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Laser–RF synchronization based on digital phase detector

Jin Yang[1,2] · Ying-Chao Du[1,2] · Li-Xin Yan[1,2] · Gang Huang[3] · Qiang Du[3] · Yi-Lun Xu[1,2,3] · Wen-Hui Huang[1,2] · Huai-Bi Chen[1,2]

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Abstract Laser oscillator synchronization with RF reference signal is ultra-important for a modern light source based on the accelerator. For Tsinghua Thomson scattering X-ray source, we have synchronized the mode-locked laser oscillator to RF reference signal with 48.2 fs RMS relative jitter. Both fundamental and harmonic signals derived from photo diode detection are used for laser–RF synchronization in our scheme. The fundamental signal is for coarse laser–RF synchronization and multiple laser oscillator synchronization. The harmonic signal is for high precise phase locking. The digital phase detector is implemented in the synchronization scheme for less noise, replacing the mixing to DC phase detection scheme. The digital processing algorithm for synchronization is commonly used in low-level RF control field. In order to test the phase locking loop logic without damaging the real laser oscillator, a laser oscillator emulator was developed for phase locking. This paper will report the laser–RF synchronization scheme and its performance. The laser oscillator emulator system will also be introduced here.

Keywords Laser oscillator · Synchronization · RF · LLRF · Emulator

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✉ Wen-Hui Huang
huangwh@mail.tsinghua.edu.cn

1 Department of Engineering Physics, Tsinghua University, Beijing 100084, China

2 Key Laboratory of Particle and Radiation Imaging (Tsinghua University), Ministry of Education, Beijing 100084, China

3 Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA

1 Introduction

Synchronization system is ultra-important for a modern light source based on accelerator [1–3]. For a Tsinghua Thomson scattering X-ray source, laser–RF synchronization is important for the stability of the scattered X-ray pulse. In a TTX project, the UV laser (266 nm) for photoelectron generation and terrawatt infrared laser (800 nm) should be tightly synchronized with the 2856 MHz reference signal. The laser synchronization will affect the final colliding of the picosecond electron bunch and subpicosecond infrared laser pulse. The stability of final scattering X-ray pulse generation will be limited by the synchronization system [4]. To maintain high stability, the laser–RF synchronization requirement is less than 100 fs RMS.

In the laser–RF synchronization system, harmonic signal is commonly used for precise laser–RF synchronization [4, 5]. By mixing the RF reference with laser harmonic to the DC signal, the phase information can be measured. This scheme is simple, but it will add significant amplitude to the phase conversion phase drift [6]. Mixing the laser signal to non-DC signal with the digital phase detector will improve the system performance a lot. In our system, the digital phase detector was used for phase measurement, which adds high flexibility and precision to the whole system.

During the test of the TTX laser–RF synchronization system, it is very convenient to have an emulator to do the bench test for laser–RF synchronization. By adding only a small modification to the reference and local oscillator (LO) generation chassis, the chassis turns the role to a laser oscillator emulator.

In this paper, we detail the structure, simulation, and performance of our laser–RF synchronization system. The laser emulator for feedback loop test is also introduced here. The emulator system also can be used for RF recovery in fiber-based timing system [7].

2 Laser–RF synchronization scheme

The laser–RF synchronization scheme is shown in Fig. 1. The laser pulse trains from the mode-locked laser oscillator are partially reflected into a fiber photodiode from Discovery Semiconductor. Then the detected pulse signals are split into two arms with different filters. The arm with a low-pass filter is for generating the fundamental 79.3 MHz sinusoidal wave for the fundamental phase locking loop. The 2856 MHz sinusoidal wave is generated from another arm with a 2856-MHz band-pass filter for precise phase locking. In summary, the optical signal detection is composed of a free space to a fiber optical coupler and a wideband photodiode. The filtered 79.3 and 2856 MHz signals are detected by digital phase detector (Table 1).

