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High Average Power Mode Locked Ti:Sapphire Laser with Intracavity Continuous-Wave Amplifier and Strained Saturable Bragg Reflector

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We demonstrate a new scheme for the generation of high average power femtosecond pulses by incorporating an intracavity amplifier and a strained saturable Bragg reflector with low saturation fluence for self-starting mode locking. When the Ti:sapphire oscillator and intracavity amplifier are pumped at 10 W and 15 W, respectively, the average output power is as high as 1.62 W. The pulse duration is about 145 fs, and the peak power reaches 160 kW at a 68 MHz repetition rate. The pulse-formation time of 400 μs is sufficiently short to sustain stable mode locking.

KEYWORDS: High average power, mode locking, Ti:sapphire laser, strained saturable Bragg reflector (SSBR), intracavity continuous-wave amplifier

Over the last few years, great strides have been made in the development of femtosecond solid state lasers mode-locked either by the Kerr lens effect[1)] or by saturable absorbers.[2)] For application to nonlinear optics, time-resolved spectroscopy or THz-radiation generation, average or high peak power femtosecond laser systems can significantly improve the experimental results. Recently, high peak power (∼MW) Kerr-lens mode-locked Ti:sapphire laser generating about 10 fs pulses has been demonstrated using mirror-dispersion-controlled[3)] with a 100 MHz repetition rate. Cavity dumped oscillator with a repetition rate of 200 kHz, 13 fs pulse duration, and 5 MW peak power or similar performance with multiple-pass cavity geometry[4)] at 15 MHz has been demonstrated.[5)] Recent studies also demonstrated the generation of 10 W average power and 7.8 kW peak power with 16 ps optical pulses by a diode-pumped, passively mode-locked Nd:YAG laser.[6)] However, there are some difficulties in power scaling the ultrafast mode-locked lasers. The higher average power is important for the generation of THz-radiation[7)] or the intracavity doubling of a femtosecond laser.[8)] Recently, Liu *et al*.[9)] reported an average power-scaled femtosecond Ti:sapphire laser with an intracavity continuous-wave (CW) amplifier. The output power was almost doubled to 3.4 W with a 79 MHz repetition rate. However, a dye jet was used for self-starting the mode locking. This was a significant drawback of the previous system. To maintain femtosecond pulses at a high average power, a scheme to achieve self-starting mode locking is required. Thus, solid-state saturable absorbers are desirable. In most cases, tight focusing of the intracavity beam was required to achieve the required saturation intensity.[10)] Such intracavity focusing increases the possible risk of optical damage to the delicate saturable absorber, particularly in the case of high average power operation. In this paper, we propose and demonstrate a compact, high output power femtosecond mode-locked laser that does not require the intracavity beam to be focused on the saturable absorber. This is realized by incorporating a previously developed strained saturable Bragg reflector (SSBR)[11)] with a saturation fluence as low as 7 mJ/cm^2 with an intracavity CW amplification system.

The laser cavity with two 1-cm-long Brewster-cut Ti:sapphire rods is shown in Fig. 1. The Z-folded cavity contains two 10 cm and two 20 cm radius of curvature folding mirrors which focus the intracavity laser beam on the main and amplifier rods, respectively. A 10 W solid-state green laser (Millennia X, Spectra Physics) was focused through a 10-cm-focal-length lens on the main laser rod. Intracavity dispersion compensation was provided by a pair of SF11 Brewster prisms separated by about 42 cm. The SSBR,[11)] which served as the saturable absorber for passive mode-locking, was placed in the end mirror position of the dispersion-compensation arm. A slit was put between the SSBR and the adjacent prism to tune and stabilize the laser wavelength and to reduce the timing-jitters. Due to the low saturation intensity of the SSBR, we can use a rather high transmission (25%) output coupler for producing higher output power and maintain the mode-locking without focusing on the SSBR. Without pumping the amplifier rod, the output average power of the Ti:sapphire laser was 1.1 W, and nearly transform-limited 130 fs pulses can be generated. The center wavelength of the laser was about 787 nm with a spectral width of 5.8 nm.

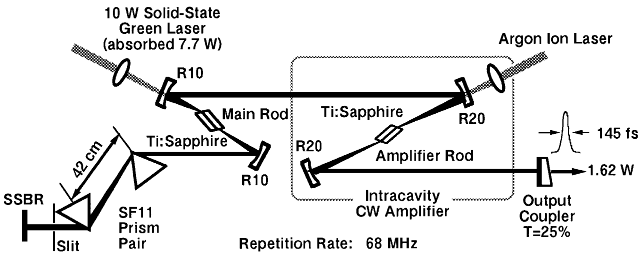

Fig. 1. Cavity configuration of the compact, high average power mode-locked femtosecond Ti:sapphire laser with intracavity CW amplifier

The intracavity amplifier was pumped by an argon laser which was focused through a 20-cm-focal-length lens onto the amplifier rod. The laser output power increased linearly with the amplifier pumping power (see Fig. 2), and the behavior is the same as that of the dye jet mode-locking system.[9)] With a 10 W green laser pumping the main rod and a 15 W argon ion laser pumping the amplifier rod, the laser power reached 1.62 W with a 145 fs pulse width. The autocorrelation trace and spectrum of the transform-limited pulse train are shown in Figs. 3 and 4, respectively. The corresponding

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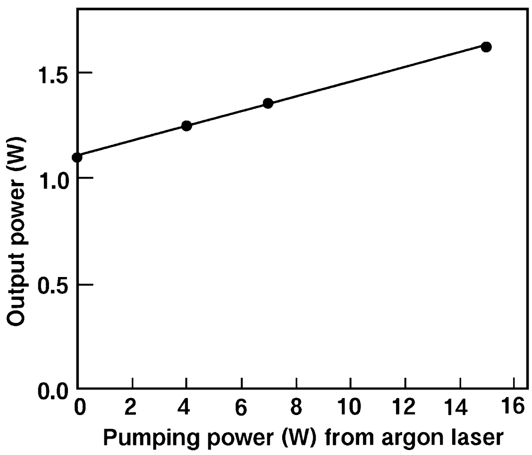

Fig. 2. Amplified power dependence on the argon ion laser pumping power.

