



Direct diode-pumped Kerr Lens 13 fs Ti:sapphire ultrafast oscillator using a single blue laser diode

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Abstract: We demonstrate a direct diode-pumped Kerr Lens Modelocked Ti:sapphire laser producing 13 fs pulses with 1.85 nJ energy at 78 MHz (145 mW) using a single laser diode pump. We also present a similar laser using three spectrally combined diodes, generating >300 mW output power with >50 nm bandwidth. We discuss the use of far-from TEM₀₀ pump laser sources, and their effect on the Kerr lens modelocking process.

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OCIS codes: (320.0320) Ultrafast optics; (140.0140) Lasers and laser optics.

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1. Introduction

Commercial Ti:sapphire laser oscillators have in the past employed pump laser sources including Argon Ion, intra-cavity doubled Nd:YVO₄, frequency-doubled optically-pumped semiconductor lasers (OPSLs), and doubled IR laser diodes [1–3]. However, for Kerr-Lens Modelocked femtosecond Ti:sapphire lasers, it was found very early-on that the mode-matching process that sustains KLM is very sensitive to the mode quality of the pump light [4]. For example, degradation of Argon-ion lasers to a “donut” TEM₀₁ + TEM₁₀ mode was observed to greatly degrade the stability of modelocking.

However, recently the development of high power laser diodes in the blue and green region of the spectrum (based on GaN, and InGaN) has made it practical to implement direct diode-pumped Ti:sapphire (DDPTS) [5–10]. Because these pump diodes have far-from-diffraction-limited beam quality, initial work in mode locked DDPTS employed saturable absorber (SESAMs) modelocking rather than KLM [11]. However, recently we successfully demonstrated a KLM Ti:sapphire laser, pumped by multiple single-emitter diodes, and which exhibited surprising modelocking stability and overall efficiency. Subsequent work has proven a wide range of CW, saturable absorber modelocked, and Kerr Lens Modelocked DDPTS configurations [7, 11], including KLM configurations with power as high as 350 mW in 39 fs pulses @414 MHz (0.85 nJ) [8].

The surprising success of the KLM process, even using such relatively poorly-focused pump light, can be explained by the fact that the mode-matching optimization required for good power discrimination for the modelocked mode (i.e. higher power when the laser is modelocked than when running CW) can be obtained when the M² of the pump light is relaxed in *one* dimension of the pump and maintained in the other. A typical 400-532 nm laser diode emits in a stripe with M²~1-1.5 in the fast axis, and M²~3-15 in the slow axis. A relatively tight focus in one dimension still allows for better mode-matching when the laser is running ultrashort-pulse (Patents 8,976,821/9,425,581). Furthermore, the asymmetry of the Kerr lens—the pulse cycles back and forth in the cavity, but is short traveling only in *one* direction—assists with efficient energy extraction.

A long-term degradation in the output power from DDPTS oscillators has been reported by several groups [5, 12]. However, we have never seen this effect in our work. This may be due to our use of high figure of merit crystals (FOM ~400), which is related to the Ti⁴⁺ concentration in the material. This is still under investigation. Our initial work [13] in KLM DDPTS demonstrated 15 fs pulses with 34 mW output, pumped by 2 x 1.4 W, 445 nm diodes in a side-by-side pumping configuration. This configuration, as well as the subsequent work, has not to-date demonstrated the specifications required to reliably seed an ultrafast laser amplifier: sufficient bandwidth (>50 nm) and pulse energy (>1-2 nJ) to generate pulses from an amplifier with duration 20-35 fs limited primarily by gain narrowing, and with a low-enough repetition rate (<100 MHz) to electro-optically select an isolated pulse. This work provides a first such demonstration, in two configurations: the first optimized for overall output power using a configuration of 3 spectrally-combined diodes, and the second demonstrating sufficient performance for amplifier seeding using a simple, *single* diode pumping configuration.

