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Generation of 10 fs Ti:sapphire laser at repetition rate of 525 MHz and measurement of carrier-envelope phase frequency*

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This paper presents a Kerr-lens mode-locked Ti:sapphire laser at the repetition rate of 525 MHz, stable laser pulse as short as 10 fs with average output power of 480 mW is obtained. By injecting the pulse into photonics crystal fibre, octave-spanning spectrum covered from 500 to 1050 nm is generated, carrier-envelope phase frequency with signal-to-noise ratio of 31dB is measured, which paves the way for the generation of a compact frequency comb.

Keywords: high repetition rate, femtosecond, supercontinuum, carrier-envelope phase
PACC: 4280W，4262E

1. Introduction

As the conjunction of the ultrashort laser and the laser spectroscopy, the femtosecond laser frequency combs based on mode-locked Ti:sapphire lasers have been successfully used in the high precision optical frequency measurements and comparisons.[1−5] To pursue an ultra-broadening band spectrum for frequency comb application, in general a femtosecond Ti:sapphire laser with sub-10 fs pulse duration is necessary. Although such kind of lasers have been well developed by few groups,[6−10] the repetition rate is less than 100 MHz. In general, high repetition rate (HHR) femtosecond lasers have tremendous advantages in comparison with the 100 MHz femtosecond lasers as the optical frequency comb.[11,12] Given a constant average power, HHR lasers can provide more optical power per mode, which is advantageous for the optical frequency metrology. In addition, HHR lasers also allow compact configuration because of the short cavity length. Since the shorter cavity length leads to fewer longitudinal modes inside the laser resonator and weakens the self phase modulation (SPM), it is a challenging work to generate shorter pulse from the HHR laser. For example, the HHR femtosecond Ti:sapphire laser up to 1GHz has been realized and octave-spanning spectrum has also been directly obtained by some groups with ring cavity design,[13] however, to generate laser pulse as shorter as 10 fs still remains difficult, the ring cavity also results in a lower power in comparison with the linear cavity. In this paper, we report a 10 fs Ti:sapphire laser at a repetition rate of 525 MHz by using a linear cavity configuration, to the best of our knowledge, this is the highest repetition rate for supporting 10 fs laser pulse with linear cavity setup, corresponding to the 1.05GHz repetition rate for ring cavity. By coupling the laser pulse into a photonics crystal fibre (PCF), an octave-spanning spectrum was generated. Furthermore, we measured a beat frequency with signal to noise ratio (SNR) of 31 dB by the self-reference technology, which supplies a feasible way toward control the carrier-envelope phase (CEP) of the HHR Ti:sapphire laser.

2. Experimental setup

The experimental scheme is shown in Fig.1, we use a linear laser cavity configuration which is composed of only 4 mirrors. To reduce the material dispersion, we used a thin Ti: sapphire crystal plate with the path length of 2.1 mm as the gain medium, the crystal was doped with absorption coefficient of 7.2 cm^{-1} at 532 nm and mounted at Brewster's angle. Considering the equivalent optical length of the crystal, we approximately introduce the group delay dispersion (GDD) of 120 fs^2 at 800 nm. The plane chirped mirror CM

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gives negative GDD of $-60\,\mathrm{fs}^2$ per bounce over 700–1000 nm range, F1 and F2 are pair of concave chirped mirrors with radius of curvature of 50 mm, the dispersion oscillation is compensated each other and results in a net GDD of $-70\,\mathrm{fs}^2$ per bounce with the wavelength range from 680 nm to 940 nm. OC is the output coupler with 3% transmission over 700 − 850 nm and near zero GDD.

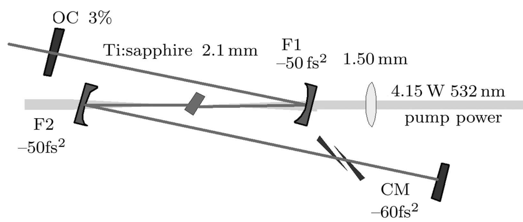

Fig.1. Experimental setup of the femtosecond Ti:sapphire oscillator with linear cavity configuration at 525 MHz.

Calculating the total GDD of all elements in the cavity, we find that the net GDD is about $-10\,\mathrm{fs}^2$. To well compensate the net dispersion intracavity, we use a pair of fused silica wedges with minimized thickness of about 200 μm to adjust the material dispersion, the wedge pair also can fine tuning the laser offset frequency corresponding to the CEP.

