FEMTOSECOND SYNCHRONIZATION OF 80-MHz TI:SAPPHIRE PHOTOCATHODE LASER OSCILLATOR WITH S-BAND RF OSCILLATOR*

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Abstract

We present the femtosecond synchronization between an 800-nm photocathode laser and an S-band RF oscillator using an optical-RF phase detection system at KAERI-WCI Accelerator. A 79.33-MHz commercial Ti:sapphire photocathode laser oscillator is locked to a 2.856-GHz RF master oscillator (RMO) using a fiber-loop-based optical-microwave phase detector (FLOM-PD), which results in 13 fs (rms) out-of-loop residual timing jitter integrated from 1 Hz to 10 MHz offset frequency. We also measured the long-term out-of-loop timing drift between the 800-nm optical pulse train and the RF signal, which results in 28 fs (rms) integrated over 1 hour.

INTRODUCTION

Investigation on atomic and molecular scale dynamics has recently become an active field of research. The time-resolved pump-probe experiment using ultrafast electron beams or X-rays can observe the atomic scale phenomena with femtosecond time resolution. In doing so, femtosecond-precision synchronization between lasers and RF sources is crucial to achieve femtosecond-resolution measurements. As a result femtosecond-precision laser-RF synchronization has been actively studied in the last decade [1-5]. For large-scale FELs, RF-modulated cw lasers or low-jitter mode-locked lasers at telecommunication wavelength have been used as the optical master oscillator (OMO) and the timing signals generated from the OMO are distributed via stabilized fiber links. However, for smaller-scale FELs and UED, this approach may be a complex and high cost method. In this paper, as an alternative, we studied the possibility of using the commercial Ti:sapphire photocathode laser as the OMO as well. We show 13 fs (rms) synchronization between a Ti:sapphire photocathode laser and an RF oscillator. We also measured the long-term out-of-loop timing drift of 27.8 fs (rms) integrated over an hour. To achieve this <30 fs stability long-term synchronization, we used a fiber-loop optical-microwave phase detector (FLOM-PD) to measure and lock the phase difference between optical and RF signals [6].

SYNCHRONIZATION OF PHOTOCATHODE LASER TO RMO

A 79.33 MHz repetition rate Ti:sapphire laser (Coherent Vitara-T) and a 2.856-GHz RF oscillator (Keysight N5181B) are used in this work. Figure 1 shows the structure of the FLOM-PD. The FLOM-PD is based on the fiber Sagnac-loop interferometer, and it detects phase difference between optical pulse train and RF signal using phase error-dependent intensity imbalance between two detector outputs [6]. The FLOM-PD can reduce the excess phase noise and drift added in the optical-to-electronic conversion process compared to direct photodetection method.

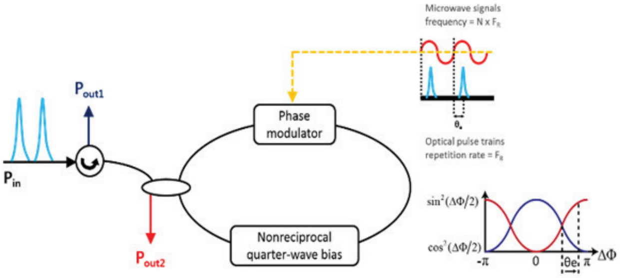

Figure 1: Schematic fiber-loop-based optical-microwave phase detector [6].

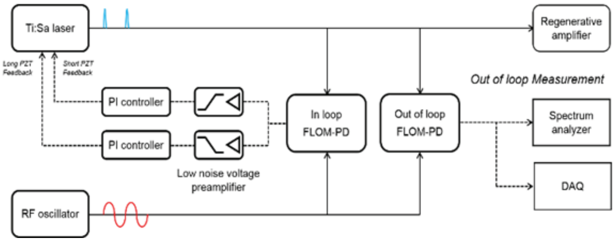

Figure 2: Schematic of the synchronization system.

Figure 2 shows the schematic of the synchronization between a photocathode laser and an RF oscillator. The synchronization setup is composed of three parts, a photocathode laser, an RF oscillator and a FLOM-PD. A Ti:sapphire laser generates 480 mW average output power with 79.33 MHz repetition rate. The laser is locked to a 2.856-GHz RF oscillator, which is used as an RF master oscillator (RMO). One FLOM-PD is used to lock the laser with the RMO and the other FLOM-PD is used to measure the residual phase noise and drift in an out-of-loop way. To operate a FLOM-PD, we used 12 mW average optical power and +19 dBm average RF power. The in-loop FLOM-PD measures phase difference between optical and RF signals and generates an error signal. Two piezoelectric transducers (PZT) inside the Ti:sapphire laser are controlled by using the error signal from FLOM-PD. The high and low offset frequency noise

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is controlled by short and long PZTs, respectively. The synchronization feedback loop consists of a low-noise voltage preamplifier (Stanford Research Systems, SRS560) and a PI servo controller (Newport, LB1005). The out-of-loop FLOM-PD monitors the residual phase noise and drift between the locked optical and RF signals.

