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LASER-TO-RF SYNCHRONISATION DRIFT COMPENSATION FOR THE CLARA TEST FACILITY

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Abstract

Femtosecond synchronisation between charged particle beams and external laser systems is a significant challenge for modern particle accelerators. To achieve femtosecond synchronisation of the CLARA electron beam and end user laser systems will require tight synchronisation of several accelerator subsystems. This paper reports on a method to compensate for environmentally driven long-term drift in Laser-RF phase detection systems.

INTRODUCTION

The Compact Linear Accelerator for Research and Applications (CLARA) facility [1] is a test bed for accelerator and Free Electron Laser technology. CLARA will deliver a 250 MeV electron beam to the Full Energy Beam Exploitation (FEBE) [2] experimental hutch, and femtosecond synchronization of particle beams to an external laser is a foreseen requirement for future exploitation. To recover femtosecond dynamics from pump-probe experiments on CLARA will require femtosecond synchronisation between end station laser systems and several RF accelerator components.

LASER-RF PHASE DETECTOR CONCEPT

CLARA is a normal-conducting linear accelerator where an electron beam is generated by a UV photo-injector laser system in an s-band electron gun and then accelerated to full energy by four traveling wave linacs. The CLARA photo-injector (PI) laser system and high power RF systems are seeded by pulsed laser and RF master oscillators respectively. The PI (mode-locked) laser master oscillator, is currently locked to the RF master oscillator using a direct photodetection Phase Locked Loop (PLL) based on analogue electronics. The noise performance and long term stability of the laser-RF Phase Locked Loop has a significant impact of the quality of CLARA electron beam.

Direct photodetection Laser-RF phase locked loops use a fast photodetector and analogue electronics to determine the laser-RF phase error and a control loop to reduce this phase error to zero. This approach is very robust, well understood and has been widely used. However non-linearities in the standard photodetectors result in unwanted amplitude-to-phase (AM-PM) noise conversion [3] which limits the synchronisation between mode-locked laser systems and RF master oscillators. Laser-RF synchronisation on the order of several tens of femtoseconds would be acceptable for most applications, however to resolve femtoseconds level dynamics with pump-probe experiments, such X-ray FEL pump-probes schemes, requires sub 10 femtoseconds synchronisation. Several approaches to resolve AM-PM noise conversion have been proposed in the literature [3].

To resolve limitations related to direct detection Laser-RF PLL, a Laser-RF PLL system was developed that is immune to AM-PM conversion noise and is able to compensate for the inherent system drift that results from using Mach Zehnder Modulators (Fig. 1). The method of Mach Zehnder Phase Detector Reverse Bias Detection (MZPD-RBD) (Fig. 2) developed in this paper follows the work of [4-6]. Here an emphasis was placed on developing a system that could be easily constructed within limited space, which used commercially available optical components and required a minimal number of free-space optical components.

Short term locking performance is achieved by imprinting the phase error information between mode-locked laser pulse train and radio-frequency wave as an amplitude modulation of the laser pulse train itself (at half the laser repetition rate) using a Mach Zehnder (Intensity) Modulator. The amplitude modulation is enabled by simultaneously applying an alternating bias signal to the MZM. The alternating bias signal flips the MZM total phase advance by π at rate of half laser repetition rate. At the output of the MZM the laser pulse train has the following pulse pattern,

$$I_n = 0.5 * I_0[1 + (-1)^n \sin(\phi_{RF} \sin(\phi_e + \phi_b)] \qquad (1)$$

where I_0 is the input laser pulse intensity, ϕ_e laser-RF phase error, bias drift term ϕ_b, and ϕ_{RF} is related to the electro-optic conversion efficiency of the MZM. Note the sign flip in equation (1) between each adjacent laser pulses from the MZM, this allows one to retrieve laser-RF ϕ_e phase error by simply subtracting the optical intensity (or heights) of adjacent optical pulses, assuming that the bias drift term ϕ_b is set to zero. In this paper Laser-RF phase error information is extracted using a fast photodetector and traditional RF frequency down-conversion techniques. The alternating bias signal is triggered by laser pulse train itself and is therefore intrinsically synchronous to the laser pulse train at a fixed rate of $f_{rep}/2$. This method is effectively immune to laser amplitude noise and AM-PM conversion noise. This technique is similar to that developed in [4, 5], the main advantages here are; interleaving the optical pulse train is not required for bias drift detection and each optical pulse we always ‘see’ the correct bias voltage regardless of relative phase.

