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Green-diode-pumped femtosecond Ti:Sapphire laser with up to 450 mW average power

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Abstract: We investigate power-scaling of green-diode-pumped Ti:Sapphire lasers in continuous-wave (CW) and mode-locked operation. In a first configuration with a total pump power of up to 2 W incident onto the crystal, we achieved a CW power of up to 440 mW and self-starting mode-locking with up to 200 mW average power in 68-fs pulses using semiconductor saturable absorber mirror (SESAM) as saturable absorber. In a second configuration with up to 3 W of pump power incident onto the crystal, we achieved up to 650 mW in CW operation and up to 450 mW in 58-fs pulses using Kerr-lens mode-locking (KLM). The shortest pulse duration was 39 fs, which was achieved at 350 mW average power using KLM. The mode-locked laser generates a pulse train at repetition rates around 400 MHz. No complex cooling system is required: neither the SESAM nor the Ti:Sapphire crystal is actively cooled, only air cooling is applied to the pump diodes using a small fan. Because of mass production for laser displays, we expect that prices for green laser diodes will become very favorable in the near future, opening the door for low-cost Ti:Sapphire lasers. This will be highly attractive for potential mass applications such as biomedical imaging and sensing.

OCIS codes: (140.7090) Ultrafast lasers; (140.4050) Mode-locked lasers; (140.3590) Lasers, titanium.

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1. Introduction

Thirty years after their invention, Ti:Sapphire lasers remain widely used in industry and research [1]. Their broad gain bandwidth ranging between 650 nm and 1100 nm make them the most popular choice for widely tunable laser sources both for continuous wave (CW) and pulsed operation [2]. The unique properties of this gain material enabled laser systems for a multitude of applications, such as biomedical imaging, microscopy, optical coherence tomography, spectroscopy, remote sensing and many more [3–7]. The large gain bandwidth is particularly attractive for ultrashort pulse generation. Ti:Sapphire can achieve shorter pulses than any other laser gain material, and Ti:Sapphire amplifiers are currently the most widely used laser technology for strong-field science and attosecond pulse generation [8,9].

The relatively high thermal conductivity of the Ti:Sapphire crystal enables high power levels without strong thermal aberrations. However, the saturation power of a Ti:Sapphire laser is relatively high due to its short upper state lifetime [2]. This requires high pump brightness for efficient laser operation. Pumping in the blue-green spectral region is mandatory, which was initially done by Ar:ion lasers and frequency-doubled diode-pumped solid-state lasers (DPSSLs), and in the last years also by frequency-doubled vertical external-cavity surface-emitting lasers (VECSELs) [10]. These pump lasers impose a high complexity of the overall system, leading to a lower efficiency than for typical DPSSLs and therefore to higher costs. Furthermore, an important number of applications rely on stabilization of the carrier-envelope offset (CEO) frequency via fast modulation of the pump power. In the most traditional pumping schemes for Ti:Sapphire lasers, an additional acousto-optical modulator is often required for sufficiently fast control of the pump power [11]. Moreover, the need for versatile and compact frequency comb sources have put Ti:Sapphire lasers in competition with emerging low-cost fiber lasers [12].

Recent developments in indium gallium nitride (InGaN) high-power laser diodes [13] can facilitate the development of simple cost-efficient diode-pumped Ti:Sapphire lasers. Comparisons of previous results with diode-pumped CW and mode-locked Ti:Sapphire lasers are shown in Tables 1 and 2. The first breakthrough was achieved in 2009, when Roth et al. demonstrated the directly diode-pumped CW Ti:Sapphire laser achieving 19 mW [14]. Followed in 2012 by a second breakthrough with the demonstration of the first mode-locking experiment showing 13 mW of average power and 142-fs pulse duration using a SESAM [15]. Initially, a pump wavelength of 452 nm was used, which led to a slow deterioration of the output power due to a pump-induced loss mechanism as the authors have reported [14,15]. Furthermore, the relatively low pump absorption cross-section in the blue region made efficient laser operation challenging in this first experiment. In a following experiment, the same authors demonstrated 101 mW of average output power with 111-fs pulse duration by adding a second pump, with a total pump power of 2 W [16]. In 2012, Durfee et al. achieved KLM of a Ti:Sapphire DPSSL with 15-fs pulses at 34 mW average power using 2 W of pump at 445 nm [17]. However, in contrast to Roth et al., they did not observe any pump-induced loss in their laser. The highest output power of an ultrafast Ti:Sapphire DPSSL demonstrated so far was 105 mW in 50-fs pulses, which required two 445-nm pump diodes with a total power of 4 W [18].