Figure 3 shows the collection of phase noise power spectral density. Curve (a) shows the phase noise of a free-running Ti:sapphire laser, measured by a signal source analyzer (SSA) and a balanced optical cross-correlator (BOC) in the low (<10 kHz) and high (>10 kHz) offset frequency, respectively. To measure the high offset frequency precisely, two-color balanced optical cross-correlator (TC-BOC) [7] is used with a 1550-nm solid-state laser (One-Five Laser, Origami-15) as an optical reference. Curve (b) shows the phase noise of an RF oscillator measured by the SSA. Curve (c) shows the residual phase noise when the OMO and RMO are locked, measured by an out-of-loop FLOM-PD. Note that the phase noise for >10 kHz offset frequency is limited by the FLOM-PD resolution. The RMO-OMO locking bandwidth is about 9 kHz. Outside this locking bandwidth, the optical pulse train carries the phase noise of free-running OMO. Curve (d) shows the residual timing jitter between a Ti:Sapphire laser and an RF oscillator projected in the optical domain (i.e., the timing jitter of optical pulse train follows the RMO phase noise inside the locking bandwidth and free-running laser jitter outside the locking bandwidth).

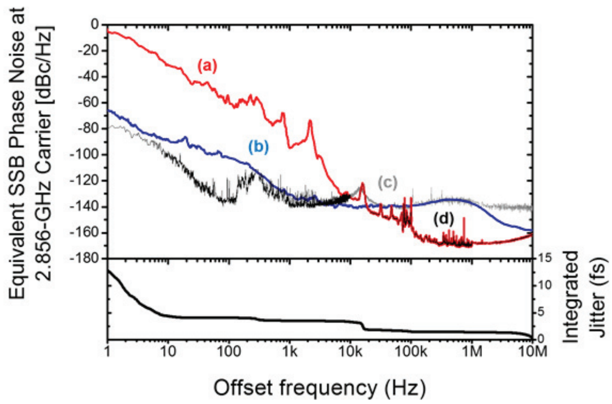

Figure 3: Phase noise measurement results. (a) Phase noise of a free-running Ti:sapphire laser, (b) Phase noise of an RF oscillator, (c) Residual phase noise measured by out-of-loop FLOM-PD, (d) Integrated timing jitter of locked optical pulse train.

For the optical pulse train, the rms timing jitter is 13 fs when integrated from 1 Hz to 10 MHz offset frequency. Note that the intrinsic rms timing jitter of the used Ti:sapphire laser is 2.6 fs [10 kHz – 10 MHz], which sets the fundamental limit in achievable synchronization. As can be seen from curve (d), majority of timing jitter is contributed in 1 – 10 Hz offset frequency. Preliminary analysis suggests that it is mostly originated from the amplitude-to-phase conversion in FLOM-PD. Figure 4 shows the long-term out-of-loop timing drift measurement. The measured long-term timing drift is 27.8 fs (rms) for an hour.

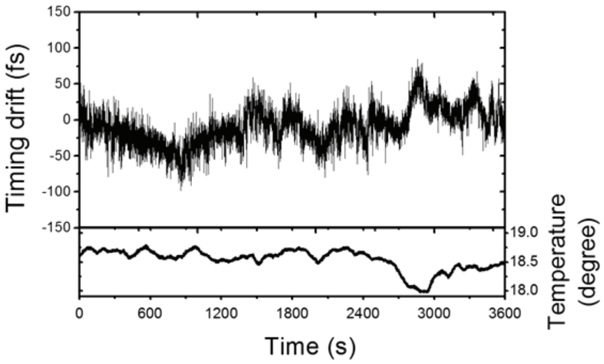

Figure 4: Long-term timing drift measurement for 1-hour.

SUMMARY

We show laser-RF synchronization between an 800 nm Ti:sapphire photocathode laser and a 2.856-GHz RF oscillator with 13 fs residual rms timing jitter. The measured long-term timing drift is 27.8 fs (rms) for an hour. These results suggest that a commercial Ti:sapphire photocathode laser can serve as an OMO, which is tightly locked to an RMO, for small-scale FELs and UEDs. With several technical improvements for reducing amplitude-to-phase conversion in FLOM-PD, few-femtosecond synchronization will be possible in the near future.

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