2. Spectrally-combined pumping

Our first demonstration of increased output from a KLM DDPTS laser employs three individual emitters spectrally-combined using sharp-edge dielectric filters by choosing wavelengths of 445 nm, 448 nm, and 451 nm. Each diode is rated for 1.4 W of power, and the M² was measured to be 1.2 in the fast axis and 3.1 in the slow axis. We found that, in practice, these diodes could be significantly overdriven to obtain output power of 2.1-2.5 W each. Many laser diodes were tested above spec, and the highest output power diodes from three spectral ranges were selected for combination.

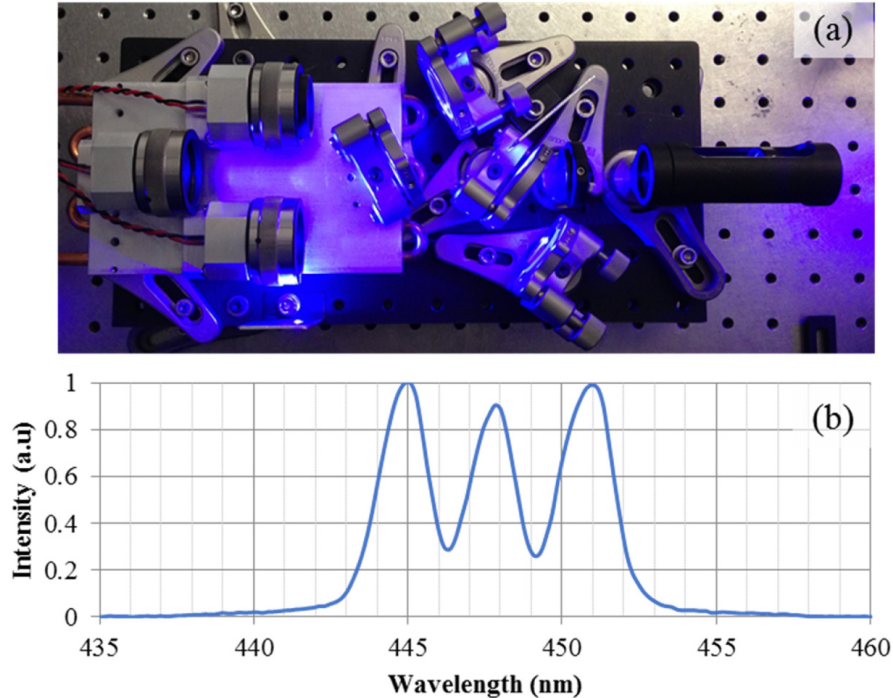


Fig. 1. (a) – picture of setup for spectral beam combination to obtain >6.2 W CW output in a single beam. (b) – spectrum of combined beam.

The single-beam combined pump source generated a total output of greater than 6.2 W CW, with a combining efficiency of 88% [combined spectrum is shown in Fig. 1(b)]. The diode laser stripes were collimated with a fast asphere and a 3x beam expander was used to expand the slow axis relative to the fast axis. The aspect ratio of the pump beam into the lens was approximately 1.5x (slow axis wider than the fast axis). This led to a focal spot ratio of roughly 2:1 in the crystal. M^2 was not measured for the combined beam.

We found that this configuration, when properly aligned, was capable of pumping a standard prism-dispersion-compensated (~ 400 fs² of group velocity dispersion compensation) Ti:sapphire KLM laser oscillator (KMLabs GriffinTM), with output power up to 350 mW in sub-20 fs pulses, and up to 200 mW with bandwidth >130 nm FWHM (shown in Fig. 2 (a)). This laser output is ideal for seeding a regenerative amplifier and has enough pulse energy to seed a multipass amplifier. This laser could have equivalently employed chirped mirror dispersion compensation—this has no material distinction for modelocking operation— but the combination of broad bandwidth and tunability typically allows the prism-dispersion-modelocked laser to be more-easily optimized for the shortest-pulse operation of an ultrafast laser amplifier [14].

