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SUB-20 fs SYNCHRONIZATION BETWEEN MODE-LOCKED LASER AND RADIO-FREQUENCY SIGNAL *

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Abstract

The femtosecond synchronization and distribution system of the Shanghai soft X-ray free-electron laser facility (SXFEL) and Shanghai high repetition rate XFEL and extreme light facility (SHINE) are based on the optical pulse trains generated by passively mode-locked lasers. The passively mode-locked laser has ultralow noise in the high offset frequency (<5 fs, [1 kHz- 1 MHz]). In this paper, we report precise synchronization of the low-noise passively mode-locked laser to the radio frequency (RF) master oscillator. RF-based phase-locked loop scheme, the absolute jitter of the phase-locked passively mode-locked laser is less than 20 fs integrated from 10 Hz up to 1 MHz.

INTRODUCTION

Large-scale femtosecond stability has become an urgent requirement in modern free-electron lasers (FELs) facilities. At SXFEL [1] and for the SHINE, a pulsed optical synchronization has been used. The central component of the pulsed optical synchronization is the low-noise mode-locked laser which operates at telecommunication wavelength(~1550 nm). The use of low noise mode-locked laser as the optical master oscillator has become an excellent way to achieve an effectively synchronized network by distributing the optical master oscillator output to the individual end stations by length stabilized and dispersion compensated fiber links. The fiber links are based on a balanced optical cross-correlation method [2-4].

The optical synchronized network composed of fiber links distribute high-purity pulsed reference signals to three different types of end stations along the complete FEL facility to achieve femtosecond synchronization.

The bunch arrival time monitor based on the electro-optical modulator (EOM) scheme [5] is used to measure the arrival time of electron bunch with femtosecond accuracy at some special positions along the accelerator and undulator.

The remote lasers synchronization using two-color balanced optical cross-correlation [6, 7] is used to synchronize remote lasers, such as the photocathode lasers in the injector, the seed lasers near the undulator, and the pump-probe lasers in the experiment stations, to the output of fiber links

The laser-RF synchronization using a balanced optical microwave phase detector enables timing detection between the output fiber link and radio frequency signal zero-crossing for stable RF signal re-generation which is needed in the SRF cavities and beam-diagnostic devices.

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Being the heart of the optical synchronized network, the low-noise performance of the optical master oscillator is of tremendous importance. Due to the inherent characteristic of the optical master oscillator, the cavity length is easily affected by environmental fluctuations. The optical master oscillator is stabilized by the phase-locked loop against the radio frequency master oscillator to ensure long-term stability.

RF-BASED OPTICAL MASTER OSCILLATOR SYNCHRONIZATION

A common microwave phase-locking technique is used for synchronization between the optical master oscillator and RF master oscillator.

Figure 1 describes the RF-based experimental setup of synchronization between the optical master oscillator and RF master oscillator. For this test setup a commercial mode-locked laser from Menhir Photonics, which operates at 238-MHz repetition rate with 1558-nm center wavelength and 170-fs pulse duration, was used as the optical master oscillator. The RF reference signal at 1428-MHz is supplied by a 1428-MHz RF master oscillator (Rohde & Schwarz).

In order to achieve phase detection for synchronization purposes, it is necessary to convert pulsed optical signals into electrical signals. The photodetector generates electrical signals with high spectral purity harmonics of the laser repetition rate. A power splitter is used to split the electrical signal from the photodetector into two parts. A sixth harmonic of the photodetected electronic spectrum is filtered out using an RF bandpass filter and a low noise amplifier in combination with an RF phase detector. Meanwhile, another frequency comb with the same repetition rate as the optical master oscillator is filtered out using another bandpass filter and a low noise amplifier in combination with an RF phase frequency detector. The fundamental frequency is used for coarse tuning for the setting phase point. The sixth harmonic frequency is used for fine-tuning for precise synchronization. The lock on the higher harmonic improves the performance. The phase error signal between the RF reference signal from the RF master oscillator and optical master oscillator signal is fed to the digital controller. Once the phase-locked loop (PLL) was established using the RF-based laser-to-RF synchronization setup, a traditional method of measuring the timing jitter of the optical master oscillator was used. The scheme has been widely adopted by the current state-of-the-art signal source analyzers (SSAs). The phase noise of the obtained RF signal from the optical master oscillator is converted to ampli-

