DRIFT-FREE, COST-EFFECTIVE DETECTION PRINCIPLE TO MEASURE THE TIMING OVERLAP BETWEEN TWO OPTICAL PULSE TRAINS

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Abstract

At the Free Electron Laser in Hamburg, FLASH, photon pulses with durations down to below 10 fs are generated. To benefit from the short pulse duration in pump-probe experiments, external lasers have to be closely synchronized to the FEL pulses on the same order. To meet these stringent requirements, an optical synchronization system is currently being installed. The system is based on the distribution of reference laser pulses over actively stabilized fiber links. The fiber length stabilization is carried out by overlapping two optical pulse trains. Currently, the overlap is measured by optical cross-correlation techniques that require defined polarizations of the two pulse trains, short laser pulses, and free space optics.

In this paper, we present a drift-free, low-cost detection principle based on a photo detector and RF devices. We plan to use this scheme, which has a resolution of better than 20 fs, for the stabilization or length measurement of short optical fiber-links. Our proof of principle test has shown that this cost-effective sub-distribution of an optical reference signal to multiple locations is possible a viable scheme.

INTRODUCTION

To perform pump-probe experiments on a sub-10 fs time scale with the FEL pulses and an external laser, the arrival time of both laser pulses has to be known with this precision. For FLASH, a novel synchronization system is currently being developed in order to meet these stringent requirements. The system is based on a mode-locked doped Erbium fiber laser emitting a stream of laser pulses with a repetition rate of 216 MHz. The laser pulse stream is distributed over actively length stabilized optical fibers to different locations in the facility, such as RF-stations, beam diagnostic instrumentation, and the pump-probe laser.

The active length stabilization of fibers is crucial for the performance of the synchronization system, since the optical path length in fibers changes, for example, due to temperature fluctations or ambient vibrations, can be worse than for high quality coaxial RF-cables. To measure the path length change of the fiber link, a fraction of the laser pulse stream is reflected at the link-end and its round-trip time is measured against a reference.

The straight forward-technique to measure the reflected laser pulse arrivals is to bandpass filter a photo detector signal at a high harmonic of the laser repetition rate. Then, phase changes of high harmonics due to arrival-time changes of the laser pulses are detected by microwave mixing the signal against an RF-reference generated, for example, from laser pulses emitted directly out of the fiber laser oscillator [1]. Limitations of the microwave phase detection technique include amplitude-to-phase conversion in the photo detection process, thermal phase drifts of the photo detector, and offset drifts of the RF-mixer. This typically restricts the long term stability of this technique to about 50 fs to 100 fs.

A much higher precision and long-term stability is achieved by using a background-free, balanced optical cross-correlator based system for the link stabilization. A resolution of some 100 as short-term and a few femtoseconds long-term is reached by using this technique [2], [3]. The scheme is based on temporal overlap of the reference and a second pulse train which has been reflected at link-end in a nonlinear crystal. It requires a defined polarization and short laser pulses, thereby neccecitating polarization control and dispersion compensation.

Cross-correlation techniques can be used for fiber link stabilisation and can have been demonstrated to offer the possibility to synchronize two laser systems with sub-femtosecond resolution [3]. Such techniques will be applied to synchronize external lasers to the reference system [4].

The scheme we present in this paper is an RF-based technique which overcomes the various drift problems mentioned above. This low-cost detector with a stability down to the 10 fs level offers the possibility to easily connect many subsystems to the optical reference without the expensive/costly disadvantages of the cross-correlation.

DETECTION PRINCIPLE

A single train of laser pulses spaced by the period T_0 produces a frequency comb spectrum with lines separated by $f_0 = 1/T_0$. In the detection scheme presented here, we superimpose the reference pulse train upon a second pulse train whose temporal changes with respect to the reference signal must be measured. These two signals are guided onto the same photo detector. For two pulse trains with the same repetition rate f_0, the superimposed signal leads again to a frequency comb with comb lines separated by f_0. The intensity of the lines, however, is modulated and

