Femtosecond laser–RF synchronization based on all-fiber optical-microwave phase detector

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Background

- Mode-locked lasers emit ultrashort pulse sequences for studying ultrafast phenomena. The precision of laser-microwave synchronization has been greatly improved by optical frequency combs based on mode-locked lasers, which have theoretical optical frequency instability reaching 10^{-18}.
- After years of development, the phase-locked loop technology has matured. The photoelectric phase-locked loop based on an optical-microwave phase detector meets the high-precision synchronization requirements of scientific facilities like **UED** and **XFEL**.

Introduction

- In this study, we propose an all-fiber optical-microwave phase detector based on a Sagnac interferometer, which effectively suppresses various noise sources introduced during the phase detection process.
- This advancement enables the transfer of ultra-high laser stability to microwave signal sources, benefiting RF synchronization in accelerator equipment.

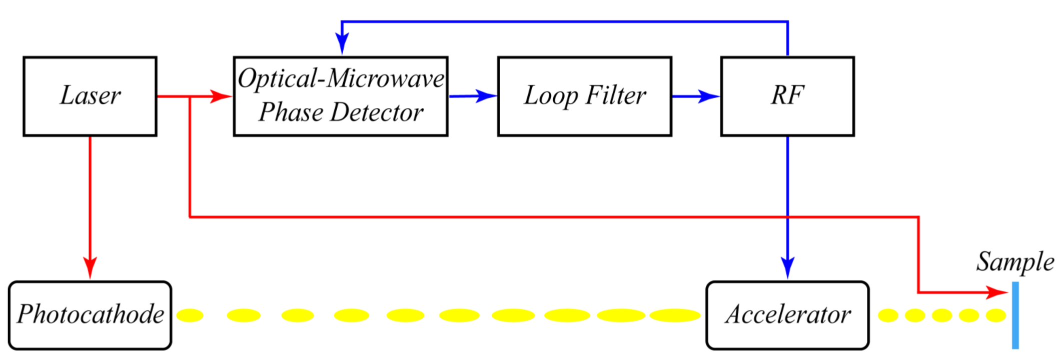

Fig.1 Simplified schematic of a laser-microwave synchronization system based on a photoelectric phase-locked loop

Methods

- The optical-microwave phase detector based on electro-optic sampling technology and a Sagnac fiber loop interferometer has the advantages of high phase detection sensitivity, strong anti-interference capability, and low phase noise.
- The all-fiber structure, including phase bias unit, enhances the stability of system.
- A temperature monitoring and control module is used to record and automatically regulate the temperature in real-time.
- A fast servo PI controller ensures high-speed processing and precise feedback.
- An optical path length and intensity difference adjustment device is incorporated.

