Direct amplification of terawatt sub-10-fs pulses in a CPA system of Ti:sapphire laser

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Abstract: We have developed a chirped pulse amplification system of Ti:sapphire laser generating a 9.9 fs pulse with a pulse energy of 11 mJ at a repetition rate of 10 Hz. Spectral narrowing during amplification is successfully compensated by using specially designed partial mirrors and broadband high-damage-threshold mirrors. This is the first demonstration, to the best of our knowledge, of the direct amplification of terawatt sub-10-fs pulses in a chirped pulse amplification system of Ti:sapphire laser.

OCIS codes: (320.7090) Ultrafast lasers; (140.3280) Laser amplifiers.

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1. Introduction

The mainstream for generating few-cycle intense laser pulses is now splitting into two classes of techniques, namely, hollow fiber compression [1, 2, 3] and optical parametric chirped pulse amplification (OPCPA) [4]. The former approach has yielded many of the significant results in attosecond science [5]. The energy of the laser pulse is, however, limited to a few mJ because of the low damage threshold of the hollow fiber, even though state-of-the-art techniques for supplying gas to a hollow fiber [6] and the pointing stabilization of the laser pulse [7] are adopted. The other method of OPCPA takes advantage of the broadband gain of a noncollinear OPA process in a nonlinear crystal to obtain a terawatt-class sub-10-fs pulse [8, 9, 10], which is a promising light source for generating an intense isolated attosecond pulse and extremely high harmonic fields in the water window spectral region.

In spite of the superiority of the OPCPA for ultrashort pulse amplification, it is not easy for general users of the conventional chirped pulse amplification (CPA) system of Ti:sapphire laser to modify their CPA system to an OPCPA one as long as it requires customized pumping laser sources. The duration of the pumping pulse must be shorter than $\sim$ 100 ps, thus, the seed pulse of the pump should either originate from a picosecond mode-locked oscillator strictly synchronized with a sub-10-fs mode-locked oscillator supplying the seed pulse for amplification [8] or it should be generated from the sub-10-fs mode-locked oscillator itself [9, 10]. The CPA system of Ti:sapphire laser, on the other hand, can be pumped by commercially available Q-switched laser sources and is a conventional tool in many scientific fields. Therefore, it is noteworthy to show how we can upgrade a CPA system to generate an intense sub-10-fs pulse in a simple manner.

In this paper, we present the first demonstration, to the best of our knowledge, of the direct amplification of a terawatt sub-10-fs pulse in a CPA system of Ti:sapphire laser without using any nonlinear spectral broadening effects [11] or broadband amplification with noncollinear OPA [12]. What only we had to do was to compensate for the gain narrowing during amplification by adding specially designed partial mirrors (gain narrowing compensator, GNC) in a regenerative amplifier and a multi-pass amplifier. Spectral narrowing due to the bandwidth limitation of the mirrors has been avoided by using high-damage-threshold chirped mirrors (HDTCM) as well. Therefore, this technique is practical for general users of the CPA system and easily applicable to even higher energy CPA systems. In fact, we could easily upgrade our CPA system [13] to a terawatt sub-10-fs system.

2. The sub-10-fs regime

Regenerative pulse shaping by inserting a spectrally dependent loss in the cavity of a regenerative amplifier [14] is a well-known technique for canceling the reduction of spectral width caused by the spectrally dependent gain of a laser medium. Takada and co-workers, for example, have already demonstrated the amplification of a 12 fs pulse in a terawatt-class CPA system by this scheme [15, 16]. Thus, our main concern for achieving direct amplification of sub-10-fs pulses should be how accurately we apply a proper loss profile to a GNC.

