A Broadly Tunable Ultrafast Diode-Pumped Ti:sapphire Laser

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Abstract: We report a diode-pumped ultrafast Ti:sapphire laser tunable over a 50 nm range. Sub-100 fs pulses are generated at a pulse repetition rate of 139 MHz with a maximum average output power of 430 mW.

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

1. Introduction

During the past few decades Ti:sapphire lasers have found a range of applications in industry, applied and fundamental research primarily due to the unique properties of the gain medium, which allows for ultra-broad wavelength tunability and femtosecond pulse generation at high pulse energies and average powers [1-4]. However, typical ultrafast Ti:sapphire laser systems are relatively expensive and possess a large footprint, mainly due to the solid-state laser pump source, which limits their wider use in many more applications. Therefore, an attractive solution would be to replace this pump with compact and lower cost laser diodes that directly emit in the required wavelength region of ~ 450-550 nm thus reducing the system complexity and increasing overall efficiency.

Previously, direct diode-pumping was not feasible for Ti:sapphire, due to its high intrinsic threshold, low pump absorption and high parasitic losses that require the use of a high-power and high brightness pump source. However, with the advent of new high-power GaN laser diodes operating in the blue region of the spectrum, in 2009 Roth et al. demonstrated the first continuous-wave direct diode pumped Ti:sapphire laser using a 1 W, 452 nm laser diode [5]. It was successfully mode-locked afterwards using a SESAM (semiconductor saturable absorber mirror) device, producing pulse durations as short as 114 fs with an average output power of 13 mW [6].

Since then the performance level of GaN laser diodes have been improved drastically. Laser diodes with up to 3.5 W of output power are now commercially available at around 450 nm, and powers up to 1 W at around 520-525 nm can also be produced. Using two 520 nm diodes with 1.5 W of output power each, Gürel et al. demonstrated a Kerr lens mode-locked Ti:sapphire laser producing 58 fs pulses with 450 mW average output power [7], and pulses as short as 39 fs were generated at a slightly lower power level. Using a SESAM in the same configuration, 68 fs pulses were produced with an average output power of 200 mW. Further development of this system resulted in the first demonstration of a diode-pumped ultrafast Ti:sapphire laser-based frequency comb [8]. However, it should be noted that the high power green laser diodes used in these systems were run at higher than the recommended current levels, likely having detrimental effects to their lifetime.

Despite the sharp decrease in Ti:sapphire absorption in the blue spectral region and additional induced loss associated with pumping at wavelengths below 478 nm [5,9], a similar performance level has been achieved by Resan et al. from a blue diode pumped Ti:sapphire laser [10].They used two 3.5 W, 450 nm laser diodes to obtain 82 fs pulses at a repetition rate of 92 MHz with an average power of 460 mW using a SESAM. In a slightly different cavity configuration, 65 fs pulses with 350 mW average power were produced. Despite the lower optical-to-optical efficiency of this system compared to the green diode pumped one, the blue diodes in this configuration were driven at much more sustainable current level and the maturity of the blue diode technology means they are more likely to scale up in power in the near future.

In this paper 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, a 37 nm tuning range from 788 nm to 825 nm was demonstrated with sub-100 fs pulse durations and average powers in excess of 430 mW. A 50 nm tuning range from 780 nm to 830 nm was demonstrated using 2% output coupling at lower power levels of 130-294 mW.

2. Experimental setup and results

For the laser experiments a 4.8 mm-long, Brewster-cut Ti:sapphire crystal with absorption coefficient of 2.13 cm^{-1} at 450 nm and a figure of merit (FOM) of 200 was used. The crystal was mounted on a copper heat sink maintained

