Communications in Physics, Vol. 29, No. 3SI (2019), pp. 331-340
DOI:10.15625/0868-3166/29/3SI/14334

AMPLIFICATION OF ULTRASHORT TITAN-SAPPHIRE LASER PULSES USING CHIRPED-PULSE AMPLIFICATION TECHNIQUE

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Received 22 August 2019
Accepted for publication 28 September 2019
Published 18 October 2019

Abstract. *We report on a Chirped Pulse Amplification (CPA)-based Titanium:Sapphire (Ti:Al_2O_3 or Ti:Sapphire) amplifier that uses a 8-pass configuration, a single-grating stretcher and single-grating compressor. This amplifier is used to amplify nanojoule and femtosecond Ti:Sapphire laser pulses to yield a 70 μJ pulse energy at 10 Hz repetition rate, which corresponds to an amplification factor of 10000 times. The amplified laser pulses are expected to be nearly transform-limited with a pulse duration of less than 100 fs. Such an amplifier will expand applications of ultrafast mode-locked Ti:Sapphire laser oscillator.*

Keywords: Ti:Sapphire laser; chirped pulse amplification; ultrashort laser pulse; pulse stretcher and compressor.

Classification numbers: 42.50.Nn; 42.55.-f; 42.60.-v; 42.60.Da; 42.60.Fc; 42.65.Re; 42.65.Yj; 42.79.-e.

I. INTRODUCTION

High-power femtosecond (fs) laser pulses are required in many applications spanning a vast range of scientific disciplines [1–7]. For example, single molecule motion, transition states, reaction intermediates, and dissociation reactions all occur in time scales of the order of 10^{-12} to 10^{-15} seconds, making it necessary to use ultrafast fs pulses to observe these processes using time-resolved measurements [3–5]. The Titanium:Sapphire (Ti:Al_2O_3 or Ti:Sapphire) laser is the primary source of fs pulses whose tunability spans a broad range of wavelengths from 650 nm to 1100 nm [8]. Various applications, however, rely on the availability of ultrafast fs pulses with at least μJ pulse energy. The existing pulse energy of such commercially available Ti:Sapphire lasers is still below the threshold of many applications. Typically, a regenerative amplifier module is installed after the Ti:Sapphire laser oscillator [9, 10]. However, this module comes at a high cost.

In this work, we build an amplifier in-house in order to amplify the fs pulses from a commercial mode-locked Ti:Sapphire laser oscillator and achieve pulse energies that are usable for some projects such as pump-probe measurements of transient effects in nano particles and quantum dots, and generation of THz radiation. Our approach is to employ the classic Chirped Pulse Amplification (CPA) scheme [11], but we simplified the stretcher and compressor modules by using one grating for each. The use of diffraction grating pairs to compress optical pulses was first proposed by Treacyl in 1969 [12]. Grating-based laser pulse stretcher-compressors were investigated by Martinez and demonstrated by Pessot *et al.* in 1987 [13]. In the early design by Pessot et al., four identical diffraction gratings were used. Two of the gratings were used in the stretcher to lengthen ultrashort laser pulses by introducing positive group-velocity dispersion to the pulses [14]. The other two gratings were used in the compressor to reverse precisely the stretching process by introducing negativegroup-velocity dispersion. Modified designs of the Pessot stretcher-compressor use two or three gratings. Although the basic mechanism of phase modulation remains the same, these new designs greatly simplify the structure of the instrument and reduce the difficulty in alignment. However, a major problem remains in all multiple grating stretcher-compressors. Namely, all of the gratings require precise readjustment when the laser wavelength is changed. These readjustments are extremely inconvenient and time consuming when frequent tuning of the laser wavelength is desirable. In addition, strictly matched grating pairs are required in the stretcher and the compressor for maintaining good beam profiles and obtaining a good pulse-stretching-pulse-compressing ratio. In our experiment, we eliminated the above problems by using the single-grating confuration for the pulse stretcher and compressor. By doing so, we are able to maintain good beam profiles and a good pulse-stretching-pulse-compressing ratio without having to strictly match grating pairs as is required conventionally. Using the 8-pass Ti:Sapphire crystal amplifier for amplifying nanojoule and femtosecond Ti:Sapphire laser pulses, we are able to obtain 70 μJ pulse energy at 10 Hz repetition rate, corresponding to 10000 times amplification in pulse energy.

