RF-Based Detector for Measuring Fiber Length Changes with Sub-5 Femtosecond Long-Term Stability.

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FEL 2009, Liverpool, United Kingdom
**Goal:** Synchronization system with a long-term stability of sub-10 fs

- Modelocked Erbium-doped Master Laser Oscillator with 216 MHz repetition rate
- Distribution of the laser pulses to 14 endstations using optical fiber links
- Link stabilization with optical cross correlator (OCC)
- Endstations like beam arrival-time monitor (BAM), two-color OCC or local RF generation (Sagnac loop)
Motivation for RF-Based Detector.

Optical Cross Correlator and Conventional RF-Phase Detector

Optical Cross Correlator:

- Necessary: Exact pulse overlap, dispersion compensation, feedback
  ⇒ Rather complex, cost intensive but allows fs or < fs resolution.

  Femtosecond timing not required for most endstations

Conventional RF-phase detector:

- Limitations: AM to PM, offset drifts of the mixer, thermal phase drifts of the photo detection process and the filter
  ⇒ Long-term drift $\sim 50 - 100$ fs

Alternative solution:

- Amplitude measurement of high harmonics of the interference pattern of two superimposed pulse trains.
  ⇒ Less complex, less expensive system
**Frequency Spectrum of the Photodiode Output.**

**Basics**

- Laser pulse train leads to a frequency comb
- Frequency lines are spaced by \( f_0 = 1/T_0 \)
- The superposition of two laser pulse trains \((I_1 = I_2)\) leads to:
  - \(\Rightarrow\) Modulated frequency comb
  - \(\Rightarrow\) Modulation of the \(n^{th}\)-harmonic: \(I(n f_0) \propto \cos^2(\pi n f_0 \Delta t)\)
  - \(\Rightarrow\) Intensities of the harmonics depend on the temporal offset \(\Delta t\)
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![Graph showing intensity vs. time and frequency](attachment:image.png)
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![Graph 1](image1.png)

![Graph 2](image2.png)
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Frequency Spectrum of the Photodiode Output.

Basics

- With the observation of one harmonic a change of the temporal offset is possible
- Change of the observed harmonic \( n \)-times larger for the \( n^{th} \)-harmonic
- Observing two harmonics separated by a minimum resp. maximum of the modulation eliminates amplitude dependence

\[
I \propto \cos^2 (\pi n f_0 \Delta t) - \cos^2 (\pi (n + 1) f_0 \Delta t)
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![Graph](image-url)
**Detection Principle**

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Optical Part.

Schematics of the Superposition of the both Pulse Trains

- Laser
- 50/50 FRM
- ~20m
- collimator 1
- 2
- b
- 3
- half wp
- quarter wp
- movable mirror
- detector inloop
- to end-station
Optical Part.

Schematics of the Superposition of the both Pulse Trains

- Laser
- half wp 1
- collimator 1
- half wp 2
- collimator 2
- quarter wp 3
- movable mirror
- detector inloop
- detector outloop
**RF-Part.**

Balanced Detection Scheme.

- Photodiode with 10 GHz bandwidth
- Power-detector: Zero Bias Schottky Detector
- ADC with 1 MHz sampling rate and a bandwidth of 40 MHz
Calibration.

The Voltage Change of the Detector Channels.

2nd-order polynomial is fitted to the data to calculate the voltage into time

\[ \frac{dV}{dt} \approx 10 - 15 \frac{mV}{ps} \]

Blue: Inloop detector
44 \( f_0 = 9.53 \text{ GHz} \)

Red: Inloop detector
45 \( f_0 = 9.75 \text{ GHz} \)

Green: Outloop detector
44 \( f_0 = 9.53 \text{ GHz} \)

Black: Outloop detector
45 \( f_0 = 9.75 \text{ GHz} \)
**50 h Long-term Measurement.**

Balanced Time Change of the Inloop and Outloop Detector

\[ t_{1,2} = \frac{1}{2} (t_{9.53 \text{ GHz}} + t_{9.75 \text{ GHz}}) \]

**Red:** Inloop detector

\[ t_{pp} = 1.24 \text{ ps} \]

**Black:** Outloop detector

\[ t_{pp} = 0.61 \text{ ps} \]

Inloop detector measures fiber length changes twice

Measurement bandwidth:

500 Hz
50 h Long-term Measurement.

Time Difference of the Inloop and Outloop Detector

\[ \Delta t = \frac{1}{2} t_1 - t_2 \]

Peak-to-peak of the time difference:
\[ t_{pp} = 20 \text{ fs} \]

Standard deviation of the time difference over 50 h:
\[ \Delta t = 4.6 \text{ fs} \]

Resolution of one detector:
Blue: \( t_{Res} = 3.2 \text{ fs} \)

Measurement bandwidth:
Blue: 500 Hz
Red: 10 mHz
Application of the Detector

Length Change Measurement of PSOF Link

Temperture change for the fiber $\Delta T = \pm 3^\circ C$

$t_{pp} = 55 \text{ fs} @ \pm 3^\circ C$, link length $\sim 20 \text{ m}$

$T_k = 0.4 \text{ fs/m K}$

$\Delta t = 3 \text{ fs (RMS)}$

$t_{Res} = 2.1 \text{ fs (RMS)}$
Conclusion and Outlook.

- New detection principle based on interference pattern of two superimposed pulse trains.
- Drift-free because of the use of only one photodiode and an amplitude measurement instead of a phase measurement.
- Long-term resolution over 50 h of 3.2 fs could be achieved.

- Try to use the scheme for longer fiber links.
- Comparison with the optical cross correlator.
- Install a stabilized link to connect the photo injector laser at FLASH to the synchronization system.
Acknowledgements.

On behalf of the FLASH-LbSyn-Team and involved DESY-Groups

Thank you for your attention!