Amplification of CEP stable pulses with a reproducible waveform under the pulse envelope is an enabling technology for a variety of strong-field control applications typified by the generation of isolated attosecond (10−15 s) pulses and directional electron emission in above-threshold ionization. Both actively stabilized laser chirped pulse amplifiers (CPA) systems [1] and passively CEP stabilized parametric amplifiers [2] were reported. To date, amplified Ti:sapphire based laser systems delivering actively CEP stabilized few-cycle submillijoule pulses were successfully employed in numerous strong-field experiments. Femtosecond diode-pumped ytterbium laser amplifiers present an interesting alternative to Ti:sapphire because of the average power and repetition rate scalability [3]. The importance of CEP control is obvious for quasi-monocycle pulses and, therefore, is naturally linked to broadband Ti:sapphire amplifiers. However, CEP control is also a prerequisite for the generation of reproducible multicolor fields comprised of carrier waves at arbitrary frequencies [4].

Although CEP-locked Yb fiber oscillators are widely used in frequency comb metrology [5], such oscillators are not well suited for time-domain applications due to a significant phase jitter on the order of a few hertz. In precision frequency metrology, phase jitter does not play a dramatic role as the drift of the CEP can be measured and taken into account during the measurement. An additional complication with dispersion-managed Yb fiber systems is a relatively low attainable pulse energy insufficient for strong-field applications. A solid-state Yb:KGW oscillator for metrology with CEP stabilization at a 160 MHz repetition rate was reported [6]. However, due to the difficulties with pulse picking from a high-repetition-rate pulse train and reduced pulse energy, it is not suitable for seeding a kilohertz-repetition-rate amplifier.

Here we present the first to our knowledge all-solid-state CEP stable CPA laser system based on an ytterbium-doped potassium gadolinium tungstate (Yb:KGW) oscillator and regenerative amplifier (RA). The energy of the high-repetition-rate pulses is sufficient to reach the 1014 W/cm² intensity level with soft focusing (f = 20 cm), which is ideal for experiments like above-threshold ionization and THz generation in plasma [4].

A general scheme of the amplified laser system and the CEP stabilization feedback loop is summarized in Fig. 1. The Yb:KGW laser system is a CPA laser system based on a solid-state Kerr-lens mode-locked Yb:KGW oscillator, which is used as a seed for the Yb:KGW RA (Light Conversion Ltd.). The oscillator delivers 8 nJ pulses at a 75 MHz repetition rate. Both the oscillator and RA are longitudinally pumped by 980 nm laser diode bars fitted with customized micro-optics. Half of the oscillator output power is split off with a beam splitter and passed through a transmission grating pulse stretcher/compressor unit to extend the pulse duration to 250 ps before injecting it into the RA. The repetition rate of the amplifier can be continuously tuned in the 1−200 kHz range. The amplifier delivers an approximately constant average power of 6 W at 10−200 kHz repetition rate. The maximum energy of 1 mJ after a 80% efficient pulse compressor is reached at 1 kHz. Central wavelength of the amplified pulses is 1030 nm. The pulse duration is close to the transform limit and slightly varies in the range of 175–180 fs depending on the repetition rate (1−200 kHz) due to gain narrowing and saturation effects. The beam quality after amplification in RA is nearly Gaussian with beam quality parameter M² < 1.1.

Since the stretcher and compressor are highly dispersive elements, beam pointing instability is sensitively reflected in the CEP noise. Because of a sufficiently large gain bandwidth of Yb:KGW that supports 180 fs amplified pulses, both the oscillator and the RA were operated at the highest available repetition rates.

Fig. 1. Scheme of CEP stabilization of the Yb:KGW CPA amplifier. FI, Faraday isolator; PLL, phase-lock-loop electronics; BS, beam splitter.

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pulses with the spectral FWHM >15 nm, the pulses can be stretched to a given pulse duration using a lower chirp rate, compared to the case of a robust but narrowband gain medium, such as Yb:YAG. Therefore, the broadband Yb:KGW system is potentially superior in terms of its CEP stability and susceptibility to external mechanical noise as a consequence of the short grating separation distances in the stretcher/compressor.

