Seeding of an Eleven Femtosecond Optical Parametric Chirped Pulse Amplifier and Its Nd^{3+} Picosecond Pump Laser From a Single Broadband Ti:Sapphire Oscillator

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***Abstract*—We demonstrate direct simultaneous seeding of a few-cycle optical parametric chirped pulse amplifier (OPCPA) in the 700–1000-nm spectral range, and of a Nd:YLF amplifier emitting 30-ps pulses at 1053 nm by use of a chirped-mirror 6-fs Ti:sapphire oscillator. This approach of employing a single master oscillator to drive two power amplifiers simplifies the pump laser design and is applied to eliminate the timing jitter between the seed and the pump pulses in the OPCPA chain. We show that 10 mJ fundamental picosecond pump pulses with the intensity contrast in excess of 10^4 relative to the nanosecond *Q*-switched background can be achieved with the seed intensity available in the edge of the oscillator spectrum around 1053 nm. Cross-correlation measurements between the picosecond pump and femtosecond oscillator pulses reveal no traceable timing jitter between the OPCPA pump and seed pulses. The estimated long-term jitter of 0.3 ps is attributed to the thermal expansion of the cavity of the Nd:YLF regenerative amplifier.**

***Index Terms*—Laser amplifiers, optical oscillators, optical parametric amplifiers, ultrafast optics.**

I. INTRODUCTION

CURRENT rapid advancement in the fields of extreme nonlinear optics and high-field physics [1], and in attosecond physics [2], relies on the availability of high peak-intensity few-cycle drive lasers with carrier envelope phase (CEP) control [3]. Optical parametric chirped pulse amplification (OPCPA) [4]–[6] offers a promising route toward developing compact few-cycle high-intensity laser systems. Key advantages of this technique, compared to regenerative and multipass laser amplification, include very broadband gain, negligible thermal load on transparent nonlinear crystals in the parametric amplifier, and an extremely high gain—even in a thin crystal. To date, OPCPA systems producing high-energy several hundred femtosecond pulses [7]–[11], sub-20-femtosecond pulses with the CEP locked [12], [13], and few-cycle terawatt-class pulses [14], [15] have been demonstrated.

II. BROADBAND OPCPA

A. Pump Pulse Synchronization

One of the most attractive features of parametric amplification, its extremely low waste heat due to the lack of inversion storage, is intrinsically related to one of its main challenges-the requirement for strict synchronization between the seed and pump pulses. The timing precision within a fraction of the pulse durations is required because of the instantaneous energy exchange in parametric three-wave mixing. Obviously, the difficulties with pump synchronization directly depend on the pump pulse duration. Synchronization of nanosecond *Q*-switched pulses does not involve a major effort. Such pulses have been used in hybrid parametric and laser amplifiers schemes [8], [16], [17] for the generation of pulses in the 100-fs range. For few-cycle OPCPA, nanosecond pump pulses are rather unattractive for several reasons. First, the parametric gain and its bandwidth are determined by the combination of pump intensity and crystal thickness which cannot exceed 4–5 mm for few-cycle amplifiers. Therefore, efficient broadband amplification calls for the highest safe pump intensity [18]. The damage threshold intensity for nanosecond pulses is lower than for picosecond pulses, which makes the latter a more favorable choice. Second, the temporal stretching of the seed, which is needed to match the pump and seed pulse durations, and a reliable, clean recompression of the amplified signal duration by approximately six orders, become impractical. Third, since the spatial length of the pump pulse is much longer than the thickness of the nonlinear crystal in the parametric amplifier, reflections of the amplified seed pulse from the crystal surfaces creates conditions for parasitic oscillation and amplification of post-pulses [19].

The use of picosecond (Nd:YAG, Nd:YLF, $Nd:YVO_4$) pump lasers or subpicosecond (Yb^{3+}-doped host materials, Ti:sapphire, Nd:glass) pump lasers relaxes the preceding concerns about the bandwidth, damage threshold, and amplified pulse recompression. Instead, the shorter pump duration aggravates the problem with pump pulse synchronization. Millijoule to one Joule pulses of several tens of picoseconds from Nd:YAG and Nd:YLF lasers are currently available in many laboratories,

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and can be utilized as efficient OPCPA pump sources. Such systems, however, require sub-few-picosecond synchronization with the seed pulse of the OPCPA.

Although less than 1-ps synchronization is possible by electronic phase lock loop (PLL) stabilization of the cavity lengths of the pump and seed oscillators [20], a double-balanced mixer used in the PLL has a critical disadvantage of causing long-term phase drifts, which originate from thermal drift and phase noise converted from an amplitude noise [20]. These drifts change the relative timing of the pump and seed pulses in the parametric amplifier so that the long-term stable operation required for experimental applications is difficult to maintain. A PLL loop that does not involve the use of a mixer and is potentially insensitive to thermal drift was demonstrated in [21]. The timing jitter in this loop is below 20 fs (25 mHz–10 kHz). However, this system is fairly complex and its long-term stability has not yet been proven, whereas such tight synchronization precision is superfluous. Even with rigorous cavity synchronization of the two master oscillators in an OPCPA system, the actual pump-seed timing at the nonlinear crystal is affected by the thermal expansion of the beam path length. The latter can reach many tens of meters in a typical regenerative or multipass amplifier, which results in the timing drift between the pump and seed pulses by hundreds of femtoseconds.

In other OPCPA systems [4], [7], [12], one oscillator delivered a seed pulse to an OPCPA and a pump amplifier; however, so far this scheme has only been applied to optical parametric amplification (OPA) operating at the degeneracy point because the choice of available wavelengths was limited to the fundamental and its harmonics. A degenerate OPA provides a narrower bandwidth than noncollinearly phase-matched OPA, and restricts wavelength tunability.

