Ultrabroadband TW-class Ti:sapphire laser system with adjustable central wavelength, bandwidth and multi-color operation

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Abstract: We demonstrate a versatile tunable and highly stable ultrabroadband Ti:sapphire chirped pulse amplification system with a compressed pulse energy of 20 mJ at 100 Hz repetition rate. High power Ti:Sa systems in principle do not offer wavelength tunability due to gain narrowing. Here we demonstrate transform limited pulse generation from 15 fs to 94 fs with tunable central wavelength ($\lambda_c$ from 755 nm to 845 nm) and bandwidth (130 nm $< \Delta\lambda < 16$ nm) as well as multi-color, time synchronized, sub-100 fs pulses with user defined central wavelength separation. The unique wavelength tunability capabilities have been expanded into the UV and deep-UV by second and third harmonic generation with excellent energy stability. Enhanced energy stability is achieved by multiplexing six ultrastable diode-based solid state pump lasers.

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References and links
1. D. Strickland, P. Maine, and G. Mourou, “Generation of ultrahigh peak power pulses with the technique of chirped pulse amplification,” J. Opt. Soc. Am. 3, 97 (1986).
2. A. Dubietis, G. Jonusauskas, and A. Piskarskas, “Powerful femtosecond pulse generation by chirped and stretched pulse parametric amplification in BBO crystal,” Opt. Commun. 88(4-6), 437–440 (1992).
3. A. Cianchi, D. Alesini, A. Bacci, M. Bellaveglia, R. Boni, M. Boscolo, M. Castellano, L. Catani, E. Chiadroni, S. Ciaidì, A. Clozza, L. Culturera, G. Di Pittro, A. Drago, A. Esposito M. Ferrario, L. Piccadenti, D. Filippetto, V. Fusco, A. Gallo, G. Gatti, A. Ghigo, L. Giannessi, C. Ligi, M. Mattioli, M. Migliorati, A. Mostacci, P. Musumeci, E. Pace, L. Palumbo, L. Pellegrino, M. Petrarca, M. Peveri, M. Quattromini, R. Ricci, C. Ronsivalle, J. Rosenzweig, A. R. Rossi, C. Sanelli, L. Serafini, M. Serio, F. Sgamma, B. Spataro, F. Tazzioli, S. Tomassini, C. Vaccarezza, M. Vespignani, and C. Vicario, “High brightness electron beam emittance evolution measurements in an rf photoinjector,” Phys. Rev. ST Accel. Beams 11(3), 032801 (2008).
4. D. H. Dowell, J. Castro, P. Emma, J. Frisch, S. Gilevich, G. Hays, P. Herring, C. Limbrog-Deprey, H. Loos, A. Miahnahr, and W. White, “LCLS injector drive laser,” in Proceedings of PAC07, Albuquerque, New Mexico, USA, TUPMS058 (2007).
5. C. Vicario, R. Ganter, C. Hauri, S. Hunziker, F. Le Pimpec, C. Ruchert, and A. Trisorio, “Photocathode drive laser for SwissFEL,” in Proceedings of FEL’10, Malmö, Sweden WEPB14 (2010).
6. C. P. Hauri, R. Ganter, F. Le Pimpec, A. Trisorio, C. Ruchert, and H. H. Braun, “Intrinsic emittance reduction of an electron beam from metal photocathodes,” Phys. Rev. Lett. 104(23), 234802 (2010).
7. A. Zhodinski, “Next generation X-ray free electron lasers,” IEEE J. Sel. Top. Quantum Electron. 99, 1–10 (2011).
8. M. B. Danailov, A. Demidovich, R. Ivanov, I. Nikolov, and P. Sigalotti, “Performances of the fermi FEL photoinjector laser,” in Proceedings of FEL 2007, Novosibirsk, Russia, WEPH014 (2007).
9. TOPAS-white data sheet, Light Conversion Ltd., www.lightcon.com.
10. G. Lambert, M. Bousgard, W. Boutu, B. Carre, D. Garzella, M. Labat, M. E. Couprie, O. Chubar, T. Har, H. Kitamura, and T. Shintake, “Seeding the FEL of the SCSS prototype accelerator with harmonics of a Ti:Sa laser produced in gas,” in Proceedings of FEL 2006, Bissy, Berlin, Germany, MOPPH046 (2006).
