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Sub-10 fs laser pulses with repetition rate of 1.1 GHz by a Ti: sapphire oscillator

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We demonstrate a compact Ti: sapphire oscillator with ring cavity configuration. By optimizing the intra-cavity dispersion with chirped mirrors, pulses with repetition rate of 1.1 GHz are coupled out by the uncoated wedges in the cavity. Under 7W CW pump laser centered at 532 nm, the average power of the output pulses is about 30 mW, the duration is less than 10fs and the spectrum spans from 670 nm to 920 nm.

Ti:sapphire laser, high repetition rate, few cycle pulse, broadband femtosecond laser pulse

Femtosecond laser pulses generated by Ti: sapphire have arouse great interest since 1990[1]. And femtosecond laser has found more and more application potential because of its compactness, stabilization and high output power. In the last two decades, the pulse duration is refreshed day by day, which makes the ultrafast laser advantageous in the high precision metrology and other fundamental science fields.

With the development of dispersion compensation technique, the record of the pulse duration has been broken time and again, and up to now it has even reached to about 5 fs[2–6]. The few cycle laser pulses have become a predominant tool in the research of ultrafast phenomena in physics[7], chemistry[8], and biology[9]. The ultra-short pulse duration has broadened the application in the field of high precision optics, optical frequency metrology[10], and time resolved spectroscopy[11,12]. On the other hand, pulses with high repetition rate are of great advantage in improving the signal noise ratio (SNR), which is of great importance in the optical frequency measurement and optical communication systems[13]. Therefore, the dominant station of the ultrafast laser pulses with high repetition rate[14] in the field of optical metrology and optical communication is obvious. Based on this, ring cavity configuration is attractive in maintaining high repetition rate[15]. Until now, the repetition rate of laser pulses generated from Ti: sapphire with ring cavity configuration has reached 5 GHz[16], even 10 GHz[17]. Moreover, pulses with repetition rate higher than 1 GHz have been successfully used in the optical metrology experiment. However, there are few oscillators with both high repetition rate and sub-10 fs duration[18]. Thus the generation of sub-10 fs laser pulses with repetition rate higher than 1 GHz is significant.

1 Experimental setup

As shown in Figure 1, a four-mirror ring cavity configuration is used to maintain high repetition rate. The Ti: sapphire is a high doped crystal with Brewster-cut angle, which is pumped by a CW all solid state laser centered at 532 nm (Coherent Verdi laser). The thickness of the gain medium is 1.85 mm, and the FOM is larger than 150. The focal length of the lens L is 30 mm, and the radius of curvature of M1—M2 is 30 mm. M1—M4 are the four intra-cavity mirrors, which make the total length of the cavity to be about 29 cm. And M1—M2 are chirped-mirror pair with a reflectivity larger than 99.8%

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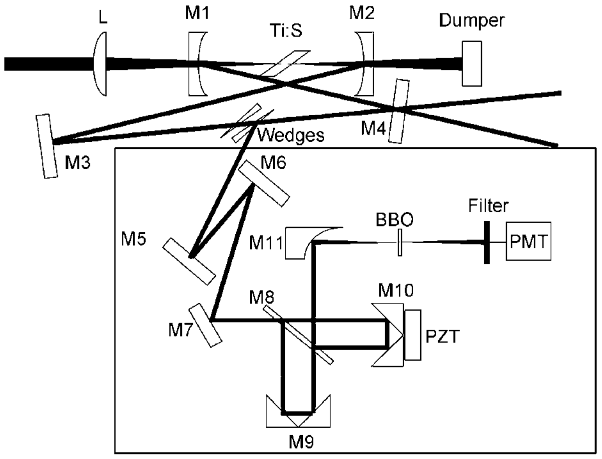

Figure 1 Schematic diagram of experimental setup. L is a lens with focal length of 30 mm; M1 and M2 are concave mirrors with ROC of 30 mm; the elements in the box are used for interference autocorrelation.

