REMOTE RF-SYNCHRONIZATION WITH FEMTOSECOND DRIFT AT PAL

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Abstract

We present our recent progress in remote RF synchronization using an optical way at PAL. A 79.33-MHz, low-jitter fiber laser is used as an optical master oscillator (OMO), which is locked to the 2.856-GHz RF master oscillator (RMO) using a balanced optical-microwave phase detector (BOM-PD). The locked optical pulse train is then transferred via a timing-stabilized 610-m long optical fiber link. The output is locked to the 2.856 GHz voltage controlled oscillator (VCO) using the second BOM-PD, which results in remote synchronization between the RMO and the VCO. We measured the long-term phase drift between the input optical pulse train and the remote RF signals using an out-of-loop BOM-PD, which results in 2.7 fs (rms) drift maintained over 7 hours.

INTRODUCTION

In the last decade, optical timing and synchronization techniques, based on CW lasers or pulsed mode-locked lasers, have been intensively investigated for next generation light sources such as X-ray free-electron lasers (XFELs) [1-3]. One of the most important requirements for such femtosecond synchronization systems is precise (e.g., <10 fs rms phase drift) synchronization between multiple, remotely located accelerator-driving RF sources, which may enable lower jitter electron beam generation. For PAL-XFEL facility, we currently investigate the RF synchronization techniques based on an ultralow-jitter femtosecond mode-locked fiber laser as an optical master oscillator (OMO). In this paper, we present our recent progress toward the sub-10-fs drift remote RF synchronization. We used a balanced optical cross-correlator (BOC) [4] for the fiber link stabilization and a balanced optical-microwave phase detector (BOM-PD) [5] for the optical-RF synchronization. We also propose a new remote RF link stabilization scheme based on a fiber loop optical-microwave phase detector (FLOM-PD) [6,7], instead of BOC, to distribute RF through standard single-mode fiber links (such as SMF-28) without dispersion compensating fiber (DCF).

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REMOTE RF SYNCHRONIZATION USING A BOC-STABILIZED FIBER LINK AND BOM-PDS

The first type of a pulsed mode-locked fiber laser-based remote RF synchronization technique uses a BOC-based, timing stabilized fiber link and two BOM-PD-based local optical-RF synchronization units, as shown in Fig. 1. A 79.33-MHz repetition rate Er-fiber laser (manufactured by Toptica Photonics AG) is used as an OMO in this work. The OMO is locked to a 2.856-GHz RF master oscillator (RMO, Agilent E4438C vector signal generator in this work) by using a BOM-PD, which is based on a synchronous detection between the optical pulse train and the RF signal (more detailed information on the BOM-PD can be found in previous publications, such as refs. [1] and [5]). The use of a BOM-PD for optical-RF synchronization enables long-term stable, sub-10-fs precision synchronization between the mode-locked laser and the RF source. To lock the OMO to the RMO, an internal PZT in the OMO is used. The fiber link is a PPKTP-BOC stabilized, dispersion compensated (by connecting 160-m DCF with 450-m SMF-28), 610-m long fiber link, similar to the design shown in [1] and [4]. A PZT stretcher and a fiber coupled motor stage are used to compensate for the length fluctuations in the fiber link.

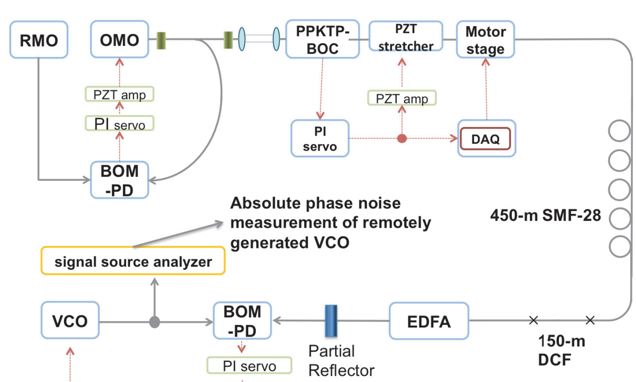

Figure 1: Schematic of remote RF synchronization. PI, proportional-integral; PZT, piezoelectric transducer; DAQ, data acquisition board; DCF, dispersion compensating fiber; EDFA, Er-doped fiber amplifier; VCO, voltage-controlled oscillator.

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Once the stabilized pulse train arrives at the remote location via the fiber link, a second BOM-PD is used to synchronize the remotely located 2.856-GHz voltage controlled oscillator (VCO) to the delivered optical pulse train. Figure 2 shows the absolute single-sideband (SSB) phase noise of the synchronized VCO, measured by a signal source analyser (Rohde and Schwarz, FSUP). Below ~ 400 Hz (which is the locking bandwidth of RMO-OMO synchronization, limited by the PZT bandwidth in the OMO) offset frequency, the phase noise follows that of the RMO as expected. Outside this locking bandwidth, the phase noise of the locked VCO will follow that of the free-running OMO and the free-running VCO. From ~400 Hz to ~10 kHz, the phase noise follows that of the OMO. In the offset frequency higher than ~10 kHz (which is the locking bandwidth of the synchronization between the delivered optical pulse train and the VCO using the second BOM-PD), the phase noise follows that of the VCO.

