MTCA.4 PHASE DETECTOR FOR FEMTOSECOND-PRECISION LASER SYNCHRONIZATION

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Abstract

For time-resolved experiments at FELs such as the European XFEL an accurate synchronization of the machine is essential. The required femtosecond- level synchronization we plan to achieve with an optical synchronization system, in which an inherent part is the master laser oscillator (MLO) locked to the electrical reference. At DESY we develop a custom rear transition module in MTCA.4 standard, which will allow for different techniques of phase detection between the optical and the electrical signal, as well as locking to an optical reference using a cross-correlator. In this paper we present the current status of the development, including two basic solutions for the detection to an RF. One of the methods incorporates an external drift free detector based on the so-called MZI setup. The other one employs the currently used down-converter scheme with subsequent improvements. The module can serve for locking a variety of lasers with different repetition rates.

INTRODUCTION TO OPTICAL SYNCHRONIZATION SYSTEM AT THE EUROPEAN XFEL

The optical synchronization system planned for the European XFEL has a range of uses. It is employed in these locations of the facility, where the most demanding synchronization precision is necessary. First of all, it serves as a reference for a number of lasers in the machine, including pump-probe laser for time resolved experiments. The lasers can be directly locked to the optical synchronization system using laser-to-laser locking stations (L2L) described in [1]. Another applications are precise bunch arrival-time monitors or a support for the 1.3 GHz coaxial cable based timing distribution, suffering from the drifts arising with a distance from the signal source in the cables because of their thermal expansion. The electrical synchronization system, mainly supplying the LLRF stations along the FEL, comprises of so-called interferometer links which task is to extend the possible synchronization distances [2]. Nevertheless, to achieve the required stabilities of the timing signal at different locations along over 3km long accelerator, the system has to be resynchronized to the optical reference. At DESY, we have developed a module called REFM-OPT, which promises to achieve sub-10fs synchronization precision between electrical and optical signal over longer time periods [3]. The REFM-OPT utilizes the laser-to-RF phase detector (L2RF)

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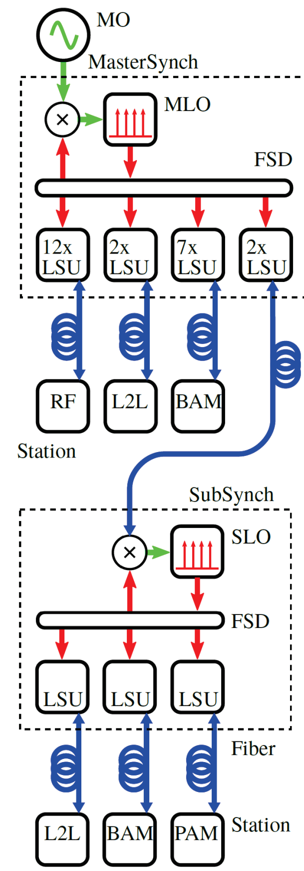

Figure 1: Optical synchronization scheme of the European XFEL. Description of system components: Master Oscillator (MO), Master Laser Oscillator (MLO), Slave Laser Oscillator (SLO), Free-Space Distribution (FSD), Link Stabilization Unit (LSU), Laser-to-Laser synchronization (L2L), Laser-to-RF synchronization (RF), Bunch Arrival-time Monitor (BAM) - beam diagnostics directly using the laser pulse train, Photon Arrival-time Monitor (PAM). Figure source: courtesy of Cezary Sydlo

of an extraordinary performance presented in [4], where we obtained 3.6 fs peak-to-peak phase drift over 24 h.

