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We report on the characterization and long-term compensation of additive timing jitter introduced by a femtosecond ytterbium regenerative amplifier with a 100 kHz repetition rate. A balanced optical cross-correlation technique is used to generate a jitter error signal. This approach is well suited to characterize the additive timing jitter of Yb amplifiers seeded by narrow spectrum Yb oscillators. The balanced optical cross-correlator is in a noncollinear configuration allowing a background free coindence detection. This setup enables the measurement of additive timing jitter from the amplifier, with a noise floor of 300 as integrated from 10 Hz to 10 kHz. The measured additive timing jitter level is about 5 fs, integrated from 0.1 Hz to 10 kHz. The amplifier timing drift characterization and control are performed for more than an hour.

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Ultrafast amplifiers seeded by femtosecond oscillators are widely used in scientific experiments requiring high energy laser pulses such as free electron lasers (FELs), petawatt lasers, high harmonics generation, plasma physics, terahertz (THz) generation, and optical parametric amplifiers (OPA) applications [1 4]. These experiments aim at reaching wavelengths ranging from x rays to THz waves by converting NIR laser pulses in highly nonlinear media. The input pulse energy required ranges from 100 μJ to 100 mJ to overcome low efficiency conversion processes. Despite significant improvements of other laser architectures in the last few years, especially concerning diode pumped solid state lasers [5,6], the regenerative amplifier remains the most suitable approach to deliver multi millijoule output energy.

However, the inherent principle of regenerative amplifiers implies a pulse buildup time on the order of a few microseconds which is equivalent to an optical path length of hundreds of meters. Thus, the regenerative amplification architecture is potentially sensitive to external perturbations such as mechanical vibrations, temperature fluctuations, and pressure variations. This becomes critical when the laser pulses must be synchronized at a sub picosecond precision with other events, for instance, in a synchrotron. In such conditions, the regenerative amplifier may become a dominant source of timing jitter in the synchronization budget.

Beyond particle accelerators, timing jitter is a crucial parameter for several applications. For example, femtosecond OPA efficiency depends on the temporal overlap of pump and seed pulses in a nonlinear crystal, the pump pulse being often provided by a regenerative amplifier to reach high output energies [3,7]. Relative pump to seed timing fluctuations result in amplitude variations of the OPA output. These thematics can be extended to a general issue concerning drift from free space optical links [8,9].

Several approaches have been pursued to reduce the timing jitter and drift from a laser amplifier. One method consists of using sum frequency generation (SFG) or an OPA to convert the seed pulse arrival time into a wavelength information [10,11]. Another method is to use an OPA technique instead of second harmonic generation to build a balanced optical cross correlator (BOC) [7]. To be effective, both methods require large seed spectra and pump pulse energies of several microjoules. Moreover, these setups are built for specific experiments; therefore, it may be difficult or impractical to adapt them to a simpler seeder to amplifier configuration.

Our scope is to investigate short and long term timing jitter from an ytterbium regenerative amplifier with a 100 kHz repetition rate, seeded by an ytterbium oscillator. We evaluate the excess timing jitter introduced by the amplifier by comparing its output timing with the seeding oscillator signal, using a balanced optical cross correlator [12]. This scheme gives a noise floor as low as 300 as integrated from 10 Hz to 10 kHz and a measured timing jitter of 5 fs, integrated from 0.1 Hz to 10 kHz. The stabilization of the amplifier repetition rate for more than an hour is also demonstrated.

The experimental setup for amplifier stabilization and characterization is described in Fig. 1. A commercial S pulse

Ytterbium regenerative amplifier is seeded by a home built ytterbium oscillator with an average output power of 1 W at a 50 MHz repetition rate and a pulse duration of 250 fs. The integrated timing jitter of the oscillator is <15 fs from 1 kHz to 10 MHz. The regenerative amplifier yields an average output power of 1 W at a 100 kHz repetition rate and a pulse duration of 700 fs. The amplifier buildup time is 1 μs which corresponds to a free space travel distance of 300 m. The amplifier output beam travels across a tunable optical delay line (ODL). About 1% of the amplifier output power is injected into the balanced cross correlator. The tunable ODL range is 60 mm, which is equivalent to a timing compensation of about 200 ps. 30% of the oscillator output power is dedicated to seed the amplifier. The remaining 70% is sent to the BOC.

