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DEVELOPMENT OF THE RF PHASE SHIFTER WITH FEMTOSECOND TIME DELAY RESOLUTION FOR THE PAL-XFEL LASER SYSTEM*

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Abstract

We introduce the RF Phase Shifter (RPS) developed in the Pohang Accelerator Laboratory X-ray Free-Electron Laser (PAL-XFEL) to control the timing of optical laser system. This equipment is designed to finely adjust the timing of laser pulses with femtosecond scale by manipulating the phase of the RF reference using a couple of Direct Digital Synthesizer (DDS) devices. Furthermore, it is designed with low phase noise and low phase drift features in order to minimize the impact on the system in an open-loop operation.

Currently these units are installed at the Injection site, Hard X-ray and Soft X-ray Beamline. They are implemented for the feedback control of the photocathode gun phase at the Injector and for the use in pump-probe experiments at the Beamlines. This paper describes the design, fabrication, and experimental results of the RPS, as well as its usage status at PAL-XFEL.

INTRODUCTION

Optical Laser systems have been established in the Injector and Beamlines at PAL-XFEL for generating a highly stable electron beam and ultrafast X-ray sciences.

Time delay is a critical function in laser systems. In the Injector section of PAL-XFEL, laser time delay is utilized to compensate for drift of the electron beam. In the Beamline, it is employed to control the time delay of the pump laser in pump-probe experiments. The time delay of lasers can typically be adjusted by altering the physical length of the laser path using mirrors and delay stages. The PAL-XFEL laser system has employed this method since its early operational stages [1].

However, the approach involving delay stages can lead to degradation in laser quality due to vibration and shift in laser focus. Additionally, the difficulty in adjusting the time delay at pulse-to-pulse speed (60 Hz) results in the waste of the probe laser in pump-probe experiments.

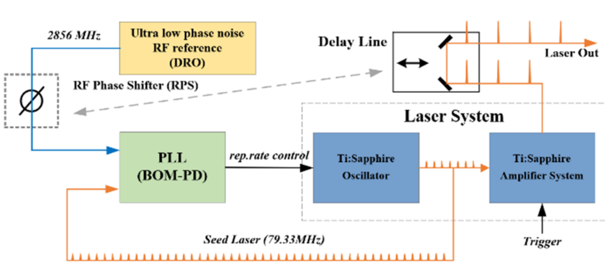

Figure 1: RPS and delay stage in the injector laser.

To address these aspects, we believed that a digital time delay control device would be more effective than mechanical time delay methods. As shown in Fig. 1, we considered installing an RF phase shifter between the REF and PLL to modify the phase. By adjusting the phase in this manner, we expected that a corresponding time delay proportional to the phase change would naturally occur during the Lock Tracking process of the PLL. Additionally, we fabricated a prototype device and confirmed its operation to be as expected.

We manufactured and installed a total of six devices in both the Injector laser and Beamline laser systems. In the following section, we will introduce the fabrication process and outcomes of the RF Phase Shifter.

DESIGN OF THE RPS

Key Specifications

Considering the requirements from the laser team and the limitations of electronic devices, we have defined the specifications as follows:

- Phase Control Resolution: 0.0055 degrees
- Control Range: $(-2^{30} \sim 2^{30})$×resolution
- Linearity (0~360 degrees): ≤ ±0.05 degrees
- Update Rate: ≥ 10 kHz
- Stability degrees/day: ≤ 0.1 degrees
- Phase Noise: ≤ -150 dBc@100 kHz~1 MHz

Determination of Phase Shifting Methods

We explored various phase shifting methods to develop a unit that satisfies the specifications at a reasonable cost. Initially, we considered Digital/Voltage Controlled Phase Shifter components due to their affordability and straightforward control mechanisms. However, after reviewing the datasheets, we determined that they would not meet the required resolution and linearity specifications [2, 3].

The vector modulation approach allows for high resolution implementation, but due to hardware issues such as phase unbalance in Hybrid and Combiner, as well as I/Q DC offset, the linearity of the output phase deteriorates. Therefore, meticulous calibration efforts are required to meet the linearity specifications. However, even with such calibration, we had determined that achieving the less than ±0.05 degrees linearity is very challenging [4].

Next, we examined the DDS device. The DDS enables precise frequency/phase control and fast response characteristics by converting digital values obtained through the 'Phase Accumulator' and 'Amplitude/Sine Converter' into RF signals via the DAC (Digital-to-Analog Converter) [5].

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Figure 2 shows the block diagram of the AD9914 DDS that we applied. The AD9914 has a 16-bit phase offset value, providing a phase resolution of approximately 0.0056 degrees (360/2^16). Although the DAC's resolution is limited to 12 bits, the phase truncation process that maintains the higher bits ensures that all 16 bits of phase information are preserved [5].

