# Low-threshold sub-10 fs mode-locked Ti:sapphire laser pumped by 488 nm fiber laser



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# Low-threshold sub-10 fs mode-locked Ti:sapphire laser pumped by 488 nm fiber laser

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We demonstrated the first low-threshold mode-locked Ti:sapphire oscillator pumped by a 488 nm fiber laser. Laser pulses as short as 8.2 fs with a bandwidth wider than 400 nm at a repetition rate of 148 MHz were generated under a pump power as low as 504 mW. Using a 0.5% output coupler, we further realized a 280 mW threshold power for mode-locking operation. 

The titanium-doped sapphire (Ti:S) crystal is the most widely used near-infrared gain medium owing to its high thermal conductivity, large stimulated emission section, and broad absorption gain bandwidth. Since the first Kerr lens mode-locked (KLM) laser pulse was generated from a Ti:S laser in 1991 by Spence et al.,[1] the use of various types of pump sources has been attempted to pump a Ti:S laser both in CW and mode-locked operations.[2–6] Among those sources, frequency-doubled all-solid-state lasers at 532 or 515 nm are demonstrated to have the most excellent performance in terms of both spatial beam quality and relative intensity noise (RIN). In 2011, frequency-doubled 532 nm diode lasers were also reported as a pump option for Ti:S crystals.[7] However, for those pump lasers, the wavelengths are not well matched to the Ti:S peak absorption of about 490 nm. The recent 450[8–11] and 518 nm[12] laser diode (LD) pump sources with gallium nitride (GaN) materials combine the advantages of cheap prices and small sizes, which considerably reduce the cost of Ti:S lasers. On the other hand, the small absorption coefficient, weak brightness, and poor beam profile of the LD pump sources restrict the optical-to-optical conversion efficiency and the potential for high power output of Ti:S lasers.[13]

Recently, 488 nm fiber lasers[14] have shown promising potential as the pump source for the Ti:S laser since their emission wavelength is just the absorption peak of the gain crystals and their beam quality is high owing to the fiber's waveguide properties. Those comprehensive advantages, as verified in our experiment, make these novel lasers an ideal pump source for the Ti:S laser, especially for the oscillator operated in a low-threshold mode-locked mode. In this letter, we report on the first mode-locked Ti:S oscillator pumped by a 488 nm fiber laser. Sub-10 fs mode-locked pulses with a repetition rate of 148 MHz were produced under a pump power of only 504 mW. This is, to the best of our knowledge, the lowest threshold for a sub-10 fs mode-locked Ti:S laser to date.

The experimental setup is schematically shown in Fig. 1. The pump source that we used is a frequency-doubled, ytterbium-doped fiber laser with an emission wavelength of 488 nm and an instantaneous linewidth of <1 MHz. With a 50-mm-long periodically poled lithium tantalate (PPLT) frequency-doubled crystal, the maximum 2 W 488 nm linearly polarized laser can be obtained with ±0.5% long-term power stability (over 9 h). Using a commercial laser beam profiler (Spiricon M2-200s), the horizontal and vertical M2 values of the blue beam are measured to be 1.081 and 1.098, respectively. A 2.9-mm-thick, Brewster-cut Ti:S crystal (GT Crystal Systems) with $\alpha_{532} = 7\,\mathrm{cm}^{-1}$ and figure of merit (FOM) > 100 was chosen as the gain medium whose single-pass absorption coefficient was measured to be 92% for the 488 nm pump light, which is higher than 85% for 532 nm. The Ti:S cavity has an astigmatically compensated Z design. The lengths of the highly reflecting and output coupling arms are 15 and 81 cm, respectively, corresponding to a repetition rate of 148 MHz. Two folding mirrors with 50 mm radii of curvature are used to increase the power intensity in the crystal. To satisfy the mode match requirement of the laser cavity, the blue pump beam is expanded (expansion ratio: 1 : 2.5) before focusing by a 50 mm focusing lens. The waist radii of the cavity mentioned above are calculated to be $7.6 \times 10.5\,\mu\mathrm{m}^2$ ($1/e^2$), and the pump radii are measured to be $6.9 \times 7.8\,\mu\mathrm{m}^2$ ($1/e^2$).