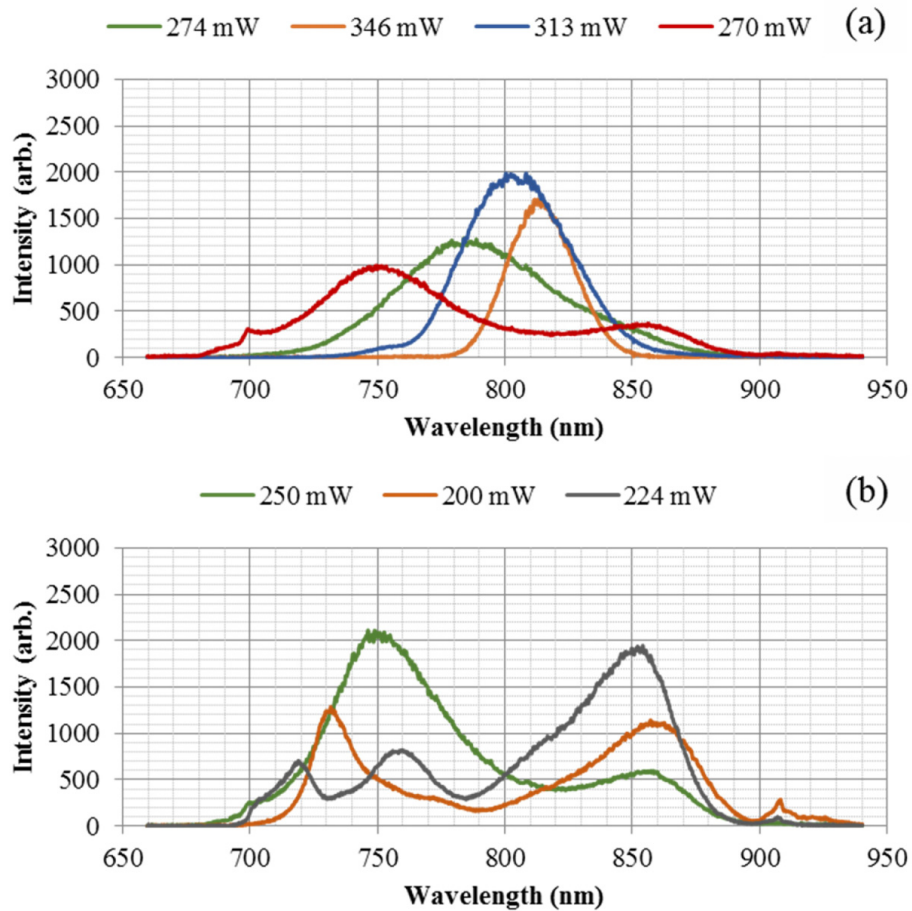


Fig. 2. Kerr-lens modelocked Ti:sapphire oscillator pumped by spectrally-combined single emitter diodes. A variety of output spectra and powers can be obtained by varying the oscillator adjustment. (a) shows the configurations suitable for seeding regenerative and multipass amplifiers, while (b) shows the broader-bandwidth, more structured spectra attainable with this configuration.

Although this laser is essentially a drop-in equivalent to the “standard” modelocked Ti:sapphire laser [4] and is very capable of seeding any ultrafast laser amplifier, the major drawback is that with 3x 1.4 W diodes, it is still necessary to overdrive the emitters. The spectrally-combined pump decayed to less than 6 W power after only 500 hours, and continued decaying beyond that. This is not a practical source for research or commercial use. Attempts to combine more (non-overdriven) emitters resulted in less spectrally-combined power due to the natural linewidth of the diodes and limited spectral variability of the 450 nm diodes. Efforts are ongoing to combine more-broadly spaced 450 nm, 462 nm and 520 nm diodes. The complexity of this approach, however, is not ideal.

