SUB-10 FEMTOSECOND STABILIZATION OF A FIBER-LINK USING A BALANCED OPTICAL CROSS-CORRELATOR

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Abstract

A drift free synchronization distribution system with femtosecond accuracy is of great interest for free-electron-lasers such as FLASH or the European XFEL. Stability at that level can be reached by distributing laser pulses from a mode-locked erbium-doped fiber laser over length-stabilized fiber-links. In this paper, we present a prototype of a fiber-link stabilization system based on balanced optical cross-correlation. The optical cross-correlation offers drift-free timing jitter detection. With this approach we were able to reduce the timing jitter added by a 400 m long fiber-link installed in a noisy accelerator environment to below 10 fs (rms).

INTRODUCTION

The operation of ultra-violet and X-ray free electron lasers like FLASH (Free electron LASer in Hamburg) or the planned European XFEL requires synchronization of various devices in the accelerator to better than 10 fs. The most critical devices are the photo-injector laser, the RF gun, the accelerating modules in front of the bunch compressors, and pump-probe and seed lasers for user experiments. Their locations are separated by 400 m for FLASH and by 3.5 km for the XFEL.

The high accuracy of synchronization required over these large distances cannot be achieved by conventional coaxial RF distribution systems. At FLASH and for the XFEL, an optical synchronization will be used [1]. The reference oscillator is a mode-locked erbium-doped fiber laser which is locked to a microwave oscillator. Two diffent kinds of fiber lasers are under investigation. The first one operates in the stretched-pulse regime at a repetition rate of 54 MHz [2], the second one is a soliton laser at 216 MHz [3]. The light pulses generated by these lasers are distributed to the remote locations via length-stabilized and dispersion compensated fiber-links. There, the light pulses are either converted into RF signals which are needed in the accelerating cavities, they are used to synchronize external lasers by optical cross-correlation or seeding, or they are directly used for opto-diagnostic devices [4, 5].

NOISE CHARACTERIZATION OF ERBIUM-DOPED FIBER AMPLIFIERS

At several locations inside the optical synchronization system, erbium-doped fiber amplifiers (EDFAs) are used to compensate for losses of optical power. The noise contribution of EDFAs is, therefore, an important aspect. To measure the timing jitter added by an EDFA with sub-femtosecond resolution, an optical setup based on a balanced optical cross-correlator was used (see Fig. 1). The setup consists of a erbium-doped, mode-locked, 200 MHz soliton laser which generates 100 fs long pulses. These pulses are amplified by a dispersion compensated EDFA and timing changes of the amplified pulses with respect to the laser system are measured inside a balanced optical cross-correlator.

The principle of the cross-correlator is shown in Fig. 2. Two light pulses with orthogonal polarization pass through a type-II PPKTP crystal. Inside the crystal, the two polarizations experience a different group delay. With a dichroic mirror, the second harmonic generated in the crystal is sent to detector 1, while the fundamental harmonic is back-reflected, passing the crystal once more. The second harmonic generated during this passage is separated out by another dichroic mirror and directed to detector 2. Using the difference signal of the two detectors, amplitude fluctuations of the incoming pulses can be strongly suppressed. Figure 3 shows the response of the cross-correlator as a function of the delay between the two pulses. The timing stability is measured at the zero-crossing of the balanced detector signal.

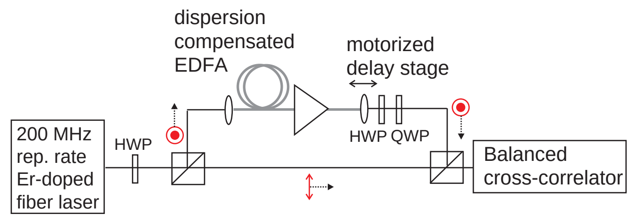

Figure 1: Experimental setup for the noise characterization of EDFAs.

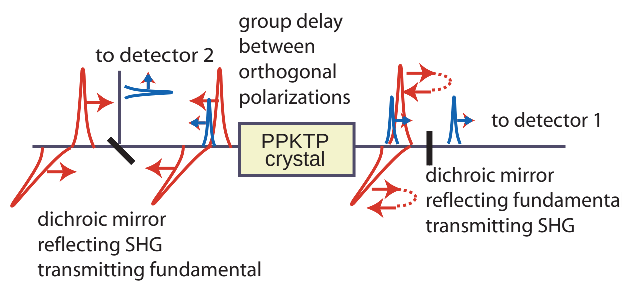

Figure 2: Principle of the balanced optical cross-correlator.

