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TIMING STABILITY COMPARISON STUDY OF RF SYNTHESIS TECHNIQUES

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Abstract

In this paper, we implement and compare two of the most common techniques used for laser-to-RF synthesis in FEL facilities: (i) microwave signal extraction from the optical pulse train using photodiodes (i.e. direct photodetection), and (ii) voltage-controlled oscillator (VCO)-to-laser synchronization. Test setups are built to measure both the absolute phase noise of the generated RF signal and the relative timing jitter with respect to the mode-locked laser. Short-term timing jitter values varying between 10s and 100s of femtoseconds are achieved for different test setups, while long term timing drift ranging to some hundreds of femtoseconds due to environmental influence are observed.

INTRODUCTION

High-precision and low-noise timing transfer from a master oscillator to different end stations of a free-electron laser (FEL) is a critical requirement. Timing precisions ranging from a few femtoseconds, to sub-femtosecond are required for seeded FELs and attosecond science centers for the generation of shorter x-ray pulses with unmatched brightness [1], which ultimately enables subatomic and attosecond spatiotemporal resolution.

Mode-locked lasers referenced to RF standards are commonly used as master oscillators, due to their superior stability and timing precision, depicting timing jitter in the attosecond range [2]. In this matter, one of the biggest challenges is to transfer the timing stability of mode-locked lasers to RF sources.

Recently, timing distribution systems (TDS) have been demonstrated and implemented, taking advantage of the timing stability of pulsed-optical sources to perform timing distribution along different links, creating a link between different remotely located lasers, through balanced optical cross-correlators (BOCs) and laser-to-microwave synthesis and synchronization based on balanced optical-microwave phase detectors (BOMPDs). These devices can deliver sub-femtosecond precision between remotely synchronized lasers and microwave sources [3,4]. Figure 1 depicts a general overview of the TDS as deployed in [5]. Despite many achievements in these techniques over the last years, laser to microwave synchronization is still one of the bottlenecks of the system by being affected by so many noise sources and perturbations.

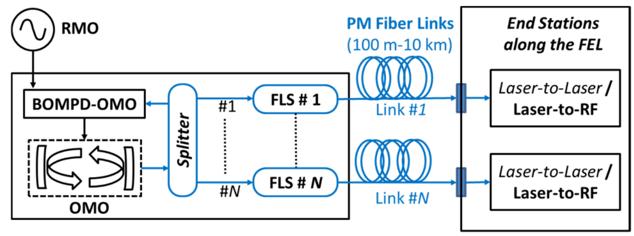

Figure 1: Layout of timing distribution system as deployed in [5]. RMO: RF master oscillator; OMO: optical master oscillator; FLS: fiber link stabilization; BOMPD: balanced optical-microwave phase detector.

Here, we focus on two of the most common techniques used for laser-to-RF synthesis in FEL facilities: (i) RF signal extraction from the optical pulse train using photodiodes, and (ii) VCO-to-laser synchronization. First, we describe the implementation and the test setups. Then, we present measurements of both the absolute phase noise of the generated microwave signal and its relative timing jitter with respect to the mode-locked laser, together with the relative timing drift.

DIRECT PHOTODETECTION

The simplest approach to synthesize microwave signals from an optical source coming from mode-locked lasers is by using a fast response photodiode. Here the optical pulse train envelope is detected by the photodiode and then transduced into an electrical current pulse train, which is limited by the photodiodes response (i.e. bandwidth). A further limitation is the so-called AM-PM conversion which translates amplitude noise, i.e. power fluctuations, from the optical pulse train, into phase noise in the electrical signal [6,7]. Figure 2 illustrates the optical pulse train and the electrical current pulse train after photodetection in time and frequency domain.