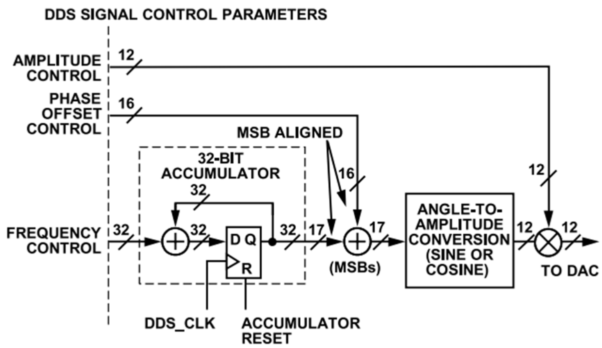

Figure 2: AD9914 block diagram [6].

Frequency Plan of the System

When performing frequency up-conversion and down-conversion, the phase of the output signal generally mirrors the changes in the phase of the input signal. Therefore, we had planned to utilize the DDS output as an Intermediate Frequency (IF) signal and feed it into the mixer in the process of converting the RF 2856 MHz REF input frequency. Then we can control the output phase by manipulating the phase of this DDS signal.

The design concept is shown in Fig. 3.

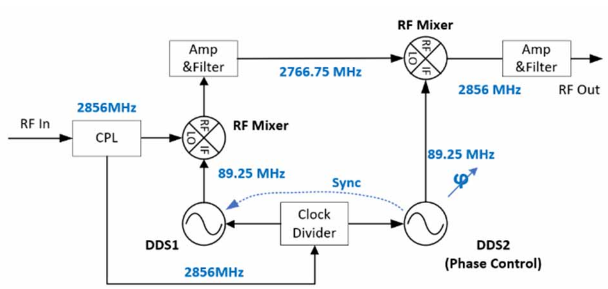

Figure 3: RPS frequency plan.

On the other hand, in order to minimize the generation of spurious signals during the conversion process, we initially set the DDS output frequency to a few hundred MHz. However, based on the information from the datasheet of AD9914, we confirmed that higher output frequencies lead to deteriorated residual phase noise performance [6]. Therefore, we made a trade-off between spurious reduction and phase noise performance. Consequently, we determined the DDS output frequency to be 89.25 MHz.

FABRICATION OF THE RPS

The following block diagram shows the internal structure of the fabricated unit.

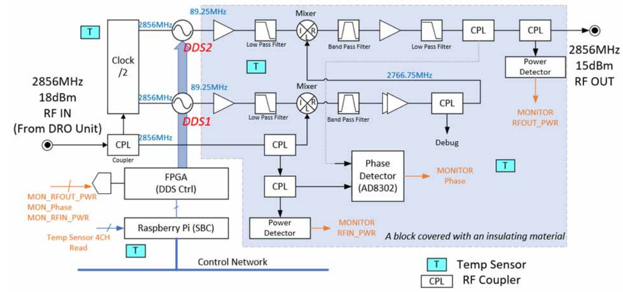

Figure 4: RPS block diagram.

The Power of the input REF signal is sufficiently large to drive the mixer, so it is directly routed to the mixer's LO port after passing through the coupler without an additional amplifier. The output from the coupler serves as the master clock for the DDS, and an ADCLK925 1:2 clock buffer is employed to supply the signal to two DDS chip.

The frequency of the down-converted signal at the first mixer is 2766.75 MHz, and this signal is then passed through a filter and amplifier before being fed into the LO port of the second mixer. The IF signal produced by the second DDS and the 2766.75 MHz signal are mixed together at the up-conversion mixer and it generates an RF signal at 2856 MHz. The phase control in this process is achieved by adjusting the phase offset value of the DDS dedicated to up-conversion. An FPGA was utilized for DDS timing control, and a Raspberry Pi, acting as a Single Board Computer, was employed for EPICS IOC processing.

In Fig. 4, the blue region represents the temperature-controlled area. To minimize drift caused by external temperature variations, this area is surrounded by thick insulation material, and external chiller along with specially designed heat dissipation plates are used to control the temperature. For precise temperature monitoring, temperature sensors are placed at four locations within the unit. Additionally, power detectors and phase detectors are mounted inside the RF modules for continuous monitoring of input/output power and phase. Figure 5 shows the fabricated unit.

