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Generation of 7-fs laser pulse directly from a compact Ti:sapphire laser with chirped mirrors

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A compact femtosecond Ti:sapphire laser resonator consisting of three chirped mirrors and one output coupler was designed. By accurately balancing the intracavity dispersions between Ti:sapphire crystal, air and chirped mirrors, we directly generated the laser pulse shorter than 7 fs at the average power of 340 mW with 3.1 W pump. The repetition rate of the laser oscillator is 173 MHz at the centre wavelength of 791 nm, and the ultrabroaden spectrum covers from 600 nm to 1000 nm. To the best of our knowledge, this is the simplest laser resonator capable of generating sub-10 fs laser pulse.

Ti:sapphire laser, chirped mirror, femtosecond, few cycles pulse

Ultrashort laser pulse has wide applications in ultrafast spectroscopy and nonlinear optics[1]. Since sub-10 fs laser pulse has been obtained by compression technology in dye mode-locking laser in the 1980s, few-cycle pulse has become one of the most important topics in this field[2]. With the discovery and development of the solid state mode-locking Ti:sapphire laser, laser pulse shorter than 5 fs, corresponding to less than two cycles, has been generated by different compression technologies in the last 10 years[3−5]. Compared to the complex technology of compression, similar laser pulse can be generated directly from the oscillator with chirp mirrors, prisms or material which are used to compensate the dispersion inside the cavity[6−8]. Although these pulses are a little longer than those generated by compression technology outside cavity, they have more feasible applications because of much lower cost and higher repetition rate, especially in the optical frequency comb. Up to now, pulses of 5—8 fs are directly obtained from the specially designed oscillators by some groups[6−10], however, those laser cavities usually contain a lot of special optics, such as prisms, chirped mirrors and wedges, even the metal mirror, which greatly complicate the

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cavity geometry and sacrifice the power, and the repetition rate is only about 70—80 MHz. As to the domestic research, some groups have obtained short pulses around 10 fs[11,12], but for few-cycle pulses, it is still challenging work. In this paper, we report the generation of 7-fs laser pulse from a novel Ti:sapphire laser cavity which only consists of four mirrors. With 3.1 W pumped power at 532 nm wavelength, the stable mode-locking laser at the average power of 340 mW is obtained at 173 MHz repetition rate, and the corresponding spectrum is beyond 600—1000 nm. To the best of our knowledge, this is the simplest laser resonator capable of generating sub-10 fs laser pulse. Compared to previous works, this work demonstrates a new sub-10 fs laser with the simplest configuration and higher repetition rate.

1 Dispersion analysis

Ultrabroadband spectrum is a necessary specification for supporting ultrashort laser pulse[13]; in addition, the optimized dispersion compensation is also very important. In fact, one of the key techniques of generating very ultrashort pulse is the perfect management of dispersion; however, exactly compensating the dispersion within the ultrabroadband spectrum is challenging work because of the complicated distribution within the spectrum range. Usually, combining the different optical components can supply a more desirable dispersion characteristic to balance those dispersions arising from the laser gain medium, and in general, a single kind of optics cannot cancel the total dispersion completely. To realize an ideal compensation, the accurate calculation on dispersion of different optical components is necessary.

For a femtosecond Ti:sapphire laser with chirped mirrors, the chirped mirrors contribute the negative dispersion, and the gain medium and the bulk materials contribute the positive dispersion. To achieve an accurate compensation, the positive dispersion of air should be also considered. According to the Sellmeier equation, the dispersion formula of Ti:sapphire crystal is[14]

$$n_o^2-1=\frac{1.4313493\lambda^2}{\lambda^2-0.0726631^2}+\frac{0.65054713\lambda^2}{\lambda^2-0.1193242^2}+\frac{5.3414021\lambda^2}{\lambda^2-18.028251^2},$$

and for the typical bulk material of fused silica, the dispersion equation can be expressed as[14]

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

The dispersion function is[15]

$$(n-1)\times 10^8 = 8060.51+\frac{2480990}{132.274-\dfrac{1}{\lambda^2}}+\frac{17455.7}{39.32957-\dfrac{1}{\lambda^2}}.$$