We have designed the partial mirror coating of dielectric films on a silica substrate such that the reflectance of the GNC becomes similar to an analytical function which mimics the gain profile of Ti:sapphire laser [17] in a wavelength range from 700 nm to 950 nm and becomes zero outside this region. The incident angle is set to be near the Brewster angle of the silica substrate ($\sim 54.5°$). The film composite calculated using the iterative algorithm with the dumped least-squares method [18] is completely different from the typical $\lambda/4$ stacks reported in refs. [15, 16] or the dielectric multilayer filter reported in ref. [19]. In fact, in the sub-10-fs regime this is a novel optic that did not exist to the date, which led us towards the direct amplification of high-energy sub-10-fs pulses. The full details of the GNC design will be reported elsewhere.

The calculated transmittance of the GNC (Sigma Koki Inc., TFMQ-30C02-10-5, Type Y2) we used in the regenerative amplifier is shown by the solid curve in Fig. 1 together with the dashed curve which shows the transmittance of a previously designed GNC (Type B) which we used for direct amplification of terawatt-class 12-fs laser pulses in a more compact laser system [20]. The group delay dispersion (GDD) of the transmitted light obtained from calculation on the new GNC (Type Y2) is also shown by the dotted curve in Fig. 1. The modulation amplitude of the GDD is sufficiently low to be eliminated with a phase controller (PC) of a liquid crystal spatial light modulator (LC-SLM), which is located between the stretcher and the regenerative amplifier in our CPA system (see Fig. 3).

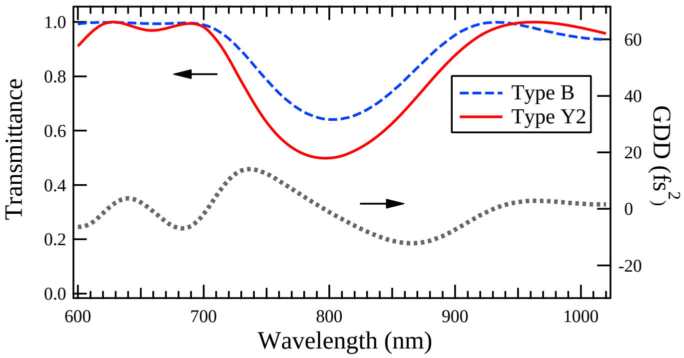

Fig. 1. Spectral characteristics of the new GNC. The solid curve shows the calculated transmittance and the dotted curve shows the calculated GDD posed on the transmitted light. The dashed curve shows the transmittance of a previously designed GNC (Type B) for direct amplification of terawatt-class 12-fs pulses.

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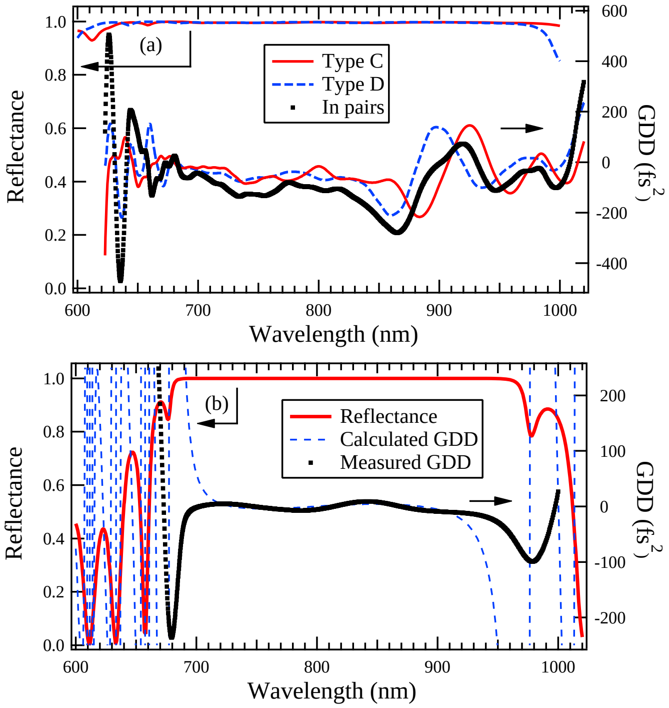

Fig. 2. (a) Spectral characteristics of the HDTCMs to be used in the regenerative amplifier. The dots show the total GDD of these chirped mirrors measured in pairs. (b) Spectral characteristics of the hybrid laser mirror to be used in the multi-pass amplifier.

