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High-power, continuous-wave Ti:sapphire laser pumped by fiber-laser green source at 532 nm

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ABSTRACT

We report the first experimental demonstration of efficient and high-power operation of a Ti:sapphire laser pumped by a simple, compact, continuous-wave (cw) fiber-laser-based green source. The pump radiation is obtained by direct single-pass second-harmonic-generation (SHG) of a 33 W, cw Yb-fiber laser in a 30-mm-long MgO:sPPLT crystal, providing 11 W of single-frequency green power at 532 nm in TEM_{00} spatial profile with power and frequency stability better than 3.3% and 32 MHz, respectively, over 1 h. The Ti:sapphire laser is continuously tunable across 743–970 nm and can deliver an output power up to 2.7 W with a slope efficiency as high as 32.8% under optimum output coupling of 20%. The laser output has a TEM_{00} spatial profile with $M^2 < 1.44$ across the tuning range and exhibits a peak-to-peak power fluctuation below 5.1% over 1 h.

1. Introduction

Titanium-doped sapphire (Ti:sapphire) is the most successful solid-state laser material in the near-infrared wavelength range due to its high saturation energy, large stimulated emission cross-section, and broad absorption gain bandwidths [1]. It has been extensively developed for continuous-wave (cw) operation, ultra-short pulse generation, high-power amplification, and much more, and has been successfully deployed in a wide range of applications from high-intensity physics, frequency metrology, and spectroscopy to pumping of tunable optical parametric oscillators (OPOs). Although Ti:sapphire has broad absorption bandwidth, due to the relatively weak absorption peak in the blue–green wavelength range, its successful operation requires high-power blue–green pump sources. As such, Ti:sapphire lasers have been pumped with multiwatt argon-ion [1,2], copper-vapor [3], and most notably frequency-doubled all-solid-state green lasers [1,4], resulting in fairly bulky, complicated and expensive setups. For further progress in Ti:sapphire laser technology, it would be desirable to devise more simplified pump laser designs to reduce system complexity and cost, while maintaining or enhancing device performance with regard to all important operating parameters. Recently, a cw Ti:sapphire laser pumped directly by a GaN diode laser in the blue was reported [5], but the limited pump powers available from diode lasers with good spatial beam quality restrict the effectiveness of this approach only to low-power cw operation. On the other hand, optically pumped-semiconductor-lasers (OPSL) in the green can in principle be used to pump cw Ti:sapphire laser [6], but limited progress has been achieved in this area so far, leaving open the need for the development of powerful alternative green sources with high spatial quality and in simple, practical all-solid-state design to pump high-power cw or mode-locked Ti:sapphire lasers.

A major step in this direction is the development of novel green sources based on second-harmonic-generation (SHG) of the rapidly advancing fiber laser technology to replace the relatively complex and expensive cw solid-state green lasers at 532 nm. Among all existing frequency-doubling techniques, such as intracavity, multi-pass, or resonant enhancement, external single-pass SHG is the most direct route for the realization of a compact, cost-effective, and practical green source in simple design. Moreover, single-pass SHG avoids the traditional "green problem" [7], commonly observed in intracavity frequency doubling of solid-state lasers. At the same time, single-pass SHG of fiber lasers offers additional advantages of air-cooling and flexible packaging, making the fiber pumping approach highly attractive over solid-state green sources. Recently, we demonstrated an efficient and high-power green source based on direct single-pass SHG of a cw Yb-fiber laser in MgO-doped stoichiometric periodically poled

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lithium tantalate (MgO:sPPLT) crystal, providing up to 9.6 W of power at 532 nm in TEM_{00} spatial beam with power stability of 9% over 13 h [8,9]. As such, we were able to successfully deploy this source to pump a high-power cw OPO for the near-infrared [10].