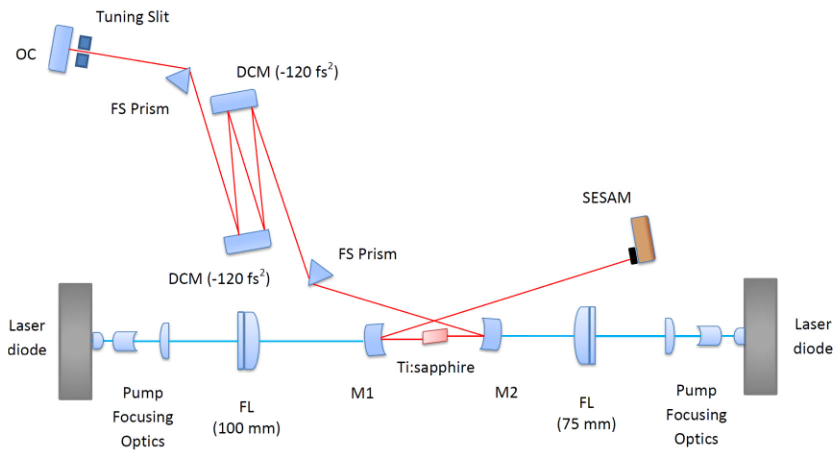

Figure 1. Cavity configuration, where DCM is double chirped mirror, OC is output coupler (either 2% or 5% was used), and M1 and M2 are -75 mm ROC dichroic pump mirrors.

at 22ºC using a thermoelectric cooler. Two 3.5 W, 450 nm laser diodes (Nichia Corp) were used to pump the Ti:sapphire laser in a double-end pump configuration (Fig. 1).

The pump focusing system includes a 4.51 mm focal length aspheric lens with a high numerical aperture to collimate the output along the fast axis, a combination of -9.7 mm and 80 mm focal length cylindrical lenses to reshape the beam in the x-axis, and 75 mm and 100 mm plano-convex achromatic doublet lenses to focus the beam into the gain medium. The M^2 values of the two pump beams were measured to be 9.2, 9.0 and 1.2, 1.6 for the slow and fast axes, respectively. The pump beam waist radii of 39×13 µm for focusing with the 100 mm lens, and 29×11 µm for focusing with the 75 mm lens were measured. The single pass pump absorption of the crystal at 450 nm was measured to be 64%.

An X-fold resonator was configured with two folding mirrors M1 and M2 (full angle of 17º), an output coupler (OC), a double chirped mirror (DCM) pair, a fused silica prism pair and a SESAM. The 75-mm radius of curvature zero lens mirrors M1 and M2 are dichroic mirrors, designed for high transmission at 450 nm (>95%), and high reflectivity between 720-940 nm (>99.9%). The OCs had 5% or 2% transmission at around 800 nm.

The SESAM used for initiation and stabilization of the passive mode-locking process is based on a GaAs quantum well structure (Reflekron Ltd.). It incorporates a distributed Bragg reflector (DBR), and demonstrated a low-signal reflectivity of ~97.5% in the 775-840 nm range. Non-saturable losses of <1% and a saturation fluence of around 50 µJ/cm^2 were estimated. The resonator was designed to operate in stability zone II to create a second mode waist on the SESAM. The cavity mode inside the crystal was 29×13 µm.

To add negative group delay dispersion (GDD) to the cavity for stable soliton modelocking we used a combination of a fused silica prism pair and a double chirped mirror pair. The prism pair had a tip-to-tip separation of 50 cm providing a total of -677 fs^2 of GDD per cavity round trip at 800 nm. For the chirped mirror pair two bounces per mirror per pass were used to give a total GDD of -960 fs^2. The total negative GDD contributed to the cavity was 1637 fs^2, which was used to support soliton mode-locking regime.

When the beam waist radius on the SESAM was set to be 85 µm and a 5% OC was used, stable mode-locked operation was observed at a centre wavelength of 810 nm at a range of absorbed pump power of 3.4-4.2W (Fig 2.(a)). A maximum average output power of 433 mW was observed during mode-locking. The pulse duration at this point was derived from the intensity autocorrelation traces and, assuming a sech^2 pulse intensity profile, was calculated to be 85 fs (Fig. 2(b)). The corresponding optical spectrum was measured to be 8.5 nm (full width at half maximum), which implies a time-bandwidth product of 0.33 (Fig. 2(c)). The repetition frequency of the pulses was 139 MHz resulting in a pulse energy of 3.1 nJ.

