Operation of Kerr-lens mode-locked Ti:sapphire laser in the non-soliton regime*

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A Kerr-lens mode-locked Ti:sapphire laser operating in a non-soliton regime is demonstrated. Dispersive wave generation is observed as a result of third order dispersion in the vicinity of zero dispersion. The characteristics of the Ti:sapphire laser operating in a positive dispersion regime are presented, where the oscillator directly generates pulses with duration continuously tunable from 0.37 ps to 2.11 ps, and 36 fs pulses are achieved after extracavity compression. The oscillation is numerically simulated with an extended nonlinear Schrödinger equation, and the simulation results are in good agreement with the experimental results.

Keywords: Kerr-lens mode locking, dispersive wave generation, positive dispersion regime, Ti:sapphire laser

PACC: 4260, 4280W, 4265J

1. Introduction

Since it was first demonstrated in 1991,[1] the Kerr-lens mode-locked (KLM) Ti:sapphire laser has been widely used in ultrafast science. The improving performances of peak power and pulse duration of these lasers offer great potential to widespread applications. To date, pulses with peak power exceeding the megawatt level[2] and duration shorter than two optical cycles[3,4] have been generated directly from Ti:sapphire oscillators. Previous intensive studies have shown that it is in the negative group delay dispersion (GDD) regime that these pulses with little chirp are produced. In this regime, the soliton-like pulse shaping process, originating primarily from the interplay between self-phase modulation (SPM) and negative GDD, is considered as a major pulse shortening mechanism.[5−7] The main role of self amplitude modulation (SAM) caused by the Kerr-lens effect is to initiate pulse formation and to provide stability against noise buildup. Most studies about KLM Ti:sapphire lasers concentrated on this negative GDD operating regime.[8−10] However, with positive net cavity GDD, stable and highly chirped pulses formed by another pulse shaping mechanism were demonstrated theoretically and experimentally.[11,12] In the positive dispersion regime (PDR) gain dispersion plays a primary role in the pulse shaping process by cutting the temporal wings of the highly chirped pluses. Theoretically, Ti:sapphire lasers operating in PDR can deliver high energy pulses directly from the oscillators, because the long pulses due to high chirp can offer a relatively low peak power and thereby suppress instabilities caused by excessive intensities in the laser crystal.[13] Great potential for high power operation makes these lasers an alternative technique to replace complex and expensive ultrashort pulse amplifier systems.[13−15] In addition to stable operating regimes with negative and positive GDDs, there is an unstable region in the vicinity of zero GDD.[11] A lot of phenomena such as multipulse operation and dispersive wave generation have been observed in this region.[16−19]

In the present paper, we demonstrate a KLM Ti:sapphire laser operating in a non-soliton regime, i.e. in the vicinity of zero dispersion and PDR. A relatively long Ti:sapphire crystal serves as the gain medium and provides more nonlinearities. Dispersive

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wave generation due to the effect of third order dispersion (TOD) is observed with small negative GDD. As the cavity GDD decreases, the Ti:sapphire laser transfers from the negative to the positive GDD operating regimes. Characteristics of the KLM Ti:sapphire operating in the PDR are revealed as the positive dispersion is continuously increased. It is shown that pulses generated from the Ti:sapphire laser operating in PDR are highly chirped and have a large tunability in pulse duration. The direct output chirped pulse can be tuned continuously from 0.37 ps to 2.11 ps, and the pulse duration is achieved to be as short as 36 fs after extracavity compression. A theoretical model is developed to simulate the practical laser operation, and numerical results accord well with the experimental results.

2. Experiment and results

The experimental setup of the Ti:sapphire laser is shown in Fig. 1. The laser cavity is an x-fold configuration with a 9-mm long Brewster-cut Ti:sapphire crystal as the gain medium. Two dichroic spherical mirrors (M_1, M_2), with a 100 mm radius of curvature, are highly transmissive for the pump light and focus the laser near 800 nm into the crystal. M_4 is a high-reflection flat mirror and serves as one of the cavity mirrors. The wedged output coupler (OC) is the other cavity mirror and has a transmission of approximately 22%. A pair of fused silica prisms (P_1, P_2) for dispersion compensation are placed in the longer arm with an apex-to-apex distance of 950 mm. The intracavity dispersion can be tuned continuously by adjusting the insertion length of prisms. The total cavity length is about 1.82 m.

