Outline

Part II

- Femtosecond to attosecond precision timing distribution for large scale facilities: Example X-ray FEL
- Synchronization system layout for a seeded X-ray FEL
  - Advantages of a pulsed optical distribution system
  - Timing jitter of femtosecond lasers
  - Timing distribution over stabilized fiber links
  - Optical-to-optical synchronization
  - RF-Extraction and locking to microwave references
- Outlook: Photonic ADCs
Next Generation X-ray Source Schematic

(Seeded, high repetition rate X-Ray FELs)

Pulsed Klystron

Photo-injector Laser

Low-Level RF Systems

High-Level RF Systems

Seed Laser

Probe Laser

Electron Gun

Linear Accelerator

Undulator

300 m - 3 km

Today long-term sub-10 fs synchronization over entire facility desired.

Tomorrow sub-fs synchronization will be required.

Seeding with various schemes demonstrated:

For lasers the challenge comes with high repetition rates
Pulsed femtosecond timing distribution

Optical Master Oscillator Mode-Locked Laser

Microwave/Optical Standard

Timing Stabilized Optical Fiber Links

Optical-to-RF Synchronization
Pulsed Klystron

Optical-to-Optical Synchronization
Photo-Injector Laser

Optical-to-RF Synchronization
Low-Level RF Systems

Optical-to-Optical Synchronization
Seed Laser

Optical-to-Optical Synchronization
Probe Laser

Electron Gun

Linear Accelerator

High-Level RF Systems

Undulator

fs x-ray pulses


Other approaches: R. Wilcox, LBNL, cw-distribution, or post stamping
Timing jitter of femtosecond lasers

Electronic Oscillator

Femtosecond Laser

Optical Cavity

Dissipation-Fluctuation Theorem

\[ \frac{d}{dt} < \Delta t_R^2 > \approx T_0^2 \cdot \frac{1}{W_{mode}} \cdot \frac{kT}{\tau_{cav}} \]

period ~100ps
cavity lifetime

Pulse width ~100fs

\[ \frac{d}{dt} < \Delta t_M^2 > \approx \tau^2 \cdot \frac{1}{W_{pulse}} \cdot \frac{\hbar \omega_c}{\tau_{cav}} \]

\( \hbar \omega_c \sim 50kT \)

\( kT = \) thermal energy

\( \hbar \omega_c = \) photon energy

Why Optical Pulses (Mode-locked Lasers)?

- **Real marker in time and RF domain**, 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, EO-sampling, ….**
- **Group delay is directly stabilized**, not optical phase delay.
- After power failure system can **auto-calibrate!**

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

\[ f \quad 2f \quad Nf \]

\[ f_R \quad 2f_R \quad Nf_R \]
Single-Crystal Balanced Cross-Correlator


Type-II phase-matched PPKTP crystal

Transmit fundamental
Reflect SHG

Reflect fundamental
Transmit SHG

Type-II phase-matched PPKTP crystal

Transmit fundamental Reflect SHG

Reflect fundamental Transmit SHG
Single-Crystal Balanced Cross-Correlator

Type-II phase-matched PPKTP crystal

Transmit fundamental
Reflect SHG

Reflect fundamental
Transmit SHG
Single-Crystal Balanced Cross-Correlator

In comparison:
Typical microwave mixer
Slope ~1 \( \mu \text{V/fs} @ 10 \text{ GHz} 
Greatly reduced thermal drifts!