II. EXPERIMENT

The CPA scheme is shown in Fig. 1. The detailed schematic diagram of the experimental set-up is shown in Fig. 2.

The seed fs pulses are delivered at a repetition rate of 80 MHz from a mode-locked Ti:Sapphire laser oscillator (Tsunami femtosecond laser, Model 3960-X1BB Spectra- Physics). The pulse has

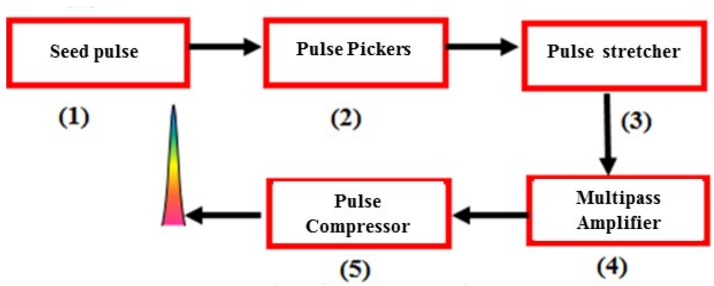

Fig. 1. Block diagram of experiment setup for fs laser amplifier.

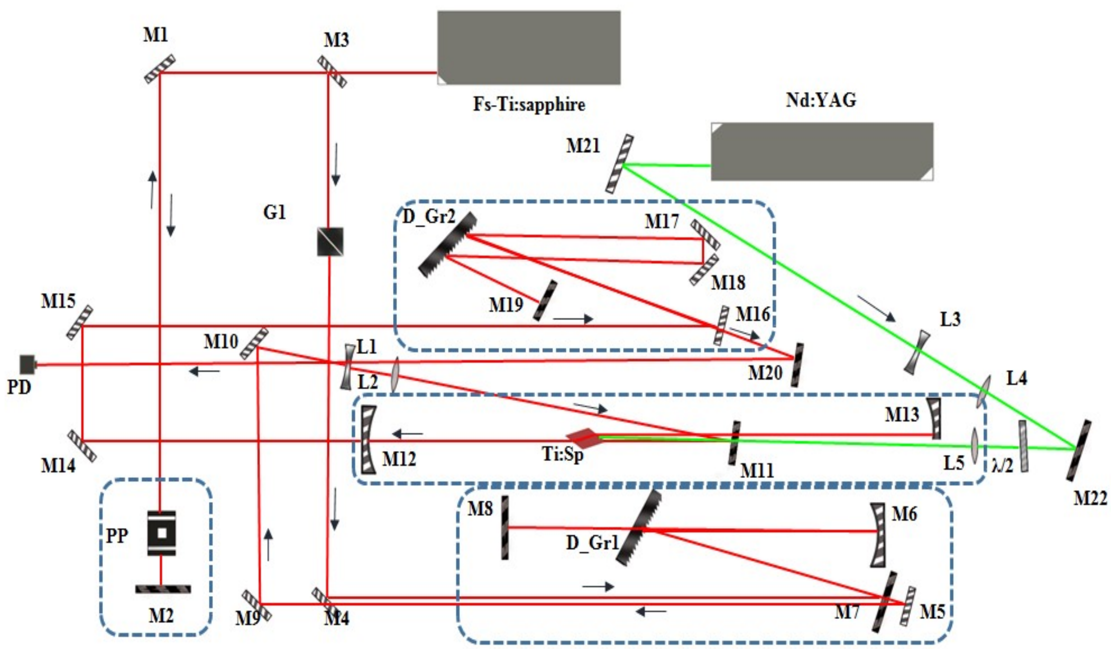

Fig. 2. Schematic diagram of Chirped Pulse Amplification fs laser amplifier experiment.

an energy of 10 nJ. The temporal profile of the seed pulse was measured using a Femtochrome Autocorrelator (FR-103XL). As shown in Fig. 3, the pulse duration measured by the autocorrelator was τ_{out} = 14.09 μs. The actual pulse duration of the seed pulse is then calculated to be 85 fs.

