CHARACTERIZATION OF THE ENGINEERED PHOTODIODE-BASED FIBER LINK STABILIZATION SCHEME FOR OPTICAL SYNCHRONIZATION SYSTEMS

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Abstract

Pulsed optical synchronization systems are used in modern FELs like FLASH and will be used in the upcoming European XFEL. Their purpose is to distribute synchronization signals with femtosecond stability throughout the machine. Optical fibers are used to transport the pulses carrying the timing information to their end-stations. These fibers have to be continuously delay stabilized in order to achieve the desired precision. In this paper, a photodiode-based detector to measure the drifts of the fiber delay and allows their active correction is presented. Promising results from a first prototype setup of a photodiode-stabilized optical fiber link were the starting point for an engineering of this concept. An enclosure with free-space optics, fiber optics and integrated electronics for the detector, operating at 9.75 GHz, was designed. This unit includes all required parts to stabilize four fiber links. It allows to investigate the temperature sensitivity of the detector. Furthermore, results from drift measurements carried out with a two channel engineered detector are presented in this paper.

INTRODUCTION

In nowadays optical synchronization systems, pulsed lasers are widely used as so called master laser oscillator (MLO) and serve as timing reference for the synchronization system. To overcome long-term drifts, these lasers usually are phase-locked to the RF master oscillator of the accelerator. The timing information is encoded in the precise laser repetition rate and the pulses are distributed over actively delay stabilized fibers in the optical synchronization system to their end-stations. The established way of stabilizing these fiber links are optical cross-correlators, that promises an accuracy in the sub-fs range, while having some drawbacks like the need for high optical power levels or a precise dispersion compensation in the fiber link. This type of synchronization system is implemented for example at FLASH in Hamburg [1].

The alternative link stabilization setup is comprised of an optical and an electronic part, both initially built from stock components in a breadboard-type approach. The prototype for an alternative link stabilization scheme with a photodiode-based detector has now evolved towards an integrated and engineered setup. The overall system is integrated in a housing that contains four identical units and allows for the stabilization of four individual fiber links. The low optical power (below 1 mW typically) required to operate the detector makes it possible to supply four links from a single optical input signal. Additionally, some components like LO generation or an erbium-doped fiber amplifier (EDFA) are only needed once per four links.

The optical part of the setup was tested in a rapid prototyping process and will be manufactured soon. Furthermore the RF part of the detector was integrated into an engineered prototype.

The system is intended to provide optical synchronization signals to the low-level RF (LLRF) systems at FLASH and the European XFEL [2] together with a laser-to-RF (L2RF [3]) converter.

DETECTOR INTEGRATION AND MEASUREMENT PRINCIPLE

Detailed information on the detection principle and the general setup can be found in [4]. A block diagram of the detector is presented in Fig. 1.

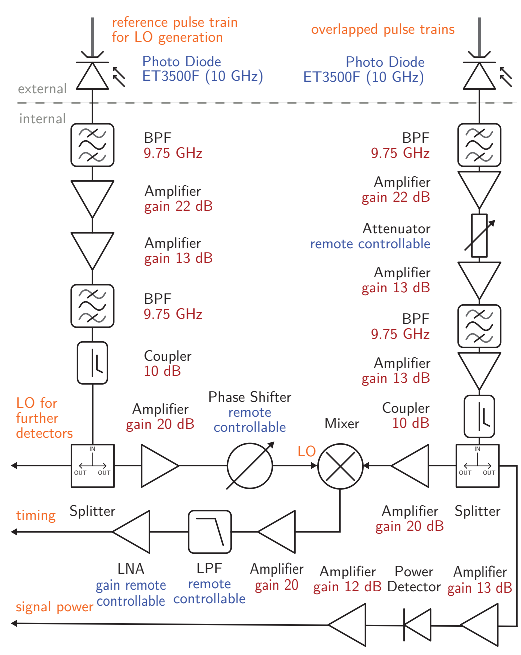

Figure 1: Block diagram of one channel of the engineered detector.

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The integrated detector includes all RF components and amplifiers, but not the photodiodes, that are still connected externally for flexibility reasons. The frequency tracked in the setup is at 9.75 GHz which corresponds to the 45th harmonic of the laser repetition rate. The observed harmonic is filtered out of the frequency comb from the photodiode signal. Furthermore the signals are amplified. Remote controllable attenuators allow precise adjustment of power levels. The LO phase can be tuned by an also remote controllable phase shifter. Behind the mixer, an amplifier with remote selectable gain and a low-pass filter with selectable cut-off frequency are located.