Another reason for spectral narrowing is the restriction of the spectral width of HDT mirrors used in the amplifiers. To avoid this spectral narrowing, we developed a pair of HDTCMs (Type C & Type D). The GDD of these chirped mirrors measured by a spectral interferometry technique using a Ti:sapphire laser oscillator is shown in Fig. 2(a) by the solid curve for Type C and by the dashed curve for Type D. We intended to cancel out the large GDD oscillation [21] ranging from 830 nm to 970 nm by using these mirrors in pairs. Yet, the net GDD oscillation (dots in Fig. 2(a)) of the HDTCM pair does not fully disappear. The spectral phase distortion due to the remaining GDD oscillation, however, can be removed by using the LC-SLM. It is even possible to remove the spectral phase distortion due to single use of the chirped mirrors by an LC-SLM, however it could make the process of pulse compression more time demanding in the longer wavelength component of the spectrum (near 900 nm). The calculated reflectance (upper curves in Fig. 2(a)) of both types of HDTCM coatings exhibit a sufficiently broad spectral width for the amplification of sub-10-fs pulses.

To reflect high-energy sub-10-fs pulses in a multi-pass amplifier, we still need another low-dispersion broadband HDT laser mirror. We developed a hybrid coat of two kinds of dielectric film stacks with a $\lambda/4$ period providing high reflectivity with a sufficiently broad spectral width for s-polarized light at 45° incidence. It was designed on the basis of the hybrid $\lambda/4$ film stacks for 0° incidence already reported by Takada et al. [22]. The calculated reflectance of this hybrid laser mirror is shown by the solid curve in Fig. 2(b) and its calculated GDD by the dashed curve together with the measured GDD shown by the dots. It has a damage threshold comparable to commercial high-damage-threshold mirrors, since we managed to use it in a multi-pass amplifier bearing a pulse with an instantaneous peak pulse energy of $\sim$ 40 mJ.

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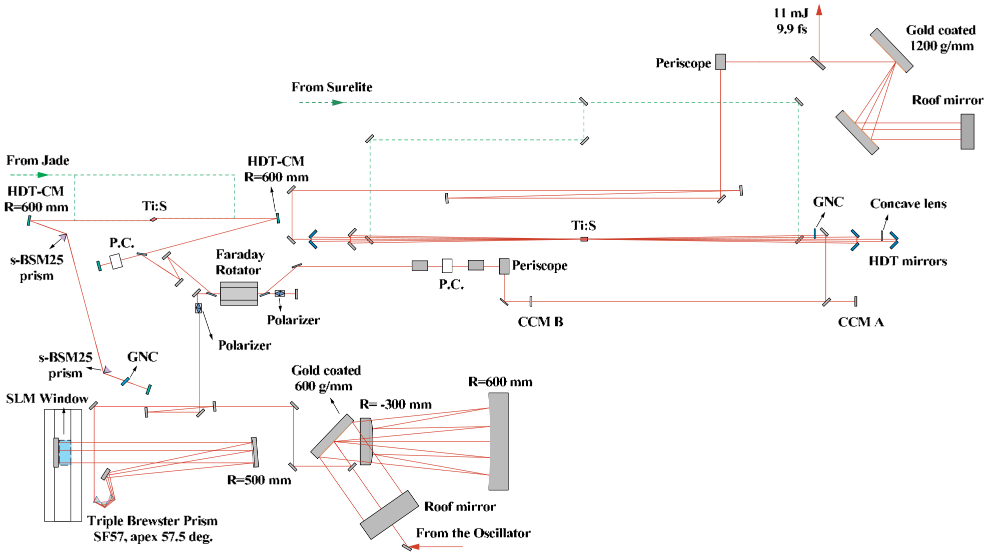

Fig. 3. Schematic of the upgraded laser system. Ti:S: Ti:sapphire crystal, P.C.: Pockels Cell, GNC: Gain Narrowing Compensator, CCM: Concave Chirped Mirror.