11. AS Photonics website: www.as-photonics.com/SNLO.html.
12. S. Chelkowski and D. Bandrauk, “Control of vibrational excitation and dissociation of small molecules by chirped intense infrared laser pulses,” Chem. Phys. Lett. 186(2-3), 264–269 (1991).
13. F. Eckemeyer, R. A. Kaindl, M. Woerner, T. Elsaesser, and A. M. Weiner, “Controlled shaping of ultrafast electric field transients in the mid-infrared spectral range,” Opt. Lett. 25(19), 1472–1474 (2000).
14. X. F. Li, A. L’Huillier, M. Ferray, L. A. Lompre, and G. Mainfray, “Multiple-harmonic generation in rare gases at high laser intensity,” Phys. Rev. A 39, 5751 (1989).
15. K. Yamakawa and C. P. J. Barty, “Two-color chirped-pulse amplification in an ultrabroadband Ti:sapphire ring regenerative amplifier,” Opt. Lett. 28(23), 2402–2404 (2003).
16. C. P. J. Barty, G. Korn, F. Raksci, C. Rose-Petruck, J. Squier, A. C. Tien, K. R. Wilson, V. V. Yakovlev, and K. Yamakawa, “Regenerative pulse shaping and amplification of ultrabroadband optical pulses,” Opt. Lett. 21(3), 219–221 (1996).
17. F. Verluise, V. Laude, Z. Cheng, C. Spielmann, and P. Tournois, “Amplitude and phase control of ultrashort pulses by use of an acousto-optic programmable dispersive filter: pulse compression and shaping,” Opt. Lett. 25(8), 575–577 (2000).
18. C. P. Hauri, M. Bruck, W. Kornelis, J. Bieger, and U. Keller, “Generation of 14.8-fs pulses in a spatially dispersed amplifier,” Opt. Lett. 29(2), 201–203 (2004).
19. T. Oksenhendler, D. Kaplan, P. Tournois, G. M. Greetham, and F. Estable, “Intracavity acousto-optic programmable gain control for ultra-wide-band regenerative amplifiers,” Appl. Phys. B 83(4), 491–494 (2006).
20. H. Takada and K. Torizuka, “Design and construction of a TW-class 12 fs Ti:sapphire chirped pulse amplification system,” IEEE J. Sel. Top. Quantum Electron. 12(2), 201–212 (2006).
21. A. Amani Eilanou, Y. Nabeewa, K. L. Ishikawa, H. Takahashi, and K. Midorikawa, “Direct amplification of terawatt sub-10-fs pulses in a CPA system of Ti:sapphire laser,” Opt. Express 16(17), 13431–13438 (2008).
22. E. Zeek, R. Bartels, M. M. Murnane, H. C. Kapteyn, S. Backus, and G. Vdovin, “Adaptive pulse compression for transform-limited 15-fs high-energy pulse generation,” Opt. Lett. 25(8), 587–589 (2000).
23. J. F. Xia, J. Song, and D. Strickland, “Development of a dual-wavelength Ti:sapphire multi-pass amplifier and its application to intense mid-infrared generation,” Opt. Commun. 206(1-3), 149–157 (2002).
24. Litron website: www.litron.co.uk/pages/nano_trl.html

1. Introduction

Ti:sapphire (Ti:Sa) laser sources based on chirped pulse amplification (CPA) [1] now permit the routine production of ultrashort, high energy femtosecond pulses in the near infrared (NIR). Despite the tremendous opportunities of such high-power amplifier systems, some limitations are apparent. Conventional Ti:Sa TW-class amplifier systems do in general not offer transform-limited (TL) (i.e. *chirp-free*) pulses tunable in duration, central wavelength, spectral shape and spectral width due to spectral gain narrowing intrinsically linked to high gain amplification. Optical parametric amplifiers (OPA) provide wavelength tunability but at a cost of a significantly lower pulse energy and pulse-to-pulse stability compared to Ti:Sa systems. In principle the energy limitation of OPAs could be overcome by stretching the pulse prior to amplification (OPCPA [2]) but further development seems required to reach stability, reliability and user friendliness similar to Ti:Sa amplifier systems.