III. RESULTS AND DISCUSSION

The amplifier gain medium is a Ti:Sapphire crystal pumped by the second harmonics (532 nm) of a Q-switched Nd:YAG laser operating at 10 Hz repetition rate (Quanta-Ray INDI, Spectra-physics, Model INDI – HG10S). Therefore, the seed pulses were fed to a pulse picker (PP) after being reflected 100% by mirror M_1 in order to reduce the repetition rate. The PP (SPS–0902H) consists of a Pockels cell, a high voltage driver, and synchronization devices for selecting single pulses from a train of femtosecond pulses. The frequency of the selected pulse was set to 10 Hz to match the repetition rate of the 532 nm pump pulses from the Q-switched Nd:YAG laser. After exiting the PP, the pulses are then steered towards a Glan – Taylor prism (G_1) through mirrors M_1 and M_3 before being steered towards the stretcher using mirrors M_4 and M_5.

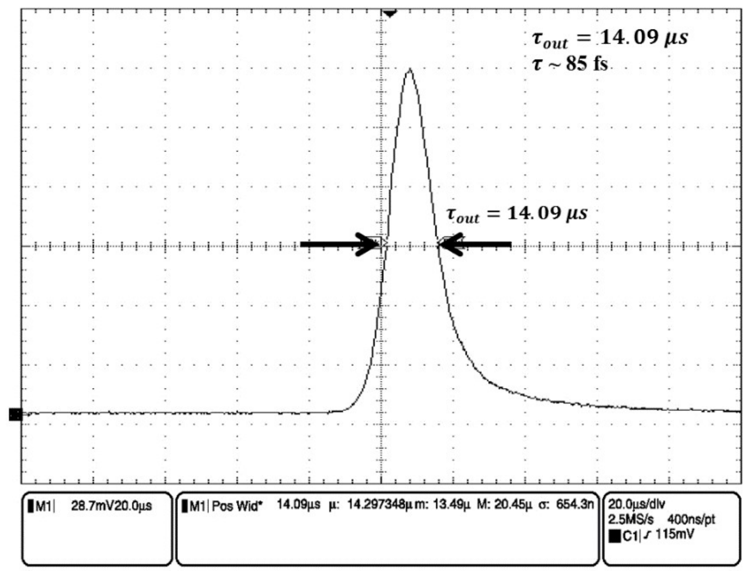

Fig. 3. Temporal profile of the seed pulse.

Stretcher module

In a conventional pulse stretcher, two gratings are used as shown in Fig. 4.

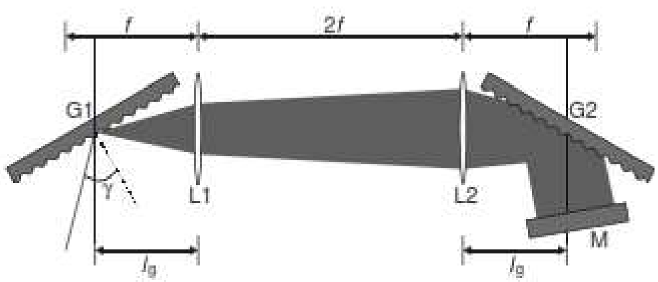

Fig. 4. Schematic diagram of a grating-pair pulse stretcher showing the arrangement for positive dispersion. G_1 and G_2 are diffraction gratings, L_1 and L_2 are identical lenses separated by twice their focal length, f, and M is a mirror acting to double-pass the beam through the system. The distance $l_g \pm f$ determines the total dispersion [15].

We evaluate the effect of the grating density, angle of laser beam on the grating surface, and distance between the middle of the grating and the lens on the group delay dispersion (GDD) of a pulse stretcher as shown in Ref. [15, Eq. (15)]

$$GDD = -\frac{\lambda^3 L_g}{\pi c^2 d2}\left[1-\left(\frac{\lambda}{d}-\sin\gamma\right)^2\right]^{-3/2} \tag{1}$$

where γ is the angle of incidence on the first grating and d the grating groove frequency, λ is the central wavelength, c is the speed of light, and $L_g$is the distance from the lens to the grating. In the case of a grating compressor, $L = L_g$ whereas for a grating stretcher, $L = 2(L_g - f)\cos\gamma$. Here, f is the focal length of the lens. We also investigated the pulse duration of the stretched pulse as shown in [15, Eq. (6)]:

$$\tau = \tau_0\sqrt{1+(\frac{4.\ln 2.GDD}{\tau_0^2})^2} \tag{2}$$

where τ_0 is the pulse duration of the seed pulse.