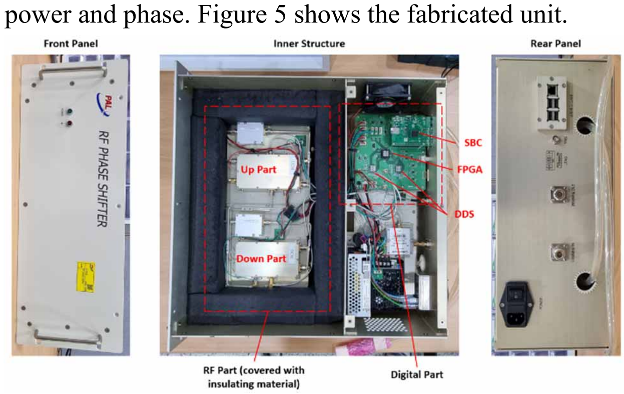

Figure 5: The fabricated unit.

The control board containing the DDSs was exposed to room temperature due to the longer wavelength of the IF band, which results in reduced sensitivity to temperature changes.

Meanwhile, the RF circuitry is placed in an area with temperature control. It is tightly integrated within a metal

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housing which is further affixed to a metal heat dissipation plate, enhancing thermal conductivity between the heat dissipation plate and the RF circuitry. Furthermore, as the cooling fluid flows through the heat dissipation plate from the chiller, heat exchange takes place. Therefore, to ensure a high level of temperature stability, it is important for the insulation performance to be excellent, and the temperature of the cooling fluid should remain consistent.

PERFORMANCE AND USAGE

Performance

Phase Noise Figure 6 displays the measurement results of the input and output phase noise characteristics of the RPS, displaying that the desired phase noise performance of 150 dBc or lower is achieved in the target frequency range exceeding 100 kHz.

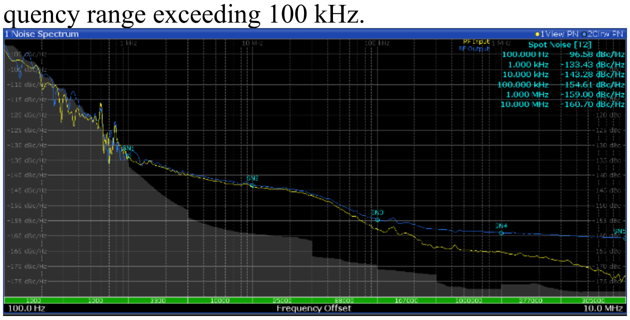

Figure 6: Phase noise, yellow: REF, blue: RPS output.

Long Term Stability The measurement of long-term stability utilized the Phase Detector from i-tech Corp., as well as the LLRF deployed at PAL-XFEL.

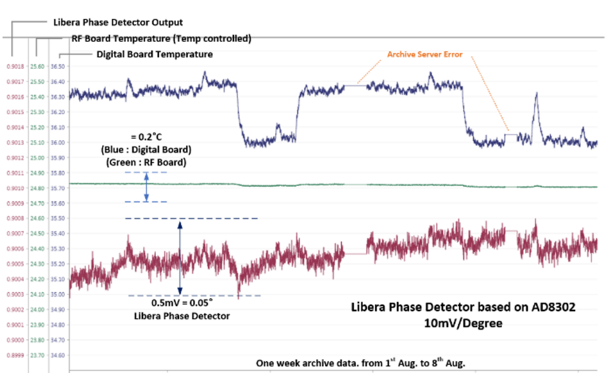

Figure 7: Long-term stability by i-tech phase detector.

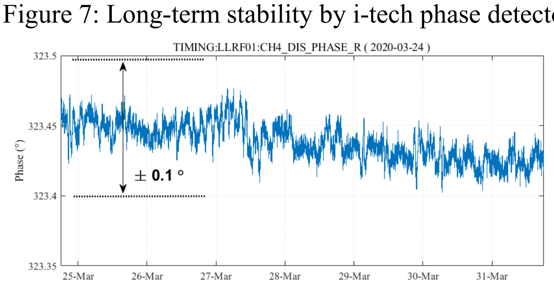

Figure 8: Long-term stability by LLRF.

As shown in Figs. 7 and 8, both sets of results demonstrated a stability of 0.1 degrees per week. To minimize errors, the output voltage of the Phase Detector was set to 0.9 V. This device features an output characteristic of 10 mV per degree [7].

Resolution and Linearity To demonstrate the resolution performance of the RPS, we incrementally increased the phase of the RPS by 0.0055 degrees using LLRF for testing. Figure 9 shows the results, clearly indicating increments of 0.0055 degrees. For reference, the phase measurement performance of LLRF is rms 0.01 degrees.

Figure 10 shows the results of the linearity measurements for the RPS. The RPS phase was incremented in 10 degrees steps from 0 to 350 degrees, and the phase measurements obtained through LLRF are displayed on the left vertical axis, with the relative error indicated on the right vertical axis. It can be observed that the relative error remains within ±0.05 degrees.

