Multi-pulse operation of a Kerr-lens mode-locked femtosecond laser

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Our experimental results show that the presence of a proper amount of negative group velocity dispersion is essential to multi-pulse operation of a Kerr-lens mode-locked femtosecond laser. We demonstrate that the pulse separations and the number of pulses contained within a cavity round trip are strongly dependent on the initial perturbations. The results allow us to get a better understanding on the influences of the convoluted self-phase modulation and intra-cavity dispersions on the stable multi-pulse oscillation in a Kerr-lens mode-locked femtosecond laser.

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Multi-pulse emissions from solitary lasers containing more than one pulse within a round trip of laser oscillation have been observed in the last decades[1−11]. Recent rapid progresses in ultrafast laser techniques and the extensive applications have made such a phenomenon receive much attention. Experimentally, multi-pulse operations have been obtained in colliding-pulse mode-locked dye lasers[1,2], fiber lasers[3,4], and semiconductor saturable-absorber mode-locked[5,6] or Kerr-lens mode-locked (KLM)[7−9] solid lasers. In KLM Ti:sapphire lasers, it is reported that the pulse separations are dependent on the pulse width and increased by a multiple of a time constant for two-pulse operation[8]. Recent work on multi-pulse generation is taken to investigate the relationships between the cavity stabilities and output pulse shapes in a KLM Ti:sapphire laser[9]. Theoretically, multi-pulse phenomenon is investigated by solving the nonlinear Schrödinger equation which describes the pulse evolution in a KLM laser cavity with self-phase modulation (SPM), Kerr-lens effect, and cavity dispersions[10,11]. It has been demonstrated that pulse splitting is originated from the presence of an amount of high order dispersions in the laser cavity[10]. It is also predicted that two-pulse operation can only be obtained in a narrow range of physical parameters[11]. On the other hand, multi-pulse can be generated due to pulse splitting induced by modulational instability[12,13] in dispersive media. However, the underlying physical mechanism and characteristics for such a phenomenon in laser cavities are not totally evidenced yet.

In this paper, we perform a further experimental study of the influences of intra-cavity dispersions on the multi-pulse operation of a KLM Ti:sapphire laser. Our experimental results show that the presence of a proper amount of negative group velocity dispersion (GVD) is essential to multi-pulse operation of a KLM femtosecond laser. We demonstrate that the pulse separations and the number of pulses contained within a cavity round trip are strongly dependent on the initial perturbations. It is also shown that stable multi-pulse oscillation in a KLM femtosecond laser is a consequence of the separated interplay between the complicated SPM in the gain medium and the intra-cavity dispersions.

As shown in Fig. 1, we constructed a five-mirror cavity with a thin Brewster-cut Ti:sapphire crystal (2.5 mm thick along pulse propagation) as the gain medium. There are two pairs of broadband high-reflection (HR) coated chirped mirrors (M_1-M_2 and M_3-M_4) with each mirror providing an average GVD of -70 fs^2. The intrinsic GVD oscillations originated from the chirped layer structures of the chirped mirrors are automatically compensated by introducing a relatively small frequency shift in one of the mirrors when they are used in pair. The mode locking of our oscillator could start readily by pushing and pulling one of the Brewster-angled fused silica prisms, which introduce an initial perturbation to the laser cavity. These prisms provide an additional tunable dimension to our laser as compared with only chirped mirrors based one, and play an important role in tuning the output spectrum. The output coupler (OC) provides a transmission of 3% centered around 800 nm. A Verdi-V5 laser (Coherent) at 532 nm with a greatly good spatial mode and stability was used as the pump for our laser. By properly optimizing the cavity, pulse duration down to 10 fs could be obtained from our oscillator. In order to finely tune the intra-cavity dispersions and keep the output spectrum unaffected, an additional pair of fused silica wedges (W_1 and W_2) was used.

A periodically modulated spectrum, as shown in right column of Fig. 2, indicates a stable multi-pulse operation of our Ti:sapphire laser[6−9]. In frequency domain, pulse separations between the output pulses can be derived from the intervals between the fringes in the modulated

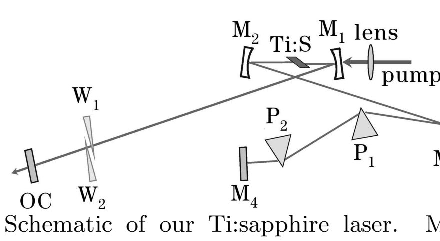

Fig. 1. Schematic of our Ti:sapphire laser. M_1—M_4 are broadband HR coated chirped mirrors and OC is the output coupler. The curvature radii of M_1 and M_2 are 100 mm. The prisms P_1 and P_2 are used to start the mode locking of the laser. The intra-cavity dispersions can be tuned finely with two fused silica wedges W_1 and W_2.

