

First prototype of an optical cross-correlation based fiber-link stabilization for the FLASH synchronization system

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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 master oscillator over actively optical-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) over 12 hours.

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. These 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, developed in collaboration with MIT (see [1]), will be used. The system uses a mode-locked Erbium doped fiber laser which is locked to a microwave RF master oscillator. Two different kinds of fiber lasers are under investigation, one operating in the stretched-pulse regime at a repetition rate of 54 MHz [2], the other one is a soliton laser operating at 216 MHz [3]. The light pulses generated by these lasers are distributed to the remote locations via actively length-stabilized, 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]).

INVESTIGATED FIBER LASERS

For the prototype of the fiber-link stabilization a 200 MHz soliton laser was used. The higher repetition rate compared to a 54 MHz stretched-pulse laser has several advantages: The maximum pulse energy which can

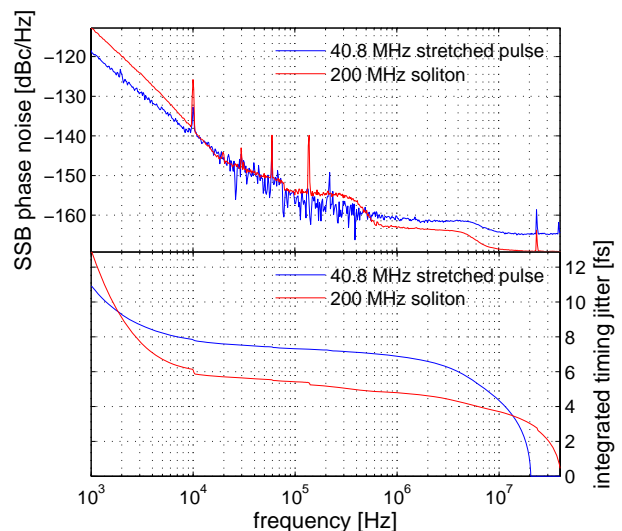


Figure 1: Phase noise comparison between a 40.8 MHz stretched-pulse laser and a 200 MHz soliton laser. Top: single-sideband phase noise measured at the harmonics at 980 MHz (stretched-pulse) and 1.2 GHz (soliton), respectively. Bottom: integrated timing jitter starting integration at 20.4 MHz (stretched-pulse) and 40 MHz (soliton). The measurements for the stretched-pulse laser are from [2].

be transmitted through the fiber-links is limited by nonlinearities and the higher repetition rate allows for four times more average power inside a link with the same pulse energy and, consequently, the same amount of non-linear behaviour. Since the pulse spacing is reduced by a factor of four, timing adjustments to overlap the laser pulses with other signals are much easier. The soliton lasers we use generate optical pulses with a Fourier limited pulse duration of around 130 – 160 fs. The stretched-pulse lasers generate a much broader optical spectrum which complicates dispersion compensation of the fiber-links. Limiting the wavelength spectrum by an aperture in a dispersive section is possible but leads to a loss of optical energy. The effect of the optical spectrum shape on the system performance must still be investigated.

On the other hand, single laser pulse detection, which is used for several electron beam diagnostic devices ([4], [5]) as well as RF phase detection with the fundamental laser repetition rate used as an intermediate frequency, is more complicated at higher repetition rates because it requires faster ADCs or an optical gating unit.

