EXPERIMENTS ON FEMTOSECOND STABILIZATION OF FIBER LINK FOR SHANGHAI SOFT-XFEL

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Abstract

The Shanghai Soft X-ray Free Electron Laser (SXFEL) facility will be constructed in the Shanghai Synchrotron Radiation Facility (SSRF) campus. SXFEL will operate in the HGHG and/or EEHG mode and require a femtosecond timing distribution system as well as the synchronization between femtosecond pulsed lasers, femtosecond pulsed X-rays, CW microwave signals and electron bunches with 10 fs precision. The pulsed fiber laser based femtosecond T&S system which has been proposed by the MIT/DESY team is adopted. In this paper the status of the femtosecond T&S system for SXFEL is introduced. Some initial progress of the phase stabilization by electronics control when laser pulses transport though long optical fibers is presented.

INTRODUCTION

The next generation light source, X-ray free electron laser (XFEL), is considered as the most powerful scientific instrument and it will bring unprecedented breakthroughs in multiple disciplines. XFEL requires a femtosecond (fs) timing distribution system as well as synchronization between fs pulsed lasers, fs pulsed X-rays, CW microwave signals and micro-bunches with 10 fs precision [1]. Transporting an RF signal through long coaxial cables would suffer great from attenuation, temperature drift, mechanical vibration and electromagnetic radiation. Recent research shows the optical fiber is a better candidate. Distributing signals with multiple frequencies to multiple locations along one kilometer FEL facility could be realized by either transporting a chain of fs laser pulses through length-stabilized optical fibers and then regenerating the RF downstream (taken by Euro-XFEL [1], SwissFEL [2], SXFEL), or modulating the RF signal directly on a CW laser which also transports along optical fibers and then demodulate the RF when needed (taken by LCLS [3], FERMI [4]). This article focuses on the investigation of long-term phase drift due to the environment temperature change after the femtosecond laser pulses transport several hundred meters long within optic fibers. This study will be used on the femtosecond timing and synchronization system of the Shanghai SDUV-FEL and future SXFEL facility.

FEMTOSECOND TIMING AND SYNCHRONIZATION SYSTEM

A typical femtosecond T&S structure based on the femtosecond pulsed fiber laser [1, 5] is shown in Fig. 1. This structure will be implemented on the SDUV-FEL facility in SINAP, Shanghai, which is a test facility for the HGHG and EEHG modes of future SXFEL operation. Technical challenges center on:

(1) The fs mode-locked pulsed fiber laser called Optical Master Oscillator (OMO) should be phase-locked with an ultra-low noise microwave oscillator (MO).

(2) The timing and frequency distribution system based on the phase-stabilized optical fibers requires sub-10 fs short-term jitter as well as long-term drift.

(3) Pump-probe experiments need a timing resolution of sub-fs between two pulsed lasers. The driver laser for the photocathode RF gun and the seeded laser for HGHG operation mode of XFEL also request accurate synchronization with laser pulses of the OMO.

(4) Sub-10 fs synchronization between RF signals and pulsed lasers is required as low noise microwave signals for accelerate cavities and the LLRF system must be regenerated or extracted from the timing distribution system.

(5) Beam Arrival Monitors (BAM) are inserted at different positions along the XFEL facility to meet with 10 fs synchronization between one-pass electron bunch and the seeded laser.

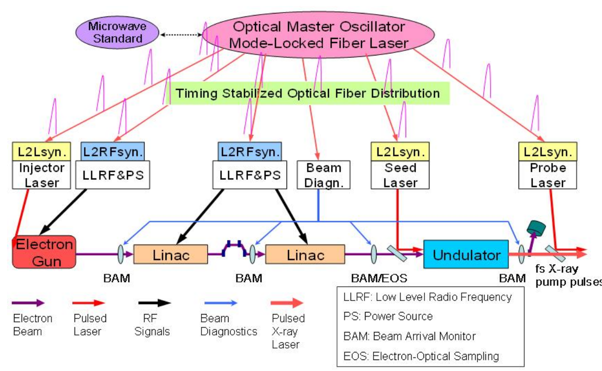

Figure 1: Layout of femtosecond T&S system based on the femtosecond pulsed fiber laser.

From the analysis above, the backbone of the whole femtosecond T&S system is the long distance phase-stabilized fiber link which distributes frequency/phase information to multiple locations along the whole facility. This paper focuses on a digital phase detector used for stabilization of fiber link and study of influence of environment temperature on the timing delay at each local station.