B. Seeding From a Common Oscillator

In this paper, we demonstrate a simple and reliable technique, based on the use of a single master oscillator, for all-optical synchronization between picosecond pump and seed pulses in a few-cycle OPCPA system. To achieve broadband amplification, we used a noncollinearly phase-matched optical parametric amplifier (NOPA), in which a type I phase-matching BBO crystal is pumped by the frequency-doubled output of a picosecond Nd^{3+} laser. The gain bandwidth supported by such type of OPCPA [13], [14] covers the spectral range from 700 to 1050 nm, and is suitable for amplification of sub-10-fs pulses with a flat spectral gain. The first OPCPA systems, based on the seed from a broadband Ti:sapphire oscillator and an external Nd:YAG pump laser, relied on electronic repetition rate synchronization between the femtosecond Ti:sapphire oscillator and a picosecond $\mathrm{Nd{:}YVO_4}$ oscillator (the seeder of the Nd:YAG amplifier). Recently, we implemented a scheme for passive repetition rate synchronization based on soliton self-frequency shift in a photonic crystal fiber [22] which was used to synchronize a 1064 nm Nd:YAG pump laser with an OPCPA seed pulse. In comparison with earlier papers [13]–[15] the main novelty introduced in our present work is that the optical seed of the parametric amplifier and of a picosecond pump laser are derived from a single source. In this method, a picosecond 1053-nm Nd:YLF laser used for pumping a broadband parametric amplifier and the parametric amplifier itself are seeded in parallel from one ultrabroadband Ti:sapphire oscillator. Suitably broadband oscillators have been developed in several laboratories [23]–[26]. With such seed sources, no additional extracavity spectral broadening that might impair the critical stability of the seed source is required. In addition, the use of a broadband Ti:sapphire oscillator with megahertz-repetition-rate CEP stabilization [23], [25], [27] permits further straightforward amplification of CEP-controlled pulses in kilohertz-repetition-rate OPCPA [12], [13]. The seeding method, demonstrated here, also opens a simple way toward all-optical synchronization of amplifiers based on different gain media in the spectral range from 600 to 1100 nm. This spectral range covers workhorse solid-state laser media such as Ti:sapphire, Yb^{3+}-doped, and Nd^{3+}-doped host materials.

III. EXPERIMENTS

A. Optically Synchronized Pump Laser System

The layout of the OPCPA system is shown in Fig. 1. A detailed description of the 76-MHz-repetition-rate Ti:sapphire seed oscillator is given elsewhere [24]. In comparison with [24], the configuration of chirped mirrors in the current oscillator was changed to enhance the IR spectral wing. The seed spectrum is presented in Fig. 2(a). A 50% broadband beamsplitter (BS in Fig. 1) divides the 6-fs 5-nJ oscillator pulse into two replicas that are sent into the Nd:YLF regenerative amplifier and the NOPA, respectively. The estimated seed energy into the regenerative amplifier within the fluorescence bandwidth of Nd:YLF centered at 1053 nm is 1.3 pJ. Our 1-kHz-repetition-rate regenerative amplifier is based on a cw-laser-diode gain module (model RD40, Northrop Grumman Cutting Edge Optronics) that pumps a 63-mm-long 3-mm-in-diameter a-cut Nd:YLF rod. The small signal roundtrip gain is kept at approximately 2.2. The intracavity pulse train and the ejected pulse of the regenerative amplifier are depicted in Fig. 2(b). The maximum energy of the amplified pulses is 3.7 mJ, which is limited by the average power saturation and the optical damage of the $\mathrm{KD^*P}$ Pockels cell [28], [29]. Efficient frequency doubling is obtained in a 10 mm critically phase-matched Type I LBO crystal, resulting in 1.6-mJ pulses at 527 nm. The measured energy stability of the second harmonic output is 1.4% rms because of the average power saturation. An etalon was introduced into the Nd:YLF amplifier cavity to broaden the pulse duration and avoid nonlinear effects. Without the etalon, we observed pulse splitting and spectral broadening. The output spectra of the regenerative amplifier operating with and without the etalon are shown in Fig. 3(a). The insertion of a 0.8 mm thick etalon results in a smooth, narrow spectrum (Fig. 3(a), shaded contour), which corresponds to the spectral resolution limit of the optical frequency analyzer (AQ6315B, Ando). Fig. 3(b) depicts the intensity autocorrelation of clean near-Gaussian sub-30-ps fundamental pulses obtained with the 0.8-mm etalon.

B. Pump Pulse Contrast

Because the energy of the seed pulses is comparatively weak in our system, the competition between the amplified