Table 1. Comparison of CW Ti:Sapphire DPSSL Performances

Author	*Pump Power*	*Pump Wavelength*	*Average Power*	*Optical Efficiency*
Roth et al. [16]	2 x 1 W	452/454 nm	159 mW	8.0%
Tanaka et al. [21]	2 x 1 W	518/520 nm	92 mW	4.6%
This work	**2 x 1.5 W**	**520 nm**	**650 mW**	**21.6%**

Table 2. Comparison of Mode-Locked Ti:Sapphire DPSSL Performances

Author	*Pump Power*	*Pump Wavelength*	*Saturable Absorber*	*Average Power*	*Pulse Duration*	*Repetition Rate*	*Optical Efficiency*
Durfee et al. [17]	2 x 1 W	445 nm	KLM	34 mW	15 fs	-	1.7%
Roth et al. [15]	2 x 1 W	452/454 nm	SESAM	101 mW	111 fs	127 MHz	5.1%
Young et al. [18]	2 x 2 W	445 nm	KLM	105 mW 70 mW	50 fs 15 fs	100 MHz	2.6% 1.8%
Sawai et al. [20]	1 x 1 W	518 nm	SESAM	23.5 mW	62 fs	92 MHz	2.4%
Tanaka et al. [21]	2 x 1 W	518/520 nm	SESAM	44.8 mW	74 fs	-	2.2%
This work	**2 x 1 W**	**520 nm**	**SESAM**	**200 mW**	**68 fs**	**379 MHz**	**10.0%**
	2 x 1.5 W		**KLM**	**350 mW**	**39 fs**	**414 MHz**	**11.7%**
				450 mW	**58 fs**	**418 MHz**	**15.0%**

The second breakthrough towards simpler, more cost-efficient Ti:Sapphire sources was recently enabled by the first high power green laser diode providing 1 W of optical power at 525 nm, which was fabricated by Nichia Inc [19]. The demonstration of the first directly green-pumped Ti:Sapphire DPSSL followed: Sawai et al. achieved 23.5 mW of average power in 62-fs pulses using a 1-W laser diode at 520 nm, and a SESAM for mode-locking [20], corresponding to an optical-to-optical efficiency of <2.5%. The same group later improved this result to 44.8 mW using two 1-W laser diodes [21]. However, in these first proof-of-principle experiments, the power level was too low for many applications, and it remained unclear whether other limiting factors were hindering more efficient ultrafast Ti:Sapphire DPSSLs.

Here, we report on a green-diode-pumped ultrafast Ti:Sapphire laser, generating up to 450 mW of average power at a repetition rate of 418 MHz with 58-fs pulses that is four times higher average power compared to any previously published diode-pumped Ti:Sapphire laser. The simple, compact, and cost-efficient setup makes these lasers highly attractive for applications, for which the previous ultrafast Ti:Sapphire technology has so far been too complex and expensive. The six-fold improvement in optical-to-optical efficiency compared to previous results obtained with green-diode pumping [20,21] indicates that air-cooling and battery-driven operation can also be easily realized. Therefore, our results show that green diode-pumped Ti:Sapphire lasers are an outstanding solution for more compact and cost-efficient ultrafast Ti:Sapphire laser systems.

2. Experiment

We used two pump laser diodes (model NDG7475 from Nichia Inc.) each delivering up to 1 W of output power at a wavelength of 520 nm when nominally driven at a current of 1.5 A in a counter-pumping scheme. The diodes were placed in small, simple, compact, and air-cooled copper heat sink housings. Optionally the diodes were operated at a current of 2.5 A that is higher than the specified standard operating condition in order to achieve around 1.5 W output power. However, we did not observe any sign of degradation over >100 hours of operation.

