Soliton-based pump–seed synchronization for few-cycle OPCPA

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Abstract: We demonstrate a significant simplification of the scheme for few-cycle Optical Parametric Chirped Pulse Amplification (OPCPA) which results in the elimination of a picosecond master oscillator and electronic synchronization loops. A fraction of a broadband seed pulse centered at 760 nm from a 70-MHz Ti:sapphire oscillator was frequency-shifted in a photonic crystal fiber to enable synchronized seeding of a picosecond Nd:YAG pump laser. The seed radiation at 1064 nm is produced in the soliton regime which makes it inherently more intense and stable in comparison with other methods of frequency conversion. The remaining fraction of the Ti:sapphire output is amplified with a FWHM bandwidth of 250 nm in a single timing-jitter-free OPCPA stage. Our work opens up the exciting possibility to use sub-picosecond pump pulses from highly efficient Yb-based amplifiers for jitter-less parametric amplification of carrier-envelope phase stabilized pulses from Ti:sapphire oscillators.

OCIS codes: (140.4480) Optical amplifiers; (190.4370) Nonlinear optics, fibers; (190.4970) Parametric oscillators and amplifiers.

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1. Introduction

Broadband, few-cycle and frequently carrier-envelope phase (CEP-) controlled laser sources are urgently required in many applications of high-intensity and laser field-sensitive physics [1]. Optical parametric chirped pulse amplification (OPCPA) [2,3] offers a particularly promising route toward compact ultrashort ultrahigh-peak-power laser systems because of its very broad gain bandwidth, negligible thermal load on a nonlinear crystal, and an extremely high single-pass gain as compared to amplifiers based on laser gain media. High-intensity and high-energy sub-ps OPCPA pulses as well as sub-100-µJ few-cycle pulses have been

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demonstrated to date [4-7]. Recently, 10-fs TW-class multi-millijoule OPCPA systems were reported [8,9].

Unlike gain media with inversion storage, the parametric amplifier poses a severe challenge of ensuring strict synchronization between the pump and seed pulses. In this paper, we aim at finding a reliable and technologically attractive solution for passive synchronization between a picosecond laser amplifier and a femtosecond OPCPA seed oscillator that operates outside the gain region of the pump laser.

2. Known pump–seed synchronization techniques

The problem of optical synchronization is easily solved in superfluorescene-seeded [10] and white-light-continuum-seeded parametric amplifiers [11-14], where the color-shifted seed pulse is derived directly from the pump pulse or from its (sub-) harmonics. In amplifiers of superfluorescence, the seed originates from quantum noise. Consequently, the duration of the amplified pulse is near to the pump duration and the phase of the pulse may experience shot-to-shot variations. By contrast, amplifiers seeded with coherent white light are capable of reducing the duration of the amplified pulse down to several optical cycles, i.e. by orders of magnitude below the pump pulse duration [12,13]. Nevertheless, these devices require short, typically sub-200-fs intense pulses for reliable white light generation. Therefore, white-light-seeded few-cycle amplifiers are driven exclusively by chirped-pulse amplifiers (CPA) predominantly based on Ti:sapphire [11-14] and, more recently, on Yb-doped laser crystals [15]. Dependence on ultrashort pump lasers severely limits the practical power scalability of both superfluorescence- and white-light-seeded amplifiers. Superfluorescent devices are unsuitable for CEP-controlled amplification, whereas white-light-seeded amplifiers may exhibit CEP self-stabilization under special conditions [16,17].

A straightforward solution to CEP-controlled parametric amplification, similarly to the case of its laser-amplifier counterpart [18], is to use a pre-stabilized seed source [19,20]. This idea was recently implemented by Hauri *et al.* [6], who demonstrated CEP stability preservation in an OPCPA seeded from a CEP-locked Ti:oscillator and pumped by the second harmonic of a Ti:sapphire amplifier that was also seeded by the same oscillator. While offering a very elegant solution to the problems of CEP control and optical synchronization, this system, nonetheless, has the power upscale constraints mentioned above. Scaling up the output of the CPA Ti:sapphire pump laser becomes particularly unattractive because this laser in turn requires an upgrade of its own pump source – a green Q-switched ns laser.

