

A NOVEL MICROWAVE SWITCH-BASED LLRF SYSTEM FOR LONG-TERM SYSTEM PHASE DRIFT CALIBRATION

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Abstract

Long-term phase stability is a significant issue for Low-level RF systems. Crosstalk and temperature effect on the RF field detectors would significantly limit the performance of phase detecting and phase locking. A novel microwave switch-based LLRF system has been developed in Tsinghua Accelerator Lab. Microwave switches are applied in the chopper circuit to turn continuous waves into pulse waves in the time domain to avoid mutual interference of signals. In this paper, the LLRF system based on microwave switches is presented. The result of preliminary long-term experiments shows the phase stability can achieve about 50fs RMS slow drift. The peak-to-peak value of the slow drift was ~ 100 fs ($\sim 2^\circ\text{C}$ p-p) over 4 days.

INTRODUCTION

The long-term stability is required in the Thomson scattering X-ray source, high-intensity X-ray light sources based on free electron laser (FEL) and MeV ultrafast electron diffractions. Tsinghua Accelerator Lab, cooperating with LBNL, has developed the timing and synchronization system. The system has been demonstrated at the Tsinghua Thomson scattering X-ray (TTX) source successfully [1-2]. However, it is found in the previous test that there is a slow drift in the LLRF system, which is about 0.5ps p-p. The Fourier transform of the phase drift shows the peak frequency of the spectrum was closely related to the change of temperature in the same period, which indicates the temperature as the main factor of the slow drift of the system. Considering the long-term operation of particle accelerators, the change in environmental temperature over time would cause great impact on not only the microwave phase control of the accelerator but user experiments which based on the accelerator as well. Therefore, it is important to solve the issue of long-term stability in the LLRF control system [3-4].

THE CAUSES OF LONG-TERM PHASE DISTORTION AND DRIFT

There are numerous devices and complex signal loop in the synchronous control system, which tends to cause signal crosstalk in the LLRF system. Crosstalk is the noise caused by the coupling of the two signals as well as the mutual inductance and capacitance between them. Capacitive coupling leads to coupling current, while inductive coupling leads to coupling voltage. There are several fac-

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tors which may have certain influences on the crosstalk: the parameters of the PCB layer, signal line spacing, electrical characteristics of the drive end and the receiver end as well as the connection mode of the line end.

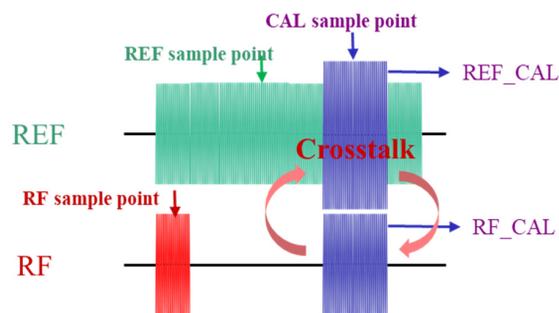


Figure 1: Signal crosstalk in the LLRF system.

The microwave signals in Tsinghua LLRF control system are continuous REF signal, pulse RF signal and CAL signal [4]. The CAL signal is combined with the REF signal and the RF signal using power division modules, and they are sent through their own routes. Therefore, crosstalks are most likely to occur because of the introduction of the CAL signal. After the CAL signal is combined with the REF signal and the RF signal, they relatively trigger the REF_CAL signal and the RF_CAL signal, so the crosstalk occurs mainly between REF_CAL and RF_CAL, and they would exert an effect on each other. The RF signal and the REF signal have different sampling points in the time domain. Because the REF signal is continuous while the RF signal is a pulse, the phase detection of REF signal would not be affected by the crosstalk with the RF signal, but it would influence the phase detection of the RF signal, as shown in Figure 1.

Analysis of Signal Phase Distortion

The turbulence of the REF signal would be coupled to the REF_CAL signal and result in distortion of the signal. Based on the empirical speculation of the performance of the devices used in the experiment, the main causes of phase distortion of signals in the synchronous control system are list as follows:

The Reflection between the Power Divider and Amplifier The typical reflection coefficients of the three ports of the power divider were 0.034 (S), 0.09, and 0.05, respectively. The VSWR Output of the last stage amplifier zx60-33ln + in the Receiver (RxC) chassis was 1.6, and the reflection coefficient was 0.23. Therefore, if there was a superposition of the CAL signal and the REF signals output by RxC chassis, then the coupling effect of superimposed

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signals was $1 * 0.23 * 0.09 = 0.021$ (only once reflection was considered temporarily).