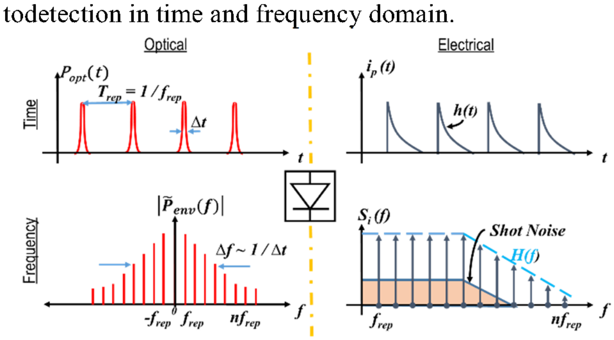

Figure 2: Optical pulse train transduced by fast photodetector in the time and frequency domain.

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Despite its drawbacks, we wanted to measure the limits of this synthesis technique and its potential for timing stability demanding applications. Following this idea, we built a setup, as depicted in Figure 3. Here, the fast photodiode is followed by a high Q bandpass filter, whose central frequency matches to a harmonic of the repetition frequency of the pulse train, so that a pure sinusoidal signal is obtained. This signal ultimately inherits the timing stability from the optical pulse train, minus the aforementioned disturbances. The bandpass filter is followed by a carefully selected preamplifier stage, which ensures a high gain and minimum added phase noise. The setup is also built in a sealed box to mitigate the influence of environmental factors.

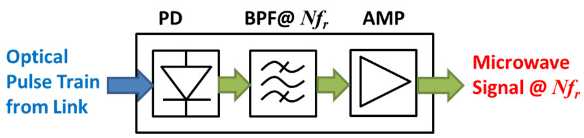

Figure 3: Direct photodetection microwave synthesis setup.

The optical master oscillator (OMO) has a repetition frequency of 238 MHz. The output of the OMO is coupled into a fiber patch cord (i.e. few meters long) and fed to the setup, as shown in Figure 1. The synthesized microwave is then connected to a signal source analyzer (SSA), calibrated for measurements at 5.712 GHz which is the transmitted signal frequency of the band-pass filter. This measurement gives the single-side-band phase noise and absolute timing jitter as shown in Figure 4. An absolute timing jitter of 55.6 fs RMS is obtained integrated from 100 to 100 MHz.

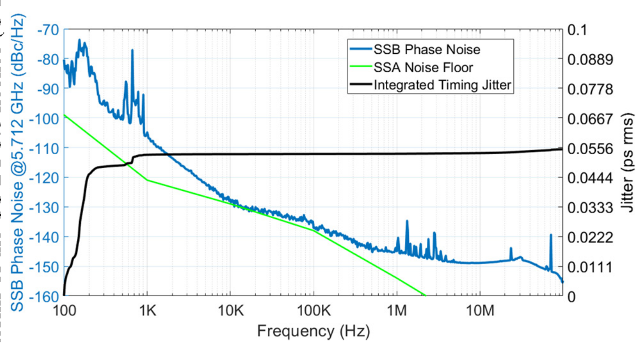

Figure 4: SSB Phase Noise for synthesized microwave from photodetection, Signal Source Analyzer (SSA) noise floor and absolute integrated timing jitter.

VCO-TO- LASER SYNCHRONIZATION

The second technique is the synthesis of a microwave signal of a VCO synchronized to the the optical pulse train by using an opto-electronic phase-locked loop (PLL).

A basic description of this setup is shown in Figure 5. Here, a PLL system is implemented on a standalone board which performs the phase frequency detection and the reverse loop division digitally.

The reference signal is obtained from the optical pulse train using direct photodetection synthesis at the repetition frequency. Then, the microwave signal provided by the VCO is locked to that reference by designing the appropriate integrator (loop filter) in the PLL.

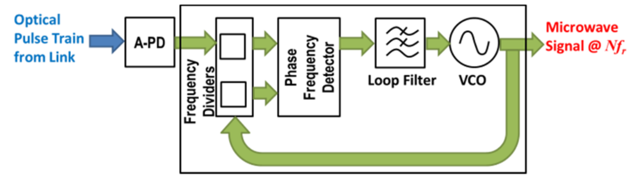

Figure 5: Digital VCO synchronization scheme for microwave synthesis.

As with previous technique, the single side band phase noise and absolute time jitter was measured by calibrating the SSA at 2.856 GHz to match the VCOs frequency. Figure 6 shows the SSB spectrum and the timing jitter integration, which is 90 fs from 100 to 100 MHz.

