ISBN: 978-3-95450-193-9 doi:10.18429/JACoW-ICALEPCS2017-THPHA090

CHANNEL SELECTION SWITCH FOR THE REDUNDANT 1.3 GHz MASTER OSCILLATOR OF THE EUROPEAN XFEL

B. Gasowski*, K. Czuba, L. Zembala, Institute of Electronic Systems,
Warsaw University of Technology, Warsaw, Poland
H. Schlarb, Deutsches Elektronen-Synchrotron, Hamburg, Germany

Abstract

The phase reference signal reliability is of utmost importance for continuous operation of the European XFEL machine. Since even very short interruption or glitch in the reference signal might break the precise synchronisation between subsystems, it is desirable to minimize probability of such events. While master oscillators often have a hot-spare to speed-up recovery after a failure, whether switched manually or electronically, it does not save from time-consuming resynchronisation.

Our experience from testing and commissioning E-XFEL 1.3 GHz Master Oscillator (MO) shows that a struggle to achieve demanding phase-noise requirements might negatively impact reliability of the system. In this paper we present an approach which allows for quick switching between independent reference generation channels while maintaining continuity of the output signal. This is a first step towards autonomous redundancy solution for the E-XFEL MO which will maintain continuous reference signal even in case of a failure of one of the generation channels.

INTRODUCTION

In modern accelerators, very precise synchronisation is required, especially in Free-Electron Laser (FEL) applications, often down to femtosecond levels. One of such facilities was recently put into operation: European X-ray FEL (E-XFEL) [1], located at Deutches Elektronen-Synchrotron (DESY) site in Hamburg, Germany. Whole facility spans over 3.4 km, which makes achieving such precision especially challenging. General issue of correct synchronisation can be split into two:

- short-term phase stability of reference signal (jitter or phase noise)
- long-term drifts of electrical (or optical) lengths in the distribution network

Such approach is of course a simplifiaction of many interconnected sub-issues, but allows for easier overview of system structure.

E-XFEL's Master Oscillator (MO) [2], a relatively complex system in itself, delivers 1.3 GHz signal with rms jitter below 20 fs[1] [3]. This signal is then distributed as a phase reference signal by the distribution system whose task is management and compenstation of drifts. E-XFEL utilises a hybrid RF-optical distribution scheme: reference signal is delivered to all users by low-drift and relatively low-cost RF interferometric links and then further corrected at several points using laser-based links for improved precision [4] [5].

It is also important to note that using provided reference signal, with help of various frequency conversion techniques, users derive other signals of different frequencies, such as local-oscillator (LO) and clock signals. These derived signals are in a very specific time relation to the reference signal. If the reference signal disappears, even for a brief moment, all these precise relations between nodes and signals are disrupted or even lost completely. Similar result may come from other significant disturbances in the reference signal.

The following resynchronisation of whole facility will usually take at least several hours, which means that it is unavailable for the users for a significant period of time. It is then obvious that reliability of the synchronisation system is very important and largely depends on continuity the reference signal delivery.

While failures in the distribution network will also result in, at least partial, loss of synchronism, this work focuses on dealing with failures in the source of the reference signal—Master Oscillator itself. Our experience from development, tests, commissioning and operation of the part of E-XFEL's MO which is responsible for reference signal generation, shows that reliability vs performance trade-off can be an issue. Demanding requirements, especially for phase noise, often call for novel solutions and constrain component selection. This can leave little space for reliability considerations.

CONCEPT OVERVIEW

It is customary to have a hot spare of the MO, which in case of failure in the main MO allows for quick recovery of the reference signal, without need for immediate repair of the failed components. However, whether the switchover is done manually or electronically, loss of signal has already propagated downstream and, possibly, resulted in loss of synchronism.

We found that in order to solve issue of inferior reliability there is a need for a true redundancy solution which could react automatically to a failure and avoid any interruptions in the reference signal. In that case, there are two main issues to be solved:

- How to switch between sources without propagating loss of signal (or other large disturbances) downstream?
- How to detect a failure, quickly and reliably?

