FS LEVEL LASER-TO-RF SYNCHRONIZATION AT REGAE

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Abstract

The Relativistic Electron Gun for Atomic Exploration (REGAE) is a unique linear accelerator capable of producing ultrashort (~ 10 fs) electron bunches for studying fast processes in matter by means of ultrafast electron diffraction (UED) experiments [1]. Additionally, REGAE is suitable for upcoming external injection experiments for laser wakefield acceleration (LWFA) [2, 5]. In order to carry out both mentioned experiments, it is crucial to achieve fs level stability in terms of laser-to-RF synchronization. In this paper we present an advanced laser-to-RF synchronization scheme based on integrated Mach-Zehnder Modulator (MZM). The setup demonstrated the Titanium Sapphire photoinjector laser synchronization with 11 fs (rms) precision in the bandwidth up to 100 kHz. Long term timing drift measurements showed unprecedented peak-to-peak stability of 31 fs (7 fs rms) over 43 hours of measurement time. In addition, AM-PM coefficient of the MZM based laser-to-RF synchronization setup has been evaluated and showed a factor of 10 improved performance compared to conventional direct conversion based laser synchronization setup.

INTRODUCTION

At REGAE a commercial Titanium Sapphire (Ti:Sa) laser system from Coherent Inc. is used as a photocathode laser to generate electron bunches by means of photoelectric effect. The generated electron bunches are accelerated up to 5 MeV in a S-band (f =2.9979 GHz) 1.5 cell RF gun and further bunched by the 4 cell RF buncher using a technique called ballistic bunching [3–5] before reaching the UED target chamber. At the target chamber a part of the laser beam together with the electron bunches are used to conduct UED experiments on a femtosecond level in a pump-probe fashion. Therefore, in order to achieve femtosecond level temporal resolution between the laser and electron beams, precise laser-to-RF synchronization is required.

For the past decade, various precise laser-to-RF synchronization methods have been carried out with femtosecond level residual timing instabilities (jitter and drift) [6–12]. The most recent publication [13] showed very impressive performance of Ti:Sa laser oscillator synchronization to a 2.856 GHz RF source with the residual timing jitter of 3.9 fs (12.2 fs) in the bandwidth up to 100 kHz (1 MHz) and with long term timing drift of 12.5 fs (rms) (> 150 fs peak-to-peak) over 24 hours. The synchronization method in [13] is based on a fibre-loop optical-microwave phase detector (FLOM-PD) [7]. In this paper we present the experimental evaluation of the limitations for the direct conversion based synchronization setup by means of amplitude-to-phase conversion (AM-PM) effects. Experimental results of an alternative laser-to-RF synchronization method based on 800 nm integrated MZM [14, 15] is discussed and corresponding out-of-loop residual timing jitter and drift characterization are manifested. In addition, the measurement results of the AM-PM effects for MZM based laser-to-RF synchronization setup are presented in comparison to direct conversion based laser-to-RF synchronization setup.

DIRECT CONVERSION BASED LASER-TO-RF SYNCHRONIZATION

One of the most common techniques to synchronize the mode-locked lasers to RF reference signal is using a fast photodetector. The idea of employing a photodetection for synchronization purposes is to convert pulsed optical signals to electrical signals. Electrical signals generated by the photodetector are composed of high spectral purity harmonics of the laser repetition rate. The cutoff frequency of the frequency comb is given by the bandwidth (BW) of the photodetector. Typical fast photodetectors are fiber coupled PIN photodiodes (e.g. EOT4000F). Usually, one of the harmonics of the frequency comb can be filtered out using an RF band-pass filter and a low noise RF amplifier in combination with an RF phase detector (e.g. double balanced mixer) can be employed for laser-to-RF synchronization [11, 16]. However, there are several limitations related to the photodetection technique. The two main problems are, AM-PM effects [17, 18], where the optical power fluctuation is converted to phase fluctuation of each frequency component of the generated frequency comb. Second, the power level in the generated frequency comb lines is rather low, leading to the limited signal-to-noise ratio (SNR). Mainly these two effects limit the laser-to-RF synchronization performance.