An overview of the optical synchronization system is shown in Figure 1. It incorporates the current solution used at DESY's mother facility FLASH (about ten times smaller than the European XFEL), with subsequent improvements and extensions. The signal source is a master laser oscillator (MLO), which is a commercial mode-locked laser with pulse duration of 200 fs at a repetition rate of 216.67 MHz. The MLO in turn is locked to the master oscillator (MO), the

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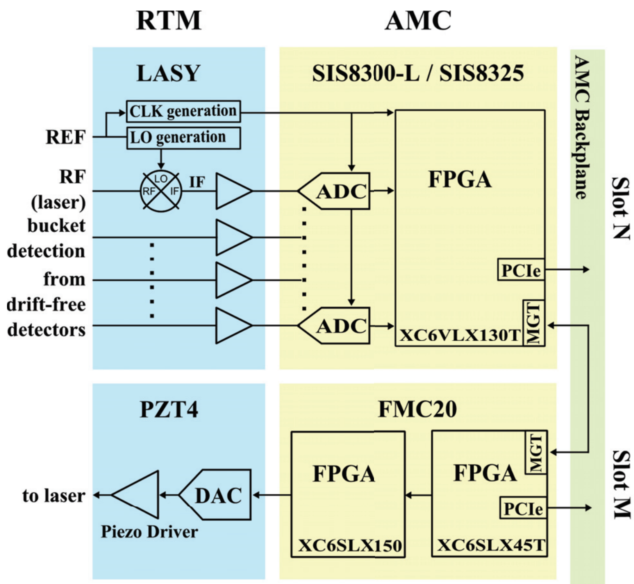

Figure 2: MTCA.4 components for laser locking application. Description of the terms: RTM-Rear Transition Module, a board connected to a specific AMC from the rear side of a MTCA.4 crate, AMC-Advanced Mezzanine Card, LASY-LAser SYnchronization board, SIS8300-L/SIS8325-digitizer board, where the controller is implemented, PZT4-4 channel piezo driver to control the piezo of the laser, FMC20-dual FPGA mezzanine card, here used for backplane and RTM interconnections.

ultra-stable signal source of a six times higher frequency (1.3 GHz) for the electrical reference distribution system. The signal distribution is done through the free-space distribution (FSD) and link stabilization units (LSUs) and it has been presented in more detail in [1], whereas the MLO locking scheme together with supplementary locking schemes implemented on the same hardware for another lasers is a subject of this paper.

LASER LOCKING SCHEME BASED ON MTCA.4 STANDARD

Laser synchronization in the European XFEL will utilize the MTCA.4 standard [5]. In the current development state, the system is built out of MTCA.4 cards, from which the phase detector item DRTM-DWC10 was designed to fulfill LLRF system needs and adapted for laser locking purpose with external RF components [6]. In the near future, the setup will be enriched by a dedicated rear transition module DRTM-LASY, first mentioned in [7]. It will exchange the currently used external RF components and DRTM-DWC10 board, and provide a set of new functions. The laser locking MTCA.4 setup supplemented with this module is presented in Figure 2.

In order to lock the laser to the reference (which can be either optical link end or RF signal), the phase difference between these two signals is first detected on LASY board (in one of the methods described below) or by a connected to it drift-free detector. The resulting error signal is processed to its Advanced Mezzanine Card (AMC). There it is digitized and the phase difference is stabilized by a controller, which acts on the laser's frequency/phase via piezo driver board called DRTM-PZT4 [8]. Alternatively, an external actuator can be used, but it has naturally a disadvantage of more external components. Taking into account the flexibility of the setup, the photo detectors to convert the laser signal to RF are not placed on LASY. However, there is foreseen a regulated power supply to drive an external photo diode. Additional feature enabling extension of board usage are two DAC outputs, which are planned to be added at the front panel. Having discussed what the complete synchronization setup looks like, the following sections move on to review various phase detection methods supported by LASY RTM.

DOWN-CONVERTER LOCKING SCHEME

The laser lock using a down-converter scheme is the most straightforward and bases on two-steps locking procedure described in [6]. All the RF components placed before out of a MTCA.4 system are now integrated on the LASY PCB (Figure 3). In order to achieve a flexibility over possible LO frequencies, independent of available reference, the board provides an LO generation functionality. Similarly, there is a clock generation section foreseen, thus an optimal clock frequency at ADC for non-IQ detection may be derived. For the sake of better performance in case of noise and phase drift, two compensation methods are implemented.