The detection principle is based on destructive interference of two RF-signals. The phase-stable pulse train from the MLO is split in a free space optical setup into three signals. One signal serves as LO signal for the integrated RF mixer, the second one is used as a phase stable reference signal. The last signal is traveling down the fiberlink, partly reflected at the link end and traveling back the fiber. At the beginning, this signal is combined with the phase stable reference signal onto a broadband photodiode and transfered to the electrical domain. As mentioned previously, one RF frequency (9.75 GHz) is extracted with a band pass filter from the frequency comb. The optical power of both, reference and link pulse train are adjusted to be equal, thus the two signals cancel out each other in the electrical domain if they have a phase relation of 180 deg.

The two channels of the integrated detector are completely independent, except for the LO, which is shared for both of them. The layout already foresees a four channel configuration, that would stabilize 4 links located in a single housing. The detector footprint is small compared to the test setup. The remote controllable components allow automated operation through the accelerator control system. A power detector for automated calibration and adjustment is also included.

MEASUREMENT RESULTS

The measurement accuracy that can be reached by the setup is limited by the noise floor of the detector. Therefore it can be characterized by measuring the output baseband noise spectrum of the detector. Integration of this curve reveals the rms voltage noise at the detector output. A previously obtained calibration constant of $K_\varphi = 2.04\,\mathrm{mV/fs}$ is used to convert this number to timing jitter. The calibration is obtained by moving a free space optical delay line in the link and recording the detector output.

The upper plot in Fig. 2 shows the output voltage spectral density, once without filtering at the output (blue curve) and once with the integrated low pass filter set to a cut-off frequency of 10 kHz (green curve). The lower plot shows the integral, which is already converted to femtoseconds here. The numbers on top indicate the corresponding timing jitter in femtoseconds per decade. The single spike degrading the performance around 86 kHz is caused by an internal switched capacitor voltage converter and will be addressed in the next revision.

The noise of the unfiltered output is found to be 1.85 fs in the frequency range of 10 Hz to 100 MHz. With the low pass filter enabled, this value goes down to 0.15 fs. As the piezo stretcher involved in the link stabilization has its first resonance around 18 kHz this bandwidth is considered to be reasonable for the detector.

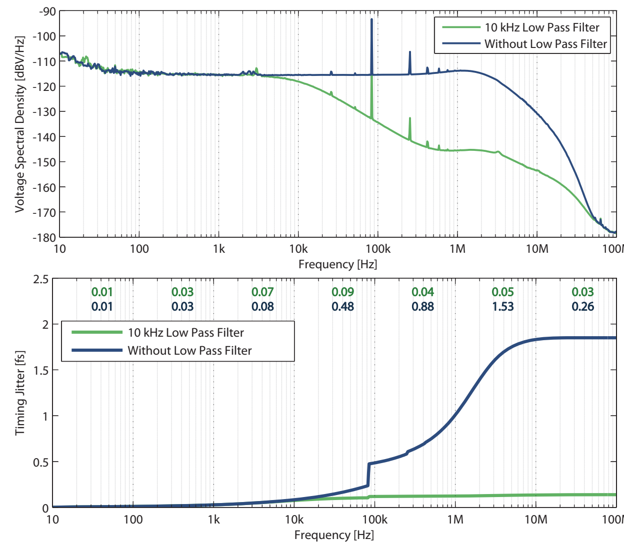

Figure 2: Baseband noise floor measured at the detector output, integrated and converted to timing jitter.

The temperature sensitivity of the setup has also been investigated. For this, the link fiber and the Faraday Rotating Mirror (FRM) at its end are completely removed. The light is now reflected directly in the free-space part of the detector. Without any link fiber, drifts observed in a long-term measurement will now reveal imperfections of the detector. In this particular case, the drifts observed are well correlated with the temperature change of the setup, thus a temperature coefficient can be calculated from this measurement. In Fig. 3 the detector output converted to femtoseconds (left axis) and the temperature of the electronics (right axis) are presented. The correlation coefficient between these two data traces calculates to 0.81 which confirms the drifts being mainly caused by temperature changes of the setup.

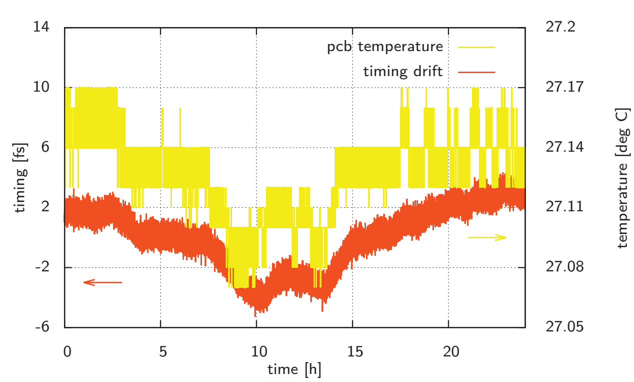

Figure 3: Drift and temperature changes of the detector, link removed for this measurement.