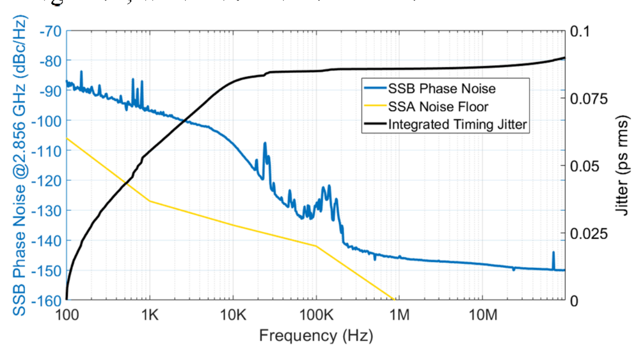

Figure 6: SSB phase noise for locked VCO, signal source analyzer (SSA) noise floor and absolute integrated timing jitter.

RELATIVE TIMING JITTER AND DRIFT MEASUREMENT

Having the two setups ready, we proceed with the characterization of relative timing jitter and drift between the generated microwave and the OMO. Figure 7 shows the experimental setup. Here, a BOMPD is used as a free-running phase detector to compare the optical pulse train from the OMO directly with the microwave synthesis technique under test..

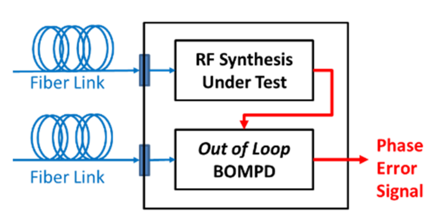

Figure 7: Measurement setup for relative timing hitter between the OMO and the RF synthesized signal using BOMPD as out-of-loop phase detector.

Figure 8 and Figure 9 show both the long term and short term stability measurement results for the direct microwave synthesis and the synchronized VCO, respectively.

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The long term measurement is performed by tracking the phase error signal of the BOMPD and measuring its drift. The timing drift over a period of 8 hours was measured for both setups, obtaining 167 fs for direct synthesis and 645 fs for the synchronized VCO. Here, a direct correlation with the environmental fluctuations in the measurement laboratory was observed, which can be mitigated by further temperature control.

The short term stability measurement is calculated from the baseband analysis of the error signal obtained from the BOMPD, taking into account the noise floor of the detector. Here, we obtain an integrated timing jitter of 17 fs for the direct synthesis and 67 fs for the synchronized VCO.

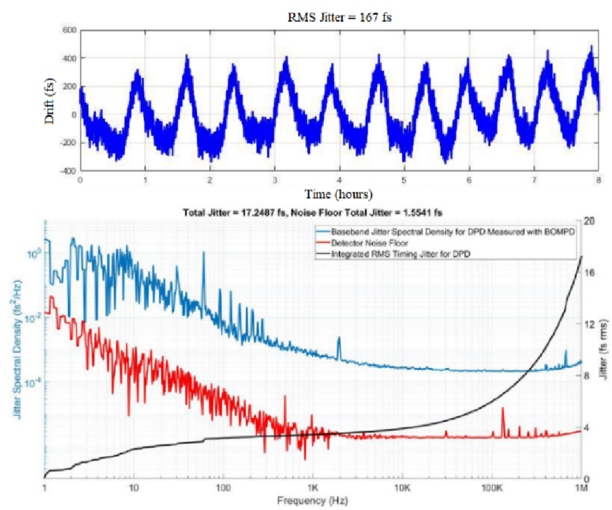

Figure 8: Timing stability of direct photodetected synthesis (a) Long term stability (b) Short term relative jitter given by Jitter Spectral Density.