in the range of 630—980 nm. Simultaneously, M3 is a broadband plane chirped mirror with a reflectivity larger than 99.7% in the range of 540—1040 nm. Meanwhile, M4 is an output mirror with a transmission of 1%. The wedges in the cavity are used to finely tune the dispersion to ensure the perfect status of mode locking. Besides, M5—M6 is the broadband chirped-mirror pair for extra-cavity dispersion compensation to kill the dispersion induced by the beam-splitter in pulse duration measurement. The ultra-short pulses are reflected by the Ag coated mirror M7 to the commercial autocorrelator (FEMTOLASER PC-DAQ) to realize the duration measurement.

2 Experiment results

Based on the technique of dispersion compensation using chirped mirrors, we maintain a broadband mode locking oscillator by analyzing and optimizing the intra-cavity group velocity dispersion (GVD). The dispersion induced by the elements in the cavity can be calculated by taking the second order derivative of refraction equation. Thus, the GVD induced by air with a length of 1m for the laser centered at 800 nm is about 21.3 fs^2, and 58 fs^2 by Ti: sapphire with a length of 1mm. In order to compensate the positive dispersion, we use the chirped mirrors to supply negative dispersion, and in addition, a pair of wedges to finely optimize the intra-cavity dispersion to obtain a broadband mode locking oscillator.

When the bi-directional CW laser running is realized, we choose the optimized ratio of the cavity length and finely tune the distance between the key elements until the bi-directional mode locking appears. Then we move M2 towards the Ti: sapphire to find the perfect mode-locking range for unidirectional output with broadband and stabilization. By optimizing the cavity configuration, we finally obtain ultra-fast pulses with quite broad bandwidth ranging from 690 nm to 910 nm, which is shown in Figure 2(a). The interference autocorrelation is shown in Figure 2(b), in which there are 6.9 fringes, as a result, the pulse duration is about 9.5 fs. Besides, the repetition rate of the pulses, which is about 1.1 GHz, is obtained by a commercial Agilent Spectrum Analyzer, as shown in Figure 2(c). The average power of

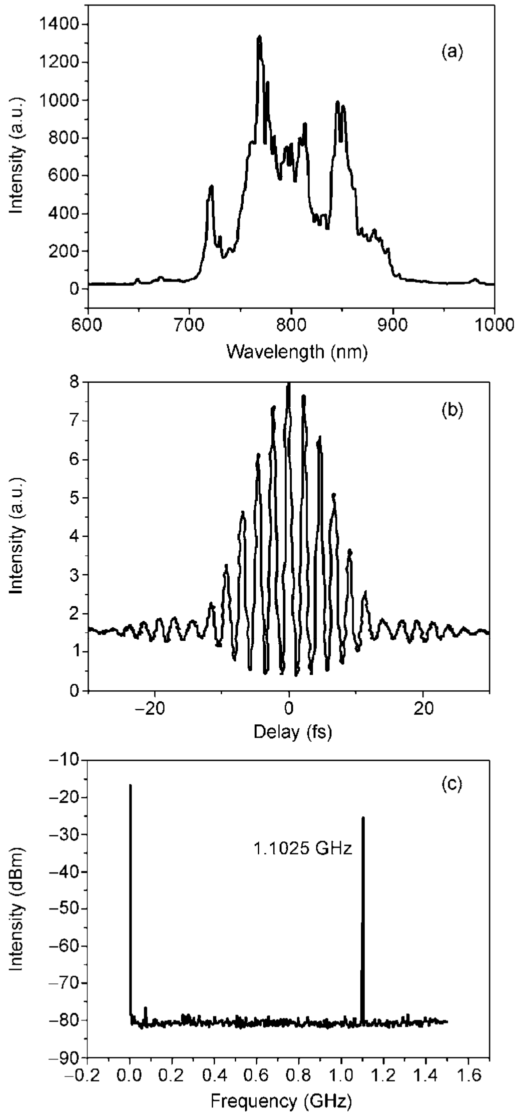

Figure 2 (a) The spectrum of the pulses which are output coupled from the uncoated wedges intra-cavity; (b) The interference autocorrelation of the pulses which are output coupled from the uncoated wedges intra-cavity; (c) The repetition rate of the output pulses.