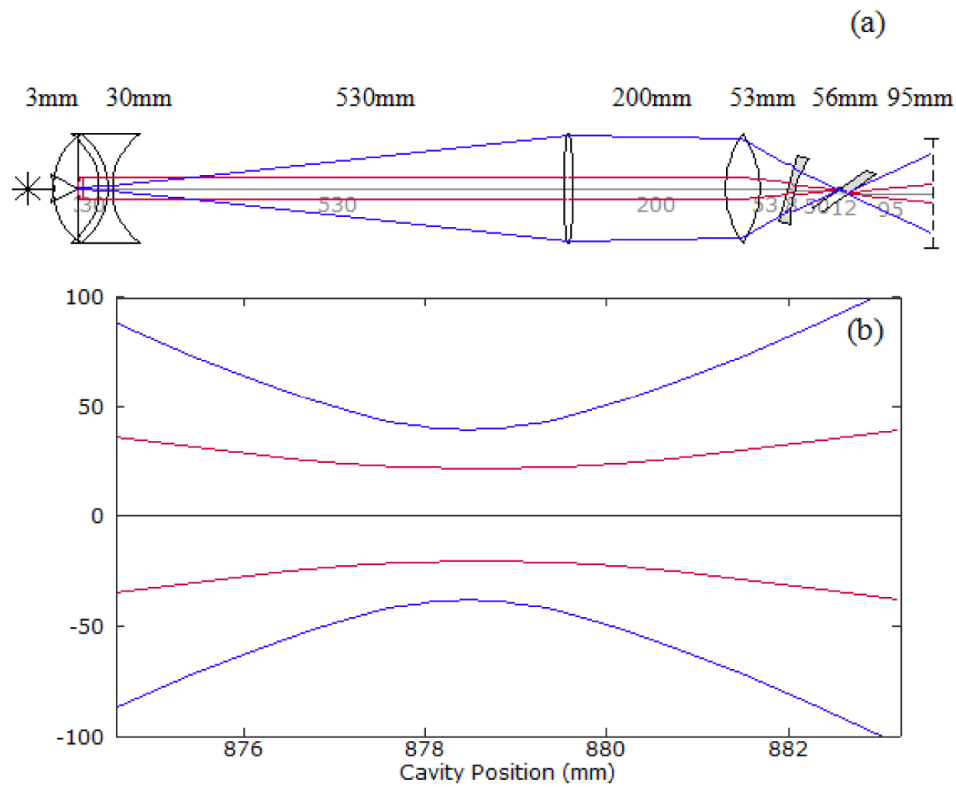


Fig. 3. Beam propagation software output showing the apodization and anamorphic focusing of the single emitter pump laser based on measured M^2 values. (a) full propagation numbers in mm between elements, and where mode size is exaggerated to ease viewing, (b) focus in Ti:sapphire crystal where the Y axis is in μm , and cavity position denotes focal position from source.

3. High power single emitter pumped KML oscillator

More recently, higher power single emitter diodes have become available. We obtained a single 465 nm laser diode rated at 4W, with 10,000 hour rated lifetime. The M^2 was measured as 1.5 in the fast axis, and 12 in the slow axis—nearly 4x worse than the previously-utilized 1.4 W emitters. However, using careful modeling of the source beam propagation, and anamorphic focusing in an effort to apodize the mode at the oscillator crystal, we obtained tight focusing and efficient KLM operation.