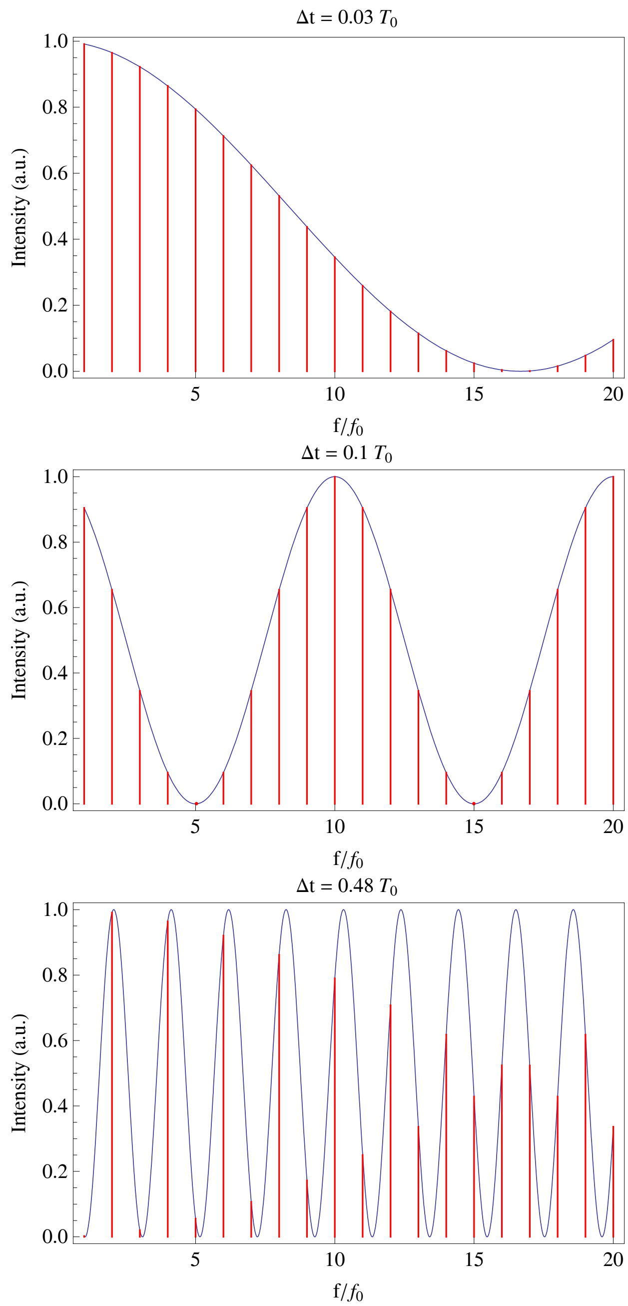

Figure 1: Calculated frequency spectrum of the superposition of two pulse trains for different Δt with the repetition rate $f_0 = 1/T_0$ of the laser. Top, $\Delta\,\mathrm{t} = 0.03\,\mathrm{T}_0$ shows a first minimum. Middle, $\Delta\,\mathrm{t} = 0.1\,\mathrm{T}_0$ a second minimum occours. Bottom, $\Delta\,\mathrm{t} = 0.48\,\mathrm{T}_0$ shows a preferred temporal offset for observing the 16^{th} and 17^{th} harmonics.

the intensity of the n-th harmonic is

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

where Δt is the time offset between the two pulse trains.

Figure 1 shows the frequency spectrum of two overlapping pulse trains of a photo detector for several Δt. For a temporal offset, $\Delta t = 0$, the frequency response of the detector is like a single pulse train. The high harmonics in the frequency spectrum begin to vanish when a small temporal offset with respect to the repetition rate f_0 between the two pulse trains is arranged. This is shown in the upper picture for a timelag $\Delta t = 0.03\,T_0$. This minimum moves to lower frequencies when the temporal offset becomes bigger and new minima occur, as shown in the middle figure, for a $\Delta t = 0.1\,T_0$. When the temporal offset is $T_0/2$, every second harmonic vanishes. The largest change of the frequency amplitude for a temporal offset is close to $T_0/2$. This is the offset for which an observed frequency line conforms to the inflexion point of the envelope. This case is shown in the lower picture for a temporal offset $\Delta t = 0.48\,T_0$, where the frequency lines of the 16^{th} and 17^{th} harmonics are located on an inflexion point. The sensitivity of the signal change is n-times bigger when the n-th harmonic is observed relative to the fundamental.

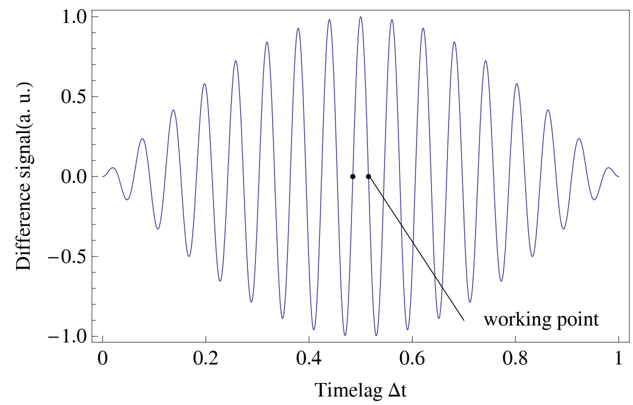

Figure 2: difference signal of the two arms depending on Δt.