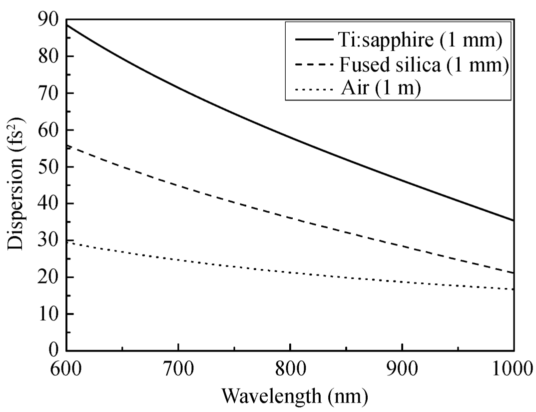

Figure 1 Dispersion calculation.

Based on the above dispersion equations, we calculated the dispersion functions of Ti:sapphire crystal, fused silica and air in unit length as in Figure 1. From the figure, we can know that these dispersions at the wavelength of 800 nm are 21.3 fs^2 for 1 m optical path in air, 58 fs^2 for 1 mm Ti:sapphire crystal and 36.1 fs^2 for 1 mm fused silica, respectively. Although the dispersion of the air is very small, the long cavity length can also lead to a considerable contribution compared to the material dispersions of Ti:sapphire crystal and fused silica, and therefore, choosing a suitable cavity length will be helpful to the dispersion balance inside the cavity, and support the generation of very short laser pulse.

2 The experiment

According to the calculation, the material dispersion of the Ti:sapphire crystal plays the most important role for pulse duration. The Ti:sapphire crystal with shorter thickness will support a shorter laser pulse. For this reason, we used a high doped Ti:sapphire crystal (produced by Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences) with thickness of 2 mm as the gain medium. The laser cavity consists of a pair of concave mirrors, a plane mirror and an output coupler. Figure 2 shows the schematic experimental setup, the focal length of the lens L is 50 mm, M1 and M2 are a chirp mirror pair with radius of curvature (ROC) of 50 mm, the transmissivity is over 90% between 503 nm and 535 nm, and the reflectivity is over 99.9% between 700 nm and 950 nm. The group dispersion delay (GDD) of the M1 and M2 oscillates around -50 fs^2, but the net GDD is very flat between 680 nm and 940 nm. M3 is a plane chirp mirror, the reflectivity is over 99.6% between 580 nm and 1020 nm, and the GDD oscillates around -60 fs^2 between 700 nm and 1000 nm. The output coupler is 10% over 660—920 nm. The 2 mm Ti:sapphire crystal has a GDD of about 120 fs^2 and 1 m air has a GDD of about 20 fs^2 at 800 nm. By calculating all the GDD of the three chirp mirrors and the Ti:sapphire crystal as well as the air, the net dispersion inside the cavity is near zero.

Few-cycle laser pulse can be produced based on the accurate dispersion calculation for all the