the output pulses is about 30 mW, because we use the uncoated wedges in the cavity as the output coupler rather than the ordinary output mirror. Although the average power is not very high, the pulse duration can be compressed to shorter than 10 fs without the large dispersion induced by the output mirror. Thus, comparing with the ordinary output method, we find it more advantageous, and this will be demonstrated in detail in the following section.

3 Result analysis

According to the experimental setup, if we use M4 as the output coupler, the thickness of the mirror is about 6.35 mm, which will induce quite large second order and high order dispersion. In addition, the extra-cavity chirped-mirror pair for dispersion compensation will induce high order positive dispersion, which makes the extra-cavity compensation quite difficult and even limits the shortest pulse duration that can be obtained.

The spectrum of the pulses from M4 is shown in Figure 3(a). By using the fft function in Matlab, we can take the Fourier transformation of the spectrum and obtain the limited compressed pulses in time domain. As shown in Figure 3(b), the full width of the half maximum (FWHM) is 7.1 fs.

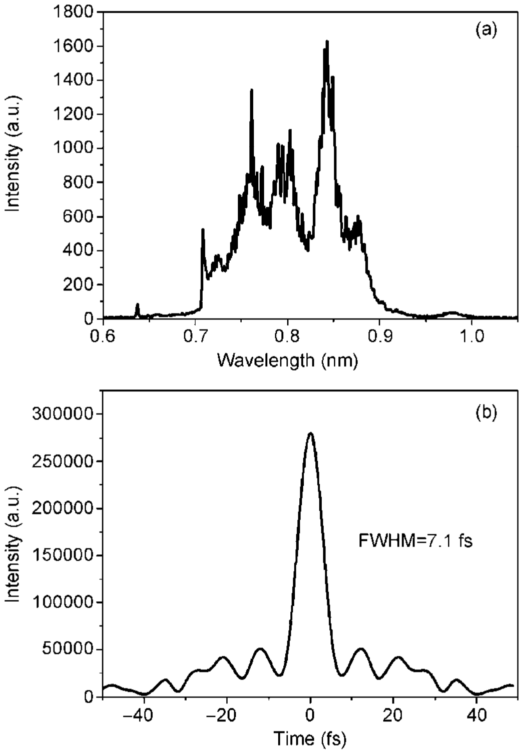

Figure 3 (a) The spectrum of the pulses which are output coupled from M4; (b) the limited compressed pulses from M4 in time domain, which is obtained by Fourier transformation.

If the pulses transmit a fused silica mirror with thickness of 6.35 mm, according to the refractive equation based on Sellmeier equation[19]:

$$n^2-1=\frac{0.6961663\lambda^2}{\lambda^2-0.0684043^2}+\frac{0.4079426\lambda^2}{\lambda^2-0.1162414^2}+\frac{0.8974794\lambda^2}{\lambda^2-9.896161^2}.$$

By taking second order and third order derivation of refractive index, we can get the second order and third order dispersion curve of laser pulses centered at 800 nm, as shown in Figure 4. Then the pulses will be broadened to longer than 20 fs. In order to avoid this, we use chirped mirrors in the cavity to provide second order negative dispersion with small fluctuation. If the dispersion of the extra-cavity chirped mirrors is about –40fs^2, the total dispersion induced by reflection for seven times is about –280 fs^2, which is enough to compensate the dispersion induced by fused silica mirror. However, the dispersion of fused silica mirror increases versus the center frequency of laser and is not as flat as that of the chirped mirrors, which makes it difficult to deal with the broadening of the pulses. If only the second order dis-