Here, we report the successful use of this simple, high-power, cw, fiber-based green source to pump a Ti:sapphire laser, generating an output power of >2.7 W with tunability of >227 nm in a TEM_{00} spatial profile. Although operation of a Ti:sapphire laser was previously reported using a pulsed frequency-doubled fiber laser [11], to our knowledge, this is the first report of a Ti:sapphire laser pumped by a cw fiber laser source, which also demonstrates the competitive performance of the source compared to the well-established solid-state green pump lasers at 532 nm.

2. Experimental set-up

A schematic of the experimental setup is shown in Fig. 1. The fundamental pump source is a cw, single-frequency Yb-fiber laser (IPG Photonics, YLR-30-1064-LP-SF) at 1064 nm, providing a linearly polarized output beam with $M^2<1.01$ and a nominal linewidth of 89 kHz. A 30-mm-long MgO:sPPLT crystal [10], containing a single grating (Λ=7.97 μm), is used for single-pass SHG into the green at 532 nm. At the highest available fundamental power of ~33 W, our SHG source provides as much as 11 W of green power in a TEM_{00} spatial profile ($M^2<1.3$) with a frequency stability better than 32 MHz over 1 h. However, since our earlier reports [8,9], we have improved the output power stability of the green source from 7.9% to better than 3.3% peak-to-peak, measured over 1 h. This improvement has been obtained using a novel uniform crystal heating configuration, where the crystal is placed at the center of a large-area oven used to heat a 50-mm-long crystal. As compared to the small-area oven used previously [8,9], the central part of the new oven provides higher temperature uniformity and is less sensitive to the instability (±0.1 °C) of the temperature controller. As a result, it maintains improved temperature stability over the full crystal length, resulting in higher green output power stability. The fiber green source is so robust that it takes only 30 min to reach stable output power during the fiber laser warm-up time. We have operated the source reliably and regularly on a daily basis for over 2 years, without any degradation in output power or stability.

In the present experiment, to maintain stable output characteristics, we operated our green source at the maximum power and used an attenuator comprising a half-wave-plate (HWP) and a polarizing beam-splitter (PBS) to vary the input power to the Ti:sapphire laser. Using plano-convex lens (L_2), we focused the green pump beam to different waists at the center of the 10 mm-long, Brewster-cut Ti:sapphire crystal (0.15 wt% doping, $FOM>270$), which is located on a brass slab, and water-cooled only on the lower side. The green beam was polarized along the *c*-axis of the crystal to maximize absorption [1,2], which we measured to be $>80\%$. The laser was configured in an astigmatic-compensated, standing-wave cavity, comprising two concave mirrors, M_1 and M_2, and a plane output coupler (OC). To access the wide tuning range of the Ti:sapphire laser, we used two sets of concave mirrors, all of the same radius of curvature (r=10 cm), providing high reflectivity ($>99\%$) across 760–840 nm and 840–1000 nm. For wavelength tuning and control, we used a birefringent filter (BRF).

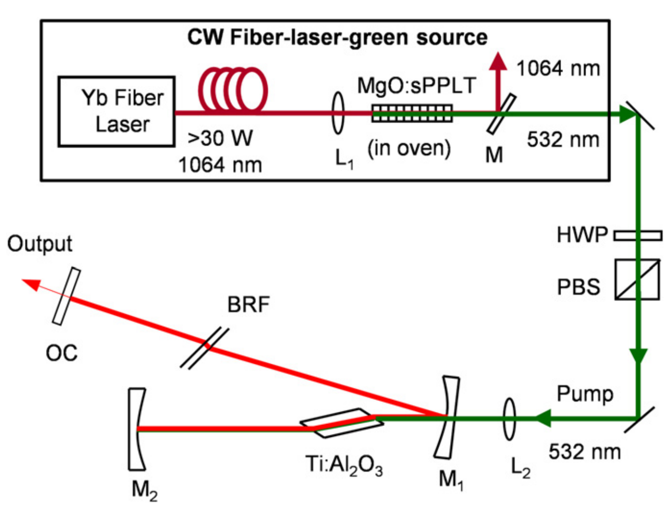

Fig. 1. Schematic of the fiber-laser-green-pumped cw Ti:sapphire laser: $\lambda/2$, half-wave plate; PBS, polarizing beam-splitter, L, lens, M, mirrors, BRF, birefringent filter, OC, and output coupler.