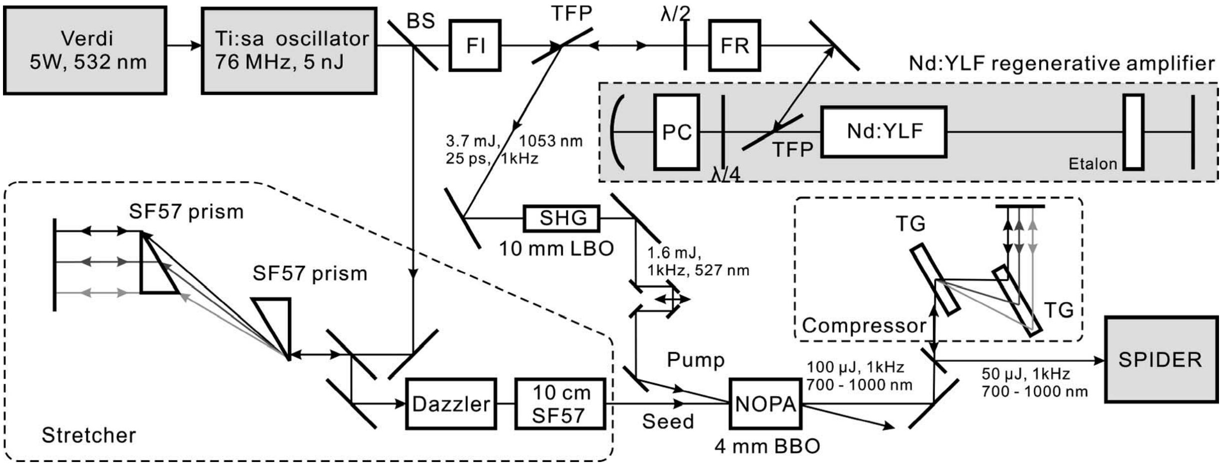

Fig. 1. Schematic of optically synchronized few-cycle OPCPA. BS: broadband 50% beam splitter; FI: Faraday isolator; TFP: thin-film polarizer; $\lambda/2$: half-wave plate; FR: Faraday rotator; $\lambda/4$: quarter-wave plate; PC: KD*P Pockels cell; Nd:YLF: Nd:YLF cw-pumped gain module; SHG: second-harmonic generator; NOPA: noncollinearly phase-matched optical parametric amplifier; TG: transmission grating; SPIDER: spectral phase interferometry for direct electric field reconstruction.

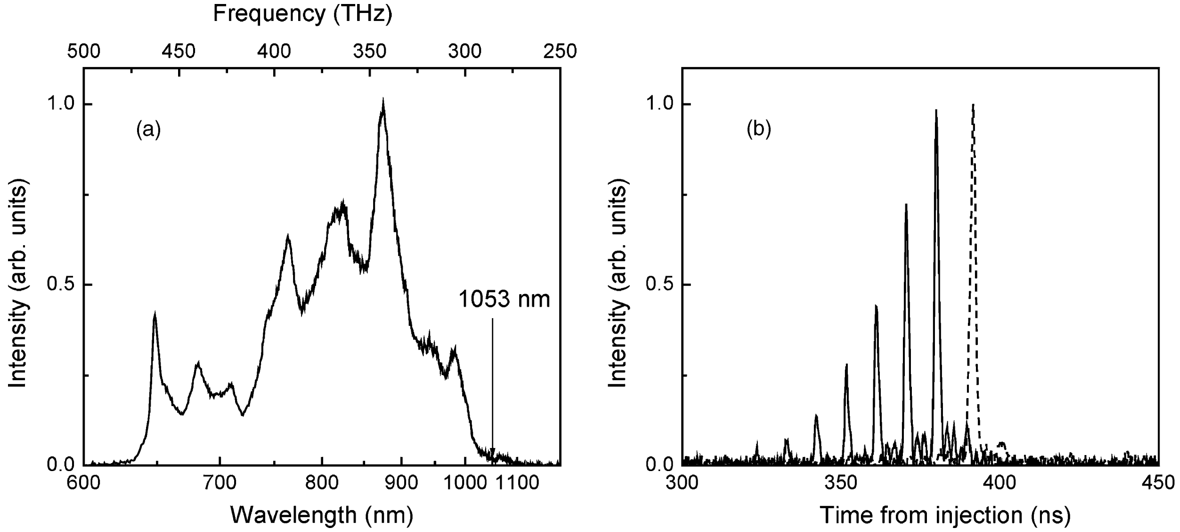

Fig. 2. (a) Ti:sapphire oscillator spectrum. (b) Intracavity pulse train of regenerative amplifier (solid line) and ejected pulse from the amplifier (dashed line).

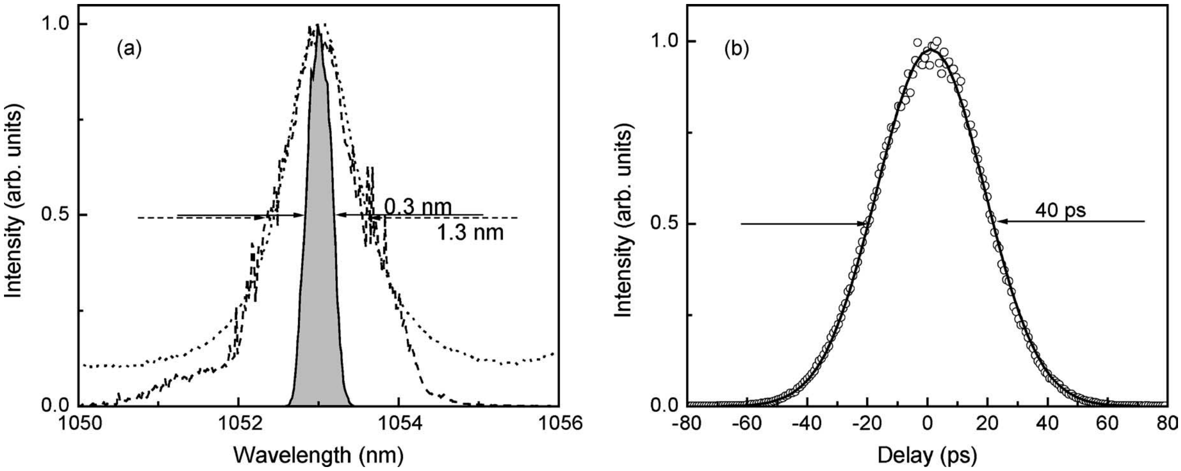

Fig. 3. (a) Output spectra of Nd:YLF amplifier. Solid line: spectrum with 0.8-mm-thick etalon in regenerative amplifier cavity. Dashed line: spectrum without etalon. Dotted line: fluorescence spectrum of Nd:YLF around 1053 nm. Note that 0.3-nm spectral width in the case of intracavity etalon is limited by resolution of the spectrometer. (b) Autocorrelation trace of picosecond pulses from amplifier with intracavity etalon. Solid line: Gaussian fit.

