FEMTOSECOND OPTICAL SYNCHRONIZATION SYSTEM FOR THE EUROPEAN XFEL

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Abstract

Accurate timing synchronization on the femtosecond timescale is an essential installation for time-resolved experiments at free-electron lasers (FELs) such as FLASH and the upcoming European XFEL.

Conventional RF timing systems suffer from RF attenuation for such long distances and have reached to date a limit for synchronization precision of around 100 femtoseconds. An optical synchronization system is used at FLASH since a decade and is based on the distribution of femtosecond laser pulses over actively stabilized optical fibers.

The European XFEL has raised the demands due to its large number of stabilized optical fibers and a length of 3400 m. The increased lengths for the stabilized optical fibers necessitated major advancement in precision to achieve the requirement of less than 10 femtosecond precision. This paper reports on the status of the laser-based synchronization system at the European XFEL.

INTRODUCTION

For the European XFEL a very strong emphasis is put on the optical reference distribution. Already in the very first expansion stage 24 stations will receive optical synchronization with the possibility to extend this number to 44 stations. The overall scheme is depicted in Fig. 1. The master-oscillator (MO) distributes a stabilized 1.3 GHz reference to which the master laser-oscillator (MLO) is locked.

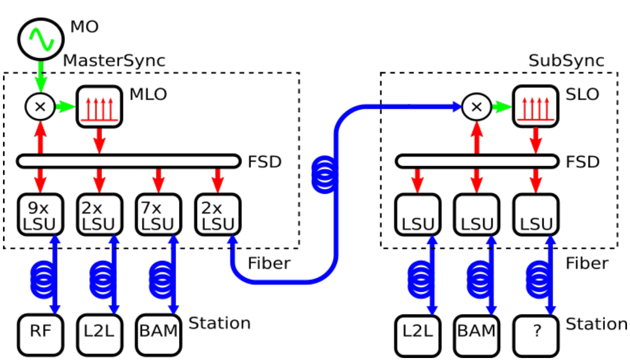

Figure 1: Optical reference distribution scheme.

This stabilized pulse train from the MLO is split into multiple channels and guided to the individual link stabilization units (LSUs) through the free-space distribution. Each LSU actively stabilizes the effective length of its assigned optical link fiber, which can conveniently be guided through the entire FEL to stations obliged to femtosecond timing stability.

The optical synchronization has to supply 9 stations stabilizing the RF reference [1], 7 laser-to-laser locking stations [2] and 7 stations with direct usage of the pulse train for bunch arrival-time measurement [3].

A sub-synchronization facility is located in the experimental hall at the end of the beamlines to facilitate the synchronization needs for the pump-probe lasers on-site. Additionally, it will stabilize all stations between 2.1 km and the end of the experimental hall.

Hence, two more links with a length of 3.6 km are provided for the synchronization of the sub-synchronization facility. On one hand, this serves as a redundancy improving reliability and robustness. On the other hand, these two long links can be cross-correlated in-situ for diagnostics providing a measure for the actual synchronization accuracy.

MASTER LASER OSCILLATOR

The MLO has a repetition rate of 216.7 MHz (a sixth of the MO frequency) and its seventh harmonic (1516.7 MHz) is used for locking. The lock on a higher harmonic improves the performance. In this locking scheme the harmonic is mixed with the signal from the MO to an intermediate frequency and is then digitized. This way any issues with DC offsets, drifts and 1/f noise are avoided.

In Fig. 2 the measured phasenoise of the MO and the MLO are compared with a signal source analyzer E5052 from Keysight. The measurement of the MO took place in the actual syncronization room which gets the MO signal via 25 m of coaxial cable.

The measurement of the MLO needs more attention. The presented measurement has been performed with a commercial photodiode ET3010 from Electro-Optics Technology Inc., a custom bandpass filter from Integrated Microwave Corporation and a RF amplifier ZX60-33LN from Mini-Circuits. Nonetheless, different photodiodes, bandpass-filters and amplifiers have been deployed to verify these results.

In a bandwith from 100 Hz up to 1 MHz the resulting RMS jitter for the MO and the MLO is 7.4 fs and 9.6 fs, respectively. The large descrepancy of nearly 2 fs results mostly from the increased phasenoise of the MLO around 500 Hz and is currently subject of investigation. Considering a reduced bandwidth from 1 kHz up to 1 MHz the RMS jitter values drop to 5.1 fs for the MO and 4.1 fs for the MLO.

It should be noted that not the absolute jitter is relevant for FEL operation but the differential jitter between the MO and the MLO.