Measurement Results of AM-PM Coefficients

Already in our previous work related to REGAE facility [15] we have shown that the AM-PM effects in the direct conversion based laser-to-RF synchronization setup induces significant timing disturbances. Indirect measurement of AM-PM coefficients in [15] revealed that it varies between 160 fs $\%^{-1}$ to 300 fs $\%^{-1}$ of input optical power change[1]. Dedicated measurements have been carried out to deduce the AM-PM coefficients of the direct conversion based laser-to-RF synchronization setup. The measurement setup is shown in Fig. 1. The optical pulses from Ti:Sa laser oscillator (Micra) with a repetition rate of f_{rep} = 83.275 MHz (multiple of 2.9979 GHz RF reference) are split into two

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[1] AM-PM coefficient is defined as $\alpha_{\mathrm{am-pm}} = \frac{\Delta\varphi}{\Delta P/P}$ in units of femtosecond per percent of input optical power change.

branches. 10 % of its initial power is dedicated for synchronization purposes while the remaining 90 % is used for laser amplifier seeding. The 10 % branch of the laser pulses is further split into two parts using the optical band-pass filter (F1) to operate both in-loop and out-of-loop phase detectors respectively. Fiber coupled collimators are used to couple optical beam from free space to single-mode fibers for both in-loop and out-of-loop phase detectors (yellow, blue lines). A 12 GHz bandwidth fast photodiode (EOT4000F) is used as an in-loop photodetector together with the 3 GHz RF band-pass filter and low noise RF amplifier. The amplified ≈ 3 GHz laser signal is provided to the readout electronics and the phase error information between the RF reference signal from the RF master oscillator (MO) and laser signal is fed to the digital controller (see [11]).

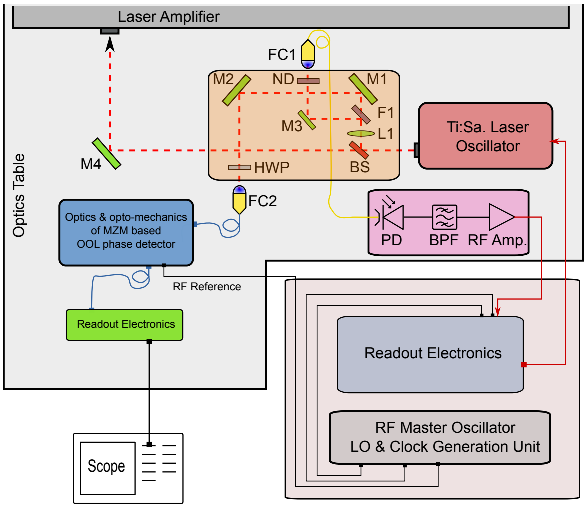

Figure 1: Block diagram of the AM-PM coefficient measurement setup.

Once the phase locked loop (PLL) was established using the direct conversion based laser-to-RF synchronization setup, the artificial amplitude modulation was introduced to the in-loop photodiode. The amplitude modulation was performed by rotating the free space optical neutral density filter (ND) in front of the in-loop fiber collimator (see Fig. 1). Simultaneously, the out-of-loop MZM based laser-to-RF phase detector was used to monitor the phase/timing changes corresponding to the artificial amplitude modulation due to the AM-PM effects. This procedure has been carried out for discrete optical power levels from 1 mW to 8 mW in steps of 0.5 mW and repeated for three different applied bias voltages (3 V, 5 V, 10 V). The measurement results are summarized in Fig. 2. Figure 2 shows the three curves of the AM-PM coefficients as a function of average optical power for different photodiode bias voltages. At low optical powers the AM-PM coefficient starts out at approximately 300 fs $\%^{-1}$ of input optical power change and is independent from the photodiode bias voltage. As optical power increases this coefficient starts to change sign and oscillate between ±300 fs $\%^{-1}$ of input optical power change. At certain optical power levels when the photodiode undergoes the deep over-saturation regime, the AM-PM coefficient becomes very large (see Fig. 2, $P > 7$ mW, bias voltage 3 V). For the laser synchronization purposes, the most interesting regions in Fig. 2 are the zero crossings of the $\alpha_{\mathrm{am-pm}}$, because ideally, $P(\alpha_{\mathrm{am-pm}} = 0)$ is a desired operating point for regular REGAE operation. However, the optical power of the Micra Ti:Sa laser oscillator at REGAE was changing 2 % to 3 % moving the AM-PM coefficient to undesired operating point.

