ISBN: 978-3-95450-168-7 doi:10.18429/JACoW-IPAC2015-MOPHA026

PRESENT AND FUTURE OPTICAL-TO-MICROWAVE SYNCHRONIZATION SYSTEMS AT REGAE FACILITY FOR ELECTRON DIFFRACTION AND PLASMA ACCELERATION EXPERIMENTS

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Abstract

Relativistic Electron Gun for Atomic Explorations (REGAE) is a Radio Frequency (RF) driven linear accelerator. It uses frequency tripled short photon pulses (~ 35 fs) from the Titanium Sapphire (Ti:Sa.) Laser system in order to generate electron bunches from a photo-cathode. The electron bunches are accelerated up to ~ 5 MeV kinetic energy and compressed down to sub-10 fs using the so called ballistic bunching technique. REGAE currently is used for electron diffraction experiments (by Prof. R.J.D. Miller's Group). In near future within the collaboration of Laboratory for Laser- and beam-driven plasma Acceleration (LAOLA), REGAE will also be employed to externally inject electron bunches into laser driven linear plasma waves. Both experiments require very precise synchronization (sub-50 fs) of the photo-injector laser and RF reference. In this paper we present experimental results of the current and new optical to microwave synchronization systems in comparison. We also address some of the issues related to the current system and give an upper limit in terms of its long-term performance.

INTRODUCTION

Ultrafast Electron Diffraction (UED) as well as planned external laser plasma wave injection experiments at REGAE require stable (sub-picosecond) electron beam arrival at the target chamber [1–3]. Mainly, two sub-systems of the accelerator - Low-Level RF (LLRF) system and injector laser - play a significant role to deliver low jitter electron bunches. Since REGAE is a normal conducting S-band accelerator, it uses a 2.997 GHz radio frequency (RF) signal for electron beam acceleration and bunching. This 2.997 GHz reference signal from a RF Master Oscillator (MO) is distributed to the LLRF system and injector laser synchronization system. The LLRF system controls the amplitude and phase of the RF reference signal while the laser synchronization system ensures the stability of the laser beam arrival on a photocathode. Figure 1 shows the layout of the REGAE facility including its sub-systems.

Different schemes can be employed to synchronize optical lasers to a microwave reference [4–8]. Currently, REGAE is using a so called down conversion (DWC) based setup to synchronize a 83.25 MHz repetition rate Ti:Sa. laser to the 2.997 GHz reference signal from the MO [9]. Later, this DWC based scheme will be replaced by a new balanced Mach-Zehnder Modulator (MZM) based synchronization setup which is currently under development [3]. It has been shown that the short term locking performance of the DWC based setup is in the order of ~ 20 fs RMS [9]. In this paper we show that the long term locking performance of the DWC based scheme is limited by AM/PM effects and environmental dependencies of the RF reference and optical components. We also present for the first time the long term detector stability of the new single output MZM based setup and its potential for synchronizing the Ti:Sa. lasers to microwave signals or vice versa.

LONG TERM PERFORMANCE OF DWC BASED SETUP

Description of the DWC Locking Setup

Long term out-of-loop (OOL) measurements have been carried out while the Ti:Sa. laser oscillator was locked to the RF reference using the DWC setup.

Some part of the light from the Ti:Sa. laser oscillator has been coupled into the pigtailed fiber collimator connected to a fast 10 GHz bandwidth photodiode (EOT4000F). This photodiode converts laser pulses to electric signals producing an RF frequency comb, containing a fundamental frequency of 83.25 MHz and its corresponding harmonics. The 36th harmonic of the repetition rate is filtered out using a 3.0 GHz RF bandpass filter and is further amplified. This filtered signal is used to downconvert the reference frequency of 3.025 GHz derived from the Local Oscillator (LO) generation box, which receives the reference 2.997 GHz signal from the MO. The downconversion and digitalization is done by employing a commercially available MicroTCA standard boards from Struck GmbH. The DWC board provides an intermediate frequency (IF) of ~ 25 MHz which is sampled by the 125 MS/s SIS 8300 ADC board. After digitalization, the digital IF signal is further processed by the controller firmware, where amplitude and phase information is extracted using a so called digital IQ demodulation technique. The obtained phase error information is fed to a piezo driver acting on a piezo mirror inside the laser cavity to match the frequency and phase of the reference signal. More details about controller firmware and the FPGA signal processing chain can be found [9].