3. Results and discussion

3.1. Output power across the tuning range

We investigated the output power of the Ti:sapphire laser across the tuning range using both sets of concave mirrors, by deploying different output couplers of varying transmission across 740–970 nm. Tuning was achieved using the BRF. The results are shown in Fig. 2, where the output power across the obtained tuning range is plotted for three different output couplers. For OC1 (T=5%–0.74% over 780–970 nm), the output power exactly follows the transmission curve (inset of Fig. 2) up to the wavelength ~940 nm, with no evidence of the expected drop in power due to gain reduction in the Ti:sapphire crystal at longer wavelengths [1]. This can be attributed to the high intra-cavity power due to the combination of high pump power (10.5 W) and low output coupling, pointing to the possibility of extracting higher power across the tuning range using larger output coupling. However, beyond ~940 nm, there is a drop in output power due to the lower gain of the Ti:sapphire crystal [1]. Tuning below 780 nm is limited by the higher loss due to increasing output coupling at shorter wavelengths. Therefore, using OC1 and both sets of cavity mirrors, the Ti:sapphire laser can be continuously tuned over 780–970 nm with a maximum power of 1 W at 780 nm.

To enhance the tuning range and output power, we deployed two additional output couplers of varying transmission, OC2 (T=4.4%–3.12% across 743–800 nm) and OC3 (T=25%–18.6% across 767–812 nm), also shown in the inset of Fig. 2. With OC2, we obtain tuning across 743–800 nm with a maximum

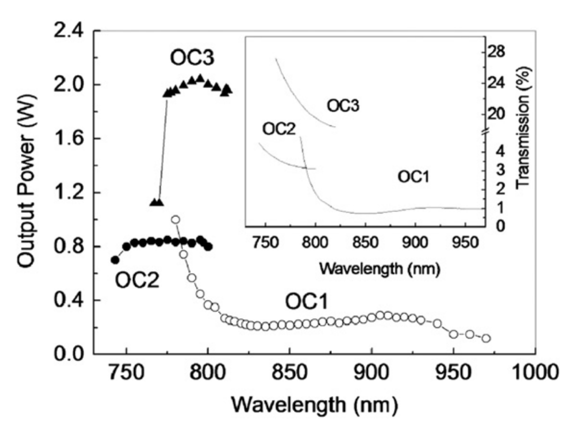

Fig. 2. Extracted output power across the tuning range of the Ti:sapphire laser using three different output couplers and two set of cavity mirrors access 743–970 nm. Inset: transmission of the output couplers OC1, OC2, and OC3 versus wavelength.

power of 0.85 W at 795 nm. With OC3, we obtain an output power up to 2.04 W at 795 nm for an output coupling of 20%, with >1.12 W available across 767–812 nm. Hence, using two sets of cavity mirrors and three output couplers, we achieve a total wavelength tuning range of ~227 nm across 743–970 nm and generate up to 2.04 W of output power. Wavelength tuning below 743 nm is limited by the reflectivity fall-off of the cavity mirrors, whereas coverage beyond 970 nm was limited by the free spectral range of the BRF.