In Fig. 1, the "Ref/LO Chassis" is for generating the harmonic/fundamental reference signal and LO signal (for up-/down-conversion). The master oscillator (MO) in "Ref/LO Chassis" is a 119 MHz crystal oscillator. Using several frequency multipliers and dividers, the chassis generates laser oscillator a 79.3 MHz fundamental reference signal, 2856 MHz harmonic signal, and 404.6 MHz LO signal. The laser oscillator fundamental reference signal is for coarse laser–RF synchronization and for multiple oscillator synchronization. The 2856 MHz RF signal is the reference signal for the laser oscillator and also for low-level RF system. Because the coaxial cable becomes much more lossy when it comes to a higher frequency, the relative lower frequency 404.6 MHz was selected as the distributed LO signal.

Table 1 Frequency configuration in Ref/LO Chassis

Signal	Frequency (MHz)
Laser fundamental	79.3
Distributed LO	404.6
RF reference	2856.0
Down-conversion LO	2832.2
IF	23.8
FPAG clock	101.15

The "Receiver Chassis" is for fundamental/harmonic signal phase detection and feedback signal generation. In the chassis, the distributed 404.6 MHz signal is multiplied by a factor of 7–2832.2 MHz as a down-converter LO signal. The 404.6 MHz is also divided by 4–101.15 MHz as a field-programmable gate array (FPGA) digital signal processor (DSP) clock.

LLRF4 [8] boards are used in our project as digital phase detectors inside the "Receiver Chassis." The 79.3 MHz is sampled by the ADC channel directly with 101.15 MHz sampling rate. The heterodyne method [9] is used to detect the 2856 MHz signal phase. The 2856 MHz signal is mixed with the 2832.2 MHz signal to generate 23.8 MHz intermediate frequency (IF). The slow DAC on the LLRF4 board is fed to the piezo driver to tune the laser oscillator cavity length for phase locking.

3 Phase locking algorithm

The most important part is the phase locking algorithm. The RF signal detection algorithm and feedback control loop structure will be shown in this section.