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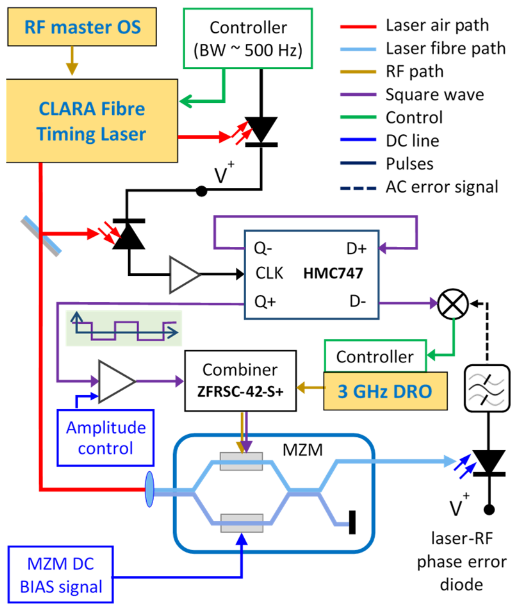

Figure 1: Mach Zehnder Modulator Phase Detector: Laser-RF phase error information is imprinted as an amplitude modulation on the laser pulse train. The Laser-RF phase information can then be extracted using a fast photodetector with a fast ADC or using an RF down-conversion mixer based scheme. As the Laser-RF phase measurement is performed in the optical domain the effects of AM-PM noise conversion are effectively eliminated. The switching bias signal is generated using a d-latch (HMC747) evaluation board. Using a d-latch to generate the switching bias signal has the benefit of ensuring the correct phase advance is applied to the optical pulse regardless of relative timing between optical pulse switching bias signal.

Using the Mach-Zehnder Modulator as a Laser-RF phase detector requires that the working (quadrature) point of the MZM is carefully controlled by an externally applied DC voltage. The optimal working point/voltage is equal to the applied external DC voltage that results in an optical transmission through the MZM of 50%. Unfortunately this working point (often referred to as the bias point) is known to have a substantial drift over several hours. Several groups [7, 8] have attempted to establish the environmental and physical origins of the MZM bias drift with significant results, however the most common approach to MZM bias drift mitigation is to develop systems that monitor and control the bias point without unduly affecting the operation of the MZM.

Here the method of bias point stabilisation takes advantage of the traveling wave design of the Mach Zehnder Modulator by injecting the bias-detection laser pulse train in the counter propagating direction to the radio-frequency wave in the device. When the system is locked, the counter propagating pulse will measure the DC bias drift ϕ_b only. This is because the optical pulse train propagating in the reverse direction is not phase matched to the input RF wave. This results in each counter propagating optical pulse sampling a constant number of RF waves as it travels through the device, which will average the input RF waves to a DC level. The RF wave contribution will be seen as a constant offset on the DC bias drift as the counter propagating laser pulses will be modulated by an equal number of radio frequency waves on each reverse pass of the MZM waveguide structure.

To allow injection of the counter propagating bias detection laser pulse train a pair of fibre coupled circulators are inserted into the setup before and after the Mach Zehnder Modulator. The forward photodetector will have contributions from the laser-RF phase and bias drift, whereas the reverse photodetector detects MZM bias drift only. A PID feedback routine was developed in the LabVIEW FPGA and implemented on an NI CompactRIO device, this enables high bandwidth feedback to the bias point of the Mach Zehnder Modulator and should allow 'drift free' performance over several hours.

