Fiber Lasers for Timing Distribution

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Optical Timing Synchronization

- We demand increasingly precise timing sync ($\ll 100$ fs)
- Must sync multiple locations separated by $\sim 1$ km distances.
Optical Timing Synchronization

- We demand increasingly precise timing sync (<< 100 fs)
- Must sync multiple locations separated by ~ 1 km distances.
- One way is to distribute timing information via short optical pulses of a definite repetition rate.

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

![Diagram showing time and frequency with repetition rates](image)
Synchronization System Layout

- **Master Laser Oscillator**
- **Fiber couplers**
- **Stabilized fibers**
- **RF-optical sync module**
- **Remote locations**
- **Low-level RF**
- **Low-noise microwave oscillator**

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**Components:**
- Master Laser Oscillator
- Fiber couplers
- Stabilized fibers
- RF-optical sync modules
- Remote locations
- Low-level RF

**Additional Notes:**
- Low-bandwidth lock
- Low-noise microwave oscillator
Synchronization System Layout

A master mode-locked laser producing a very stable pulse train,
The master laser is locked to a microwave oscillator for long-term stability.
Synchronization System Layout

Stabilized fiber links that transport the pulse train to multiple locations

- Master Laser Oscillator
- Fiber couplers
- Stabilized fibers
- RF-optical sync module
- Remote locations
- Low-level RF
- Low-noise microwave oscillator
- Low-bandwidth lock

RF-optical sync module

www.rle.mit.edu
Synchronization System Layout

Other lasers can be locked to this train or can generate an RF signal locally.
Optical Timing Synchronization

We envision that

i. a ultra-low noise master mode-locked laser,

ii. locked to an external source for long-term stability,

iii. with links to remote locations,

iv. and local generation of an RF signals,

form a complete scheme with < 100 fs, eventually few fs precision.
Frequency standard or highly stable microwave oscillator
Commercial Low-Noise Microwave Oscillators

- Very good microwave oscillators are commercially available for low frequencies (< 1 kHz).

- Eventually can lock to an optical standard for µHz-level stability.
Timing stabilized fiber links
Assuming no fiber length fluctuations faster than $T=2nL/c$.

$L = 1 \text{ km}, n = 1.5 \implies T=1 \mu s, f_{\text{max}} = 1 \text{ MHz}$
RF-synchronization module
for RF-optical & optical-optical
Direct Detection to Extract RF from the Pulse Train

Optical Pulse Train (time domain)

$T_R = 1/f_R$

Amplitude-to-phase conversion introduces excess timing jitter
Amplitude to Phase Conversion: Experimental Setup

- determine timing jitter due to power fluctuations
- mix 1.3 GHz component of laser signal to baseband and vary optical power
Amplitude to Phase Conversion in the PD

To minimize timing error at photodetection:

- increase bias
- use higher bandwidth detector
RF-Synchronization Module

Transfer timing information into intensity imbalance

The pulses sit on the zero-crossings of VCO output when synchronized.

mode-locked laser

 GHZ phase modulator

VCO

Loop filter

Balanced detector

F(s)

π/2

The RF-Synchronization Module transfers timing information into intensity imbalance. When synchronized, the pulses sit on the zero-crossings of the VCO output. The module includes a GHz phase modulator, a VCO, a loop filter, a balanced detector, and an F(s) block. The phase shifts are accurately controlled to ensure precise timing information transfer.
RF-Synchronization Module

Transfer timing information into intensity imbalance

The pulses sit on the zero-crossings of VCO output when synchronized.

mode-locked laser

60 fs (100 Hz-10 MHz) demonstrated
<10 fs possible on the long run

Optical-to-Optical Synchronization

ML-laser 1 \(\rightarrow\) \(\text{synchronized}\) \(\rightarrow\) \(F_1(s)\) \(\rightarrow\) Balanced detector \(\rightarrow\) VCO \(\rightarrow\) \(F_2(s)\) \(\rightarrow\) Balanced detector \(\rightarrow\) ML-laser 2

Cavity length change by PZT-mounted mirror
Low-Noise Master Laser Oscillator
Robust, Low-Noise Laser Oscillator Development

- Passively modelocked lasers, superior high-frequency noise.

- Er-fiber lasers:
  - sub-100 fs to ps pulse duration
  - 1550 nm (telecom) wavelength for fiber-optic component availability
  - repetition rate 50-100 MHz

- Reliable, long-term operation without interruption:
  - weeks of uninterrupted operation, with minimal environmental protection (just a box around)
  - use multiple lasers for redundancy
Passively Mode-locked Fiber Lasers

- Pulse builds up by itself from noise (ns-ps domain)
  - A saturable absorber ensures higher intensity <=> higher gain
  - Given constant intra-cavity energy, the stable solution is a localized solution (a single pulse).

- Picture is different in the femtosecond domain:
  - Dispersion and nonlinear dominate pulse shaping.
  - Soliton-like pulses balance these effects => very short pulses
Phase Noise (Timing Jitter) Measurements

- Quantum mechanical fluctuations in the photon number cause jitter: (for soliton laser)

\[ \Delta t \sim \frac{\tau_p}{f_{\text{min}}} \sqrt{\frac{g \theta f_R}{N_p}} (1 + D^2) \]

- Measurement Setup:

  mode-locked fiber laser → photodiode → BPF → LNA → SSB phase noise measurement (Agilent E5052)
Phase Noise (Timing Jitter) Results

Er-fiber laser at normal dispersion: \(~50\) fs (10 kHz - Nyquist)
Phase Noise (Timing Jitter) Results

Yb-fiber laser near zero dispersion: ~23 fs (10 kHz - Nyquist)
Amplitude Noise

Recall that amplitude noise is converted to phase noise at the photodetector. Preliminary data indicate this contribution is substantial -- under investigation.
One of our Er-fiber lasers
One of our Yb-fiber lasers
Conclusions

- Optical timing synchronization based on:
  - Ultra-low noise, long-term stabilized mode-locked fiber lasers,
  - Stabilized fiber links to distribute to remote locations,
  - A scheme to extract low-level RF from optical pulse train locally.

- Most critical component is the **master laser**:
  - Laser dynamics important (dispersion, nonlinear effects).
  - Ultimate limit set by quantum fluctuations in the photon number.
  - Currently noise < 30 fs possible, may be lower.

- Currently < 100 fs seems achievable.

- Following a few years of development, < 10 fs may be reached.
\[
\frac{z, t}{2} - i\gamma |a(z, t)|^2 a(z, t)
\]
\[
a(z, t) = -q(a(z, t)) a(z, t)
\]

\[
E_{1,n+1} = \frac{g_{\text{net},0} / 2}{1 + (E_{1,n} + E_{2,n}) E_{\text{sat}}} \left[ 1 - q \cos(\pi E_{1,n}) \right] E_{1,n+1}
\]

\[
E_{2,n+1} = \frac{g_{\text{net},0} / 2}{1 + (E_{1,n} + E_{2,n}) E_{\text{sat}}} \left[ 1 - q \cos(\pi E_{2,n}) \right] E_{2,n+1}
\]
Timing jitter measurement with stretched pulse fiber laser

@ 2 GHz

cw spike results in significant increase in phase noise around 10 kHz
RF-Synchronization Module

It is difficult to accurately measure very small timing variations.

Transfer of timing information into intensity imbalance in optical domain --- easier to measure

\[ f = f_0 + KV \]
Phase Noise Measurement

Free-running VCO
 Locked VCO
 Residual phase noise

<60 fs jitter
(100Hz-10MHz)