Low Phase Noise
Local Oscillator and Clock Generation
for Cavity Field Detection

Mateusz Żukociński,
Krzysztof Czuba, Łukasz Zembala
Institute of Electronic Systems
Warsaw University of Technology
Warsaw, Poland
* M.Zukocinski@elka.pw.edu.pl

Uros Mavrič,
Matthias Hoffmann, Frank Ludwig
Deutsches Elektronen-Synchrotron
Hamburg, Germany

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Outline

> Introduction
> Frequency synthesis concepts
> Mixing technique
> Analysis
> Prototyping
> Final design
> Results
> Summary
Introduction

> RF cavity field control system

| LO Generation Module - LOGM |

> Local Oscillator (LO) signal is a crucial contributor to the receiver phase noise

> Ultra-low phase noise LO is a must

- < 3 fs RMS time jitter [10 Hz ÷ 1 MHz]
- < -160 dBC/Hz noise floor

> Low phase noise Clock (CLK) is needed

spec for the European XFEL
Introduction

> LOGM requirements

- **Input signal:**
  - 1x REF 1300 MHz +21 dBm

- **Output signals:**
  - 3x REF 1300 MHz +11 dBm (uVM, HOM, KLM)
  - 2x REF 1300 MHz +3 dBm (uDWC)
  - 9x LO 1354 MHz +14 dBm
  - 9x CLK 81 MHz 1.2 Vpp square

- **Synchronization RESET** functionality for 81 MHz CLK signal

- **LO power adjustment** [+12 … +17 dBm]

- **LO performance:**
  - RMS additive jitter < 3 fsec (10Hz - 1MHz)
  - Phase noise floor < -160 dBc/Hz
  - Spurious-free range > 80 dBc

- **Diagnostics:**
  - RF signals monitor outputs
  - Power level detectors, temperature sensors
  - Power supply management

- **Packaging:**
  - standard 19” crate, low-profile (1U high)

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**XFEL system frequency configuration:**

- REF 1300 MHz
- LO 1354 MHz
- IF 54.16 MHz (1300 / 24)
- CLK 81.25 MHz (1300 / 16)
Frequency synthesis concepts

> **Phase-lock loop technique**

Advantages

• shaping phase noise characteristic
• superior performance possible

Disadvantages

• lack of small PCB-mount oscillators with sufficiently good performance

> **Mixing technique**

Advantages

• low phase noise
• sufficient performance possible
• components easily available
• easy to integrate on PCB
Mixing Technique

> Single-stage mixing

- Simple design
- Minimum number of components
- High spec for LO filter

> Multi-stage mixing

- Complex design
- High number of components
- Relaxed spec for LO filters

RF and LO are close each other!!

it is hard to select the LO out of the mixer spectrum (filtration)
Analysis

> Single-stage mixing

\[ |\Delta \phi_{\text{out}}|^2 = \left[ \left( \frac{|\Delta \phi_{\text{REF}}|^2}{M_1^2} + |\Delta \phi_{D_1}|^2 \right) \cdot \frac{1}{M_2^2} + |\Delta \phi_{D_2}|^2 \right] \cdot \frac{1}{M_3^2} + |\Delta \phi_{D_3}|^2 + |\Delta \phi_{\text{MIX}}|^2 + |\Delta \phi_{\text{AMP}}|^2 \]
Analysis

Single-stage mixing

\[
\Delta \varphi_{\text{out}}^2 = \left( \frac{\left| \Delta \varphi_{\text{REF}} \right|^2}{M_1^2} + \left| \Delta \varphi_{D_1} \right|^2 \right) \cdot \frac{1}{M_2^2} + \left| \Delta \varphi_{D_2} \right|^2 \cdot \frac{1}{M_3^2} + \left| \Delta \varphi_{MIX} \right|^2 + \left| \Delta \varphi_{\text{AMP}} \right|^2
\]

Double-stage mixing
Prototyping

> Single-stage mixing

Residual phase noise measurements (2DUT phase detector method)

> Double-stage mixing

![Diagram of single-stage mixing with components labeled: AD9515, Multiple Div., -6dB (2xSplitters), FRF = 1.3GHz, ZRL-1150LN, 1313 MHz, SBP-60, MDC-179, /32, HMC794.]

