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10-fs-LEVEL SYNCHRONIZATION OF FEMTOSECOND LASER WITH RF MASTER OSCILLATOR*

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Abstract

Laser-to-RF synchronization plays a crucial role in various scientific and technological domains. It is instrumental in generating high-quality electron beams, producing high-performance FEL pulses, exploring ultrafast dynamical processes, and achieving precise measurements and transmission. Passively mode-locked femtosecond lasers are known for their exceptionally low noise characteristics, particularly in the high-offset frequency range, where jitter remains less than 5 fs from 1 kHz to 1 MHz. Meanwhile, RF master oscillators provide outstanding long-term stability in the offset frequency range. This paper demonstrates that integrating the low-noise performance of passively mode-locked femtosecond laser with the superior stability of RF master oscillator enables the achievement of 10-fs-level synchronization. By implementing an RF-based phase-locked loop (PLL) scheme, we achieved an absolute timing jitter of 17.4 fs integrated from 10 Hz to 1 MHz.

INTRODUCTION

Laser-to-RF synchronization technology has a wide range of applications in various fields, especially in areas requiring precise timing control.

Free Electron Lasers (FELs) [1-10]: In FELs, precise synchronization between laser pulses and microwave signals is essential for generating stable and controllable high-intensity light pulses used in studies of ultrafast physical and chemical processes.

Particle Accelerators [11, 12]: Laser-to-RF synchronization is used for beam control in accelerators, ensuring the proper alignment of the time distribution and phase of accelerated particles, which improves accelerator performance.

Ultrafast Electron Diffraction (UED) [13, 14]: In UED experiments, synchronization between laser pulses and microwave sources ensures temporal and spatial alignment of the electron beam and laser pulses, enabling observation of atomic-level structural changes in materials.

Ultrafast Optical Experiments [15-17]: This technology is used to generate and control ultrashort laser pulses for probing transient dynamic processes in materials, with applications in photonics, condensed matter physics, and quantum information.

Extreme Light Infrastructures [18, 19]: Precise synchronization of RF and lasers is crucial in extreme light facilities, which produce and manipulate high-intensity beams for applications in particle physics, high-energy physics, and related fields.

Precision Metrology and Time/Frequency Transfer [20, 21]: Laser-to-RF synchronization is important in metrology, including precision clocks, frequency standards, and atomic clocks, enabling high-precision time and frequency transmission.

Several methods have been developed to achieve laser-to-RF synchronization, such as photodetector direct extraction [22-24], balanced optical microwave phase detection [25-28], and femtosecond optical frequency comb synchronization [29-31], each offering distinct advantages based on the required level of precision and the specific application. Photodetector direct extraction is based on the principle of detecting periodic optical pulses and translating them into an RF domain signal. Once the electrical signal is extracted, the system utilizes feedback to match the laser's output to the reference RF signal, ensuring precise synchronization. Balanced optical microwave phase detection (BOMPD) provides a high precision by directly measuring the phase difference between the optical laser pulses and the RF signal. A balanced detector is used to suppress common-mode noise, enabling highly accurate phase synchronization. The femtosecond optical frequency comb synchronization technique generates a series of evenly spaced optical frequency "teeth", enabling frequency locking between optical and RF signals. The femtosecond frequency comb provides an extremely precise frequency reference, allowing for highly accurate synchronization between the optical and RF domains.

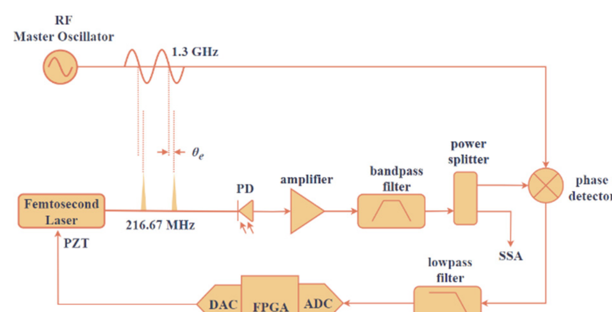

Figure 1: Simplified block diagramme of the RF-based laser-to-RF synchronization. PD: photodetector; SSA: signal source analyzer; ADC: analog-to-digital converter; DAC: digital to analog converter; FPGA: field program-mable gate array; PZT: piezoelectric.

In terms of application domains, photodetector direct extraction features a simpler structure while maintaining sufficient precision to meet the demands of most practical scenarios. Here, we demonstrate a digital phase detector designed based on the principle of photodetector direct

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extraction (as shown in Figure 1), achieving 10-fs level synchronization precision from 1 Hz to 1 MHz offset frequency.

RF-BASED FEMTOSECOND LASER SYNCHRONIZATION

Microwave phase-locking is a commonly employed technique for achieving precise synchronization between a femtosecond laser and an RF master oscillator. In this system, a commercial mode-locked femtosecond laser from Menhir Photonics is utilized as the optical master oscillator, operating at a repetition rate of 216.67 MHz, with a center wavelength of 1555 nm and a pulse duration of 139 femtoseconds. The RF reference signal, with a frequency of 1300 MHz, is generated by a high-stability RF master oscillator (Rohde & Schwarz).

To achieve RF-based phase detection for synchronization, pulsed optical signals must first be converted into electrical signals. The photodetector converts these pulses into electrical signals with high spectral purity, generating harmonics of the laser's repetition rate. The sixth harmonic is first amplified using a low-noise amplifier, then filtered out using an RF bandpass filter before being processed by an RF phase detector. This sixth harmonic frequency is crucial for fine-tuning and precise synchronization. Locking onto a higher harmonic enhances the system's overall performance.