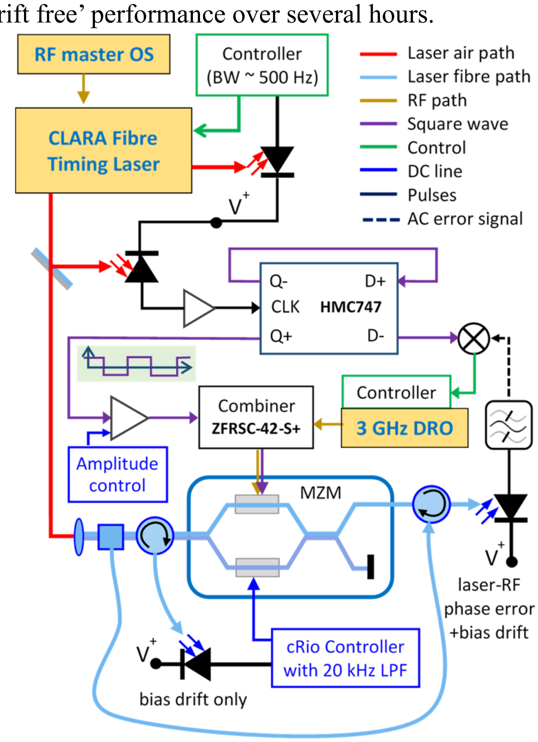

Figure 2: Mach Zehnder Phase Detector Reverse Bias Detection (MZPD-RBD) working principle: The optical pulse train is split via a 50:50 fibre coupler and injected into both input and output ports of the Mach Zehnder Modulator using a pair of fibre coupeld circulators Optical pulses captured by the forward photodetector (normal operating mode) contain contributions from both laser-RF phase error and the MZM bias drift. Signal detected by the reverse photodetector will have contribution from the MZM bias drift, and therefore can be used to drive a PI controller that stabilises MZM bias point.

RESULTS

Short Term Performance

The Mach Zehnder Phase Detector Reverse Bias Detection (MZPD-RBD) system was experimentally demonstrated by locking a Dielectric Resonator Oscillator (DRO) with a resonant frequency of 2.9985 GHz to the CLARA fibre timing laser. The CLARA timing laser is a

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Origami-15 Yb/Er fibre laser oscillator from OneFive. The Origami-15 produces ultra-short optical pulses (177fs, 1560 nm, 30 nm BW) with exceptionally low timing jitter performance (<20 fs rms over a BW 1 kHz – 10 MHz). The short term locking performance of the MZPD-RBD PLL is show in Fig. 3, an absolute integrated timing jitter of sub 20 femtoseconds rms of the DRO output was measured using the Rohde and Schwarz Phase Noise Analyser (FSWP). The absolute integrated jitter of locked DRO is an important parameter as it will influence any subsequent systems that are driven by the DRO.

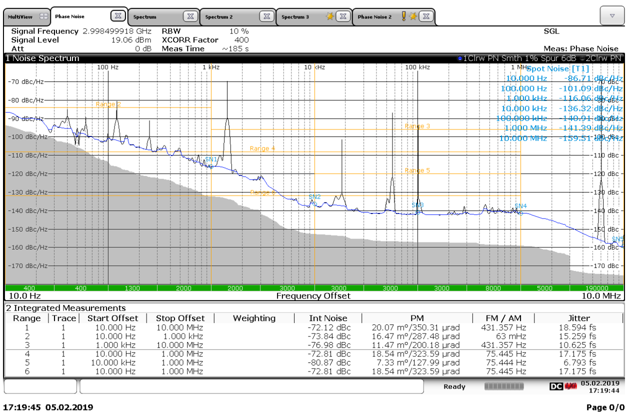

Figure 3: Absolute phase noise measurement of a locked DRO using the MZI phase detector. The absolute integrated jitter is 18.6 femtoseconds over a bandwidth of 10 Hz – 10 MHz.

To the verify the Phase Locked Loop performance shown in Fig. 3 a second MZPD-RBD system was constructed to allow out-of-loop phase noise measurements with results shown in Fig. 4. After optimising the system sub 5 femtosecond out-of-loop timing jitter was achieved.

