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Ultrafast diode-pumped Ti:sapphire laser with broad tunability

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Abstract: We report a broadly wavelength-tunable femtosecond diode-pumped Ti:sapphire laser, passively mode-locked using both semiconductor saturable absorber mirror (SESAM) and Kerr-lens mode-locking (KLM) techniques. Using two pump laser diodes (operating at 450 nm), an average output power as high as 433 mW is generated during mode-locking with the SESAM. A tunability range of 37 nm (788-825 nm) was achieved with the shortest pulse duration of 62 fs at 812 nm. In the KLM regime, an average output power as high as 382 mW, pulses as short as 54 fs, and a tunability of 120 nm (755-875 nm) are demonstrated.

OCIS codes: (320.7090) Ultrafast lasers; (140.4050) Mode-locked lasers; (140.3480) Lasers, diode-pumped.

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1. Introduction

Over the past few decades Ti:sapphire lasers have become an invaluable tool covering a wide range of applications ranging from the industrial to applied and fundamental research [1–4]. This is primarily due to the unique properties of the gain medium, which offers unrivalled bandwidth [5] allowing for ultra-broad wavelength tunability and femtosecond pulse generation at pulse energies and average powers suitable for many applications [6]. However, typical Ti:sapphire laser systems remain relatively expensive with a large footprint, which limits their wider use. This is mainly due to the pump source, which is typically a relatively complex and expensive diode-pumped solid state laser (DPSSL) or optically-pumped semiconductor laser (OPSL). Therefore, an attractive solution would be to replace such pump options with a laser diode, bringing simultaneous reductions in size, cost and complexity, whilst also increasing overall system efficiency.

Until recently, direct diode pumping of Ti:sapphire was not a viable option, as the high intrinsic threshold and the presence of parasitic losses at higher doping concentrations dictated the use of a high brightness pump source with diffraction-limited beam quality. However, due to advances in GaN laser diodes emitting in the blue region of the spectrum (~420-450 nm), developed initially for the laser projector industry, the first continuous-wave, direct diode-pumped Ti:sapphire was demonstrated in 2009 by Roth et al. [7]. Building upon these results, they then successfully realized mode-locking using a SESAM device, generating 114 fs pulses with 13 mW of average output power [8]. The first demonstration of KLM in a diode-pumped Ti:sapphire laser was carried out by Durfee et al. in 2012 [9]. Using two 445 nm laser diodes of 1.2 W each, 15 fs pulses were produced with 34 mW of average output power. Further development of such a system resulted in the first demonstration of multiphoton imaging with a diode-pumped Ti:sapphire laser [10].

In more recent years the performance levels of GaN laser diodes have seen dramatic improvements. Laser diodes producing up to 5 W of output power are now commercially available in the 450 nm spectral region, while laser diodes with up to 1 W of output power at 518-525 nm are demonstrated as well. The first demonstration of a green diode-pumped Ti:sapphire laser was carried out by Sawai et al. using a 518 nm diode with 1 W of output power [11]. This SESAM-mode-locked Ti:sapphire laser produced 62 fs pulses with 23.5 mW of average output power. Using two 520 nm diodes delivering 1.5 W of output power each, a KLM Ti:sapphire laser producing 58 fs pulses with 450 mW of average output power was demonstrated by Gürel et al., with 39 fs pulses generated at a lower power level [12]. Using a slightly different configuration with a SESAM, they demonstrated 68 fs pulses with an average output power of 200 mW. Further development to this system lead to the first demonstration of a diode-pumped ultrafast Ti:sapphire laser based frequency comb [13]. However, it is important to note that the green laser diodes used in that system were run at current levels higher than specified by the manufacturer, and this is likely to have had a detrimental effect on their lifetime.

Despite the sharp decrease in the absorption coefficient of Ti:sapphire in the blue region of the spectrum and the additional loss associated with pumping at wavelengths below 478 nm (first identified by Roth et al. [7] and further explained by Kannari et al. [14]), a similar performance level has been achieved by Resan et al. from a blue diode-pumped Ti:sapphire laser [15]. Using two 3.5 W laser diodes at 450 nm, they obtained 82 fs pulses with an average output power of 460 mW in a SESAM mode-locked configuration. In a slightly modified cavity configuration, they produced 65 fs pulses at 350 mW of average power. Despite the lower efficiency of this system compared to the green diode pumped one in [12], the blue diodes in this configuration were driven within the manufacturer's limits. A performance summary of the state-of-the-art ultrafast diode-pumped Ti:sapphire lasers is provided in Table 1. It should be noted that all previously demonstrated diode-pumped Ti:sapphire lasers operate at a fixed wavelength, while providing a broad tunability during mode-locking would advance further a range of applications including two-photon microscopy and the development of a broadband sources using optical parametric conversion or supercontinuum generation techniques.