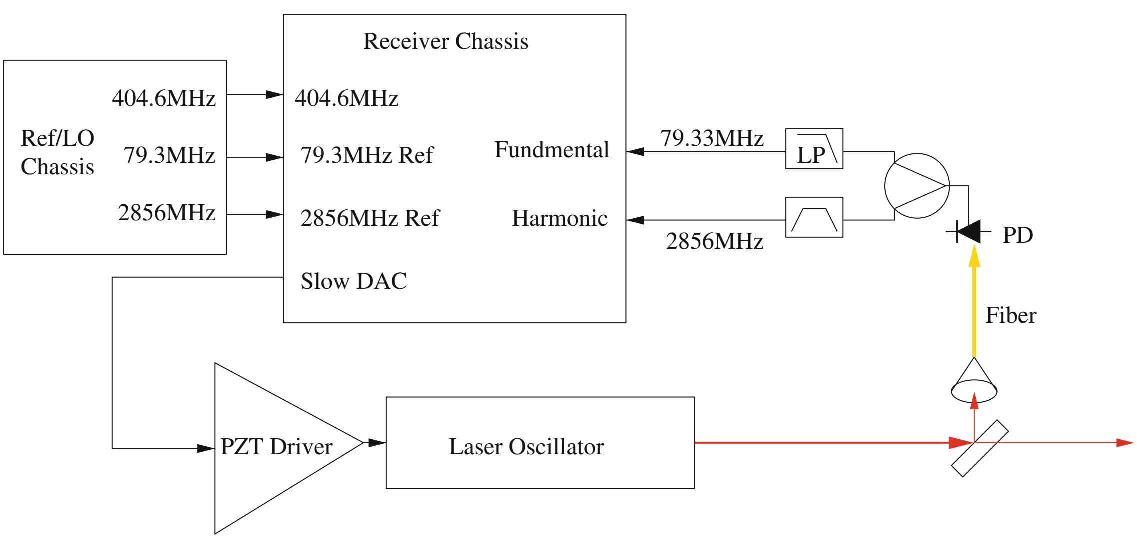

Fig. 1 Laser–RF synchronization scheme

3.1 Digital phase detector

The phase detector is commonly used in the low-level RF control system [2, 9]. Figure 2 shows the structure of the phase detector. The frequency ratio between measured IF signal and the FPGA clock signal is *m*:*n* (*m* and *n* are integers). It is suitable to use the non-IQ method to get the I/Q component [10]. The "LUT" stands for lookup table which contains the LO sine/cosine value for generating down-mixing raw ADC data to in-phase and quadrature-phase component inside FPGA. The "CIC" stands for cascaded integrator-comb filter, which is a simple low-pass filter [11].

For 23.8 MHz IF signal, the frequency ratio with 101.15 MHz clock is 4:17. In order to get lower noise, the averaging factor was chosen as 85. For the 79.3 MHz fundamental signal, the frequency ratio is 40:51 and the averaging factor is 102. The CIC filter in this design is a two-stage integrator-comb filter.

The coordinate rotation digital computer algorithm (CORDIC) is for I/Q to amplitude/phase conversion [12]. The additive phase noise added by the good phase detector for 2856 MHz signal will be around several femtoseconds($\sim$5 fs RMS), which needs careful hardware and firmware designs. In our system, the additive phase noise is 8 fs RMS.

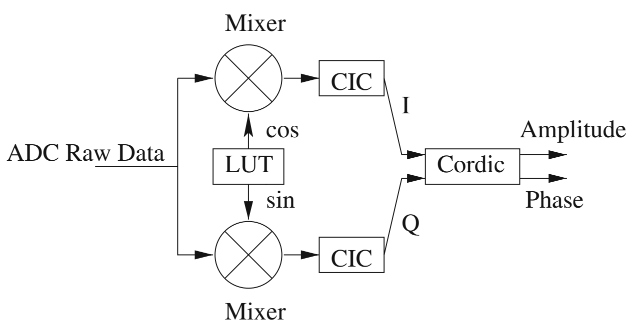

Fig. 2 Phase detector module

3.2 Feedback loops

The proportional–integral (PI) controller was used in this synchronization system. There are two PI control loops. One loop is for fundamental phase locking and another is for harmonic phase locking. Figure 3 shows the control loops. There is a switch to select the phase error source between "Fundamental Error" and "Harmonic Error." There is a phase_shift register called "REG phase_shifter" for shifting the measured phase of fundamental reference by small amount to make sure "Fundamental Error" and "Harmonic Error" are both around zero degree.

The "Hi_error Calc" module takes two input parameters, "fund_error" and harmonic phase difference, for calculating the final "Harmonic Error" for harmonic phase locking. The range of all these phase parameters is in $[-\pi, +\pi]$. In Eq. 1, ϕ_{ferr} is the "fund_error", ϕ_{hdiff} is the "harmonic_diff", and ϕ_{Herr} is the final "Harmonic Error." This equation implies that to lock the laser to the harmonic reference, the fundamental phase error must be within $[-\pi/72, \pi/72]$ of the 79.3 MHz signal. This design eliminates the harmonic locking ambiguity. Using this scheme, multiple laser oscillators can be synchronized without ambiguity harmonic bucket selection.

$$\phi_{\mathrm{Herr}} = \begin{cases} \mathrm{sign}(\phi_{\mathrm{ferr}}) \cdot \pi, & |\phi_{\mathrm{ferr}}| \geq \dfrac{\pi}{72} \\ \phi_{\mathrm{hdiff}}, & |\phi_{\mathrm{ferr}}| < \dfrac{\pi}{72} \end{cases} \tag{1}$$

From the requirement of Eq. 1, the procedures for the locking laser to both fundamental and harmonic reference are clear.

