High-repetition-rate, high-average-power, mode-locked Ti:sapphire laser with an intracavity continuous-wave amplification scheme

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We have demonstrated a high-average-power, mode-locked Ti:sapphire laser with an intracavity continuous-wave amplification scheme. The laser generated 150 fs pulses with 3.4 W average power at a repetition rate of 79 MHz. This simple amplification scheme can be applied for the power scaling of other lasers. [S0003-6951(99)02124-5]

Some years ago, there was a breakthrough in mode-locking techniques for solid-state lasers.[1,2] Applying the techniques utilizing Kerr-type nonlinearity, most solid-state lasers could be mode-locked down to the femtosecond region. Shortly after that, amplification of these ultrashort pulses to gigawatt peak power was demonstrated[3] using chirped pulse amplification.[4] However, this kind of amplification reduces the pulse repetition rate to the order of ~100 kHz, and there is often a loss of time resolution in the final pulse. A higher repetition rate results in much smaller pulse fluctuation and excellent experimental signal-to-noise ratios. Much progress has been made in extending the spectral range of high-repetition-rate femtosecond pulses throughout the ultraviolet, visible, and infrared (IR) regions by using frequency conversion in crystals. The ~80 MHz, 2-W-level femtosecond Ti:sapphire lasers have been used for fourth harmonic generation near 200 nm,[5] visible range,[6–8] and IR range[9] optical parametric oscillator and coherent THz-radiation from semiconductors.[10] If there is some scheme to scale the power of high-repetition-rate femtosecond lasers, there will be interesting applications for the various wavelength conversion techniques mentioned above. The requirement for the average power has been one of the most important factors especially for these lasers used as pump sources of THz-radiation from InAs in a magnetic field,[10] because THz-radiation power is known to have a quadratic dependence on the excitation high-repetition-rate femtosecond laser average power. Also, the average power is important for the intracavity doubling of a femtosecond laser.[11] In contrast to continuous wave (cw) high-average-power lasers, the power scaling of the high-repetition-rate femtosecond mode-locked lasers is difficult. This is partly due to the limitation of available power from the pumping source. The major problem was the difficulty of maintaining the beam quality good enough for mode locking and balancing the thermal lens effect and Kerr lens effect at the same time. With these limitations, the output average power of femtosecond mode-locked lasers has been limited to the 2 W level.[12] In this letter, we describe a high-repetition-rate (79 MHz), high-average-power (3.4 W), mode-locked femtosecond Ti:sapphire laser realized by applying an intracavity cw-amplification scheme.

The configuration of the laser cavity with two Ti:sapphire crystals is modified from a conventional mode-locked Ti:sapphire laser as shown in Fig. 1. A rather high transmission (15%) output coupler was used to obtain higher output power. An intracavity slit was provided as a tuning element. A pair of SF11 high-dispersion Brewster prisms with 45 cm separation were selected for dispersion compensation. For easier setup to initiate mode locking, a saturable-absorber dye jet (1,1′,3,3,3′,3′-hexamethylindo-tricarbocyanine iodide in ethylene glycol) was introduced at the Brewster angle to an additional focus point in the laser cavity. Laser power of 7.7 W at 532 nm from a cw 10 W solid-state green laser (Millennia X) was absorbed by the 1 cm Brewster-cut Ti:sapphire crystal. By just pumping this crystal, the laser can be mode locked to generate 150 fs pulses with 1.5 W average output power.

The intracavity cw amplifier was a half cut Brewster crystal with a dichroic coating at the end and with high reflection at around 800 nm and high transmission for the green wavelength. The pumping Ar-ion laser beam was focused by a 10 cm focal-length lens. The Ti:sapphire laser beam was focused on the amplifier crystal by a 10 cm focal-length concave mirror. The amplifier crystal can be easily introduced into the cavity without changing the wavelength by inserting a temporary output coupler before the 10 cm focal-length concave mirror, and starting the laser and using the output beam for alignment. The 7 W power from a cw all-line Ar-ion laser was adsorbed by the 1 cm half cut Brewster Ti:sapphire crystal. The adjustment of the distance from the amplifier crystal to the 10 cm focal-length concave mirror is very critical to improve amplification efficiency due to the thermal lens effect. The laser does not oscillate only by