In high-power OPCPAs, due to the heat disposal and pumping efficiency reasons, it is more economical to employ a stand-alone (multi-)kHz picosecond pump laser that is optimized for production of high-energy narrow-band pulses. This approach was used in Refs. [7-9], where a broadband Ti:sapphire oscillator, employed as OPCPA seed, was synchronized with the master oscillator of a picosecond pump laser based on Nd:YAG using a complex electronic servo loop [21]. State-of-the art active synchronization loops [7], based on pricy GHz electronics, make it possible to keep the r.m.s. timing jitter between the seed and pump pulses on a sub-picosecond level. Whereas this locking precision satisfies well the demands of OPCPA pumped by Nd-based picosecond lasers (pulse duration range 20-100 ps), it is insufficient for use with subpicosecond Yb-based pump lasers.

As prospective OPCPA pump sources, Yb lasers [22] promise to be vastly superior to their Nd counterparts because of the shorter pulse duration, reduced parasitic heat, higher output power, and suitability for CPA operation. Using pump pulses in a 1-ps range, one can realize ultrabroadband saturated parametric gain in nonlinear crystals as thin as 1 mm [23] without running into problems with the B-integral of the parametric amplifier. Shaped pulses with a bandwidth of several nanometers from Yb-based lasers are also advantageous in terms of maximizing OPCPA conversion efficiency, reducing superfluorescence background and avoiding gain narrowing. The desired near-rectangular pump pulse profile can be attained by temporal stretching and pulse wing shaping of the broadband pump pulse. The use of such chirped multi-ps pump pulses, however, will not lower the demand for femtosecond timing precision, because the latter is dictated by the steepness of the pump pulse edges.

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In this work we set out to reduce the complexity of the laser and electronic setups in present-day OPCPAs based on a broadband seed oscillator and an external pump laser [7-9] and pave the way for the use of substantially shorter pump pulses in the near future. Below we survey different opportunities for passive optical seed–pump pulse synchronization in OPCPA and explain our chosen strategy.

3. Injection seeding of the pump laser

An ideal potential solution for seeding both the OPCPA and its pump laser, as well as for providing initial CEP stabilization of the seed light, is an octave-spanning Ti:sapphire oscillator [24,25]. However, these oscillators, based on highly advanced broadband chirped mirrors, cannot ensure picojoule energy level within the bandwidth of a typical picosecond regenerative amplifier. Such level of the injected seed is required to compete efficiently with the amplified stimulated emission (ASE) in the picosecond amplifier.

Instead of employing a continuous-bandwidth pulse that covers the entire frequency range supported both by the OPCPA gain and the picosecond laser gain, we consider two-color passively synchronized sources. The motivation behind this approach is the need to provide strong seed signals that are sufficiently above the ASE level in both the OPCPA and the injection-type pump laser. One possibility of realizing a two-color scheme is to employ self-stabilization of two mode-locked oscillators lasing at the seed and pump wavelengths, respectively, via a nonlinear optical (Kerr-lens) mechanism [26]. In terms of complexity, however, this method is not easier to implement than active synchronization of two independent mode-locked oscillators. Another option to consider is a parametric or Raman type frequency converter that creates a narrowband spectral component at the wavelength of the picosecond amplifier. A suitably intense frequency-shifted pulse can be generated in a synchronously pumped optical parametric oscillator (OPO) driven by the broadband seed laser oscillator. Unfortunately, the OPO itself requires active cavity stabilization. In a cavity-less alternative, a very weak frequency-shifted pulse was produced in a traveling wave superfluorescent parametric generator [27]. A separate two-stage cw-pumped parametric amplifier was used to boost this signal to the level suitable for seeding a laser amplifier.