A versatile tunable Ti:Sa TW-scale laser source capable of delivering TL pulses with user defined spectral shape and central frequency would be an appropriate source for a variety of applications in different research fields. A few examples shall be mentioned. Frequency-tripled Ti:Sa laser systems are used in some Free Electron Lasers (FEL) facilities to drive photo-injector electron guns [3–5]. Wavelength tunability of the deep-UV laser is shown to reduce the electron beam emittance by matching the laser photon energy to the work function of the cathode material [6]. A low emittance electron beam is a prerequisite to improve today’s FEL performances and for realization of future more compact and stable FEL’s [7]. These electron gun drive lasers need to be easily tunable in central wavelength at a high energy stability of less than 1% rms [8]. Such stringent stability requirements are presently not provided by OPAs [9]. The development of an ultrastable wavelength-tunable Ti:Sa amplifier is equally important to improve the coherence properties and spectral stability of an FEL. Seeding FELs with high-order harmonics (HH) produced in a rare gas [10] is shown to improve both. Ideally the HH source should emit highest yield at the resonant frequency of the FEL undulator to optimize the coupling efficiency of the seed to the electron beam while keeping the NIR driving pulse optimally compressed. Finally, a tunable two-color Ti:Sa system is an excellent frontend for the realization of a tunable femtosecond IR/midIR source by difference frequency generation (DFG) [11]. Femtosecond (mid-)IR sources find applications in coherent control of molecules [12], material research [13] and high field physics such as HH generation [14].
In the past, several ways have been presented to overcome gain narrowing in Ti:Sa systems such as intracavity spectral filters (e.g. Fabry-Perot etalons) [15] and spatial masks located in a wavelength dispersed beam section [16]. Yamakawa et. al. [15] demonstrated amplified 20 mJ pulses with 128 nm FWHM, but the scheme did not allow temporal compression of the amplified pulses due to high order spectral phase distortions. Later, Verluise et. al. used a technique based on an acousto-optic programmable dispersive filter (AOPDF, DazzlerTM) located before the amplifier. There the effect of gain narrowing was pre-compensated by introducing spectral losses prior to amplification [17] and 17 fs-1 mJ compressed pulses were obtained. However, enhancement of the bandwidth prior to amplification goes along with strong reduction of the seed pulse energy and with an increase of parasitic amplified spontaneous emission (ASE) deteriorating the stability, efficiency and temporal contrast. Hauri et. al. demonstrated another scheme based on wavelength-selective pumping in an angularly dispersed multipass amplifier [18] resulting in 14.8 fs-450 µJ pulses. Wavelength-selective pumping, however, adds a lot of complexity and is furthermore sensitive to spatial chirp due to locally inhomogeneously distributed pump power in the crystal across the different frequencies. Finally, low-loss acousto-optic programmable gain control filter (AOPGCF, MazzlerTM) in a regenerative cavity has been shown to successfully counteract gain narrowing. A proof-of-principle experiment yielded 500 µJ, sub-20 fs pulses duration with an 80 nm FWHM spectrum [19]. Other groups reported passive regenerative pulse shaping with specially designed gain-narrowing compensators and mirrors [20,21] or adaptative pulse compression with deformable mirror [22] resulting in sub-15 fs pulses. Two-color amplification has also been demonstrated in Ti:Sa systems. Two different schemes have been reported based on a conventional Ti:Sa CPA system seeded with a dual color broadband oscillator [23] or regenerative amplification using intracavity spectral etalon filters [15]. None of the above mentioned techniques, however, allow the user to switch easily between ultrabroadband amplification and other configurations, such as multi-color amplification, wavelength tuning, or spectral shaping.