3. Generation of 10-fs laser pulse

To run the laser at a high repetition rate, we set one laser arm from F1 to OC as 85 mm, the other laser arm from F2 to CM as 150 mm, the 2.1 mm Ti:sapphire crystal was set around the con-focal point between two concave chirped mirrors F1 and F2, so that the total cavity length is about 285 mm. Based on the above configuration, we calculated the beam waist in the Kerr medium which is about 18 μm with $ABCD$ matrix. The distance between two concave mirrors is a crucial parameter for starting the mode-locking operation, by optimistically aligning the second concave mirror F2, we generated stable mode-locking laser at the average output power of 480 mW under 4.2 W pump power (Verdi-5 Coherent Inc). A spectrometer (HR2000CG-UV-NIR, Ocean optics Inc.) was used to measure the laser spectrum. Figure 2(a) shows the typical result, it covers from 675 nm to 975 nm, the full width at half maximum (FWHM) bandwidth is about 82 nm, centre wavelength is 790 nm, corresponding to a 8 fs laser pulse with the Fourier transform limited in theory. With a spectrum analyser (E4402B, Agilent Inc.), we measured the repetition rate to be 525 MHz as shown in Fig.2(b).

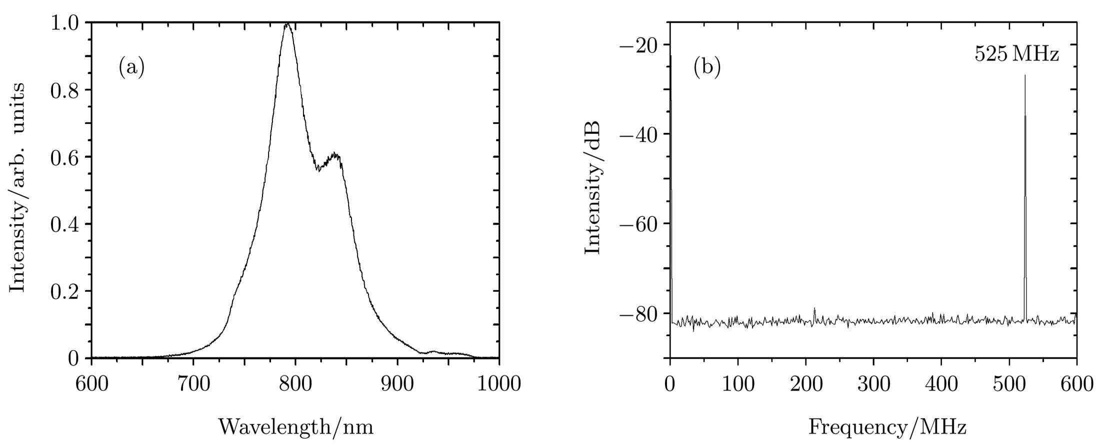

Fig.2. The laser spectrum (a) and the repetition rate (b) of the mode locking Ti:sapphire laser.

For a sub-10 fs laser pulse, the pulse duration will be greatly stretched by dispersion. Considered the GDD by the 6.35-mm-thick output coupler, we used a pair of plane chirped mirrors with GDD of $-30\,\mathrm{fs}^2$ per bounce over 700 nm–890 nm before the interferometric autocorrelator to measure the pulse. With six bounces reflection and a pair of fused silica wedges to finely compensate the dispersion, we measured the autocorrelation trace as shown in Fig.3 (solid line), it shows about 7.2 fringes above the half of the normalized intensity, corresponding to a pulse duration of 10 fs with sech square shape pulse assumption. Simulation fit the pulse envelope (dash line in Fig.3) also reveals a 10 fs laser pulse, it well agrees with the experimental result.

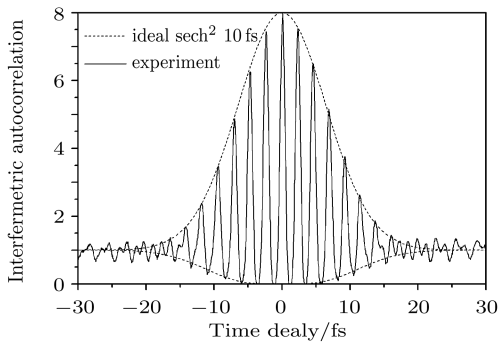

Fig.3. The interofermetric autocorrelation trace (solid line) and the fitted envelope (dash line). Both support 10fs laser pulse with sech square shape.