Step 1: Close the fundamental signal phase lock loop by selecting "Fundamental Error" as error source. Adjust k_{i}, k_{p} parameters.

Step 2: Move phase shifter to decrease the absolute value of "harmonic_diff" to around zero.

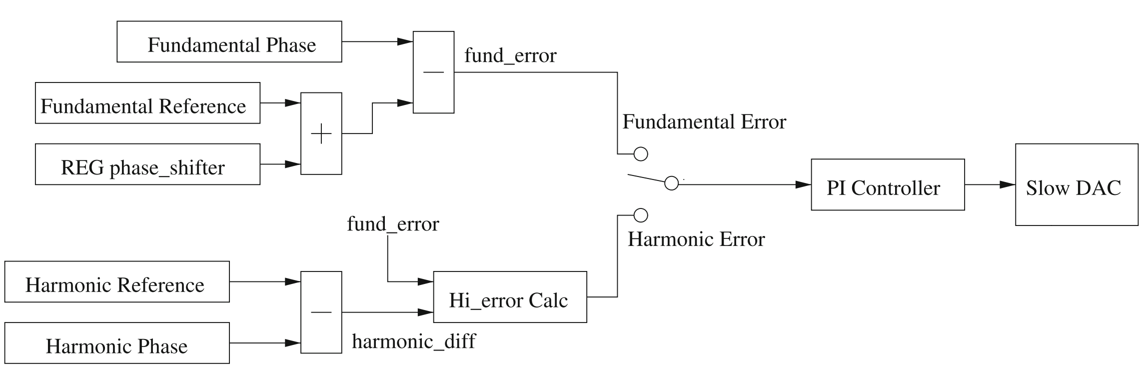

Fig. 3 Control loops

Step 3: Switch to "Harmonic Error" and adjust k_i, k_p. Then the laser oscillator will be precisely locked to both fundamental reference and harmonic reference.

4 Laser emulator structure

Inferred from the laser–RF synchronization scheme, the key features of the laser oscillator are the fundamental/harmonic signal generation ability and frequency tunability. The "Ref/LO Chassis" just has the key features, which include fundamental/harmonic signals and voltage tunable crystal oscillator. By adding only a voltage tuning port, the chassis turns out to be a laser emulator.

The laser oscillator emulator structure is shown in Fig. 4. The voltage-controlled crystal oscillator (VCXO) with the tuning range of 0–200 Hz@119 MHz corresponding to tuning voltage from 0 to 2.5 V. 119 MHz signal was generated by VCXO then multiplied by 24–2856 MHz, which acts as fake harmonic signal. The 79.3 MHz fake fundamental signal was generated by passing 119 MHz through a double frequency multiplier and a divider with a factor of three.

5 Simulation model

In order to do a functional test for phase locking, a model using Simulink will give a demonstration of the phase locking procedure [13]. It is not the full functionality test. The simulation will tell us how to adjust the "Proportional Gain" and "Integral Gain."

The structure of the model is shown in Fig. 5. The transfer function for master oscillator (MO) is just an integrator. The full tuning range for the laser oscillator is (f_0,f_0 + 4.8 kHz), where f_0 is around 2856 MHz. In our model, by eliminating frequency f_0 in the MO model, the residual radial frequency is set to 20,000 rad/s. The residual frequency is free to be chosen in the range of 0–30000 rad/s. Just make sure by tuning the oscillator, the oscillator can catch up to the MO frequency. So set the reference MO transfer function as "20,000/s." The laser oscillator is tuned by the piezo driver, so there is a transfer function for piezo driver in the laser oscillator model, which is just a 10-kHz low-pass filter "6.3e4/(s + 6.3e4)." The other part of the laser oscillator model is an integrator almost the same as the one in MO.

