FEMTOSECOND STABLE LASER-TO-RF PHASE DETECTION USING OPTICAL MODULATORS

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Abstract

Free-Electron Lasers like FLASH and the European XFEL require the synchronization of RF stations to the optical timing reference of the accelerator. For this purpose, a new technique to phase-lock RF sources to an optical pulse train has been invented. The new technique uses an opto-microwave coupling device together with an ultra-low phase-noise RF source operating at a frequency of 1.3 GHz. In our arrangement, the Laser-to-RF phase detector is insensitive to amplitude fluctuations of the optical reference pulse train, which allows the detector to achieve femtosecond precision over long time periods. In this paper, we present the balanced Laser-to-RF phase detection principle along with a tolerance study of the arrangement and first results from our prototype setup.

INTRODUCTION

Laser-to-RF conversion is a critical technique concerning the further spread and implementation of optical synchronization systems at accelerators like Free-Electron Lasers. Different subsystems of the accelerator rely on classical RF reference and synchronization signals. The stability of those signals, mostly in terms of timing jitter and long-term drifts suffers from cable length and imperfections in amplifiers and similar components. A new reliable Laser-to-RF conversion scheme was recently developed and tested thoroughly at DESY, which will be used to supply the RF stations at FLASH with a precise synchronization signal derived from the master laser oscillator (MLO). The connection of those critical RF endstations to the optical synchronization system with its actively stabilized fiber links will offer the possibility to supply a sub-10 fs stable synchronization signal to them.

Different approaches for a reliable Laser-to-RF conversion were tested in the past, all with particular problems. The so-called direct conversion, which involves the use of photo diodes and succeeding band pass filters for the RF generation mainly suffers from AM/PM effects [1] and temperature drifts. Especially the AM/PM conversion makes it hard to extract a drift free RF signal from a laser pulse train. A second setup, feasible for the Laser-to-RF conversion is the so-called Sagnac loop. This scheme uses a Mach-Zehnder interferometer (MZI) as opto-microwave coupling device, which is inserted into a fiber loop, modulating the amplitude of co- and counter-propagating pulses in this loop. The loop itself is hard to build and to operate,

because all lengths have to be adjusted very accurate in the order to achieve a good performance. This scheme already was demonstrated to be working at a level of peak-to-peak drifts of 6.1 fs over a time span of 8 h and measured at a frequency of 10 GHz [2], while 10.7 fs (rms) over a timescale of 15 h and at a frequency of 1.3 GHz were demonstrated, but connected to a worse peak-to-peak value [3]. The lower operating frequency renders this scheme more difficult in operation in the same order of magnitude.

The Laser-to-RF conversion setup presented in this paper, is in principal a highly accurate and sensitive phase detector between the optical pulse train and the RF signal. It also relies on a Mach-Zehnder interferometer as opto-microwave coupling device, but in a different configuration. It is operating at a frequency of 1.3 GHz, which is the common accelerator frequency for FLASH and the European XFEL, but other frequencies are also feasible for the operation. The scheme is insensitive to input power fluctuations because it is balanced. It allows the precise control of the working point of the Mach-Zehnder interferometer with an active bias feedback.

PRINCIPLE OF OPERATION

The setup presented in this paper has specific demands on the relation between RF frequency and laser repetition rate. In our case, the RF frequency has to be an even, whole-number harmonic of the laser repetition rate. Uneven harmonics can also be used in this scheme, but in this case, the optical delays have to be adjusted different from those used here.

The principle of operation relies on the sampling of the RF signal with the laser pulses. In the ideal operating point, when the phase-locked loop (PLL) is closed, the laser pulses always pass the Mach-Zehnder interferometer at different zero-crossings (with positive and negative slope) of the RF. At the output of the setup three control signals are obtained. One signal is used to lock the RF to the laser pulse train, it's called the phase signal. The bias signal, which is proportional to the bias mismatch, is used to balance the Mach-Zehnder interferometer continuously with the correct bias voltage. The last output signal gives a measure for the split ratio mismatch, which will later be explained in detail. Figure 1 shows a block diagram of the detector.

The VCO (voltage controlled oscillator) is locked with a PID controller to the phase output of the Mach-Zehnder setup and thus the laser pulse train. The RF signal from the VCO is amplified with a high power amplifier and then fed

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Figure 1: Block diagram of the Laser-to-RF scheme including phase, bias and split ratio control.

through the MZI, which also has an RF output, from where the synchronized 1.3 GHz signal can be used to connect any device that needs such a precise and stable synchronization signal. The bias voltage is controlled by another PID controller depending on the bias signal from the detector.