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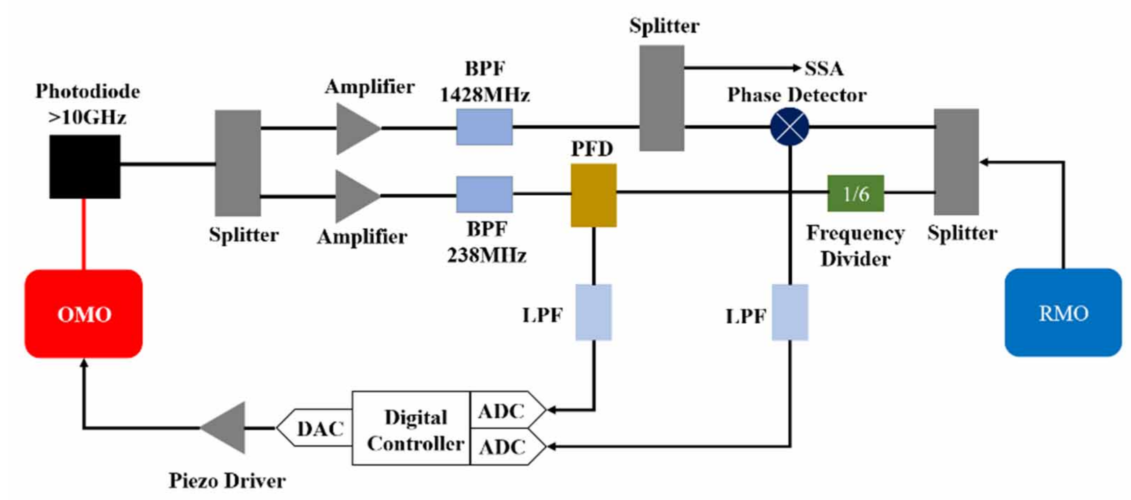

Figure 1: A block diagram of the RF-based synchronization between optical mater oscillator and RF master oscillator. Abbreviations: OMO: optical master oscillator; RMO: RF master oscillator; BPF: bandpass filter; PFD: phase frequency detector; ADC: Analogue to Digital Converter; DAC: Digital to Analogue Converter; SSA: signal source analyzer.

tude change by phase detection with a lower noise local oscillator.

MEASUREMENT RESULT

As mentioned before, in order to obtain the test results, we have built an experimental setup. Simultaneously, we measured the phase noise of the RF master oscillator and the optical master oscillator using a signal source analyzer APPH20G from Anapico.

The measurement of the RF master oscillator took place in the femtosecond synchronization laboratory in the SXFEL. The measurement of the optical master oscillator needs a part of the experimental setup. The pulsed optical signals from the optical master oscillator are coupled to the fiber-coupled photodetector, and the converted RF signals are divided into two by the power splitter. One of them is further boosted by the high gain low noise amplifier and transmitted to a custom bandpass filter.

The phase noise of the RMO (in Fig. 2), the free-running OMO (in Fig. 3), and the synchronized OMO (in Fig. 4) were measured using a signal source analyzer, respectively.

In the bandwidth from 10 Hz up to 1 MHz the integrated RMS jitter for the RF master oscillator is 8.0 fs.

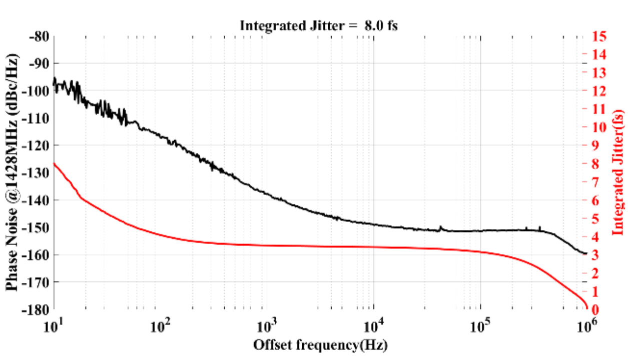

Figure 2: Phase noise measurement result of the RF master oscillator and its integrated timing jitter for the frequency range [10 Hz, 1 MHz].

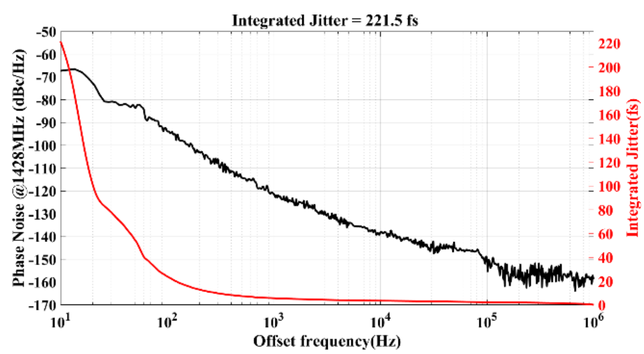

Figure 3: Phase noise measurement result of the free-running optical master oscillator and its integrated timing jitter for the frequency range [10 Hz, 1 MHz].

