A compact Ti:sapphire femtosecond pulse amplifier without stretcher at high repetition rate

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We report a simple approach to amplify Ti:sapphire femtosecond pulses to moderate energy levels by a chirped regenerative amplifier. The seed pulses are broaden naturally because of the material dispersion of system components in regenerative cavity. The off-focusing Ti:sapphire crystal avoids effectively the optical damage. It sustains amplification over a wavelength range from 775 nm to more than 810 nm with a birefringent filter and an oscillation bandwidth of 7.7 nm, and produces 2.1 ps chirped output pulse energy of 100 μJ at 1.1-mJ pumping energy. This system shows good performances in stability and efficiency with the benefits of two thin-film polarizers and TEM_{00} mode pumping laser.

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Micro-fabrication with femtosecond laser pulse is of growing interest for microsystems manufacture, semiconductor devices, and material processing. In particular, femtosecond laser pulse can process the wide-bandgap transparent material with sub-micrometer precision inside samples. By means of femtosecond pulses, a direct solid-vapor translation occurs at 10^{14} W/cm^2 intensity to most of transparent materials[1,2]. With 0.65-NA objective focusing laser pulse to sample, a few micro joule femtosecond pulse can reach the intensity. In order to achieve good performance for practical application, high stability and good beam quality femtosecond pulse source at high repetition rate is necessary. However, most of femtosecond laser amplifier is not compact due to complicated system consisting of stretcher, amplifier and compressor[3−5]. In this letter, we introduce amplification of femtosecond pulses to the 100-μJ-level in a much more compact, reliable, and user-friendly regenerative amplifier, which uses Ti:sapphire crystal as the gain medium.

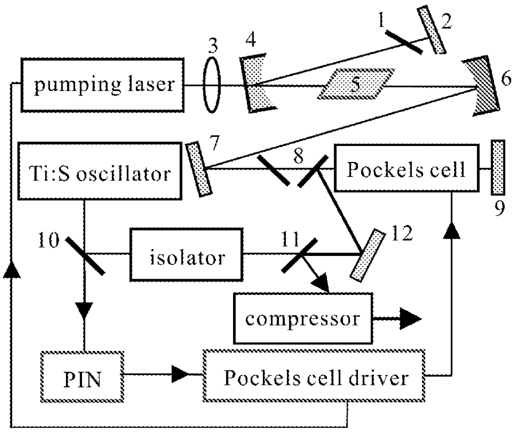

Fig. 1. Schematic of the regenerative amplifier. 1: Birefringent filter; 2,7,9,12: high reflection mirrors; 3: convex lens; 4,6: concave lens at 800 nm; 5: Ti:sapphire crystal; 8: thin film polarizers pairs; 10,11: splitter (90/10, at 800 nm).

The schematic of our experimental setup is shown in Fig. 1. The resonator design is based on an M confocal arrangement with a pair of mirrors of 250-mm radius of curvature. All cavity mirrors have high-power coatings centered at 800 nm with reflectivity > 99%. The cavity utilizes a Medox 700 KDP Pockels cell assembly in combination with two broad bandwidth thin-film polarizers to achieve switching of the chirped pulse into and out of the cavity. The thin-film polarizers have a transmission of 98% for p polarization and a reflectivity of 90% for s polarization, the gain medium is a 6 mm length Brewster-cut Ti:sapphire crystal.

Less than 80-fs seed pulses from Ti:sapphire oscillator (MaiTai RS232 Spectrum-Physics) is seeded into amplifier. It passes through an optical isolator rather than conventional stretcher system, then injects into the regenerative cavity. In general, stretcher is made from the grating pairs, high dispersion optical glass, or hole core fiber, whose elements will introduce spatial dispersion, aberration, and astigmation. The absence of stretcher can improve the beam quality of amplifier. The absence of stretcher makes it possible for us to use low dispersion and low loss two prism pairs to compress amplified pulse. It improves the amplifier efficiency, and saves the volume of amplifier system, in favor of the integration of the system.