The setup itself incorporates some additional components, which are needed to generate all three measurement signals. Before the reference pulse train enters the MZI, it is split up, while one part (X2) is delayed by one quarter of the repetition rate. The splitting ratio mismatch can be detected and controlled, as previously mentioned. Then the pulses are recombined and guided through the MZI, where their amplitude is modulated. The MZI itself has two optical outputs, compared to only one output at a traditional modulator. Those two output signals show an inverted modulation (labeled with X and $\overline{X}$) relative to each other. If the optical power at one output rises, the power at the other output decreases and vice versa. Behind the MZI a second delay line follows for one of those two outputs, with a length of half the repetition rate. Now, both signal are recombined and guided onto a photo diode. At this point, the repetition rate has increased by a factor of four, compared to the original repetition rate. If the detector is in its operating point, all laser pulses have the same power. Phase, bias or splitting errors lead to different modulations of the laser pulses, which can be detected in the order to generate the control signals.

The detection is implemented with RF mixers. The LO signal, which is needed to drive those mixers is also derived from the reference pulse train, thus it has a fixed phase relation to the signal measured after the test setup by the photo diodes. In Figure 2 the modulated pulse train for all three detectable errors is presented. Part a) of the figure shows the modulation caused by a phase error between the laser pulse train and the RF. The pulse amplitude is in this case modulated with the fundamental frequency of the laser, while the phase of this modulation is shifted by

-45 deg with respect to the first laser pulse. Part c) shows a typical modulation caused by a bias voltage mismatch, which shows up at the same frequency, but this time shifted by +45 deg with respect to the first laser pulse. The two RF mixers (at the bottom of Figure 1) used to detect those signals are both driven as amplitude detectors. The phase difference of 90 deg between the two signals allows each RF mixer to detect only one signal while the other one, located at the zero crossing of the RF mixer characteristic does not show up in the output. The measurement phases for both fundamental detectors are highlighted in Figure 2 to emphasize this fact. Part b) shows the last signal, which is proportional to the splitting ratio mismatch in front of the first delay line and shows up at a different frequency, in this case twice as large as the fundamental repetition rate. The amplitude of every second pulse is modulated. This signal is also detected with an RF mixer (at the top of Figure 1).

Figure 2: Modulated pulse trains before the photo diode, showing different errors and their measurement points.

TOLERANCE STUDY

Internally the Mach-Zehnder interferometer consists of a splitter, after which one branch is delayed by a small amount of time. Then those two signals are recombined,

which leads to an amplitude modulation at the output of the Mach-Zehnder interferometer proportional to the applied bias and RF voltages. $U_{b,0}$ is the voltage, which has to be applied to the MZI to achieve equal transmission to both output ports, while U_b and $\hat{U}_{RF}$ are the voltages actually applied to the corresponding inputs. $U_{b,\pi}$ and $U_{RF,\pi}$ are the voltage levels required to achieve a phase shift of π in the MZI, which covers the transition from minimum to maximum transmission for one output port, while the second port is inverted to the first one.

$$\Phi_b = \pi \cdot {(U_b-U_{b,0})}/{U_{b,\pi}} \qquad (1)$$

$$\Phi_{RF} = \pi \cdot \hat{U}_{RF}/U_{RF,\pi} \qquad (2)$$

The optical powers of all four pulses travelling through the MZI (two input pulses, transmitted to the normal and the inverted output) are given by Eq. 3. The signs have to be chosen according to the investigated pulse. The first sign must be negative for the inverted output of the MZI, else positive, the second one has to be selected according to the first delay line (negative for X2).

$$P_n = {P_0}/{2}\left[1 \pm \sin\left(\Phi_b \pm \Phi_{RF} \cdot \sin\left(\Delta\phi_{RF}\right)\right)\right] \quad (3)$$

This formula is already simplified in the order give an insight in the mechanisms, which render this scheme usable and robust. P_0 is the optical input power of the pulses, which is apparently assumed to be equal for all pulses. $\Delta\phi_{RF}$ is the phase shift between RF and pulse train in the MZI. After the RF mixer, which mixes the measurement signal down to the baseband, the following voltage can be observed, proportional to the phase shift between laser pulses and RF in the MZI.

$$U_\phi = {A}/{2} \cdot \sum_{n=1}^{4} P_n \cdot \cos\left[(2n-1)\cdot{\pi}/{4}\right] \qquad (4)$$

$$A = R_{PD} \cdot G_{RF} \cdot K_M \cdot G_{LNA} \qquad (5)$$

The parameter A is the product of all electrical gains involved in the detection, particularly the conversion efficiency from the photo diode R_{PD}, the gains of the RF (G_{RF}) and the low noise (G_{LNA}) amplifiers and the conversion loss of the RF mixer K_M. By putting all values into this formula and simplifying it, one finds

$$U_\phi = {A}/{\sqrt{2}} \cdot P_0 \cdot \Phi_{RF} \cdot \Delta\phi_{RF} \qquad (6)$$