3. The laser system

The upgraded laser system consists of typical elements of a CPA system in addition to the special optics mentioned above. The schematic of this laser system is shown in Fig. 3. The seed pulse is generated from a mode-locked Ti:sapphire oscillator having a pulse duration of 7 fs. The oscillator is followed by an Öffner type [23] pulse stretcher consisting of a 600 g/mm diffraction grating and a telescope with a radius of curvature of 600 mm for the concave mirror and −300 mm for the convex mirror. With this configuration, the input pulse is stretched to 200 ps. The stretcher is followed by a PC with an LC-SLM with 640 channels. To avoid the loss due to the use of diffraction grating pairs in the SLM 4f-setup, we used a sequence of three Brewster-cut prisms (SF57, Schott) to provide angular dispersion. Note that the PC is necessary to compensate for the high-order material dispersion in the laser system, even if the net GDD oscillation of the HDTCM pair could be eliminated with optimum design and fabrication.

The output pulse of the PC is injected into a regenerative amplifier. The regenerative amplifier consists of two concave mirrors with a radius of curvature of 600 mm and two other flat end mirrors, resulting in an X-fold cavity. We also inserted a pair of prisms (s-BSM25, Ohara) in one arm of the X-fold cavity to relax the condition of compensation for high-order dispersion [24]. We installed a Pockels cell and a thin film polarizer (TFP) in another arm of the X-fold cavity for the injection and rejection of the pulses. A Ti:sapphire crystal placed near the confocal position of the two concave mirrors is pumped by the second harmonic of an LD-pumped cw Q-switched Nd:YLF laser (Jade, Thales) at a repetition rate of 1 kHz.

The GNC is located between the end mirror and one of the prisms. The spectrum of the Q-switched self oscillation of the X-fold cavity of the regenerative amplifier is shown in Fig. 4(a) by the solid curve together with the spectrum of the injected pulse behind the LC-SLM (dashed curve). The amplified pulse is switched out by the combination of the Pockels cell, the TFPs, a quartz rotator and a Faraday rotator [24] after 37 round trips in the X-fold cavity. Then the amplified pulse is sent to a pulse slicer to reduce the ASE (Amplified Spontaneous Emission) and to isolate the two stages in the amplifier chain and also to reduce the repetition rate to 10 Hz. Behind the pulse slicer, ASE has a share of $\sim 11\%$ of the amplified pulse which is

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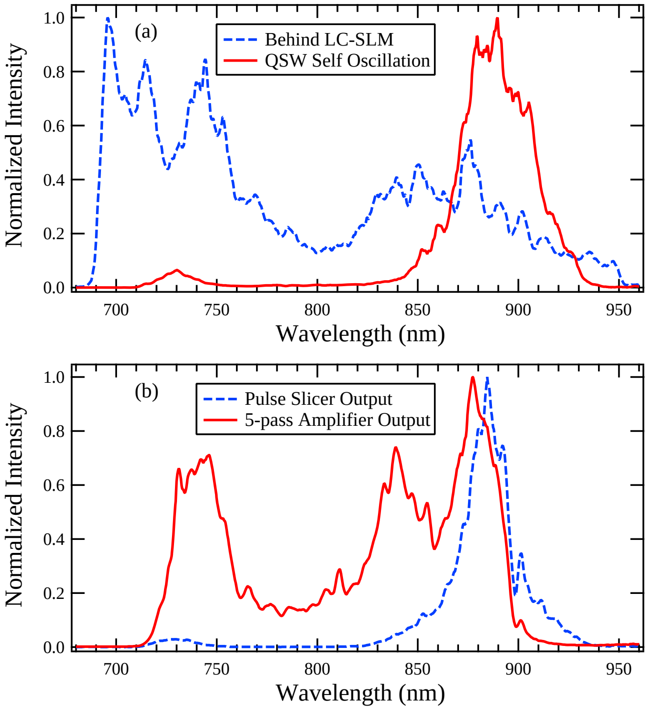

