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2009 Chinese Phys. Lett. 26 044208

(http://iopscience.iop.org/0256-307X/26/4/044208)

CHIN. PHYS. LETT. Vol. 26, No. 4 (2009) 044208

Generation of a Sub-10 fs Laser Pulse by a Ring Oscillator with a High Repetition Rate *

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(Received 25 August 2008)

A compact femtosecond Ti:sapphire ring oscillator composed of chirped mirrors is designed. By accurately optimizing the intra-cavity dispersion and the mode locking range of the ring configuration, we generate laser pulses as short as 7.7 fs with a repetition rate as high as 745 MHz. The spectrum spans from 660 nm to 940 nm and the average output power is 480 mW under the cw pump laser of 7.5 W.

PACS: 42. 55. Rz, 42. 60. Da, 42. 60. Fc

Since the Ti:sapphire laser was proven to generate ultrashort laser pulses with self-mode-locked mechanism in 1990,[1] femtosecond Ti:sapphire lasers have attracted more and more interest because of their stability and simplification. Laser pulses as short as 5 fs, less than two optical cycles, have been directly generated from the oscillators by some groups,[2−5] enabling us to explore the unprecedented ultrafast phenomena in physics,[6] chemistry,[7] and biology.[8] Simultaneously, the development of femtosecond lasers with a high repetition rate and high optical power is of great advantage and highly desirable in high precision optical frequency metrology,[9] time-resolved spectroscopy[10,11] and optical communication systems.[12] To set a femtosecond oscillator working at a high repetition rate, ring cavity configuration is superior to linear configuration because of the half optical path in the cavity. In addition, laser oscillators with ring cavity design have many other advantages as follows. The self-phase modulation (SPM) and group-delay dispersion (GDD) are automatically distributed as homogeneously as possible with no spatial hole-burning effects in a ring resonator. The pulse travels through the gain medium only once per round trip during which the dispersion induced by the crystal can be reduced by a factor of 2. The relative insensitivity to optical feedback in the ring cavity is advantageous for further application due to the fact that the reflected light is injected into the cavity in the direction opposite to the unidirection of the output laser pulse. Moreover, under high pump power, the asymmetry of the bidirectional lasers in a ring configuration makes the possibility of double pulsing or multi pulsing much less than that in a linear oscillator.[13] Although femtosecond oscillators with gigahertz repetition rate have been realized and successfully used in frequency combs,[14] few lasers at a high repetition rate are in the sub-10fs range.[15] Thus it is highly desirable to generate ultrashort laser pulses with both sub-10 fs pulse duration and a high repetition rate.

In this Letter, we demonstrate a compact Kerr-lens mode-locked (KLM) Ti:sapphire oscillator generating sub-10 fs laser pulses with a repetition rate of 745 MHz. Figure 1 shows the schematic layout of the oscillator. The gain medium is a high doped Ti:sapphire crystal with Brewster-cut angle and thickness of 1.85 mm, which is pumped by a cw all-solid state laser centered at 532 nm (Coherent Verdi laser). The lens L with a focal length of 50 mm is used to focus the pump laser into the laser medium. M1, M2 and M3 are all chirped mirrors for intra-cavity dispersion compensation, of which M1 and M2 is a pair of concave chirped mirrors with radius of curvature (ROC) of 50 mm. In addition, a fused silica wedge (W) with an apex angle of about 2°48′ and tip thickness of only 200 µm is inserted into the cavity to provide finely tunable positive dispersion. The broadband output coupler has a transmission of 3% with a bandwidth of 200 nm centered at 800 nm. The total length of the cavity is about 40.3 cm.

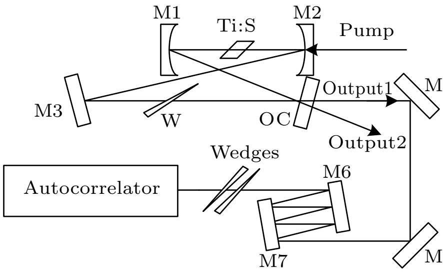

Fig. 1. Schematic of the Ti:sapphire ring oscillator. The pump laser is focused with a 50 mm lens onto the Ti:S crystal. M1–M3, M6 and M7 all are chirped mirrors; W is a fused silica wedge; OC is the broadband output coupler with transmisson of 3%. The radius of curvature of M1 and M2 is 50 mm.