* bgasowsk@mion.elka.pw.edu.pl
[1] integration bandwidth: 10 Hz–1 MHz

ISBN: 978-3-95450-193-9 doi:10.18429/JACoW-ICALEPCS2017-THPHA090

Coherent Switching

Even without any failure in the signal sources, straightforward switchover to another source can already disturb output signal enough to count it as a failure of whole system. In order to make sure that such switching is safe, it is required to maintain continuity of the signal. That is: minimise the changes in the amplitude and phase in case of switching, and make any transients smooth.

For this purpose, the sources are synchronised with each other, so that difference in their phases is less than 1° (ca 2 ps) at the switching point. Low-drift phase detectors are incorporated into the switch module to minimise influence of the local drifts on synchronisation and offer better repeatability than possible when using mechanical connectors.

Secondly, energy storage in a microwave filter with a high quality factor value is applied. This filter is based on dielectric resonators, and has a Q-factor (loaded) of about 4000 and a bandwidth of about 300 kHz. Such a filter is able to reasonably sustain output signal on its own for few hundred nanoseconds and significantly suppresses short transients. Thanks to this approach, in case of a failure happening there is still reasonable time available for detection and reaction.

Failure Detection

Unfortunately, it is impractical to try to predict failures and switch in advance, because in case of many failure modes it is very hard or even impossible to do so reliably enough, even with complex models and diagnostic circuits. Therefore, it is necessary to detect failure when it already happened, with low latency and good sensitivity, while avoiding false positives. In order to achieve these goals, we decided to focus on critical disturbances in the reference signal. By critical disturbance we understand one that can potentially disrupt synchronism in the facility. For example, sudden drop in amplitude of the signal or large jumps in signal's phase. Performance degradation, however, like for example increased jitter or small changes in output amplitude, are not considered as such.

Critical disturbances in the reference signal can manifest only as large changes of phase or/and amplitude. Therefore, the switch module incorporates fast amplitude and phase detectors. Phase detectors are shared with channel synchronisation function which was described in previous subsection.

Detection of amplitude changes is straightforward, because it is measured as an absolute value. However, phase can be only measured in relative manner—as a difference between two signals. When only two signals are available, it is impossible to determine whose phase has changed, i.e. which source has failed. This is one of the main reasons why we decided to implement triple modular redundancy (TMR), with three equal and independent Generation Channels (GCs). Each GC is continously delivering a reference signal of its own, and then in the switch module one of them is chosen to be output to the distribution system. Phases are measured differentially for each signal pair. With this approach it is possible to identify the source that has failed when the failure manifests in phase disturbances.

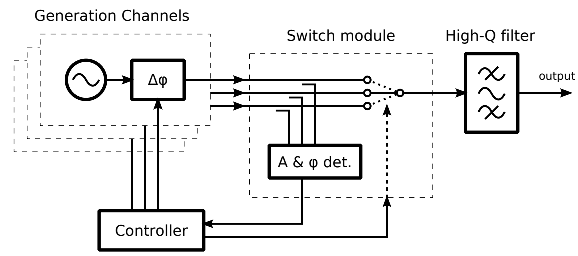

Figure 1: Simplified block diagram of the E-XFEL's MO.

System Integration

Simplified block diagram of the redundant E-XFEL MO is presented in Fig. 1. The switch module, presented in this work, contains three-way microwave switch together with amplitude and phase measurement circuits: high-directivity couplers and amplitude/phase detectors. Signal processing, control algorithms, and other tasks are handled by a separate module: a dedicated real-time controller which is currently in a development phase. Each GC has an internal phase-shifter which is used by the controller to align phases of all three signals.

The MO is required to deliver reference signal of significant power, exceeding +35 dBm. Therefore, in order to account for all losses (in switches, filter, cables, etc.), the switch module has to be able to operate correctly with levels of the input signals of at least +40 dBm.