Here we demonstrate, for the first time to our knowledge, a broadly tunable ultrafast Ti:sapphire laser pumped with 450 nm laser diodes. Using a knife edge tuning technique, broad tunability is demonstrated in both SESAM and Kerr-lens mode-locking regimes. In the SESAM mode-locked configuration, tuning from 788 nm to 825 nm was demonstrated with pulses as short as 62 fs and an average output power of up to 433 mW. A tuning range of 120 nm (from 755 nm to 875 nm) was demonstrated in the KLM regime with the pulse duration as short as 54 fs and an average power of up to 382 mW.

Table 1. Comparison of ultrafast diode-pumped Ti:sapphire lasers.

Pump LDs	Pump power, W	ML mechanism	Self-starting	Output power, mW	Pulse duration, fs	Optical-to-optical efficiency, %	Tuning range	Ref.
2 × 445 nm	2 × 1.2	KLM	No	34	15	1.7	-	[9]
2 × 520 nm	2 × 1	SESAM	Yes	200	68	10	-	[12]
	2 × 1.5	KLM	No	450	39	15		
2 × 450 nm	2 × 2.9	SESAM	Yes	460	65	7.9	-	[15]
2 × 450 nm	**2 × 3.5**	**SESAM**	**Yes**	**433**	**62**	**6.6**	**37 nm**	**This work**
		KLM	**No**	**382**	**54**	**5.9**	**120 nm**	

2. Experimental setup and results

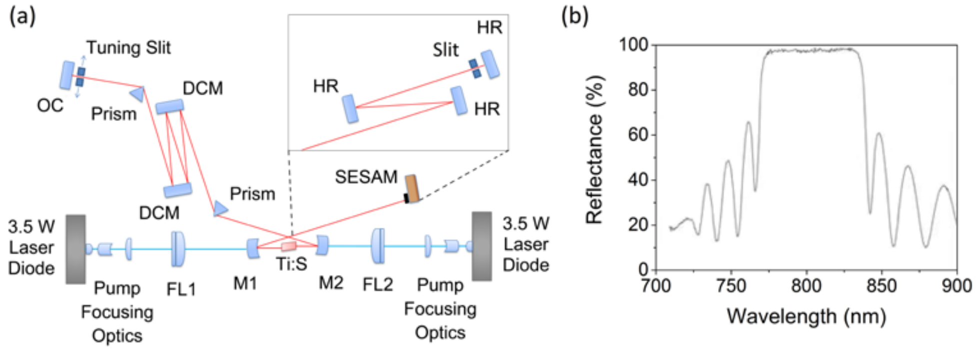

Fig. 1. (a) Schematic of the SESAM mode-locked experimental setup. Inset: modifications to the cavity for KLM operation. (b) The SESAM low signal reflectivity spectrum.

The SESAM mode-locked experimental set-up is depicted in Fig. 1(a). A double-end pumped X-fold resonator consisted of folding mirrors M1 and M2 (placed at a 17° angle of incidence), a fused silica prism pair, a double chirped mirror (DCM) pair, a SESAM and an output coupler (OC). For KLM operation the short arm of the resonator included two additional high reflector (HR) mirrors providing a more compact folded geometry, while another HR mirror was used instead of the SESAM. In addition to this, a hard aperture was introduced to the cavity close to the HR end mirror. M1 and M2 mirrors had radii of curvature of 75 mm and were characterized by a high transmission at 450 nm (>95%) and a high reflectivity between 720 and 940 nm (>99.9%). The OC used for the SESAM mode-locked laser experiments had a 5% transmission around 800 nm. For the KLM laser experiments, the OC used had a transmission of 3% around 800 nm.

The Ti:sapphire gain medium (GT Advanced Technologies) used for the laser experiments is a 4.8 mm long, Brewster-cut rod with a figure of merit (FOM) of 200 and an absorption coefficient of 2.13 cm^{-1} at 450 nm. The crystal was placed in a copper heat sink maintained at a temperature of 22°C and was placed between two curved mirrors where the cavity mode radii were set to be 29 × 13 µm.