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*Supported by the National Natural Science Foundation of China under Grants Nos 60490281 and 10874237, and the National Basic Research Program of China under No 2007CB815104.

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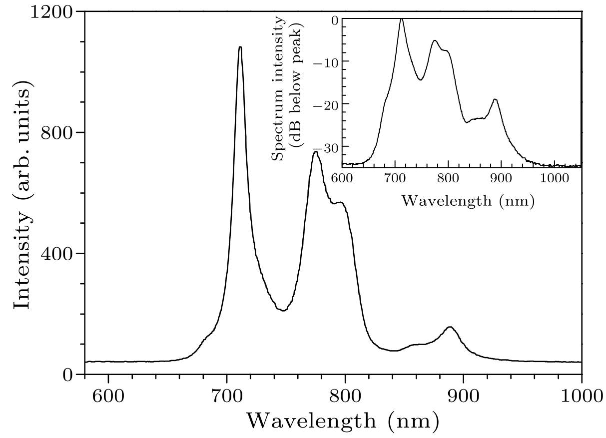

Fig. 2. Spectrum of the output pulses directly from the oscillator.

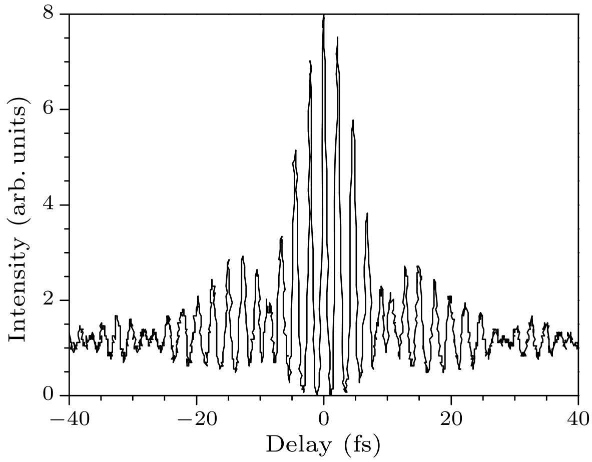

Fig. 3. Interferometric autocorrelation trace of the pulses after extracavity compression.

Initially, the oscillator is aligned for maximum power in bidirectional continuous wave operation at the inner edge[16] of the cavity stability range, where the output powers of laser pulses in both directions are around 100–150 mW. After optimizing the laser operation, we translate M1 towards M2 to start mode locking, until the bidirectional pulses operation is realized with two counter-propagating mode-locked lasers. However, in this situation, the mode locking is unstable, and the bandwidths of both the counter-propagating pulses are not broad enough to support sub-10 fs pulses. With further translation of M1 towards M2, we obtain strongly asymmetric power distribution in the cavity so that the unidirectional mode-locking laser can be realized when we tap mirror M3. In this case, the laser spectrum in a logarithmic coordinate system spans from 660 nm to 940 nm, broad enough to support sub-10 fs pulses, which is shown in Fig. 2. Because of the strong self phase modulation (SPM) caused by the high intra-cavity power of femtosecond pulses, the dispersion within the broadband spectrum, and the asymmetrical transmission of the output coupler, the spectrum is not flat at different wavelengths. It is a typical spectrum of sub-10 fs laser pulses, and the strong SPM in the spectrum is a convincing proof of sub-10 fs pulses, which is similar to the results reported in previous works. In order to obtain pulses as short as possible, we use a pair of chirped mirrors (M6, M7) and a pair of wedges to compensate for the extra-cavity dispersion induced by the output coupler, air, and the beam-splitters of the interference autocorrelator. Based on the optimized balance among all the dispersion, we obtain the shortest pulse duration of the output laser as short as 7.7 fs by a commercial autocorrelator (FEMTOMERER PC-DAQ, Femtosecond Inc.). The interferometric autocorrelation trace of the pulse is shown in Fig. 3. With a commercial spectrum analyzer (Agilent E4402B), we obtain a repetition rate of the pulses of 745 MHz as shown in Fig. 4, which is very consistent with the corresponding cavity length of 40.3 cm.