The M^2 of the two pump beams was measured to be 2.7 x 5.5 and 2.2 x 5.4, in the fast and slow axes, respectively. Each pump output was collimated using a lens with a focal length of 4 mm [Fig. 1]. In the first laser configuration, the pump beams were directed through a half-wave plate and a polarizing beam splitter for variable power adjustment onto the crystal. This arrangement was only used in the SESAM mode-locked configuration of the laser as shown in Fig. 1(c). Each collimated beam width was enlarged in the slow axis using a set of cylindrical lenses with focal lengths of 15 mm and 100 mm, respectively. The beams were then focused into the gain crystal using 75 mm focal length lenses, followed by the pump mirrors that have an effective focal length of about −100 mm [Fig. 1]. The total pump power incident onto the crystal was 2 W in this configuration. In the second configuration, which resulted in the highest CW power levels and which was the basis for the KLM results, no variable attenuator was used and the pump diodes were slightly overdriven to achieve a total pump power incident onto the crystal of 3 W. The design of the pump spot size was similar in both configurations. The pump beam profile was measured using a beam profile camera (Dataray Bladecam XHR) and corresponds to a waist radius of 24 µm x 50 µm in the Ti:Sapphire crystal.

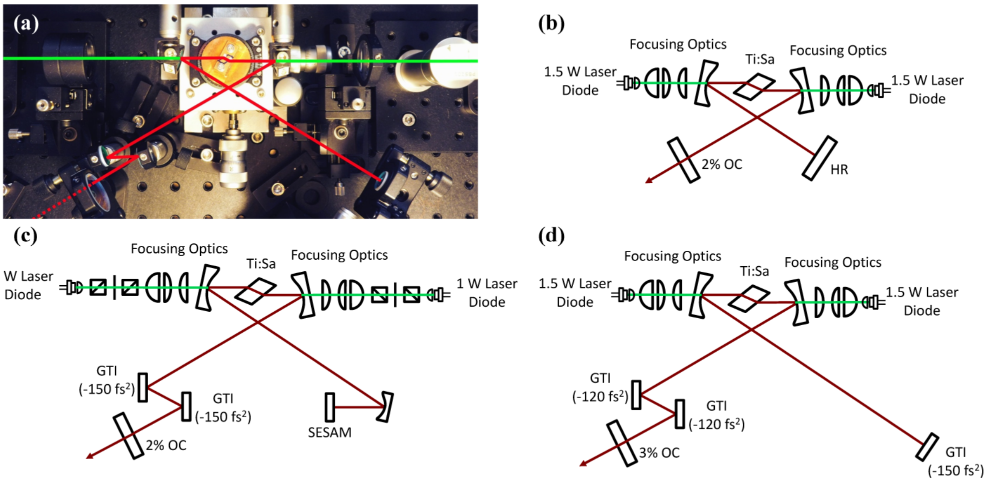

Fig. 1. (a) Cavity picture with pump beam drawn in green and the oscillating laser beam in red. Laser setup for (b) CW, (c) SESAM mode-locked operation, (d) KLM operation.