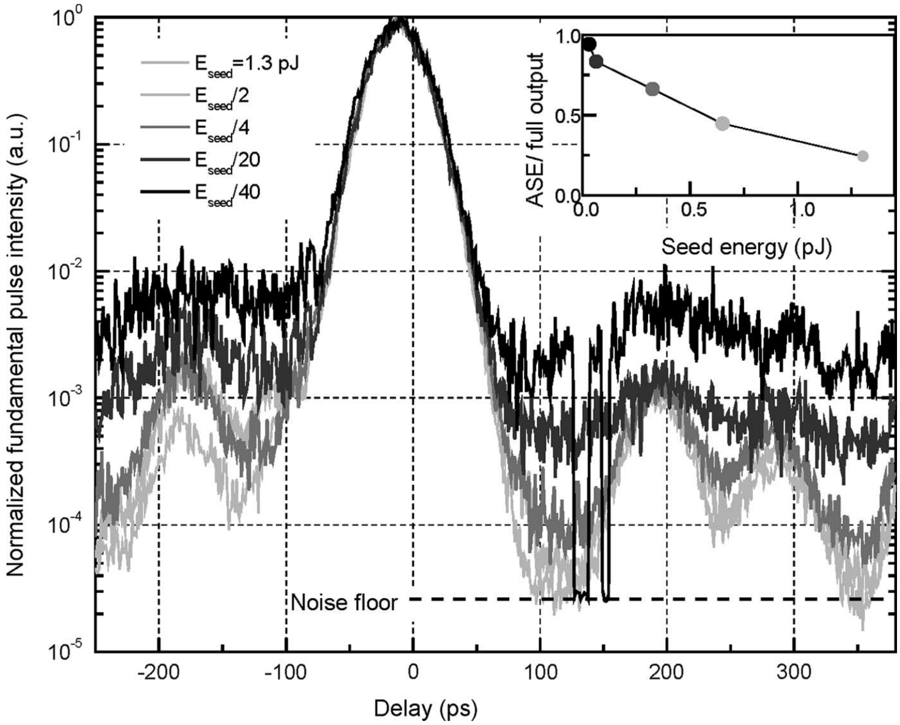

Fig. 4. Third-order correlation traces of amplified picosecond pulses seeded with full available seed energy (thin light-gray line), half energy (thick light-gray line), quarter energy (gray line), one-twentieth energy (dark gray line), and one-fortieth energy (black line). Inset: ratios between output power of seeded regenerative amplifier and Q-switched output power in the absence of the seed pulse. Seed energies and color notations are the same as in main panel.

injected seed and the amplified spontaneous emission (ASE) may severely reduce the usable energy in the amplified picosecond pulse. To examine the ratio between the picosecond pulse and the nanosecond ASE background (Q-switched pulse), we conducted a series of high dynamic range third-order autocorrelation measurements [30], presented in Fig. 4. To collect these data, we varied the seed energy and adjusted correspondingly the roundtrip number to maintain a constant output power of the amplifier. The inset in Fig. 4 shows the relative fraction of the Q-switched pulse energy, obtained by blocking the seed, with respect to the total amplifier output energy when the seed pulse is injected. This fraction gives the worst case assessment of the nanosecond background of the picosecond pulse. However, injection seeding suppresses ASE to some extent, and improves the actual contrast. Unfortunately, the scanning range of the third-order autocorrelator does not cover the entire extent of the nanosecond pulse pedestal. We assume that the intensity of the nanosecond background is flat in time and has the duration of 6 ns, which is determined by the switching time of the Pockels cell. Under these assumptions, only a 2% fraction of the total energy is carried by the nanosecond pedestal if its level in Fig. 4 corresponds to 10^{-4}. For a 10^{-3} level in Fig. 4, this fractional energy increases to 17%. The measurements, presented in Fig. 4, prove that the seed energy of 1.3 pJ is sufficiently high to suppress the ASE background and produce a reasonably clean picosecond pump pulse for the OPCPA.

C. Timing Jitter

The temporal structure of second harmonic pump pulses was characterized by cross-correlation with femtosecond pulses from the Ti:sapphire oscillator. The parametric amplifier, in this case, performed the function of the cross-correlator [31]. The only difference with the parametric amplification in OPCPA is that the seed pulses are not stretched, and therefore provide the highest temporal resolution to measure the profile of the pump pulses and assess the timing jitter between the OPCPA seed and pump pulses. Fig. 5(a) presents the parametric cross-correlation with the 26-ps pulses. This measurement is consistent with the autocorrelation measurement results of the fundamental pulses from the regenerative amplifier [Fig. 3(b)]. No detectable broadening of the cross-correlation trace which might be attributed to the timing jitter is observed.

Envisaging applications of the pump-seed pulse synchronization method explored here, in laser systems with shorter pump pulse durations, we artificially shortened the pulse from the Nd:YLF amplifier. To this end, we removed the intracavity etalon and observed self-compression of split laser pulses in the amplifier [32], [33]. The parametric cross-correlation trace, shown in Fig. 5(b), has the FWHM of only 1 ps, which gives the upper limit of the possible synchronization imperfection in our system.