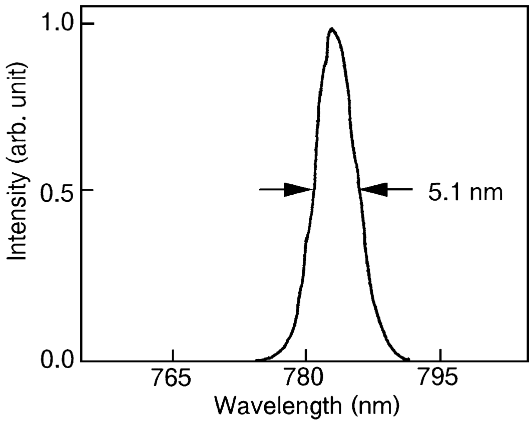

Fig. 4. Optical spectrum of center wavelength at 783 nm, spectral width around 5.13 nm.

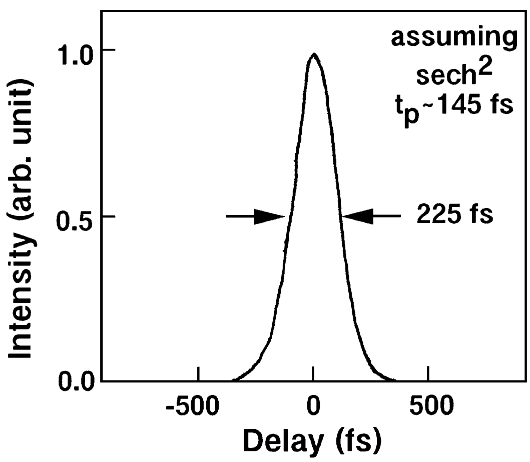

Fig. 3. Autocorrelation trace of the output pulse with 1.62 W output power. The pulse width is measured to be about 145 fs assuming a sech^2 pulse shape.

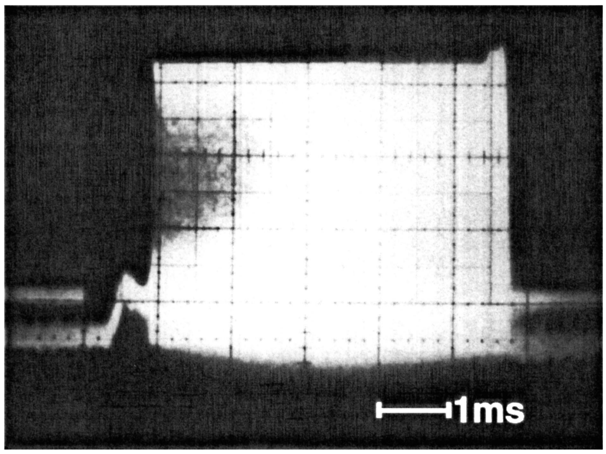

Fig. 5. Pulse build-up trace with fast response photodiode detector which was recorded using a 400 MHz storage oscilloscope. The mode locking starting time was calculated to be about 400 μs.

time and bandwidth product was 0.36. The peak power of the laser reaches 160 kW with a 68 MHz repetition rate, which is slightly lower than the previous case which used a dye jet,[9] and is partly due to higher loss in the cavity.

The pulse build-up time was also measured to evaluate the self-starting performance of the laser. A chopper with a frequency of about 87 Hz was put inside the cavity. The fundamental pulse train was measured using a photodiode detector with a fast (~1 ns) response time.[2,12,13] The pulse evolution was recorded using a 400 MHz storage oscilloscope, as shown in Fig. 5. After the relaxation oscillation, the time taken to reach the steady state was about 400 μs with high stability. Compared with the pulse build-up time (~5 ms) of the mode-locked Ti:sapphire laser with the SSBR but without an intracavity amplifier, this build-up time was significantly shorter. This is reasonable, since the intracavity pulse energy is higher in the present system.

In summary, we have reported a new type of femtosecond amplification scheme in which an SSBR with low saturation fluence was used for self-starting mode locking, and an intracavity CW amplifier system was used to scale the average output power. As the amplifier rod was pumped from 0 W to 15 W, the output power linearly increased from 1.1 W to 1.62 W, and stable mode locking was sustained. Compared with our previous system using the dye jet saturable absorber, the present system is more compact and stable, and exhibits lower noise. To our knowledge, this is the highest average power reported for a mode-locked Ti:sapphire laser with a semiconductor saturable absorber. The peak power of the laser reaches 160 kW, with a 145 fs pulse duration and a 68 MHz repetition rate. The pulse formation time of 400 μs was short enough to sustain stable self-starting mode locking. By optimizing the output coupling, increasing the pumping power and fine tuning the cavity, we expect to achieve an even higher output power with reduced pulse width.

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