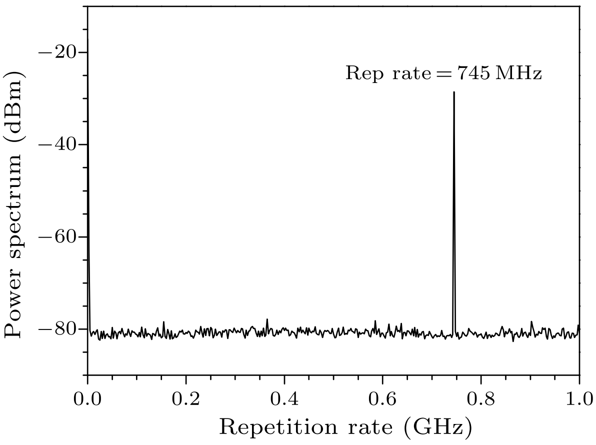

Fig. 4. Repetition rate measured by the spectrum analyzer.

Theoretically, for KLM oscillators, the duration of the laser pulses is given by[17]

$$\tau = 3.53|D|/\phi E_P + \alpha\phi E_P, \qquad (1)$$

where D is the net GDD in the cavity, $\phi = 2n_2L_{\mathrm{Kerr}}/\lambda_0\omega_0^2$ is the Kerr induced phase shift per unit power in the gain medium, E_P is the intra-cavity pulse energy expressed as $E_P = P_{\mathrm{av}}/(T_{\mathrm{OC}}f_{\mathrm{rep}})$, P_{av} is the average power of the output laser pulses, T_{OC} is the transmission of the output coupler and f_{rep} is the repetition rate of the laser pulses. Considering that the dispersions induced by the Ti:sapphire crystal, fused silica and air in unit length are 58 fs^2/mm, 36.1 fs^2/mm, and 21.3 fs^2/m respectively, we calculate that the total positive GDD is 146.56 fs^2 in the cavity. With the chirped mirrors to compensate for the positive GDD, the net GDD intra-cavity is around −33.43 fs^2. To further estimate the phase shift, we also calculate the beam waist in the Kerr medium by using the standard ABCD-matrix, the typical result shows that the beam waist ω_0 is about 13.1 µm. Considering that the central wavelength λ_0 is 800 nm, the nonlinear refractive index n_2 of the Ti:sapphire crystal is $3.2 \times 10^{-20}\,\mathrm{m^2/W}$, and the length of the Kerr gain medium L_{Kerr} is 1.85 mm, we find that the Kerr induced phase shift Ø is $1.027 \times 10^{-6}\,\mathrm{W^{-1}}$. Furthermore, according to the repetition rate of 745 MHz, the average output power of about 480 mW, and the output coupler with transmission of 3%, we may estimate that the intra-cavity pulse energy E_p is 2.24×10^{-8} J. Finally, putting the values of D, Ø, and E_p into the formula (1), we conclude that the pulse duration is 7.43 fs, which is in good agreement with the measured data by the interference autocorrelator, as shown in Fig. 3.

In conclusion, we have demonstrated a compact mirror-dispersion-controlled Ti:sapphire ring oscillator. By optimizing the intra-cavity dispersion and the mode locking range of the ring configuration, laser pulses as short as 7.7 fs with a repetition rate as high as 745 MHz are generated. Considering that there are few oscillators at high repetition rate with pulse duration shorter than 10 fs, these new few cycle laser pulses represent a remarkable new progress in the high repetition rate femtosecond laser field and will be an ideal source in the applications of metrology, spectroscopy, optical communication and other research fields.

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