The timing jitter contribution of the EDFA was measured

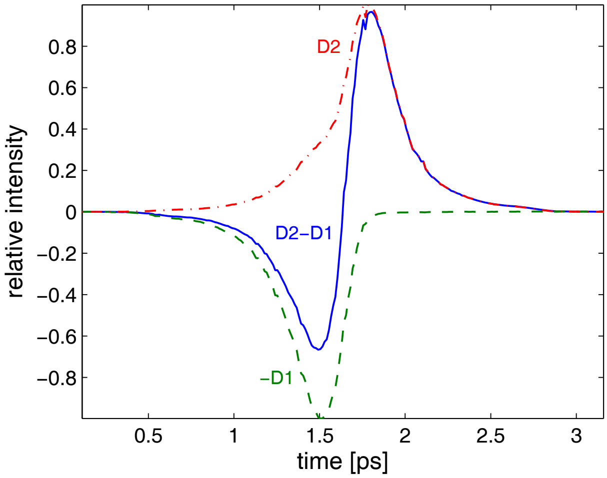

Figure 3: Response of the balanced optical cross-correlator. The signals of the two detectors D1 and D2 (dashed traces) are combined digitally, giving the difference signal (solid trace). Timing jitter measurements are performed at the zero crossing of the difference signal.

as a function of the optical input power and the power of the $980\,\mathrm{nm}$ pump light. Since the response of the cross-correlator depends on the intensity and length of the incoming laser pulses, a new calibration of the detector was performed for every set of parameters. Figure 4 shows the integrated timing jitter ($500\,\mathrm{Hz}$ - $4.5\,\mathrm{MHz}$) added by the EDFA. If the EDFA is too weakly pumped, it reaches up to $70\,\mathrm{fs}$. For optimal working conditions, it is only $0.5\,\mathrm{fs}$ and thus negligible.

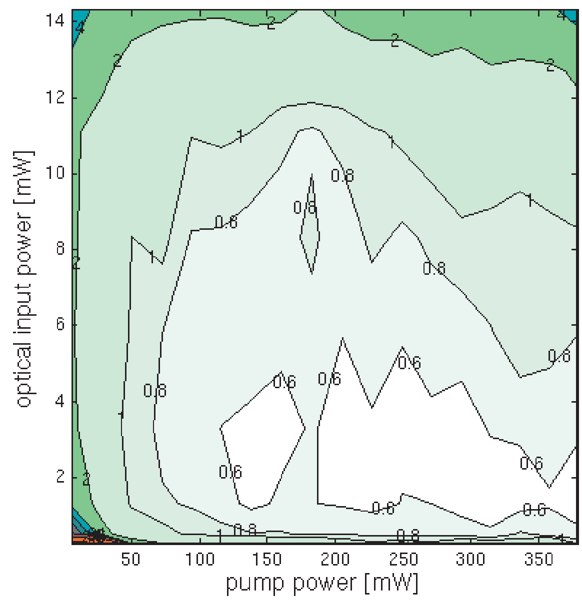

Figure 4: Integrated timing jitter ($500\,\mathrm{Hz}$ - $4.5\,\mathrm{MHz}$) in femtoseconds added by the EDFA as a function of the optical input power and the power of the $980\,\mathrm{nm}$ pump light.

FIBER-LINK STABILIZATION

The fiber-link stabilization setup has been tested in a laboratory environment [6]. It is schematically depicted in Fig. 5. In order to test the influence of a noisy enviroment, the fiber is installed around the circumference of an accelerator hall.

The laser pulses are coupled into a 400 m long, dispersion compensated single-mode fiber. At the end of the fiber, part of the light intensity is back-reflected using a Faraday rotator mirror. The returning pulses are combined with the pulses emitted directly from the laser. The overlap between the two signals is measured by a balanced cross-correlator. Timing changes are corrected by a digital feedback system which drives a piezo stretcher inside the link. The bandwidth of the feedback loop is around $1\,\mathrm{kHz}$. Timing changes larger than $\pm 2\,\mathrm{ps}$ are corrected by a motorized optical delay stage allowing to operate the closed loop over days.

The timing stability of the fiber-link is evaluated with a second optical cross-correlator in which the arrival time of pulses out of the link is compared with pulses coming directly from the laser.

The slow compensation introduced by the optical delay stage amounts to $40\,\mathrm{ps}$ over 12 hours, as depicted in Fig. 6 a). This is caused mainly by enviromental temperature changes. Figure 6 c) shows the residual timing change of the stabilized fiber. A slow timing drift of $25\,\mathrm{fs}$ is observed over 12 hours. This is most likely an artefact of the arrival time measurement which is influenced by polarization changes inside the fiber-link. This change of the polarization state causes a variation of the optical power entering the out-of-loop cross-correlator. An imperfect balance therefore causes systematic errors in the arrival time detection. Over 12 hours this amplitude change was $20\,\%$, corresponding to about 1 fs timing change per percent laser amplitude change. The red line depics the floating average over two minutes. Excluding this slow drift the remaining timing jitter amounts to $(4.4 \pm 1.1)\,\mathrm{fs}$.

To reduce effects of polarization changes inside the fiber-link, a measurement with a polarization controller installed at the link-end is foreseen. Then other systematic effects on the fiber-link stabilization such as polarization mode dispersion can be evaluated. Further potential candidates for timing drifts of the link are gain or offset drifts of the two cross-correlator detectors. A detection scheme is in development in which the two second harmonic signals are combined optically and read out by a single detector.