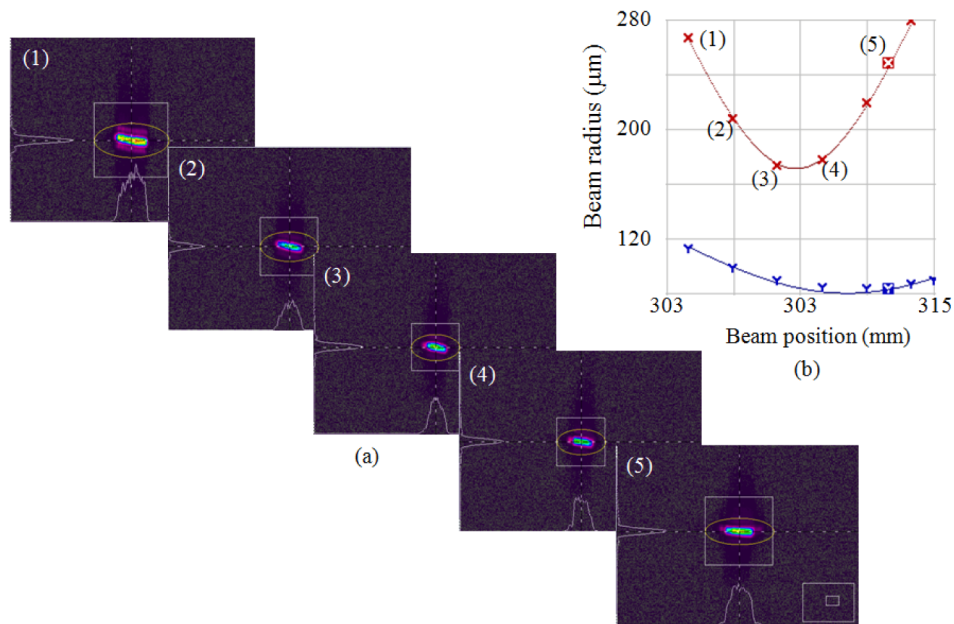


Fig. 4. (a) 465nm pump beam measured after the first three elements of optical system modeled in Fig. 3 (effectively the pump source input to the oscillator), with a 300mm focal length lens to resolve the focus on the camera. Images 1-5 shown used for M^2 calculation. (b) M^2 measurement of the 465nm single emitter laser diode after collimation and cylindrical telescope. Red X are horizontal beam radii, Blue Y are vertical radii, with respect to the optical table. The output beam has an M^2 of 1.5 in the fast (Y) axis, and M^2 of 12 in the slow (X) axis.

A 4 mm aspheric lens is used to collimate the fast axis. A 50 mm cylindrical negative lens is used to expand the slow axis to $\sim 5\times$ the fast axis, then the beam is collimated with a 500 mm cylindrical positive lens producing a 1:5 ratio stripe (longer dimension is the low beam quality slow axis). Using a 105 mm focusing optic and pumping through a 100 mm radius-of-curvature ultrafast mirror (at 8 degrees angle of incidence), we show a predicted Y focal diameter (fast axis) of $\sim 56 \mu\text{m}$, and an X focal diameter (slow axis) of $\sim 102 \mu\text{m}$, shown in Fig. 3.

Figure 4 shows the M^2 and mode at the focus of the pump beam, using a longer (300 mm) focal length than the final lens in the actual laser, to allow us to resolve the focal spot. At the crystal, a focal spot diameter is $\sim 56 \mu\text{m} \times 118 \mu\text{m}$ not accounting for the Brewster angle crystal; this value is close to our simulation. This approximately 2-1 ratio was optimal for maximum power extraction in our 4.75 mm path length crystal. Figure 5 shows a calculation of the absorbed energy density in the crystal, using the measured focal spot sizes and M^2 values and assuming the beam waist is positioned in the center of the crystal.

Using commercial KMLabs Griffin 2 [Fig. 6], we integrated our pump source in the place typically reserved for a standard Nd:YVO₄ pump laser. With 3.1 W of pump from our 465nm diode, 70 percent is absorbed into the 4.75 mm long crystal, depositing 2.17 W of usable power.

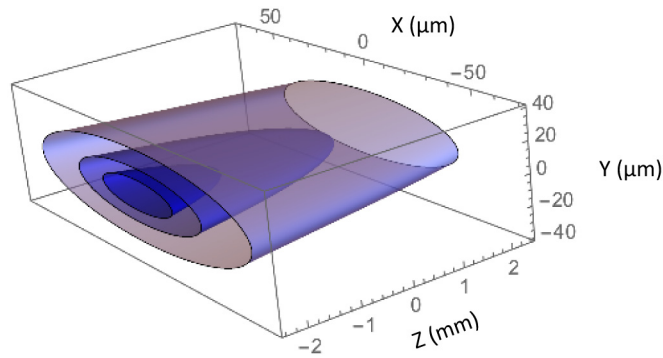


Fig. 5. Calculated absorbed energy density in the Ti:sapphire crystal, based on the measured focal spot dimensions and M^2 values. The contours are at 80%, 50% and 13.5% of peak intensity. The stretching factor that results from the Brewster angle refraction has been backed out in order to illustrate the gain distribution seen by the incoming beam.