To stretch an ultrashort pulse (having a large spectral width), positive group velocity dispersion is added to the spectral components of the pulse by delaying the blue wavelengths relative to the red wavelengths. The output is a stretched and positively chirped pulse. Different designs have been proposed to achieve this purpose [15], most of them use a pair of diffraction gratings in an anti-parallel configuration, and a telescope with 1x magnification placed between them to invert the sign of the dispersion from the gratings. A second pass is introduced to increase the stretching factor and to avoid the spatial separation of the pulse spectral components (spatial chirp).

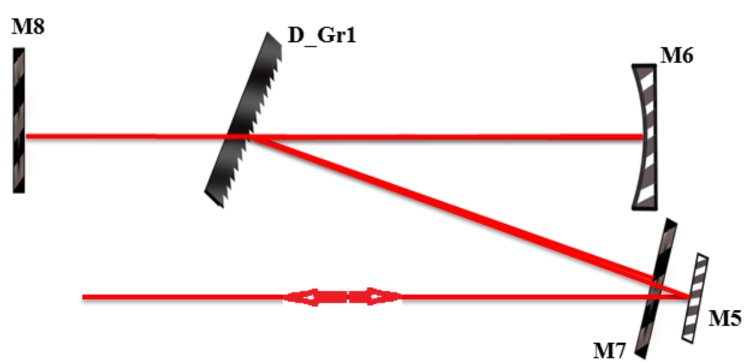

Fig. 5. Schematic diagram of the single-grating pulse stretcher introducing positive dispersion into the fs seed pulses.

Based on the results of our numerical calculations, we designed a pulse stretcher using only one grating as shown in Fig. 5. The conventional pulse stretcher is modified by putting a plane mirror between lenses L_1 and L_2, causing the beam to reflect back on G_1 and eliminating the second grating, G_2. This plane mirror is shown as M_8 in Fig. 5. We also replace the two lenses L_1 and $L_2$with a concave mirror to focus the pulses onto G_1, thereby eliminating lenses L_1 and L_2 altogether. The concave mirror is shown as M_6 in Fig. 5. The specifications of the optical components used in the stretcher are summarized in Table 1.

Table 1. Specification of the optical componentsused in the pulse stretcher.

Name	Specification
M_5, M_7	Flat mirror, HR @ 740-840 nm at 0° incident angle, Ø 1'
M_6	Concave mirror R= 10 cm, HR @740÷840 nm at 0 ° incident angle, 60 × 40 × 10 mm
M_8	Flat mirror, HR @ 740÷840 nm at 0° incident angle, 60 × 40 × 10 mm
D_Gr1	Grating 1200 lines/mm, 60 × 40 × 10 mm

The seed pulses from the PP are steered by mirror M_5 towards the grating. The pulses have energy of about 9 nJ and repetition rate of 10 Hz. The pulses are incident on the grating at an angle of about 30^o. For ease of adjustment, the grating is mounted on a rotary switch. After being diffracted by the grating, the pulses are reflected by concave mirror M_6 towards mirror M_8. The concave mirror M_6 serves a similar purpose to L_1 in the conventional grating pair as shown in Fig. 4. The distance between M_6 and the grating is 25 cm while the distance between M_6 and M_8 is 60 cm. M_8 reflects the pulses back to M_6, which now serves a similar purpose as L_2 in the conventional grating pair configuration at the same time steering the pulses back to the grating. After being diffracted the second time, the pulses reach mirror M_7, which is a plane mirror. This completes the first cycle of stretching. M_7 reflects the pulses back the grating for the second cycle of stretching. After the second cycle, the pulses would have been diffracted 4 times by the grating. The temporal profile of the stretched laser pulse was measured by the Femtochrome Autocorrelator as shown in Fig. 6. The stretched pulses have pulse duration of 72 ps (FWHM), repetition rate of 10 Hz, and pulse energy of ∼7 nJ. At this point, the stretched pulses are delivered to the amplifier module through mirrors M_5, M_9 and M_{10}.