The oscillator output spectrum [see the inset of Fig. 2(a)] supports FWHM 62 fs transform-limited pulses. The cavity dispersion is balanced by chirped mirrors and finely tuned with an intracavity prism pair, which is also used to adjust the $f_{\text{ceo}}$ offset frequency. A Faraday isolator is installed at the oscillator output in order to suppress parasitic feedback from the nonlinear interferometer and the amplifier. Without the isolator, the feedback caused additional noise that disrupted the phase lock. The remaining half of the oscillator output power (approximately 250 mW) is directed into the nonlinear interferometer (MenloSystems GmbH) for $f_{\text{ceo}}$ detection. The oscillator output is spectrally broadened in a 5 cm long piece of photonic crystal fiber (PCF) that has a zero of group velocity dispersion at 850 nm. The resultant supercontinuum spectrum has two pronounced maxima at 1000–1300 nm and 520 nm, as shown in Fig. 2(a). The optical delay between the two spectral parts is adjusted and the infrared continuum part is frequency-doubled in a two-color Mach–Zehnder interferometer. The beat signal in the output of this nonlinear $f–2f$ interferometer is then detected with a fast avalanche photodiode. Beat note signal of the unlocked oscillator is >50 dB above the noise floor in 20 kHz resolution bandwidth. Using a phase-lock-loop (PLL), the carrier-envelope offset frequency $f_{\text{ceo}}$ is locked to a reference signal, which is a quarter of the pulse repetition rate $f_{\text{rep}}/4$. The feedback loop is closed by supplying the signal from the phase locking electronics to the oscillator laser diode driver (Newport, 5600 Series controller). A significant advantage of a Yb DPSS Kerr-lens mode-locked oscillator over its Ti:sapphire counterpart is the possibility to control the CEP by modulating the laser diode current with up to a multi-megahertz modulation frequency, i.e., much faster than the system memory effect determined by the rather long 0.6 ms upper-state lifetime. The oscillator was optimized to mode lock-in a regime where the dependence of $f_{\text{ceo}}$ on pump current is the weakest (0.01 MHz/mA). This greatly reduces amplitude-to-phase noise coupling from the pump source (the laser diode driver and the diode itself) [7]. The offset frequency sensitivity to the diode current $\Delta f_{\text{ceo}}/\Delta I$ is strongly dependent on the output power of the oscillator and in our case has a minimum at around 580 mW, as shown in Fig. 2(b). Further increase of the output power leads to the appearance of a CW peak in the oscillator spectrum and makes the operation of the oscillator unstable. Because of power-to-phase coupling, the phase jitter $\sigma$ increases with increasing sensitivity, which suggests that the noise of the oscillator can be further reduced by suppressing the noise of the power supply electronics.

Using a specially designed electronic second-order active high-pass filter, which improved the amplitude and phase transfer function of the oscillator, we extended the bandwidth of the feedback loop approximately fivefold to 50 kHz, which greatly reduced the jitter of the amplified pulses. The amplitude and phase of the laser power modulation were measured as a function of modulation frequency and the filter was tuned to compensate the decrease of amplitude and the phase lag at high frequencies. An approximate $f_{\text{ceo}}$ transfer function of the unlocked oscillator can be determined from the oscillator output power transfer function, which was measured by sweeping the modulation frequency of the pump current in the 1 Hz–50 kHz range and monitoring the oscillator output power modulation amplitude using a photodiode and a lock-in amplifier. With the filter included in the scheme, the bandwidth of the power modulation reaches 50 kHz at –10 dB, as shown in Figs. 2(d) and 2(e).

The phase stability of the oscillator was measured using a second out-of-loop $f–2f$ nonlinear interferometer (MenloSystems GmbH) with the goal to quantify the noise level induced during spectral broadening in the PCF. The measured power spectral density (PSD) of $f_{\text{ceo}}$ [8] phase noise [Fig. 2(c)] drops down rapidly at around 20 kHz, consistent with the slow response of the laser gain medium shown in Fig. 2(d). The integrated phase jitter Eq. (1) from 10 MHz to 3 Hz corresponds to 0.16 rad:

$$\Delta\phi(f) = \left[2 \int_{f_1}^{f_2} S(f') df'\right]^{1/2}.$$  (1)
The fiber introduces approximately 30 mrad integrated phase jitter, as deduced from the comparison of the in-loop and out-of-loop measurement of PSD, while the main part of the noise comes from the residual noise of the pump diode power supply.

Phase stability of the amplified pulses was measured using a third out-of-loop interferometer where spectral broadening is performed in a bulk sapphire plate. The interference pattern and the reconstructed phase over time is shown in Figs. 3(a) and 3(b). In addition to the (fast loop) oscillator stabilization, the phase drift in the amplifier is compensated using an additional slow loop stabilization. A personal computer is used to determine the CEP from an $f^{-2f}$ spectral interferogram and to send a feedback signal to the oscillator PLL electronics. A single-shot measurement of CEP with and without slow loop is shown in Figs. 3(c) and 3(d). To facilitate root-mean-square (r.m.s.) phase noise characterization, the pulse repetition rate of the amplifier was reduced to 10 kHz at which the spectrometer (Thorlabs Inc.) is still capable of capturing a nonlinear $f^{-2f}$ spectral interferogram in each laser shot. The r.m.s. width $\sigma$ of the CEP distribution [Fig. 3(e)] is 0.45 rad, which corresponds to ±250 as timing jitter. The remaining phase jitter of the amplified pulses is due to the residual phase jitter of the oscillator pulses and phase distortions accumulated during amplification. One important difference as compared to the typical CEP stabilized Ti:sapphire systems in a multipass amplifier configuration, is that the gain of Yb:KGW laser medium is much lower (±1.3 per pass), which implies a large number of round trips in the RA cavity. This elongates the effective beam path of the injected pulse and increases the sensitivity to the acoustic vibrations of the Pockels cell [9]. The number of round trips in a 2.2 m long RA cavity was set to 20, which is optimal for the 10 kHz repetition rate used for the measurements.

In conclusion, we demonstrated the first all-solid-state actively CEP stabilized amplified Yb CPA laser system that delivers 180 fs mJ level pulses with r.m.s phase jitter of approximately 0.45 rad, which is close to the established Ti:sapphire laser systems despite the orders of magnitude longer upper lasing state lifetime in the Yb medium. This development opens a way to cheaply up-scale the repetition rate and the average power of amplified CEP stable systems.

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