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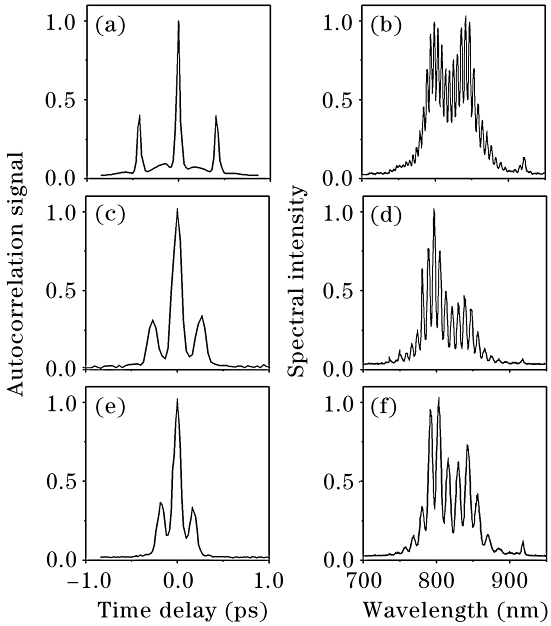

Fig. 2. Measured autocorrelation traces (left column) and corresponding spectra (right column) of the laser output in two-pulse operation mode. The pulse separations are measured to be (a) 414, (c) 266, and (e) 175 fs, respectively.

spectrum[6−9]. However, it is a little bit involved to derive the pulse distributions for multi-pulse trains containing three or more pulses in a cavity round trip since the output spectrum is modulated with more than one frequency. Moreover, multi-pulse trains containing more than two pulses in a cavity round trip with the same time interval between these pulses result in the same modulated spectrum as a two-pulse output does, which destroys the uniqueness of spectral derivation and reduces its robustness. This could be overcome by a direct measurement in time domain with an autocorrelator. We constructed a non-collinear autocorrelation instrument with a thin BBO crystal as a sum-frequency generator to measure the distributions of the generated pulses in time domain. For two-pulse operations, the products of $\delta\nu \times \delta t$ for the data presented in Fig. 2 were computed and found to be a constant as 0.99 ± 0.01, where $\delta\nu$ is the frequency interval between the adjacent fringes in the modulated spectrum and δt is the pulse separation between the output double pulses measured in time domain.

By adjusting the inserts of the wedges, the intra-cavity dispersions (GVD and higher-order dispersions) can be finely tuned. Interestingly, for our oscillator, we found that stable multi-pulse operation can be observed only in a small range of GVD from −11 to −50 fs^2. Such a requirement of negative GVDs for multi-pulse operation is consistent with previous theoretical predictions[10,11]. Beginning with periodical perturbations, stable operation of mode locking is obtained by combining the effects including self-amplitude modulation (SAM), SPM, and dispersion delays. The frequency chirp introduced by SPM in the gain medium is then compensated by the intra-cavity dispersions, which leads to a solitary wave evolution.

The presence of negative GVD indicates that stable multi-pulses are originated from the positive chirped portions of the initial pulse in our laser. The strong SPM in the gain medium will introduce linear or even nonlinear frequency chirp to the pulse depending on the initial pulse[14,15]. For example, for a super-Gaussian pulse, SPM introduces positive frequency chirps at the edges of the pulse, while keeping the pulse center unaltered. When such a pulse undergoes a negative GVD, only the leading and tailing parts of the initial pulse are compressed, amplified, and sustainable. Eventually, pulse splitting occurs in the initial pulse and a stable two-pulse operation is formed. Therefore, the pulse interval between adjacent pulses should strongly depend on the initial perturbations and the amount of intra-cavity dispersions. Different periodical perturbations with different initial pulses as the beginning of the oscillation will result in different chirping structures owing to the corresponding SPM in the gain medium. For a given intra-cavity dispersion, only the chirp-matched parts in the initial pulse can sustain and grow into stable pulses. It is consistent with the experimental observation in our KLM Ti:sapphire laser. Keeping all the cavity parameters unchanged, stable double-pulse operations with different pulse separations could be obtained when the mode locking was restarted at different times by pushing and pulling the prisms. For example, pulse separations from 122 to 723 fs were observed as the GVD was −30 fs^2 when the mode locking was restarted from time to time with different initial perturbations. However, the multi-pulse operation was quite stable since it was formed. This indicates that the multi-pulse oscillator is a result of solitary evolution of the initial perturbations by properly balancing the intra-cavity dispersions and SPM induced frequency chirp. Figure 2 shows some typical autocorrelation traces and the corresponding modulated spectra output from our laser as it was operated in two-pulse mode. It is unclear yet why the negative chirped portions in the initial pulse cannot grow into stable multi-pulse