Two 3.5 W laser diodes (Nichia Corp.) operating at 450 nm were used as pump sources in a double-end pump configuration. They had an emitter size of 28 × 1 µm and were characterized to have M^2 values of around 9.1 and 1.4 for slow and fast axes, respectively. High numerical aperture aspheric lenses with focal length of 4.51 mm were used first to collimate the output beam in the fast axis direction. A combination of cylindrical lenses (–9.7 mm and 80 mm focal lengths) were used to reshape and collimate the beam in the slow axis direction. Plano-convex achromatic doublet lenses (FL1, FL2) were used to focus the beam into the gain medium. To avoid any feedback effects, slightly different focusing lenses were used (75 mm and 100 mm focal lengths). The pump beam waist radii were measured to be 39 × 13 µm and 29 × 11 µm with the 100 mm and 75 mm lenses, respectively. The Ti:sapphire crystal absorption at 450 nm was measured to be around 64%.

To operate in the CW regime, a HR mirror was inserted into the cavity in place of the SESAM shown in Fig. 1(a). In this configuration we achieved 722 mW of output power with a 5% output coupler and a combined 6.5 W of pump power incident on the crystal. This corresponds to an optical-to-optical efficiency of 11.1%. The pump-induced loss described in [7] and [14] was present in our system, corresponding to up to 15% drop in output power over a timescale of several minutes, after which a steady state value was reached and the output power remained constant.

For the laser experiments with a saturable absorber, a GaAs quantum well based SESAM (Reflekron Ltd.) was used to initiate and stabilize passive mode-locking regime. It was characterized by a low-signal reflectivity of ~97.5% across the 775-840 nm range [Fig. 1(b)], a saturation fluence of 50 $\mu J/cm^2$ and non-saturable losses of <1%. In order to create a second mode waist on the SESAM (85 µm beam radius), the resonator was designed to operate within stability zone II.

To maintain stable soliton mode-locking operation, a fused silica prism pair and a DCM pair were used. With a 50 cm tip-to-tip separation, the prism pair contributed around –677 fs^2 of group delay dispersion (GDD) per cavity round trip at 800 nm. The DCM pair provides an additional –960 fs^2 of GDD per roundtrip based on two bounces per mirror per pass. When the positive GDD from the crystal (556 fs^2 per round trip) is taken into account, this equates to a net cavity GDD of –1087 fs^2 per round trip at 800 nm, which was used to support the soliton mode-locking regime [16,17]. The use of a combination of chirped mirrors and prisms allowed for a relatively compact cavity design and GDD tunability for mode-locking process optimization.

The maximum average output power achieved during stable mode-locked operation with the SESAM was 433 mW (from 6.5 W of incident pump power), resulting in an optical-optical efficiency of 6.6%. The pulse duration at this point was deduced to be 85 fs [Fig. 2(a)] based on the intensity autocorrelation measurements and assuming a $sech^2$ pulse shape. The full width at half maximum (FWHM) of the optical spectrum centered at 812 nm is 8.5 nm [Fig. 2(b)]. This equates to a time-bandwidth product (TBP) of 0.33. The radio frequency (RF) spectrum taken with a fast Si detector with 2 GHz bandwidth [Fig. 3(c)] shows stable pulsed operation with the pulse repetition frequency of around 135 MHz.

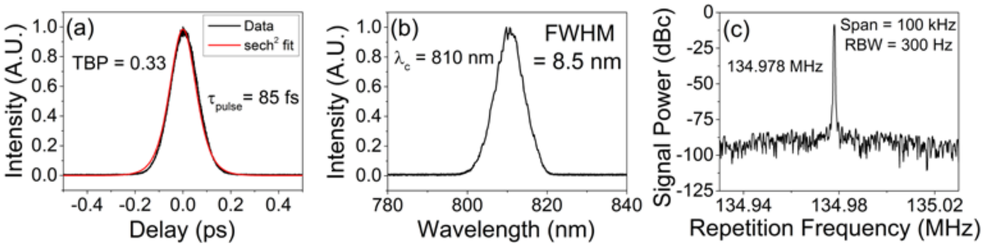

Fig. 2. (a) Intensity autocorrelation and (b) corresponding optical spectrum of the SESAM mode-locked Ti:sapphire laser producing a maximum average output power of 433 mW. (c) Corresponding radio frequency spectrum recorded with 100 kHz frequency span and 300 Hz resolution bandwidth.