In the approach described in this paper, we attempt to combine the advantages of the broadband Ti:sapphire oscillator for seeding an OPCPA stage and of the frequency shifter for seeding a pulsed pump laser. In our setup, schematically presented in Fig.1, the output of a 6-fs 5-nJ 70-MHz chirped-mirror Ti:sapphire oscillator [28] is divided into two equal parts. One part is directed into an OPCPA stage and the other is frequency converted to obtain the seed for a picosecond Nd:YAG regenerative amplifier.

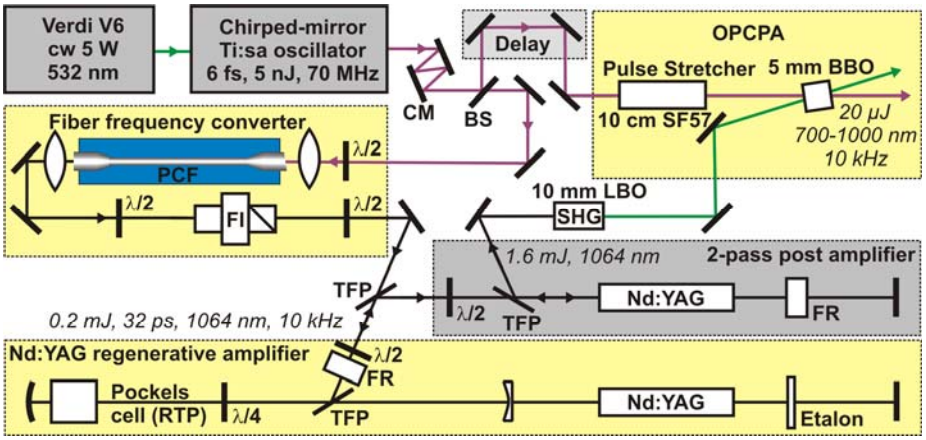

Fig. 1. Layout of experimental setup for all-optically synchronized OPCPA. PCF, photonic crystal fiber; TFP, thin-film polarizer; CM, chirped-mirror pair; BS, 50% beamsplitter; λ/2, half-wave plate; λ/4, quarter-wave plate; Nd:YAG, side-cw-diode-pumped gain modules; FI, Faraday isolator; FR, Faraday rotator.

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In the case of our unamplified oscillator pulses, parametric frequency shifters [27] become extremely inefficient because of the low pump field intensity and group-velocity matching issues. Under these circumstances, soliton phenomena in optical fibers suggest an interesting alternative to standard strategies of frequency conversion. Optical solitons propagating in media with a nonlinear response experience reshaping and continuous frequency down-shifting due to the Raman effect [29]. This phenomenon, called soliton self-frequency shift (SSFS) [30,31], provides a convenient way of generating ultrashort pulses with a tunable carrier frequency. Photonic-crystal fibers (PCFs) [32] substantially enhance this nonlinear-optical process [33] due to a strong field confinement in a small-size fiber core and the possibility to tailor dispersion of guided modes by varying the fiber structure [34].

The key advantages of the SSFS-based strategy of frequency shifting originate from the intrinsic properties of Raman-shifted solitons [35]. In particular, the central frequency of the red-shifted soliton can be tuned by varying the fiber length and the input pulse energy. Radiation energy carried by this signal is localized in the time domain within a short spike, dominating the temporal envelope of radiation intensity in the fiber. Because of the anomalous group-velocity dispersion of the PCF, the red-shifted soliton becomes delayed and eventually isolated, both spectrally and temporally, with respect to the rest of the pump field. This isolation of the frequency-shifted soliton suppresses the interference between the solitonic part and the rest of the spectrum of radiation field. For a PCF with a characteristic length of tens of centimeters, the amplitude of the soliton spike in the temporal envelope of radiation intensity is typically an order of magnitude higher than the intensity of the remainder of the SPM-broadened pump field and Cherenkov-type emission, both of which are spread out in time. As a result, the frequency-shifted solitonic component is observed in experiments as the most stable part of the output spectrum [35], which is free of interference fringes, typical of the nonsolitonic part of the radiation field, including Cherenkov emission.