All the output couplers used in the current report are subject to availability in our laboratory. However, close observation of the Fig. 2 shows that the Ti:sapphire output power exactly follows the transmission of the output coupler OC1, which can be attributed to saturation of the intra-cavity power to a constant value due to high pump power and low cavity losses, irrespective of the varying Ti:sapphire gain across the emission spectra. As a result, the out-coupled power was determined by the transmission of the output coupler. On the other hand, for varying output coupling close to the highest available coupling (OC3), the laser output power follows the gain curve of the Ti:sapphire laser, as evident from the output power data of OC3. However, at moderately higher output coupling (higher than that of OC1 and much lower than that of OC3), as in the case of OC2, the output power is almost constant despite the varying output coupling and gain across the tuning range. In this case, the maximum intra-cavity power is different across the tuning range depending on the total cavity losses and gain reduction across the tuning range. Thus, we obtain a constant out-coupled signal power across the tuning range due to the varying output coupling. This behavior is expected only when the variation in output coupling is small compared to the total cavity losses and has a negligible effect on threshold, which is the case here. Similar effects are also observed in cw out-coupled singly resonant optical parametric oscillator [12].

3.2. Optimization of output coupling

To optimize the output coupling for maximum power extraction, we focused the pump beam to a beam waist radius of w_p ~30 μm and operated the Ti:sapphire laser in free-running cavity at a fixed pump power of ~10.5 W (at the Ti:sapphire crystal) and used several additional output couplers with transmissions ranging from 1.4% to 40.7% at ~812 nm, where the laser operated at a wavelength with the lowest cavity loss in the absence of BRF. We measured the extracted power and corresponding operation threshold of the Ti:sapphire laser as a function of output coupling, with the results shown in Fig. 3. The output power rises from 1 W to 2.24 W with the increase in output coupling from 1.4% to 19.9%. However, further increases in output coupling result in reduced output power with a clear peak near 20%, implying an optimum output coupling of 20% for our laser. As expected, the laser threshold increases linearly with the output coupling and reaches 6 W at 40.7%, with an output power of 1.66 W. Higher output coupling is possible with our laser for the available pump power, but will result in reduced output power. It is to be noted that the temperature rise in the Ti:sapphire crystal due to pump absorption effectively decreases the fluorescence lifetime and quantum efficiency by ~10% [13] and thermo-optical aberrations due to temperature gradients in the crystal also limit the laser output power [14]. Therefore, an enhancement in output power is feasible by implementing further thermal management of the crystal by water cooling from four sides.

3.3. Power scaling

Having determined the optimum output coupling of 20%, we investigated power scaling of the Ti:sapphire laser. Fig. 4(a) shows the variation of output power as a function of pump power without the BRF (laser wavelength ~812 nm), for two different pump beam waist radii of 25 μm (closed circle and solid line) and 30 μm (open circle and dotted line). With a pump beam waist of 25 μm and 20% output-coupling, the Ti:sapphire laser has a threshold of 2.51 W and the output power increases with pump power with a slope efficiency of 31.8%, reaching a maximum value of 2.7 W at ~11 W of pump power. With a pump beam waist of 30 μm, the laser threshold increases to 3.27 W, but the output power rises with a slope efficiency as high as 32.9%, reaching 2.22 W for 10.57 W of pump power. It may, thus, be concluded that the laser operates robustly with an output power >2.2 W and slope efficiency

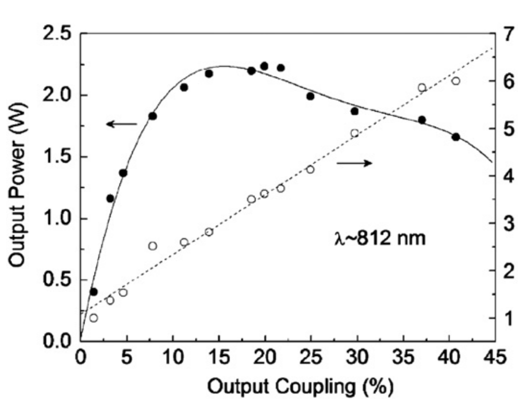

Fig. 3. Dependence of the extracted output power and threshold power of the Ti:sapphire laser on output coupling at ~812 nm. The solid line shows polynomial fit and the dashed line shows the linear fit to experimental data.