80 pJ, 200 fs
1550nm input pulses
at 200 MHz rep. rate

200 MHz Soliton Er-fiber Laser

- 167 fs pulses
- 200 pJ intracavity pulse energy
- 50% loss

Timing Jitter of Fiber Lasers

Phase detector method $\rightarrow$ Timing Detector method

Modelocked Laser 1

Modelocked Laser 2

HWP

PBS

Single crystal balanced cross-correlator

Detector output

RF-spectrum analyzer

Oscilloscope

Detector output

Time delay (fs)

Timing Jitter in Stretched Pulse Lasers

80 MHz Er-fiber Stretched Pulse Laser

- 3 fs rms [100 kHz, 40 MHz]
- Additional noise present at $f_{\text{rep}}/2$ and $f_{\text{rep}}/4$

How do we get to Attosecond Jitter Lasers?

\[ \frac{d}{dt} < \Delta t_{ML}^2 > \approx \tau^2 \cdot \frac{1}{W_{\text{pulse}}} \cdot \frac{h\omega_c}{\tau_{\text{cav}}} \]

Solid-state lasers

Intracavity losses down (Factor of 50)

Intracavity energy up (Factor of 50)

10-fs pulses (Factor of 100)

\[ \sim 10^6 \]

Is it true?
Two 10-fs Ti:Sapphire Lasers Synchronized within 13 as

Ref @ 10 GHz
Timing jitter of OneFive:Origami Laser

Phase Noise @ 10GHz (dBc/Hz)

Jitter Spectral Density (fs²/Hz)

Noise Floor

Integrated Jitter at [f, 1MHz] (fs)

f > 15 kHz

Timing - Stabilized Fiber Links
Timing-stabilized fiber links

Cancel fiber length fluctuations slower than the pulse travel time (2nL/c).

1 km fiber: travel time = 10 µs \( \rightarrow \) \( \sim \)100 kHz BW
1-week operation with SMF/DCF

Timing Link System Performance

5 fs (rms) drifts over one week of operation

FLASH, FERMI, and tests at PAL and LCLS (2008-2014)
Clocking the European XFEL

High precision PM-link developed jointly with OFS

- Fiber 1: Std. PM 1550, Length: 4m
- Fiber 2: Std. PM 1550, Length: 2946m
- Fiber 3: Bridge Fiber, Length: 2m
- Fiber 4: PM DCF, Length: 511m
- Fiber 5: Bridge Fiber, Length: 2m
- Fiber 6: Bridge Fiber, Length: 19m
- Fiber 7: Std. PM 1550, Length: 3m

Dispersion-compensating PM Fiber
D = -102.5 ps/nm·km @1550nm, slow axis
D' = -0.33 ps/nm²·km, slow axis

High precision PM-link results (OFS)

Laser-to-Laser Remote Synch.: 100 as RMS & 0.6 fs Pk-Pk drift (< 1Hz) over 44 h

- Outloop Drift (fs)
- Rel. Temperature (K)
- Time (hours)
- Rel. Humidity (%)
Optical-to-Optical Synchronization
Ti:sapphire Laser + Cr:Forsterite Laser

Spanning over 1.5 octaves
Sub-femtosecond Residual Timing Jitter

Balanced optical cross-correlator based on GDD (T. Schibli et al, OL 28, 947 (2003))

>12 hours long-term timing lock
(380 ± 130 as jitter integrated from 0.02 mHz to 2.3 MHz)

Long-term drift-free sub-fs timing synchronization over 12 hours

J. Kim et al, EPAC 2006.
Optical-to-RF Conversion
or
Optical-to-RF Locking
Excess Phase Noise in Photo Detection


**Thermal phase drift (~350 fs/K), B. Lorbeer et al, PAC 2007**

**Amplitude-to-phase conversion (~ ps/mW)**

It is difficult to stabilize the phase of microwave signals to better than 10 fs precision over many hours or days of operation.
Balanced Optical-Microwave Phase Detector

Convert Phase /Timing information in optical domain into intensity modulation

Electro-optic sampling of microwave signal with optical pulse train

Regeneration of a high-power, low-jitter and drift-free microwave signal whose phase is locked to the optical pulse train.