The balanced optical cross correlator (BOC) seen in Fig. 1 is based on a noncollinear SFG configuration similar to refer ence [13]. This approach allows one to spatially separate both the oscillator and amplifier beams and their undesired frequency doubled pulse trains from the cross correlation signal. The amplifier large beam diameter facilitates the spatial overlap of the beams in the noncollinear configuration. A 50:50 beam split ter and two 100 μm glass plates are included to introduce a time delay and allow the balanced detection operation. The SFG signals are then detected by two GaP photodetectors. The photo diode signal difference and filtering operation are made by custom low noise electronics.

The tunable ODL travel range allows us to evaluate the BOC transfer function over a span of 10 ps and to measure its slope in volts per femtosecond. To perform long and short term timing jitter measurement, we first acquire the BOC output signal with a data logger. The signal is then processed with a computer which returns a control signal to the transla tion stage, with a control bandwidth of about 1 Hz. Oscillator repetition rate fluctuations are converted in timing jitter and drift due to the large unbalance between the optical paths before the BOC. To limit this parasitic effect, the oscillator repetition rate is phase locked with the tenth harmonic detected by a fast photodiode to a stable 500 MHz radio frequency oscillator with a 1 kHz bandwidth. This allows us to set the optical path length between the oscillator and the BOC as the remainder of the division of the amplifier total path length by the oscillator path length.
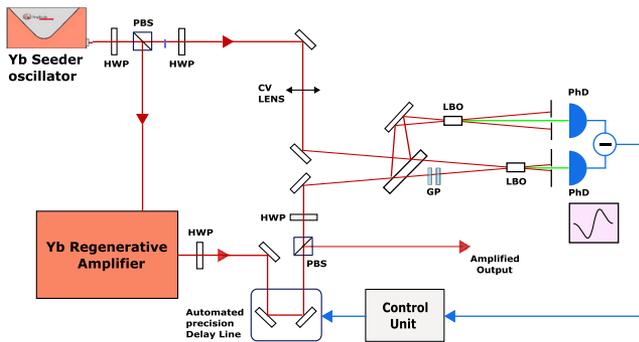
Figure 2(a) shows the power spectral density (PSD) of the additive timing jitter introduced by the amplifier when the syn chronization is on. The PSD is measured at the BOC output from 10 Hz to 10 kHz with a fast Fourier transform (FFT) analyzer and with a data logger (NI USB 6210) to access the frequencies from 0.1 Hz to 10 Hz. The additive noise from the amplifier is below the typical jitter level of our oscillator. Figure 2(b) is the timing noise floor of the BOC. We evaluate the noise floor of our system by replacing the oscillator optical pulse train with an attenuated version of the amplifier output. The noise floor PSD we obtain is well below the measured additive timing jitter. This noise floor may be dominated by residual AM to PM conversion and/or mechanical instabilities of the BOC setup. The integrated timing jitter (0.1 Hz to 10 kHz) is also plotted in Fig. 2(c). The amplifier additive integrated jitter amounts to about 5 fs RMS from 0.1 Hz to 10 kHz. This value is dominated by acoustic like peaks in the kHz region. We attribute these peaks to mechanical reso nances in the laser amplifier enclosure. The integrated timing jitter measurement floor seen in Fig. 2(c) is about 300 as RMS from 10 Hz to 10 kHz. These values are consistent with previous published results for utrafast regenerative amplifiers [7,10,13]. The electronic noise floor is measured to be 10^{-7} fs^2/Hz, which corresponds to an integrated noise floor of 40 as RMS from 10 Hz to 10 kHz.

It is worth noting that the system has not been optimized for vibration sensitivity. One possibility to improve the design would be to change the delay line architecture between the oscillator and the BOC with a configuration that is less sensitive to mechanical perturbations. The BOC common mode rejec tion ratio has to be investigated as well. The SFG intensity can be improved by pulse picking and amplifying the seed oscillator prior to beam splitting and regenerative amplification. As a consequence, we can expect an even better resolution of our system over the observed bandwidth if needed. Note that our approach allows low measurement floor, even with a narrow spectrum seed oscillator.