In the context of laser amplifier seeding, the combined spectro-temporal localization of the SSFS pulse makes it ideally suited for suppressing the ASE inside the laser cavity. In addition, the high amplitude stability of the SSFS pulse is very important for maintaining stability of the amplifier output at repetition rates that are well above the inverse population relaxation time of the laser gain medium. At such repetition rates, although the average output power can be saturated, the energy of each amplified pulse cannot be saturated individually. Therefore, stable and intense seed pulses are required.

4. Optically synchronized OPCPA

We have investigated several commercial and research types of PCF that are capable of supporting the SSFS regime and selected the commercial fiber NL-PM-750 (Crystal Fibre A/S) for a clear solitonic feature in the NIR. The output spectrum of a 20-cm-long PCF injected with 2-nJ oscillator pulses is presented in Fig.2. The oscillator light was injected with a f = 7.5 mm aspheric lens. The central wavelength of the spectral soliton was fine-tuned by adjusting the waveplate in front of the PCF and optimizing the focusing. To improve mechanical stability of the PCF and avoid problems with optical damage, a monolithic fiber assembly was prepared by Menlo Systems GmbH. Larger-core-diameter end caps were spliced to the PCF and the end cap on the in-coupling side was wedge polished to avoid retro-reflection into the Ti:sapphire oscillator. The fiber assembly was fixed directly on the oscillator breadboard whereas the focusing and collimating lenses were mounded on *xyz*-translators. Mounting the fiber assembly in this way permits alignment-free operation for several weeks. A small adjustment of the in-coupling objective is only necessary upon the realignment of the oscillator.

The output of the PCF is directed into a home-made Nd:YAG regenerative amplifier (Fig.1). To protect the fiber from a back reflection or leakage through the out-coupling polarizer of the regenerative amplifier, a Faraday isolator was introduced after the PCF. The estimated seed pulse energy contained within the gain bandwidth of Nd:YAG is ~2 pJ, which proved to be sufficient to obtain clean pulse amplification and suppress the nanosecond Q-switched-pulse background. This is evidenced by Fig.3(a), which shows the intracavity pulse

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train corresponding to the buildup of the amplified pulse in each cavity roundtrip. The regenerative amplifier operates in the regime of average power saturation and delivers 240-µJ pulses at a 10-kHz repetition rate (2.4 W average power). If the seed pulse from the PCF is blocked, the output power of the regenerative amplifier drops to 50 mW, which corresponds to the onset of an unsuppressed nanosecond Q-switched pulse. In order to generate a nanosecond pulse of the same energy as in the regime of seeded picosecond amplification, we extend the opening time of the Pockels cell by 5-10 additional cavity roundtrips. Therefore, for the given roundtrip gain of the amplifier, the seed pulse energy is clearly sufficient to overcome ASE issues.

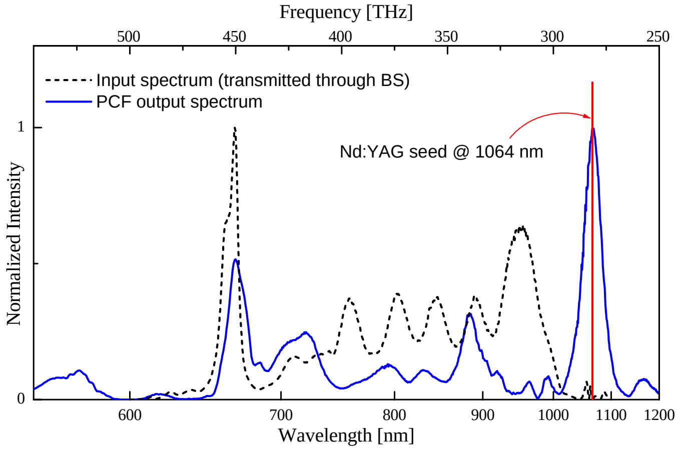

Fig. 2. Frequency shift in the photonic crystal fiber. Solid curve shows an output spectrum optimized for injection seeding at 1064 nm. The input spectrum from the Ti:sapphire oscillator is shown as dashed curve.