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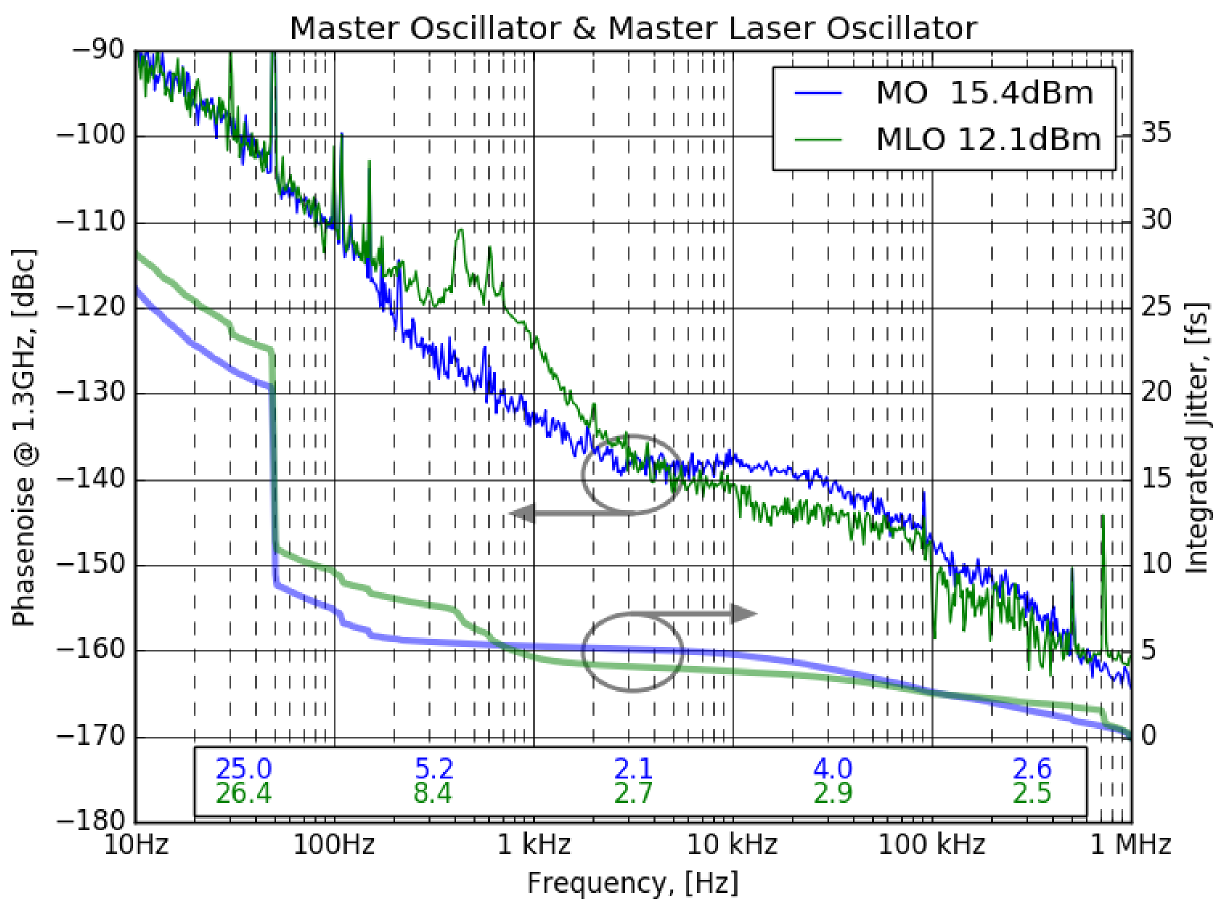

Figure 2: Phasenoise of the Master Oscillator and the Master Laser Oscillator. The inset in the lower area of the graph shows the RMS jitter for each correspondig frequency decade.

FIBER LINK STABILIZATION

The stabilized MLO signal is distributed in free space to the individual LSUs. To accommodate the large number of LSUs - up to 24 LSUs are used on one optical table - they need to be placed efficiently. The optical free space distribution for each individual LSU reaches a certain length. These lengths are kept identical to maintain identical beam parameters for each LSU. This distribution occupies a large amount of the optical table and each path from the MLO to a LSU has a length of about 2625 mm.

Conventional optical tables are composed of 4.8 mm thick steel plates as top and bottom sheet. Steel has a thermal expansion coefficient of about 10 ppm/K or about 33 fs/K/m [4]. For a climatization environment a thermal stability of 0.1 K is ambitious, but realistic. That would result in more than 6 fs drift for the optical table alone and is already outside the acceptable range. Therefore, the optical table supporting the MLO and the LSUs - more specifically the top and bottom sheet - are made from Superinvar, which has a very low thermal expansion coefficient resulting in less than 1 fs/K/m [4]. Both sheets have been manufactured from Superinvar to avoid a bimetallic effect.

The most dominant contribution for drift is now the change of the refractive index of air which is about 3 fs/K/m [5]. This issue can easily be overcome by placing the laser locking scheme at the same distance from the MLO as the LSUs to exploit the common mode drift. While the temperature distribution on an optical table is usually not uniformly distributed due to the finite thermal conductivity, the temperature distribution of air is governed by movement. Consequently, this optical table incorporates dedicated holes for this purpose and a ventilation system is integrated into the climatization system. These holes are used to gently vent the table during operation avoiding trapped heat. The LSUs and the distribution have been described in [6] and an updated and detailed version is presented in [7]. A photography of the main optical table is presented in Fig 3.