In this paper, we demonstrate a TW-class, versatile tunable Ti:Sa CPA system capable of providing an ultra-broadband spectrum of 130 nm at full width as well as two-color and multi-color amplification. The system makes use of an ultra-wide-band regenerative amplifier hosting an AOPGCF [19] that allows amplification from 735 to 865 nm. Pulse compression is achieved down to 15 fs with 20 mJ energy, corresponding to a peak power of 1.3 TW. In addition, remote control selection of the laser pulse bandwidth between 16 to 130 nm and the central wavelength between 755 to 845 nm is provided by an AOPDF device located prior to the amplifiers. With the ultrabroadband spectral intensity and spectral phase control given by the AOPDF our source delivers TL (i.e. unchirped) pulses with durations from 15 fs to 94 fs with a typical energy of 20 mJ and a stability of 0.5% rms. Narrowband operation of the amplifier results in a user-friendly wavelength-selective high-power amplifier tunable across the 130 nm gain bandwidth. We finally demonstrate synchronous generation and temporal compression of two-color 18 mJ, sub-100 fs pulses with a central wavelength separation tunable over 85 nm that is suitable for intense mid-IR pulse generation tunable within 7.5 to 15 µm. Multi-color amplification with up to five colors shows the versatility of our amplifier system. The wavelength-tuning capability of our system is extended towards the UV and deep UV by second and third-order harmonic generation resulting in wavelength-tunable femtosecond pulses in the deep-UV at the mJ energy level with a remarkable stability superior to OPA systems. The system is an ideal frontend for high-field physics, such as HHG, attosecond science and for novel applications in accelerator science.

2. Laser system

The schematic of our Ti:Sa CPA system is shown in Fig. 1. The oscillator (Rainbow system, Femtolasers GmbH) delivers ultra-broadband pulses at 83 MHz and is used as seed for the 100 Hz booster amplifier which increases the pulses energy to 1µJ.
After pre-amplification, the pulses are stretched to 500 ps in a double-pass Offner triplet and sent through an AOPDF (DAZZLER™ HR800 – Fastlite). The AOPDF allows the user to easily define the spectral amplitude filter prior to regenerative amplification and is furthermore used for optimal pulse compression by higher-order phase compensation via phase-error feedback from an online SPIDER measurement. The core device of our amplifier is the regenerative amplifier (RA) with an intracavity Brewster-cut AOPGCF (MAZZLER™ – Fastlite). It provides ultra-wide-band amplification to pulse energies of 0.4 mJ. The AOPGCF is a computer controlled programmable gain filter which allows gain narrowing compensation. This is done via a computer-based feedback optimization loop based on an error signal derived from the amplified output spectrum (after compressor) and a user-defined reference. The AOPGCF introduces spectral losses through partial diffraction of spectral components taking into account the gain shaping effects from all amplifier stages and all optical elements like mirrors, polarizers, gratings and waveplates. Both booster and RA are pumped with one diode-pumped solid-state frequency doubled Nd:YAG unit (Centurion-Quantel, 20 mJ @ 100 Hz). After the last two multipass amplifiers (MA) a pulse energy of 27 mJ is reached. Six Centurion units are used to pump the two power amplifiers (1(5) for multipass amplifier I (II)). Multiplexing five pump lasers with 20 mJ instead of using one 100 mJ pump laser is motivated by energy stability issues which are discussed in section 3. The grating-based compressor (1200 g/mm – Jobin & Yvon) supports a spectral bandwidth of 130 nm and delivers compressed 20 mJ pulses. A complete spectro-temporal pulse characterization is performed with a commercial SPIDER apparatus (APE GmbH) and the measured residual spectral phase is compensated with the AOPDF by feedback loop. This accurate compensation allows for ultrashort transform-limited pulse generation down to 15 fs.
(corresponding to 1.3 TW) as well as for pulse compression in the multi-color or wavelength-tuning operation mode. UV and deep-UV pulses are generated by second-order and third-order harmonic generation both performed in type I BBO crystals (see Fig. 1 for details). The delivered energies are up to 6 mJ in the UV and 1 mJ in the deep-UV, respectively.

