Large Scale Femtosecond Timing Distribution and RF-Synchronization

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I. Master Oscillator

II. Timing stabilized Links

III. Optical-Synchronization

IV. RF-Synchronization

Master oscillator
Mode-locked laser

Microwave Oscillator

Photo-Inj. $\Delta t = 10$ fs

HHG-Seed $\Delta t = 10$ fs

Opt. Probe $\Delta t = 10$ fs

RF-components, GHz $\Delta t = 10$ fs

Pulsed Klystron

Gun

LINAC

Undulator

Fs X-rays

Max timing jitter in each section $\Delta t$: 10 fs $\sim$ 3$\mu$m
Demands on Optical Timing Distribution

- 4-th Generation Light Sources demand increasingly precise timing
  
  today $\ll 100$ fs, in 3 years: $< 10$fs , in 6 years: $< 1$fs, ?
  
  $\rightarrow$ Scalability to these levels should be possible!

- Must serve multiple locations separated by up to 1-5 km distances.

- This is beyond what a direct RF-distribution system (coaxial cables) can handle
  
  - thermal drifts of coaxial cables
  - drifts of microwave mixers
  - etc.

- It will lead to a considerable reduction in cost and space!
Synchronization System Layout

1. Low-noise microwave oscillator
2. Low-jitter modelocked laser
3. Fiber couplers
4. Optical to RF sync module
5. Optical to optical sync module

- Master laser oscillator
- Optical to RF sync module
- Optical to optical sync module
- Laser
- Fiber couplers
- Stabilized fibers

low-bandwidth lock

www.rle.mit.edu
Why Optical Pulses (Mode-locked Lasers)?

- RF is encoded in pulse repetition rate, every harmonic can be extracted at the end station.
- Suppress Brillouin scattering and undesired reflections.
- Optical cross correlation can be used for link stabilization or for optical-to-optical synchronization of other lasers.
- Pulses can be directly used to seed amplifiers at end stations.
- Group delay is directly stabilized, not phase delay as would be the case in an interferometric link stabilization. (For L=1km, and 1° C, \( \tau_{\text{phase}} - \tau_{\text{group}} > 10\text{fs} \), Polarization Mode Dispersion: 0.01-0.1ps/Sqrt[km])
Highly Stable Microwave Oscillator
Microwave Master Clocks

Typical Phase Noise of PSI SLCO-BCS at 10.240 GHz

This graph shows TYPICAL PHASE NOISE offset from a 10.240 GHz carrier.

Guaranteed noise is as per specifications.

Consult PSI for noise at other frequencies

Timing jitter: \[ \Delta t_{rms} = \frac{\sqrt{2 \int_{f_1}^{f_2} L(f) df}}{2\pi f_0} \]

< 1fs
Optical Master Oscillator

A master mode-locked laser producing a very stable pulse train

Low-noise microwave oscillator

Master laser oscillator

fiber couplers

stabilized fibers

Optical to optical sync module

Optical to RF sync module

Optical to RF sync module

remote locations

low-level RF

Laser
Er-Fiber Laser

Phase Noise (Timing Jitter) Measurements

- Noise floor limited by photo detection
- Theoretical noise limit <1 fs

\[ \Delta t_{\text{rms}} = \frac{\sqrt{2 \int_{f_1}^{f_2} L(f) \, df}}{2\pi f_0} \]

\[ \Delta t_{\text{rms}}[10\text{kHz}, 22\text{MHz}] = 10\text{fs} \]

\[ f_0 = 1.3\text{GHz} \]
System Test in Accelerator Environment

- Test done at MIT Bates Laboratory:
  - Locked EDFL to Bates master oscillator
  - Transmitted pulses through 400 meter partially temperature stab. fiber link
  - Close loop on fiber length feedback

~ 500 meters
RF-Transmission over Stabilized Fiber Link

- Passive temperature stabilization of 500 m
- RF feedback for fiber link
- EDFL locked to 2.856 GHz Bates master oscillator
Fiber link extremely stable without closing loop (60 fs for 0.1 Hz…5 kHz)
Closing feedback loop reduces noise (12 fs for 0.1 Hz .. 5kHz)
No significant noise added at higher frequencies

(2-4) jitter: < 22 fs
Phase Noise (Jitter) of Transmitted Signal

- Jitter between Bates MO and optical master laser ~30 fs (10 Hz..2 kHz)
- Jitter added by Link < 22fs
- Total jitter added (1- 4 ) < 52 fs
How to improve on these results and make it long term stable?

Transition from microwave to optical techniques
Optical to RF-Conversion

- Low-noise microwave oscillator
- Master laser oscillator
- Low-bandwidth lock
- Fiber couplers
- Stabilized fibers
- Optical to RF sync module
- Remote locations
- Optical to optical sync module
- Laser
- Low-level RF
Direct Extraction of RF from Pulse Train

$T_R = 1/f_R$

Optical Pulse Train
(time domain)

Amplitude-to-phase conversion introduces excess timing jitter.

Amplitude to Phase Conversion Measurement

Typical AM-to-PM:
1 – 10 ps/mW

RIN~0.04% (10kHz-22MHz)
→ $\Delta t_{\text{excess}} \sim 5-20$ fs

Conversion of optical signal into electronic signal is the major bottleneck in signal properties (noise, stability, and power).

Limitations in direct photodetection
1. Amplitude-to-phase conversion
2. Limited SNR by small-area high speed detector
3. High temperature sensitivity of photodiode

Consistent with NIST result
Optical/Electrical Phase-Locked Loop (PLL)

Can we regenerate a high-power, low-jitter RF-signal whose phase is locked long term stable to the optical pulse train?

