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Frequency-doubled diode laser for direct pumping of Ti:sapphire lasers

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ABSTRACT

A single-pass frequency doubled high-power tapered diode laser emitting nearly 1.3 W of green light suitable for direct pumping of Ti:sapphire lasers generating ultrashort pulses is demonstrated. The pump efficiencies reached 75 % of the values achieved with a commercial solid-state pump laser. However, the superior electro-optical efficiency of the diode laser improves the overall efficiency of the Ti:sapphire laser by a factor > 2. The optical spectrum emitted by the Ti:sapphire laser shows a spectral width of 112 nm (FWHM). Based on autocorrelation measurements, pulse widths of less than 20 fs are measured. These results open the opportunity of establishing diode laser pumped Ti:sapphire lasers for e.g. biophotonic applications like retinal optical coherence tomography or pumping of photonic crystal fibers for CARS microscopy.

Keywords: Diode lasers, Frequency conversion, Optical pumping, Ti:sapphire lasers, Ultrashort pulses

1. INTRODUCTION

The relatively broad emission spectra of Ti:sapphire (Ti:Al_2O_3) lasers ranging between 700 nm and 1100 nm and the resulting capability of generating ultrashort fs laser pulses in mode-locked operation[1] makes them very attractive for several applications within imaging, spectroscopy or materials processing. Due to the absorption spectra of Ti:sapphire laser crystals, showing maximum absorption around 500 nm, mostly frequency doubled solid state lasers are used as pump sources. While providing multiple watts of green light such lasers often increase the dimensions and especially the costs of low-power Ti:sapphire laser systems. This leads to the question whether diode lasers could be a competitive alternative. Diode lasers are the most efficient laser sources emitting several watts of output power. Being based on chip technology, their reduced dimensions highly increase the potential of developing low-cost Ti:sapphire lasers with higher wall-plug efficiencies and smaller footprints. Furthermore, flexibility in emission wavelengths based on different material compositions might be an advantage for the optical pumping compared to lasers based on atomic transitions.

In the context of diode laser pumped Ti:sapphire lasers Resan et al. demonstrated a frequency doubled optically pumped semiconductor laser as a suitable pump source[2]. Based on intracavity frequency doubling of a diode pumped vertical emitting semiconductor gain medium 5 W of green light were generated, resulting in an average output power of 0.5 W from the Ti:sapphire laser. The 105 nm bandwidth (FWHM) corresponded to a pulse duration of 12.6 fs. A more straightforward approach of direct pumping would be the use of direct emitting blue-green emitting diode lasers. Regarding green diode lasers Avramescu et al. demonstrated emitters with 50 mW of continuous wave output power[3]. Unfortunately, thermal roll-over limited the performance and more work needs to be done to achieve output powers around 1 W to overcome the short fluorescence lifetimes and high pump thresholds of Ti:sapphire lasers. Within the blue spectral range, 450 nm GaN based diode lasers with one Watt of pump power are currently available. Direct pumping resulted in 114 fs pulses and average powers up to 13 mW. The limiting factor here has been the short wavelength introducing additional losses not seen for green pump lasers[4].

This leaves the third option of using single-pass frequency doubled high-power edge emitting diode lasers. In this context Sumpf et al. demonstrated 1060 nm distributed Bragg reflector (DBR)-tapered diode lasers emitting nearly

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diffraction limited beams with up to 12 W of output power[5]. Single-pass frequency doubling resulted in 1.58 W of green light[6] enabling competitive direct optical pumping of Ti:sapphire lasers.
Based on earlier results we now present a simple diode laser system directly pumping a Ti:sapphire laser that delivers < 20 fs laser pulses. To classify our results, the same oscillator is pumped with a commercially available DPSS-laser system. In comparison, direct diode laser pumping results in pump efficiencies reduced to about 75 % of the values achieved with the commercial laser. Nevertheless, the overall efficiency is still improved by a factor > 2 due to the superior electro-optical efficiency of the diode laser. Independent of the pump laser the emission spectrum of the Ti:sapphire laser shows a spectral bandwidth of 112 nm resulting in sub-20 fs pulses. These results indicate the great opportunity for single-pass frequency doubled diode lasers as direct pump sources providing similar performances as their solid-state counterparts. Continuing the work in this field increases the potential of diode laser pumped Ti:sapphire lasers to be used in many applications e.g. retinal optical coherence tomography (OCT) or pumping of photonic crystal fibers for CARS (coherent anti-stokes Raman spectroscopy) microscopy.