As previously mentioned, the long-term drift, regardless of the type of pump and seed laser synchronization, is related to the thermal expansion of the cavities of the regenerative amplifier and the seed oscillator. The amount of drift depends on thermal variation of the total path length from the beamsplitter to the nonlinear crystal in the OPCPA. Assuming a 100-m path length on a stainless steel breadboard, a relative temperature change by 0.1 K between the seed and the pump arms of OPCPA will result in a 0.3-ps timing shift. The 0.1 K temperature stabilization

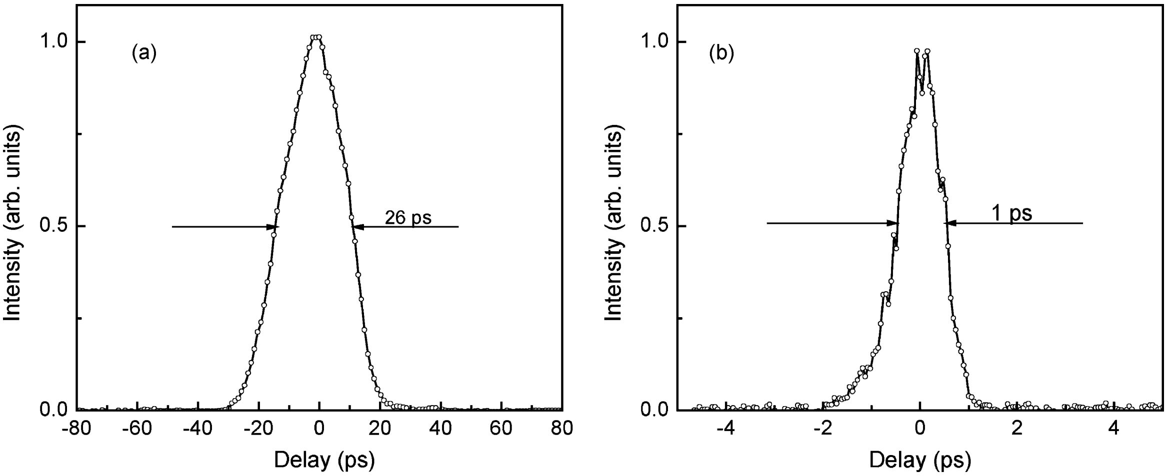

Fig. 5. Parametric cross-correlation traces between frequency-doubled pulses from Nd:YLF amplifier and femtosecond pulses from Ti:sapphire oscillator. (a) With intracavity etalon in Nd:YLF regenerative amplifier. (b) Without etalon.

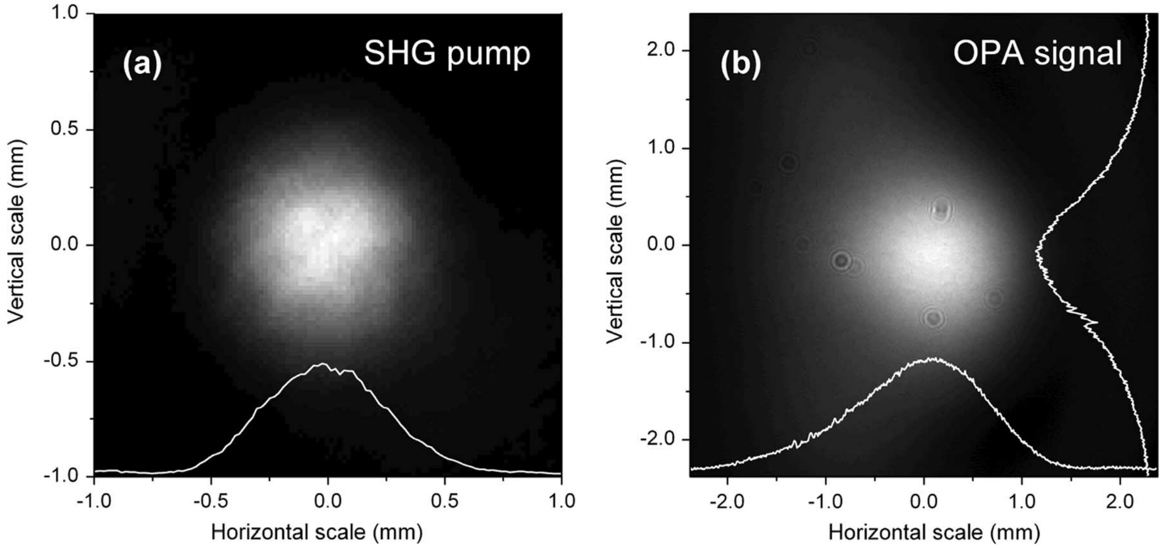

Fig. 6. Beam profiles. (a) 527-nm pump beam at position of BBO crystal in optical parametric amplifier. (b) Amplified beam 40 cm behind BBO crystal.

of the table top represents the practical limit for the laboratory environment. Further improvement of the timing synchronization has to rely on active stabilization of both the oscillator and the regenerative amplifier cavities to a frequency standard. Such measures might be required for pump lasers with the pulse duration less than a couple of picoseconds.

