RF-BASED DETECTOR FOR MEASURING FIBER LENGTH CHANGES WITH SUB-5 FEMTOSECOND LONG-TERM STABILITY OVER 50 h

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Abstract

At the Free-Electron Laser in Hamburg (FLASH), an optical synchronization system is being installed with a projected point-to-point stability of 10 fs. The system is based on the distribution of laser pulses over fiber links whose optical path length is actively stabilized. The optical path length can be measured very accurately with an optical cross-correlator. As an alternative to the complex cross-correlation scheme, which can achieve sub fs long-term stability and works well over several 100 m long fiber links, an RF-based technique which is much less complex and expensive could be used. It is based on the power detection of high harmonic frequencies in such a way that common-mode laser amplitude is removed. For a 20 m long fiber link, it was demonstrated that sub-5 fs rms stability over 50 hours can be achieved. The average of the signal drifted by 19 fs over the same time-period.

INTRODUCTION

The **F**ree **E**lectron **LAS**er in **H**amburg (FLASH) produces laser pulses with wavelengths from 60 nm down to 6.5 nm. The FEL-pulse duration ranges from 10-40 femtoseconds for long wavelengths down to below ten femtoseconds for short wavelengths [1]. For pump-probe experiments to benefit from these ultra-short pulses, various components in the FLASH facility have to be synchronized to within the pulse duration. An optical synchronization system is being constructed to meet this demanding requirement. It is based on a **M**aster **L**aser **O**scillator (MLO) providing short optical pulses of about 100 fs duration whose repetition rate of 216 MHz is stabilized by a narrow band phase-lock loop to the facility master RF oscillator [2].

The optical pulses are distributed to remote locations along fiber links whose optical path-lengths are actively stabilized. In one design, the optical path-length is monitored using an optical cross-correlation technique in which, at the link-end, a fraction of the optical pulse is reflected back and overlapped with a pulse emitted directly from the master laser oscillator. The temporal overlap of the two pulses is measured by monitoring the second harmonic

produced in a non-linear crystal. The production of the second-harmonic light requires spatial and temporal overlapping of short laser pulses at the non-linear crystal. To maintain spatial overlap, the design must be mechanically stable. To maintain temporal overlap, the round-trip time of the pulse must be equal to a multiple of the repetition rate of the MLO. To keep the pulses short, the fiber link has to be precisely dispersion compensated, ideally below a fiber dispersion length of SMF-fiber (10 cm). Despite the technical complexity and expense, the method has achieved femtosecond and even sub-femtosecond precision over several days and even sub-femtosecond precision over hours [3, 4].

Many of the of the potential end-station users do not require such highly stable laser pulses since other sources of timing jitter are much larger and it is not feasible to build a cross-correlator link for every single location that requires a reference laser signal. The cross-correlator link can supply fiber-link hubs from which multiple, adjacent devices can be supplied. However, even a few meters of unstabilized standard fiber is unacceptable for some applications and so, as an alternative or supplement to this system, a simpler and less expensive RF-link stabilization technique is presented here. An older version of the design was presented in [6].

This RF link stabilization technique requires a pulsed MLO and it avoids the uncontrollable drifts associated with the use of photo-detectors through a balanced amplitude detection arrangement. It also has a much larger measurement range and can be used passively, without actively stabilizing the link. In this paper we present the measurements for a 20 m long fiber with sub-5 fs rms stability and a 15 fs drift of the averaged signal. It is anticipated that the fiber length can be extended without degrading the performance and can be used as a substitute for the optical cross-correlator in many cases.

DETECTION PRINCIPLE

The optical path length in a fiber varies due to changes of the refractive group velocity by temperature and length changes due to acoustic vibrations. The measurement of optical path length changes in the new RF scheme differs from the optical cross-correlation scheme by the relaxed demands on dispersion compensation and pulse overlap. In addition, because of its larger detection range compared to the optical cross-correlator method, it allows for pas-

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sive monitoring of the optical path length without actively changing the length to keep the measurement in range. When used in a passive fashion, the system becomes significantly cheaper.

If a laser pulse train with a repetition rate of $f_0 = 1/T_0$ is incident on a photodetector, a frequency comb spectrum is generated with frequency harmonics separated by f_0. The frequency spectrum will be modulated when a second optical pulse train derived from the same source is superposed. For example, the modulated intensity of the n-th harmonic is given by

$$I(nf_0) \propto \cos^2\left(n\pi f_0 \Delta t\right), \tag{1}$$

where Δt correspond to the temporal offset between the two pulse trains.