2. EXPERIMENTAL SETUPS

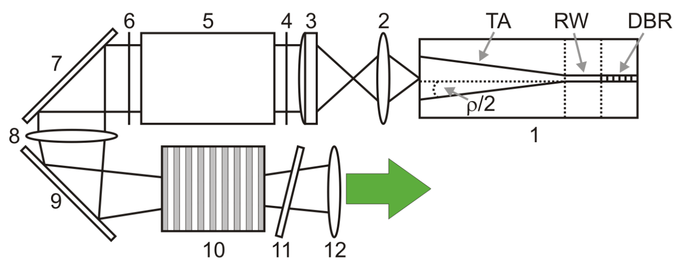

Figure 1. Setup of a single-pass frequency doubled DBR-tapered diode laser.

Figure 1 shows a top-view illustration of our pump laser. The diode laser used within our pump laser is a high-power DBR-tapered diode laser mounted p-side up on a CuW heat spreader on a 25 x 25 mm^2 conduction cooled package (CCP) mount. The laser (1) has a total length of 6 mm and consists of a 1 mm long, un-pumped 6th order surface grating[7], a 1 mm long ridge waveguide (RW) section and a 4 mm long, 6° tapered amplifier. The ridge waveguide and the tapered amplifier have separate contacts through which the injection currents are individually controlled. More information on the growth structure of the laser can be found in earlier publications by Sumpf et al.[8] and Hasler et al.[9], respectively.
The elliptic and divergent beam emitted from the diode is collimated using a pair of an aspheric lens (2, f = 3.1 mm, NA = 0.68) and a cylindrical lens (3, f = 15 mm). The collimated beam has a size of about 2 mm. Both lenses are AR-coated to avoid feedback from the lens surfaces towards the laser. The two lenses furthermore help to compensate the astigmatism of these lasers typically in the range of 1.4 mm. To avoid feedback from successive frequency conversion we use two half-wave plates (4, 6) and a 30 dB optical isolator (5). The first half-wave plate is used to minimize or maximize the light transmitting the isolator. The second one adjusts the polarization as required by the crystal for efficient frequency conversion. One advantage is that the output power available for frequency conversion can be adjusted without changing the injection current to the tapered section. A change of the injection current would affect the astigmatism and would require a re-positioning of the cylindrical lens. The position of the collimation lenses in our setup can therefore be kept constant.
After the optical isolation, two folding mirrors (7, 9) are used to reduce the overall size of the laser. Between the two mirrors a spherical lens (8) with a focal length of f = 100 mm focuses the beam into the nonlinear crystal (10). The beam waist radius is about 60 µm large, which proved to be best in our experiments. To regulate the phase-matching temperature for efficient frequency doubling the crystal is positioned inside an oven. The crystal we selected is a plain cut, periodically poled MgO-doped lithium niobate crystal (*HCPhotonics*). Its poling period is 6.92 µm and the overall dimensions are L x W x H = (30 x 2 x 0.5) mm^3. The crystal facets are AR-coated for both the fundamental and the second harmonic wavelength. The divergent green beam leaving the crystal is separated from the fundamental beam using a mirror (11) highly reflecting at wavelengths around 1060 nm (R > 99.9 %) and transmitting at wavelengths around 530 nm (R < 5 %). After the separation, a spherical lens (12) collimates the green beam. In our experiments, we

use different lenses. One with a focal length of $f = 200$ mm generating a 2.5 mm beam diameter. Another one with a focal length of $f = 160$ mm generating a 2 mm beam.

