100-MHz multi-terawatt femtosecond Ti:sapphire laser with a regenerative amplifier

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We suggest and demonstrate an approach to generate a femtosecond multi-terawatt pulse train at repetition rate of 100 MHz in a 10-Hz chirped pulse amplification Ti:sapphire laser system. With an electro-optic Q-switch regenerative amplifier, we can obtain an adjustable repetition-rate chirped pulse train. After amplification and compression, the 100-MHz pulse train with 46-fs pulse width and 1-TW peak power per pulse is obtained in our 10-TW-class Ti:sapphire laser system.

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Chirped pulse amplification (CPA) has become a common technique for damage-free amplification of short optical pulses to terawatt levels and beyond^[1]. To date, this technique has extended to produce sub-20-fs pulses with peak power ranging from multi-terawatt up to petawatt level^[2-4]. Such laser systems permit studies of high-field (> 10^{19} W/cm²) phenomena and research on the generation of coherent ultraviolet and soft X-ray radiation by means of high-order harmonic generation. Continued advances in these areas will benefit greatly from development of these laser systems with shorter pulse duration, higher pulse energy and average power. In addition, for some other applications such as white-light continuum generation and long-life plasma channel generation, higher repetition rate is also desirable.

Typical high-repetition-rate Ti:sapphire chirped pulse amplification laser systems using electro-optic pulse selection method operate at the range from 10 Hz to 20 $kHz^{[5-7]}$ with an energy of ~ mJ, whereas those using acousto-optic pulse selection method can operate at the range from 100 to 250 kHz with an energy of $\sim \mu J^{[8,9]}$. The former is limited to approximate 20 kHz mainly by the repetition rate of the pump lasers and the operation repetition rate of Pockels cell. In this letter, a new electro-optic regenerative amplifier is put forward, which can generate chirped pulses at higher repetition rate. In the 10-TW class CPA Ti:sapphire laser system^[10], we change not only the operating mode of the electro-optic Q-switch (Pockels cell) in the regenerative amplifier, but also the opening duration of a pulse selector synchronously, to generate a chirped pulse train including finite pulses with a 2L/c interval (L is cavity length of the regenerative amplifier, c is the light in vacuum velocity). After the chirped laser pulses are amplified through the laser amplifier chain and recompressed by the grating pair compressor, a femtosecond, multi-terawatt pulse train is obtained. The operating process of the CPA Ti:sapphire laser system is explained as follows.

The mode-locked Ti:sapphire oscillator pumped with 5-W power from a Verdi-V5 diode pumped solid state laser (Coherent Inc.) delivers pulses as short as 15 fs at a repetition rate of 80 MHz. The 4-nJ, 15-fs pulses from the oscillator are then stretched to 370 ps. The stretcher

design is based on an Öffner triplet^[11,12] which has the advantage of aberration free. The stretched pulses are then amplified in three amplifier stages.

The first one is a regenerative amplifier optimized for high-gain production. Figure 1 shows the schematic diagram of our regenerative amplifier. This amplifier uses a 15-mm-thick Ti:sapphire crystal and is pumped with a Nd:YAG laser that is capable of producing 45 mJ of 532-nm radiation at a 10-Hz repetition rate. A Faraday rotator, thin-film polarizer (P1) and half-wave plate are used to separate the input and amplified pulse train. The Pockels cell, combining with a thin film polarizer (P3), traps one of the injected pulses in the cavity. Following approximately suitable round trips, the cavity-dumping



Fig. 1. Schematic diagram of the regenerative amplifier. FR, Faraday rotator; PC, Pockels cell; P1–P3, broadband thinfilm polarizers; L, 40-cm focal-length lens; M1, M2, end-cavity mirrors.



Fig. 2. Temporal profile of bias voltage of the Pockels cell in the cavity.



Fig. 3. Pulse train ejected after saturation with m = 33.

Pockels cell is triggered and a pulse train is rejected from the regenerative amplifier.