MODULE DESIGN

The simplified block diagram of the switch module is shown in Fig. 2. The manufactured device (installed in the test setup) is shown in Fig. 3. The following subsections discuss essential points of module design.

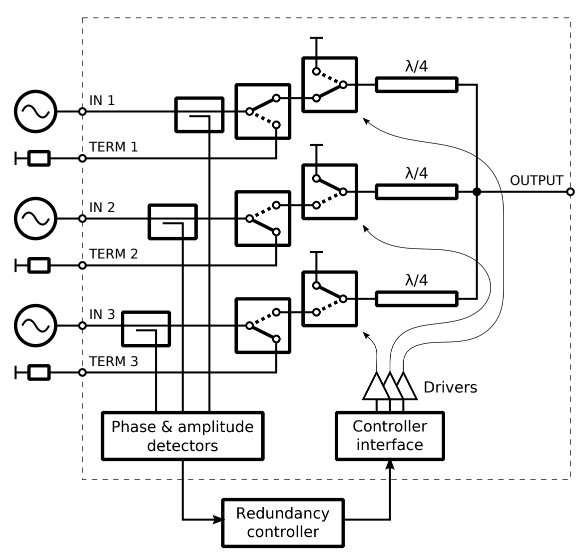

Figure 2: Simplified block diagram of the switch module.

ISBN: 978-3-95450-193-9 doi:10.18429/JACoW-ICALEPCS2017-THPHA090

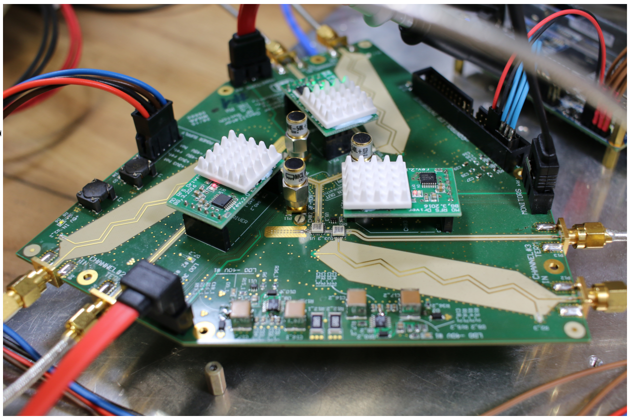

Figure 3: Photo of the manufactured device (in test setup).

RF Switches

Many various solutions for switching RF signals are available on the market, however, quick switching (sub-100 ns) and high power handling (+40 dBm) are requirements that are often contradictory. High isolation (>60 dB) is important as well, because it is desirable to isolate a potentially malfunctioning source from the output. Nevertheless, we found that switches based on relatively new technology, gallium nitride (GaN) material, can fulfil such requirements simultaneously.

At the time of component selection, feasible switches were available only in SPDT variant, but the system requires a SP3T switch. Therefore, six SPDT switches were arranged as to work as a single absorptive SP3T switch (Fig. 4). Such topology offers acceptable losses, very good isolation and symmetry. It also directs signals from unselected GCs to external matched loads, in order to avoid dissipating large power locally. On the other hand, such topology results in significant cost and is narrowband due to presence of quarter-wave transformers, but these are acceptable trade-offs. Selected switch components are able to work with signal power up to +43 dBm and in this arrangement provide isolation of more than 80 dB, which exceeds requirements.

GaN technology offers very good parameters, but it requires relatively large negative control voltages (-40 V in case of components used in this design). This led to design

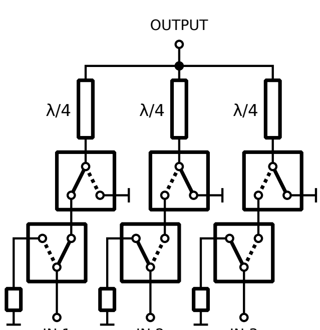

Figure 4: Used topology of microwave SP3T absorptive switch constructed from six DPDT switches.

of dedicated driver circuits which convert LVCMOS signals to required voltage levels of 0/-40 V while adding less than 20 ns of delay. The drivers are designed as small piggyback modules with heatsinks, visible in Fig. 3.