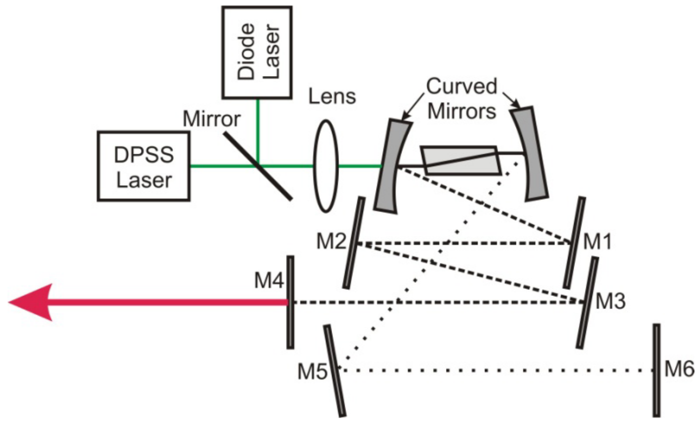

Figure 2. Simple illustration of the x-folded Ti:sapphire oscillator. The Ti:sapphire crystal is placed in between two folding mirrors. The dashed line indicates the light path of the first oscillator arm. The dotted line shows the light path of the second arm.

Figure 2 shows a simple illustration of the x-folded, Kerr-lens mode-locked Ti:sapphire laser oscillator. A similar oscillator has been introduced earlier by Unterhuber et al.[10], being user friendly and offering high stability and reproducibility. An incident green pump beam is focused by a spherical lens ($f = 35$ mm) into the Ti:sapphire crystal positioned between two curved mirrors with a radius of curvature of $R = 50$ mm. The Brewster cut laser crystal has a total length of 3 mm, a figure of merit > 150 and an absorption coefficient $\alpha = 4.5$ cm^{-1}. The beam waist generated by the curved mirrors is about 18 µm large. The length of the cavity is extended to a total length of 1.75 m by several chirped mirrors (M1-M6) also compensating for dispersion. The output coupler (M4) transmits 3 % of laser radiation at each round-trip for further measurements. The oscillator has a repetition rate of approximately 80 MHz and mode-locking is initiated by external perturbations of the end-mirror (M6). In our experiments, the diode pump laser is positioned orthogonal to the commercial laser. An extra mirror positioned outside the oscillator is used to switch between the two pump sources.

3. LASER CHARACTERISATION

As mentioned above, the ridge waveguide and the tapered amplifier section have separate contacts and the injection currents are controlled individually. In our experiments we operate the laser at 300 mA to the ridge-waveguide and 14 A to the tapered amplifier. The maximum output power available for frequency conversion is 8.8 W measured in front of the nonlinear crystal. The generated green beam has a maximum power of 1.28 W, resulting in a conversion efficiency of 14.5 % (Figure 3). The normalized conversion efficiency is calculated with 1.9 %/W, using the following equation[6]:

$$P_{SHG} = P_{Fundamental} \times \tanh^2\left(\sqrt{\eta \times P_{Fundamental}}\right) \tag{1}$$

In this equation, η represents the normalized conversion efficiency, $P_{Fundamental}$ the fundamental pump power and P_{SHG} the power of the generated second harmonic wave. The numeric fit in Figure 3 is in good agreement with our measurements. The electro-optical efficiency of our laser is calculated to be 4 %.

During the second harmonic generation experiments, the crystal temperature is set to 37°C and phasematching is achieved by changing the laser wavelength with the laser temperature. At maximum performance, the laser temperature is set to 17.66°C resulting in a near infrared emission at 1062.45 nm. The green emission is therefore located at 531.22 nm, as shown by the inset of Figure 3. All spectra are measured with a spectrum analyzer (*Advantest Q8347*), showing spectral widths around 6 pm (FWHM). The wavelength stabilisation of the 1 mm long, intrinsic grating of the DBR-tapered diode laser causes single-mode emission. The side-mode suppression is > 25 dB.