If one pulse train lies exact upon the other one the modulation vanishes; the response is like that of a single pulse train. For small temporal offsets high harmonics begin to vanish. Figure 1(a) shows the modulated frequency comb for a certain $\Delta t = 0.03\,T_0$ where the 17th harmonic vanishes. This minimum of the modulation moves to lower frequencies and further high harmonics vanish if the temporal offset Δt is increased (Fig. 1(b)). For $\Delta t = T_0/2$, every second harmonic vanishes and the frequency spectrum is like a pulse train with the double repetition rate $2\,f_0$. As Eq. 1 shows, the intensity of the nth-harmonic depends on the temporal offset Δt but also on amplitude variations of the laser. The variation of the intensity of higher harmonics grows with the harmonic number n.

To distinguish between changes of the laser amplitude and a change of the temporal offset, two harmonics which are separated by a minimum or maximum of the modulation curve have to be observed (Red curve in Fig. 1). For amplitude changes, both harmonics move up and down simultaneously. For length changes of the fiber, both frequency lines move contrarily. For a defined temporal offset $\Delta t = T_0/2\,(1 \pm 1/(2\,n+1))$ the harmonics $n\,f_0, (n+1)\,f_0$ are separated by a minimum or maximum and correspond with an inflexion point of the modulation Eq. 1 [7]. This is shown in Fig. 1(c) for the 16th and 17th harmonic.

The signal change of the both harmonics is given by

$$I \propto \cos^2\left(\pi f_n \Delta t\right) - \cos^2\left(\pi f_{n+1} \Delta t\right), \tag{2}$$

In Figure 2 the dependence is pictured for the 16th and 17th harmonic. The black dots are the optimal working point where the slope is the largest.

EXPERIMENTAL SETUP

The detection scheme is described in two parts. The optical part and the electronic part of the detector.

The optical part consists of a mode locked 216 MHz Erbium-doped fiber laser. The laser amplitude is stabilized with a PID-controller. The reference pulse train for the out-of-loop detector is generated at a polarizing beam splitter (a) (PBC) (Fig. 3(a)). At PBC (b) the reference
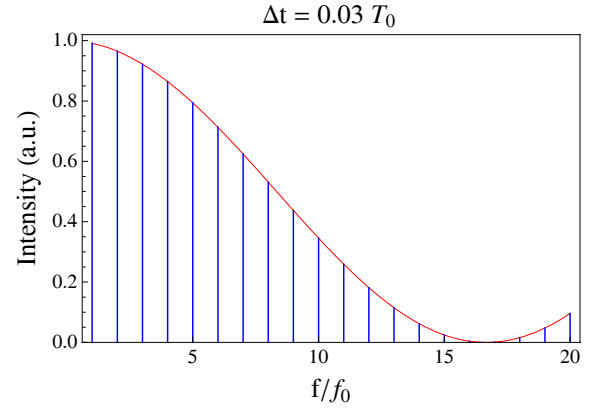
(a) Modulation of the frequency comb with a temporal offset of $\Delta t = 0.03\,T_0$
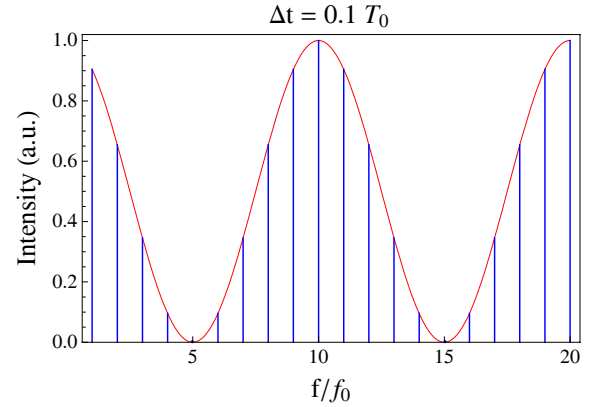
(b) Modulation of the frequency comb with a temporal offset of $\Delta t = 0.1\,T_0$
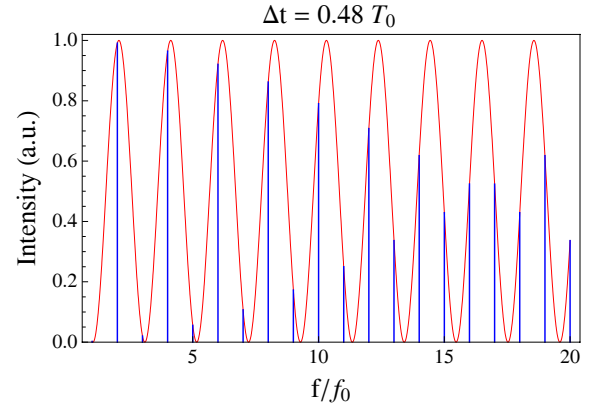
(c) Modulation of the frequency comb with a temporal offset of $\Delta t = 0.48\,T_0$. Possible setpoint if the 16th and 17th harmonics are observed.