The distribution scheme relies on low phase noise for

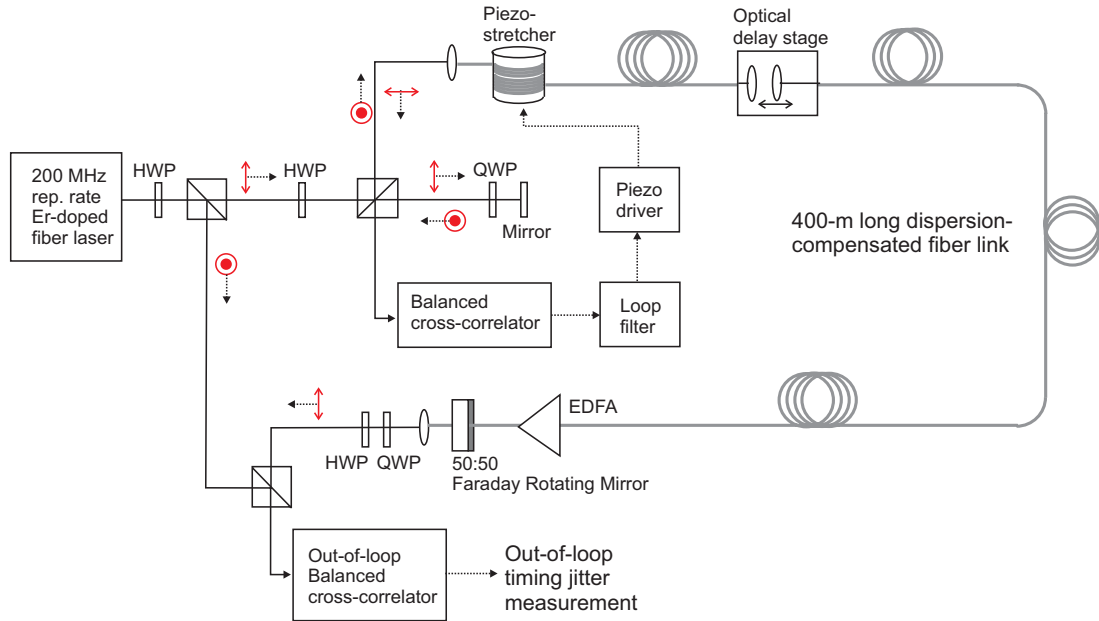


Figure 2: Experimental setup for the fiberlink stabilization.

frequencies above the link roundtrip frequency. This frequency is on the order of 250 kHz for the maximum link length of 400 m at FLASH and 25 kHz for the 4 km long links for the XFEL. Both fiber-laser types have very low integrated phase noise above these frequencies. Figure 1 shows the single sideband phase noise and the integrated timing jitter of a 40.8 MHz stretched-pulse laser and of a 200 MHz soliton laser. The measurement is done by evaluating the phase stability of high harmonics of the repetition rate, filtered out from the signal of a fast photo detector. At high offset-frequencies the detection scheme is limited by the photo detection process [6]. Due to the higher repetition rate of the soliton laser, the intensity is distributed to fewer frequency components giving this laser type clear advantages in this frequency range. In the frequency range from 1 – 10 kHz the soliton laser is less stable than the stretched-pulse one. With a 10 kHz fast phase-lock loop to a microwave oscillator, however, this could be overcome.

MEASUREMENT SETUP

A schematic of the experimental setup, similar to the laboratory setup used in [7], is shown in Fig. 2. The laser pulses are coupled into a 400 m long, dispersion compensated fiber-link. In order to test the influence of a noisy environment, the fiber is installed around the circumference of an accelerator hall. At the end of the link, part of the light intensity is back-reflected using a Faraday rotator mirror. The returning pulses are combined with the pulses coming directly out of the laser. Inside a balanced optical cross-correlator (see Fig. 3) the overlap between the two signals is measured. Changes are corrected by a DSP based feedback system which drives a piezo stretcher inside the link. The bandwidth of the feedback loop is around 1 kHz.

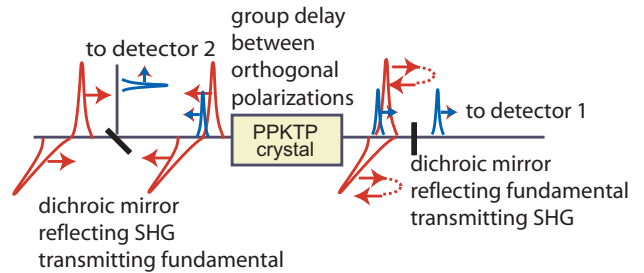


Figure 3: Principle of the balanced optical cross-correlator. Two light pulses with orthogonal polarization pass through a type-II PPKTP crystal. Inside the crystal the two polarizations experience a different group delay. With a dichroic mirror the second harmonic generated in the crystal is sent to a first detector, while the fundamental is back-reflected, passing the crystal a second time. The second harmonic is separated by a second dichroic mirror and directed to a second detector. Using the difference signal of the two detectors, amplitude fluctuations of the incoming pulses can be suppressed by a large amount.

Larger timing changes are corrected by a motorized optical delay line (ODL). To evaluate the timing stability of the fiber-link, a second optical cross-correlator is used in which the pulses out of the link are overlapped with pulses coming directly from the laser.

MEASUREMENT RESULTS

Figure 4 shows the response of the out-of-loop cross-correlator as a function of the delay between the two pulses. The link stability has been measured at the zero-crossing

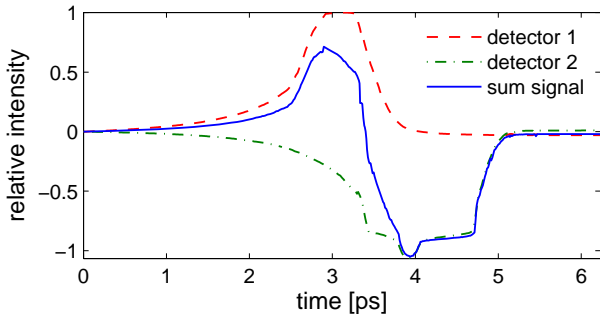


Figure 4: Response of the balanced out of loop optical cross-correlator. The signals of the two detectors (dashed traces) are combined digitally giving the sum signal (solid trace). The link timing jitter measurement is performed at the zero crossing of the sum signal.

of the balanced detector signal. This has the advantage that amplitude fluctuations are suppressed. Having a motorized optical delay stage installed inside the link, the limitations of a too small adjustment range of the piezo stretcher to keep the lock closed over hours [7] could be overcome. With this we were able to close the feedback loop over days.