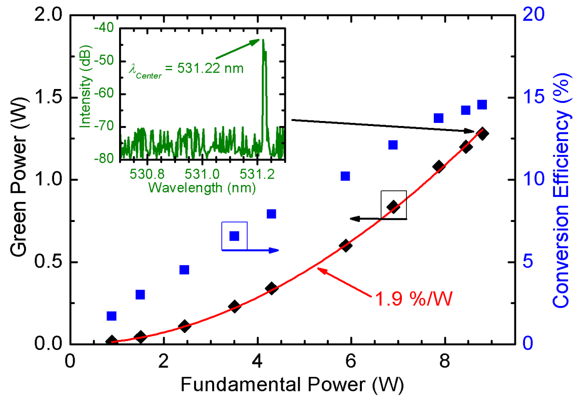

Figure 3. The diamond symbols show the measured output power of the second harmonic wave versus the fundamental pump power. The line represents the numeric fit for the normalized conversion efficiency. The square symbols plot the corresponding conversion efficiencies. The inset of the figure shows the green spectra measured at maximum performance.

To calculate the beam propagation parameters, beam widths in both axes are measured along a generated beam waist (Figure 4) using a beam scanner (*Photon, Inc*). The propagation parameters are calculated with the following equation[11]:

$$d(z) = d_0 \times \sqrt{1 + \left(\frac{M^2 \times (z - z_0)}{z_R} \right)^2} \quad (2)$$

In this equation $d(z)$ is the beam diameter along the beam waist, d_0 is the focus diameter, z_0 is the focus position, z_R is the Rayleigh length and M^2 is the beam propagation parameter. The M^2 values calculated from this relation are 1.3 in the fast axis and 1.4 in the slow axis, both using the $1/e^2$ criteria. The focus profiles in the inset of Figure 4 show some additional structures in the lower wings, possibly reducing the beam quality and affecting the efficiency of the direct pumping.

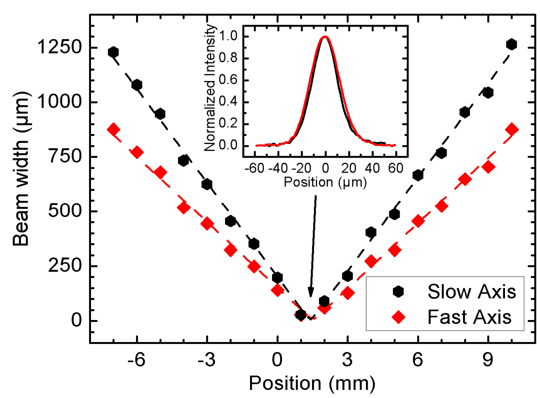

Figure 4. Beam widths along the beam waist for both axes of the focused green beam. The dashed lines show the corresponding numeric fits to calculate the beam propagation parameters. The inset shows the focus profiles in both axes.

The commercial green DPSS laser (*Laser Quantum, Excel Laser*) offers 1.5 W at 532 nm with an electro-optical efficiency below 2 %. The beam diameter is 1.8 mm and the beam propagation parameters are measured with $M^2 < 1.1$.

4. DIRECT OPTICAL PUMPING

Using our diode laser system, a maximum output power of 110 mW (CW) from the Ti:sapphire oscillator is achieved (Figure 5)[12]. Pumping is carried out at 1.2 W, resulting in a pump efficiency of 9.2 %. Switching between two lenses collimating the green beam emitted from the nonlinear crystal in our laser has a negligible effect. For comparison, the maximum output power achieved with the commercial pump source is 180 mW at 1.5 W of pump power. At comparable green light the performance of the Ti:sapphire laser is reduced between 20 mW and 30 mW, using our diode laser. The pump threshold increases from 0.2 W to 0.33 W and the slope efficiency drops from 13.8 % to 12.7 %. However, the measured reduction in pump efficiency (75 % of the values with the DPSS laser) is easily compensated by the superior electro-optical efficiency of the diode laser. The electro-optical efficiency of the whole system is increased by a factor > 2 using our laser.