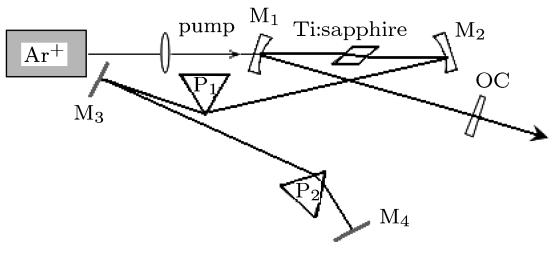


Fig. 1. Schematic of the experimental setup. M_1, M_2, dichroic spherical mirrors (R = 100 mm); M_3, M_4, flat high-reflection mirrors; P_1, P_2, fused silica prism sequence for dispersion control with an apex-to-apex distance of 950 mm; OC, 22%-transmission wedged output coupler.

The Ti:sapphire laser is pumped by a cw argon-ion laser. With a pump power of 6 W, the output average power is about 500 mW. The output power is insensitive to the change of intracavity dispersion in the experiment. The Ti:sapphire laser can operate in different regimes in terms of the net intracavity GDD, which is controlled by adjusting the insertion length of prism P_2. When the prism has a relatively small insertion, the Ti:sapphire laser operates in the negative dispersion regime, where femtosecond pulses are generated by soliton-like pulse shaping mechanisms. With the increase of the prism insertion, the net negative GDD decreases and approaches the vicinity of zero. The operation state of the Ti:sapphire laser in this region is unstable and complicated.[11,16−19] Rapid variations of the spectra are recorded with different insertions of prism P_2 as shown in Fig. 2. Obviously, sideband is generated on the high frequency side of the spectra (curves b, c, d in Fig. 2), which is due to the enhanced effect of TOD. As the negative GDD decreases, the influence of TOD becomes significant, causing dispersive wave (i.e. sideband) generation.[6,16] The sideband also becomes stronger as TOD increases. It should be noted that the dispersive wave in Fig. 2 appears on the high frequency (short wavelength) side of the spectra, which is opposite to the previous observations.[17,18] Such a difference should be attributed to different signs of the TOD.[6,16] It is noticeable that curve e in Fig. 2 shows a unique spectrum: on the low-frequency side, it exhibits a Gaussian shape profile which is generated from the dispersion managed mode-locking process with low negative dispersion,[5] while on the other side, the steep edge of the spectrum

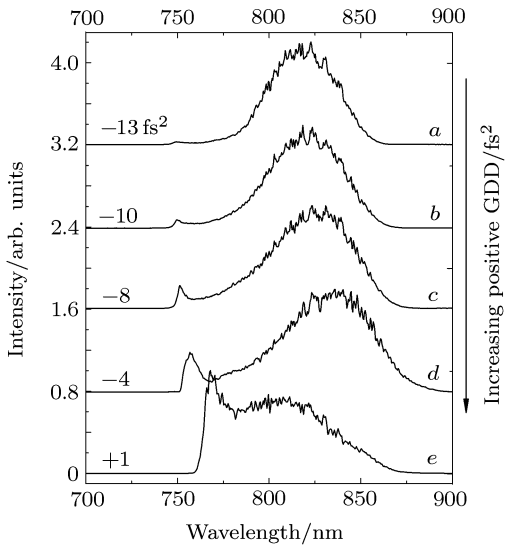


Fig. 2. Spectra with different net cavity dispersions in the vicinity of zero GDD. The GDD values are calculated at a central wavelength of 800 nm.

characterizes the Ti:sapphire laser operating with positive dispersion. So this spectrum shows the intergradation of the operating regime from negative dispersion to positive dispersion. The oscilloscope recording shows that this mode-locking state is unstable.