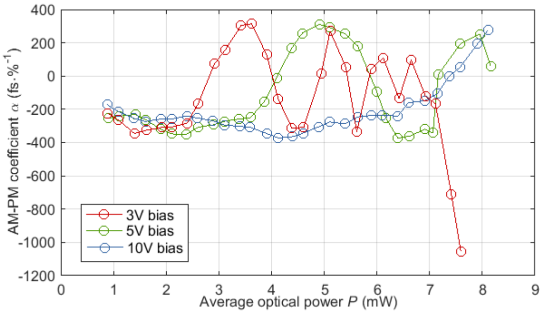

Figure 2: Measured AM-PM coefficients as a function of average optical power incident on a photodiode.

MZM BASED LASER-TO-RF SYNCHRONIZATION

The main idea of using a MZM based laser-to-RF synchronization setup is to mitigate the problems associated to the direct conversion based laser-to-RF synchronization setup (AM-PM effects).
The approach of using a MZM for laser-to-RF synchronization is based on sampling of the RF reference signal zero crossings with optical pulses from a Ti:Sa laser oscillator within the integrated MZM. This allows to convert the relative timing error between these two sources into an amplitude modulation of the optical pulses. For more details about the principle of operation of the setup see [14, 15].

Measurement Setup

Two identical MZM based laser-to-RF synchronization setups have been commissioned at REGAE. One was used to synchronize the laser oscillator to the RF reference ($f = 2.9979$ GHz), while the second one was employed as an out-of-loop phase detector to evaluate the relative timing jitter performance between these two sources. The simplified block diagram of the measurement setup is shown in Fig. 3. The optical pulses from the laser oscillator are coupled to the fiber collimator and provided to the MZM based synchronization setups via 50/50 fiber splitter. The RF reference signal is transmitted from the RF master oscillator which is further boosted by the high gain RF amplifier. The input optical power of ≈ 4.5 mW and ≈ +20 dBm of input RF power per setup resulted the in-loop and out-of-loop detector sensitivities of 0.275 mV fs^{-1} and 0.43 mV fs^{-1} respectively. The relative phase error signal from the in-loop MZM based phase detector is fed to the analog PI controller and the output of the controller is applied to the fast PZT actuator to close the feedback loop.

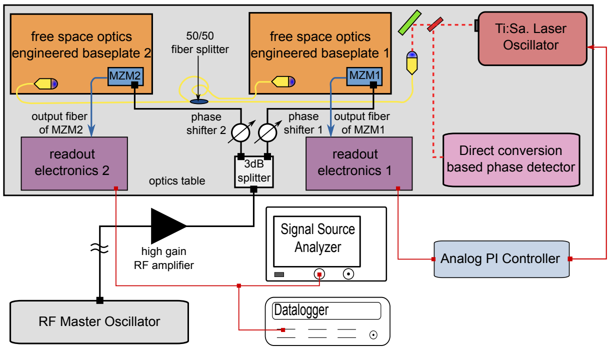

Figure 3: Block diagram of the residual timing jitter and drift measurement setup.