3. Generation of 20 mJ – 15 fs FWHM pulses at 100 Hz

A necessary condition for ultra-short pulse generation is an amplified spectrum as broad as possible. In our amplifier this is achieved by doing adaptive regenerative pulse shaping with the AOPGCF amplitude filter that accurately controls the spectral losses in our RA’s cavity [19]. Figure 2 shows the capabilities of the AOPGCF device: we measured the amplified spectra after amplifier 2 without (black dashed line) and with programmable gain control (red solid line). The natural gain narrowed amplified spectra (black, dashed line) has a bandwidth of 36 nm full width half maximum (FWHM) corresponding to a TL pulse duration of 26 fs FWHM. After spectral gain optimization with the AOPGCF device, the amplified spectrum has a flat-top like shape and a much broader bandwidth of 120 nm FWHM. The full bandwidth is 130 nm spanning from 735 to 865 nm. This corresponds to a TL pulse duration of 14.9 fs FWHM. The amplified spectral width is limited by the optical aperture and spectral acceptance of the stretcher mirrors. More broadband pulses could potentially be achieved using optics with larger geometrical aperture and spectral bandpass.

![Fig. 2. Spectra of the amplified pulse. The ultra-wide-band spectrum generated via regenerative reshaping is measured after the regenerative amplifier (black squares) and after the compressor (red line). The spectrum exhibits a bandwidth of 120 nm FWHM and no significant narrowing or reshaping occurs in the multi-pass amplifiers. As a comparison the natural gain narrowed amplified spectra is shown in black dashed line having a bandwidth of 36 nm FWHM.](image)

The spectrum reshaping is done iteratively starting from the gain-narrowed amplified spectrum $S(\lambda)$ (i.e. AOPGCF off). The following procedure is applied: from the gain-narrowed amplified spectrum, an algorithm computes the new AOPGCF spectral filter function $R(\lambda)$ in order to equalize the spectral gain over the AOPGCF bandwidth (200 nm full width). The normalized merit function used by the algorithm is a flat spectral response $M(\lambda) = 1$. The algorithm computes $R(\lambda) = \frac{M(\lambda)}{\beta * S(\lambda)}$ where $\beta$ is a ponderative factor varying through the iterative process. With this filter response loaded in the AOPGCF, the spectral transmission of the RA is thus correspondingly modified. The typical amount of introduced integrated loss per roundtrip is on the order of 4 to 6%. Next, the RA pump energy level is slightly adjusted in order to compensate for the introduced losses. Finally the new amplified spectrum is recorded followed by another iteration until the desired broadband spectrum is achieved. Only a few iterations are required (5-8) and the procedure needs to be
done only once. The merit function corresponds to a wavelength-independent gain function of the amplifiers, which is a prerequisite for wavelength-tunable pulses at constant energy and constant bandwidth (see section 4). Once the target spectrum is achieved the day-to-day reproducibility throughout one week is very good and requires no further iterations.

The AOPGCF is used in a collinear geometry so that the incident optical and acoustic beam Pointing vectors are nearly collinear leading to a long interaction length and correspondingly to a high diffraction efficiency and high spectral resolution. The Brewster cut of the optical faces avoids Fresnel losses and spurious pulse replicas in the RA. Compensating the introduced losses after each loop by slightly increasing the RA pump energy by a few percent allows operating the RA in saturation ensuring highest output energy stability. The amount of round trips in the RA (10 roundtrips) are kept constant throughout the optimization procedure.

For sake of completeness the spectrum recorded directly after the RA is also displayed in Fig. 2 (black dots). A comparison to the spectrum measured after the compressor (red solid line) clearly demonstrates that spectral gain-narrowing/reshaping in the two high-power amplifying stages after the RA and in the compressor is negligible. For ultra-broadband spectral amplification we conclude that active spectral shaping is required up to several hundred uJ. Then, the spectral shape is preserved in the power amplifiers up to the TW level.

