Design and Performance of the Optical Fiber Length Stabilization System for SACLA

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Introduction

- X-ray Free Electron Laser Facility “SACLAL”
  - Low-emittance thermionic electron gun ($\varepsilon_n \sim 1 \mu m$ rad)
  - 238 MHz, 476 MHz, L-band (1428 MHz) and S-band (2856 MHz) accelerators for acceleration and bunch compression
  - High-gradient C-band Main Linac (5712 MHz, $> 35$ MV/m)
  - Short-period in-vacuum undulator ($\lambda_u = 18$ mm)
- Accelerator components must be precisely synchronized
  - Bunch length is compressed to be $30$ fs.
- Pump-and-probe experiment also needs precise synchronization with accelerator
- Required timing stability: $50$ fs
  - throughout the 700m-long facility
- Optical timing and RF distribution system
  - Wavelength region of $1550$ nm
  - Phase-stabilized optical fiber ($5$ ps/km/K) is used
  - Temperature of optical fiber cables is regulated within $0.4$ K.
  - Electronics are enclosed in water-cooled 19-inch racks ($0.4$ K pk-pk)
**XFEL Stability**

- Present performance of SACLA
  - 24-hour trend graph during a user operation
  - With various feedbacks and manual tuning
- XFEL Intensity: ~500 μJ/pulse
- Intensity fluctuation: ~10% (std. dev.)
- Pointing Stability: ~10 μm (std. dev.)
• Stability data was taken without any beam feedbacks or manual tuning in order to investigate perturbation sources
  – In the early stage of the XFEL operation
• XFEL intensity was not stable
• Timing drift more than 500 fs was observed.
  – One of the reasons could be timing drift due to optical fiber length variation.
• Regulation of the optical fiber length is demanded.
System Overview

Optical Fiber Length Stabilization System

- Frequency Stabilized Laser
- EDFA
- Interferometer
- Piezo-electric Fiber stretcher
- Fiber Length Controller
- O/E
- 5712 MHz Phase Detector
- Mirror
- WDM Divider
- Optical RF Receiver
- EDFA
- 238 MHz

• **Optical Timing and RF Distribution System**
  - Master Oscillator generates low-noise RF signals
  - E/O and O/E Converters for each RF frequency
  - Wavelength-division multiplexing (WDM) technology for multiple signal transmission

• **Optical Fiber Length Stabilization System**
  - Frequency-stabilized laser for a length standard
  - Interferometer detects the optical length variation and fed back to piezo-electric fiber stretcher
  - 5712 MHz RF signal is also transmitted for the phase reference.

• **Optical fibers for these systems are separated**
  - Flexible design for the optical fiber length stabilization system
  - Failure resistant
  - Length variation of optical components (EDFA etc.) can be regulated.
Two length standards and two feedback control loops
- Fine Loop: Frequency-stabilized laser (1549 nm, ~193 THz, 5 fs)
  - For precise control
- Coarse Loop: Optical millimeter-wave signal (91.4 GHz, 11 ps)
  - This loop can restore the absolute length after the power off of the system.
  - For redundancy and for cross-check of the accuracy

**Interferometer**
- Polarization beam splitter (PBS) and Faraday rotating mirror (FRM) to eliminate scattered light.
- Reference light is frequency-shifted by a 238 MHz signal with an acousto-optic modulator (AOM).
- Each optical signal is separated by a band-pass filter and detected with a photo-diode (PD).
- 238 MHz beat signal is obtained from the PD as an interferometry signal.
- 238 MHz phase is detected by a phase-frequency discriminator (PFD).
Frequency-Stabilized Laser

- Length standard for the fine loop
- Optical frequency is locked to an absorption line of hydrogen cyanide.
  - Wavelength: 1548.955 nm (193.545 THz)
  - P9 absorption line of H_{13}C_{14}N
- Frequency stability: $1 \times 10^{-9}$
  - Corresponding to 1 μm accuracy for 1km-long distance measurement.
Light Source for Coarse Loop

- External cavity laser diode (ECLD)
- LiNbO$_3$ modulator (LN-MOD)
  - Driven by a 45.7 GHz signal ($f_m = 5712$ MHz x 8)
  - LN-MOD produces two sidebands ($f_+$ and $f_-$)
- Band-reject Filter
  - Eliminates the input light ($f_{in}$)
- Two sidebands, $f_+$ and $f_-$, are utilized for the length measurement.
  - $f_+ - f_- = 2f_m = 91.4$ GHz
- Stability
  - Frequency stability of 5712 MHz: $< 1 \times 10^{-9}$
  - This light source is carefully designed to obtain almost same frequency stability as 5712 MHz.
  - Same level as the frequency-stabilized laser for the fine loop
Corner frequency: 1 kHz