D. Eleven Femtosecond NOPA

As shown in Fig. 1, about 50% of the energy of the Ti:sapphire oscillator pulses is directed into the NOPA. Prior to their parametric amplification, the seed pulses are stretched to approximately 22 ps to ensure appropriate overlap with 30 ps pump pulses for efficient parametric energy conversion. The stretcher consists of a SF57 prism pair, a programmable acoustooptic modulator Dazzler (Fastlite) and a 10-cm SF57 block. The energy of the seed pulse behind the stretcher is reduced from about 2.5 nJ to 50 pJ because of the low diffraction efficiency of the broadband Dazzler and combined optical losses. In a single-pass 4-mm BBO NOPA, the pulse energy is boosted to 100 μJ. The pump beam profile at the crystal and the beam profile 40 cm after the amplifier are shown in Fig. 6(a) and (b), respectively. The slight asymmetry of the amplified beam mode in the horizontal plane results from the cone-like phase matching condition in the Type I noncollinearly phase-matched OPA [34]. The amplified pulses are recompressed in a grating compressor consisting of a pair of 900 lines/mm transmission gratings (Wasatch Photonics) separated by $\sim$14 mm. The throughput of the pulse compressor after a four-fold diffraction is 50%.

The compressed pulses were characterized by a spectral phase interferometry for direct electric field reconstruction (SPIDER). The residual spectral phase retrieved by SPIDER was used to fine tune the dispersion of the Dazzler for optimal pulse compression. The amplified spectrum after the grating compressor (solid line) and the residual spectral phase (dashed line) are plotted in Fig. 7(a). Fig. 7(b) depicts the retrieved temporal pulse shape with a FWHM of 11.3 fs (solid line), a

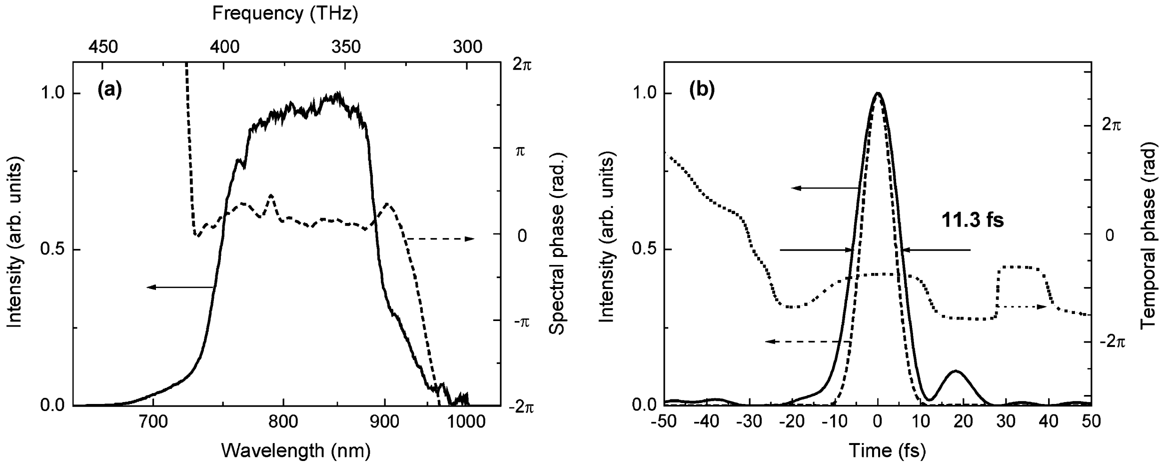

Fig. 7. Parameters of the amplified OPCPA pulses characterized with SPIDER. (a) Amplified spectrum in front of SIPDER apparatus (solid line) and residual spectral phase (dashed line). (b) Retrieved 11.3-fs pulse intensity profile (solid line), temporal phase of retrieved pulse (dotted line), and transform-limited pulse with duration of 8.3 fs (dashed line) calculated from amplified spectrum.

calculated transform-limited pulse shape from the amplified spectrum (dashed line), and the retrieved temporal phase (dotted line). The high-order dispersion of the 10-cm SF57 block, used in the stretcher, could not be fully compensated over the entire spectral range of interest because of the limited aperture of the second prism in the prism pair and the limited dispersion tuning range of the Dazzler.

IV. Energy Scaling

A major concern in the direct seeding scheme is the weak seed energy, which limits the usable amplified pulse energy. In our laboratory, Ti:sapphire oscillators are being modified to further extend the infrared wing of the spectrum to exploit the entire gain bandwidth of the BBO (700–1050 nm) or LBO (750–1150 nm) parametric amplifiers pumped at 527 or 532 nm. Currently, a modified oscillator produces five times more energy at 1053 nm compared to the oscillator used in this work. The new oscillator with a frequency conversion stage serves as a seed source for an infrared OPCPA [35]. In this system, a post amplifier is added to boost the output of the Ti:sapphire-seeded regenerative amplifier to 10 mJ at 1 kHz without any noticeable increase of the relative ASE fraction in the output. Similarly, the ratio of the ASE versus picosecond pulse is preserved in a much larger 75-ps 1.5-J 10-Hz Nd:YAG amplifier system. This laser consists of a 1 mJ regenerative amplifier seeded by an $\sim$4-pJ solitonic pulse from a photonic crystal fiber, described in [22], followed by a chain of post-amplifiers. The energy of the Q-switched pulse in the absence of the seed pulse is 150 mJ. This amounts to just 10% of the seeded amplified pulse energy and, based on the considerations presented in Section III-B, correspond to a sub-2% ASE background in the 1.5-J output. Therefore, the main source of the contrast deterioration of the OPCPA pump pulses is the regenerative amplifier because of its very high total gain, typically 10^9 in our cases, and energy or average power saturation. Consequently, an unsaturated power booster following the regenerative amplifier does not enhance the ASE background.