By assuming the output range of the PI controller is from 0 to 1, we can infer from the oscillator transfer function "6.3e4/(s + 6.3e4) * 30,000 rad/s" that the tuning range of laser oscillator model is from 0 to 4800 Hz. The open-loop transfer function can be easily received from the model. By bode analysis, how to set k_i and k_p will be implied from the bode plot. Figure 6 shows the bode plot where $k_i = 0.1$ and $k_p = 0.1$.

As shown in Fig. 6, the phase margin is 45°. The control bandwidth is limited by the piezo driver bandwidth. If there is a "Differential Gain" in the feedback controller, the control bandwidth would be extended. Because differential of error signal is less accurate than the error signal itself, to add differential gain or not to is a trade-off between accuracy and control bandwidth.

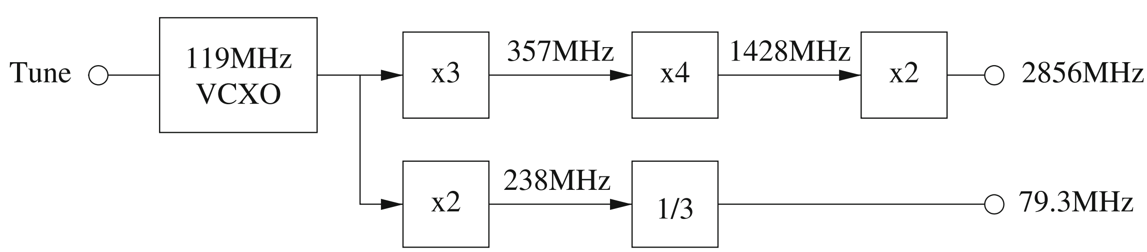

Fig. 4 Laser oscillator emulator structure

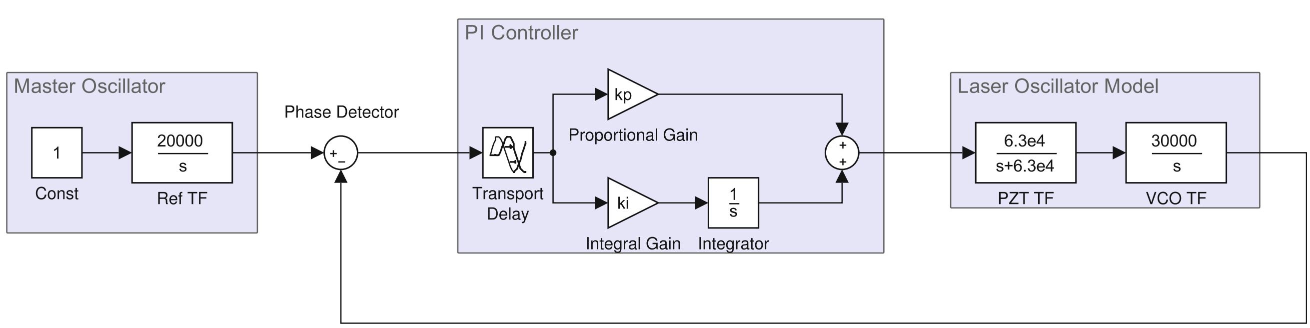

Fig. 5 Laser–RF synchronization model

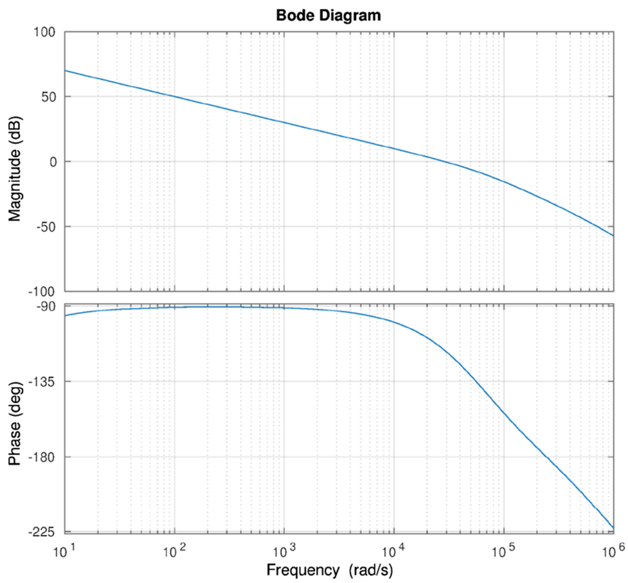

Fig. 6 Open-loop bode plot

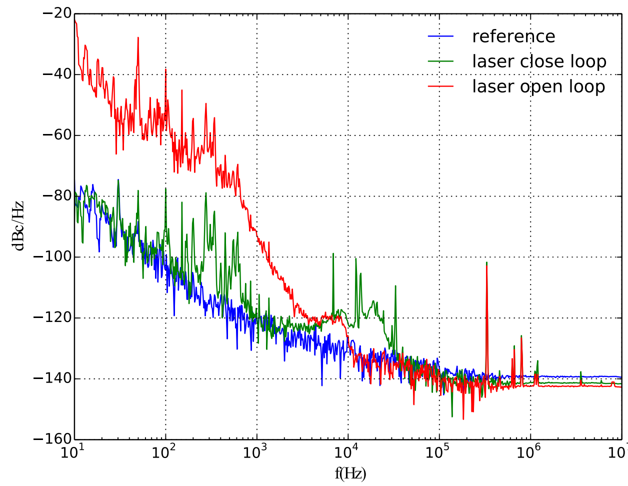

Fig. 8 Absolute phase noise density for laser oscillator

6 Test result

In this section, the phase noise result will be shown. The phase jitter can only tell the final control ability. The phase noise density will tell us much more information. During the test, the E5052B Signal Source Analyzer [14] is used to measure the phase noise directly.