Crosstalk between Two Ports of the Power Divider The isolation ratio of power divider device depends on the device manufacturing process. Generally, the two ports of power divider device are isolated about 20 dB. In other words, the amplitude of coupling through one port of the power divider to another port is 0.1 times, and the reflected signals are coupled through a port of power divider to signal of about $0.1 * 0.021 = 0.002$ times (about 34 dB), which is also a great value.

LLRF CONTROL SYSTEM BASED ON MICROWAVE SWITCH

As shown in Figure 2, in the scheme based on continuous reference signal REF, since the correction signal CAL was at the same position in the time domain, signal intersection and crosstalk problems occurred in the process of signal transmission, and the system error when the correction signal was used was as follows:

$$Error = (RF - RE_CAL) - (REF - REF_CAL)$$

Where, RF denotes pulse signal, and REF denotes CW signal.

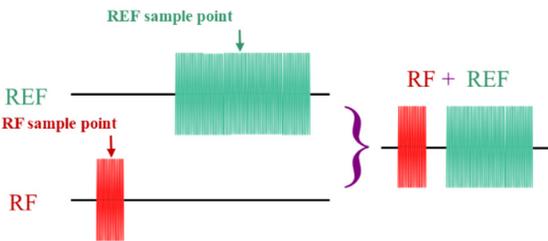


Figure 2: Schematic diagram based on pulse signal.

Based on the previous design, if the REF signal was chopped into the same pulse signal as RF, the RF signal and the REF signal could be transmitted through the same line. The calibration function of the CAL signal is provided accordingly.

$$Error = RF - REF$$

$$RF_CAL - REF_CAL = 0$$

The problem of handing over and crosstalk in the time domain could be solved by using a chopper circuit or device to turn the REF signal into a pulse signal.

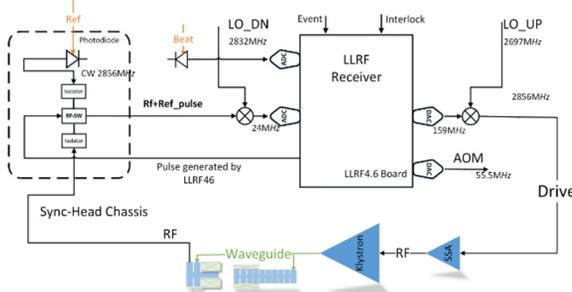


Figure 3: LLRF system based on microwave switch.

As shown in Figure 3, the LLRF control system based on the microwave switch maintains its original basic struc-

ture. As for the main improvement of the system, the correction CAL signal synthesized by reference signal and microwave sampling signal in the original Synchrad was removed; synthesizing was achieved directly by microwave switch RF-SW, and then the signal was transmitted to the Receiver chassis for data signal processing. It was necessary to use an isolator before and after the microwave switch signal synthesis to reduce the noise in the process of signal reflection.

In principle, this scheme avoids distortion of the correction signal in the time domain and microwave signals in the process of signal superposition ($RF + RF_CAL = RF + CAL$), as well as the signal interference of continuous signal ref coupling to CAL and RF. Additionally, the scheme greatly simplified the system complexity by subtracting CAL signal line, reduced the original three cables from Synchrad chassis to Receiver chassis to one cable. Moreover, it saved system resources and eliminated the need for specific phase-stabilizing function and other requirements for the performance of the cables.

The solid-state microwave switch of HMC8038 chip based on mini circuits was adopted in the system design, as shown in Figure 4 below.

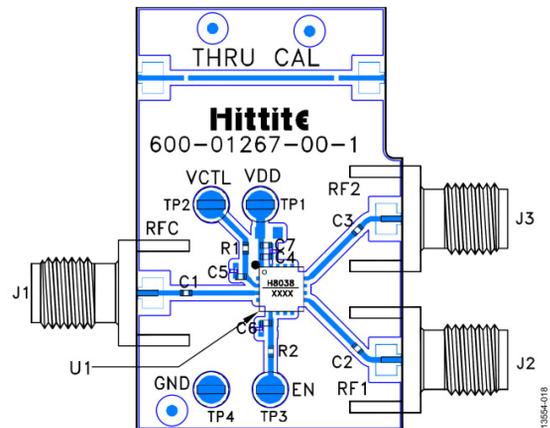


Figure 4: Microwave switching device circuit prototype.

The microwave switch, also known as the RF switch, is a device for routing the transmission path of high-frequency microwave signals, whose main function is to control the conversion of microwave signal channels. The solid-state switch is currently more commonly used microwave switch type, and it is based on semiconductor technology electronic switch structure. Its biggest characteristic is the fast response time, which is normally nanosecond-level.