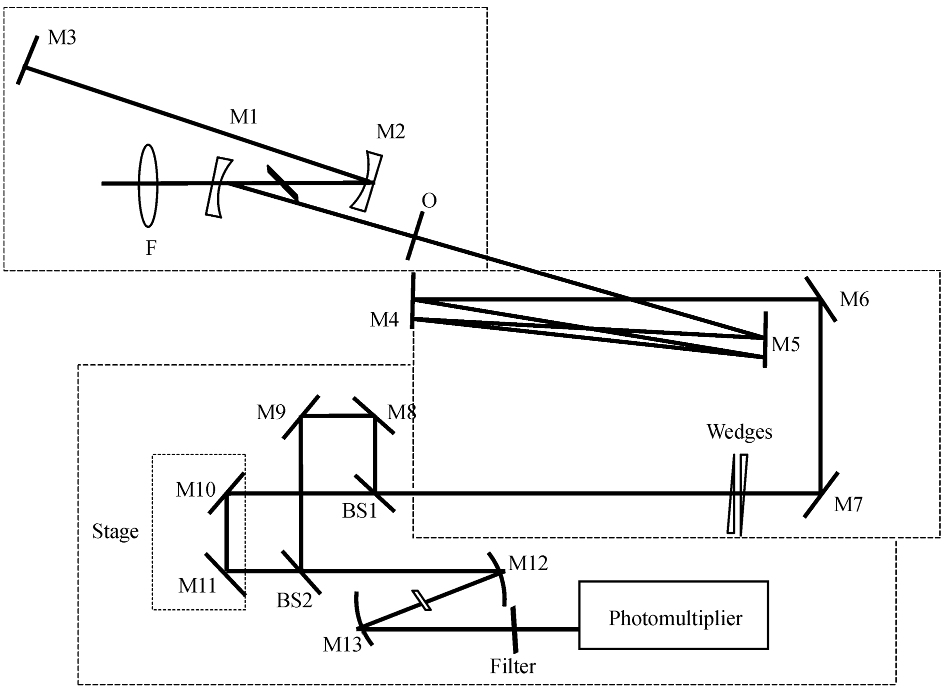

Figure 2 Schematic layout of laser generation and pulse measurement.

optical components inside the cavity. However, because of the material dispersions arising from the output coupler, air and the beam splitter, etc., in general we could not get very short pulse by direct measurement. To pre-compensate the dispersions, we add a pair of chirped mirrors and wedges before the autocorrelator, and the schematic layout of laser measurement is also shown in Figure 2. M4, M5 are plane chirp mirrors, the reflectivity is over 99.6% between 500 nm and 1000 nm, and the GDD oscillates around -40 fs^2 between 500 nm and 930 nm. M6, M7 are protected plane silver mirrors. The fused silica wedge has an apex angle of about 2°48′ and the thinnest thickness at tip is only 200 μm. By changing the inserting amount, the dispersion of wedges can be adjusted from 15 fs^2 to 110 fs^2, so that the total dispersion among the 1 mm output coupler, the 1 mm beam splitter, the air, the protected silver mirrors as well as the chirped mirror pair can be well balanced to zero. In this case, the shortest laser pulse can be measured.

We measured the pulse duration by a homemade autocorrelator and a commercial autocorrelator (FEMTOMERER PC-DAQ, Femtosecond Inc.) respectively. By comparing both curves of the autocorrelation traces, we can confirm the correctness of measurement. In Figure 2, M8—M11 are plane silver mirrors, M12 and M13 are curved silver mirrors with ROC 50 mm, and BS1 and BS2 are the 1-mm-thin beam splitters (BS). Besides the thin output coupler OC and BS, the BBO is a thin nonlinear crystal with thickness of 20 μm.

3 Results and discussion

The femtosecond laser oscillator is pumped with an all-solid-state 532 nm doubled frequency Nd:YVO4 laser (S-P Inc., Millennia). Considering the application for frequency comb, we design the cavity length less than 1 m for the high repetition rate. With 3 W pumped power, we can easily obtain the continuous-wave (CW) running because of the concave mirror with ROC of 50 mm, and the typical average power is higher than 300 mW. By further aligning the distance between two concave mirrors, the stable mode-locking operation is realized by pushing the OC or the end mirror M3 which is mounted on the translational stage. The instability of the average power of the mode-locking is 0.9% measured by a power meter, and the instability of the peak-to-peak amplitude precedes 5% measured by an oscilloscope. In the experiment, we find that the tolerance of M2 moving for realizing the mode-locking is about 200 μm. The color of laser spot is very different when the M2 moves at different positions, and we even can directly recognize the weak yellow color when dispersing the laser with a prism. Under the case of the widest spectrum, we find that the beam spot is anomalous, and it is also bigger than that longer than 10 fs laser pulse. We can easily understand that it is because the wider spectrum worsens the focused ability. We measure the largest spectrum (Ocean Optics Inc) as in Figure 3.