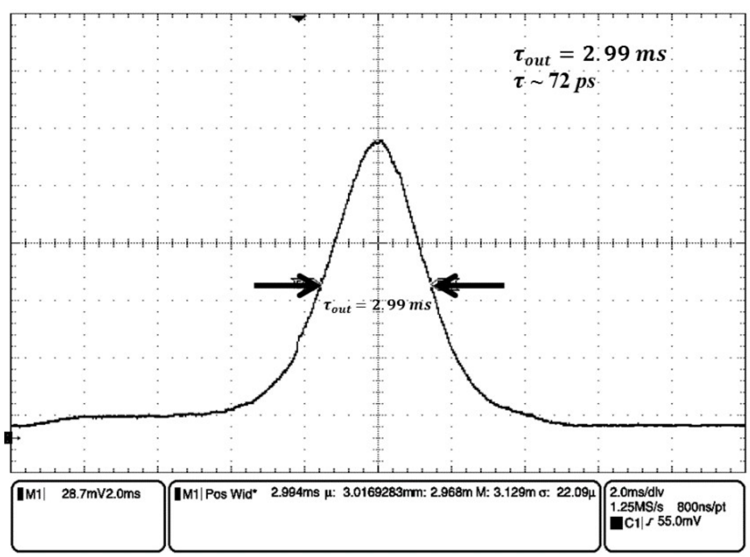

Fig. 6. Temporal profile of the stretched pulse with a 72 ps duration.

Amplifier module

The stretched pulse is amplified using an 8-pass Ti:Sapphire crystal amplifier as shown in Fig. 7. The flat mirror M_{11}, which is of high reflection at wavelengths from 740 to 840 nm at an incident angle of 45^o is used to guide the laser beam into the amplifier. Concave mirrors M_{12} and M_{13} have a diameter of 4 cm and curvature radii of 50 cm and 60 cm, respectively. They are of high reflection from 740 nm to 840 nm wavelength at zero degree incident angle. The distance between these two mirrors is 55 cm. Mirror M_{12}has a small hole 3 mm in diameter, 2 mm away from the center so that the laser pulses can exit the amplifier after amplification. Mirror M_{13} is cut into a semicircle in order to allow axial pumping of the Ti:Sapphire crystal so that the overlap between the seed and the pump pulses in the Ti:Sapphire crystal is maximized. Axial pumping will optimize the amplification of the laser pulse injected to the amplifier. Photographs of M_{12} and M_{13} are shown in Fig. 8. The Ti:Sapphire amplifier crystal is placed at the focus of both mirrors. The dimensions of the crystal are 7x6x3 mm and both ends are Brewster cut at 60.4°, considering the central wavelength of the laser pulses at 800 nm. The crystal is pumped axially