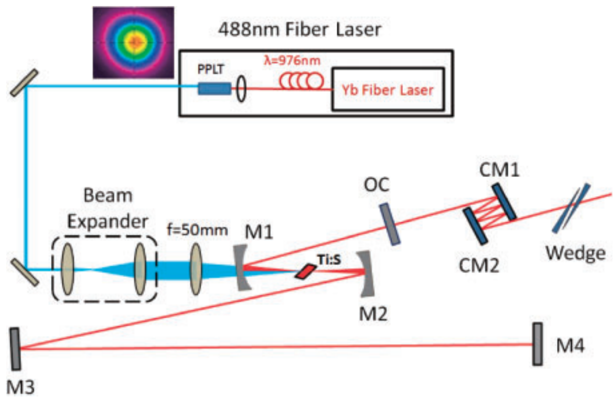


**Fig. 1.** Experimental setup of the sub-10 fs Ti:S laser pumped by a 488 nm fiber laser.

Double-chirped mirror (DCM) pairs (HR from about 600 to 980 nm, group delay dispersion (GDD) from about 650 to 1000 nm) were used in our experiment to compensate for the positive dispersion introduced by the gain medium. Compared with the prism pair and unpaired-chirped mirrors, the DCM pair will to a larger extent cancel the oscillations of the intracavity GDD.[15,16] Our experiences indicate that the sub-10 fs KLM oscillators will remain in the most stable state in the case of the net GDD of approximately $-20\,\mathrm{fs}^2$ in the laser cavity. In terms of this empirical rule, a concave DCM pair (M1 and M2) with $-70\,\mathrm{fs}^2$ GDD for each piece and a plane DCM pair (M3 and M4) with $-50\,\mathrm{fs}^2$ GDD for each piece were employed. The output couplers used in this work have nominally zero GDD. Considering the positive dispersion introduced by air, there should be a total of $-18\,\mathrm{fs}^2$ net GDD within the cavity, which is very close to the empirical value. In addition, relatively thinner 3 mm output couplers were chosen to reduce the extracavity second-order material dispersion introduced by the output coupler.

The RIN of the 488 nm fiber laser, as shown in Fig. 2, was first measured and compared with that of a commercial

 

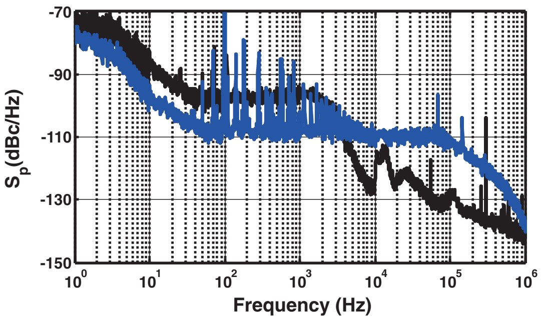


Fig. 2. RINs of the 488 nm fiber laser (blue line, ALS-Blue-2000-SF) and the 532 nm all-solid-state laser (black line, Laser Quantum Finesse 10).

532 nm all-solid-state laser (Laser Quantum Finesse 10) before being utilized to pump the Ti:S crystal in our laboratory. To ensure accuracy, both measurements were accomplished on the same optical table and both pump sources ran at their maximum output power, in which case their best running status could be guaranteed. The RIN curve was obtained in six consecutive frequency ranges (e.g., 1–10 Hz, 10–100 Hz, and 100 Hz–1 kHz) with a fast Fourier transformation (FFT) analyzer (Agilent HP89410A). In Fig. 2, the noise platform of the 488 nm fiber laser, ranging from 100 Hz to 100 kHz, is mainly caused by the white-noise characteristics of the fundamental semiconductor diode pump source of the Yb-doped fiber laser.[17,18] Although future improvement should be carried out to suppress the RIN for noise of more than 3 kHz, the 488 nm fiber laser has fine RIN characteristics in the area of low frequency, which is more important for maintaining the stability of the mode-locked Ti:S laser, because the phase noise of the femtosecond oscillator is more sensitive to the low-frequency RIN of the pump source in terms of the complex transfer function.[19–21]