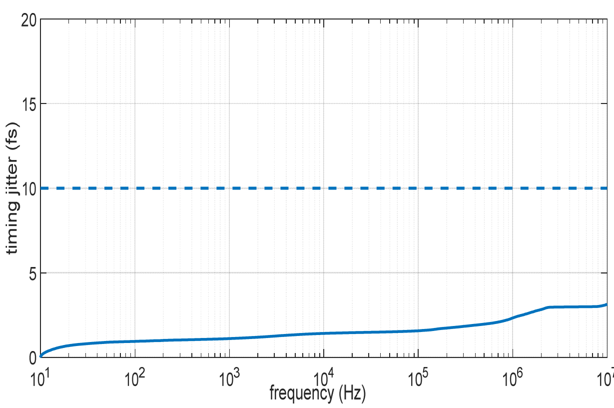

Figure 4: Out of loop phase noise measurement of Locked DRO. An out of loop timing jitter of sub-5 femtosecond was measured within the locking bandwidth of the phase locked loop.

Long Term Performance

The setup from the previous section was used to measure the out-of-loop long term performance of the system. The bias point of both in-loop and out-of-loop phase detectors was stabilised using the CompactRIO feedback routine.

Figure 5 shows the problems associated with MZM bias drift, when no feedback is applied to the in-loop MZM phase detector the bias point drift is an equivalent of >300 fs per minute. Bias point drift [7] has several physical origins including humidity, thermal, photorefractive and charge relaxation effects. However once feedback is enabled the rms drift has been reduced to 30 fs over 12 hours as shown in Fig. 6.

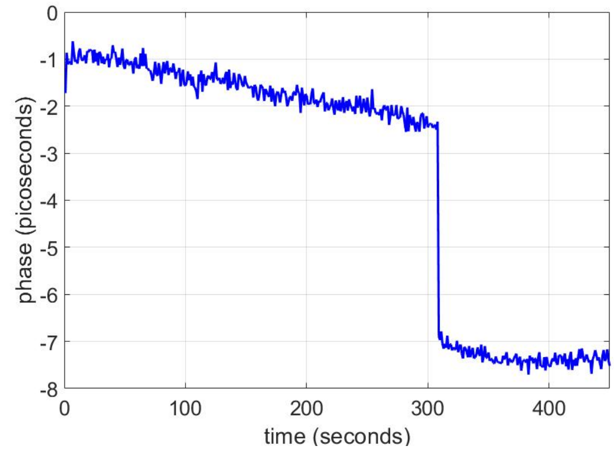

Figure 5: Without bias correction drift in the MZI bias can be a significant challenge. Without bias feedback 1 picosecond of drift can observed over 3 minutes.

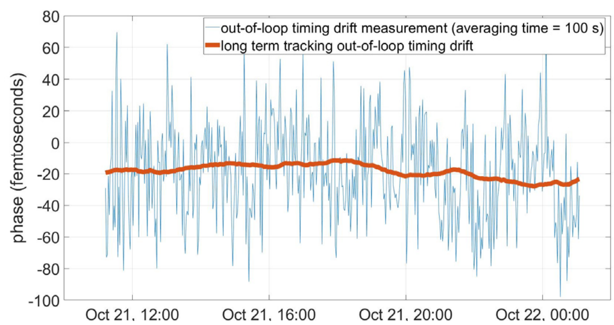

Figure 6: The locked DRO shows significantly improved long term drift performance when bias stabilisation is enabled over.

CONCLUSION

A drift free laser-RF Phase Locked Loop (MZPD-RBD) has been developed that uses a novel MZM bias stabilisation system. The system was locked and the MZM stabilised was for 12 hours and verified for using an out-of-loop laser-RF phase measurement. Short term performance of the system was measured at sub 5 femtosecond residual rms timing jitter and 30 femtoseconds rms drift. The MZPD-RBD system is in the process of being professionally packaged with electronic and optical components mounted onto temperature stabilised plates.

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