In Fig. 7, the blue line shows the reference RF phase noise density (2856 MHz). The green line in Fig. 7 shows the close-loop phase noise density of the laser oscillator emulator. The bulge around 200 Hz tells the control bandwidth that this emulator is only 200 Hz. The close-loop relative phase noise is 19 fs RMS for this emulator (noise bandwidth is 150 k̃Hz). The relative jitter measurement is from the digital phase detector in loop measurement. The laser emulator open-loop and close-loop phase noise density are almost the same except the bulge due to two identical VCXO are used as the reference and emulator, respectively. It is hard to tell the control ability from the noise density directly, so we use in loop measurement in stead.

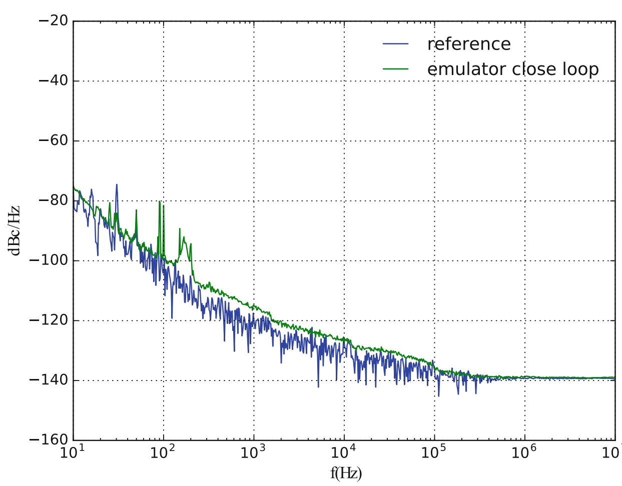

Fig. 7 Absolute phase noise density for laser emulator

In Fig. 8, the blue line shows the reference RF (2856 MHz) phase noise density. The integral reference RF phase noise from 10 Hz to 100 kHz is 31 fs RMS. The red curve is open-loop real laser oscillator phase noise density. The integral phase noise for 10 Hz–100 kHz is 7.8 ps RMS. The phase noise in low frequency range comes from acoustic noise. The control loop is to suppress the noise lower than tens of kHz. The green line shows the real laser oscillator close-loop phase noise density. The noise in the lower frequency range is apparently suppressed to follow the track of the reference, RF. The absolute integral phase noise from 10 Hz to 100 kHz for locked laser oscillator is 57.3 fs RMS. By a rough calculation, the relative jitter will be 48.2 fs RMS from 10 Hz to 100 kHz.