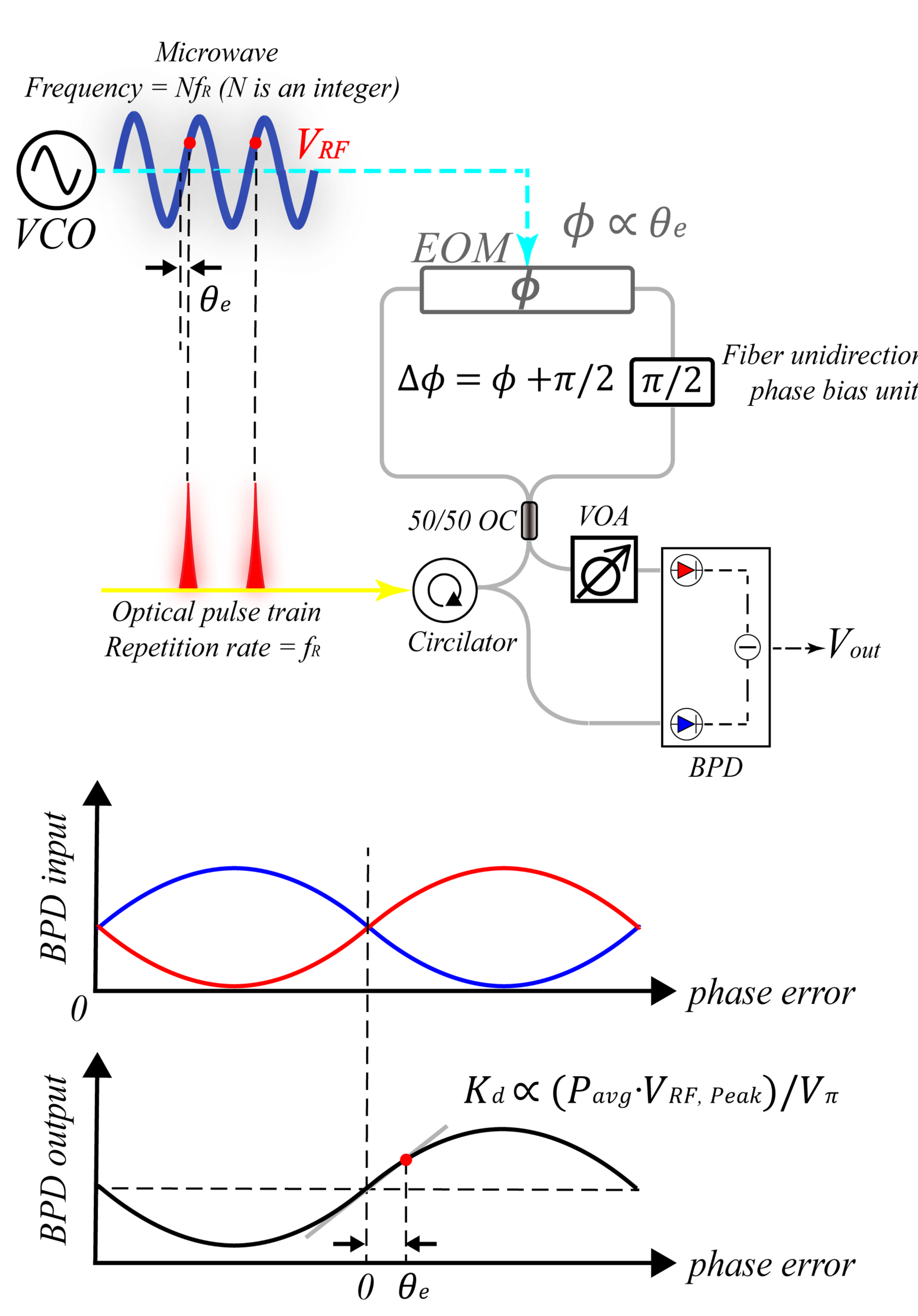

Fig.2 Schematic of all-fiber optical-microwave phase detector

Measurements

All-fiber non-reciprocal phase bias unit

- Employing a custom-made fiber phase delay polarization-maintaining Faraday rotator, instead of a magneto-optic device composed of two Faraday rotators and one quarter-wave plate, as a non-reciprocal phase bias unit to provide an inherent phase difference of π/2.

Temperature monitoring and control module

- To mitigate temperature the impact of fluctuations on phase detector sensitivity and prevent temperature-induced phase drift, temperature control modules with semiconductor coolers are used for internal and external phase detectors. This improves synchronization system performance by minimizing temperature interference.

Optical path length adjustment facility

- To address fiber optic device errors, an adjustable space optical delay line is used to redirect the light beam by 180° and change the optical path length, which eliminates phase differences between split optical signals, improving synchronization accuracy.

Temperature monitoring and control module

- To achieve precise frequency stability transfer from optical to microwave signals, a high-speed servo controller efficiently processes error signals and accurately controls the microwave signal source, such as a Voltage-Controlled Oscillator (VCO), to generate RF signals with minimal phase noise.