As the insertion of prism P_2 continues to increase, the net dispersion becomes positive and the mode-locking turns stable again. The mode-locking can be initiated by perturbing the cavity mirrors or the intracavity prisms slightly. Figure 3 shows the variation of spectra as a function of the insertion length of prism P_2. As a comparison a typical spectrum generated in the negative dispersion regime is shown as curve a in Fig. 3. The corresponding net GDD values labelled in Fig. 3 are theoretical values at 800 nm calculated according to the dispersion parameters of the Ti:sapphire crystal and the prisms.

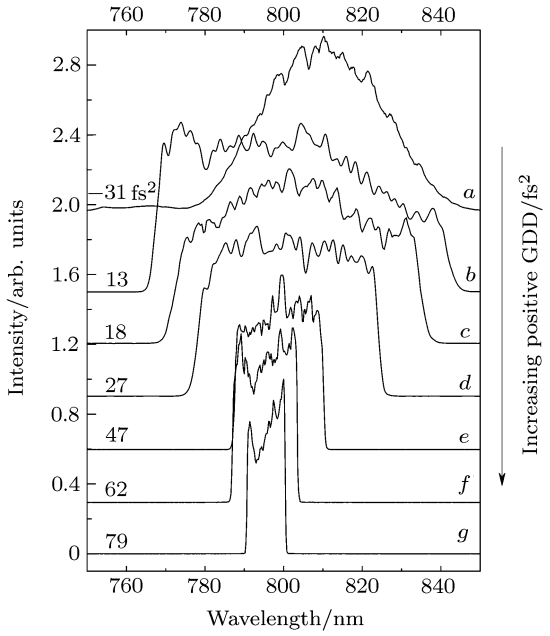


Fig. 3. Variations of power spectra with different insertions of P_2 in the positive dispersion region. The GDD values are calculated at a central wavelength of 800 nm. Curve a: sech^2 profiles, b: asymmetrical spectrum, c: parabolic-like spectrum, d: flat-top spectrum.

As shown in Fig. 3, spectra generated in the PDR have a nearly rectangular shape with steep edges. These spectra are distinct from the sech^2 profile (curve a in Fig. 3), because they are produced by different mode-locking mechanisms. For the positive dispersion, the stable pulse spectra are formed by the interplay of SPM and spectrum filtering originating from the limited gain bandwidth and the Kerr-lens effect. The former generates new frequencies in the gain medium, whereas the latter cuts off two low intensity edges of the highly chirped pulses, i.e. the high and the low frequency sections. As a result of the dynamic balance, rectangular-like spectra profiles are generated. The stable spectral profiles are dramatically affected by the intracavity dispersion as shown in Fig. 3. Asymmetrical (curve b), parabolic-like (curve c), and flat-top (curve d) spectral profiles can be observed with corresponding GDDs of 13 fs^2, 18 fs^2, and 27 fs^2, respectively. These spectra are qualitatively similar to those in the previous studies.[15,20] Theoretically, the rapid evolution of spectral profile is attributed to a different distribution of the intracavity dispersions,[20] which is frequency dependent and changes as the prism insertion changes.

In the PDR, the positive GDD introduces large chirp to the pulses and thereby stretches them. Figure 4 shows the intensity autocorrelation traces of the direct output pulses with different positive GDDs. Pulse durations (assumed to be of Gaussian pulse shape) are 0.428 ps (solid curve), 0.94 ps (dashed curve) and 2.11 ps (dotted curve), with the associated spectra shown in Fig. 3 as curves c, e and g, respectively. Large time-bandwidth products indicate that the output pulses are highly chirped and can be compressed externally. A pulse duration of 0.428 ps can be extracavity dechirped into 36 fs as shown in the inset of Fig. 4. Side wings on the autocorrelation trace imply some residual uncompressed chirp and capability of further compression. With optimized dispersion compensation, a shorter pulse can be obtained.