Figure 1: Intensities of the calculated frequency comb of the superposed pulse trains for different Δt with a repetition rate $f_0 = 1/T_0$.

pulse train for the in-loop detector is produced. The power of the reference pulse trains of the in-loop and out-of-loop detector can be adjusted with half wave plates 1, 2. The rest of the light is guided onto a mirror which is placed on a motorized linear stage. This stage is used for adjusting the temporal overlap for the in-loop detector and for the
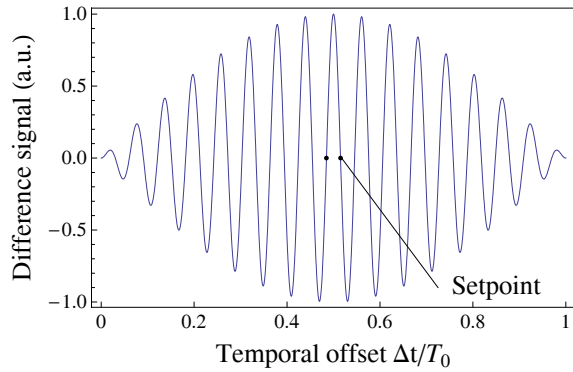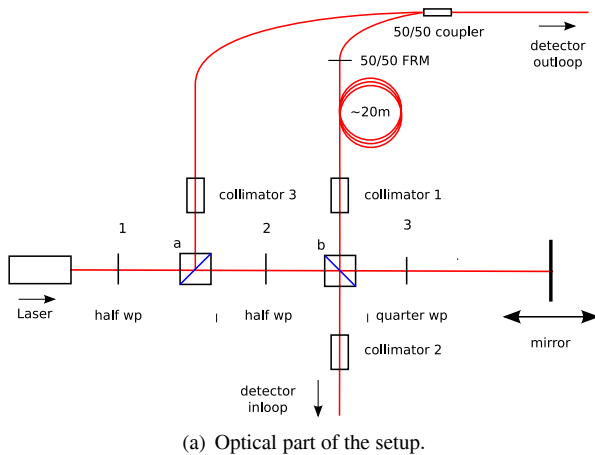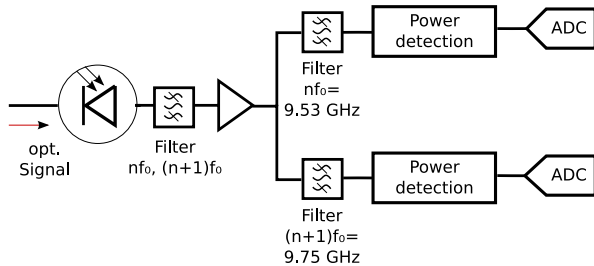
Figure 2: Intensity difference of both observed harmonic against Δt

(a) Optical part of the setup.

(b) Electronic part of the setup.

Figure 3: Schematic of the Setup

calibration of both detectors. The light is coupled into the 20 m long optical fiber link. At the end of the link, a Faraday rotating mirror reflecting 50 % back and rotating the polarization by 90°. The reflected part is superposed with the reference pulse train at PBC (b). The light is guided onto the in-loop detector. The transmitted part is superimposed with the reference pulse train from PBC (a) at a 50 %/50 % coupler. The temporal overlap for the pulse trains for the out-of-loop detector can be adjusted with a linear stage on which the collimator for the coupling of the reference pulse train from PBC (a) is placed. The light is guided to the out-of-loop detector.

In Figure 3(b) the RF-temporal offset detection setup is

depicted. It is based on a fast photo-diode with a bandwidth of 10 GHz. The output of the photo-diode is filtered and amplified. For the balanced scheme, the output of the amplifier is split. The two harmonics ($44 \times f_0 = 9.53$ GHz, $45 \times f_0 = 9.75$ GHz) are filtered within each arm. The power of the signal is detected with a Zero-Bias-Schottky detector. The DC-signal is detected with a 10 MHz ADC with 1 MHz sample rate.

MEASUREMENT RESULTS

When the power of the pulse trains and the temporal offset are adjusted, the calibration is done with the motorized stage shown in Fig. 4(a). The signal change for the in-loop and the out-of-loop detector are nearly equal. A polynomial fit on the data is done to calculate a time from the voltage,

$$t_{\mathrm{Ch}(i)} = \sum a_i V_i. \qquad (3)$$

On the calibration data a 2nd order polynomial is used to fit the data. Only the points around the in an array of ± 4 ps around the mid point are taken for the fit. The parameters for the polynomial are noted in Tab. 1

In order to produce the measurement of the delay change of the fiber shown in Fig. 4(b), the voltage of each detector channel is converted with the calibration curve Eq. 3 into a time value that contains errors from the laser amplitude changes. In order to remove these errors, the times from each pair of detectors are added to one another, giving the delay change of the link

$$\Delta t_{1,2} = \frac{1}{2}\left(t_{ch1} + t_{ch2}\right).$$

The peak-to-peak change of the in-loop measurement is $t_{pp,in} = 1.24$ ps and shows, as expected, twice the length change of the out-of-loop detector peak-to-peak change $t_{pp,out} = 0.61$ ps.