In the bandwidth from 10 Hz up to 1 MHz the integrated RMS jitter for the free-running optical master oscillator is 221.5 fs.

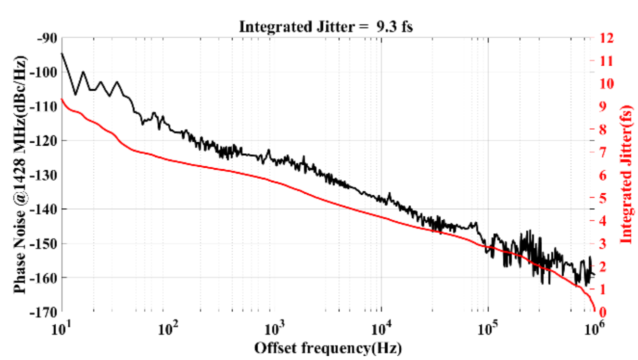

Figure 4: Phase noise measurement result of the synchronized optical master oscillator and its integrated timing jitter for the frequency range [10 Hz, 1 MHz].

In the bandwidth from 10 Hz up to 1 MHz the integrated RMS jitter for the synchronized optical master oscillator is 9.3 fs.

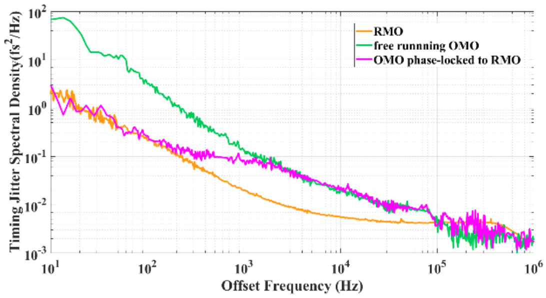

Figure 5: Timing jitter spectral density of the RF master oscillator, the free-running optical master oscillator, and the phase-locked optical master oscillator.

Figure 5 summarizes the phase noise measurement results. Curves RMO and free-running OMO are the absolute phase noise of the RF master oscillator and the optical master oscillator, respectively. By locking the optical master oscillator to the RF master oscillator with ~2 kHz PLL bandwidth, we can achieve a better absolute phase noise in optical pulse trains by combining the phase noise of the RF master oscillator (inside the locking bandwidth) and the optical master oscillator (outside of the locking bandwidth).

In Fig. 5, it can be seen that the spectral density of free-running OMO from 1-kHz to 100-kHz offset frequency is higher than the RMO. This is limited by the fundamental noise sources such as thermal noise and shot noise. Actually, the optical master oscillator displays ultralow noise performance at high offset frequency [8, 9].

OUTLOOK

Due to the low sensitivity of the RF-based synchronization, residual phase noise and long-term stability have not yet been carried out. Furthermore, there are several particular problems related to the RF-based microwave phase-locking technique, which involves the use of a photodetector, low-noise amplifier, and bandpass filter. In addition to the fundamental noise sources mentioned, the RF-based technique also has several issues. Typical sensitivity of the RF phase detectors on the order of a few μV/fs. Relative amplitude fluctuations of optical pulse trains lead to phase noise (AM-to-PM effects) [10-13].

In order to achieve high sensitivity and long-term stability, a balanced optical microwave phase detector (BOMPD) scheme based on a 3X3 coupler is being studied and tested.

In the future, the RF-based synchronization will introduce an out-of-loop measurement setup based on the BOMPD to achieve a more comprehensive stability evaluation.

CONCLUSION

In this paper, we have presented the use of an RF-based phase-locking technique to achieve sub-20 fs synchronization accuracy between mode-locked laser and RF master oscillator. The RMS timing jitter of the RF-locked optical pulse train is 9.3 fs when integrating from 10 Hz to 1 MHz offset frequency. As expected, inside the locking bandwidth (~1 kHz), the absolute phase noise of the optical master oscillator follows that of the RF master oscillator, and the phase noise outside the locking bandwidth follows the absolute phase noise of the extracted RF signal from the optical master oscillator. Due to the noise floor of the measurement setup, the actual phase noise at high offset frequency is smaller.

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