Mechanical resonance of the fiber stretcher: 15 kHz

Phase margin: ~70 deg.
Closed Loop Response (Fine)

Gain [dB] vs Frequency [Hz]
- Simulation
- Measurement

Phase [deg] vs Frequency [Hz]
- Simulation
- Measurement
Present Status

- 8 channels of the optical fiber length stabilization system are installed into SACLA.
  - Under engineering run
  - 12 channels in total will be utilized for user-time operation from October.
- Data from a 400m-long optical fiber are shown for example.
Short-term Data

• To estimate length measurement resolution
• Data for 1 hour stable period are plotted
  – Fiber length (~400 m) was regulated by the fine loop

![Graph showing measurement resolution and data stability](image_url)
Only the fine loop was activated. Optical Fiber Length was regulated within 2 fs pk-pk for two weeks. Coarse loop was not activated. (just measured the length variation)

This data shows 50 fs pk-pk variation.

Length data from fine and coarse loops were consistent within 50 fs. We can conclude that the control accuracy is 50 fs.

~ 1 ps drift of the fiber length was compensated with the fiber stretcher.
Length Regulation of RF Distribution Fiber

- Optical fiber length of the optical RF distribution system is regulated by a fiber stretcher at the receiver.
  - According to the detected phase of 5712 MHz

![Graph showing measurement and control over time]

- Measurement (RF)
- Fiber Stretcher (RF)

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**Graph Details:**
- **Measurement / Control [fs]**
- **0:00 6:00 12:00 18:00 0:00 6:00 12:00 18:00 0:00**
- **Fiber stretcher control**
- **5.7GHz Phase det.**

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**Diagram:**
- Optical Fiber Length Stabilization System
- Frequency Stabilized Laser
- EDFA
- Interferometer
- Piezo-electric Fiber Stretcher
- Optical RF Transmitter
- WDM Combiner
- Optical RF Receiver
- 5712MHz Phase Detector
- Piezo-electric Fiber Stretcher
- Optical Fiber Length Stabilization System
- 238MHz
- Master Oscillator

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Summary

- **An optical fiber length stabilization system** for the timing and RF signal distribution system was developed.
  - For the x-ray free-electron laser facility, SACLA
  - To synchronize accelerator components with a master clock within **50 fs**

- **Setup**
  - Additional optical fiber is prepared for the optical fiber length stabilization system.
  - Frequency-stabilized laser (1549 nm, fine loop) and **91.4 GHz optical signal (coarse loop)** for length standards
  - Optical interferometer to measure the optical length variation
  - Optical fiber length drift is compensated by a piezo-electric fiber stretcher.
  - Optical 5712 MHz is also transmitted for the phase reference of the timing and RF signal distribution system.

- **Performance**
  - Measurement resolution: **0.13 fs rms** (fine loop) and **2.8 fs rms** (coarse loop)
  - Control accuracy: **50 fs pk-pk**
    - Estimated from the length difference between the fine and coarse loops.
  - Optical fiber length for the timing and RF distribution system was also regulated properly.

- **Required performance for the optical fiber length stabilization system was obtained.**
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Backup
Frequency-Stabilized Laser Data

Frequency Stability

Ambient Temperature

Output Power

1 hour

1x10^-9

Frequency Difference [MHz]
Phase Noise of 45.7 GHz Signal

• Almost no additive noise from frequency multiplier
• Integral of the phase noise
  – RMS jitter: 25 fs (10 Hz – 10 MHz)
Fiber Stretcher

- Optical fiber is coiled around a cylindrical piezo-electric actuator
- Dynamic range 3 mm peak-to-peak
  - Bias voltage: 0 V – 300 V
- Frequency response
  - Sufficiently flat up to 3 kHz
  - Mechanical resonance at 15 kHz.

Mechanical resonance: 15 kHz
Other Loop Filters

• Coarse Loop
  – PI control
  – Corner frequency: ~0.01 Hz

• Fiber stretcher for the RF distribution system
  – PI control
  – Corner frequency: ~0.1 Hz

• Fine loop uses a wide band loop filter (1 kHz).
  – Fine loop is sensitive to small amplitude but high frequency vibration.
  – Phase detection range is only 1.5 μm
  – For a stable control under high-frequency perturbation
• Polarization Mode Dispersion for a usual optical fiber
  – $< 1 \text{ ps/√km}$

• If the length of a 1km-long optical fiber varies 1mm ($1 \times 10^{-6}$), the optical length for different polarization varies only 1 as ($=1 \text{ ps} \times 10^{-6}$).