Implementation of optical-RF phase detectors for high-power, low-jitter and drift-free RF-signal regeneration
Sagnac-Loop for Electro-Optic Sampling

$\Delta \Phi = \text{phase difference between counter-propagating pulses in the Sagnac-loop}$

$T_R = 1/f_R$

Phase Modulator

50:50 coupler

Output power

$\pi - \pi$

No phase modulation

$T_{M/2}$
Sagnac-Loop for Electro-Optic Sampling

$\Delta \Phi = \text{phase difference between counter-propagating pulses in the Sagnac-loop}$

$T_R = 1/f_R$

Phase Modulator

50:50 coupler

Freq divided by 2

$\pi - \pi$

Output power

Synchronous modulation

Output
Sagnac-Loop for Electro-Optic Sampling

\[ \Delta \Phi = \text{phase difference between counter-propagating pulses in the Sagnac-loop} \]

\[ T_R = \frac{1}{f_R} \]

When a phase error between pulses and RF-source exists, the amplitude modulation depth is proportional to the phase error. 

\[ \text{Output power} \sim \frac{f_R}{2} \sim Nf_R \]

\[ 50:50 \text{ coupler} \]

External RF-source with phase error \( \theta_e \)
Sagnac-Loop for Electro-Optic Sampling

Phase Modulator

Pulse train input

\[ T_R = \frac{1}{f_R} \]

Amplitude modulation depth is proportional to the phase error.

Output

To read out amplitude modulation depth in the baseband.

Freq divided by 2

\[ \frac{f_R}{2} \]

\[ \sim N f_R \]

VCO

50:50 coupler

Phase Modulator

\[ \frac{f_R}{2} \]
Sagnac-Loop for Electro-Optic Sampling

\[ \Delta \Phi = \text{phase difference between counter-propagating pulses in the Sagnac-loop} \]

When the RF-source is locked (\( \theta_e = 0 \))

\[ \theta_e \]

\[ 0 \]

\[ \pi \]

\[ -\pi \]

\[ f_{R/2} \]

\[ N_{f_R} \]

\[ \text{Locked VCO} \]

\[ \text{Phase Modulator} \]

\[ \text{Output power} \]

\[ 50:50 \text{ coupler} \]

\[ T_R = 1/f_R \]
Balanced Optical-RF Phase Detector

- Capable of driving high-power VCO → High-power regenerated RF-signal
- Scalable phase detection sensitivity → Low-jitter synchronization
- Fiber-based “balanced” scheme → Long-term drift-free operation
Demonstration Experiment
In-Loop Phase Noise Measurement

Residual timing jitter = 3 fs ± 0.2 fs (1Hz-10MHz)
Scalability in Phase Detection Sensitivity

Scalable Phase Detection Sensitivity

\[ K_d = \frac{V_d}{\theta_e} \propto P_{\text{avg}} \Phi_0 \Phi_m \]

Shot Noise Floor Scalability

\[ S_{\Phi,\text{shot}} = \frac{<V_{\text{shot},\text{mix}}^2>}{K_d^2 / N^2} = \frac{8q}{RP_{\text{avg}} \Phi_0^2} \]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(P_{\text{avg}})</td>
<td>Optical power circulating Sagnac-loop</td>
<td>10 mW</td>
</tr>
<tr>
<td>(\Phi_0)</td>
<td>Phase modulation depth from VCO signal</td>
<td>0.4 rad</td>
</tr>
<tr>
<td>(\Phi_m)</td>
<td>Phase modulation depth from synchronous signal</td>
<td>0.2 rad</td>
</tr>
<tr>
<td>(R)</td>
<td>Photodetector responsivity</td>
<td>0.9 A/W</td>
</tr>
<tr>
<td>(q)</td>
<td>Electron charge</td>
<td>(1.6 \times 10^{-19}) C</td>
</tr>
</tbody>
</table>

Shot noise limited jitter = 0.5 fs (currently limited by other noise sources)

\(\rightarrow\) Scalable by increasing optical power and RF modulation depth
Optical to Optical Synchronization

- Master laser oscillator
- Low-noise microwave oscillator
- Fiber couplers
- Stabilized fibers
- Optical to RF sync module
- Remote locations
- Optical to optical sync module
- Low-level RF
- Low-noise microwave oscillator
- Laser
Balanced Optical Cross-Correlation

Output (650-1450nm) → SFG → Jitter Analysis

Cr:fo

Ti:sa

(1/496nm = 1/833nm+1/1225nm).

Rep.-Rate Control

Measured 0.3 fs jitter in 10mHz to 2.3 MHz
Long-Term Locking Between Two Lasers
(Out of Loop Measurements)

>12 hours long-term stability in timing lock (380 as ± 130 as jitter)

intentionally broke the lock
Timing stabilized fiber links
Timing-Stabilized Fiber Links

Assuming no fiber length fluctuations faster than $T=2nL/c$.

$L = 1 \text{ km, } n = 1.5 \implies T=1 \mu s, \quad f_{\text{max}} \sim 100 \text{ kHz}$

K. Holman, et al. Opt. Lett. 30, 1225 (2005); < 40 fs in 1Hz-100kHz
Summary

- Ultrashort pulse trains from mode-locked lasers have excellent phase/timing noise properties.
- They can be used as optical master oscillators
- Optical/Electrical PLLs: Balanced optical-RF phase detectors are proposed for femtosecond and potentially sub-femtosecond optical to RF-synchronization.
- Optical/Optical Synchronization: Based on balanced optical cross-correlation. Long term stable sub-femtosecond precision is already achieved.
- Together with timing stabilized fiber links a (sub-) femtosecond timing distribution and synchronization system for 4th generation light sources can be accomplished.