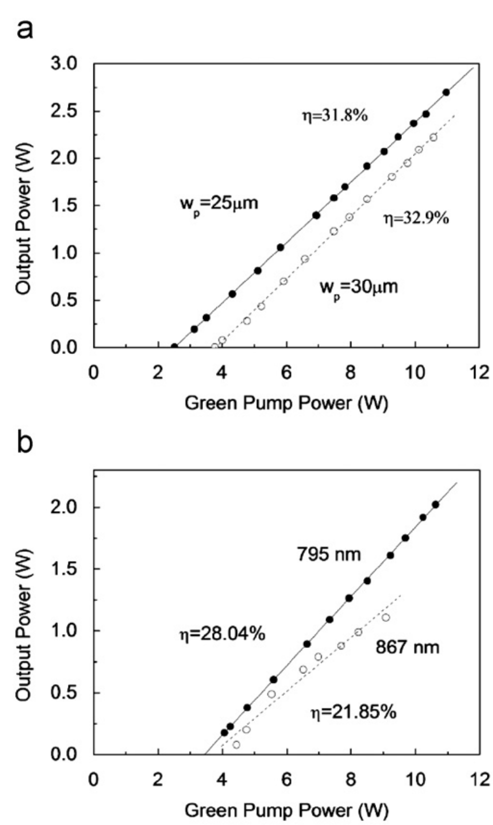

Fig. 4. Variation of the output power of the Ti:sapphire laser with input power (a) for different pump waists and (b) at different wavelengths. Output coupling is 20%. The lines (solid and dashed) show linear fit to experimental data.

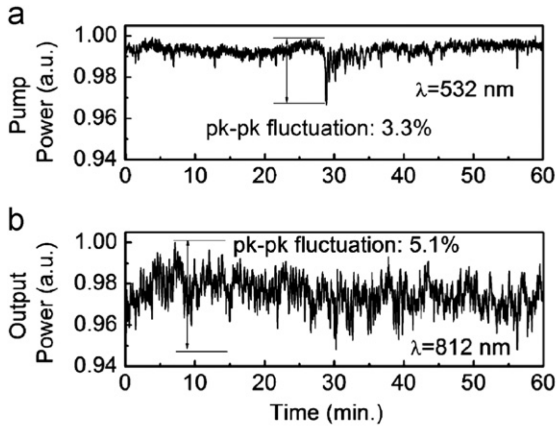

Fig. 5. Time-trace of the (a) frequency-doubled green pump power and (b) Ti:sapphire output power, at 11 W and 2.7 W, respectively, over 1 h. Here, pk–pk fluctuation refers to output power fluctuation from maximum to minimum cw power level about the mean value.

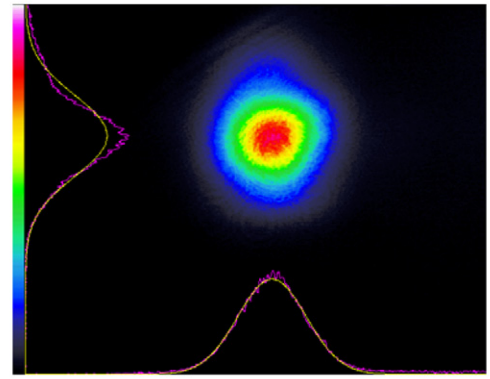

Fig. 6. (Color online) Far-field TEM_{00} energy distribution along with intensity profiles (pink curve) and corresponding Gaussian fits (yellow curves) of the Ti:sapphire output beam at 823 nm.