We used a 4 mm long Brewster-cut Ti:Sapphire crystal (Roditi Ltd.) with 0.25% doping, 4.1 cm^{-1} (± 20%) of small signal pump absorption at 532 nm and figure of merit (FOM) of absorption cross-section ratio at 820 nm to 514 nm of 150. The single pass pump absorption is measured to be 86%. The dichroic pump mirrors have a radius of curvature (ROC) of 50 mm and were placed at 15° with respect to the laser beam and 28 mm away from the beam focus in the crystal. The dispersion due to the crystal was calculated to be 464 fs^2 per cavity round trip. For CW lasing, the cavity was closed at each end with a highly reflective (HR) mirror and an output coupling (OC) mirror with a transmission of 2%, respectively. The two mirrors were placed at a distance of 160 mm [Fig. 1(b)]. In order to achieve soliton pulse formation, we introduced two GTI-type mirrors (Layertec GmbH) in one arm [Fig. 1(c)-1(d)]. The GTI-type mirrors are followed by the 2% OC mirror as one end mirror in the cavity, resulting in an arm length of 160 mm. In the other arm, the beam was focused using a mirror (ROC of 150 mm, tilted by 13°) onto either an HR mirror for CW operation, or onto a SESAM (provided by JDSU Ultrafast Lasers AG) that is optimized for 810 nm with a modulation depth of 1%. The total arm length was 185 mm. For the KLM operation, this arm was shortened to around 140 mm and consisted of only a GTI-type mirror as the end mirror [Fig. 1(c)], mounted on a translation stage for varying the laser spot size in the crystal and initiating mode-locking. The other cavity arm was lengthened to 165 mm. The inserted negative dispersion for the different cavities corresponds to −600 fs^2 for the SESAM mode-locked version and −780 fs^2 and −840 fs^2 for the two KLM configurations, repectively. For KLM, 2% and 3% OC mirrors were used, respectively.

In CW and SESAM mode-locking configurations, the laser mode radii are calculated to be 20 µm x 47 µm and 26 µm x 45 µm in the laser crystal, respectively, and 56 µm x 73 µm on the SESAM.

3. Results

In CW operation [Fig. 1(b)], we achieved 650 mW of output power with 3 W of pump power, resulting in an optical-to-optical efficiency of 22%. The M^2 value of the output beam was measured to be 1.0 x 1.2. In the cavity configuration for SESAM mode-locking [Fig. 1(c)], we achieved stable and self-starting mode-locked operation with an average output power of 200 mW when pumping at 2 W. The pulses were measured with a background-free intensity autocorrelator (Femtochrome FR-103XL). The full-width at half-maximum (FWHM) of the autocorrelation trace was measured to be 105 fs, resulting in a FWHM pulse duration of 68 fs. The optical bandwidth is 15.6 nm FWHM at a center wavelength of 816 nm [Fig. 2(a)-2(b)]. The radio-frequency (RF) spectrum shows a repetition rate of 379 MHz, measured using a fast Si detector (Thorlabs DET025AFC) with a bandwidth of 2 GHz and amplified with a 1.8-GHz bandwidth RF amplifier (RF Bay LNA-1835) [Fig. 2(c)]. The output beam has a circular beam profile with an M^2 value of 1.2 x 1.2.

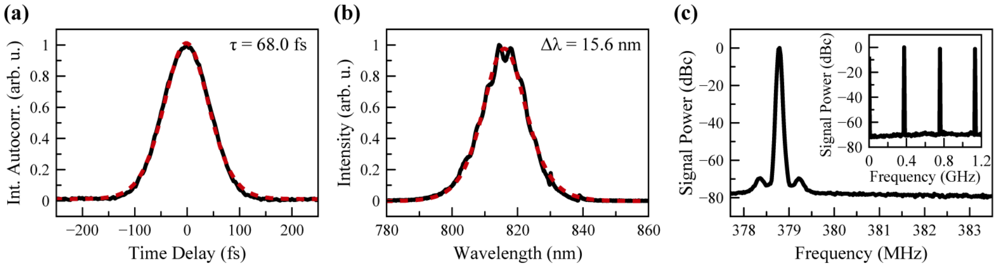

Fig. 2. Results for SESAM mode-locked operation with 200 mW output power for 2 W pump power. (a) Auto-correlation trace (solid, black: measurement; dashed, red: fit to auto-correlation of sech^2). (b) Optical spectrum (solid, blue: measurement; dashed, red: fit to sech^2). (c) RF spectrum around the repetition rate measured with a resolution bandwidth (RBW) of 30 kHz. Inset: enlarged RF spectrum up to 1.2 GHz.