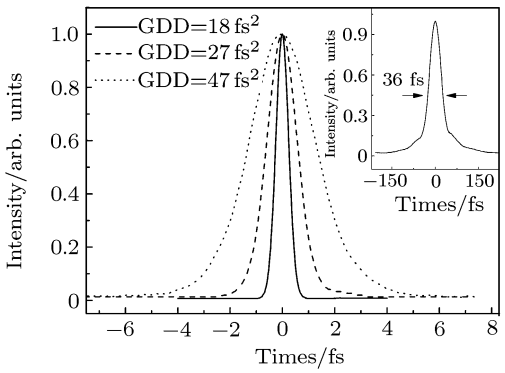


Fig. 4. Intensity autocorrelation traces of the direct output pulses with different positive GDDs. The inset shows the autocorrelation trace of the dechirped pulse (GDD=18 fs^2).

As mentioned above, spectral profiles and bandwidth of the output pulses strongly depend on the intracavity dispersion in the PDR, and the dispersion also has a dramatic effect on the time duration and

chirp. Dependences of the stable spectrum width and the pulse duration on the positive GDD are experimentally measured and shown in Fig. 5. In accordance with the previous theoretical and experimental results,[11,21] pulse duration increases monotonically with the positive GDD, whereas the bandwidth becomes narrower as the GDD grows. It is also found that lasers in the positive dispersion regime have great tunablility. The direct output pulses can be continuously tuned from 0.37 ps to 2.11 ps based on our experiment as shown in Fig. 5.

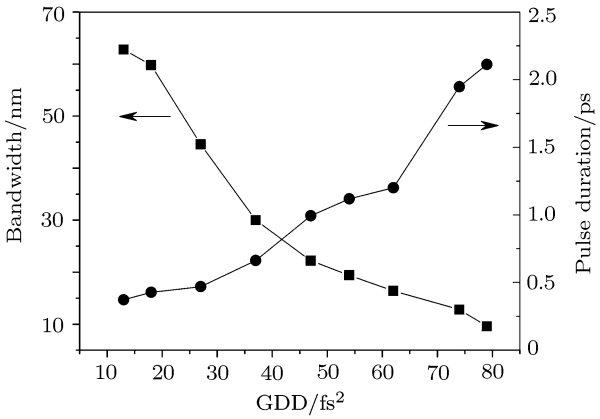


Fig. 5. Dependences of bandwidth and pulse duration on positive GDD.

3. Numerical simulation

In order to understand the properties of the Ti:sapphire laser operating in the PDR, a theoretical model that characterizes the practical laser is developed. Gain, nonlinearity in the active medium and dispersion distribution around the cavity are taken into account according to the experimental setup (Fig. 1). In detail, the simulated laser consists of three segments. The first segment is the positive GDD segment with gain, SPM and fast saturation absorber (SA) due to the Kerr-lens effect inside the gain medium. The second one is the negative GDD segment corresponding to the prism sequence in the experimental setup, and the third one is the OC with a constant transmission of 22%. Elements of each segment and respective effects on the pulse generation are illustrated in Fig. 6.

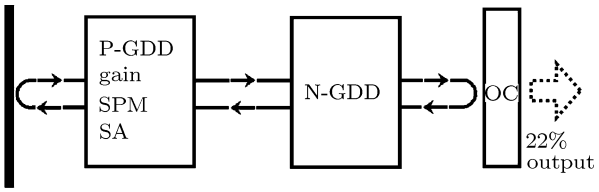


Fig. 6. Numerical model. P-GDD: positive GDD, SPM: self-phase modulation, SA: saturation absorber, N-GDD: negative GDD, OC: output coupler.