> Diagram of double-stage mixing with components labeled: AD9515, -6dB, Div = 8 (CMOS), fRF = 900 MHz, VFL-160+, /4, SLP-70+, SLP-100, SIF-60, LO, RF, IF, SYM-25DMHW (L13), 6-tap K&L (1259 MHz), SYM-30DLHW (L10), 5-tap LORCH (1313 MHz), HMC758, 18 dBm, 10 dBm, 10 dBm.]

![Photograph of prototyping setup with equipment connected.]

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Prototyping

> LO residual RMS phase noise measurements and jitter calculations

![Graph showing phase noise spectral density vs. frequency for different LO configurations.]

<table>
<thead>
<tr>
<th>LO 1313 MHz</th>
<th>single-stage</th>
<th>double-stage</th>
</tr>
</thead>
<tbody>
<tr>
<td>jitter</td>
<td>2.6 fs (1.2 mdeg)</td>
<td>3.4 fs (1.6 mdeg)</td>
</tr>
<tr>
<td>10 Hz – 1 MHz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cross-check meas. jitter</td>
<td>2.6 fs (1.2 mdeg)</td>
<td>2.8 fs (1.3 mdeg)</td>
</tr>
<tr>
<td>1 kHz – 10 MHz</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

> Compact high-quality ceramic filters available!

> Single-mixer LO synthesis for final implementation
Final design

Block diagram of the LOGM module
Final design

> PCB layout of LOGM
Final design

- LOGM module (PCB + metal case)

  > Metal casing for improved EMI/EMC
  > Reduced conductive crosstalk and radiative couplings (SFR >80 dBc)
  > Efficient heat dissipation
Final design

> LOGM 19” crate – 3D mechanical modeling (crate integration)
Final design

- LOGM 19” crate – 3D mechanical modeling (crate integration)
Final design

LOGM 19” crate – internal arrangement

- Power distribution
- RF Distribution
- Reset-Module
- LOG-Module
- FRED2
- Diagnostics TMCB2 / FMC
- Management
Final design

- LOGM 19” crate
Final design

LOGM 19” crate

- ventilation holes
- monitoring & diagnostics board
- Ethernet communication
- REF, CLK, LO monitoring outputs + RF status indicators
- ON/OFF + crate management
- Reset trigger Socket input
- REF input
- REF, CLK, LO outputs
- cooling fun panel blade fuses behind
- DC supply connector
Final design

- LOGM 19” crate in the XFEL LLRF system

- XFEL 48-channel LLRF station:
  - Cavity patch panel

- Sub-components and signal-flow:
  (standard non-iq sampling scheme)

  - Drift Compensation
  - LO-Generation
  - Down-Converter
  - Low-noise Digitizer
  - DCM 2U 19” Module
  - LOGM 1U 19” Module
  - DWC RTM MicroTCA.4
  - ADC AMC MicroTCA.4

courtesy of Frank Ludwig, LLRF Workshop 2015, Shanghai
Results

REF spectrum

- Clean spectrum
- Spurious-free-range >80 dBc
- CLK bandwidth up to 1 GHz

LO spectrum

CLK spectrum
Results

LO absolute phase noise spectrum

CLK absolute phase noise spectrum

LO amplitude noise spectrum

CLK amplitude noise spectrum

> Noise floor < -160 dBc/Hz
Results

- Residual phase noise and jitter

- RMS time jitter ~2 fs [10 Hz – 1 MHz]
Summary

> Mixing technique useful for ultra-low phase noise LO generation

> High performance LO and CLK generation module for European XFEL was developed

- LO: ~2 fs of RMS time jitter [10 Hz - 1 MHz]
- LO: <-160 dBC/Hz noise floor
- spurious-free-range > 80 dBC

> Motivation for spin-off projects:

- DRTM-LOG1300 highly compact RTM module for MTCA.4
  (poster on Tuesday by Tony Rohlev)

- Universal LO&CLK generation module for LO [300 MHz – 6 GHz]
  (poster on Wednesday by M. Żukociński)
Thank you for your attention!