One possible explanation for the lower pump efficiency is the Ti:Sapphire oscillator itself, being optimized for the commercial laser. Our laser has a slightly higher M^2 and larger beam size and no changes are made to the oscillator when comparing the pump sources. Therefore the overlap between the green beam and the Ti:Sapphire beam is different which can affect the pump efficiency. We would expect to improve the performance by re-optimizing the oscillator or the beam size of our laser. A mismatch of the polarizations between the green laser and the one required by the Ti:sapphire crystal can be neglected in the case of optimum frequency doubling.

Figure 5 furthermore shows that the difference of 20 mW to 30 mW output power also holds in the case of mode-locked operation of the Ti:Sapphire laser. With our diode laser we achieve a maximum of 82 mW at 1.2 W of pump power.

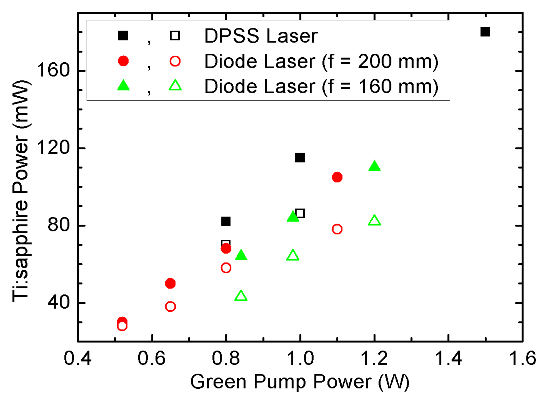

Figure 5. Direct pumping of a Ti:sapphire laser using different pump lasers. Filled symbols indicate CW operation of the Ti:sapphire laser. Open symbols represent mode-locked operation.

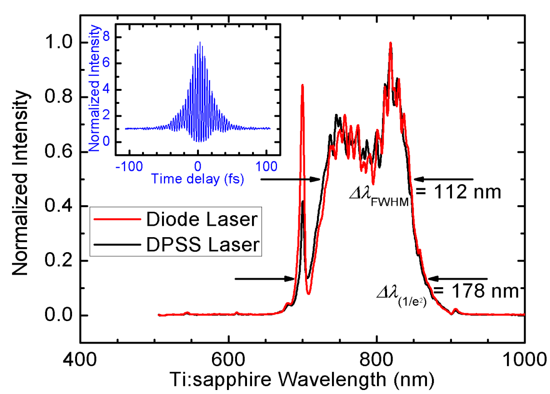

Figure 6. Ti:sapphire laser emission spectra using two different pump lasers. The inset shows an autocorrelation trace measured using the diode laser.

A spectrum of the mode-locked laser is shown in Figure 6. The direct comparison with the commercial pump laser shows a good overlap. The spectral widths are 112 nm (FWHM) resulting in spectral band widths of 54 THz. The $1/e^2$ bandwidth is 178 nm. The corresponding average power of the Ti:sapphire laser is 52 mW (diode laser) and 60 mW (commercial laser) respectively. This power level is already suitable for OCT measurements[10]. The side-peaks at 700 nm are the so-called Kelly sidebands[13], caused by sharp phase changes introduced by the chirped mirrors. Interferometric autocorrelation measurements (inset Figure 6) show that sub 20 fs laser pulses are delivered, matching the general expectation for this oscillator. The autocorrelation trace indicates non transform limited pulses due to slightly imperfect extra-cavity dispersion management. However, these results indicate the high potential for diode laser pumped Ti:sapphire lasers.

5. SUMMARY

A single-pass frequency doubled tapered diode laser system is demonstrated as a pump source for mode-locked Ti:sapphire lasers generating ultrashort laser pulses. Compared to a commercial DPSS laser, deteriorations in output power from the Ti:sapphire laser of up to 25% are measured. This can be explained by a slightly larger M^2 and beam size of our laser, and the oscillator being optimized for the commercial laser. However, the overall efficiency of the Ti:sapphire laser system is still improved by a factor > 2 using our diode laser system.

Based on these results there is a high potential for simple and robust diode laser pump sources for Ti:sapphire lasers in the near future. This could help to reduce dimensions and significantly increase the overall efficiency of ultrafast laser systems while reducing their costs and overall footprints. Improvements in diode laser technologies could even help to increase the performance of green diode laser modules towards the 3-4 W range.

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