To detect a change of the temporal offset, Δt, the observed frequency has to conform to an inflexion point to get a high measurement sensitivity. The amplitude of the observed frequency line varies if the temporal offset Δt changes, but it is not possible to distinguish a timing change from an amplitude variation caused by a laser power change.Consequently, a balanced detection schemecan is employed, such that two harmonics separated are simultaneously observed. When a timing change occurs, the intensities of the two harmonics change contrariwise and when the amplitude changes, the intensities move simultaneously up or down. The intensity difference of the two intensities is, therefore, independent of laser amplitude changes. This difference signal is proportional to

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

where f_n and f_{n+1} are the observed frequency lines and Δt is the temporal offset. In Fig. 2 the difference signal is shown for the harmonics of the 16^{th} and 17^{th} order. Due to the steepest slope, the optimum points of operation for the detector are the zero crossings of this difference curve, preferably near a temporal offset of $T_0/2$.

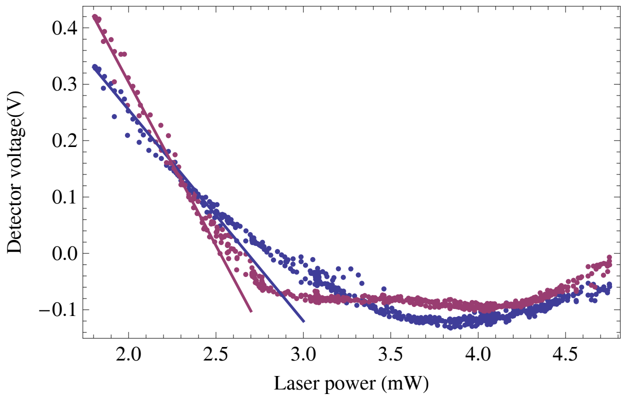

Figure 4: Change of the detector signal during a power variation of the laser.

DETECTOR DESIGN

The experimental setup is shown in Fig. 3. For the characterization of the detector, the laser pulse train is split and combined by polarizing beam cubes, so that with a λ-half waveplate, the split ratio is adjustable. One arm has a delay with respect to the first arm, so that the temporal offset is about $T_0/2$. Since both signals originated from the same laser pulse train, the only source of timing change between the two signals is the length change of the two optical paths, which corresponds to about 20 fs per degree temperature change. The laser power can be regulated by a second waveplate and a polarizer.

The pulses are guided onto a photo detector with a bandwidth larger than 10 GHz. The photo detector output is split and filtered by two bandpass filters with a center frequency of 9.53 GHz and 9.75 GHz, selecting the 44^{th} and 45^{th} harmonic. Each harmonic is amplified and the power stored in the frequency lines is detected with a linear amplitude detector. The offset voltage of the two amplitude detectors is subtracted in operational amplifiers by using a single voltage reference. These signals are sampled with an ADC.

MEASUREMENTS

Figure 4 shows the detector signal for the two observed harmonics for different settings of the laser power. The detectors were operated at a laser power of about 2 to 2.5 mW in order to have a linear dependence of the detector. One can see that at larger power levels the photo detector saturates. The two detector arms have a slightly different power dependence which has the effect that laser amplitude changes are not completely removed in the difference signal.

The dependence of the two detector arms on the temporal offset between the two optical signals is depicted in Fig. 5. Since the response of the two arms is slightly nonlinear and not completely symmetric, a polynomial fit is used to calculate separate time responses t_1 and t_2 for the

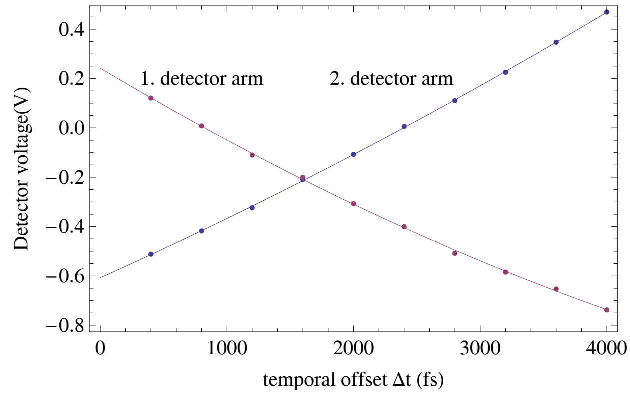

Figure 5: Signal change of the two detector arms for different temporal offsets.