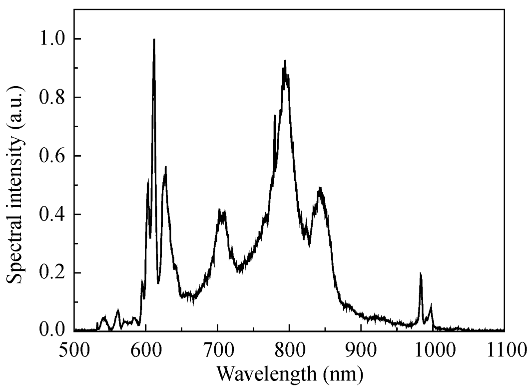

Figure 3 Ultrabroaden spectrum from the oscillator.

We first measure the pulse duration by the homemade autocorrelator. However, the measured data are not ideal and the real pulse is only about 20 fs, which reveals that the large dispersion widens the pulse duration, so that a wider spectrum could not support the short pulse. By inserting the chirped mirror M4 and M5 to compensate the net dispersion outside cavity, we finally get the short pulse less than 10 fs with the optimized alignment. Further we use a commercial PC-DAQ autocorrelator to measure the same pulse, and because the accuracy of the metallic mirrors and the BS maybe bring the difference, we find that the measured result with domestic autocorrelator is a little wider than that one with PC-DAQ autocorrelator. We believe that the PC-DAQ has a more correct measurement.

With the optimized alignment of the wedges and the cavity, we observe that the pulse duration was running between 7 and 8 fs from the PC-DAQ autocorrelator. Figure 4 shows the typical autocorrelation trace, which is 5.4 fringes corresponding to the pulse width of about 7.5 fs. The corresponding spectrum is shown in Figure 4, and it shows the width-at-half- maximum of 112 nm with the central wavelength of 791 nm. The pulse is only 2.8-cycle.

Figures 4 and 5 are the results with 3.1 W pumped power. The average power is 340 mW with 173 MHz repetition rate. We use a four-mirror linear cavity geometry which is different from those in refs. [6—10], and a higher average is obtained because of no losses from the wedges and other materials inside the cavity. In addition, the higher repetition rate makes the laser have more ideal application as the optical frequency comb. To the best of our knowledge, this is the simplest scheme for sub-10 fs laser generation up to now, and the output power is higher than those in other similar works.

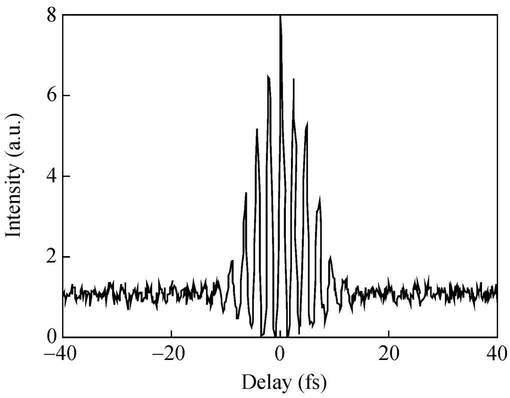

Figure 4 Autocorrelation function record.

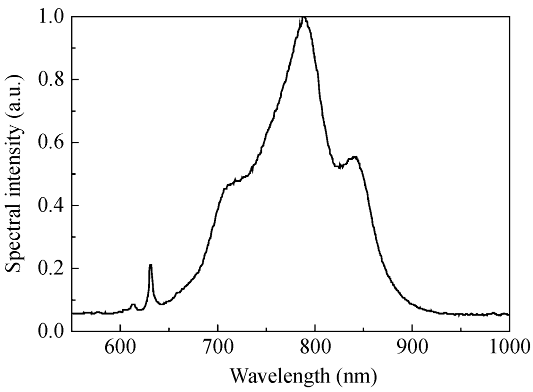

Figure 5 Spectrum.

4 Conclusion

In conclusion, based on the accurate calculation on the dispersions, laser pulse of 7.5 fs was generated directly from a femtosecond Ti:sapphire laser with three chirp mirrors. The laser cavity is a four-mirror linear configuration. To the best of our knowledge, this is the simplest laser resonator capable of generating few-cycle laser pulses. Compared to the congener reports, the higher average power and repetition rate make it more usable in the ultrafast science and as an optical frequency comb. We believe that even shorter pulse may be generated by inserting some material inside the cavity to finely tune the dispersion.

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