Here it can be seen, that all parameters in the formula change the gain or conversion coefficient of the setup, but not the working point. If the phase difference between laser pulses and RF is zero, all those parameters don't have to be taken into account, because this point is a fix point of the scheme. Furthermore, the gain can be optimized by optimizing all parameters individually. All of them have technical limits, for example their noise floor or power handling ability, but they also have room for optimizations.

If some error terms are taken into account, this formula becomes more complex. Eq. 7 shows a still simplified error estimation. The DRO (dielectric resonator oscillator) is for example considered to be locked, which means, its frequency is a perfect harmonic of the laser repetition rate. The terms δt_1 and δt_2 cover small errors in the length of the first and the second delay line, $\delta\varphi_{LO}$ takes account of possible LO drifts. ω_R and ω_{RF} are the laser repetition rate and the RF frequency given as angular frequency.

$$
\begin{aligned}
U_\phi = {A\cdot P_0}/{(2\sqrt{2})}\big[&2\cdot\Phi_{RF}\Delta\phi_{RF}\\
&+\Phi_{RF}\omega_{RF}\delta t_1 + \omega_R\delta t_2 + \Phi_{RF}\Delta\phi_{RF}\omega_R\delta t_1\\
&+2\Phi_b\delta\varphi_{LO} - \Phi_b\omega_R\left(\delta t_1+\delta t_2\right)\\
&+\Phi_{RF}\omega_R\omega_{RF}(\delta t_1)^2 + {1}/{2}\Phi_{RF}\omega_R\omega_{RF}\delta t_1\delta t_2\\
&-\Phi_{RF}\omega_{RF}\delta t_1\delta\varphi_{LO}\big]
\end{aligned}
\qquad (7)
$$

Now one can clearly see the different error terms. For a closed bias loop for example, Φ_b is supposed to be zero or close to zero, which suppresses the second order terms in line three of the equation and particularly the influence of LO drifts. The terms in the last two lines of the equation are also second order terms and can therefore be neglected. The most critical terms can be found in the second line. There the first terms can be interpreted as a phase offset, which is connected to the adjustment error and the drifts of both delay lines, where the error from the second delay line is suppressed by an additional factor of almost twenty due to the smaller laser repetition rate and the factor Φ_{RF}. The last term in this line also depends on the first delay line, but this time also suppressed. Hence the biggest effort should be spent on the careful construction of the first delay line which is the most sensitive part of this setup.

TEST SETUP AND MEASUREMENT RESULTS

As mentioned before, the optical signal will later be supplied by the optical synchronization system, while for this test setup a commercial M-Comb laser system from Menlo Systems at a repetition rate of $216.6\overline{6}\,\text{MHz}$ was used as reference source. The RF signal at $1.3\,\text{GHz}$ is supplied by a DRO.

The control of the split ratio was omitted at the test setup, because the output polarization of the reference laser has been found to be stable enough. In the order to verify the test results, two Mach-Zehnder interferometer based phase detectors were build, one used to lock the DRO to the reference laser pulse train. Its output is connected via a phase shifter to a second phasedetector, which in this case servers as an out of loop detector. For this second detector a bias feedback was implemented in the same way as for the first one, while the phase output signal was used for the out of loop phase measurement. Long term data was taken with a datalogger at a measurement rate of $0.1\,\text{Hz}$, while the detector noise was characterized with a baseband analyzer from $10\,\text{Hz}$ to $10\,\text{MHz}$.

The $40\,\text{h}$ long-term drift data taken with this setup and shown in Figure 3 (top part) is representative for many measurements. The K_φ for this measurement was determined to be $1.268\,\text{mV/fs}$. The drift in this $40\,\text{h}$ measurement
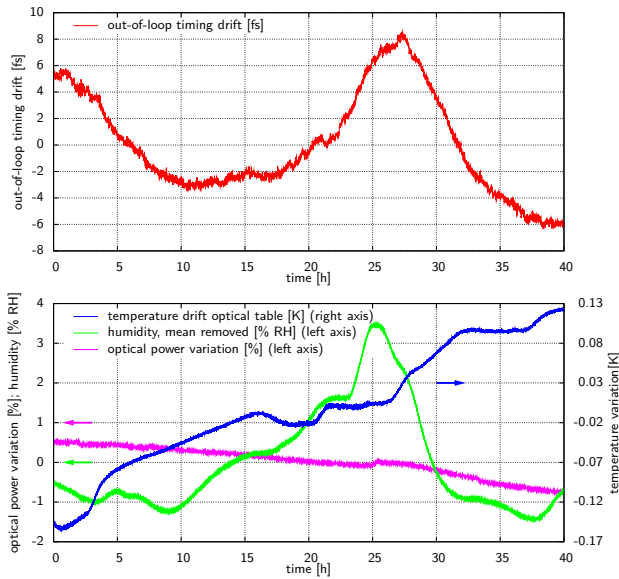
Figure 3: 40 hour drift measurement, out of loop phase detector (top), environmental conditions (bottom, mean values removed)