CURRENT STATUS

At the time of writing 11 LSUs are in operation and serve different endstations. So far the best values achieved are around 0.12 fs RMS in a bandwidth from 10 Hz up to 1 MHz. However, it has to be clarified that these values are measured within the controller loop. Therefore, an additional

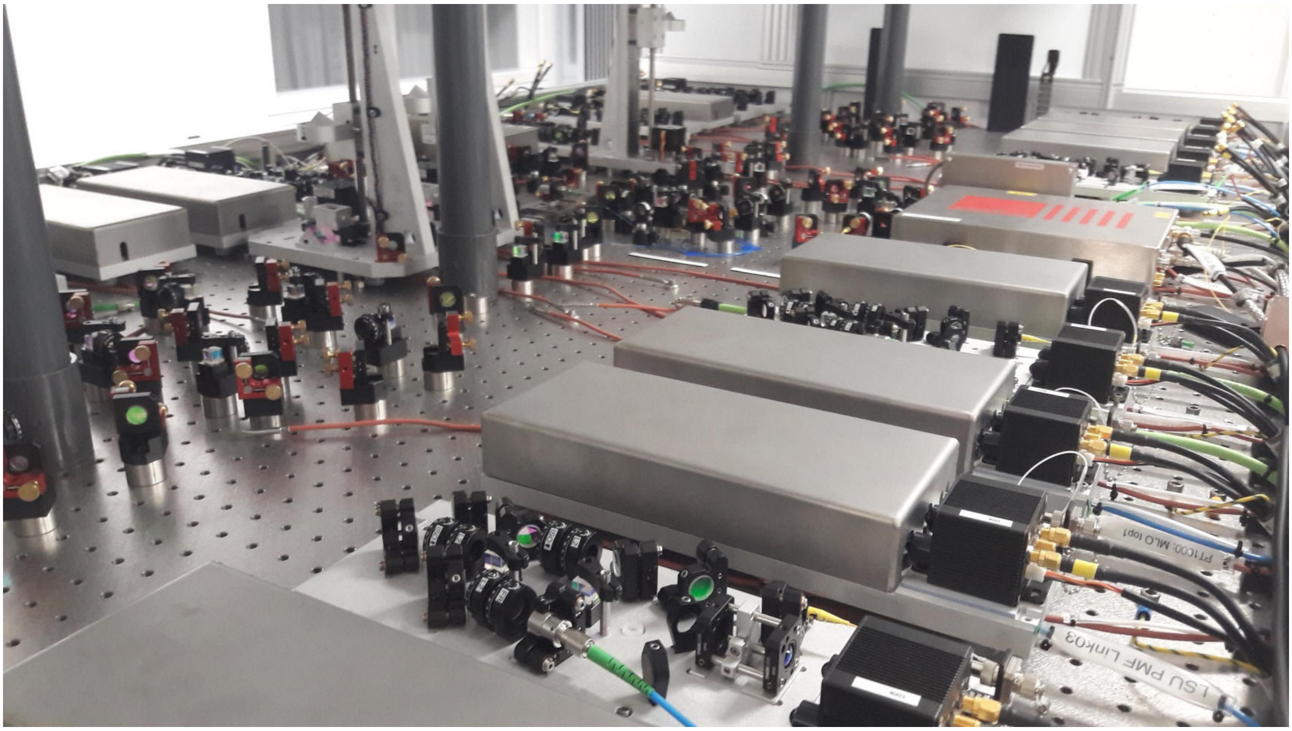

Figure 3: Main optical table for the optical reference generation and distribution. This table currently holds one MLO (the second, redundant MLO is in repair), 3 of 7 optical delay lines, 22 of 24 Link Stabilization units, 74 polarizing beam cubes and more than 250 kinematic mounts.

jitter value for the LSU can be assessed depending on the lock bandwidth, but no statements can be made regarding drifts. Independant measurements for jitter and drift are scheduled and will provide substantial stability statements for the optical synchronization within the XFEL.

These LSUs have already shown in independant measurements less than 3.5 fs RMS over more than 24 hours [6]& [8] with a 3.6 km long fiber link. In order to make useful statements about the performance this fiber had been installed in a storage hall on the DESY campus to account for realistic conditions.

OUTLOOK

The work continues to finalize the optical synchronization system at the European XFEL and prepare it for time resolved user experiments. Previous work has already demonstrated jitter levels for fiber link stabilizations of 3.3 fs RMS. The results presented in this work demonstrate a low jitter optical reference. Both results are well in agreement with the synchronization requirements for the European XFEL. The limits of achievable synchronization accuracy with reasonable complexity are not reached yet. Further work will concentrate on these limits to be prepared for potentially increased requirements in the future.

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