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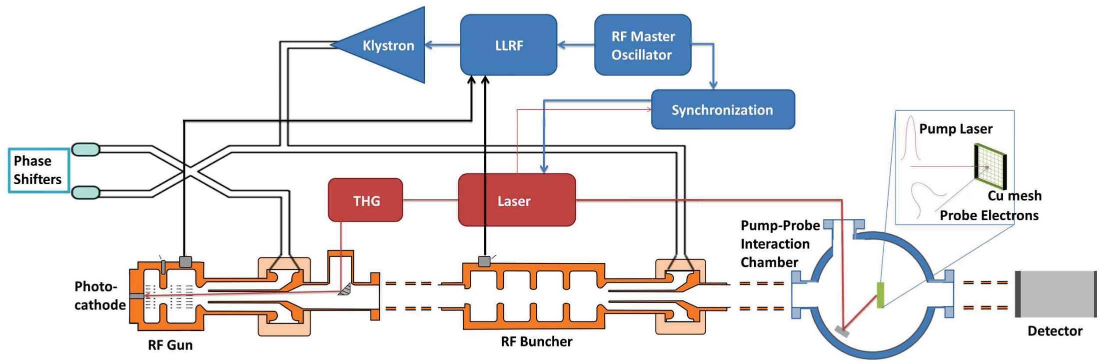

Figure 1: Layout of REGAE Facility.

Long Term Out-of-Loop Timing Stability

In order to check the long term phase stability of the DWC locking scheme, we have built a simple out-of-loop phase detector. Similarly to the earlier mentioned DWC scheme, the 36th harmonic of the frequency comb from the photodiode has been used to compare it with the 2.997 GHz reference using an RF mixer. In this case the reference signal was derived directly from the MO. Once the laser is locked to the RF reference using the DWC scheme, we get a baseband signal ($f_{baseband} \leq 1$ MHz) at the output of the RF mixer, which is directly proportional to the relative phase error between the laser and RF reference. The detailed diagram of the DWC locking scheme in conjunction with the out-of-loop phase detector is shown on Figure 2.

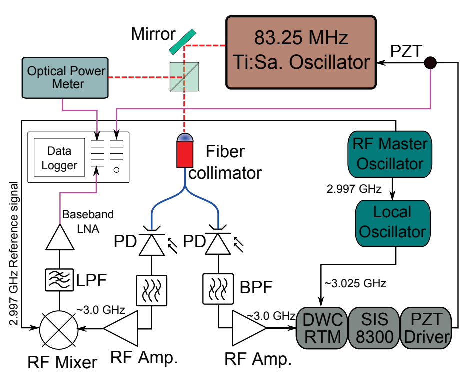

Figure 2: Detailed block diagram of DWC based locking setup with out-of-loop phase detector.

We recorded the output of the mixer as well as other important physical parameters: optical power, piezo voltage, ambient temperature and humidity over 93.3 hours using a datalogger with 0.1 Hz data acquisition rate (see Fig.2). The baseband voltage from the mixer output was calibrated using a "beatnote" calibration method, converting volts to picoseconds. Figure 3 shows the long term measurement of the phase drift, monitored optical power and piezo voltage for correlations. From these plots it is clear that the timing drift amounts to several picoseconds (5.6 ps peak-peak) over 93.3 hours. The drift measurement also shows obvious dependencies on optical power changes (AM/PM effect). It amounts to ∼ 220 fs/% optical power change when the photodiode is in saturation. The optical power changes are correlated to piezo mirror tuning (negative correlation between optical power and piezo voltage). Out of the total measured phase drift (see Fig. 3 red curve) approximately 3.1 ps have been induced due to electronics (LO box, DWC board, clock) dependency on relative humidity changes (12.5% RH over 93.3 hours), which resulted in a phase drift of an RF reference (3.025 GHz).

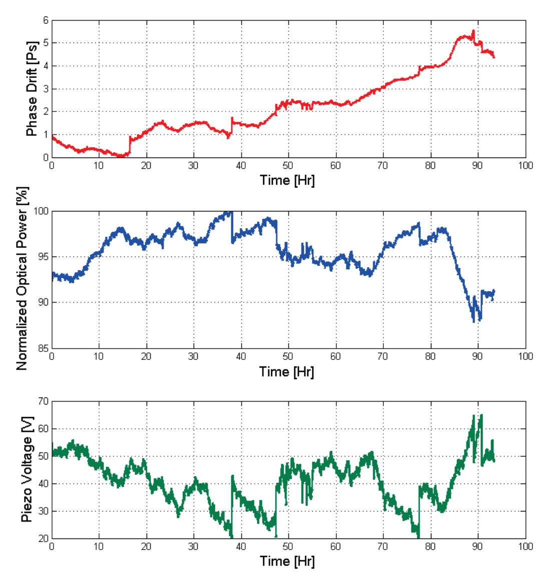

Figure 3: Measurement of long term out-of-loop phase stability, optical power and piezo voltage.

LONG TERM STABILITY OF A BALANCED MZM BASED PHASE DETECTOR

The main purpose of using a MZM based Laser-to-RF (L2RF) setup is to overcome some of the problems associated with direct conversion/DWC based setups such as AM/PM effect. The basic idea of this approach is to sample the laser pulses using an RF reference. Inside the temperature and humidity stabilized L2RF optics box (see [3]), laser pulses are intentionally split into two beams. One of the beams is delayed using an optical delay line and recombined with the

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non-delayed one. This pulse pattern is sent to the integrated MZM using a fiber collimator. Inside the MZM laser pulses are aligned to the microwave's reference zero crossings of positive and negative slopes. This arrangement gives the possibility to convert relative phase error between laser and RF reference into amplitude modulation. For more details regarding the principle of operation of this setup, amplitude readout electronics and other technical aspects please see [3].

