a pathway for diode-pumped Ti:sapphire power-scaling using a commercially available diode module. However, there is significant potential to further refine this approach. Most notably, the loss of power through pump path B as a result of beam clipping could be easily rectified with a half-wave plate of larger diameter. A total of 26% of the pump power for path B is lost between the beamsplitter cube and the crystal. This is unlikely to be attributable to the wave plate alone, however. In path A, 0.8 W of pump power is lost through the pump focussing lens and input coupler. Taken with the 2.5 W power loss through the beamsplitter, we speculate that bonded optics are not particularly well-suited to the high pump powers, and that loss of pump power could be reduced by employing singlet lenses or air-spaced doublets, rather than the cemented doublets used here. A more efficient means of polarisation-separation of the pump would also be advantageous in this regard. We ascribe the loss of pump power to optic-bonding rather than optical coatings due to the observed mode of failure in the optics that were damaged in this setup; several lenses and polarisation cubes were severely damaged during use, each of which was a bonded optic that burned at the interface between bonded surfaces. We observed no damage to singlet optics.

The efficiency of pump path B could be increased by improving the slow-axis collimation to reduce the beam waist size and better match the beam waist of path A.

A significant increase to resonator power could be achieved by substitution of the 455 nm diodes in the module with 465 nm, as a result of the increased Ti:sapphire absorption at these longer wavelengths; for the crystal used in this work, the absorption coefficient increases by a factor of

27% between 455 nm and 465 nm, translating to an increase of ~14% in the single-pass absorption. Because of similar the emitter size between 4-5 W blue diodes of different wavelengths, this substitution has little effect on the coupling optics required.

Vitally, we note that the module used in this study can also be combined with additional diodes using dichroic mirrors owing to its relatively narrow emission spectrum (~2.5 nm FWHM,). The above suggestion of replacing module diodes with longer wavelength equivalents is therefore not only valuable in its own right, but offers a means of employing two modules whose outputs can be readily combined. Even a conservative estimate of the resulting resonator power, ~5 W, is competitive with commercially available Ti:sapphire lasers e.g. the Coherent Chameleon, Spectra Physics 3900S and M Squared SolsTiS.

We must note again that only half of the pump power is utilised in our setup. A laser cutter with a 30 W output could be used to the same effect, for lower cost and higher electrical-optical efficiency. Alternatively, the unused 30 W pump power from the K60 module used here could be employed to operate a second laser or amplifier. It is possible to employ all 6 beam strips for a single resonator to make use of the full pump power available. Though this would lead to greater asymmetry in the pump spot, this could potentially be offset by replacing the single spherical focussing lens with two cylindrical lenses of different, positive, focal length, employing the smaller focal length to act upon the fast axis of the pump.

To reduce the complexity of the setup, it would be trivial to replace the pump telescope (-25 mm and 75 mm lens) by employing a collimating lens at the pump output with sufficiently long focal length to collimate the beam at the required size. We were unable to do this here due to the dimensions of the pick-off mirror; with a larger pick-off optic, the beam expansion could be implemented before separating the output into 2 sets of 3 beams.

The module itself could be improved for use with Ti:sapphire resonators by removing the chassis cooling fans and implementing either a water-cooling or TEC-cooling system. In the setup used, the cooling fans produced significant airflow across the optical table, despite attempts to mitigate these air currents with beam shielding. Alternate cooling schemes for the module would thus improve the thermal stability of the module and the power-stability of the resonator.

We have estimate the total electrical-optical efficiency of the K60 module, calculated using the quoted parameters for voltage and current, as 1.2%. However, only 30 W of the total 60 W optical power output is used here, and the quoted parameters encompass the power supply to the full module, including fans, a red alignment laser, etc. Using the typical supply parameters for 6×5 W diodes of 450 nm wavelength, the total electrical-optical efficiency is 2.8%. This second value is equivalent to our estimates of the electrical-optical efficiencies of Wang *et al.* [2] and Gürel *et al.* [21], both of whom utilised green-pumping. Our optical-optical efficiency (12.2%) is significantly lower than for these green-pumped systems (~20%), though this is expected from the lower absorption coefficient and higher quantum defect of blue-pumping. Additional considerations such as pump-induced loss [12,14,13] and pump fraction [15] can also reduce the efficiency of blue-pumping, though these are expected to be minimal here. The use of optical slits to reach near-TEM_{00} operation also reduces our efficiency; without slits we obtain 14.3% optical-optical, though at the expense of lower beam quality in the vertical axis. It is noteworthy that the lower optical-optical efficiencies of blue-pumping are compensated by the higher electrical efficiencies of blue diodes.

Our optical-optical efficiency compares favourably to the work of Miao *et al.* [8], who obtained 1.4 W resonator power from ~22 W of pump power, and 3.8 W resonator power from ~44 W pump power, giving optical-optical efficiencies of 6.4% and 8.6%, respectively. We estimate the electrical-optical efficiency of the Miao *et al.* system to be 0.6% for 2-sided pumping, as a consequence of the high numbers of single diodes required to construct the pump modules. The work by Miao *et al.* is the highest room-temperature resonator power to date for dpTiS, they report M^2 values of 1.4×1.3 and 1.9×1.8 for output powers of 1.0 W and 3.8 W respectively.

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However, in the former case data is collected over approximately a quarter of a Rayleigh range either side of the focus and over about 1 Rayleigh range in the latter case. As a result, no data is collected from the far-field, which is normally required for an accurate M-squared measurement. This means some caution is required in interpreting this data.

Backus *et al.* [10] obtained 11 W of resonator power using 100 W pump power at 450 nm; an optical-optical efficiency of 11%, and We estimate the electrical-optical efficiency to be 3.1%. Cryogenic cooling was employed in this system to mitigate thermal lensing and to increase the fluorescent yield, and so an additional 75 W of cooling was required to maintain the Ti:sapphire crystal at 130 K.

Our work compares well with these state-of-the art systems, offering high resonator power, high beam quality and good efficiencies, at room-temperature. We have also achieved this using a low-cost, off-the-shelf laser-cutting module.

There is potential to expand on this approach for blue-pumping of Ti:sapphire resonators; blue diode technology is widely used, and its ubiquity gives rise to readily available, well-engineered, pre-aligned, low-cost modules that can serve as viable pump sources for multiwatt Ti:sapphire lasers.

5. Conclusion

We have demonstrated a multi-watt (2.9 W) Ti:sapphire resonator, achieved using half of the output power (30 W) of a $900, commercially-available laser-cutting module in a two-sided pumping scheme. We employed a low-doping Ti:sapphire crystal ($\alpha = 2.37\,\mathrm{cm}^{-1}$ @ 515 nm) to mitigate the deleterious effects of pump-induced loss and pump fraction, allowing for relatively high slope efficiency (14% average between the two pump paths).

Blue diode modules such as the one used here are lower-cost than some individual green laser diodes, and are orders of magnitude lower-cost than 532 nm DPSS lasers, yet they can demonstrably be used to pump multiwatt Ti:sapphire lasers. Additionally, the overlapping of multiple stacked beams also provide a more symmetric pump spot that single-stripe pumping, reducing the requirement for sensitive cylindrical lenses. This helps to further reduce cost, complexity and bulk to diode pumped Ti:sapphire lasers.

Funding. Engineering and Physical Sciences Research Council (EP/T014288/1).

Acknowledgements. We thank Lasertree for providing the additional technical details that allowed us to determine the feasibility of the experimental setup used here.

Disclosures. The authors declare no conflict of interest.

Data availability. Data underlying the results presented in this paper are available from the University of Strathclyde data repository [22].

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