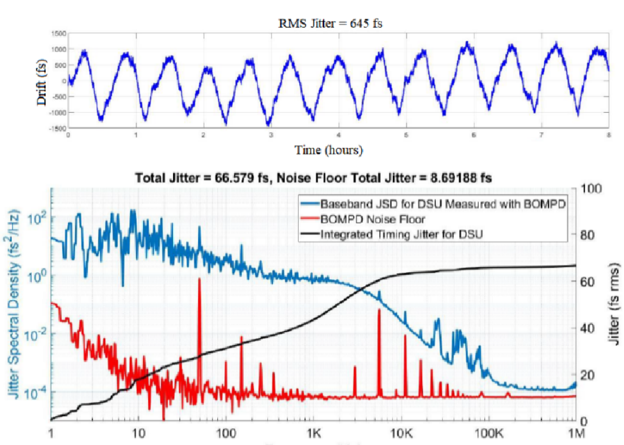

Figure 9: Timing stability of synchronized VCO (a) Long term stability (b) Short term relative jitter given by Jitter Spectral Density.

CONCLUSION

Two synthesis methods were implemented and their timing performance was measured as summarized in Table 1. The absolute timing jitter measured with the SSA gives similar synchronization stability and is limited by the noise of the SSA. The relative timing jitter measurement with an out-of-loop BOMPD shows that increased stability of the microwave signal synthesis using direct photodetection. The high frequency noise sources are mainly limited by the inherent noise of the VCO and the AM-PM conversion in the photodiode. The high frequency performance could be easily improved to the few-femtosecond regime by employing higher quality VCOs and BOMPDs as RF synthesizer. The main timing drift contribution is due to the susceptibility of fiber and electronic components to the environmental fluctuations. The long-term performance of the remote microwave synchronization could be also improved by more comprehensive temperature/humidity insulation.

Table 1: Summary Timing Stability Measurement Results

	Photodetection Synthesis	**VCO Synchronization**
Abs. Timing Jitter @100 – 100 MHz	56 fs	90 fs
Relative Timing Jitter	17 fs	67 fs
Long Term Drift RMS (8 hrs)	168 fs	645 fs

REFERENCES

[1] M. Xin, K. Shafak, and F. X. Kärtner, “Ultra-precise timing and synchronization for large-scale scientific instruments”, *Optica*, vol. 5, issue 12, pp. 1564-1578, 2018. doi:10.1364/OPTICA.5.001564

[2] K. Shafak *et al.*, “Large-Scale Turnkey Timing Distribution System for New Generation Photon Science Facilities”, in *Proc. 38th Int. Free Electron Laser Conf. (FEL'17)*, Santa Fe, NM, USA, Aug. 2017, pp. 485-487. doi:10.18429/JACoW-FEL2017-WEP030

[3] M. Xin, K. Shafak *et al.*, “Attosecond precision multi-kilometer laser microwave network”, *Light Sci. Appl.*, vol. 6, no. e16187, 2017. doi:10.1038/lsa.2016.187

[4] M. Xin, K. Shafak, F. X. Kärtner *et al.* “Breaking the femtosecond barrier in multi-km timing synchronization systems”, *IEEE J. Sel. Top. Quantum Electron,* vol. 23, no. 3, p. 8800212, 2017. doi:10.1109/JSTQE.2016.2614676

[5] H. P. Cheng, K. Shafak, E. Cano *et al.*, “Commissioning of a Fully-Automated, Pulsed Optical Timing Distribution System at Dalian Coherent Light Source”, *2018 Conference on Lasers and Electro-Optics (CLEO)*, San Jose, CA, 2018, pp. 1-2. doi:10.1364/CLEO_AT.2018.JW2A.138

[6] J. Kim, F. X. Kärtner. “Sub femtosecond-Drift Microwave Signal Synthesis from Femtosecond Mode-Locked Lasers”. in *Conference on Lasers and Electro-Optics (CLEO) and Quantum Electronics and Laser Science Conference (QELS)*, San Jose, CA, USA, 2010, paper CTuDD4. doi:10.1364/CLEO.2010.CTuDD4

[7] F. Ludwig, B. Lorbeer, H. Schlarb, A. Winter. “Noise and Drift Characterization of Direct Laser to RF Conversion Scheme for the Laser based Synchronization System for FLASH at DESY”, in *Proc. PAC'07*, Albuquerque, NM, USA, Jun. 2007, paper MOPAN017, pp. 182-184.