The phase error signal between the RF reference signal from the RF master oscillator and the femtosecond laser signal is fed into an FPGA-based digital controller, forming a phase-locked loop (PLL). Once the RF-to-laser synchronization is established, Once RF-to-laser synchronization is established, a traditional method based on signal source analyzer (SSA) are used to measure the timing jitter of the femtosecond laser.

PERFORMANCE CHARACTERIZATION

As previously detailed, a dedicated experimental setup was developed to obtain the test results. Phase noise measurements for both the RF master oscillator and femtosecond laser was analyzed using an Anapico APPH20G signal source analyzer. The phase noise of the RF master oscillator was assessed in the femtosecond synchronization laboratory at SXFEL. In contrast, the measurement of the femtosecond laser necessitated integration with specific components of the experimental setup. Optical pulse train signals from the femtosecond laser were directed into a fiber-coupled photodetector, where they were converted into RF signals. These RF pulse train signals were then split by a power splitter; one of the split signals was subsequently amplified using a high-gain, low-noise amplifier and passed through a custom bandpass filter for precise analysis.

Figure 2 illustrates the results of the phase noise measurements. The curves labeled “RF master oscillator” and “free-running femtosecond laser” represent the absolute phase noise of the RF master oscillator and the femtosecond laser, respectively.

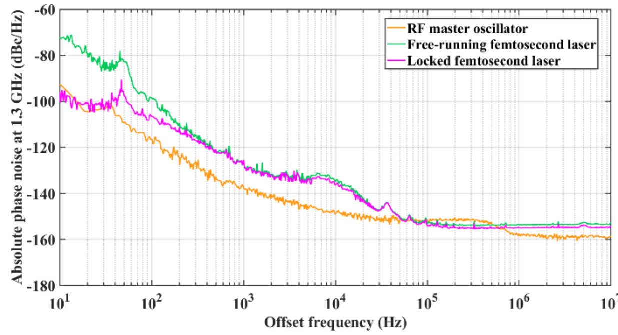

Figure 2: Absolute phase noise of the RF master oscillator, the free-running femtosecond laser, and the phase-locked femtosecond laser.

By locking the femtosecond laser to the RF master oscillator with a phase-locked loop (PLL) bandwidth of approximately 500 Hz, we can achieve an improved absolute phase noise in the optical pulse trains. This improvement arises from combining the phase noise of the RF master oscillator within the locking bandwidth and the phase noise of the femtosecond laser outside the locking bandwidth. It is evident that within the offset frequency range of 500 Hz to 100 kHz, the phase noise spectral density of the free-running femtosecond laser is higher than that of the RF master oscillator, a limitation imposed by fundamental noise sources such as thermal noise and shot noise. However, at higher offset frequencies, the femtosecond laser exhibits ultralow noise characteristics [32, 33].

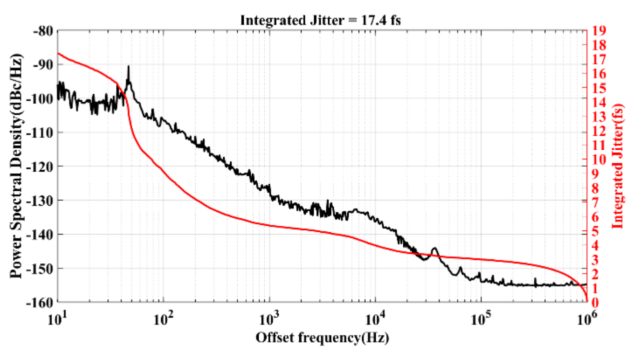

Figure 3: Phase noise measurement result of the synchronized femtosecond laser and its integrated timing jitter for the frequency range [10 Hz, 1 MHz].

The integral curve of the absolute jitter of the femtosecond laser after phase-locking is shown in Figure 3. From the curves of the RF master oscillator and the free-running femtosecond laser, a significant peak can be observed at 50 Hz, and from the integrated curve of the femtosecond laser, it can be seen that the 50 Hz power-line interference has worsened the absolute jitter after phase-locking. Figure 4 shows the photo of the laser-to-RF synchronization unit.

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Figure 4: Photo of the laser-to-RF synchronization unit.

OUTLOOK

Due to the limited sensitivity inherent in RF-based synchronization methods, issues related to residual phase noise and long-term stability remain unresolved. Additionally, the RF-based microwave phase-locking technique faces several specific challenges, such as the integration of photodetectors, low-noise amplifiers, and bandpass filters. Beyond these fundamental noise sources, the RF technique also suffers from a typical sensitivity of phase detectors in the range of a few µV/fs. Furthermore, amplitude fluctuations in optical pulse trains contribute to phase noise through AM-to-PM effects [34, 35].

To address these issues and achieve high sensitivity and long-term stability, research is focusing on a balanced optical microwave phase detector (BOMPD) configuration using a 3x3 coupler. Future efforts will involve integrating an out-of-loop measurement system based on the BOMPD to provide a more comprehensive assessment of stability.

CONCLUSION

This paper presents the implementation of an RF-based phase-locking technique, achieving synchronization precision at the 10-fs-level between a mode-locked femtosecond laser and an RF master oscillator. The measured RMS timing jitter of the RF-locked optical pulse train is 17.4 fs when integrated over an offset frequency range from 10 Hz to 1 MHz. As expected, within the locking bandwidth (~500 Hz), the absolute phase noise of the femtosecond laser follows that of the RF master oscillator, whereas outside this bandwidth, the phase noise is determined by the absolute phase noise of the RF signal extracted from the optical master oscillator. It is noted that the actual phase noise at higher offset frequencies is lower than observed, due to the noise floor limitations of the measurement apparatus.

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