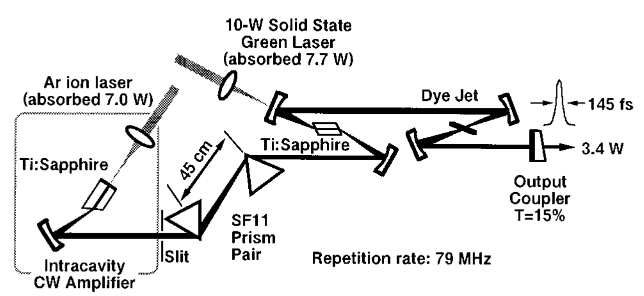

FIG. 1. Configuration of high-repetition-rate high-average-power (3.4 W) femtosecond Ti:sapphire laser with an intracavity cw amplifier. The half cut Brewster Ti:sapphire crystal composed the intracavity cw amplifier.

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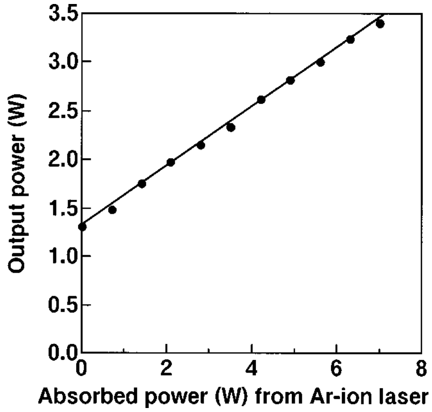

FIG. 2. Mode-locked output power dependence on the pumping Ar-ion laser power absorbed by the amplifier Ti:sapphire crystal. The mode-locked average power was more than doubled by the amplifier.

this pumping of the amplifier crystal. With dual pumping up to 14.7 W absorbed power for the two Ti:sapphire crystals, a femtosecond mode-locked laser power of 3.4 W was achieved with 23% efficiency. The output power dependence on the absorbed Ar-ion laser power is shown in Fig. 2. This simple amplifier more than doubled the mode-locked average power. Up to 3.4 W, the output power increased linearly with the pumping Ar-ion laser power. The autocorrelation trace and the spectrum were monitored with a rapid-scanning autocorrelator and an optical spectrum analyzer, respectively. When the output power was 3.4 W, 145 fs pulses assuming a $sech^2$ shape (Fig. 3) were obtained with 4.6 nm spectral width at 780 nm (Fig. 4), and these yielded a nearly transform-limited time and bandwidth product of 0.329. The peak power reaches 300 kW with a 79 MHz repetition rate. After optimization of the output coupler transmission and the

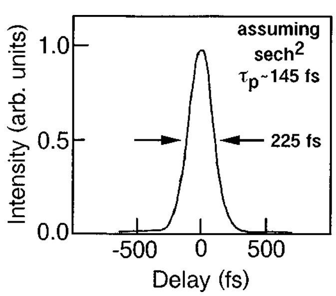

FIG. 3. Autocorrelation trace of the pulse with 3.4 W average output power with a rapid-scanning autocorrelator. The pulse width is measured to be 145 fs with pulses assuming a $sech^2$ shape.

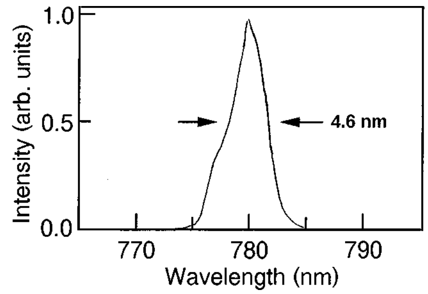

FIG. 4. Spectrum of the pulse with 3.4 W average output power with an optical multichannel analyzer. The center wavelength is 780 nm with a spectrum width of 4.6 nm, and these yielded a nearly transform-limited time and bandwidth product of 0.329.

pumping power absorbed by the amplifier crystal, the output power level will be improved even further.

In conclusion, we have demonstrated amplification of a high-repetition-rate femtosecond mode-locked pulse train by an intracavity cw-amplification scheme, and have obtained 3.4 W average power from the femtosecond mode-locked Ti:sapphire laser. This scheme will be widely applicable for other femtosecond mode-locked solid-state lasers to scale the output power up to the multiwatt level. Such average power scalability of high-repetition-rate femtosecond mode-locked solid-state lasers will be a great advantage compared with femtosecond fiber lasers that have been improved so much.[13]

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