Fig. 3. SPIDER measurement of the ultrabroadband, compressed pulse. a) Reconstructed temporal profile of the 15 fs pulse (red solid line), of the 14.8 fs transform limited pulse profile (black dots) and reconstructed temporal phase (blue solid line). b) Measured spectral intensity (red solid line) and spectral phase of of the compressed pulse (blue dots).
After compression, the pulse spectral phase was reconstructed with the SPIDER. The measured spectral phase was inverted and fed back to the AOPDF in order to achieve best compression. The resulting reconstructed temporal profile (Fig. 3a) shows a 15 fs, 20 mJ pulse with the corresponding spectral phase shown in Fig. 3b (blue dotted line). Although some satellites around the main peak are present, the duration of the pulse is close to its Fourier-limit (14.8 fs). The integrated energy in the main peak is 88% of the total energy reflecting a good compression quality and close to the perfectly transform limited pulse (95% of the energy in the main pulse - Fig. 3a, black dots). Note that the satellite pulses originate from the spectral shape and are also present for a perfectly compressed/Fourier-limited pulse.

The energy stability of this ultra-broadband 20 mJ, 15 fs pulse was measured to be ±0.27% rms (±2.2% P-P) over 5 minutes (100% of the laser shots). Detailed information about the evolution of stability along the different amplifier stages is given in Table 1. The excellent stability at the amplifier's exit measured in our scheme is achieved by choosing an ultra-stable diode-based pump laser (Centurion, Quantel, 0.4% rms over 24 h) and by multiplexing six of these. Ideally, clustering six Centurion pump lasers (6x20 mJ = 120 mJ) results in a pump energy noise level which is reduced by a factor of \( \sqrt{6} = 2.4 \) compared to one single pump laser with an equivalent output energy of 120 mJ. The stability which can be expected from an amplifier pumped with one single pump laser is at best limited by the noise floor of the pump. Our approach of multiplexing several pump lasers with moderate individual pulse energies helps to keep highest pulse stability even at ultrabroadband amplification. We estimate the stability of ±0.27% rms reached here to be an order of magnitude superior to an equivalent flash-lamp pumped amplifier system. In fact, the only presently available pump laser for Ti:Sa delivering 120 mJ energy at 100 Hz is a flashlamp type pump laser (e.g. Litron Nano TRL 250-100) whose energy stability is typically very large (>3% rms [24]).

Table 1. Measured Average Energy, Peak to Peak (P-P) and Root Mean Square (RMS) Stability after the Regenerative Amplifier (RA), the Multi-Pass Amplifier 1 and 2 and the Compressor of the System

|                | Averaged energy (mJ) | P-P stability (%) | RMS stability (%) |
|----------------|----------------------|-------------------|-------------------|
| RA             | 0.41                 | 8.9               | 1.1               |
| Amplifier 1    | 5.76                 | 5.6               | 0.7               |
| Amplifier 2    | 27                   | 4.4               | 0.54              |
| Compressor     | 20                   | 4.4               | 0.54              |

*All stability measurements are performed over 5 minutes, recording 100% of the shots at 100 Hz repetition rate.

Compared to regenerative pulse shaping techniques described before [15,16] the approach presented here has two main advantages. First, a fast change of spectral shape is possible by remote control of the amplitude and phase filters (Mazzler™, Dazzler™) without realignment of the laser system. This is a pre-requisite for demanding applications like in remotely-controlled large scale facilities. Second, ultra-wide-band gain-equalization is achieved while maintaining the nominal output energy and stability of the RA since the introduced spectral losses are compensated by a slight increase of the RA pump energy. Once the gain equalization procedure is performed, the amplifier system allows versatile tunability of spectral shapes across the full bandwidth. A few examples are given below.