Using a knife edge slit, mounted on a translation stage and placed between the output coupler and the second fused silica prism, tunability from 788 nm to 825 nm (Fig 3.(a)) was demonstrated during mode-locking. When tuned to 788 nm and the negative dispersion is adjusted, we obtained 84 fs pulses with an optical bandwidth of 8.1 nm (a time-bandwidth product of 0.33) and an average output power of 349 mW. Transform-limited 91 fs pulses were generated at 825 nm with an average output power of 251 mW. This represents a tuning range of 37 nm with sub-100 fs pulse durations at average powers in excess of 250 mW across the whole range and as high as 433 mW at the maximum.

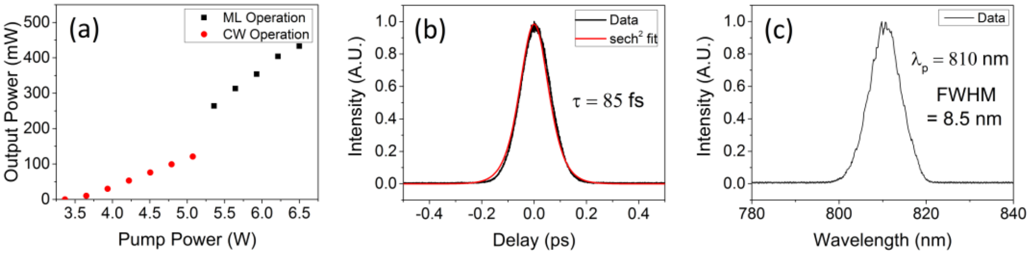

Figure 2. (a) Output power vs incident pump power of a diode-pumped femtosecond Ti:sapphire laser. (b) intensity autocorrelation trace with 5% OC, and (c) corresponding optical spectrum at 810 nm.

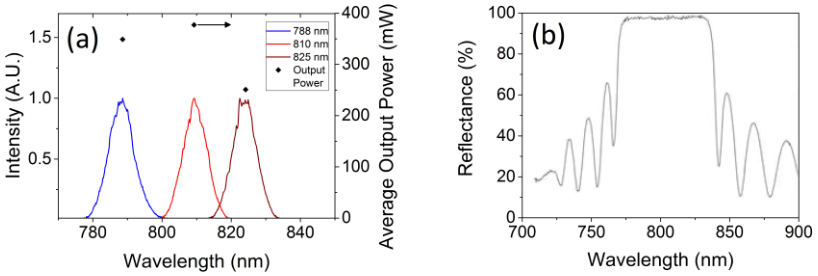

Figure 3. (a) Optical tunability spectra with 5% OC (left axis) and corresponding average output power (right axis). (b) SESAM reflectivity.

Using a 2% OC we obtained 73 fs pulses at a repetition rate of 135 MHz at a centre wavelength of 810 nm and with an average output power of 282 mW. Using a knife edge slit, we were able to tune the laser over 50 nm from 780 nm to 830 nm only adjusting the applied negative dispersion via the second prism insertion. Pulses as short as 166 fs were produced at 780 nm with an average power of 180 mW, and output power of 130 mW was observed when tuned to 830 nm with corresponding pulse durations of 200 fs.

4. Conclusion

In conclusion, an ultrafast diode-pumped Ti:sapphire laser tunable over a range of 50 nm from 780 nm to 830 nm is demonstrated. Sub-100 fs pulses and average powers in excess of 250 mW were produced over the range of about 40 nm, resulting in pulse energies above 1.8 nJ and peak powers of up to 3.6 kW. As we were limited by the SESAM reflectivity range (Fig. 3(b)), the tunability could be further extended with wider bandwidth SESAMs or using alternative mode-locking methods such as graphene saturable absorbers or KLM, making such a system even more suitable for two-photon absorption microscopy applications targeting a wider range of fluorophores currently used.

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