We change the dumping time and the voltage applied to the electro-optic Q-switch Pockels cell in the regenerative amplifier. The procedure of bias voltage applied to the Pockels cell is shown in Fig. 2. A bias-voltage step of $V_{\lambda}/4$ (V_{λ} is whole wave voltage for operation wavelength of 800 nm) is applied to the Pockels cell to reject the seed pulses out of the cavity after two passes through the gain medium and then frustrate lasing of cavity. At moment t_1 (called as injected pulse time), the voltage on the Pockels cell is turned off abruptly when the one pulse in transit between the thin-film polarizer P3 and the end-cavity mirror M2, the pulse is trapped and regeneratively amplified. At the moment t_2 (called as dumping time) when the seed pulse in the regenerative amplifier is amplified close to saturation, the Pockels cell voltage step is boosted to V' and the linearly polarized light in the cavity passes twice through the Pockels cell and becomes elliptical polarized light, so a portion of the whole energy in the cavity is cavity dumped every time the pulses are coupled out of the cavity. Thenceforward, the chirped pulses at high repetition rate are generated.

The experiment was carried out on our 10-TW-class CPA Ti:sapphire laser system^[10]. In experiment, at the moment t_2 , we applied a voltage step of $V_{\lambda}/8$ to the Pockels cell and circularly polarized light e_1 was generated and analyzed into two components with equal energy. One was vertical polarization component s_1 that was reflected by the polarizer P3 and stayed in the cavity, and the other was horizontal polarization p_1 component that was ejected out of the cavity via polarizer P3, which just was the first ejected pulse. Thereafter, the regenerative amplifier will subsequently eject a chirped pulse train as shown in Fig. 3. The dumping time determined how many pass-times the seed pulse pass through the active medium, Ti:sapphire crystal, so we defined pass number m to denote the dumping time. If the moment t_2 is ahead of the saturation time (m = 33), the regenerative amplifier will eject different chirped pulse trains as shown in Fig. 4. We use a second Pockels cell as a pulse selector and change its opening duration synchronously to select finite pulses in the pulse train for amplification. At the same time, the contrast of the pulse train will be improved.

We run routinely the 10-TW-class CPA Ti:sapphire laser system, and a 100-MHz femtosecond multi-terawatt laser pulse train including several pulses in per pumping period is obtained. The pulse interval of pulse train can be adjusted by variation of the cavity length of regenerative amplifier.

According to the above-mentioned method, we have experimentally demonstrated the generation, amplification



Fig. 4. Ejected pulse train with the dumping time (a) m = 18, (b) m = 23, (c) m = 28, respectively.



Fig. 5. Measured autocorrelation trace of the compressed pulse of 44 fs. Inset: measured amplified spectrum after compression.

and compression of chirped pulse trains of higher repetition rate and achieved the expected result. For example, five pulses are chosen from the chirped laser pulse train for further amplification and compression. A fraction of the compressor output is sent to a second-order slow scan autocorrelator with a 100- μ m BBO doubling frequency crystal. A typical autocorrelation trace and an amplified spectrum after the compressor are depicted in Fig. 5. The full width at half maximum (FWHM) of the measured pulse duration is 44 fs. The spectrum is centered at 790 nm with a 22-nm FWHM. We have obtained the 100-MHz pulse train with 1-TW peak power per pulse in our 10-TW-class Ti:sapphire laser system.

In conclusion, we have demonstrated a new approach to generate a femtosecond multi-terawatt pulse train at repetition rate of 100 MHz in a 10-Hz CPA Ti:sapphire laser system, which contains a regenerative amplifier with an electro-optic *Q*-switch. The method of producing high power laser pulse train at high repetition rate can be used to any CPA laser systems of single shot or 10-Hz repetition rate. Specially, with the pulse selector as a switch, the CPA Ti:sapphire laser system can produce a femtosecond multi-terawatt pulse train or single pulse at per pumping period. The availability of such laboratoryscaled ultrafast terawatt lasers at high repetition rate promises to open the door to investigations into the new fields of physics and applications.

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