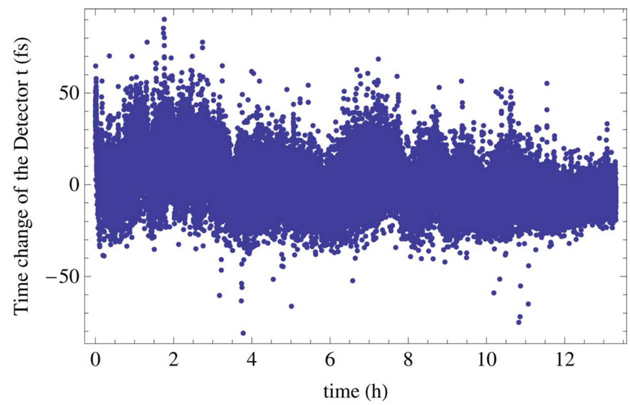

Figure 6: Long term stability of the detector.

two detector arms, resulting in

$$t_1(\text{fs}) = 3600\,\frac{\text{fs}}{\text{V}}\,V_1 - 470\,\frac{\text{fs}}{\text{V}^2}\,V_1^2$$

$$t_2(\text{fs}) = -3500\,\frac{\text{fs}}{\text{V}}\,V_2 + 1100\,\frac{\text{fs}}{\text{V}^2}\,V_2^2,$$

where V_1 and V_2 are the detector voltages.

The timing change is then calculated using

$$t = 0.5\,(t_1 + t_2), \tag{3}$$

by which the dependence on the optical amplitude is reduced.

The slope at the crossing of the two curves is $261\,\frac{\mu\text{V}}{\text{fs}}$ and $256\,\frac{\mu\text{V}}{\text{fs}}$.

The stability of the detector over a duration of 13 h is shown in Fig. 6. The rms-stability over this period is $t_{\text{rms}} = 15$ fs. The points which are far away from the noise band are possibly coming from the data acquisition system, since the two ADC channels were not read out at the same time. The small drifts which are visible could be caused by laser power changes as well as by thermal expansion of the refence arms.

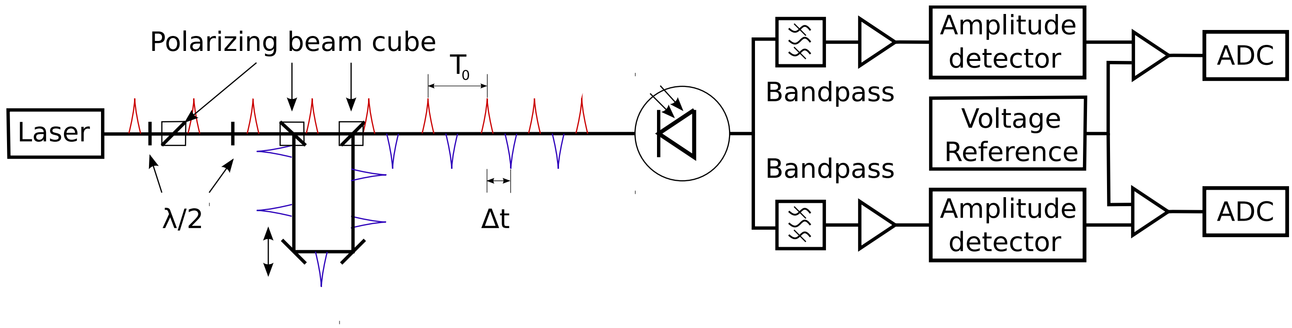

Figure 3: Schematic of the experimental setup.

CONCLUSION AND OUTLOOK

A new detection scheme based on RF devices to measure changes of the temporal overlap between two optical pulse trains was developed. Using a single photo detector and a balanced detection scheme measuring amplitudes instead of phases, the dependence of the timing measurement on the optical power could be overcome. In a first test setup, a timing resolution and long-term stability of the detection scheme of 15 fs was demonstrated.

The next steps involve using the detection principle to stabilize short fiber links providing synchronization signals to devices in FLASH which do not need the timing stability offered by an optical cross-correlation based stabilization system. The first application will be to link the photo-injector laser to the optical sychronisation system at Flash using this device. Furthermore, additional systematic studies will be carried out in order to further improve the resolution of the scheme.

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