Figure 4: Baseband detector noise (top) and interated noise, converted to femtoseconds (bottom)

is 14.9 fs peak-to-peak and 3.8 fs rms. Up to our knowledge, this is up to now the best performance measured for a 1.3 GHz Laser-to-RF conversion.

The environmental conditions in the laboratory during this measurement can be found in the bottom plot of Figure 3. Here one can see, for example, that 1.3 % drift of the optical input power did not cause a correlated drift at the output of the phase detector. The temperature drift of the optical table (0.28 K) does also not show up in the results. Nevertheless it is very interesting to see, that the humidity changes in the laboratory have a big influence on the measurement results. The effect is very slow and delayed by approximately two hours. At in-house measurements at DESY, recently a temperature coefficient of $2.5 \, \mathrm{fs/(m \cdot \% \, RH)}$ was estimated for a similar fiber type. This coefficient, together with a fiber length mismatch of 0.4 m (where the input fiber of one MZI actually is shorter) and a humidity variation of 4.9 % RH peak-to-peak would then cause an error of 4.9 fs which is in the same order of magnitude as the drifts we observed.

If a 12 h timespan with stable environmental conditions out of this measurement is analyzed (here from 7 h to 19 h from the above plots), the peak-to-peak error reduces to 2.79 fs while the rms error is 0.51 fs. This performance can be considered representative for an improved setup, where the dependency from the humidity is reduced.

Finally, Figure 4 shows the results from two noise measurements at the output of the out of loop phase detector. The first one without RF connected to the setup, which shows the noise floor of the setup, and the second one with a DRO connected and locked to the in loop detector. This measurement shows, how well the DRO is actually locked to the laser pulse train. Integrated from 1 MHz down to
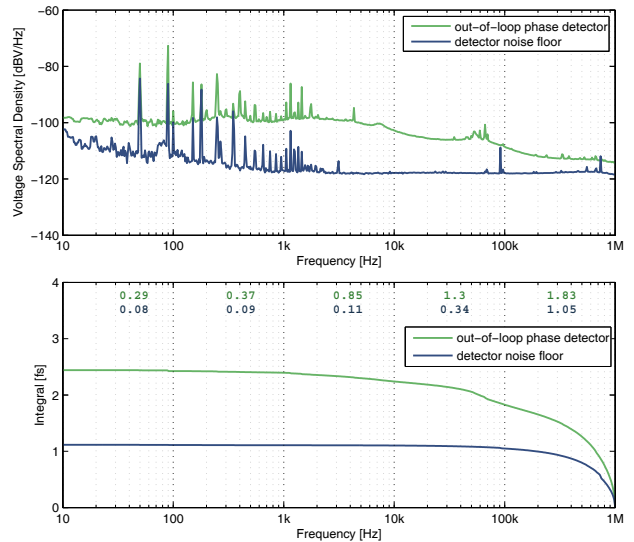
10 Hz and converted with $K_\varphi = 1.21 \, \mathrm{mV/fs}$ the contribution from the electronics amounts to 1.12 fs while the DRO is locked with a short term precision of 2.44 fs. The main contribution can be found outside the locking bandwidth of about 70 kHz.

CONCLUSION AND OUTLOOK

The Laser-to-RF scheme presented in this paper is very sensitive ($K_\varphi = 1.268 \, \mathrm{mV/fs}$) while showing an excellent long term stability of 3.8 fs rms (14.9 fs peak-to-peak) over 40 h. These are to our knowledge the best Laser-to-RF results at an RF frequency of 1.3 GHz reported yet.

The implementation confirmed the assumptions from the tolerance study. The largest remaining error source are changes of the humidity, which will be addressed in the near future with an improved setup.

This setup will be more compact than the previous one and is planned to be used at FLASH, where it is foreseen to supply a 1.3 GHz reference signal to the RF stations.

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