Fig. 4. (a) Spectrum of the injected pulse behind the LC-SLM (dashed curve) and Q-switched (QSW) self-oscillation spectrum of the X-fold cavity of the regenerative amplifier (solid curve). (b) Spectra of the amplified pulse behind the pulse slicer (dashed curve) and the 5-pass amplifier (solid curve).

low enough for further pulse amplification. The peak-to-background pulse contrast after pulse compression is estimated to be $\sim 10^6 : 1$ in the ns range from this result.

The spectrum of the amplified pulse behind the pulse slicer is shown by the dashed curve in Fig. 4(b). The foot-to-foot spectral width reaches $\sim$ 230 nm. The resultant spectral shape is a consequence of adjusting the incident angle of the GNC so as to obtain the broadest spectrum for the compressed pulse, which is successively amplified in a 5-pass amplifier set behind the pulse slicer. The energy of the pulse at this stage is 27 μJ, when the pumping pulse energy of the regenerative amplifier is 11.5 mJ. This pulse energy at the first sight could invoke a low efficiency for the regenerative amplifier, yet it is the result of the transmittance of the GNC to compensate for the gain narrowing of the Ti:sapphire crystal and shows that a great deal of the amplified pulse is reflected out of the cavity by the GNC around the wavelength component that Ti:sapphire crystal has a high gain (near 800 nm).

After passing through the pulse slicer, the amplified pulse is sent to a bowtie multi-pass amplifier. The spectral characteristics of its folding mirrors are shown in Fig. 2(b). A GNC with dielectric coatings on both sides of a silica substrate is situated such that it intersects the 1st and 3rd passes, resulting in the reduction of the net gain of the 5-pass amplifier at around 800 nm. We placed a plano-concave lens with a focal length of -1.5 m just behind the folding mirrors of the 5th pass in order to relax the thermal lens focusing of the Ti:sapphire crystal. The pumping laser pulse of the amplifier is the second harmonic of a Q-switched Nd:YAG laser with a pulse energy of 180 mJ at a repetition rate of 10 Hz. In this configuration, we obtained an amplified pulse with a pulse energy of 33 mJ.

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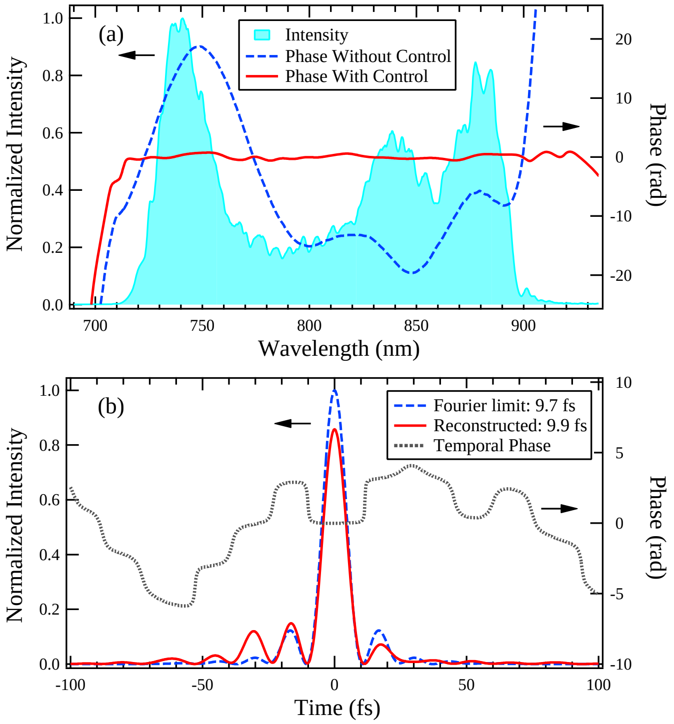

Fig. 5. (a) Measured spectral phases. Hatched area shows the spectrum behind the compressor. (b) Reconstructed temporal profile (solid curve) and the Fourier-limit temporal profile (dashed curve). Dotted curve shows the temporal phase.

