Generation of 4-nJ Pulses from a Diode-Pumped Femtosecond Ti³⁺:sapphire Laser

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Abstract: We generated 106-fs, 4.1-nJ pulses at 778 nm from a single green diode-pumped multipass-cavity Kerr-lens mode-locked Ti³⁺:sapphire laser. To our knowledge, these represent the highest pulse energies generated directly with a diode-pumped Ti³⁺:sapphire laser.

OCIS codes: (140.4050) Mode-locked lasers; (140.7090) Ultrafast lasers; (140.3480) Lasers, diode-pumped; (140.3580) Lasers, solid-state.

1. Introduction

In recent years, there has been a great deal of interest aimed at the development of cost-effective, diode-pumped 800-nm solid-state lasers which find numerous applications in many areas of science and technology, such as biomedical imaging [1-4], spectroscopy [5], and material processing [6]. One approach has utilized AlGaInP-based red laser diodes as pump sources and gain media from the colquiriite family, which includes Cr³⁺:LiSAF, Cr³⁺:LiCAF, and Cr³⁺:LiSGaF [7, 8]. By using red diode pumps with different architectures, broadly tunable continuous-wave (cw) and mode-locked operation of these colquiriite lasers have been successfully demonstrated with high slope efficiencies and low lasing thresholds [7, 8]. More recently, development of high-power laser diodes in the blue and green spectral regions has also enabled the direct diode pumping of Ti³⁺:sapphire lasers [4, 9-14]. When compared with colquiriite gain media, the Ti³⁺:sapphire gain medium offers additional advantages of broader tunability, negligible excited-state absorption, and reduced thermal effects [7, 15]. Direct diode pumping of Ti³⁺:sapphire lasers was first demonstrated by using GaN-based pump diodes operating near 452 nm [9]. To date, cw and mode-locked operations of diode-pumped Ti³⁺:sapphire lasers have been demonstrated by using blue and green pump diodes. In particular, recent studies have shown that, green AlInGaN-based laser diodes can be used to excite Ti³⁺:sapphire lasers with higher efficiency near the conventional pumping wavelength of 532 nm [13, 14]. In the mode locking experiments reported by Gurel et al., as high as 1 nJ of pulse energy was obtained by using two, 1-W pump diodes at 520 nm [14].

In this study, we describe the operation of an extended-cavity, mode-locked Ti³⁺:sapphire laser, directly diode-pumped at 520 nm with one AlInGaN diode. With 780 mW of incident pump power, we obtained as high as 81 mW of cw output power from the short cavity. After adding a q-preserving multi-pass cavity, we further achieved Kerr-lens mode locking and produced 106-fs pulses at a repetition rate of 5.8 MHz. The resulting energy and peak power of the pulses were 4.1 nJ and 39 kW, respectively. To our knowledge, this represents the highest pulse energy directly obtained to date from a mode-locked single diode-pumped Ti³⁺:sapphire laser.

2. Experimental Setup and Results

In the experiments, we used a Brewster-cut, 2.3-mm-long Ti³⁺:sapphire crystal with a figure of merit of 51 as the gain medium. The crystal was placed inside a copper holder and kept at 22°C by water cooling. Initially, a standard x-cavity was built and end pumped with a single, 1-W, 520-nm diode laser (Nichia NDG7K75T). A schematic of the experimental setup is shown in Fig. 1. The output beam of the green diode laser had different beam parameters for slow and fast axes. In particular, the divergence angle of the fast axis was 4 times larger than that for the slow axis. In order to couple the pump beam into the crystal, an aspheric collimating lens (L₁, f=4 mm), a telescope with a magnification of 4 (L₂ with f=25 mm and L₃ with f=100 mm) and an input focusing lens (L₄, f=50 mm) were used. Here, L₂ and L₃ were cylindrical lenses, providing magnification only for the slow axis. To determine the optimum pumping geometry, the position of L₁ and the separation of the telescope lenses (L₂ and L₃) were varied in order to maximize the fluorescence intensity obtained at the position of the output coupler (OC). A half-wave plate (HWP) together with a polarizing beam splitter (PBS) were used in order to vary the input pump power while keeping the diode current constant at 1.6 A. The short x-cavity consisted of a pair of curved high reflectors (C₁ and C₂, each with group delay dispersion (GDD)=-50 fs² and R=50 mm), a flat end high reflector (shown inside the dashed rectangle) and an output coupler (OC) with 3% transmission.