To achieve stable Ti:S mode-locking operation pumped by the fiber laser, we first aligned the laser cavity in CW operation running at maximum output power. After that, we carefully tuned the distance between the two curved mirrors and the angle of the output coupler until the CW beam pattern had a spider shape and a fuzzy boundary. Finally, by trapping an end mirror to introduce perturbation, stable mode locking with broad output spectra was obtained. Figure 3(a) shows a typical linear spectrum generated under 1.23 W pump power with a 3% output coupler. The corresponding transform limit is calculated to be 6.8 fs for a flat phase [inset of Fig. 3(b)]. Since the generation of sub-10 fs pulse durations is sensitive to the material dispersion, pairs of wedges and chirped mirrors were used to adjust the extracavity dispersion in the vicinity of zero GDD. Figure 3(b) shows the interferometric autocorrelation trace (IAC) of the dispersion-compensated pulses (measured with Femtolasers V1.65). Obvious side lobes aside from the main IAC peak indicate the high-order dispersion of the pulses, which is very common but difficult to eliminate in sub-10 fs lasers. A $sech^2$ fit to this IAC trace yields a pulse duration of 8.7 fs (FWHM). Note that the two peaks of the output spectrum [see Fig. 3(a) solid line], at 700 and 900 nm, result from the interaction between the emission spectrum of the Ti:S crystal and the specific design of the transmission profile of the output coupler [see Fig. 4(a) dashed line]. Owing to the pulling effect of the Ti:S emission spectrum, the KLM output spectrum is not exactly at the transmission

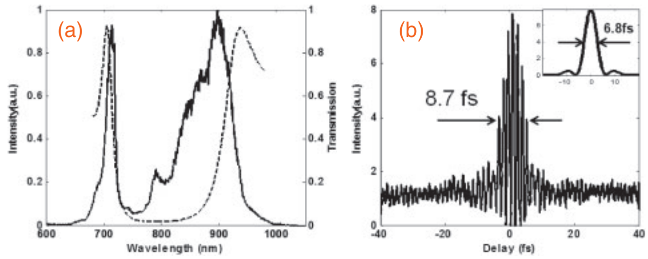


Fig. 3. (a) Transmission curve of the 3% OC (dashed curve) and linear mode-locked spectrum (solid curve) generated at 1.23 W pump power. (b) Corresponding transform limit pulse of 6.8 fs (inset) and interferometric autocorrelation trace of 8.7 fs.

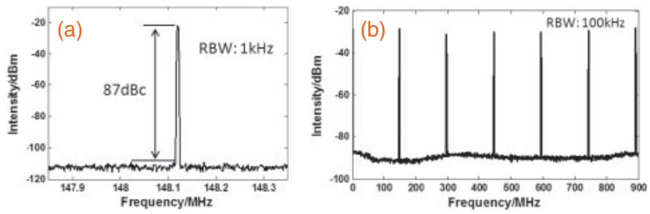


Fig. 4. Typical radio-frequency spectrum of the Ti:S laser pumped by a 488 nm fiber laser. (a) RF spectrum of fundamental beat note with 1 kHz resolution. (b) RF spectrum ranging from 0 Hz to 900 MHz with 100 kHz resolution.

peak of the output coupler, but moves about 10 and 40 nm towards 800 nm for short and long wavelengths, respectively. This double-peak design makes 80% of the sub-10 fs pulse energy concentrated around these two wavelength peaks, and thus is suitable for the difference frequency generation (DFG) between 700 and 900 nm. In Ref. 22, the corresponding DFG process in the monolithic scheme for the direct generation of the carrier-envelope (CE) phase signal has been experimentally demonstrated. At this point, our 488 nm fiber-pumped sub-10 fs mode-locked Ti:S laser has a considerable potential to be built as a CE phase-stabilized optical comb.[23]

The typical radio-frequency (RF) spectrum of the mode-locked laser was measured with a RF spectrum analyzer (R&S FSW26). Figure 4(a) shows a high signal-to-noise ratio of 87 dBc with a resolution of 1 kHz. Wide-span measurement of the high harmonics of the fundamental frequency was also carried out with a fast detector, as revealed in Fig. 4(b). The clean RF spectrum shows that the oscillator was running under a stable condition. In our experiment, over four hours of continuous running was monitored after the oscillator was finely adjusted into a stable mode-locked regime. We believe that the oscillator could maintain the KLM operation for one whole day if we isolate it from the environment with good housing.

