Sub-fs-precision, ultrafast laser-based optical and microwave timing and synchronization

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Generation of an extremely regularly-spaced ultrashort optical pulse train (close to the ideal delta-function train)

- Linear (GDD)
- Saturable absorber
- Gain
- NL (SPM)

Mode-locked (ML) laser

Femtosecond (<1 ps) pulse duration

μs – ns pulse spacing (repetition rate is in the RF/microwave frequency range)
By stabilizing $f_{\text{rep}}$ and $f_{\text{ceo}}$, a frequency comb can serve as a "clock gear" for optical atomic clocks. (Nobel Prize in Physics 2005, Ted Hänsch and John Hall)
Noise of femtosecond mode-locked lasers (intensity, frequency, phase, **timing** noise)

Optimizing and utilizing the excellent timing noise of femtosecond mode-locked fiber lasers will be the main topic of today’s talk.
Measure of noise in the time and frequency domains: Timing jitter / phase noise

**Ultrafast laser**

**Timing jitter** ($\Delta t$)
Time-domain representation of rapid, short-term, random displacement from an ideal, perfectly-periodic temporal positions

**Electronic oscillator**

**Phase noise** ($\Delta \phi$)
Frequency-domain representation of rapid, short-term, random fluctuations in the phase of a waveform, caused by time-domain instabilities (timing jitter)

\[ \Delta \varphi = 2\pi \frac{\Delta t_{RF}}{T_0} \]
Scaling of timing jitter into the **attosecond** (10^-18 s) regime

**Mode-locked laser**

\[
\frac{d}{dt} \langle \Delta t_{ML}^2 \rangle = \frac{\pi^2}{6} \cdot \frac{\tau^2}{\tau_c^2} \cdot \frac{1}{10^6 T_0^2} \cdot \frac{\hbar \omega_c}{[\text{cavity decay time}]}.
\]

\( \tau = 100 \text{ fs and below} \)

\( \hbar \omega_c = 0.8 \text{eV} \)

\( \hbar \omega_c \approx 30kT \) at 1550 nm, 300 K

\( T_0 = 100 \text{ ps for 10 GHz} \)

\( kT = 0.025 \text{ eV} \)

When quantum-noise limited,

\[ \tau^2 < \frac{1}{10^6} T_0^2 \]

**Electronic oscillator**

\[
\frac{d}{dt} \langle \Delta t_{RF}^2 \rangle = \frac{1}{(2\pi)^2} \cdot \frac{T_0^2}{10^6} \cdot \frac{1}{[\text{mode energy}]} \cdot \frac{1}{kT} \cdot \frac{\hbar \omega_c}{[\text{cavity decay time}]}.
\]

(Haus, IEEE JQE 1995; Kim and Kärtner, LPR 2009)
• In fact, without much efforts, one can immediately get sub-10-fs level timing jitter from standard, commercially-available ultrafast fiber lasers.

• We applied the idea of using an ultrafast fiber laser as an optical master oscillator (OMO) for synchronizing lasers and RF sources in X-ray free-electron lasers (XFELs).
  – First proposed by MIT Kaertner group (J. Kim et al, FEL Conference 2004)
  – Now actively researched, developed, tested, and installed at various accelerator and FEL facilities (such as DESY (FLASH and European XFEL), FERMI@Elettra, PSI, LCLS, PAL...)
Synchronization of large-scale X-ray free-electron lasers (XFELs)

Future X-ray FELs will enable **super-fine temporal (fs) and spatial (Å) resolutions** with ultra-high peak brilliance that could not be achieved before.

Requires drift-free, sub-10-fs (and **sub-fs in the future**) timing precision over the entire FEL facility.
Overview of Pulsed Optical Synchronization System

**Principle 1:** Ultralow-jitter RF/microwave is encoded in the repetition rate and the harmonics.

Can provide and synchronize *ultra-low phase noise RF signals*

\[ f_{\text{rep}} = \frac{1}{f_R} \]

If \( f_{\text{rep}} = 79.3 \text{ MHz} \), one can extract

2.856 GHz (36\textsuperscript{th} harmonic), 5.712 GHz (72\textsuperscript{nd} harmonic),

and 11.4 GHz (144\textsuperscript{th} harmonic) simultaneously at any location!
Overview of Pulsed Optical Synchronization System