Tight locking of modelocked laser to microwave reference
Stability of BOM-PDs

**BOM-PD 1:** timing synchronization

**BOM-PD 2:** out-of-loop timing characterization

J. Kim et al., Optics Express 15, 8951 (2007).
Long-term stability: 6.8 fs drift over 10 hours

RMS timing jitter integrated in 27 μHz – 1 MHz: 6.8 fs


~ rf-stability $2 \cdot 10^{-19}$
### DESY Spin-Off Company
**Products: Timing & Synchronization**

**Timing Distribution Systems**
- < 1 fs synchronization of Laser and RF-Networks

**Ultrashort Pulse Synchronization**
- < 1 fs Synchronisation of two femtosecond lasers

**Laser-Microwave Synchronization**
- < 1 fs Synchronisation of microwave sources to lasers

- Accelerators and X-ray Free-Electron Lasers
- Ultrafast Laser Labs
- Radio Telescopes
- Jitter Characterization
- Low Noise Microwave Generation
Challenge in High-Speed ADCs

Voltage

\[ V_0 \]

\[ \Delta V \]

\[ \Delta t \]

\[ T_0 \]

time

\[ \frac{\Delta V}{V_0} = 2\pi \frac{\Delta t}{T_0} = \frac{1}{\sqrt{3} \cdot 2^N} \]

\[ \Delta t = \frac{T_0}{2\pi \sqrt{3} \cdot 2^N} \]

### Targeted resolution vs. Required sampling jitter

<table>
<thead>
<tr>
<th>Targeted resolution</th>
<th>10 GHz</th>
<th>50 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>14-bit</td>
<td>0.5 fs</td>
<td>0.1 fs</td>
</tr>
<tr>
<td>12-bit</td>
<td>2 fs</td>
<td>0.4 fs</td>
</tr>
<tr>
<td>10-bit</td>
<td>9 fs</td>
<td>1.8 fs</td>
</tr>
<tr>
<td>8-bit</td>
<td>36 fs</td>
<td>7.2 fs</td>
</tr>
<tr>
<td>6-bit</td>
<td>144 fs</td>
<td>30 fs</td>
</tr>
</tbody>
</table>
State of the Art Electronic ADC and Beyond

Nortel Inc.: 40 GSa/s CMOS
Y. M. Greshishchev, et al.
ISSCC, paper 21.7 (2010).

Fujitsu Inc.: 65 GSa/s CMOS
http://www.fujitsu.com

RPI: 40 GSa/s SiGe ADC

Wavelength Multiplexed Optical Sampling

- Effective sampling rate = laser rep rate \( (1/T) \) x number of multiplexed channels \( (N) \)
- Sampling jitter is set by MLL timing jitter
- Digitization is performed in electronic domain
- Down counting by WDM

Integrated Silicon Photonic ADC

Grein et al., CLEO 2011, paper CThI1
Khilo et al., Opt. Exp. (20) 4454 (2012)
Acknowledgement

Students:
M. Peng (JPL) and P. Callahan, K. Safak, A. Kalaydzyan
J. Kim (Prof. KAIST); A. Benedick and C. Sorace-Agaskar (MIT Lincoln Laboratory)
A. Khilo and M. Dahlem (both Prof. MASDAR Institute of Technology)
J. Cox (Sandia National Laboratory), M. Sander (Prof. Boston University)
A. Motamedi (INTEL)

Postdocs:
M. Xi, Q. Zhang,
T. Schibli and M. Popovic (both Prof. University of Colorado, Boulder)
F. O. Ilday (Prof. Bilkent University)

Research Scientists: O.D. Mücke, N. Chang, A. Nejadmalayeri (Samsung)

Collaborators:
Holger Schlarb and Ingmar Hartl (DESY)
E. Ippen, F. Wong, M. Watts, R. Ram, J. Orcutt (MIT)
E. Monberg, M. Yan, L. Grüner-Nielsen, J. Fini (OFS)
S. Spector, T. Lyscczarz, M. Geis, M. Grein, J. Wang, J. Yoon (MIT – Lincoln Lab.)