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EXPERIMENTS ON PHASE-STABILIZED TIMING AND FREQUENCY DISTRIBUTION

The experiment setup is illustrated in Fig. 2. The Optical Master Oscillator (OMO) is phase-locked with the RF Oscillator. The fs laser pulses from the OMO are split into three paths, namely, the forward light, the reference light and the backward light, all of which are converted into RF signals by photon detectors (PD). Then the forward path signal generates the sampling clock and the LO signal for down-conversion. The reference light and the backward light which goes through a 100-meter-long fiber outside the room are converted, filtered and down-converted to the IF signals. Finally the IF signals are sampled into digital data. Some well-known powerful technology for modern digital low-level RF (LLRF) system in accelerator technology [6] is adopted to process the sampled signals and get the phase and the amplitude data.

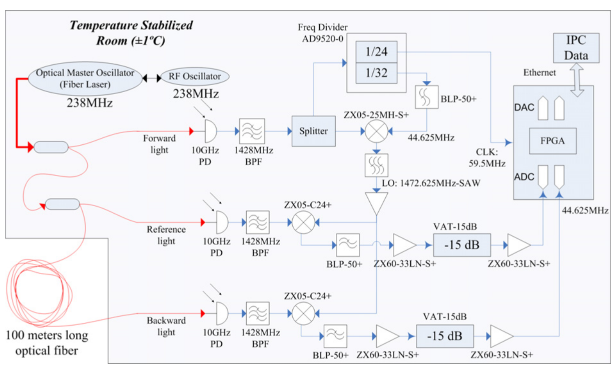

Figure 2: Experiment setup to test long-term drift of laser pulses with digital phase monitor.

Two reasons are preferable as we considered using this scheme.

- We can benefit great from the powerful and flexible IF sampling technology whereafter improve the resolution of timing/phase detection, which has been taken as the digital LLRF solution in more and more accelerator facilities.
- The detector and the control unit could be standardized easily with the LLRF hardware system or be designed as some daughter board for LLRF data bus, which simplify development efforts while enhance the reliability and maintainability.

Digital Algorism Process and Data Communication in FPGA

The digital signal process algorithm [7, 8] is implemented in the Altera StratixII 2s60 FPGA and runs in the pipeline mode, as illustrated in Fig. 3. A phase detection resolution of 0.023 degree (root-mean-square) is obtained while the total delay in the FPGA is 42, so the bandwidth of the DSP part is about 1.4MHz (59.5/42).

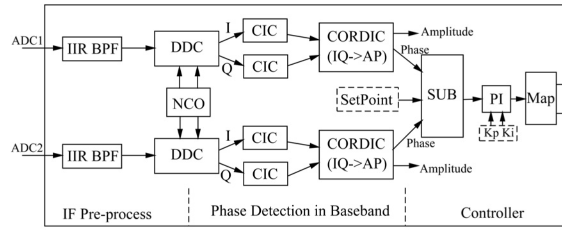

Figure 3: Digital phase&amplitude detection algorithm implemented in the FPGA.

The Cascade Integrator Comb (CIC) filter offers a good balance among the cancelation of the out-band noise, the attenuation of the in-band frequency and the delay number. For a CIC filter with S stages, D delays and decimation factor R, the frequency response is:

$$\left|H_s(e^{jw})\right| = \left|\frac{1-e^{-jwRD}}{1-e^{-jw}}\right|^S = \left(\frac{\sin\frac{wRD}{2}}{\sin\frac{w}{2}}\right)^S$$
$$= (RD)^S \cdot Sa^S\left(\frac{wRD}{2}\right) \cdot Sa^{-S}\left(\frac{w}{2}\right) \quad (1)$$

Given S=3, D=2, R=4, the suppression to the first side lobe (largest noise peak, at $w = 3\pi/(R \cdot D) = 3\pi/8$) is -39dB while at w=1MHz with F_s=59.5MHz the distortion is only -0.2dB. Table 1 lists several main specification of the phase detector.