4. Generation of transform limited pulses with tunable central wavelength/bandwith

In this section, we present the potential of our scheme to generate TL pulses with tunable pulse duration and at variable central wavelength. Figure 4 gives a few examples of the versatile shaping capabilities of our system. At first, a spectral slice of \( \Delta \lambda = 24 \text{ nm} \) (full
width) at a central wavelength $\lambda_0 = 770$ nm (Fig. 4b, green solid line) is amplified to 23 mJ and compressed to 49 fs FWHM (TL = 47 fs) (Fig. 4a, green curve) at a stability of 0.4% rms (3.2% P-P). Secondly, the central wavelength was changed to $\lambda_0 = 830$ nm and the bandwidth to $\Delta \lambda = 37$ nm (full width) (Fig. 4b, blue solid line) giving rise to a pulse duration of 55 fs FWHM (TL = 53 fs) (Fig. 4a, blue line). The pulse energy was 18.6 mJ with a stability of 0.6% rms (4.9% P-P). Finally, the longest transform-limited pulse duration the system is capable to produce at the 20 mJ level is dictated by intensity induced damage in the amplifiers. In our case the minimum applicable bandwidth is as small as $\Delta \lambda = 16$ nm (full width). An example of such a narrow-band amplified pulse at a central wavelength of $\lambda_0 = 800$ nm is shown in Fig. 4b (black solid line). After compression, a pulse duration of 94 fs FWHM (TL = 93 fs) was measured with a clean temporal profile (Fig. 4a, black curve) and 18 mJ pulse energy. We would like to stress that all presented pulses are close to transform-limit. For sake of completeness the broadest spectrum (of $\Delta \lambda = 120$ nm FWHM, $\lambda_0 = 800$ nm) and the corresponding 15 fs, 20 mJ temporal shape are also presented (Fig. 4, red solid line). This is to our knowledge the first amplifier scheme which allows such easy-to-tune pulse durations and wavelength variation at the TW level.

![Graphical representation of pulse characteristics](image)

**Fig. 4.** Versatility of the system for the generation of transform limited-wavelength tunable pulses in the near-IR. a) Reconstructed temporal profile from the SPIDER measurements. Pulses characteristics are: 15 fs (14.9 fs TL) at $\lambda_0 = 800$ nm (red), 94 fs (93 fs TL) at $\lambda_0 = 800$ nm (black), 49 fs (47 fs TL) at $\lambda_0 = 770$ nm (green) and 55 fs (53 fs TL) at $\lambda_0 = 830$ nm (blue). b) Corresponding measured spectral intensity.
The unique tunability capabilities of our setup demonstrated above have been expanded into the UV and deep-UV by second and third-order harmonic generation (see Fig. 1 for technical details). In order to demonstrate wavelength-tunability in the UV and deep-UV, 55 fs pulses ($\Delta \lambda = 30$ nm) at a variable central wavelength across 780 nm to 845 nm were doubled and sum-frequency mixed with the fundamental, respectively. The resulting wavelength of the second harmonic can be varied from 390 nm to 423 nm as depicted in Fig. 5 (dashed lines). Maximum energy (6.1 mJ) was achieved for 406 nm with a stability of 0.6% rms (4.6% P-P). Similarly, the third harmonic could be tuned from 262 to 282 nm. The corresponding measured spectra are show in Fig. 5 (solid lines). The pulse energy was varying from 250 $\mu$J at 262 nm to 1 mJ at 271 nm. The large energy variation across the bandwidth is assigned to the crystals’ cut giving rise to a wavelength-dependent conversion efficiency. The energy stability was 2% rms and 0.7% rms at 262 and 271 nm respectively. It is worth to stress that the stability of this source outperforms commercially available OPAs with stabilities typically $\geq$3% rms at these wavelengths. This laser source is thus an excellent tool for the generation of high-energy, wavelength tunable femtosecond pulses in the UV and deep-UV for high-field physics, attoscience and FEL related applications mentioned above.