Phase and Amplitude Measurement

Finite return loss in the switch module itself and further downstream will cause a certain reflected wave to propagate in the reverse direction. Aplitude and phase of this wave will change when the state of the switch is changed, which will in turn affect phase measurement through finite isolation in the couplers. Therefore, accurate phase measurement requires use of couplers with high directivity.

This design employs a variant of narrowband coupled-microstrip couplers whose characteristic zigzag shape can be clearly noticed in Fig. 3. Because parameters of such pure-layout couplers are defined only by geometry and properties of underlying dielectric, they are very robust and reliable, and offer good repeatability. Low-power signals from couplers are then delivered by low-drift network to the amplitude and phase detectors. The detectors are dedicated integrated circuits that are freely available on the market.

Supporting Circuits

The module additionally contains simple logic which allows it to operate without the controller or when controller fails, and also protects from setting the switches to an incorrect state. Since reliability of this module is critical for whole system, the design includes taps for monitoring of various internal signals and multi-point measurement of temperature, which can provide some insight in the health of the hardware.

Form Factor

Because synchronisation of the channels is not affected by absolute (or common-mode) drifts, the design exploits use of symmetry to minimise relative (or differential) drifts between channels. This is motivation behind the characteristic shape of the module, clearly visible in Fig. 3. Aluminium blocks underneath the module (not visible in the photo) are added in order to transfer excess heat into the thick base plate, which can easily dissipate it to the environment.

EXPERIMENTAL VERIFICATION

Setup and Data Processing

Block diagram of the test setup is presented in Fig. 5. As an emulation of the Generation Channels, we used multi-channel phase coherent synthesizer, which can control independently power, frequency, and phase of each channel. Two high-power amplifiers were used to achieve signal powers up to 42 dBm. Since we were limited to only two amplifiers, one of them was connected to channel 1, while the other one to channels 2 and 3 via a power splitter. Due to limitations of the test setup, results presented in next subsection were obtained with power reduced to about 37 dBm at each of the switch module's inputs. Output signal (from before and after

ISBN: 978-3-95450-193-9 doi:10.18429/JACoW-ICALEPCS2017-THPHA090

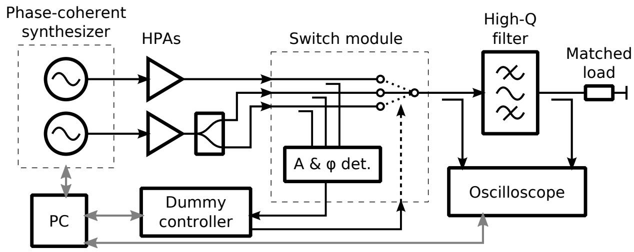

Figure 5: Block diagram of the test setup.

the filter) was probed with directional couplers and directed to an oscilloscope with 4 GHz bandwidth and 8-bit ADCs, which acted as a digitizer with a sample-rate set to 10 GS/s.

Recorded data was then processed on a regular PC. First step was demodulation to I/Q signals and averaging with sliding window of 100 samples (10 ns or 13 full periods of 1.3 GHz signal). Amplitude and phase was then derived from these averaged I/Q signals. Unfortunately, there is a considerable amount of noise present in the obtained data. Longer averaging window would reduce noise, but would also significantly impair time resolution, so we decided to keep short averaging window of 100 samples where possible.

Results

In this subsection we present results that were obtained by switching from channel 1 to channel 2 in various conditions. The most basic case, switching in near-ideal conditions (minimal phase and amplitude unbalance between channels), is presented in Fig. 6. This can be treated as intrinsic disturbances caused by the switching itself. It is clearly visible that changes of phase and amplitude after the filter are smooth and stretched in time to about 1 µs. Phase deviation from ideal value does not exceed 1° at any point of time, and amplitude fluctuates by about 0.25 dB.