Since without stretcher, seed pulse is stretched as it passes through isolator, Pockels cell, Ti:sapphire crystal, and other intracavity elements and reflection mirror. 6-mm length Ti:sapphire crystal introduces 360-fs^2 dispersion, 12-mm length KD*P crystal in Pockels cell 53000-fs^2 dispersion, and 5 cavity mirrors 1500-fs^2 dispersion[4]. $\tau_{\text{out}}/\tau_{\text{in}} = [1 + \varphi''^2/4\beta^2]^{0.5}$, where $\varphi'' = \left(\frac{\mathrm{d}^2\varphi}{\mathrm{d}\omega^2}\right)$, and $\beta = t_{\text{in}}^2/8\ln 2$. A 70-fs origin seed pulse will be stretched to 2.13 ps when it travels round-trip in regenerative cavity, then there are few changes in following propagating in regenerative cavity. To the confocal cavity made of 250-mm radius mirrors, the waist is 178 μm. A 100-μJ, 200-fs pulse is focused 178 μm on Ti:sapphire crystal, the peak intensity is 2×10^9 W/cm^2, is less than the damage threshold of Ti:sapphire crystal (10^{14} W/cm^2 to 100-fs pulse[4]). Seemingly, the stretch dependent on the cavity elements is enough to 100-μJ regenerative amplifier.

In experiment, we found that when the pumping power was beyond 2 W, Ti:sapphire crystal was damaged during the seed pulse injection. The theoretical peak intensity applied on the crystal is much less than the damage threshold of the sapphire crystal. It is due to neglecting the self-focusing effect of Ti:sapphire crystal and the intensity of pumping laser. There are considerable divergence on the factual intensity inside the crystal and the damage threshold of Ti:sapphire crystal excited by two wavelength laser. In order to decrease the peak intensity, Ti:sapphire crystal is placed off-focus of confocal cavity. The distance from Ti:sapphire crystal to one of concave lens is 110 mm, and to another one is 140 mm. At 2-W 532-nm laser pumping, the system shows a good performance.

Off-focus of Ti:sapphire crystal leads to the considerable decrease of the amplifier efficiency. To keep the acceptable output power at low pumping laser power, a TEM_{00} mode YLF frequency-doubling laser is employed. The diameter of the pumping laser beam is 1.1 mm, and the divergence of beam is less than 0.4 marc. 140-mm focusing convex lens focuses pumping laser beam on Ti:sapphire crystal. Without Pockels cell, the laser threshold of regenerative cavity is 0.4 W with 10% output couple mirror, and the slope efficiency of regenerative cavity is 20%. When the pumping power is 1.1 W, the amplifier produces a chirped output pulse energy of 120 μJ, bandwidth of 7.7 nm, 2.1-ps amplifier pulse. The peak-to-peak fluctuation is less than 8%. It can be compressed to a duration of 130 fs at 790 nm center wavelength with two prism pairs compressor with 75% efficiency. Figure 2 shows the spectral and temporal characteristics of the compressed output from the Ti:sapphire regenerative amplifier. The second harmonic autocorrelation trace indicates a pulse duration of 300 fs, owing to imperfect compensation the group velocity dispersion by the compressor.

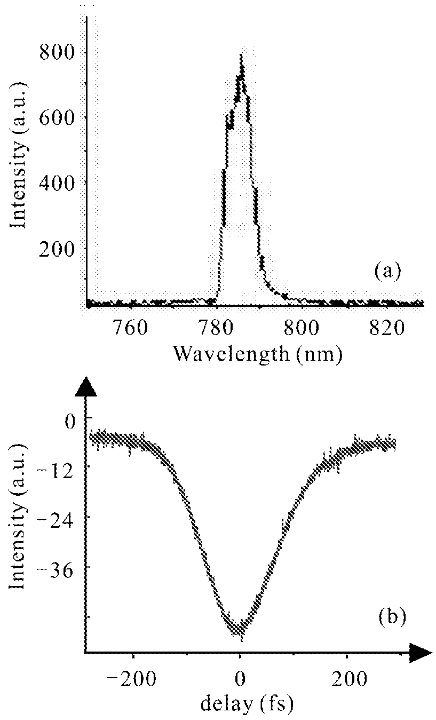

Fig. 2. The spectrum (a), and intensity autocorrelation trace (b) of the Ti:S CPA amplifier.