** Principle 2:** Timing pulse trains can be synchronized with other femtosecond lasers (Ti:sapphire lasers) using optical cross-correlator

→ Can provide **attosecond-precision synchronization** of lasers
Overview of Pulsed Optical Synchronization System

**Principle 3:** The time-of-flight of timing pulse trains can be stabilized using optical cross-correlator

→ **Can provide stable long-distance synchronization** of lasers and RF sources.
Overview of Pulsed Optical Synchronization System

Schematic of a pulsed optical timing and synchronization system

Timing transfer over hundreds m – a few km

Use for E-O sampling, amplifier seeding, RF downconversion etc
Pervasive synchronization of an FEL with an optical master oscillator

Using ultrafast fiber laser-based technology, long-term stable sub-10 fs remote timing synchronization is possible.

**Timing-stabilized fiber link**

- **3×10^{-20} relative timing stability**

**Optical-optical synchronization**

- **9×10^{-21} relative timing stability**

**Optical-RF synchronization**

- **3×10^{-20} relative timing stability**

Through technology transfer, ultrafast fiber laser-based sub-10-fs-precision timing systems are now being actively installed.

FERMI (at Trieste, Italy) results show that robust 10-fs timing and synchronization is possible in the accelerator environment.

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...tough engineering work

2-link table-top demonstrator (left, 2007) & the engineered cross correlator (below, 2009)

Pulsed optical timing

out-of-loop long term (10 days) drift measurement; local optical reference vs. 150m loop-back stabilized link

5.3fs RMS in 10 days

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M. Ferianis, FEL 2011
Through technology transfer, ultrafast fiber laser-based sub-10-fs-precision timing systems are now being actively installed.

FERMI (at Trieste, Italy) results show that robust 10-fs timing and synchronization is possible in the accelerator environment.
DESY also successfully implemented the pulsed optical timing system independently.
PAL-XFEL optical timing and synchronization system design

OMO Room

16 (or 32)-way symmetric splitter

Fiber length stabilization

BOC

Timing transfer over 100s m to 1 km

RMO

synch

OMO fs-laser

Pump probe laser

Optical-Xray experiment

BOC

O-E conv

2.856 GHz RF signals

undulator

BOC

Local distribution

LINAC (48 cavities)

BOC

O-E conv

e-gun

injector laser
Now reliable sub-10-fs precision timing and synchronization is possible based on ultrafast lasers and techniques.

How can we further scale the timing precision and synchronization toward the sub-femtosecond regime?
I. Optimization of timing jitter of ultrafast lasers toward the sub-100-attosecond regime

II. Sub-femtosecond precision and stability synchronization of lasers and RF sources
For the optimization of timing jitter of ultrafast lasers, sub-femtosecond-resolution characterization is first required.

- Conventional direct photodetection: Resolution limit: $\sim10\text{ fs}$
Optical cross-correlation enables sub-20-attosecond resolution jitter characterization.

\[ \omega_{SFG} = \omega_1 + \omega_2 \]

Signal source analyzer

>60 dB improvement
Advantages of ultrafast fiber lasers for master oscillators

- Simple and reliable operation
- Compact and alignment-free
- Various wavelength due to rare-earth doping technology
- Enhanced environmental stability with PM technology
- Large gain due to long fiber propagation
- Diffraction-limited beam quality
Dependence of timing jitter on mode-locking regime is observed with the use of high resolution BOC method.


Stretched-pulse operation at close-to-zero dispersion may lead to the lowest timing jitter in fiber lasers!
Integrated timing jitter of Yb fiber lasers [10 kHz – 40 MHz] vs intra-cavity dispersion and mode-locked regimes
Measured lowest timing jitter spectral density of ultrafast fiber lasers \(\rightarrow\) **Sub-100-attosecond timing jitter is demonstrated**


**175-as jitter from Yb-fiber lasers:** Y. Song et al, Opt. Express **19**, 14518 (2011)

How to improve the robustness of fiber lasers?
- Real saturable absorbers in mode-locked lasers

• Self-starting operation
• Robustness and long-term stability

• Soliton mode-locking in negative GVD can stabilize a pulse.

