Recent Developments and Layout of the Master Laser System for the VUV-FEL

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Overview

• Requirements for the Master Laser Oscillator (MLO) System
• Layout & Measurements
• Generation of non-integer multiples
• Locking external RF Oscillators to MLO
• Conclusion and Outlook
Requirements

• Generate optical pulse train to distribute in timing stabilized fiber links and use for synchronization, diagnostics and seeding of other laser systems

• Provide various frequencies with ultra-low phase noise, also at non-integer multiples of repetition rate

• Reliable system to guarantee required uptime
Synchronization System Layout

- **Master Laser Oscillator**
- Fiber couplers
- Stabilized fibers
- RF-optical sync module
- Remote locations
- Low-noise microwave oscillator
- Optical to optical sync module
- Laser
- Low-bandwidth lock
- Low-level RF
A master mode-locked laser producing a very stable pulse train
A master mode-locked laser producing a very stable pulse train

The master laser is locked to a microwave oscillator for long-term stability
A master mode-locked laser producing a very stable pulse train
- The master laser is locked to a microwave oscillator for long-term stability
- Length stabilized fiber links transport the pulses to remote locations
- Other lasers can be linked or RF can be generated locally
Choice of Technology

• Passively mode-locked lasers offer excellent high-frequency stability. For improved low-frequency stability, system is locked to a microwave RF Oscillator

• Er-fiber lasers:
  – sub-100 fs to ps pulse duration
  – 1550 nm (telecom) wavelength for fiber-optic component availability
  – repetition rate 30-100 MHz

• For VUV-FEL:
  – Fundamental Frequency is 1.3 GHz/144=9.02777 MHz
  – Choice of repetition rate of laser system: 9.0277 MHz*6=54.16 MHz
Passively Mode-locked Fiber Lasers

- Pulse builds up by itself from noise (ns-ps domain)
  - A saturable absorber ensures higher intensity $\iff$ 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 Nonlinearity dominate pulse shaping.
  - Soliton-like pulses balance these effects $\implies$ very short pulses
Direct Detection to Extract RF from the Pulse Train

Optical Pulse Train (time domain)

$T_R = 1/f_R$

$TR/n$

BPF

Photodiode

LNA

Direct Detection to Extract RF from the Pulse Train
Timing jitter measurements

- Signal converted to electronic domain by high-bandwidth photodetector
- Harmonic (1.3 GHz) of repetition rate filtered
- Phase noise measured with Signal Source Analyzer
Timing Jitter of fiber lasers (after amplification by EDFA)

- All measurements at 1.3 GHz
- Unity gain of PLL ~1 kHz
- Noise ~10 fs (1 kHz..Nyquist); no significant noise added by locking
- Optical power sufficient to feed ~5 optical links

Data from FEL 2005
Amplitude noise of various fiber laser

0.03% rms for Er-doped fiber laser (EDFL)
0.04% rms for Yb-doped fiber laser (YDFL)
0.1% rms for Ti:Sapphire

Some of the quietest lasers around (3x better than typical TiSa)
Design Considerations for MLO System

- Maximize uptime:
  - Redundant lasers
  - Switching from one system to another without machine interruption
    - Exception handling and switching must be fast to minimize interference to machine operation in case of failure
    - Phase of outputs of different lasers must be the same even after restart
    - Second feedback at $\frac{1}{2}$ of repetition rate needed
  - Suitable diagnostics to determine operation according to spec
    - Optical spectrum
    - Average and peak power
    - Phase noise
Layout of MLO System
Experimental setup
Generation of subharmonics

- Divide repetition rate using suitable RF pulse (~15ns pulsewidth)
- RF pulse can easily be created synchronous to laser, jitter is no issue
- Application: e.g. diagnostics with 1 MHz repetition rate
- Pick up harmonic of divided repetition rate with photodetector
Injection locking of DRO

- Pulse train is directly fed to VCO input of DRO
- Unity gain is determined by amplitude of pulse train
- Resonant circuit: phase = n*360 deg
- DRO reacts to phase shift by changing center frequency
- If locked: pulses will be at zero-crossing of 1.3 GHz wave
- High bandwidth of photodiode can be fully used
Injection Locking of DRO

• DRO follows laser phase noise for lower offset frequencies and is free running for higher frequencies.
• Extremely simple yet effective way to combine ultra-low far-from-carrier noise of DRO with optical timing system based on optical pulses
• Photodetector drifts are under investigation.
Conclusion and Outlook

• Present state:
  – Engineering and design effort on first generation master laser oscillator system for the VUV-FEL

• Things accomplished:
  – Lock of Laser to RF source
  – Switching concept to combine redundant MLO’s
  – First tests with FPGA-based regulation
  – First tests with injection locking external DRO to MLO

• Things to be done:
  – Evaluate performance of FPGA-based regulation and include second feedback and exception handling
  – Implement suitable set of diagnostics for MLO’s to assure reliable operation of system
  – Long-term tests of system
  – Evaluation of injection locking performance
Thank you for your attention !!