Fig. 1. Experimental setup of the single diode-pumped, multipass-cavity, femtosecond Ti^{3+} :sapphire laser.

After optimizing the power performance of the short x-cavity, a q-preserving multipass cavity (MPC) extension was added to reduce the pulse repetition rate [16]. The MPC consisted of a curved (M_3 , $R=2000$ mm) and a flat (M_4) high reflector, separated by 114 cm. M_3 and M_4 further had rectangular notches for beam injection and extraction. The missing round trip due to notches was compensated by using a curved retro-reflector (C_3 , $R=1000$ mm) at a distance of 114 cm from M_4 . This q-preserving MPC configuration corresponds to $m=6$ and $n=11$ [16], resulting in a total round-trip optical path length of 51.7 m for the composite cavity. The extended cavity further contained two flat folding mirrors (M_1 with $\text{GDD}=-60$ fs^2 and M_2 with $\text{GDD}=-45$ fs^2 per bounce) before M_3 and two flat GTI mirrors (M_5 and M_6 , each with $\text{GDD}=-400$ fs^2 per bounce) between M_4 and C_3 for dispersion management. The total GDD of the extended cavity including the crystal and air contributions was estimated to be -1504 fs^2 .

Power efficiency measurements were performed for both the short (x-cavity) and the extended (MPC) resonators as shown in Fig. 2(a). During cw operation, the maximum output power was measured to be 81 mW and 41 mW for x-cavity and MPC, respectively, at the pump power of 780 mW. The corresponding slope efficiencies were 15% and 10%.

Fig. 2. (a) Continuous-wave power efficiency data for the short Ti^{3+} :sapphire x-cavity and the extended resonator containing the MPC. (b) Interferometric autocorrelation of the pulses generated with the mode-locked MPC Ti^{3+} :sapphire laser.

In the mode locking experiments, cavity focusing around the gain crystal was optimized and the output coupler mirror was translated to generate a stable mode-locked pulse train. In order to characterize the mode-locked operation of the cavity, we measured the interferometric autocorrelation, optical spectrum, and the RF spectrum of the generated pulses as shown in Figs. 2(b) and 3. By assuming a sech^2 pulse profile, the pulse duration (FWHM) was determined to be 106 fs [Fig. 2(b)]. The spectral width (FWHM) of the pulses was 6 nm [Fig. 3(a)], giving a

time-bandwidth product of 0.321, in agreement with the assumed sech^2 intensity distribution. The RF measurements indicated that the fundamental beat note at 5.8 MHz was 63 dBc above the noise level. At the pump power of 750 mW, a maximum output power of 24 mW was obtained during mode-locked operation, corresponding to 4.1 nJ of pulse energy and 39 kW of peak power.

Fig. 3. (a) Mode-locked optical spectrum and (b) radio frequency (RF) spectrum of the pulses generated with the diode-pumped mode-locked MPC Ti³⁺:sapphire laser. At the pulse repetition rate of 5.8 MHz, the fundamental beat note was 63 dBc above the noise level.

In conclusion, we generated 106-fs pulses with 4.1 nJ of pulse energy at 778 nm from a single diode-pumped multipass-cavity Kerr-lens mode-locked Ti³⁺:sapphire laser. To the best of our knowledge, this represents the highest pulse energy directly generated from a diode-pumped Ti³⁺:sapphire laser. We believe that further energy scaling should be possible by using more pump diodes.

3. References

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