For the general LLRF control system, the microwave switch with the width of the microsecond level can effectively complete signal disconnection. HMC8038 is a non-reflective type switch chip with high isolation, 0.1GHz to 6.0GHz, and single pole double throw (SPDT). The switch can achieve 62dB isolation, 0.8dB low insertion, and 60dBm input third-order intermodulation cut-off point. The enable input (EN) is set to the logical high level to put the switch in the all-off state, where RFC is reflective [5].

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Table 1: Main Performance Indicators of HMC8038 Switch

Speed	Test Conditions	Type	Unit
t _{rise} , t _{fall}	10%/90% RFOUT	60	ns
t _{on} , t _{off}	50% VCTL to 10%/90% RFOUT	150	ns

Each port of the microwave switch contains a 50 Ohm matching terminal, which enables the microwave switch to present a low standing wave ratio in off and on states. The reflection switch conducts RF power when the diode is reversely biased, and RF power is reflected when the forward bias is used.

LONG-TERM STABILITY TEST OF THE SYSTEM

For the LLRF control system based on microwave switches, the long-term stability dual-machine test was conducted after the initial test mentioned above. As shown in Figure 5, the control machine operated in a closed-loop phase-locked state, and the output drive signal was sent back to the control machine and the monitoring machine respectively through the power division. The same continuous 2856MHz microwave signal source was divided into two parts through the power division as the reference signal of the two systems. The two power splitter components were connected with 10cm short wire.

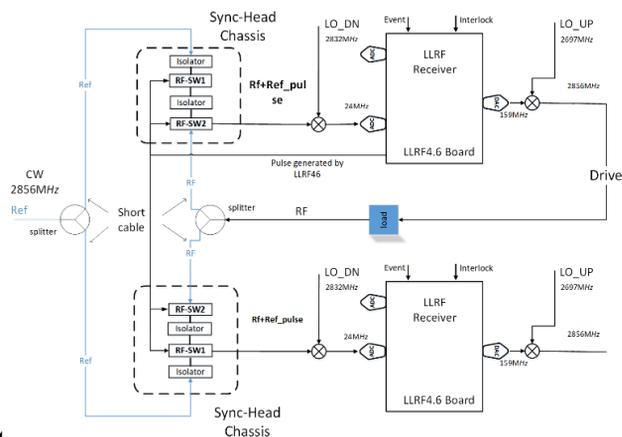


Figure 5: Dual-machine test of long-term stability of LLRF control system.

The monitoring machine detected the Reference phase and the RF phase from the control machine to evaluate the control effect of the microwave switch based LLRF system. After four days of long-term testing, the phase change of the reference signal of the system was about 40ps, the phase was obviously positively correlated with the temperature change. The phase error of the system was shown in the following figure:

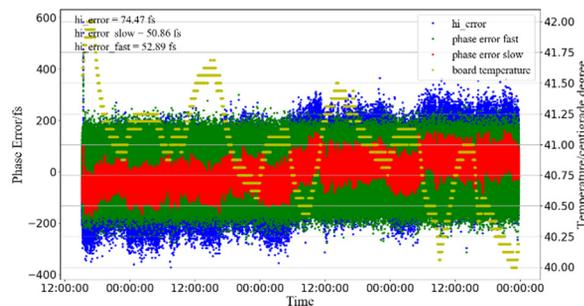


Figure 6: The test results of long-term phase slow drift of the monitoring machine.

As seen from Figure 6, the temperature varied $\sim 2^{\circ}\text{C}$ with the reference phase changed $\sim 40\text{ps}$ in the four days. The phase error (hi_error) is about 75fs RMS. We use the moving average (MA) by 100 terms to get the slow drift of the system. The drift was basically stable and changed slightly with temperature. During the four-day test, the system phase error was 74fs RMS; the phase jitter was 52fsRMS; the slow drift was 50fs RMS; the peak-to-peak value of the slow drift was $\sim 100\text{fs}$ ($\sim 2^{\circ}\text{C}$ p-p).

DISCUSSION AND SUMMARY

The way of turning a continuous reference signal into a pulse signal by building the LLRF control system based on microwave switches can solve the microwave signal crosstalk. The new LLRF scheme effectively suppresses the slow drift of the LLRF system in the long-term with the change in temperature. The experimental results show that the improved system can implement long-term temperature stability. For there are still non-equal length short-line connections in the connection of devices in the system, however, the temperature still has a certain impact on the system in the actual long-term operation. At present, the main constraint to the performance improvement of the system is the fast noise jitter of the system. The reduction of phase discrimination error of the system (phase jitter) will be the research focus in the next planning.

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