The calculated temperature coefficient amounts to 96 fs/deg C at the detector. This includes the optical setup, which in this case is the breadboard setup, the integrated detector, the photodiodes as well as the fibers connecting the photodiodes to the setup. The fibers are also much longer (about 1.5 m) as it will be needed in an integrated setup. Given the circumstances which are worse than the planned, completely integrated setup, the results are excellent. Taking into account, that the peak-to-peak temperature variations in the synchronization hutch at FLASH are in the order of 0.05 deg C and only half of an potential timing error would appear at the link end, this scenario leads to an expected peak to peak temperature drift of 2.4 fs.

To investigate the overall performance of the system, the detector is set up with a fiberlink. The setup is the same as in [4]. One channel is used to measure the in-loop drift of this link, while the second one is connected as out-of-loop measurement at the link end. In order to compare both signals the in-loop result has to be divided by a factor of two because the light passes the link fiber twice. Therefore this special configuration will reveal detector drifts.

The optical power on both photodiodes is in the order of 1 mW. The RF attenuators in the detector are used to attenuate the signals which lowers the K_φ. In order to achieve an equal measurement range for both channels, the out-of-loop K_φ is roughly chosen to be a factor of two larger compared to the in-loop one. The calibration constants for both channels are measured with $K_{\varphi,\mathrm{in}} = 1.9$ mV/fs and $K_{\varphi,\mathrm{out}} = 4.1$ mV/fs. The measurement result is shown in Fig. 4. The measurement covers a time span of 24 h, which for FLASH corresponds to three shift periods, while the error between in-loop and out-of-loop detector calculates to 8.4 fs. This is well within the design goal of 10 fs.

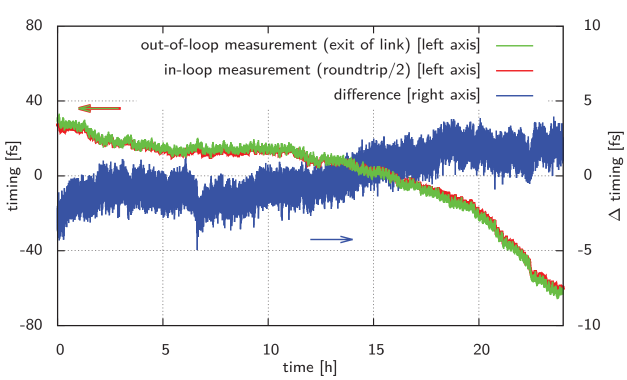

Figure 4: Longterm drift measurement, in-loop and out-of-loop signal (left axis), error between channels (right axis).

The data for all drift measurements is taken with a 14-bit ADC, reading 2048 data points every second with a sampling rate of 1 MHz. The average of those 2048 points is plotted and analyzed afterwards.

PROBLEMS AND OPEN QUESTIONS

One issue with the detector was for example LO crosstalk, that was for the second channel 15 dB higher compared to the first one. This issue was identified to be caused by a different internal shielding concept between RF components. Problems like this crosstalk or the insufficiently filtered voltage converter previously mentioned will be addressed in the next revision, that is also meant to to extend the detector to the final four channel configuration.

In order to obtain accurate results concerning the final performance measurements with a locked link have to be carried out. The error suppression of this scheme, already discussed in [4], is degrading if the detector is out of his working point. Therefore a locked link, that is actively controlled to be in his working point will show a better error suppression, compared to a link drifting out of his working point. It is supposed to give better measurement results compared to the drift measurements presented in this paper, but this assumption has to be verified.

SUMMARY AND OUTLOOK

The design of the four channel optical setup is finished and production of the first prototypes is about to start. This engineered version will also introduce a couple of improvements over the still used breadboard setup. This includes, higher mechanical stability, smaller footprint, higher optical efficiency, and full automation with motorized delay and waveplates. This will also enable automatic working point adjustment as well as calibration and long-term measurements without user interaction.

The results from these first measurements show that the performance of the integrated detector is within the targeted sub-10 fs accuracy. For a photodiode-based system 8.4 fs drift over 24 h are extremely good, while the noise floor of 0.15 fs within the 10 kHz bandwidth allows for accurate measurements.

As soon as the engineered optical setup is produced, careful tests concerning active link stabilization will be carried out in order to finalize the design.

Concerning the overall system, the first modules will be installed at FLASH in autumn 2012 together with the L2RF setup.

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