The fast changes of the fiber-link length of $1 - 3\,\mathrm{ps}$ on a timescale of 10 seconds we had encountered in [7] could be reduced by shielding the bare fiber at the link end-points against airflow and vibrations.

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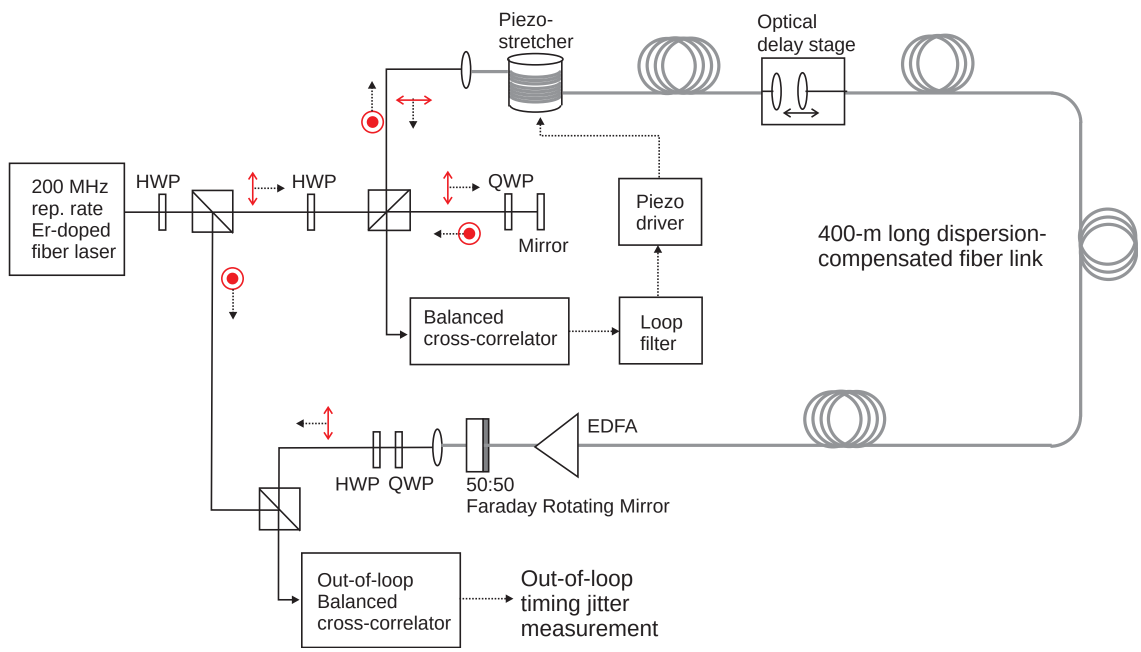

Figure 5: Experimental setup for the fiberlink stabilization.

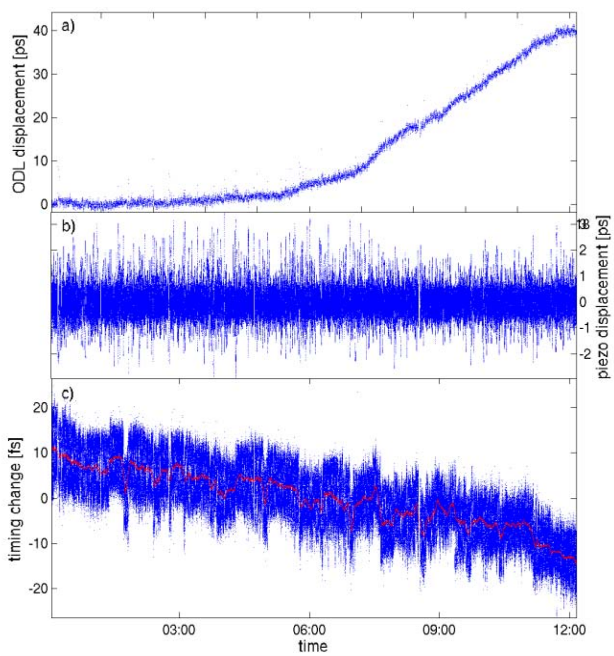

Figure 6: Drift measurement of a 400 m long fiberlink. a) Displacement of the optical delay line (ODL). b) piezo stretcher displacement. c) timing change at the end of the fiber-link. The red line indicates slow timing changes. The timing jitter is (4.4 ± 1.1) fs.

SUMMARY AND OUTLOOK

We demonstrated the proper performance of a fiber-link stabilization system based on optical cross-correlation. The fiber was installed in a noisy envirement and we achieved an rms link timing stability below 10 fs over 12 hours. The noise contribution of erbium-doped amplifiers has been investigated and less than 0.5 fs timing jitter was measured in an optimized setup. Next steps involve further investigation of polarization effects inside the link and the installation of first prototypes of the system inside the FLASH linac.

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