Table 1: Main Specifications of the Digital Phase Detector

Resolution	0.02°
Accuracy	0.02°
Detection Range	−179.9° ~ 179.9°
Response time	0.7us
Dynamic range: RF/IF	40dB/40dB

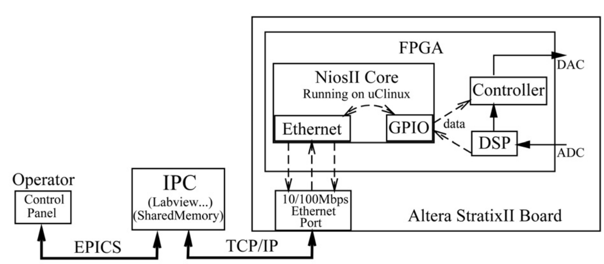

Figure 4: Scheme of data communication in FPGA.

The soft core embedded processor, NiosII, which runs the open source μClinux operation system [9], is implemented in the Altera StratixII FPGA in order to exchange the data between the GPIO and Ethernet ports, as demonstrated in Fig. 4. A device driver for the GPIO port under μClinux is specially developed and added into the kernel.

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Several daemon processes are started after the μClinux OS boots up for transporting different paths of signals. The data stream has to be down-sampled as the 100 Mbps data rate of Ethernet port cannot satisfy the bandwidth required.

Results of the Experiment

Experiments [10] are carried out with two conditions: the temperature in the room is relatively stable while another is not very stable. The stable condition enables the temperature in the room maintained within $\pm 1°$C. Results of 24 hours captured by the digital phase/amplitude monitor are shown in Fig. 5 and Fig. 6. In experiment-1, when the temperature in the room is stable, the reference timing is 1ps (p-p) while the drift outside the room over one day and night is 6ps (p-p). In experiment-2, when the temperature in the room is not very stable, the reference timing and the backward timing are 4ps (p-p) and 12ps (p-p) respectively, especially in the stable duration at night (between 20:00 and 08:00), the two numbers are 1ps (p-p) and 6ps (p-p). The relative amplitude errors are all within ± 0.5‰ in 24 hours. The results correspond well with those in Reference [10].

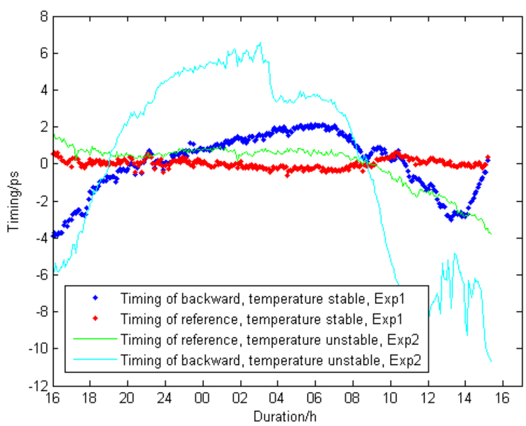

Figure 5: Phase results of two comparative experiments.

CONCLUSION AND FUTURE PLANS

From the results, conclusion could be drawn that the stability of temperature in the room is significant for the measurement of the phase monitor. Once the condition, within $\pm 0.1°$C which can be reached without much effort, could be fulfilled, the phase/timing can be detected in sub-ps scale. The timing variation of fibers can be monitored and in this way fibers are stabilized to femtosecond jitter when adding to other feedback techniques. This digital monitor can be used in the femtosecond timing and synchronization system.

The feedback control will be realized once the fiber stretcher is ready in next few months. Also the phase detection with better resolution using optical cross correlation technique is supposed to be evaluated.

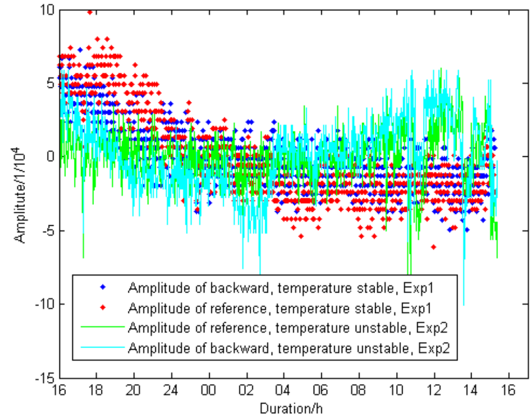

Figure 6: Amplitude results of two comparative experiments.

The RF regeneration from the pulsed fiber laser will be started from the direct extraction of high frequency signal using suitable bandpass filters. Then the idea, using the base frequency (238 MHz)followed by a phase locked loop (VCO, VCXO or DRO based) in order to obtain S-band and C-band microwave signals, could be tested. Finally some nonlinear optical methods will be particularly considered.

Actually, all the work can be done in parallel.

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