Measurement Setup of the L2RF Detector Stability.

The measurement setup splits the free space laser oscillator output to two sub-systems: The earlier described DWC based synchronization system for locking the laser oscillator to the RF reference and the MZM based L2RF temperature and humidity stabilized optics box. Since the integrated Lithium Niobate (LiNbO3) based MZM cannot handle the full spectrum of the Ti:Sa. output, some part of the laser oscillator spectrum (40 nm FWHM centered at 800 nm) is filtered out in the free space optics section and guided to the MZM based setup using a fiber collimator. Figure 4 summarizes the major blocks of the measurement setup for MZM based L2RF phase detector.

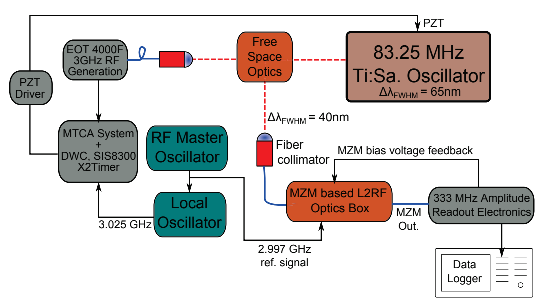

Figure 4: The block diagram of the MZM based laser to RF phase detector measurement setup.

The optical output from the MZM is sent to a readout electronics section for measuring the amplitude of the modulation frequency ~ 333.1 MHz. The EOT4000F photodiode is used to convert optical pulses from the MZM into electric pulses. After the photodiode a 333 MHz RF bandpass filter and several low noise RF amplifiers are used to filter out and further amplify the desired frequency component from the frequency comb, which is generated by the recombined laser pulses from the MZM output. An RF mixer was employed to detect the amplitude of the 333.1 MHz modulation frequency component. A small fraction of light was tapped off additionally from the laser oscillator to generate a 333.1 MHz LO for downmixing the MZM signal to baseband. A detailed description of this setup can be found in [3]. The baseband signal from the mixer output is monitored by a datalogger while the laser oscillator was locked to RF reference using a DWC based setup. The recorded voltage of the baseband signal corresponds only to the amplitude stability of the MZM based L2RF setup, which defines the resolution of the setup as a phase detector. In order to extract timing stability information from the recorded voltage, we need to convert voltage to time using a calibration constant K_ϕ which is obtained by measuring the slope of the "beatnote" when the laser oscillator is not locked and the 2.997 GHz RF reference is applied to the MZM RF input (see Fig. 5).

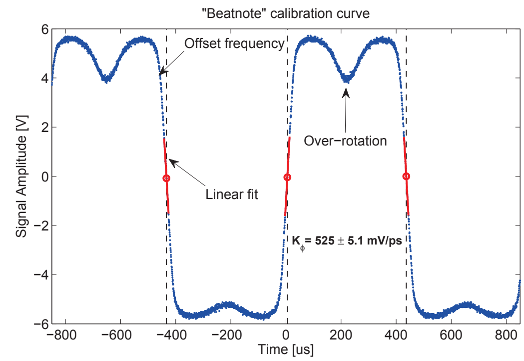

Figure 5: Calibration curve recorded by Oscilloscope.

Experimentally measured data of the long term MZM based L2RF phase detector stability is shown on Figure 6. The results presented here are the 18 hour highlighted region of the measurement. It shows 18.47 fs peak-peak and 4.1 fs RMS timing stability over 18 hours. It is worth mentioning that during this time period the laser cavity was not affected by delay line mirror movements. Therefore, we do not see any large piezo mirror tuning steps and corresponding dependencies.

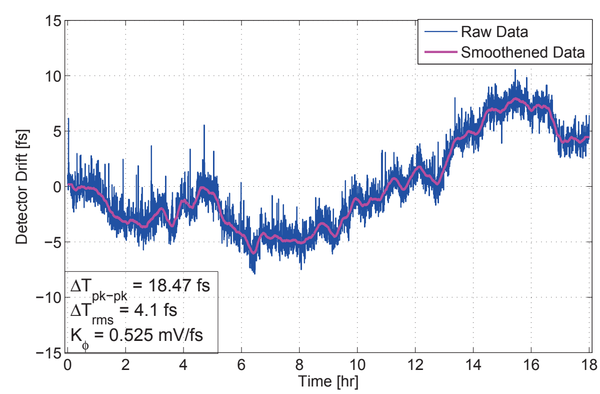

Figure 6: MZM based phase detector timing drift stability.

CONCLUSION

We show that the long term performance of the DWC based laser synchronization setup is limited to several picoseconds due to AM/PM effects, temperature and humidity changes. We also present a new balanced single output MZM based L2RF synchronization setup which shows very promising long term stability performance. This new synchronization setup is a good candidate for fulfilling the long term sub-50 fs timing stability between the Ti:Sa. laser and the 2.997 GHz RF reference. We are also confident that there is more room left to improve the long term performance of the MZM based scheme.

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