An intracavity etalon was used to control the duration of the amplified picosecond pulse and prevent optical damage and self-phase modulation inside the regenerative amplifier. With a 0.8-mm-thick etalon, we obtained clean near-Gaussian 33-ps pulses from the amplifier. The background-free autocorrelation traces obtained with different intracavity etalons are shown in Fig. 3(b).

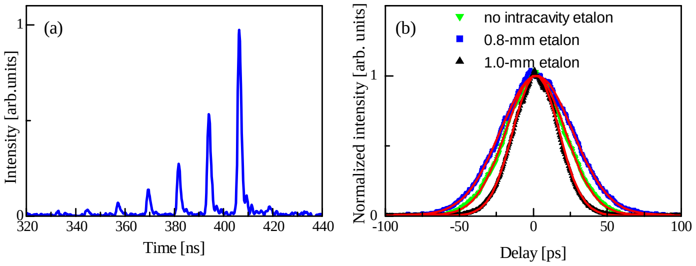

Fig. 3. Performance of the regenerative amplifier seeded with an optical solitonic pulse from PCF. (a), intracavity pulse train of pulses amplified to the energy of 0.2-mJ. (b), background-free autocorrelation traces obtained with and without an intracavity etalon for a fixed number of intracavity roundtrips. Red curves show Gaussian autocorrelation fits.

The regenerative amplifier is based on a ø4 mm Nd:YAG rod in a laser-diode cw-pumping cavity (model RD40, Northrop Grumman Cutting Edge Optronics). The length of the pumped region is about 63 mm. The 5x5-mm-aperture RTP Pockels cell was purchased from Bergmann Messgeraete Entwicklung KG. After a double-pass home-made cw-pumped 4×100-mm Nd:YAG booster, we obtained 1.6-mJ pulses at 1064 nm in a TEM_{00} spatial mode.

A Faraday rotator was installed between the passes to compensate thermally-induced birefringence of the YAG crystal and enable polarization out-coupling. 0.8-mJ pulses at 532 nm were obtained in a 10-mm-long critically phase-matched LBO crystal. The achieved 50% frequency doubling efficiency is an additional proof of the clean seeding and amplification process in our picosecond amplifier chain.

To investigate the usability of the demonstrated pulse synchronization technique, we have set up a single-stage parametric amplifier based on a 5-mm-long type I noncollinearly phase matched BBO [6-8]. Due to the noncollinear geometry and tight beam focusing, the real interaction length in BBO was below 3 mm. The seed pulses were stretched to approximately 22 ps in a 10-cm long SF57 glass block to obtain an adequate temporal overlap between the pump and signal pulses. The spectrum of the resultant 20-µJ signal pulses is depicted in Fig. 4 and corresponds to a nearly maximum theoretical bandwidth for the given crystal and pumping configuration. Remarkably, the broadband amplified spectrum shown in Fig. 4 is reliably reproduced each working day without any need to adjust the pump–seed delay, which has been previously impossible in the actively stabilized OPCPA setup developed by us previously [8].