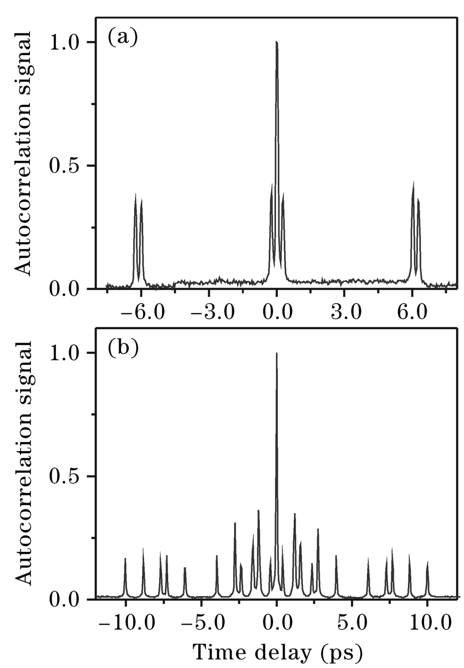

Fig. 3. Measured autocorrelation traces of the laser output in (a) three-pulse and (b) six-pulse operation modes.

mode with matched positive GVD when we increase the inserts of the wedges.

In general, a multi-period modulated spectrum indicates a multi-pulse operation containing more than two pulses in a cavity round trip[9]. Figure 3(a) shows an autocorrelation trace from our laser as it was operated in a three-pulse mode. The pulse separations between the first and second pulses, and the second and third pulses are measured to be 5973 and 266 fs, respectively. There are two possible processes to establish a stable three-pulse mode in a KLM Ti:sapphire laser: a step-wise process and a straightforward process. In a step-wise process, a three-pulse operation is established through further splitting one of the pulses from a two-pulse mode. However, it is also possible that there are three portions in the initial pulse where the SPM induced frequency chirps are matched with the cavity dispersions. In general, the strong SPM will always introduce a complicated chirp structure (linear and nonlinear) to the initial pulse depending on the pulse itself. Combining with the cavity dispersions, such an initial pulse will grow into a stable three-pulse mode in a straightforward process. Based on the observed large difference between the pulse separations (5973 fs versus 266 fs), it seems that the three-pulse mode observed in our laser most likely originates from a step-wise rather than straightforward process. As shown in Fig. 3(b), stable multi-pulse mode containing pulses up to six in a cavity round trip could be obtained from our laser. The measured pulse separations between two adjacent pulses starting from the first one are 1200, 1200, 400, 1200, and 6200 fs, respectively.

As the negative GVD decreases to near zero, for a KLM femtosecond pulse with a broadband spectrum, the influences from higher-order dispersions on its evolution become significant[7,10]. The effect from the third-order dispersion (TOD) should be included when the parameter $\beta_3 = |\mathrm{TOD}|\Delta\omega/(3|\mathrm{GVD}|)$ is close to unit[7], where $\Delta\omega$ is the full-width at half-maximum (FWHM) of the output spectrum. For our laser operated in multi-pulse modes, with $\Delta\omega \sim 0.2$ fs^{-1} centered around 820 nm, β_3 is calculated to be in the range of $0.4 - 1.5$ as the cavity dispersions are tuned. It indicates that the effect from TOD may play an important role here, which is a potential source of instability of the pulse evolution and may contribute to the pulse splitting. The influences from higher-order dispersions on pulse evolution[16−18] will be much more complicated as compared with GVD does. Further theoretical and experimental studies are desirable to fully characterize the influences from higher-order dispersions on multi-pulse operation of a KLM femtosecond laser.

In summary, we have performed an experimental study of the influences of intra-cavity dispersions on the multi-pulse operation of a KLM Ti:sapphire laser. Our experimental results show that the presence of a proper amount of negative GVD is essential to our multi-pulse oscillation. The pulse separations and the number of pulses contained in a cavity round trip are strongly dependent on the initial perturbations. By properly controlling the intra-cavity dispersions, we can switch our laser between multi-pulse and single-pulse modes. The results in this paper allow us to gain a better understanding on the multi-pulse operation of a KLM femtosecond laser. However, further studies are still desirable to fully characterize such a phenomenon.

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