Figure 3 shows long term measurement of the in loop error signal of (a) the closed loop system, (b) the ODL control signal, and (c) the measured temperature inside the laser enclosure. Note that the laser enclosure is temperature stabilized. We
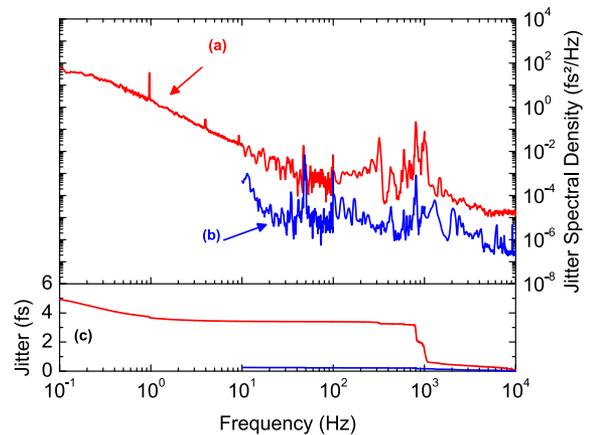

Fig. 1. Experimental setup for the characterization and stabilization of the regenerative amplifier repetition rate, with a buildup time of 1 μs, corresponding to a 300 m optical path length. BOC, balanced optical cross correlator; GP, glass plate; HWP, half wave plate; LBO, lithium triborate; M, mirror; PBS, polarizing beam splitter; PhD, photodetector.

Fig. 2. (a) Excess timing jitter spectral density from the regenerative amplifier with synchronization. (b) Measurement noise floor acquired by performing the amplifier pulses auto correlation with the BOC. (c) Corresponding integrated timing jitters.
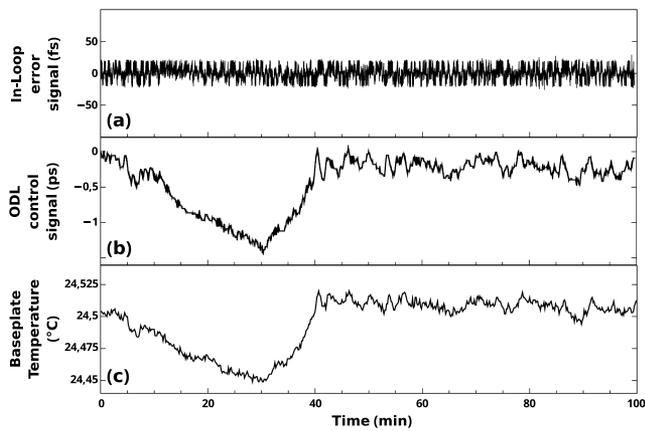
Fig. 3. Amplifier timing drift measurement over 100 min. (a) Timing error signal. (b) Tunable ODL control signal. (c) Regenerative amplifier baseplate temperature.

acquire the in loop error signal with a data logger, with a sampling rate $f_s = 100$ Hz. We can observe RMS and peak to peak fluctuations of 10 and 60 fs over 2 h correspondingly. The system has been routinely locked for more than 10 h with equivalent results. Figure 3(b) exhibits the ODL control signal with a peak to peak variation of about 1.2 ps over 1 h, which is larger than the amplifier pulse duration. Figure 3(c) shows the amplifier baseplate temperature variation which is strongly correlated to the ODL control signal. The sensitivity of the amplifier to the temperature is about 20 ps/K, which is very close to the aluminum baseplate linear thermal expansion co efficient. The long term timing fluctuations from the amplifier are dominated by residual temperature fluctuations. The addi tive amplifier short term timing jitter between 0.1 Hz and 10 kHz is below the jitter from the seeding laser oscillator, phase locked on a very low phase noise radio frequency refer ence. However, for a demanding experiment where long term synchronization is required, the additive amplifier timing drift still requires active control. Considering these results, we expect the additive timing fluctuations from the amplifier to increase with the total number of round trips inside the regenerative cavity, as the amplifier would become more and more sensitive to temperature and mechanical vibrations.

To summarize, we demonstrated a new BOC configuration allowing the characterization and control of short and long term timing fluctuations of an ytterbium regenerative amplifier. Our setup achieved a resolution of 300, as integrated from 10 Hz to 10 kHz, well below the integrated amplifier additive timing jitter of 5 fs (from 0.1 Hz to 10 kHz). The main sources of the amplifier additive timing jitter were mechanical vibra tions for short term timing jitter (10 Hz to 10 kHz) and the amplifier baseplate temperature fluctuations for the long term

drift. Thus, this system is ready to be used in high precision synchronized experiments, such as swissFEL. In principle, this detection method enables timing jitter measurement up to Nyquist frequency. Therefore, this approach may be applied to any type of ultrafast amplifier system. In the future, we plan to use this setup for the characterization and control of a ytterbium regenerative amplifier with higher output energy and longer optical path length. We also intend to apply the same approach to ultrafast ytterbium fiber amplifiers to investigate their timing fluctuations.

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