To compare the delays measured by in loop and out-of-loop detectors, the difference is calculated with

$$\Delta t = \frac{1}{2}\Delta t_1 - \Delta t_2,$$

where $\Delta t_{1,2}$ is the delay measured by each detector. This is shown in Fig. 4(c). The rms time difference is 4.56 fs. The resolution of one detector is the square root of the time difference

$$3.23 \text{ fs (rms)}.$$

The peak-to-peak value of the average of the time difference gives a 19 fs value for the drift of the measurement . The glitches on the signal are probably disturbances of the laser source which was unstable.

To improve the detector, the output signal could be amplified, since the ADC seems to limit the detector resolution. For the amplification, the offset of the Schottky detector has to subtracted.
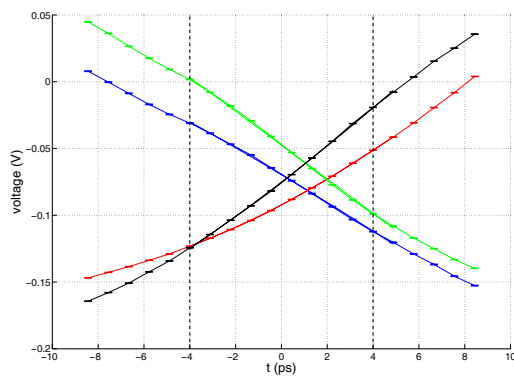
(a) Calibration curve for the conversion of the of the voltage to time change. Blue: In-loop (9.53 GHz), Red: In-loop (9.75 GHz), Green: Out-of-loop (9.53 GHz) and Black: (9.75 GHz).
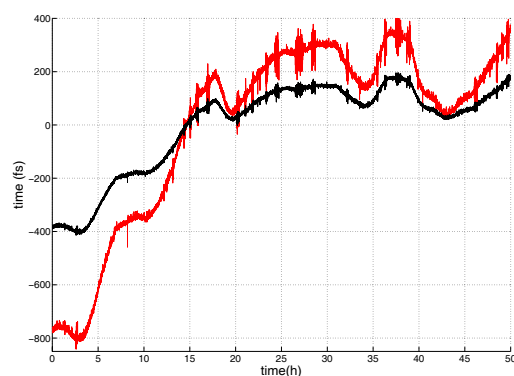
(b) Balanced time change of each detector. Red: In-loop detector. Black: Out-of-loop detector. Measurement bandwidth: 500 Hz
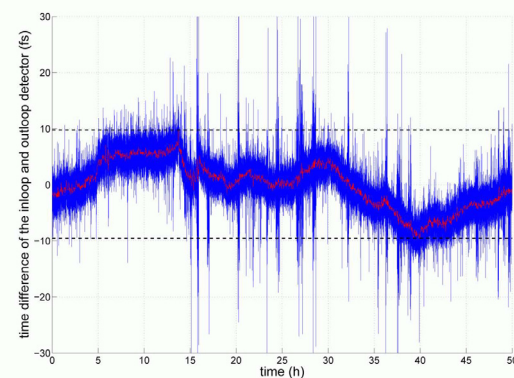
(c) Time difference $\Delta t = 0.5\, t_{\text{in-loop}} - t_{\text{out-of-loop}}$ of the two detectors. Measurement bandwidth: Blue: 500 Hz, Red: 10 mHz

Figure 4: Analysis of the data of the long-term measurement over 50 h.

CONCLUSION AND OUTLOOK

The balanced RF-scheme shows a long-term stability of 3.23 fs (rms) for a 20 m long fiber link. It will be employed to measure the length change of longer links. For a longer link the dispersion has to be compensated to min-

Table 1: Fit Parameter for the Calibration

In-loop detector

	a_0	a_1	a_2
$44\,f_0$	-0.070	$1.02\,10^{-5}$	$-8.61\,10^{-11}$
$45\,f_0$	-0.092	$0.90\,10^{-5}$	$3.03\,10^{-10}$

Out-of-loop detector

	a_0	a_1	a_2
$44\,f_0$	-0.048	$-1.27\,10^{-5}$	$-1.49\,10^{-11}$
$45\,f_0$	-0.075	$1.32\,10^{-5}$	$1.80\,10^{-10}$

imize the damping of the high harmonics. It will also be benchmarked against a measurement using a optical cross-correlator. The detector will be installed to connect the injector laser to the synchronization system and this will make a dramatic impact on the machine stability, in conjunction with a beam based feedback on the RF gun phase.

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