The mode-locked performance characteristics of the Ti:S oscillator at different pump powers (pump power incident on the crystal) are studied in further experiments. To obtain optimum laser pulses, all the optical elements were carefully readjusted when the pump power was changed. Figure 5 shows the mode-locked output power as a function of incident power. The slope efficiency for 3% output coupling is calculated to be 13.8% and the pump threshold is 504 mW. Under threshold power, pulse durations are measured to be 8.2 fs. Corresponding spectra for different pump powers are released in logarithmic coordinates, as shown in Fig. 6. It

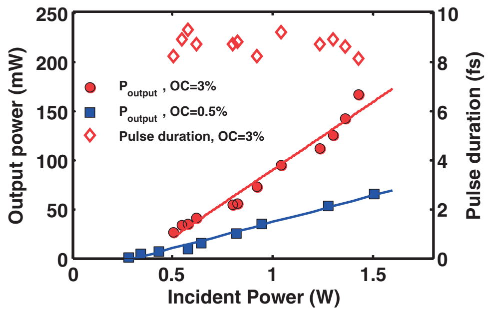


Fig. 5. Mode-locked output power (dots) and pulse duration (diamonds) as functions of incident power of 488 nm laser at 3% (red) and 0.5% (blue) output couplings. The pulse repetition rate is measured to be 148 MHz.

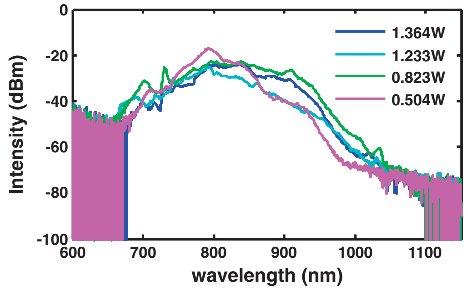


Fig. 6. Spectra on a logarithmic scale for different incident powers at 3% output coupling. Note that the spectrometer that we used (Yokogawa AQ6370C) will have an imbalanced background intensity when analyzing a relatively broader spectrum.

can be seen that, although the output power depends linearly on the incident power, the full bandwidths of the spectra remain almost the same once the KLM operation is initiated. (Note: The reason why we chose full width is that a 3 dB bandwidth cannot be easily defined here since the shape of the spectra is non-Guassian.) Those spectra, all extending approximately from 670 to 1100 nm above the noise floor, result in similar pulse durations of approximately 9 fs for different pump powers (see Fig. 5 red diamonds). It is worth noting that the discrepancy among the spectral profiles shown in Fig. 6 is mainly caused by the spatial chirp of the beam spot in the measurement process,[24] rather than the change in the output spectra. To pursue a lower mode-locked threshold for all-chirp-mirror Ti:S lasers, an output coupler with a transmission of 0.5% is used. The slope efficiency in this case is 5.4% and the corresponding threshold is reduced to 280 mW, which is also the lowest threshold for all-chirp-mirror Ti:S oscillators.

We consider that the threshold of our 488 nm-fiber-pumped Ti:S oscillator could be further reduced by using some suggested methods in cavity design. One optional method is to insert a prism pair into the cavity to continuously adjust the negative dispersion compression within the laser cavity. Another way is to adopt gain-matched output couplers (GMOCs).[25] This method is considered effective because the transmission profile of the output coupler that we used does not match well the gain spectrum of the Ti:S crystal, as shown in Fig. 3(a). However, the GMOC transmission spectral bandwidth should be designed to be relatively narrow since it is difficult to obtain simultaneous oscillation for all the longitudinal modes within the wide emission spectrum of the Ti:S crystals, especially under low-threshold conditions. (For our OC design, modes from 750 to 850 nm are suppressed.) This means that we may obtain a much lower threshold at the expense of the loss of the output spectral width. Nonetheless, there is no doubt that the 488 nm fiber source, which possesses good crystal absorption properties and beam qualities, plays a very important role in the realization of low-threshold broad-bandwidth Ti:S femtosecond oscillators.

In conclusion, we reported on a stable KLM Ti:S laser pumped by a blue fiber-laser-based source. A 2 W frequency-doubled, Yb-doped fiber laser at 488 nm is used as the pump laser and up to 92% absorption efficiency is achieved in a single pass for a 2.9 mm crystal, which increases by about 10% in comparison with that of a 532 nm pump laser. By using chirped mirrors for dispersion compensation, a stable KLM pulse with a pulse duration of 8.2 fs and a repetition rate of 148 MHz was generated under a pump power as low as 504 mW. By replacing the output coupler with a lower transmission, mode-locked thresholds were reduced to as low as 280 mW.

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