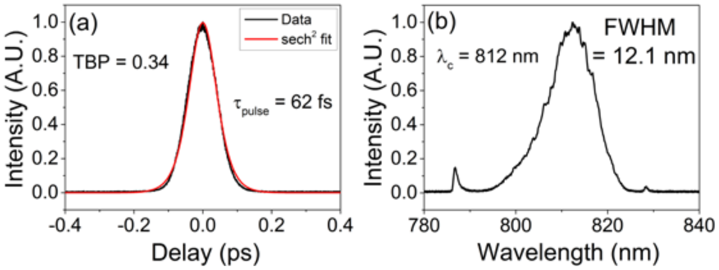

Fig. 3. (a) Intensity autocorrelation and (b) corresponding optical spectrum of the SESAM mode-locked Ti:sapphire laser producing 62 fs pulses.

By further dispersion optimization (increasing the insertion of the second prism by 1-2 mm into the intracavity beam) shorter pulses were generated. Namely, pulses of 62 fs in duration were achieved [Fig. 3(a)] with 12.1 nm FWHM spectral bandwidth [Fig. 3(b)] resulting in a TBP of 0.34. In this configuration the average output power was slightly reduced to 331 mW.

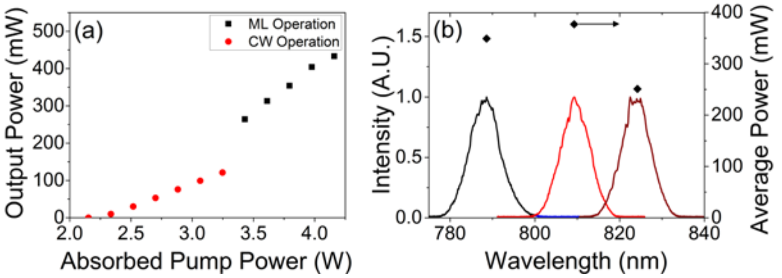

Fig. 4. The input-output characteristics of the SESAM mode-locked Ti:sapphire laser operating at the centre wavelength of 810 nm are shown in (a), while (b) shows the tuning curve of the laser with corresponding average output power.

As shown in Fig. 4(a), the mode-locking threshold was achieved at around 3.4 W of the absorbed pump power when an average output power of 264 mW was generated, resulting in 172 µJ/cm^2 fluence on the SESAM. At the maximum average output power of 433 mW the fluence on the SESAM was 283 µJ/cm^2. Stable mode-locked operation with the pulse durations decreasing from 106 fs to 85 fs was observed within this range of output powers. For the laser tunability, a knife edge slit mounted on a translation stage was placed between the OC and the second fused silica prism where the wavelength components of the beam are spatially dispersed. A maximum tuning range of 788-825 nm was achieved [Fig. 4(b)]. Tuning to 788 nm and adjusting the intracavity dispersion appropriately, 84 fs pulses were obtained with an 8.1 nm FWHM spectral bandwidth (TBP of 0.33) and an average output power 349 mW. 91 fs pulses were generated with the corresponding spectral bandwidth of 7.9

nm (TBP of 0.33) at 825 nm, at an average output power of 251 mW. This represents a 37 nm tuning range with average output powers in excess of 250 mW and sub-100 fs pulse durations. It can be seen that the main limiting factor for tunability here is the reflectivity feature of the SESAM (~775-840 nm). In order to investigate the tunability potential of the ultrafast diode-pumped Ti:sapphire system further, the KLM configuration was applied.

To move to the KLM regime, the separation of the mirrors M1 and M2 was adjusted accordingly to operate near the inner edge of cavity stability region I, the length of short arm in the resonator was extended to 2/3 the length of the long arm for optimal hard aperture mode-locking [18], and the SESAM device was replaced with a high reflector (HR) mirror. A 3% OC was used for all KLM assessments here. KLM regime was initiated by fast translation of one of the cavity folding mirrors.

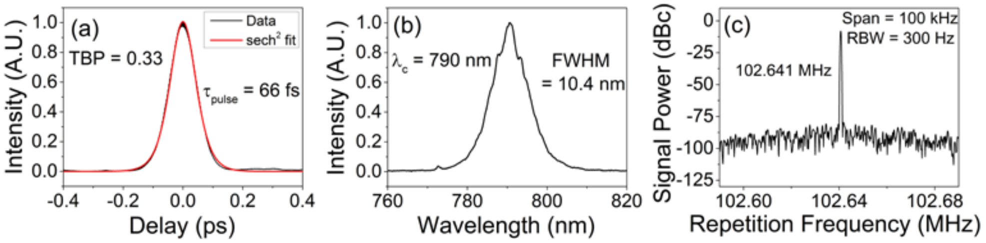

Fig. 5. (a) Intensity autocorrelation and (b) corresponding optical spectrum of the KLM Ti:sapphire laser producing 382 mW of average output power. The RF spectrum recorded with 100 kHz span and 300 Hz resolution bandwidth is shown in (c).