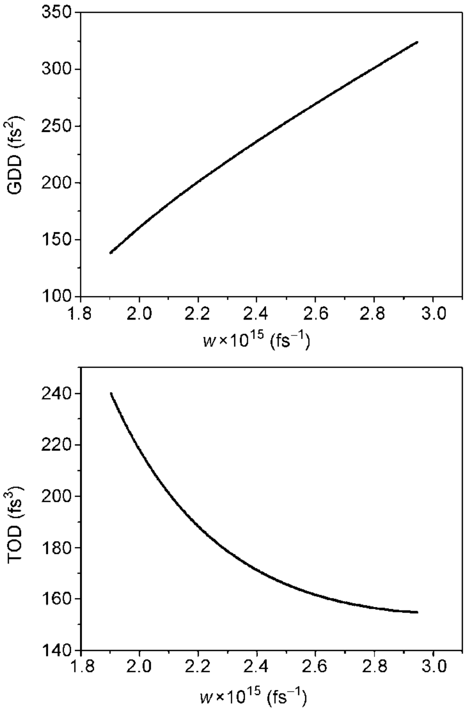

Figure 4 The second order (GDD) and third order dispersion (TOD) induced by the fused silica mirror M4 with a thickness of 6.35 mm.

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persion of the fused silica is considered, we can calculate the pulse duration of the compressed pulses as short as 8.5 fs, which is shown in Figure 5(a). Nevertheless, the high order dispersion induced by the fused silica can hardly be compensated. In addition, the chirped mirror will induce extra-high order dispersion. Considering these, and assuming the high order dispersion is in a cosine function form, we can obtain the compressed pulses with duration of 12.2 fs, which is shown in Figure 5(b). Therefore, to avoid the extra dispersion which makes the broadening of the pulses inevitable, we use the intra-cavity wedges as the output coupler rather than the fused silica mirror, as shown in Figure 1.

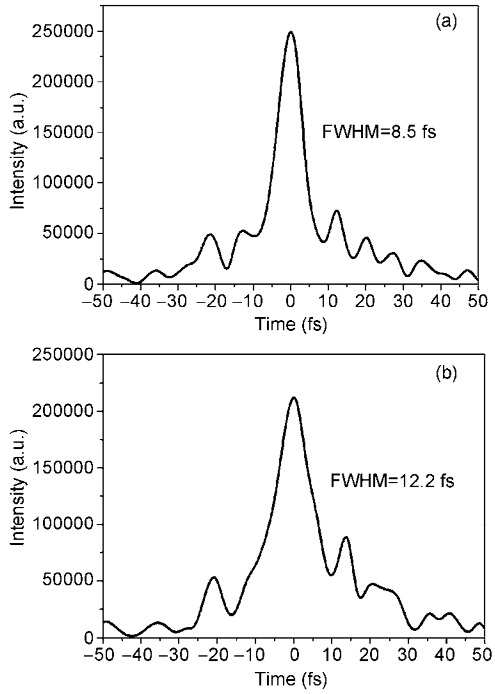

Figure 5 (a) Considering GVD compensation of the fused silica mirror, the compressed pulse in time domain; (b) The compressed pulse in time domain considering GDD compensation and additional TOD of the fused silica mirror.

By calculation, we find that the high order dispersion induced by a thick output mirror is fatal to ultra-short pulse generation, and the second order dispersion which is essential to the pulse broadening can hardly be compensated perfectly. This is why there is difference between the experimental and theoretical results.

4 Conclusions

We demonstrate a four-mirror ring cavity configuration for ultra-short pulses generation with high repetition rate. By calculation and optimization, we use the chirped mirrors as the dispersion compensation elements and intra-cavity wedges as the output coupler. Finally, we obtain ultra-fast laser pulses with duration of 9.5 fs, repetition rate of 1.1 GHz, and spectrum ranging from 670 nm to 920 nm. This is absolutely significant for the development of optical communication, optical frequency metrology and time resolved spectroscopy.

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