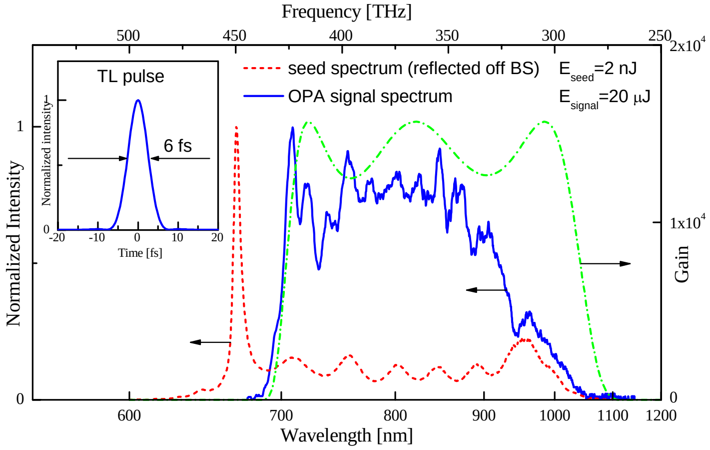

Fig. 4. Results of timing-jitter-free single-pass parametric amplification. Solid curve, amplified seed spectrum that supports a 6-fs pulse duration assuming perfect recompression (inset); dashed curve, seed spectrum; dash-dotted curve, calculated parametric gain in a 3-mm BBO.

5. Timing jitter

The evaluated residual timing jitter between the seed and the pump pulses lies in the sub-30-fs domain and could not be measured by optical cross-correlation techniques available to us. The above-shown results of parametric amplification, a type of cross-correlation measurement, reveal no traceable jitter. Below we discuss possible sources of residual timing jitter.

The most important contribution to the residual jitter in our system results from the cavity length drifts of the Ti:sapphire oscillator and of the regenerative amplifier. The short-term drift caused by mechanical instability can be disregarded, because the time span between the pulse injection into the regenerative amplifier and the Ti:sapphire pulse injection into the OPCPA stage is merely 300–400 ns, well below the period of conceivable vibrations in a laboratory. The long-term drift is related to the thermal expansion of the cavities of the regenerative amplifier and the seed oscillator and depends on the ratio of the cavity lengths and the number of cavity roundtrips from the moment of seeding of the regenerative amplifier. With simple thermal stabilization of the laser base plate, it should be possible to control the cavity length to within a fraction of 1 µm. In addition, thermal drift can be compensated by choosing approximately equal lengths of the oscillator and regenerative amplifier cavities, provided the rate of cavity expansion is similar.

Another source of timing jitter is related to the intensity noise at the input of the solitonic fiber. Because of the nonlinear nature of SSFS, intensity fluctuations of the Ti:sapphire oscillator give rise to a variance of the soliton wavelength shift $\Delta\lambda$, which is translated, through the group delay, into a timing jitter of the soliton part of the field at the output of the fiber, used as a seed in our experiments. The sensitivity of the soliton to the variations of the input intensity was evaluated using a numerical model of SSFS in PCF [35] which uses the generalized nonlinear Schrödinger equation, including high-order dispersion effects and the Raman response of fused silica. According to these simulations, a 1% variation in the input pulse energy gives rise to additional spectral, $\delta\lambda$, and temporal, δt, shifts of the soliton estimated as $\delta t/\Delta t \approx \delta\lambda/\Delta\lambda \approx 0.7\%$, where Δt and $\Delta\lambda$ are the time and wavelength Raman-induced shifts of the soliton in the absence of input energy variations. For the PCF length used in our experiments, Δt *is* ~5 ps, which corresponds to $\delta t \approx 30$ fs. Potentially, this timing jitter can be reduced through the optimization of the PCF dispersion profile. In addition, it must be pointed out that our jitter estimation is rather conservative because the pulse-energy noise of a Ti:sapphire oscillator can be below 0.2% r.m.s. [36].

6. Conclusion

In conclusion, we have achieved a significant improvement in OPCPA synchronization as well as a substantial reduction of the complexity and cost of the entire system. Our method opens the way to combine ubiquitous Nd-based picosecond amplifiers and emerging 1-ps-range Yb-based amplifiers with widely available several-nJ broadband Ti:sapphire seed oscillators. The simple all-optical seed-pump pulse synchronization permits hassle-free parametric amplification of ultrashort light pulses and can be straightforwardly scaled according to the energy of the amplified pump pulse.

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