For better insight into operation of the switch module itself, the same case limited to the first 300 ns is shown in Fig. 7. Beginning of the switching process is delayed by

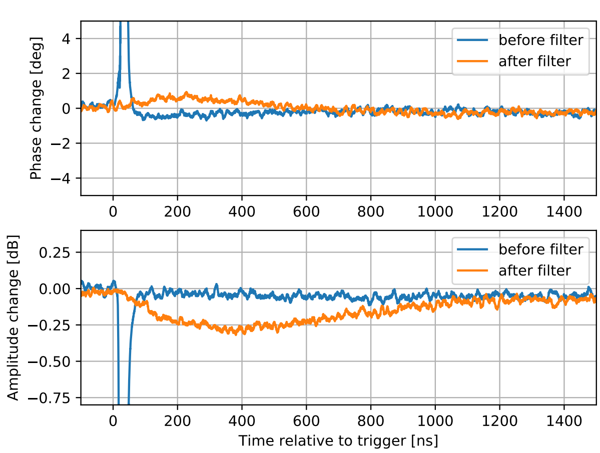

Figure 6: Phase and amplitude variations during switching in near-ideal conditions.

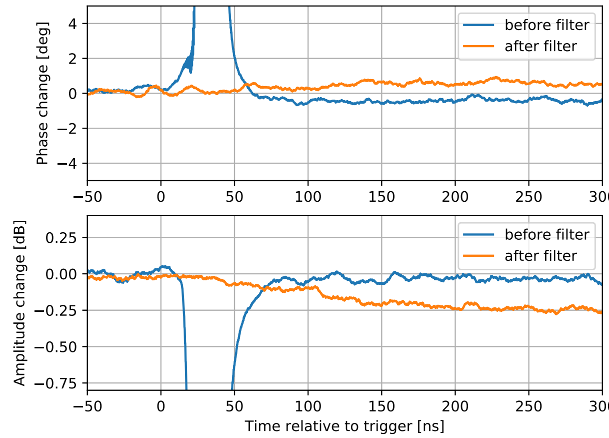

Figure 7: Phase and amplitude variations during switching in near-ideal conditions (cropped to the first 300 ns).

about 20 ns after the trigger signal from the dummy controller and then effectively completes after following 30 ns.

In order to see the influence of the synchronisation error, i.e. difference in the phase between two channels when switching from one to another, we artificially introduced errors of up to ±5°. Selected cases are presented in Fig. 8. Even for relatively large synchronisation errors, the phase change is still smooth and only slightly longer, still about 1 µs. Change of the amplitude does not vary visibly. Any differences start to be visible only with errors of several tens of degrees (not shown), which is an unacceptable error.

Switching in case of a reaction to a real failure, however, will not happen immediately. We tried to simulate such an event by adding a delay between switching one channel off and switching the other one on. Effectively, there is an additional no-signal period at the output of the switch module, whose duration equals the delay. Selected cases are presented in Fig. 9. Influence of such additional delays is clearly visible and is much stronger than than that of the synchronisation error. In case of longer delays the tail of

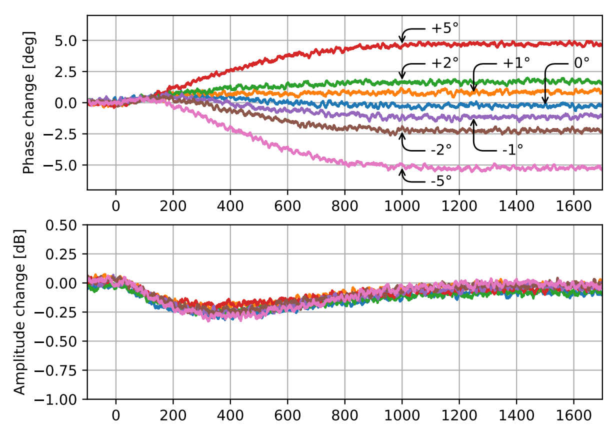

Figure 8: Influence of error in phase synchronisation.