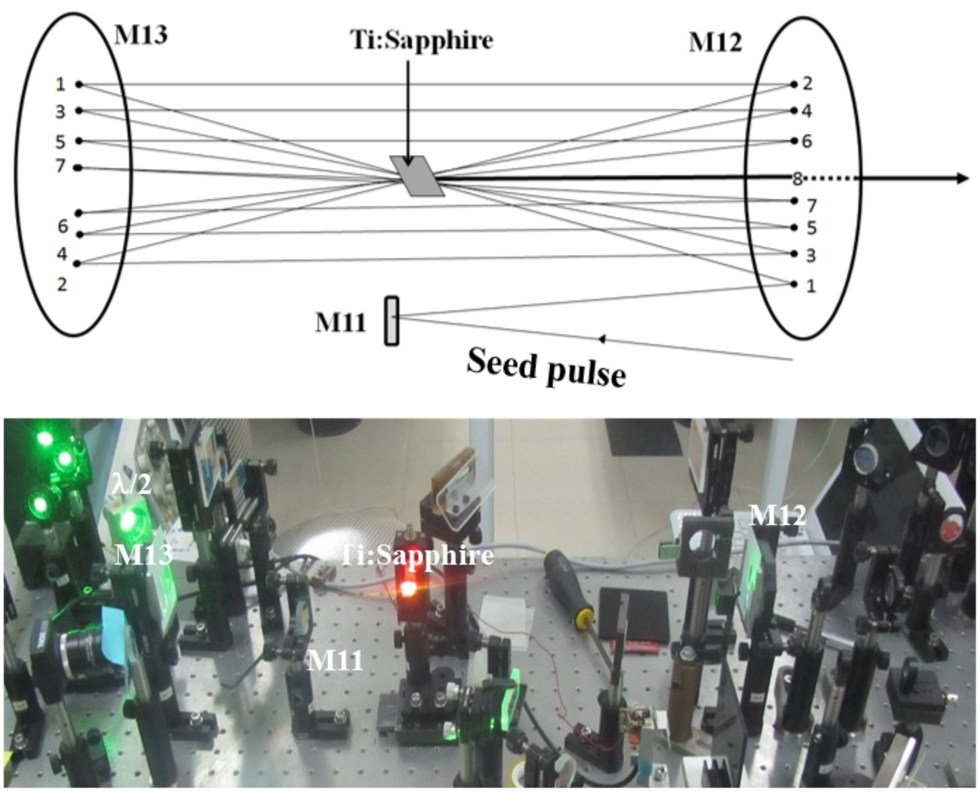

Fig. 7. a) Configuration of the 8-pass amplifier. b) Actual experimental set-up of the amplifier module.

by the second harmonics (532 nm) of the Q-switched Nd:YAG laser operating at 10 Hz repetition rate. The duration of the pump pulses is 8 ns. The maximum energy of the 532 nm pump pulse is around 200 mJ with an energy stability of $< \pm 3\%$. Lens L_5 ($f = 45$ cm) is used to focus the 532 nm pump pulses onto the Ti:Sapphire crystal. The diameter of the pump spot at the surface of the crystal is about 1 mm. A $\lambda/2$ plate is used to ensure horizontal polarization of the pump pulses.

Propagation of the laser pulses through the Ti:Sapphire amplifier is also detailed in Fig. 7. The flat mirror M_{11} reflects the fs pulses towards concave mirror M_{12}, which focuses the pulses onto the Ti:Sapphire crystal before reaching the other concave mirror M_{13}. This comprises the first amplification pass (marked as 1 in M_{12} and M_{13}). The laser pulses are then reflected back to M_{12} in preparation for the second amplification pass (marked as 2 in M_{12} and M_{13}). This process repeats eight times. The propagation of the pulses mimics that of an unstable cavity whereat each pass, the laser beam moves closer to the optical axis of the cavity. Because of the relatively small angle between the seed and pump pulses in the crystal, excellent spatial overlap between the seed and pump pulses is maintained along the length of the Ti:Sapphire crystal. Such optimized overlap in a multi-pass amplifier is only possible by using two concave mirrors. Another important technique in our amplifier module is the covering of the unused parts of mirrors M_{12} and M_{13}. By doing so, we were able to avoid ASE (Amplified Spontaneous Emission). After the eighth amplification pass, the energy of the amplified laser pulse would have reached its saturation value. It then exits the amplifier module through a 3-mm diameter hole in mirror M_{12} (marked as 8 in M_{12}).

In the initial testing of the amplifier, amplified laser energy reached 100 μJ, which corresponds to a gain of about 14000 times when the energy of the 532-nm laser pump pulse was 20 mJ. After 8 passes through the Ti:Sapphire amplifier crystal, the seed pulse would have travelled a total optical distance of 8.25 m, corresponding to a time of 27.5 ns. High amplification is possible due to the long fluorescence lifetime of the Titanium ions (3.2 μs) and high saturation fluence such that high pump energies can be used.

Table 2. Parameters of the laser pulse before and after the 8-pass amplifier.