In comparison with our past work using 450 nm pumping, the pump absorption for Ti:sapphire is $\sim 1.7\times$ higher. The laser produces 400 mW CW using a 5% output coupler, with a lasing threshold of 1.9 W. To induce KLM, the non-pump through mirror is moved closer to the laser crystal, reducing the CW power to 120 mW.

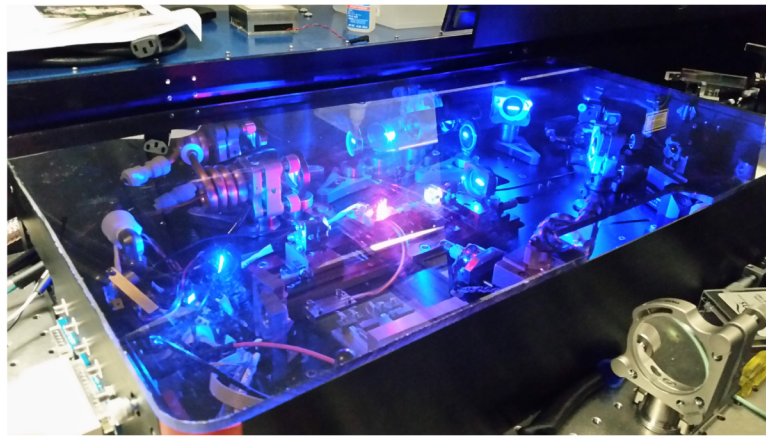


Fig. 6. Single high-power emitter pumped KLM Ti:sapphire oscillator. For a pump power of 3.1W, a Kerr Lens Modelocked output power of 173 mW was attained for an 80 nm FWHM spectrum.

The laser modelocks easily in this position and produces 173 mW of power with >80 nm of FWHM bandwidth. The detected RF pulsetrain was stable and showed no evidence of modelocking instabilities. Similarly, the RF spectrum showed a clean repetition rate tone, indicating complete modelocking. Since the oscillator is a prism based system for dispersion compensation, it is broadly tunable in wavelength and bandwidth. We believe that this is the first demonstration a Kerr Lens Modelocked Ti:sapphire laser pumped with a single diode laser emitter.

The spatial mode quality of the output modelocked beam is excellent with an M^2 of 1.02 in the X, and 1.17 in the Y. Pulses at the broadest bandwidths were measured through FROG (Mesaphotonics Video FROG Scan), and compressed with fused silica prisms separated by 50 cm [7]. Pulses as short as 13.5 fs were obtained at 145 mW of output power, giving ~ 2 nJ of energy, and a peak power of 150 kW per pulse. Long term testing of the output power demonstrated stable operation at 15.2 fs bandwidth, 173mW average power. Running the

diodes at constant current, an 0.33% RMS stability was demonstrated (limited by the power meter resolution of 1 mW) over 600 hours of uninterrupted, untouched operation.