Timing Jitter and Drift

While the feedback loop was closed, an out-of-loop MZM based laser-to-RF phase detector was used to measure the residual voltage noise of the phase detector by using a signal source analyzer (SSA) (see Fig. 4). Later it was found out that the voltage noise above 40 kHz is dominated by the noise floor of the readout electronics. The noise floor of the readout electronics originates from the thermal noise of the 50 Ω load resistor. Since the loop bandwidth is small (few kHz) and significant laser timing jitter contributions beyond 100 kHz are unlikely, the integrated timing jitter from 10 Hz to 100 kHz is evaluated (Fig. 5). In this frequency range, the noise floor amounts to 6.85 fs, while the out-of-loop detector measures 13.3 fs about a factor of two higher than the noise floor with strong contributions at 12.5 Hz, 50 Hz and 2.2 kHz. If we quadratically subtract these two numbers, one can calculate that the laser was locked with a precision of ∼ 11 fs to the RF source. The 12.5 Hz frequency line is originated from the operation of the DESY II synchrotron which is located in the vicinity of the REGAE facility.

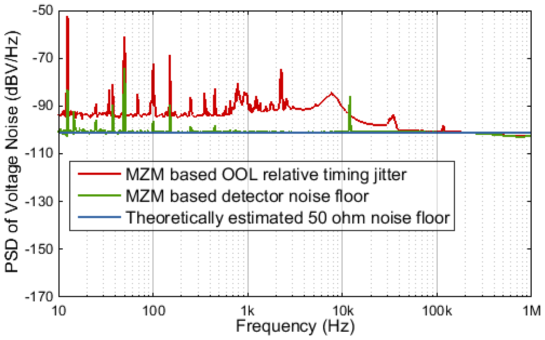

Figure 4: Out-of-loop voltage noise.

Another important parameter which has been evaluated for the MZM based laser-to-RF synchronization setup is the long term timing drift stability. Figure 6 shows the measurement of the out-of-loop timing drift recorded over 43 hours.

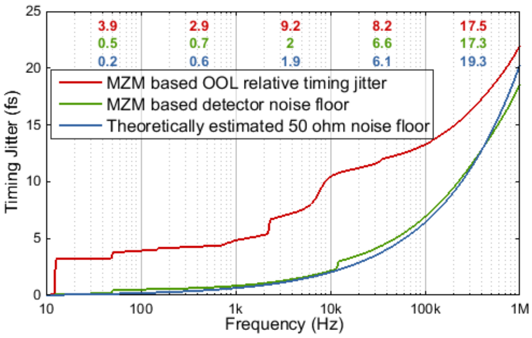

Figure 5: Residual integrated timing jitter.

The peak-to-peak timing stability resulted 31 fs while the rms of it amounts only 7 fs which is an excellent long term performance of the phase detector.

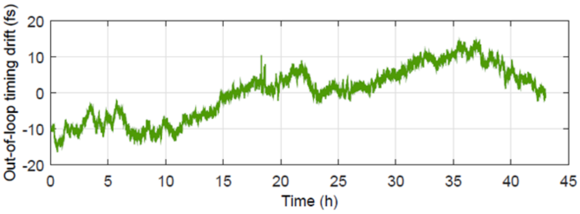

Figure 6: Residual timing drift.

AM-PM Coefficient

The last measurement which has been carried out was the measurement of the AM-PM coefficient for the MZM based laser-to-RF synchronization setup. The input optical power of the in-loop detector was varied using a neutral density filter while monitoring the corresponding timing changes by out-of-loop phase detector. The measurements showed that the mean AM-PM coefficient of the phase detector amounts 34 fs $\%^{-1}$ of input optical power change which is about factor of 10 smaller value compared to AM-PM coefficients measured for direct conversion based synchronization setup (see Fig. 1).

CONCLUSION

In this paper we have shown the limitations of the direct conversion based laser-to-RF synchronization setup. Full experimental evaluation of the MZM based laser-to-RF synchronization setup has been presented with the excellent timing jitter and drift performance of 11 fs rms and 31 fs peak-to-peak respectively. In addition, AM-PM coefficient has been measured for MZM based laser-to-RF synchronization setup with approximately one order of magnitude lower value compared to direct conversion setup. We expect to improve the overall timing performance of the MZM based laser-to-RF synchronization setup by increasing the optical power level which will reduce the noise floor and the corresponding timing jitter. We also expect to reduce the AM-PM coefficient of the MZM based phase detector by removing the DC offsets at the output of the readout electronics.

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