ISBN: 978-3-95450-193-9 doi:10.18429/JACoW-ICALEPCS2017-THPHA090

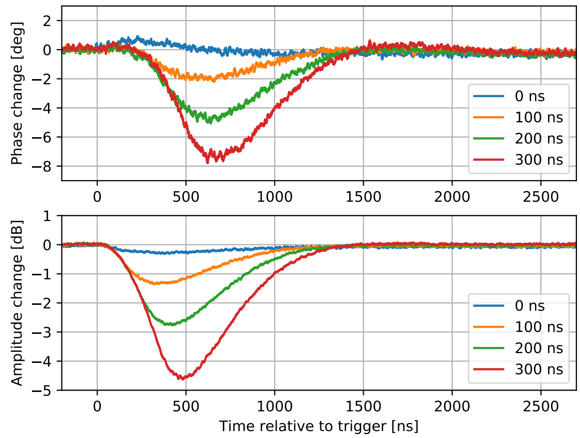

Figure 9: Influence of switching latency.

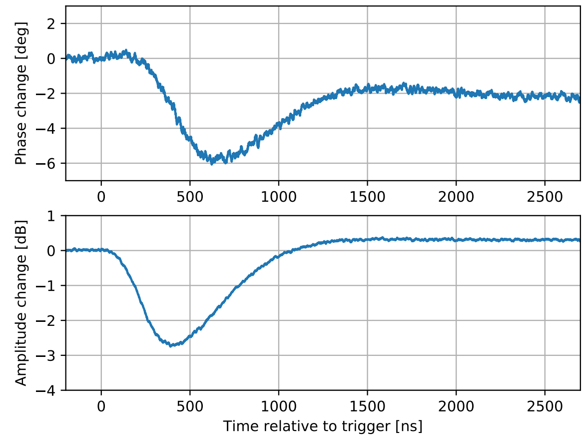

Figure 10: Phase and amplitude variations during switching in simulated failure response.

the disturbance ends after over 2 µs, but the most important part fits within 1.5 µs. This result is in good agreement with the expectations, and underlines an issue of low-latency detection of the failures.

The last measurement was taken in simultaneous presence of various nonidealities: synchronisation error set to 2°, switching delay set to 200 ns, and amplitude unbalance of about 0.5 dB. This case, simulating realistic failure response, is presented in Fig. 10.

CONCLUSION AND FUTURE PLANS

We have shown that it is feasible to switch between independent sources of the reference signal without disrupting its continuity, given appropriate methods are applied. Presented switch module is a first step towards an autonomous redundancy solution for the European XFEL's Master Oscillator. The companion real-time controller is currently in development, and after appropriate testing procedure the complete system is planned to be commissioned in the facility.

ACKNOWLEDGEMENT

Research supported by Polish Ministry of Science and Higher Education, founds for international co-financed projects for years 2016 and 2017.

REFERENCES

[1] European XFEL, `https://www.xfel.eu`

[2] L. Zembala *et al.*, "Master Oscillator for the European XFEL", in *Proc. IPAC2014*, Dresden, Germany, Jun. 2014, paper WEPRI116, pp. 2771–2773.

[3] B. Gasowski *et al.*, "Status update on the 1.3 GHz Master Oscillator of the European XFEL", unpublished.

[4] K. Czuba *et al.*, "Overview of the RF Synchronization System for the European XFEL", in *Proc. IPAC2013*, Shanghai, China, May 2013, paper WEPME035, pp. 3001–3003.

[5] C. Sydlo *et al.*, "Femtosecond Optical Synchronization System for the European XFEL", in *Proc. IPAC2017*, Copenhagen, Denmark, May 2017, paper THPAB108, pp. 3969–3971.