4. Spectrum broadening and CEP frequency

To further broaden the spectrum for CEP frequency measurement with self-reference technique,[14] we launched the 10 fs laser pulse train into a photonics crystal fibre (PCF, NL-PM-750, Crystal Fibre Inc.) with a length of 15 cm and core diameter of 1.8 μm, a standard microscope objective lens with magnification of 60X was used to couple the laser into the core of fibre. The nonlinear effect in the fibre is very sensitive to the variation of input power, so a stable mounting stage with 3-axis translation is needed. By optimizing the coupling system, the output power of the supercontinuum can reach to about 80 mW under the input power of 240 mW. Since the property of polarization depends on the fibre, a half wave plate for 800 nm is used for rotating the laser polarization. Figure 4 shows the supercontinuum spectra with two different input polarization, respectively, and an octave-spanning spectrum covered from 500 nm–1050 nm can be obtained (line B in Fig.4).

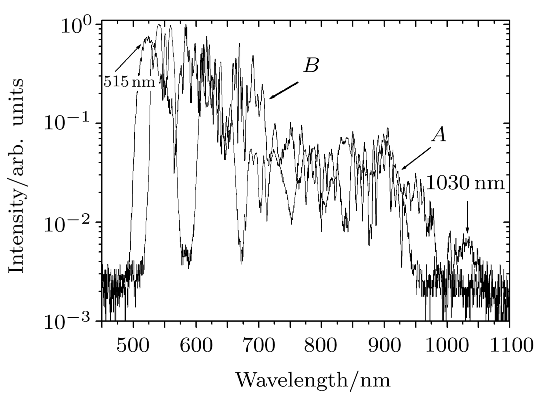

Fig.4. Supercontinuum spectra with polarization states of input laser pulse. Line A shows the spectrum covered from 525 to 950 nm, and B covered from 500–1050 nm.

The output octave-spanning spectrum from the PCF is then sent to the standard $f-2f$ interferometer for measuring the CEP frequency, a 4 mm KTP crystal was firstly used to double frequency the 1030 nm laser components in the supercontinuum spectrum. Finely overlap the second harmonic wave with the 515 nm laser component in the octave-spanning spectrum in temporal and spatial domain, we measured the laser offset frequency $f_{\rm ceo}$ with a SNR about 31dB in 300 kHz bandwidth. Figure 5 shows the frequency spectrum observed by the spectrum analyser, beside the $f_{\rm ceo}$, it also displays the repetition rate $f_{\rm rep}$ and the difference frequency between $f_{\rm rep}$ and $f_{\rm ceo}$. The measured results of 525 MHz repetition rate and 31 dB offset frequency pave a solid way toward CEP control and ideal frequency comb by further locking the frequencies to microwave atom clock.

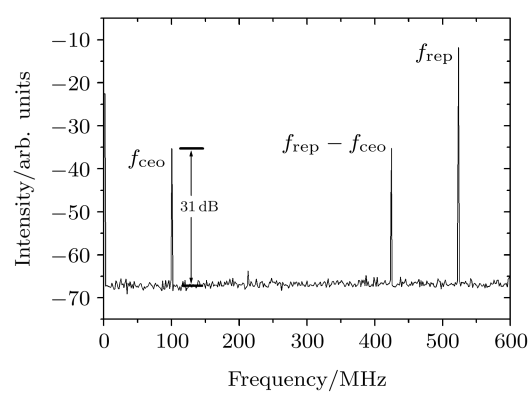

Fig.5. The frequency spectrum measured with the spectrum analyser. $f_{\rm ceo}$: offset frequency, $f_{\rm rep}$: repetition rate.

5. Conclusion

In conclusion, we have demonstrated a linear femtosecond Ti:sapphire laser oscillator with 10 fs pulse duration at 525 MHz repetition rate. Broadening the spectrum by PCF, we further measured the offset frequency with SNR of 31 dB. These results pave a solid way toward phase control of femtosecond laser and frequency comb.

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