Directly- and indirectly coupled timing jitter from ASE

\[ \Delta t_{\text{direct}} \propto (1 + \beta^2)^{3/4} \frac{\tau}{\sqrt{E_p}} \]

\[ \Delta t_{\text{indirect}} \propto |D| \cdot BW \]

Song, Y. et al, Opt. Exp. 19(15), 14518-14525 (2011);
Namiki and Haus, IEEE JQE, 33, 649 (1997);
R. Paschotta, Appl. Phys. B 79, 163 (2004);
Timing jitter of a CNT-based Er-fiber laser (which is a robust, self-starting, continuously operating commercial laser)

- **3-fs integrated timing jitter**
- **Limited by the Gordon-Haus jitter**
- Need to optimize saturable absorber’s response time for sub-fs jitter regime

C. Kim et al, accepted at Optics Express (2012)
Toward ultimate jitter performance from fiber lasers: filtering effect in stretched-pulse fiber lasers

We recently found that tight filtering in the stretched-pulse fiber lasers can reduce the timing jitter by >10 dB more, and Sub-20-attosecond jitter will be possible.
I. Optimization of timing jitter of ultrafast lasers toward the sub-100-attosecond regime

II. Sub-femtosecond precision and stability synchronization of lasers and RF sources
Ultralow-jitter microwave signals are encoded in the repetition-rate and its harmonics of optical pulse trains. Can generate **ultra-low phase noise microwave signals** from ultrafast lasers.

**Timing jitter in the optical domain**

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

**Phase noise in the electronic domain**

- Time: \( T_R/n \)
- Microwave frequency: \( f_R, 2f_R, \ldots, nf_R, \ldots \)
However, excess phase noise in the optical-to-electronic conversion process limits the achievable phase noise of extracted microwave signals.

**Timing jitter in the optical domain**

**Phase noise in the electronic domain**

+ **Excess phase noise in the O-E conversion**

\[ T_R = 1/f_R \]

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**Time**

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**O-E conversion**

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**Microwave frequency**

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Can we regenerate an **ultralow-jitter & drift** microwave signal, the phase of which is locked to the optical pulse train?

<-160 dBc/Hz residual noise floor & <1 fs long-term drift

(1) Detect the phase error between optical pulse train and microwave signal

(2) Lock the zero crossings of microwave signal to the optical pulse train by **feedback control**
Operation of the optical phase detector

Phase modulator

Nonreciprocal quarter-wave bias

Microwave signals frequency = N × f_R

Optical pulse trains repetition rate = f_R

\[ \sin^2(\Delta \Phi/2) \]

\[ \cos^2(\Delta \Phi/2) \]

\[ -\pi \rightarrow 0 \rightarrow \theta_e \rightarrow \pi \Delta \Phi \]
Synchronization using phase-locked loop

Sub-femtosecond residual phase noise of 8.06 GHz microwave synchronized with 77.5 MHz Er-fiber laser

-133 dBc/Hz at 1 Hz offset
-154 dBc/Hz at 5 kHz offset

Integrated rms timing jitter: 838 as [1 Hz–1 MHz]

Sub-femtosecond residual phase drift of 8.06 GHz microwave synchronized with 77.5 MHz Er-fiber laser

847 as rms timing drift for 2 hours

Fractional frequency instability: $2.8 \times 10^{-19}$ at 1024 s

Measured with 100 Hz low pass filter and 2 samples/s

Absolute phase noise of 8.06 GHz microwave synthesized from 77.5 MHz Er-fiber laser
(preliminary data, optimization in progress)

Integrated absolute rms timing jitter = 3.9 fs (1 kHz – 2 MHz)
One side measurement: How much excess timing jitter/drift can be introduced in propagation for table-top experiments?

~10 fs rms jitter and ~200 fs pp drift for 50 m transmission

S. Park et al, CLEO 2012
Summary

- Demonstrated the record-low timing jitter from ultrafast fiber lasers: 70 attoseconds jitter [10 kHz – 40 MHz offset frequency].
  - Now sub-30-attosecond-level jitter will be possible by intra-cavity filtering.

- Ultrafast fiber lasers and related techniques have great potentials for generating and synchronizing ultralow-noise optical and RF signals.

- Which enabling techniques and modules are available for your new experiments based on ultrafast electron sources?
  - Robust Fiber laser with sub-fs jitter; RF signal source with a few fs jitter
  - Long-term stable sub-fs synchronization between different lasers
  - Long-term stable sub-fs synchronization between lasers and RF signals
  - Long-term stable sub-10-fs distribution of timing up to ~km length scale
  - Electron-bunch arrival time monitoring with sub-10-fs precision (DESY)
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