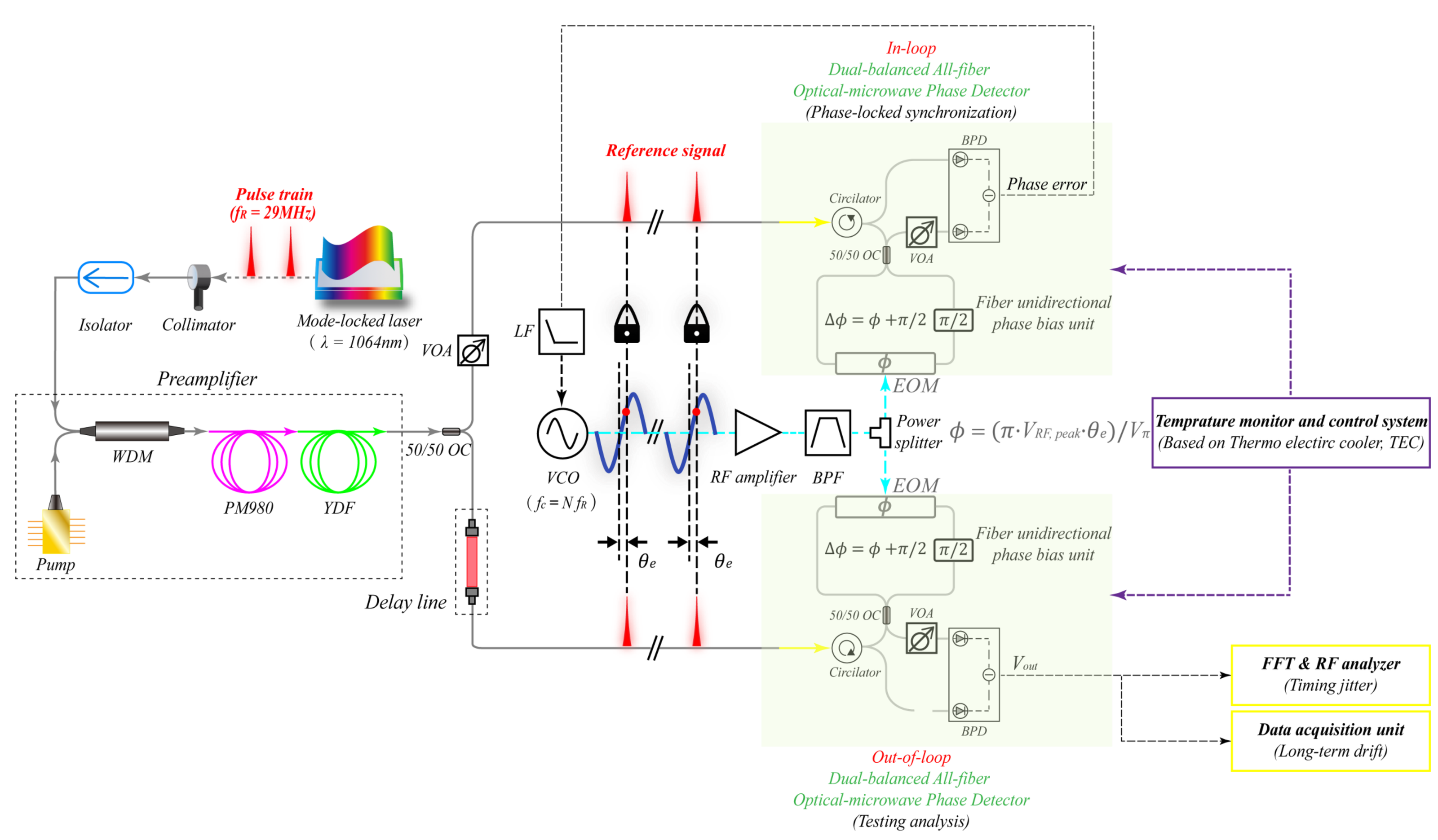

Fig.3 Schematic of the synchronization system and testing facility based on all-fiber optical-microwave phase detector