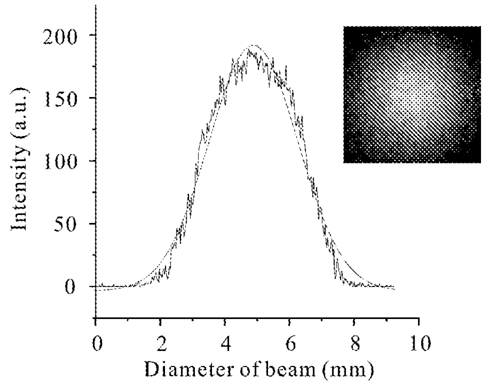

Fig. 3. Far field beam profile pattern of the amplifier. The smooth curve is Gauss fit curve, and the inset is far field pattern of the laser beam, taken by a digital camera.

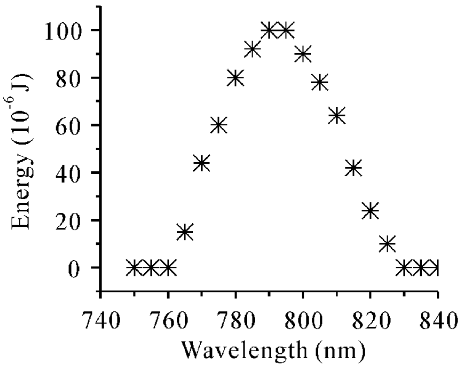

Fig. 4. The tuning curve of regenerative amplifier with 0.5-mm-thick quartz plate.

Figure 3 shows typical beam-profile patterns of the amplifier pulse. Actual cross-sectional profile is shown by the line with burr because the beam was measured at 3 m from output coupler and took it by digital camera on the surface of a paper. Ideal Gaussian curve fitted to the results is shown by the smooth curve. The diameter of beam is about 5 mm. From the results of the fitting, the spatial distribution is an almost ideal Gaussian shaped cross section.

When the wavelength of seed pulse is changed from 750 to 850 nm, the wavelength of the amplifier is not changed. It is due to the difficulty to suppress the natural tendency of the amplifier to oscillate at wavelengths near the spectral peak of the gain curve (790 nm for Ti:sapphire crystal). So it is imperative to use spectral selection techniques to suppress the natural tendency in order to change the operating wavelength of the amplifier. Spectral tunability of the amplifier from 775 nm to 810 nm can be achieved by use of a 0.5-mm-thick quartz birefringent filter[7]. When the operation off the gain peak wavelength, the output power decreases slightly. Figure 4 shows the performance of laser energy as a function of wavelength.

When the regenerative amplifier operates at saturation gain, the instability of output power comes mainly form competition of the p and s polarization light[4]. The thin-film polarizers have a reflectivity of 90% for s polarization. In order to distinguish the s polarization light in regenerative cavity, we add another thin-film polarizers in cavity shown in Fig. 1. The fluctuation of the output power was compressed within 3% over a few hours of continuous operation.

In conclusion, we have developed a novel regenerative amplifier that produced 120-μJ pulse energy at 1-kHz repletion rate without stretcher. The stretch of seed pulse comes from the dispersion of elements in cavity. Off-focusing technology avoid effectively the optical damage of Ti:sapphire crystal. The amplifier can be tuned continuously over 30-nm wavelength range by birefringent filter. The millijoule output energies, good beam quality, high stability, and compactness make this regenerative amplifier an ideal source for femtosecond laser pulse micro-machining.

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