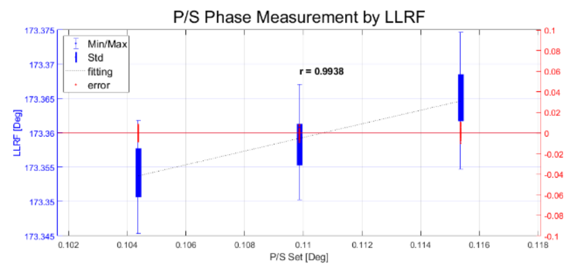

Figure 9: RPS resolution (0.0055 degrees/step).

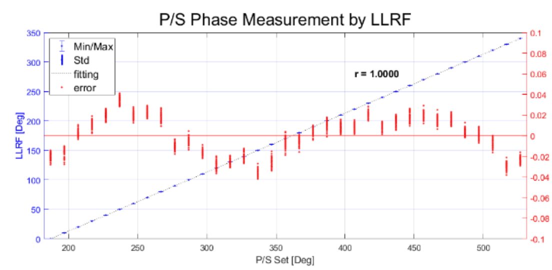

Figure 10: RPS linearity (10 degrees/step).

Usage of PAL-XFEL

PFS units have been installed in the Hard/Soft X-ray Beamline laser room and the Injector laser room. The installation images are shown in Fig. 11.

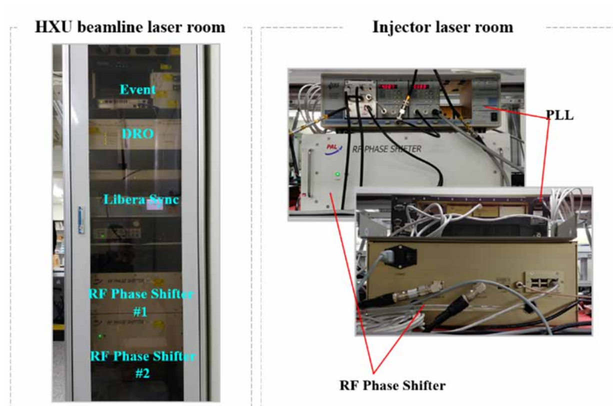

Figure 11: RPSs in the beamline and injector.

In the Injector laser, the RPS is utilized to correct phase drift between laser and electron beam. As depicted in Fig. 12, the RPS adjusts the laser delay time by reading the

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position value of the BPM located downstream of the Gun and making adjustments based on the error.

In the beamline, the RPS is currently used partially for pump-probe experiments. It appears that many users still prefer the time delay control method using the conventional motion stage. However, we plan to actively explain the advantages of the device to users in order to increase opportunities for its usage.

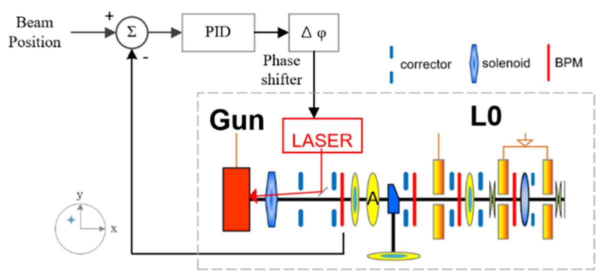

Figure 12: Feedback using RPS in the injector.

SUMMARY

We have developed a cost-effective phase controller with a manufacturing cost of less than $10,000, and through experiments, we have confirmed its satisfactory performance. As mentioned earlier, this unit is currently operated as a Gun laser feedback system for PAL-XFEL, and we anticipate its gradual expansion for pump-probe experiments in the beamline.

REFERENCES

[1] M. Kim, C.K. Min, and I. Eom, "Laser systems for time-resolved experiments at the Pohang accelerator Laboratory X-ray Free-Electron Laser beamlines", *J. Synchrotron Rad.*, vol. 26, pp. 868-873, 2019. doi: 10.1107/S1600577519003515

[2] Analog Device, "HMC647ALP6E Digital Phase Shifter Datasheet", https://www.analog.com

[3] Mini-Circuits, "JSPHS-1000 Voltage Controlled Phase Shifter Datasheet", https://minicircuits.com

[4] P. Tosovsky, D. Valuch, "Improvement of RF Vector Modulator Performance by Feed-forward Based Calibration", *Radioengineering,* vol. 19, no. 4, pp. 627-632, 2010.

[5] Analog Device, "A Technical Tutorial on Digital Signal Synthesis", https://www.analog.com

[6] Analog Device, "AD9914 Direct Digital Synthesizer Datasheet", https://www.analog.com

[7] Instrumentation Technologies, "Libera Phase Detector User Manual", https://www.i-tech.si