V. Conclusion

We have realized a scheme for direct optical seeding and reliable synchronization of two amplifiers operating in nonoverlapping spectral ranges. This method is applied to the seeding of a broadband parametric amplifier and its pump source. The use of a common Ti:sapphire oscillator dramatically simplifies the whole OPCPA system in comparison with OPCPA schemes based on PLL synchronization between the pump and seed pulses. This work offers a blueprint for building large-scale OPCPA systems that would be particularly suitable for the applications in high-field physics, extreme nonlinear optics, and attosecond spectroscopy. In addition, the demonstrated synchronization method opens a new way for all-optical synchronization of high-intensity laser amplifiers based on various gain media that do not have mutual spectral overlap.

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References

[1] T. Brabec and F. Krausz, "Intense few-cycle laser fields: Frontiers of nonlinear optics," *Rev. Mod. Phys.*, vol. 72, pp. 545–591, 2000.

[2] P. Agostini and L. F. DiMauro, "The physics of attosecond light pulses," *Rep. Prog. Phys.*, vol. 67, pp. 813–855, 2004.

[3] A. Baltuška, M. Uiberacker, E. Goulielmakis, R. Kienberger, V. S. Yakovlev, T. Udem, T. W. Hänsch, and F. Krausz, "Phase-controlled amplification of few-cycle laser pulses," *IEEE J. Sel. Topics Quantum Electron.*, vol. 9, no. 4, pp. 972–989, Jul.–Aug. 2003.

[4] A. Dubietis, G. Jonušauskas, and A. Piskarskas, "Powerful femtosecond pulse generation by chirped and stretched pulse parametric amplification in BBO crystal," *Opt. Commun.*, vol. 88, pp. 437–440, 1992.

[5] I. N. Ross, P. Matousek, M. Towrie, A. J. Langley, and J. L. Collier, "The prospects for ultrashort pulse duration and ultrahigh intensity using optical parametric chirped pulse amplifiers," *Opt. Commun.*, vol. 144, pp. 125–133, 1997.

[6] A. Galvanauskas, A. Hariharan, D. Harter, M. A. Arbore, and M. M. Fejer, "High-energy femtosecond pulse amplification in a quasi-phase-matched parametric amplifier," *Opt. Lett.*, vol. 23, pp. 210–212, 1998.

[7] X. Yang, Z. Xu, Y. Leng, H. Lu, L. Lin, Z. Zhang, R. Li, W. Zhang, D. Yin, and B. Tang, "Multiterawatt laser system based on optical parametric chirped pulse amplification," *Opt. Lett.*, vol. 27, pp. 1135–1137, 2002.

[8] I. Jovanovic, C. A. Ebbers, and C. P. J. Barty, "Hybrid chirped-pulse amplification," *Opt. Lett.*, vol. 27, pp. 1622–1624, 2002.

[9] H. Yoshida, E. Ishii, R. Kodama, H. Fujita, Y. Kitagawa, Y. Izawa, and T. Yamanaka, "High-power and high-contrast optical parametric chirped pulse amplification in ß-BaB$_2$O$_4$ crystal," *Opt. Lett.*, vol. 28, pp. 257–259, 2003.

[10] N. F. Andreev, V. I. Bespalov, V. I. Bredikhin, S. G. Garanin, V. N. Ginzburg, K. L. Dvorkin, E. V. Katin, A. I. Korytin, V. V. Lozhkarev, O. V. Palashov, N. N. Rukavishnikov, A. M. Sergeev, S. A. Sukharev, G. I. Freidman, E. A. Khazanov, and I. V. Yakovlev, "New scheme of a petawatt laser based on nondegenerate parametric amplification of chirped pulses in DKDP crystals," *JETP Lett.*, vol. 79, pp. 144–147, 2004.

[11] V. Bagnoud, I. A. Begishev, M. J. Guardalben, J. Puth, and J. D. Zuegel, "5 Hz, $>$250 mJ optical parametric chirped-pulse amplifier at 1053 nm," *Opt. Lett.*, vol. 30, pp. 1843–1845, 2005.

[12] C. P. Hauri, P. Schlup, G. Arisholm, J. Biegert, and U. Keller, "Phase-preserving chirped-pulse optical parametric amplification to 17.3 fs directly from a Ti:sapphire oscillator," *Opt. Lett.*, vol. 29, pp. 1369–1371, 2004.

[13] R. T. Zinkstok, S. Witte, W. Hogervorst, and K. S. E. Eikema, "High-power parametric amplification of 11.8-fs laser pulses with carrier-envelope phase control," *Opt. Lett.*, vol. 30, pp. 78–80, 2005.

[14] N. Ishii, L. Turi, V. S. Yakovlev, T. Fuji, F. Krausz, A. Baltuška, R. Butkus, G. Veitas, V. Smilgevicius, R. Danielius, and A. Piskarskas, "Multimillijoule chirped parametric amplification of few-cycle pulses," *Opt. Lett.*, vol. 30, pp. 567–569, 2005.

[15] S. Witte, R. T. Zinkstok, W. Hogervorst, and K. S. E. Eikema, "Generation of few-cycle terawatt light pulses using optical parametric chirped pulse amplification," *Opt. Express*, vol. 13, pp. 4903–4908, 2005.

[16] Y. Kitagawa, H. Fujita, R. Kodama, H. Yoshida, S. Matsuo, T. Jitsuno, T. Kawasaki, H. Kitamura, T. Kanabe, S. Sakabe, K. Shigemori, N. Miyanaga, and Y. Izawa, "Prepulse-free petawatt laser for a fast ignitor," *IEEE J. Quantum Electron.*, vol. 40, no. 3, pp. 281–293, Mar. 2004.