Figure 5 shows the timing stability of the fiber-link over 12 hours. The rms timing jitter is (7.5 ± 1.8) fs at a measurement bandwidth of 200 kHz. Timing changes with a time constant below 100 s are (4.4 ± 1.1) fs, the timing drift over 12 hours is 25 fs. It is surprising that the link length has to be corrected by as much as 1 – 3 ps on a timescale of 10 seconds. Furthermore we found a correlation between changes of the piezo displacement and the link timing. This, together with the small timing drift visible in Fig. 5 could be caused by two sources: Since the polarization at the end of the link is not stabilized, polarization changes (e.g. due to the piezo-stretcher or temperature drifts) inside the link cause changes of the amplitude entering the balanced detector. A non-perfect balancing would lead to an error in the arrival time detection. A second reason could be polarization mode dispersion inside the fiber-link. Since this would be an ultimate limitation when using standard single mode fiber instead of polarization maintaining fiber, we plan to repeat the measurement having a polarization feedback installed at the end of the link.

Another polarization related effect we found is caused by Erbium-doped fiber amplifiers. In several Erbium-doped fiber amplifiers, built with different kinds of fibers, we found a wavelength dependent polarization rotation which is independent of the pump power and, therefore, most probably not caused by self-phase modulation. Further investigations on this topic have to be performed.

SUMMARY AND OUTLOOK

We demonstrated the proper performance of a fiber-link stabilization system based on optical cross-correlation. The

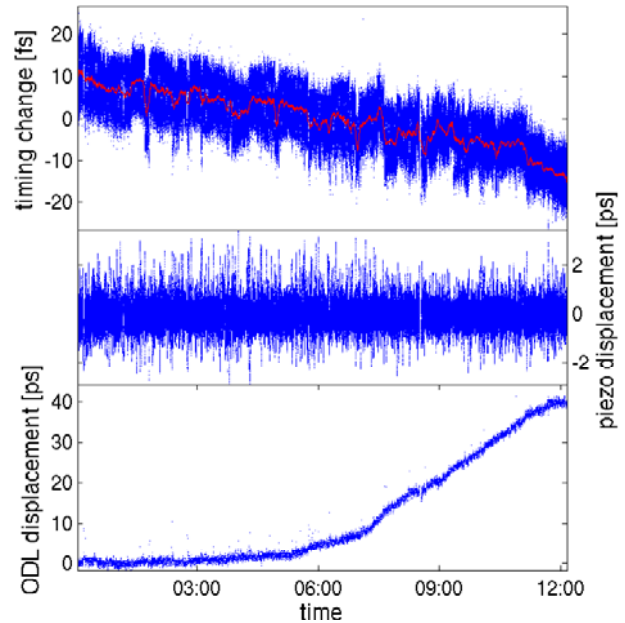


Figure 5: Out of loop drift measurement of a 400 m long fiberlink. Top: end of link timing change (blue). Over 12 hours the rms jitter is (7.5 ± 1.8) fs with a timing drift of 25 fs. The red line indicates changes with a time constant of 100 s. The timing jitter faster than 100 s is (4.4 ± 1.1) fs. Middle: piezo stretcher displacement. Bottom: Displacement of optical delay line (ODL).

fiber was installed in a noisy environment and we achieved an rms link timing stability below 10 fs over 12 hours. 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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REFERENCES

- [1] J. W. Kim et. al., “Large scale timing distribution and RF-synchronization for FEL facilities,” FEL Conference 2004, Trieste, Italy, 2004.
- [2] A. Winter et. al., “High-precision Laser Master Oscillators for Optical Timing Distribution Systems in Future Light Sources,” EPAC Conference 2006, Edinburgh, UK, 2006.
- [3] J. Chen et. al., Opt. Lett. **32**, 1566-1568 (2007)
- [4] F. Loehl et. al., “A Sub-50 fs Bunch Arrival Time Monitor System for FLASH,” this Conference, Venice, Italy, 2007.
- [5] K. Hacker et. al., this Conference TUPB20.
- [6] J. Mueller et. al., this Conference WEPB08.
- [7] J. Kim et. al., Opt. Lett. **32**, 1044-1046 (2007)