The highest average output power achieved during KLM operation was 382 mW (from 6.5 W incident pump power) resulting in an optical-to-optical efficiency of 5.9%. The generated pulses were measured to be 66 fs in duration [Fig. 5(a)] with the corresponding spectral bandwidth of 10.4 nm at a central wavelength of 790 nm [Fig. 5(b)], resulting in a TBP of 0.33. The RF spectrum shows a pulse repetition frequency of 102.6 MHz [Fig. 5(c)].

A shorter pulse duration of 54 fs was obtained [Fig. 6(a)] when the laser was tuned to a central wavelength of 810 nm. A 15.7 nm FWHM spectral bandwidth [Fig. 6(b)] was recorded resulting in a TBP of 0.39. In this configuration the average output power was 327 mW during stable mode-locked operation.

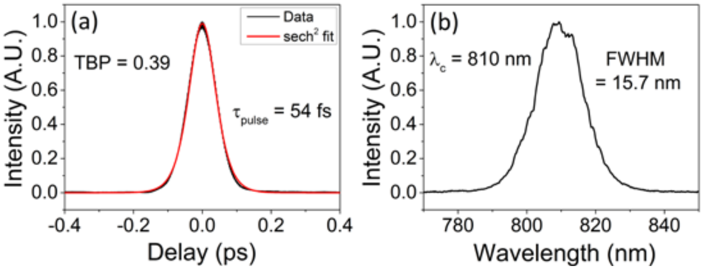

Fig. 6. (a) Intensity autocorrelation and (b) corresponding optical spectrum for the KLM Ti:sapphire laser producing 54 fs pulses.

As shown in Fig. 7(a), the mode-locking threshold was achieved at around 3.4 W of absorbed pump power when the average output power was around 308 mW. Stable operation was observed from around 3.4 W to 4.2 W of absorbed pump power. The laser was wavelength tuned in the same manner as the SESAM mode-locked one. In the KLM configuration the maximum tuning range of 120 nm was achieved (755-875 nm) [Fig. 7(b)]. Average output power was between 164 and 382 mW over this range with the corresponding pulse durations ranged from 54 to 219 fs.

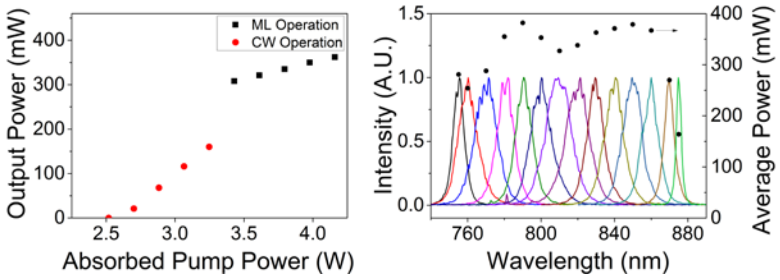

Fig. 7. (a) The input-output characteristic of the KLM Ti:sapphire laser operating at the centre wavelength of 800 nm. (b) Tuning curve of the laser with corresponding average output powers.

3. Conclusion

In conclusion, we have demonstrated the first ultrafast diode-pumped Ti:sapphire laser exhibiting a broad tunability. Both SESAM mode-locking and KLM regimes were investigated. The SESAM mode-locked configuration displayed average output powers as high as 433 mW, pulses as short as 62 fs and a tunability of 37 nm (788-825 nm).The KLM configuration produced powers as high as 382 mW, pulses as short as 54 fs and a tunability of 120 nm (755-875 nm).

The degree of tunability demonstrated by the ultrafast diode-pumped Ti:sapphire lasers described in this paper moves diode-pumped Ti:sapphire lasers a step closer to the performance of conventional DPSSL-pumped Ti:sapphire systems, where wide tunability benefits a number of applications. This includes 2-photon microscopy, where the wide tunability of conventional Ti:sapphire systems [19] enables the excitation of any marker, from short wavelength dyes (Indo) to fluorescent probes (eGFP). Additionally, for applications such as supercontinuum generation, where the output of a femtosecond laser is spectrally broadened using a highly nonlinear fiber, a degree of tunability is useful to fine tune the centre wavelength around the zero-dispersion point of the fiber to optimize supercontinuum parameters [20].

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