In KLM operation with 2% OC mirror, we achieved an average output power of 350 mW and an optical bandwidth of 20 nm at a repetition rate of 414 MHz [Fig. 3(b)-3(c)]. The RF spectra are measured using a fast Si detector (Thorlabs DET025AFC) with a bandwidth of 2 GHz and amplified with a 1-GHz bandwidth RF amplifier (Mini-Circuits ZFL-1000LN +). We compensated the dispersion of the OC substrate and the collimating lens by 4 extra-cavity reflections on GTI-type mirrors. The measurement of the autocorrelation fits well to a 39-fs sech^2-pulse [Fig. 3(a)]. Using 3% OC mirror we obtained 450 mW of average power in 58 fs pulses at a repetition rate of 418 MHz [Fig. 4], corresponding to an optical-to-optical efficiency of 15%.

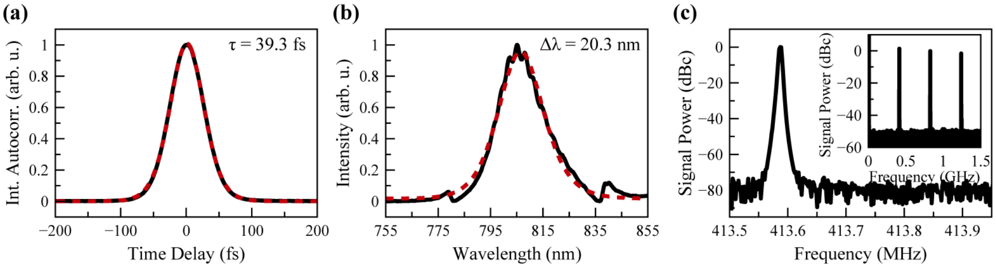

Fig. 3. Results for KLM operation with 350 mW output power for 3 W pump power. (a) Auto-correlation trace (solid, black: measurement; dashed, red: fit to auto-correlation of sech^2). (b) Optical spectrum (solid, black: measurement; dashed, red: fit to sech^2). (c) RF spectrum around the repetition rate measured with an RBW of 3 kHz. Inset: enlarged RF spectrum up to 1.5 GHz.

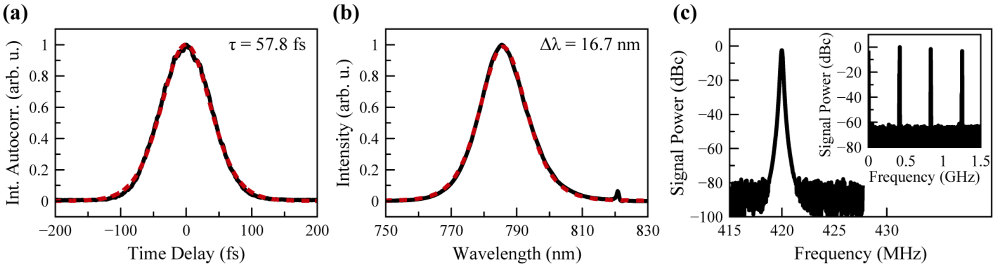

Fig. 4. Results for KLM operation with 450 mW output power for 3 W pump power. (a) Auto-correlation trace (solid, black: measurement; dashed, red: fit to auto-correlation of sech2). (b) Optical spectrum (solid, black: measurement; dashed, red: fit to sech2). (c) RF spectrum around the repetition rate measured with an RBW of 30 kHz. Inset: enlarged RF spectrum up to 1.5 GHz.

4. Conclusion

We demonstrated the highest power from any diode-pumped Ti:Sapphire solid-state laser, achieving 650 mW power in CW and 450 mW of average power in mode-locked operation with 58 fs pulses. Our results clearly show that Ti:Sapphire DPSSLs can efficiently operate at the current state of InGaN laser diode technology. The current configuration with two pumps can be further improved by using more pump diodes in a parallel co-pumping configuration to significantly increase the power levels for compact ultrafast Ti:Sapphire lasers. We expect that low cost, compact, air-cooled Ti:Sapphire lasers will soon be available for applications, both operating in the CW and ultrafast regimes. An interesting advantage for ultrafast oscillators will be the possibility for CEO stabilization in a simple way, either by direct pump current modulation or SESAM opto-optical modulation [22].