Parameters	Before amplifier	After amplifier
Center wavelength	800 nm	800 nm
Pulse duration	$\sim$ 72ps	$\sim$ 72ps
Polarization	horizontal	horizontal
Repetition rate	10 Hz	10 Hz
Pulse energy	$\sim$ 7nJ	100 μJ (at 20 mJ of pump laser energy)
Energy stability	$< \pm 1\%$	$< \pm 3\%$
Beam divergence	$< \pm 1$ mrad	$< \pm 3$ mrad

Compressor module

The amplified pulses are fed to a single-grating compressor to remove the chirp introduced by the stretcher. The schematic diagram of the compressor module is shown in Fig. 8. Similar to the stretcher module, the compressor also uses a single grating of 1200 lines/mm. The specifications of the optical components used in the compressor module are summarized in Table 3. The amplified pulses are directed towards the grating by mirror M_{16}. After being diffracted by the grating, the pulses are reflected back to the grating again using mirrors M_{17} and M_{18}. After being diffracted by the grating the second time, the pulses are reflected back to the grating by mirror M_{19} to be diffracted the third time. After being reflected by M_{18} and M_{17}, the pulses are diffracted the fourth time before finally exiting the compressor through mirror M_{20}. In principle, in order to compress the 72 ps pulses back to transform-limited 85 fs pulses, a group velocity dispersion (GDD) of -2.23x10^6 fs^2 is needed. From the required GDD, we calculate that the distance between the grating and the mirrors M_{17} and M_{18} should be 28 cm. Moreover, the incidence angle of the seed pulses on the surface of the grating should be 30^o. In order to account for the dispersion introduced by the Ti:Sapphire crystal during the 8-pass amplification stage, mirrors M_{17} and M_{18} were mounted on a two-axis stage, allowing us to change the distance between the grating and the mirrors.

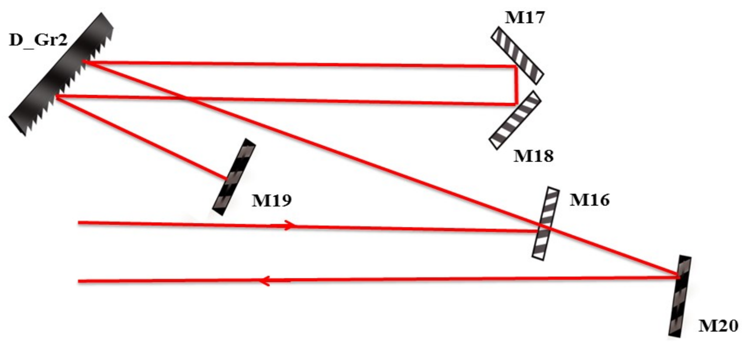

Fig. 8. Schematic diagram of the single-grating pulse compressor introducing negative dispersion into the amplified and streched laser pulses.

We have not yet evaluated experimentally the shortest duration of the amplified laser pulses after compression. However, using the parameters of the pulse compressor (distance between optical elements, laser beam arrival angle to the grating face, grating coefficient and laser pulse width before insertion into the amplifier), we estimate that the compressed laser pulse duration can be nearly transform-limited with a pulse duration close to that of the seed pulse. The pulse energy after the compressor was measured to be about 70 μJ.

Table 3. Specificaiton of the optical components used in the compressor module.

Components	**Specification**
M_{16}, M_{17}, M_{18}, M_{20}	Flat mirror, HR @ 740-840 nm at 45° incident angle, Ø 1’
M_{19}	Flat mirror, HR @ 740÷840 nm at 0^o incident angle , 40 x20 x5 mm
D_Gr2	Grating 1200 grooves/mm, 60 x40 x10 mm

IV. SUMMARY

We have developed a CPA-based Ti:Sapphire 8-pass amplifier for nanojoule and femtosecond Ti:Sapphire laser pulses using single-grating stretcher and compressor. The amplifier was successfully used to deliver up to 70 μJ pulse energy at 10 Hz repetition rate, which corresponds to an amplification factor (in pulse energy) of about 10000 times. With numerically calculated results about the pulse compression, the amplified laser pulses are expected to be nearly transform-limited with a pulse duration of less than 100 fs.

ACKNOWLEDGMENT

This work was financially supported by the Projects of Vietnam Academy of Science and Technology (VAST01.05/14-15 and VAST01.10/15-16).

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