$>31.8\%$ for a range of focused pump beam waists from 25 μm to 30 μm. Further enhancement in output power is also expected by tighter pump focusing. Using the BRF, we also investigated power scaling of the Ti:sapphire laser at two different wavelengths of 795 nm (closed circle) and 867 nm (open circle) for the same pump beam waist of 30 μm, as shown in Fig. 4(b). At 795 nm, the laser has a threshold of 3.33 W and generates an output power as high as 2.02 W with a slope efficiency of 28%. On the other hand, at 867 nm we have a maximum output power of 1.1 W, a slope efficiency of 21.8%, and higher threshold of 4 W, due to gain reduction in the Ti:sapphire crystal away from the emission peak at 795 nm [1].

3.4. Power stability

We also recorded the power stability of the green pump laser and the Ti:sapphire laser at the maximum output power of 11 W and 2.7 W, respectively, with the results shown in Fig. 5. The power stability is expressed in terms of peak-to-peak (pk-pk) fluctuation, which is the variation in the cw output power level from the maximum value to the minimum value divided by the mean value. As evident from Fig. 5(a), without any thermal isolation and control, the green source has a better peak-to-peak power fluctuation ($<3.3\%$ over 60 min) than our previous reports [8,9]. Similarly, Fig. 5(b) shows the corresponding peak-to-peak power fluctuation of the Ti:sapphire laser to be $<5.1\%$ at 812 nm over 60 min. It is to be noted that the ordinate of Fig. 5 does not start from zero. The relatively higher power fluctuation of the Ti:sapphire laser can be attributed to factors such as thermal effects in Ti:sapphire rod, mechanical instabilities in the present setup, and contributions from the green pump power instability. We expect higher stability through improvements in the green pump power stability, as well as better mechanical and thermal isolation of both the green pump and the Ti:sapphire laser from the laboratory environment.

3.5. Beam quality

The typical far-field energy distribution of the Ti:sapphire laser at 823 nm, together with the intensity profiles (pink curve) and corresponding Gaussian fits (yellow curves) in the two orthogonal directions, measured at a distance >3 m away from the output coupler, is shown in Fig. 6. Although the profile appears to confirm a Gaussian distribution with an ellipticity $>88\%$, using a focusing lens ($f=25$ cm) and scanning beam profiler we measured the M^2-values of the output beam at two different output powers obtained with two different output couplers, OC1 and OC3, to confirm the TEM_{00} spatial mode. For OC1, the M^2-values of the output beam at >200 mW power at 823 are measured as $M_x^2<1.27$ and $M_y^2<1.21$, while for OC3, the M^2-values of the output beam at 2.02 W power at 795 nm are measured as $M_x^2<1.3$ and $M_y^2<1.44$, thus confirming the TEM_{00} spatial mode. Considering the accuracy ($\pm 5\%$) of the M^2-measurement system, the Ti:sapphire output beam has almost similar M^2-values at different power levels throughout the tuning range. Although the laser output has slightly higher M^2-value than the diffraction limit, the beam quality can be further improved using proper thermal management of the Ti:sapphire rod with efficient water cooling.

4. Conclusions

In conclusion, we have demonstrated the first operation of a Ti:sapphire laser pumped by a cw fiber laser green source. We have achieved cw laser output over a wide tuning range (227 nm) across 743–970 nm. A maximum output power of 2.7 W and a slope efficiency as high as 32.8% have been obtained at 812 nm, with optimized output coupling of 20%. The Ti:sapphire laser output exhibits TEM_{00} spatial quality ($M_x^2<1.3$ and $M_y^2<1.44$), with a power fluctuation below 5.1%, which can be further improved by enhancing the power stability of the green source with mechanical and thermal isolation. The overall performance of the device is competitive with the well-established Ti:sapphire lasers pumped by diode-pumped solid-state lasers at 532 nm, confirming the practical viability of fiber-laser-pumping, while greatly reducing system complexity and cost together with the advantages of air-cooling and flexible packaging. Further enhancement in the output power and wavelength tuning to cover the entire emission spectrum of the Ti:sapphire are possible using more efficient cooling of the Ti:sapphire crystal, tighter pump focusing, and optimized broadband mirrors.

Acknowledgments

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