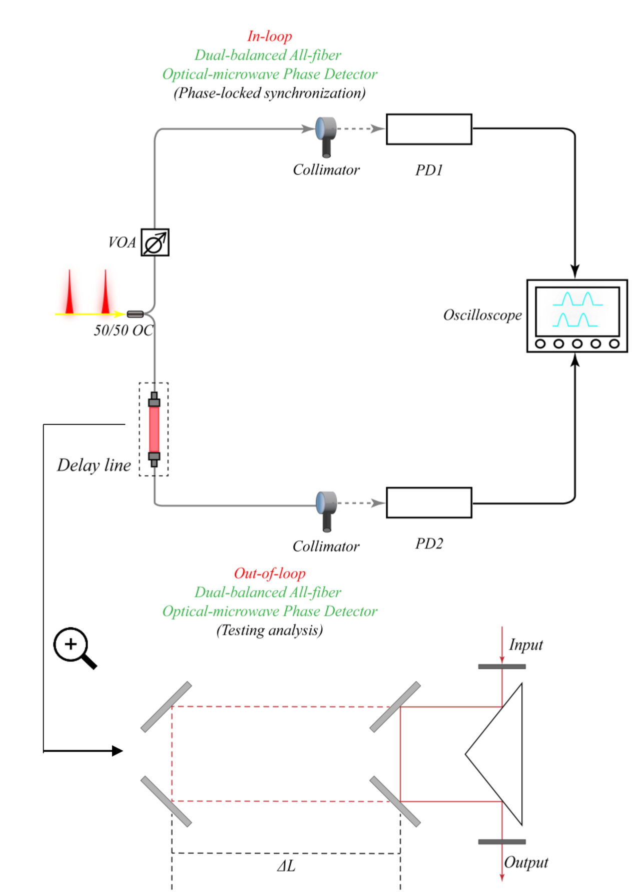

Fig.4 Schematic of optical path length adjustment

Conclusions

- In summary, we achieve precise synchronization between a 1.3 GHz RF generator and a commercial picosecond laser, reducing the rms jitter to fs-level (3.8 fs) over a frequency range of 10 Hz to 1 MHz. This is accomplished by utilizing an advanced all-fiber optical-microwave phase detector.
- During a 5-hour period, we observed a measured out-of-loop long-term timing drift of 126 fs rms, primarily caused by temperature fluctuations and optical asymmetry in the phase bias unit.
- Reducing the relative intensity noise (RIN) of the laser is considered as an optimization measure.

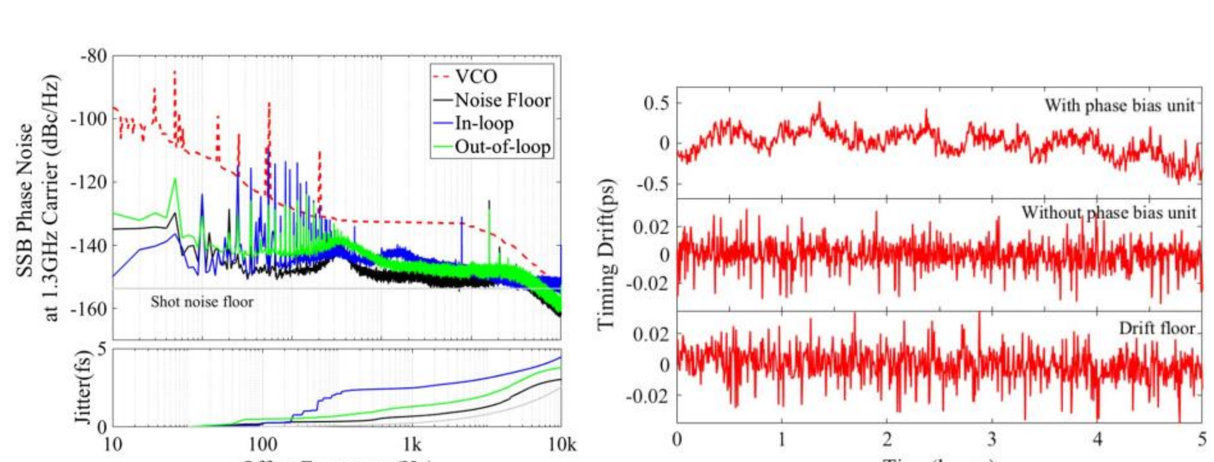

Fig.5 SSB phase noise (above), integrated timing jitter (below) and Long-term timing drift measurements

References

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