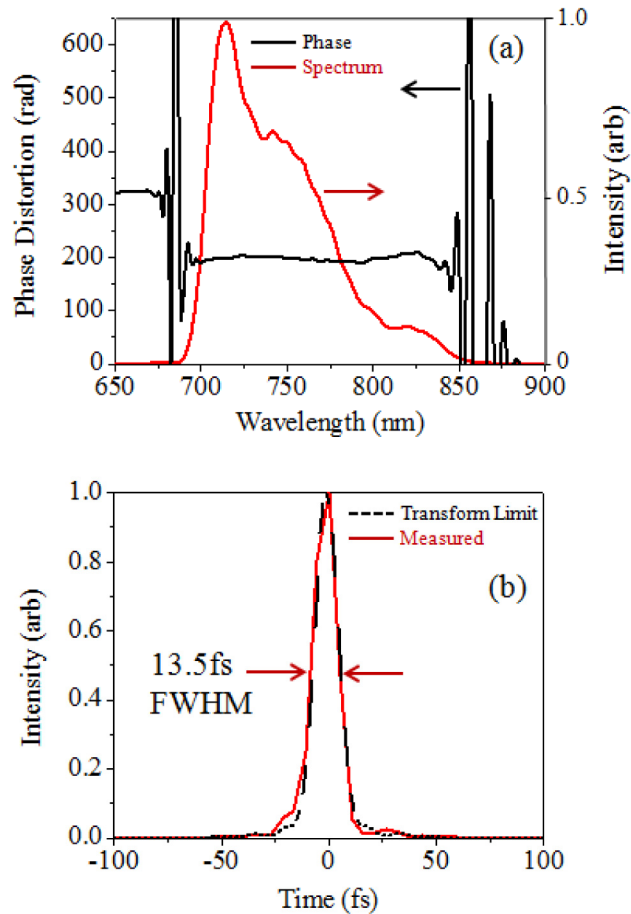


Fig. 7. (a) Output spectrum and phase as measured by FROG (error $G = 0.001$), (b) pulse duration for the compressed 13.5 fs pulses with a pulse energy of approximately 2 nJ and an average power of 140 mW after compression. A fused silica prism pair with 0.5 m separation was used to compress the pulses to near the transform limit.

No special care was taken to clean the laser enclosure or to remove contamination-inducing components, yet no evidence of crystal contamination was seen on this timescale. Typical single-mode green-pumped KLM Ti:sapphire lasers in a similar environment would have shown clear evidence of contamination on this timescale.

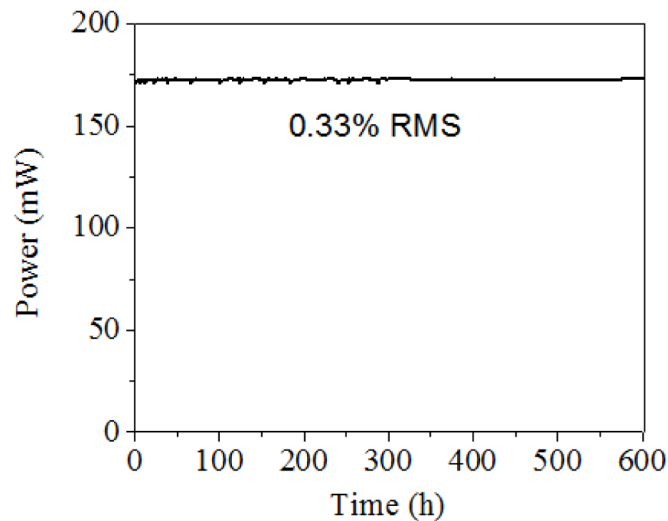


Fig. 8. Power stability of single diode-pumped KLM Ti:sapphire oscillator over 600 h. Diode current was held constant to provide 3.1W output; no power correction on the diode output was implemented. The output from the laser shows measurement-limit 0.33% RMS stability over entire run, indicating that the diode output power at constant current is not degrading significantly on this time scale. Interestingly, contamination of the laser crystal, which is often evident on this timescale using traditional TEM₀₀ green pump lasers does not occur. Data were taken at 1 h intervals for the first 300 h, and at 25 h intervals after.

Possible causes for reduction in contamination is the larger pump spot size on the faces of the laser crystal (leading to reduced optical trapping effects, particularly on the exit face), a difference in the optical trapping efficiency for blue vs green for contaminant molecules, or a difference in the femtochemistry with IR + blue vs IR + green [8].

3. Conclusion and summary

In conclusion, we presented both a high power, multiple-emitter KLM Ti:sapphire oscillator, and the first demonstration of a KLM Ti:sapphire laser oscillator driven by a single 465 nm single emitter laser diode. 15 fs pulses were produced at 173 mW, and 13 fs pulses were produced at 145 mW of average power at a repetition rate of 78 MHz. Such a source is useful for seeding regenerative ultrafast amplifiers. Further work is underway to scale power by multiplexing two high power emitters (spatially or wavelength-multiplexed). It is also likely that single element emitters will continue to increase in output power, potentially leading to an even higher power single-diode ultrafast oscillator.

Funding

Department of Energy (DOE) (DE-SC-0009707).