Pulse propagation around the cavity can be described by the extended nonlinear Schrödinger equation[22,23]

$$\frac{\partial A}{\partial z} = \frac{1}{2} g\left(E_p\right) A - \frac{\mathrm{i}}{2}\left[\beta_2 + \mathrm{i}\, g\left(E_\mathrm{p}\right) \frac{1}{\Delta\omega^2}\right] \frac{\partial^2 A}{\partial T^2} + \mathrm{i}\,\gamma\left|A\right|^2 A - q\left(A\right) A, \tag{1}$$

where A is the envelope of the field, z is the propagation distance, and T is the local time. The gain $g\left(E_\mathrm{p}\right)$ saturated by the pulse energy E_p is given by

$$g\left(E_\mathrm{p}\right) = \frac{g_0}{1 + E_\mathrm{p}/E_\mathrm{sat}}, \tag{2}$$

where g_0 is the small signal gain and E_sat is the saturation energy. The saturable gain is parabolicly frequency dependent with a bandwidth of $\Delta\omega$, $\beta_2 = 58$ fs^2/mm is the group-velocity dispersion of the Ti:sapphire crystal, and it is set to be negative in the prism sequence segment. Higher order dispersions are neglected in the simulation. γ is the SPM coefficient of the gain medium. The fast SA induced by the Kerr-lens effect is modelled by the following expression,[22]

$$q(A) = \frac{q_0}{\left(1 + \left|A\right|^2/q_\mathrm{sa}\right)}. \tag{3}$$

Here q_0 is the unsaturated loss and q_sa is the saturation power.

The model described above is solved numerically by means of the split-step Fourier method in each segment.[23] An initial pulse circulates around the cavity along the arrowed direction in Fig. 6 until the field amplitude becomes constant. The relevant parameters used in our simulation are summarized in Table 1. With positive net GDD values of 18 fs^2, 27 fs^2 and 47 fs^2, stable simulated pulses are obtained after enough round trips in the cavity.

Table 1. Typical parameters for numerical simulation.

g_0/m^{-1}	E_sat/nJ	β_2/(fs^2/mm)	$\Delta\omega$/THz	γ/(W·m)$^{-1}$	q_0/m^{-1}	q_sa/MW
100	10	58	270	0.4	5	0.3

Figure 7 exhibits the characteristics of calculated output pulses generated in the PDR. In the frequency domain, two edges of the spectral profile are steep, and the bandwidth decreases as the positive GDD increases, while in the time domain, pulses are long and up-chirped, and the duration increases monotonously as the positive GDD increases. These characteristics accord qualitatively with the experimental results. Pulse durations of simulation results (Figs. 7(d) and 7(e)) are shorter than those of measured pulses (Fig. 5) with the same values of net GDD, because the pulses are stretched when passing through the OC in the experiment.

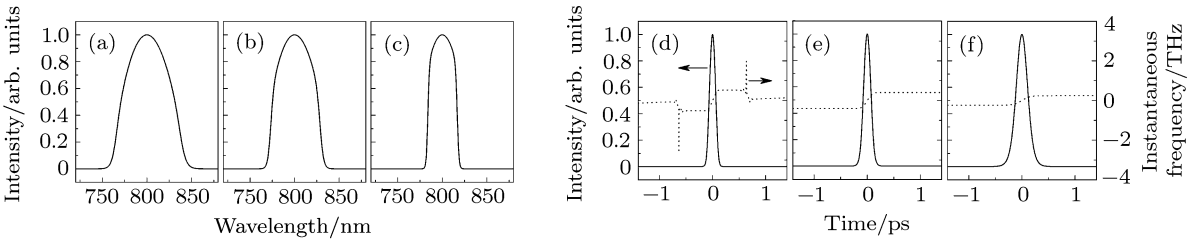


Fig. 7. Numerical simulation results with positive net GDD. Spectra with GDD: (a) 18 fs^2, (b) 27 fs^2, (c) 47 fs^2, (d) and (e) the corresponding pulse profiles and instantaneous frequencies.