Reference Tracking

One of the methods to suppress the phase detection error due to the noise and drifts in the detector hardware is reference tracking. The method requires incorporation of another down-converter channel, where the reference can be injected instead of the measured laser signal. Assuming the reference is drift-free, any detected phase differences (measured against LO derived from the same signal) could be treated as coming from the setup itself. Expressed another way, by tracking the reference, one can detect the false part of the phase difference measured between the reference and the laser signal, coming from the LO generation block, RF components or PCB traces. Consequently, the phase difference detected on the reference tracking channel can be subtracted from the one from the laser channel.

The method requires, that both down-converter channels are possibly identical. Any inaccuracy in this matter, such as component's tolerance, yields to limitation of phase correction within this scheme. From the other hand the problem can be addressed, at least to a certain degree under another constrains, by using a two-tone calibration method described in the next section.

Two-tone Calibration

To date, several studies investigating various configuration with different applications have been carried out on this phase drift calibration method [9,10], here one more method

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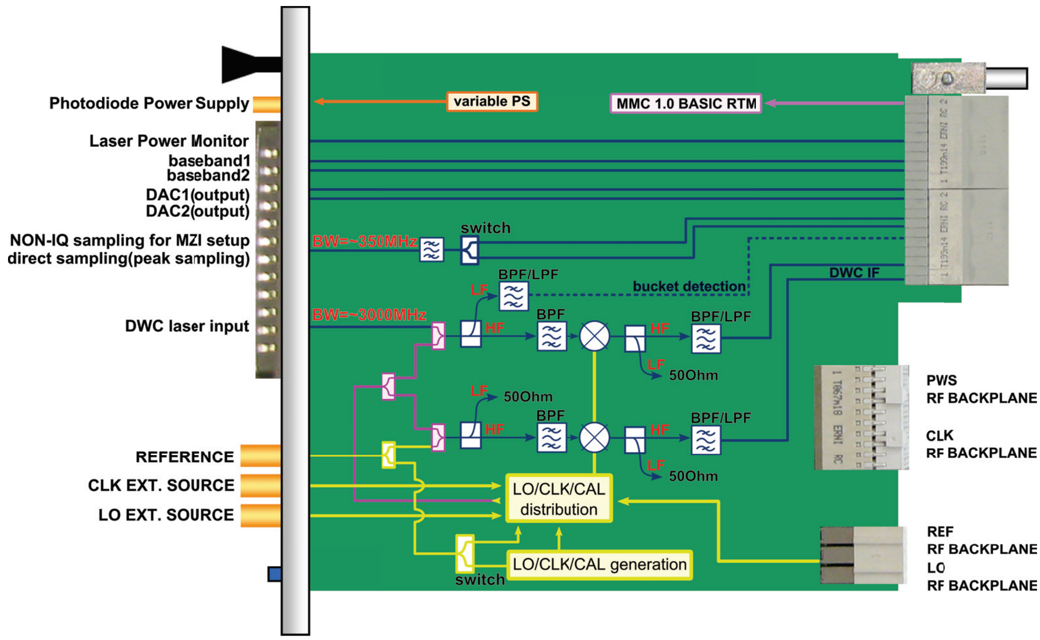

Figure 3: Block diagram of a DRTM-LASY module.

variation is applied, which corresponds to the specific application. Its advantage in respect of reference tracking consists in that the calibration signal is injected into the same hardware as the measured signal. Because of this, the frequency of a calibration signal has to be of different frequency than the measured laser harmonic to be thereby distinct from it. On the other hand, studies have shown that the chosen frequency should be also possibly close to it. Choosing an optimal calibration signal has conclusively been discussed in [10].

The method requires, that the calibration signal injection area (marked in magenta in Figure 3) is drift free, because any drift occuring here is not calibrated. The challenge lies in the fact, that the section must be also very wideband when used for this application - the same components conduct also a bucket detection signal, which is a base laser harmonic, thus of much lower frequency that the one likely used in the down-converter chain. The are several ideas how to overcome this problem, which will be addressed in the near future.