![Fig. 5. Measured second and third harmonic spectra. Dashed lines: second harmonic spectra at 390 (blue), 406 (black) and 423 nm (red) generated with 55 fs fundamental pulse at 780 nm, 813 nm and 845 nm respectively. Solid lines: corresponding third harmonic spectra at 262 nm, 271 nm and 283 nm.](image)

### 5. Multi-color operation

In addition to narrowband/broadband amplification as presented above our amplifier system is capable to provide user-defined two and multi-color spectra at various central wavelengths. Once the gain-equalization procedure is performed multi-color amplification is easily achieved by simply defining the desired spectral filter function (central wavelength, bandwidth and spectral shape) as a text file which is up-loaded to the AOPDF. It is worth to mention that this operation is again fully remote controlled and no re-alignement or fine-tuning of the amplifiers is required.
In particular two-color amplification is of interest for a potential extension of wavelength tunability towards the infrared spectral region by DFG in a nonlinear crystal. Such an NIR-to-IR conversion based on one single nonlinear stage is expected to provide pulse-to-pulse energy stabilities which are superior to the conventional multi-stage, whitelight-based OPA approach. The tunability of the infrared generated by DFG is dictated by the minimum and maximum two-color central wavelength separation in our amplifier system. For an individual pulse bandwidth of $\Delta \lambda = 20$ nm our source would be suitable to generate mid-IR radiation from 7.5 to 30 $\mu$m for a minimal/maximal spectral separation of 20 nm and 85 nm, respectively (provided an appropriate crystal exists). For demonstration we applied a spectral filter function consisting of two spectral slices of bandwidth $\Delta \lambda = 20$ nm at two different central wavelength $\lambda_{10}^0 = 760$ nm and $\lambda_{20}^0 = 845$ nm corresponding to the maximum possible separation in our amplifier (Fig. 6b).

It is important to perform carefully the following compression procedure to ensure that both pulses are compressed simultaneously. We use two reflective dichroic filters for individual characterization and optimization of the corresponding pulses with SPIDER (SPIDER cannot intrinsically measured double pulse trace). Both of the pulses are individually optimized by feeding back the residual spectral phase to the AOPDF in order to
achieve best compression. Finally the individually optimized spectral phase files were superposed to the final AOPDF phase function. Figure 6a shows the reconstructed temporal profiles of the two pulses after this procedure. Close to transform-limited compression down to 70 fs is achieved for the pulse at $\lambda_1^0 = 760$ nm (blue squared line) and to 100 fs for the second one ($\lambda_2^0 = 845$ nm, red dotted line) with pulse energies of 10.4 mJ and 7.6 mJ, respectively. The corresponding measured spectral phase (dashed lines) and spectra (solid lines) are displayed in Fig. 6b. The spectral shapes are slightly modulated since the edges of the wide spectrum were selected, but no severe constraints on the pulse temporal profile is observed. Compared to previous reported results [15,23], we demonstrate a full spectral-temporal pulse characterization and about 1.8 time more compressed pulse energy. No IR generation is performed so far due to the lack of an appropriate crystal in our lab.

Finally we illustrate the capability of our system to generate complex high-energy multi-color pulses. Again, this is simply done by designing the desired spectral filter function and apply it to the AOPDF. A 4-color and 5-color spectrum recorded after the compressor are shown in Figs. 7a and 7b respectively. We did not perform temporal compression in this case. It is worth mentioning that once the AOPGCF routine is set to get the broadband spectrum shown in Fig. 2, then multi-color operation does not require re-optimization of the system.

![Multi-color amplified spectra](image)

Fig. 7. Multi-color amplified spectra. Measured 4-color (a) and 5-color (b) spectra after the compressor.

6. Conclusion

In conclusion, we present a TW-scale Ti:Sa CPA system capable of delivering ultra-short pulses in both single and multi-color operation mode. The amplified spectrum has maximum full width of 130 nm. Single color, transform-limited pulses with durations from 15 fs to 94 fs with tunable central wavelength over a 85 nm spectral range is demonstrated. Pulse energy of 20 mJ with a remarkable stability of 0.54% rms is achieved thanks to multiplexing of several highly-stable pumping units. We also demonstrate generation and temporal compression of multi-color, 18 mJ, sub-100 fs pulses with central wavelength separation of 85 nm that is suitable for intense IR pulse generation. The laser system is shown to be an excellent frontend for the generation of wavelength tunable femtosecond pulses in the UV and deep-UV at the mJ energy level with a better stability than OPA systems and is ideal for high-field science, attosecond physics and FEL related applications.

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