The spectrum of the amplified pulse at this stage is shown in Fig. 4(b) by the solid curve. We find a notable increase of the spectral component shorter than 750 nm in addition to the reasonable growth of that at around 800 nm. Yet, we can not exactly explain its reason. It may be due to the unknown gain dynamics of lasing in Ti:sapphire, because the shorter component is reduced by advancing the time of the pump laser pulse to the seed laser pulse in $\sim$ 100 ns range, although the upper state lifetime of Ti:sapphire laser is much longer ($\sim$ 3 μs) than 100 ns. It could be explained by a wavelength-dependent lifetime, which is shorter for the shorter wavelength component of the spectrum (near 700 nm) compared to the longer one at around 900 nm.

The amplified pulse is compressed using a diffraction-grating-based pulse compressor with a groove density of 1200 g/mm. The incidence angle to the grating is set to be $\sim 43^\circ$, on the basis of a ray-trace analysis of the dispersion in the whole laser system to minimize the spectral phase error. The spectrum of the compressed pulse is shown in Fig. 5(a) by the hatched area. The longer wavelength component slightly decreases compared with the amplified spectrum (solid curve in Fig. 4(b)) because of the variable diffraction efficiency of the gratings. The Fourier transform of the spectrum with a flat phase leads to the Fourier-limit pulse (dashed curve in Fig. 5(b)) with a pulse duration of 9.7 fs in the full width at half maximum (FWHM).

We measured the spectral phase of the compressed pulse by spectral interferometry for direct electric field reconstruction (SPIDER) [25]. The spectral phase without using the LC-SLM is shown by the dashed curve in Fig. 5(a). The oscillation of the phase is mostly attributed to the remaining GDD oscillation of the HDTCMs used in pairs, while the slow variation is due to the high-order dispersion of the optical elements in the regenerative amplifier that cannot be removed by the hybrid compensation technique of using the mixed grating [26] and the prism pair. The opposite phase of this measured phase was fed back to the LC-SLM 4 times, and then we obtained the nearly flat phase shown by the solid curve in Fig. 5(a). The reconstructed temporal profile calculated using the spectrum of the compressed pulse and the spectral phase with control is shown in Fig. 5(b). Although the pedestals on the left foot of the main peak of the pulse slightly increase compared with those of the Fourier-limit pulse, the duration of the pulse is similar to that of the Fourier-limit pulse with an FWHM of 9.9 fs.

The pulse energy after compression was 11 mJ, and therefore, we conclude that the peak power of the laser system should be more than 1 TW. In another experiment, we found out that the average pulse energy could be increased even up to 12 mJ with a peak pulse energy of more than 14 mJ by a brief adjustment of the multi-pass amplifier. The main peak in the Fourier-limit pulse has an area of more than 81% of the whole pulse, while that in the reconstructed pulse is $\sim 71\%$. This fact reduces the effective pulse energy in the main peak, however the pulse energy could be further increased by replacing the old diffraction gratings used in the pulse compressor and therefore increasing the effective pulse energy in that region.

4. Conclusion

In summary, we developed a terawatt sub-10-fs CPA system of Ti:sapphire laser which has been easily upgraded by replacing ordinary passive optics with specially designed GNCs and broadband HDT mirrors used in the amplifiers. Since this terawatt sub-10-fs pulse is generated directly from a Ti:sapphire CPA laser system, its pulse energy can be scaled to result in a peak power of more than 10 TW. We plan to apply this laser pulse to generate soft X-rays in the water window spectral region in the near future.

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