LASER LOCK USING DRIFT-FREE DETECTOR

The DRTM-LASY supports several locking methods exploiting so-called drift-free detectors. In both detectors, the phase is compared in the optical domain, converted to an electrical signal and then processed further to the digitizer.

Optical Cross-correlator

Thus far, the most precise method to lock the laser is a lock to the optical reference using a cross-correlation method. Its principle and the necessary external components can be explored in various sources [1, 11, 12], the most recent report

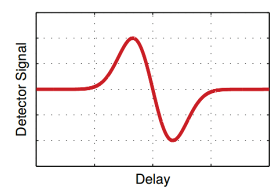

Figure 4: Example signal derived from the balanced optical cross-correlator. Figure source: [13].

can be found in [13]. The optical cross-correlator measures the relative timing between two optical pulses. These two pulses are mixed with each other on a nonlinear crystal, so that the intensity of the sum signal shows their overlap. To learn which pulse was first, there is a second setup with a known delay introduced additionally between the pulses. Then both overlapped ('sum') signals are detected on a balanced photo detector and processed via two baseband tracks on LASY to be subtracted from each other in the digital control system, giving the characteristic signal shown in Figure 4. The signals cannot be subtracted before the processing in the control system because of a certain ambiguity of the difference signal. Subtraction results in zero in both cases when the pulses do not overlap at all or if they are perfectly overlapping with each other (zero crossing on the plot). If we process both sums, then we can distinguish the situation of perfect synchronization by looking at the individual sum signals.

Laser-to-RF Detector

Locking the MLO to the reference coming from a MO will be performed using a L2RF phase detector, originally developed for a REFM-OPT module as was mentioned in the introduction to this paper. The L2RF detector principles

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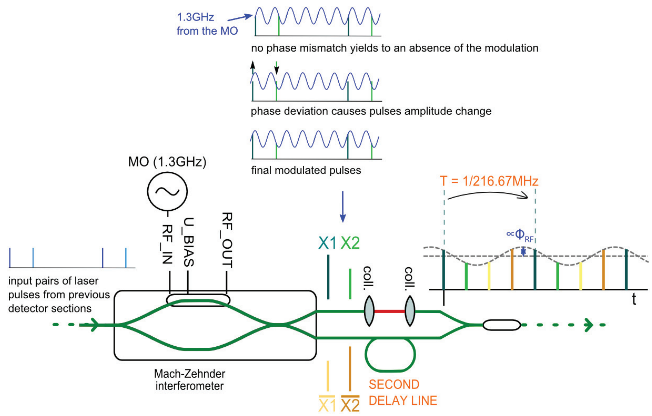

Figure 5: A scheme briefly showing phase detection in an L2RF setup. An output signal containing information about phase mismatch is in case of an MLO of frequency equal 216.67 MHz, which is also a laser pulse repetition rate. Its amplitude is proportional to the phase error.

were described in [14]. This phase detector compares the optical pulses with a RF signal in an EOM, where the optical pulses are modulated in amplitude depending on the phase shift between the signals. The phase mismatch is proportional to the modulation depth as shown in Figure 5. The amplitude of an output signal of 216.67 MHz (1/6 of 1.3 GHz) can be detected either by direct sampling or by readout electronics presented in [15]. Depending on repetition rate of the laser pulses the frequency of the L2RF output signal will change accordingly [16].

In case of using readout electronics, one can process an information signal via LASY baseband inputs like the ones from an optical cross-correlator. In the other case, there will be used a direct sampling input. An optimal configuration in which a L2RF detector should be used for MLO synchronization will be a subject of investigation in the near future.

CONCLUSION

This paper has introduced a new MTCA.4 card for laser synchronization DRTM-LASY and presented its features which are to be implemented. The board has been presented in the context of MLO synchronization to the accelerator electrical reference, although it is supposed to be used also for other lasers at FLASH, the European XFEL or other facilities. DRTM-LASY supports different synchronization schemes, including laser-to-laser method, laser-to-RF synchronization using drift-free detector or a down-converter scheme.

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