[17] C. N. Danson, P. A. Brummitt, R. J. Clarke, J. L. Collier, B. Fell, A. J. Frackiewicz, S. Hancock, S. Hawkes, C. Hernandez-Gomez, P. Holligan, M. H. R. Hutchinson, A. Kidd, W. J. Lester, I. O. Musgrave, D. Neely, D. R. Neville, P. A. Norreys, D. A. Pepler, C. J. Reason, W. Shaikh, T. B. Winstone, R. W. W. Wyatt, and B. E. Wyborn, "Vulcan petawatt-an ultra-high-intensity interaction facility," *Nucl. Fusion*, vol. 44, pp. S239–S246, 2004.

[18] I. N. Ross, P. Matousek, G. H. New, and K. Osvay, "Analysis and optimization of optical parametric chirped pulse amplification," *J. Opt. Soc. Amer. B., Opt. Phys.*, vol. 19, pp. 2945–2956, 2002.

[19] F. Tavella, K. Schmid, N. Ishii, A. Marcinkevicius, L. Veisz, and F. Krausz, "High-dynamic range pulse-contrast measurements of a broadband optical parametric chirped-pulse amplifier," *Appl. Phys. B*, vol. 81, pp. 753–756, 2005.

[20] M. J. W. Rodwell, D. M. Bloom, and K. J. Weingarten, "Subpicosecond laser timing stabilization," *IEEE J. Quantum Electron.*, vol. QE-25, no. 4, pp. 817–827, Apr. 1989.

[21] H. Tsuchida, "Pulse timing stabilization of a mode-locked Cr:LiSAF laser," *Opt. Lett.*, vol. 24, pp. 1641–1643, 1999.

[22] C. Y. Teisset, N. Ishii, T. Fuji, T. Metzger, S. Köhler, R. Holzwarth, A. Baltuška, A. M. Zheltikov, and F. Krausz, "Soliton-based pump–seed synchronization for few-cycle OPCPA," *Opt. Express*, vol. 13, pp. 6550–6557, 2005.

[23] T. M. Fortier, D. J. Jones, and S. T. Cundiff, "Phase stabilization of an octave-spanning Ti:sapphire laser," *Opt. Lett.*, vol. 28, pp. 2198–2200, 2003.

[24] T. Fuji, A. Unterhuber, V. S. Yakovlev, G. Tempea, A. Stingl, F. Krausz, and W. Drexler, "Generation of smooth, ultra-broadband spectra directly from a prism-less Ti:sapphire laser," *Appl. Phys. B, Photophys. Laser Chem.*, vol. 77, pp. 125–128, 2003.

[25] L. Matos, D. Kleppner, O. Kuzucu, T. R. Schibli, J. Kim, E. P. Ippen, and F. X. Kärtner, "Direct frequency comb generation from an octave-spanning, prismless Ti:sapphire laser," *Opt. Lett.*, vol. 29, pp. 1683–1685, 2004.

[26] O. D. Mücke, R. Ell, A. Winter, J.-W. Kim, J. R. Birge, L. Matos, and F. X. Kärtner, "Self-referenced 200 MHz octave-spanning Ti:sapphire laser with 50 attosecond carrier envelope phase jitter," *Opt. Express*, vol. 13, p. 5163, 2005.

[27] T. Fuji, J. Rauschenberger, A. Apolonski, V. S. Yakovlev, G. Tempea, T. Udem, C. Gohle, T. Hänsch, W. Lehnert, M. Scherer, and F. Krausz, "Monolithic carrier-envelope phase-stabilization scheme," *Opt. Lett.*, vol. 30, pp. 332–334, 2005.

[28] P. Bado, M. Bouvier, and J. S. Coe, "Nd:YLF mode-locked oscillator and regenerative amplifier," *Opt. Lett.*, vol. 12, pp. 319–321, 1987.

[29] M. Saeed, D. Kim, and L. F. DiMauro, "Optimization and characterization of a high repetition rate, high intensity Nd:YLF regenerative amplifier," *Appl. Opt.*, vol. 29, pp. 1752–1757, 1990.

[30] S. Luan, M. H. R. Hutchinson, R. A. Smith, and F. Zhou, "High dynamic range third-order correlation measurement of picosecond laser pulse shapes," *Meas. Sci. Technol.*, vol. 4, pp. 1426–1429, 1993.

[31] G. Dikchyus, R. Danelyus, V. Kabelka, A. Piskarskas, T. Tomkyavichyus, and A. Stabinis, "Parametric amplification and generation of ultrashort light pulses for spectroscopic applications," *Sov. J. Quantum Electron.*, vol. 6, pp. 425–428, 1976.

[32] D. F. Voss and L. S. Goldberg, "Simultaneous amplification and compression of continuous-wave mode-locked Nd:YAG laser pulses," *Opt. Lett.*, vol. 11, pp. 210–212, 1986.

[33] J. S. Coe, P. Maine, and P. Bado, "Regenerative amplification of picosecond pulses in Nd:YLF: gain narrowing and gain saturation," *J. Opt. Soc. Amer. B Opt. Phys.*, vol. 5, pp. 2560–2563, 1988.

[34] R. Danielius, A. Piskarskas, P. Di Trapani, A. Andreoni, C. Solcia, and P. Foggi, "Matching of group velocities by spatial walk-off in collinear three-wave interaction with tilted pulses," *Opt. Lett.*, vol. 21, pp. 973–975, 1996.

[35] T. Fuji, N. Ishii, C. Y. Teisset, T. Metzger, A. Baltuška, N. Forget, D. Kaplan, A. Galvanauskas, and F. Krausz, "Parametric amplification of few-cycle carrier-envelope phase-stable pulses at 2.1 μm," *Opt. Lett.*, to be published.

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