According to the numerical model, the Ti:sapphire laser has a discrete distribution of dispersions and nonlinearity in the cavity, which leads to strong dependence of pulse shaping on a section in the cavity. As shown in Fig. 8, the pulse shape varies remarkably with segment in one round trip. The pulse is up-chirped and increases monotonically throughout the segment of positive GDD (Ti:sapphire crystal), and it is compensated partly in the segments of negative GDD (pair of prism). So the pulse breathes strongly during the round trip with a maximum duration of 310 fs and a minimum duration of 200 fs. Because of the positive net intracavity GDD in the gain medium, the pulse is up-chirped in every segment of the cavity. So the pulse duration can be further compressed in extracavity, which has been verified in our experiment (Section 2). In the frequency domain, obviously, the spectrum does not change in the prism sequence. In the segment of gain medium, the combination of the SPM and the SAM due to the Kerr-lens effect broadens or cuts off the spectral width, depending on the position of the pulse in the cavity: the SPM dominates before the OC in the cavity and broadens the spectral width; however, pulse energy decreases abruptly after the OC, so the SAM dominates and narrows the bandwidth by cutting the wings of the chirped pulse.

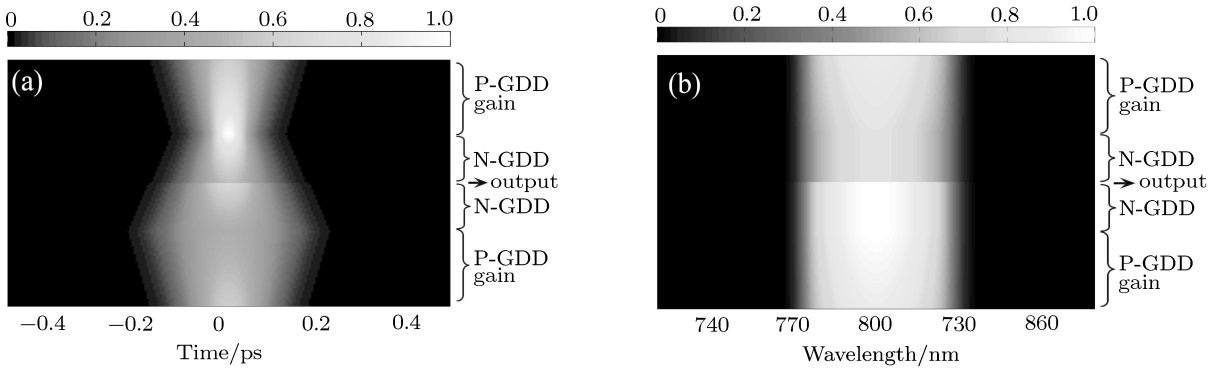


Fig. 8. Pulse evolution within one round trip (GDD=27 fs^2), (a) in time domain; (b) in frequency domain.

4. Conclusions

We demonstrate the characteristics of the KLM Ti:sapphire laser experimentally and theoretically as the net cavity GDD is continuously varied in the positive region. It is found that pulses generated from such lasers are long and highly chirped in the time domain, and the spectral profiles are nearly rectangular with steep edges. Results also show that the spectral profiles, time duration and chirp of the pulse strongly depend on the intracavity dispersion. In the experiment, direct output pulses are continuously tunable from 0.37 ps to 2.11 ps in the PDR, and a 36 fs pulse can be obtained after extracavity compression. Dispersive wave generation and a transition from the negative dispersive regime to the positive dispersion regime are observed in the vicinity of zero GDD. Theoretically, Ti:sapphire oscillators operating in PDR have great potential to obtain higher power than those in the soliton-like regime. However, in experiment semiconductor saturable-absorber mirrors (SESAM) are required to provide a reliable mode-locking mechanism and to stabilize the high power pulses, and extended-cavity is also another approach to achieving high energy pulses operating in PDR.[14,15] Furthermore, the possibility of self-similar pulse evolution in the Ti:sapphire laser with positive net GDD[22] makes this laser more attractive in high energy lasers. A large stretching ratio of the pulse in the cavity and much more dispersion in the gain medium are required to achieve self-similar operation of Ti:sapphire laser as compared with the self-similar evolution in a fibre laser.[24] A longer gain crystal can be a practical choice to increase dispersion and the stretching ratio of the pulse in future work and further studies are expected to extend to such a laser with a larger pulse energy.

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