An Integrated Femtosecond Timing Distribution System for XFELs

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4th Generation Light Sources: XFEL

Master Oscillator

Optical master oscillator
Mode-locked laser

Frequency Standard

Timing-Stabilized Link

Optical-Synch.

Timing stabilized fiber links

High-power Few-cycle lasers

RF-Synch.

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 \(\sim 3\mu m\)

4th Generation Light Sources: XFEL

High-power Few-cycle lasers
Demands on Optical Timing Distribution

- 4-th Generation Light Sources demand increasingly precise timing
today << 100 fs, in 3 years: < 10fs, in 6 years: < 1fs?
  → 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 (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!
1. Optical Master Oscillator

A master mode-locked laser producing a very stable pulse train (can be locked to a microwave oscillator for long-term stability)
Why Optical Pulses (Mode-locked Lasers)?

- RF signal is encoded in the pulse repetition rate.  
  \( \Rightarrow \) Every harmonic can be extracted.
- Suppress Brillouin scattering and undesired reflections.
- Optical cross-correlation can be used for timing stabilization.
- Pulses can directly seed amplifiers.
- Group delay is directly stabilized.
Er-Fiber Laser


Er-fiber (normal dispersion)

anomalous dispersion fiber

Output

Footprint can fit into Letter-size
Phase Noise (Timing Jitter) Measurements

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

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

\( \Delta t_{rms}[10kHz,22MHz] = 10 \text{ fs} \)
2. Timing-Stabilized Fiber Links

Stabilized fiber links delivering the pulse train to multiple remote locations

- Master Laser Oscillator
- Optoelectronic conversion
- Low-noise microwave oscillator
- Optoelectronic conversion
- Fiber couplers
- Stabilized fibers
- Regenerated RF-signal
- Low-bandwidth lock
System Test in Accelerator Environment

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

For more info: A. Winter et al, FEL 2005
F. Ö. Ilday et al, CLEO 2006
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
Jitter: Timing Stabilized Fiber Link

- Fiber link extremely stable even for open loop (60 fs for 0.1 Hz-5 kHz)
- Closing feedback loop reduces noise (12 fs for 0.1 Hz-5 kHz)
- No significant noise added at higher frequencies
3. Optical-to-RF Synchronization

Converting optical pulse train to RF-signal at remote locations

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

Low-bandwidth lock
Direct Extraction of RF from Pulse Train

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

Optical Pulse Train (time domain)

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

Typical AM-to-PM:
\[ 1 \text{–} 10 \text{ ps/mW} \]
Consistent with NIST result Bartels et al, OL 30, 667 (2005).

BPF Photodiode LNA

Phase

\[ f_R, 2f_R, nf_R, (n+1)f_R \]

\[ f \]

\[ nf_R \]
Optoelectronic Phase-Locked Loop (PLL)

Can we regenerate a high-power, low-jitter and drift-free RF-signal whose phase is locked 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

ΔΦ = phase difference between counter-propagating pulses in the Sagnac-loop

50:50 coupler

Phase Modulator

Output power

Output

Pulse train input

TR = 1/fR

No phase modulation

π - π

Output power vs. ΔΦ
Sagnac-Loop for Electro-Optic Sampling

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

Phase Modulator

FREQ divided by 2

50:50 coupler

Output power

Synchronous modulation

$T_R = 1/f_R$
Sagnac-Loop for Electro-Optic Sampling

Phase Modulator

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

\[ T_R = 1/f_R \]

Output power

When a phase error between pulses and RF-source exists.

Amplitude modulation depth is proportional to the phase error.

\[ \theta_e \]

Output

\[ f_{R/2} \]

\[ \sim N f_R \]

External RF-source with phase error \( \theta_e \)

Freq divided by 2

50:50 coupler

\[ \Delta \Phi = \pi \]
Amplitude modulation depth is proportional to the phase error.

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

Frequency divided by 2

\[ f_R/2 \sim N_f R \]

To read out amplitude modulation depth in the baseband.
Sagnac-Loop for Electro-Optic Sampling

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

\[ T_R = 1/f_R \]

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

\[ \text{Phase Modulator} \]

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

\[ \text{Output power} \]

\[ f_{R/2} + N_{f_R} \sim \text{Locked VCO} \]
Demonstration Experiment
In-Loop Phase Noise Measurement

Residual timing jitter = 3 fs ± 0.2 fs (1Hz-10MHz)
4. Optical-to-Optical Synchronization

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

Output (650-1450nm)

Cr:fo

Ti:sa

Rep.-Rate Control

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

SFG

GD

Jitter Analysis

Measured 0.3 fs jitter from 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
Summary and Outlook

- **Optical master oscillator**: Ultrashort pulse trains from mode-locked lasers have excellent phase/timing noise properties. (~10 fs → <1 fs)

- **Timing-stabilized fiber links**: Initial demonstration in the accelerator environment. Optical cross-correlation system in progress for low-jitter, drift-free operation. (~10 fs → <1 fs)

- **Optical-to-RF synchronization**: Balanced optical-RF phase detectors are proposed for femtosecond and potentially sub-femtosecond optical-to-RF synchronization. (~3 fs → <1 fs)

- **Optical-to-optical synchronization**: Balanced optical cross-correlation. Long term stable sub-femtosecond precision is already achieved. (<1 fs)

A (sub-)femtosecond timing distribution and synchronization system for 4th generation light sources can be accomplished.
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
Commercial Low-Noise Microwave Oscillators

- Very good microwave oscillators are commercially available for low phase noise in the low frequency range (< 1 kHz).
- Eventually can lock to an optical standard for μHz-level stability.
Why Optical Pulses (Mode-locked Lasers)?

- RF encoded in pulse repetition rate, every harmonic can be extracted.
- Suppress Brillouin scattering and undesired reflections.
- Optical cross correlation can be used for link stabilization or for optical-to-optical synchronization with 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, $\tau_{\text{phase}} - \tau_{\text{group}} > 10$fs, Polarization Mode Dispersion: 0.01-0.1ps/√km)
Timing-Stabilized Fiber Links

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

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

K. Holman, et al. Opt. Lett. 30, 1225 (2005); < 40 fs in 1Hz-100kHz
Amplitude-to-Phase Conversion Measurement

Typical AM-to-PM: 1 – 10 ps/mW

RIN~0.04% (10kHz-22MHz) → Δt_{excess}~ 5-20 fs

Consistent with NIST result

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

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

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

<table>
<thead>
<tr>
<th>Symbol</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>1.6x10^{-19} C</td>
</tr>
</tbody>
</table>

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

\[ \rightarrow \text{Scalable by increasing optical power and RF modulation depth} \]
Balanced Cross-Correlator

Output
(600-1500nm)

Cr:fo

Ti:sa

PZT driver

Loop Filter

(1/500nm = 1/833nm + 1/1250nm).

Fused Silica