The peaks around 200 kHz is the noise from the detection circuits due to an improper capacitor selection for the power supply. These peaks affected a lot. The upgrade of the detection circuits will definitely improve the performance.

7 Conclusion

Using the digital phase detector for laser–RF synchronization is very flexible and precise. In this paper, the laser–RF synchronization structure was shown. The synchronization algorithm includes two control loops: One is for fundamental signal synchronization, and the other is for precise harmonic synchronization. These two control loops guarantee multiple laser oscillators can be precisely synchronized with each other. The final laser oscillator close-loop phase noise from 10 Hz to 100 kHz is 48.2 fs RMS. This can still be optimized with a better phase detection system.

The laser oscillator emulator was also made for control loop evaluation. The emulator can be used in the fundamental and harmonic phase locking procedures. The emulator is made of RF component. It is much more robust than the real laser oscillator. It is convenient for laser–RF control loop test. On the other hand, the emulator give us a way to recover RF signal from the fiber-based reference distribution system with additive noise around 20 fs RMS.

References

1. P. Emma, R. Akre, J. Arthur et al., First lasing and operation of an angstrom-wavelength free-electron laser. Nat. Photonics **2010**(4), 641–647 (2010). doi:10.1038/nphoton.2010.176
2. L. Doolittle, G. Huang, A. Ratti et al., *The LCLS-II LLRF system* (IPAC, Richmond, 2015)
3. R. Wilcox, J.M. Byrd, L. Doolittle et al., Stable transmission of radio frequency signals on fiber links using interferometric delay sensing. Opt. Lett. **34**, 3050–3052 (2009). doi:10.1364/OL.34.003050
4. Q. Du, Y. Du, L. Yan et al., Precise control and measurement of laser-RF synchronization for Thomson-scattering X-ray source. Nucl. Instrum. Methods A **637**, S137–S140 (2011). doi:10.1016/j.nima.2010.02.041
5. A. Winter, E.A. Knabbe, N. Ignashin, Femtosecond synchronization of ultrashort pulse lasers to a microwave RF clock, in *Proceedings of 2005 Particle Accelerator Conference*, Knoxville, Tennessee (2005). doi:10.1109/PAC.2005.1591801
6. J. Frisch, Laser timing for accelerators. http://web.stanford.edu/~melkor/Timing_talk.pdf
7. J. Kim, J.A. Cox, J. Chen et al., Drift-free femtosecond timing synchronization of remote optical and microwave sources. Nat. Photonics **2**, 733–736 (2008). doi:10.1038/nphoton.2008.225
8. L. Doolittle, LLRF4 board. http://recycle.lbl.gov/llrf4
9. H. Lu, Q. Du, B. Shao, et al., LLRF control system for TTX, in *Proceedings of Nuclear Science Symposium and Medical Imaging Conference* (2012). doi:10.1109/NSSMIC.2012.6551207
10. L. Doolittle, H. Ma, M.S. Champion, Digital low-level RF control using non-IQ sampling, in *Proceedings of LINAC06* (2006)
11. https://www.users.snip.net/donadio/cic.pdf
12. https://en.wikipedia.org/wiki/CORDIC
13. https://www.mathworks.com/products/simulink
14. E5052B SSA Signal Source Analyzer Datatsheet. http://literature.cdn.keysight.com/litweb/pdf/5989-6388EN.pdf?id=1133300