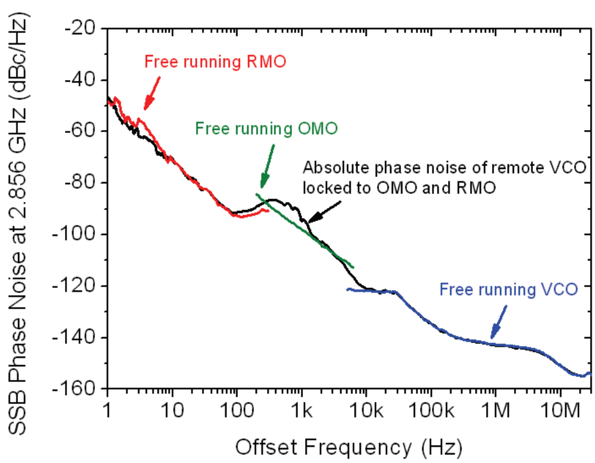

Figure 2: Absolute SSB phase noise at 2.856 GHz of the remote VCO signal, when synchronized with the RMO using an OMO and a timing-stabilized fiber link.

In order to assess the long-term residual phase noise and timing drift between the OMO and the remote VCO, we modified the first BOM-PD in Fig. 1 (which was used for locking the OMO to the RMO) to the out-of-loop BOM-PD measuring the residual phase noise between the OMO and the remote VCO, as shown in Fig. 3. The measurement result over 7 hours is shown in Fig. 4. The phase drift was measured at every 2 seconds, with a low pass filtering at 50 Hz. The integrated rms timing drift over 7 hours is 2.7 fs. To our knowledge, this is the first time to show the remote optical-RF synchronization between a mode-locked laser and an RF VCO via hundreds meters of fiber link with just few-femtosecond timing drift maintained over several hours. This excellent long-term stability result is a combined effect of long-term stable synchronization and stabilization by BOM-PDs and a BOC.

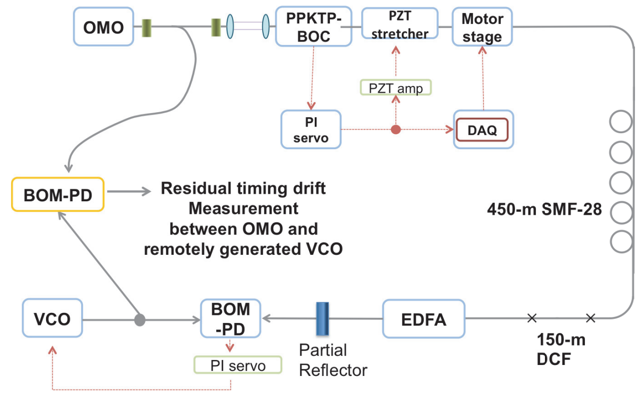

Figure 3: Scheme for the out-of-loop residual timing drift measurement between the OMO and the remote VCO.

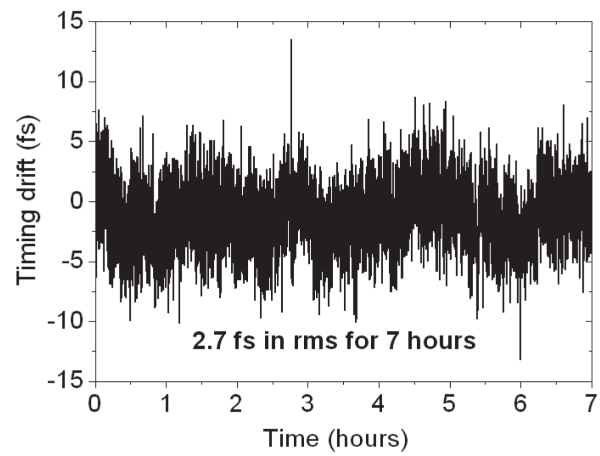

Figure 4: Timing drift measurement result between the OMO and the remote VCO.

REMOTE RF SYNCHRONIZATION USING FLOM-PDS

We are also investigating several new techniques for simpler yet better performance remote RF synchronization. Although BOM-PD provides excellent long-term phase drift performance, as shown in Fig. 4, the short-term residual phase noise performance is limited to ~ -120 to -130 dBc/Hz level. In addition, due to the synchronous detection nature, the repetition rate and RF signal frequency cannot be widely tuned for a given BOM-PD. To achieve lower residual phase noise floor down to ~ -160 dBc/Hz level and also to enable a simpler, lower-cost implementation and operation of optical-RF synchronization unit, we recently demonstrated a FLOM-PD [6,7]. The schematic is shown in Fig. 5. It is based on the conversion of phase error between the optical pulse train and the RF signal into the intensity imbalance between the two outputs from the Sagnac loop, the basic idea of which was originally proposed in [8]. With a robust fiber loop implementation, it enables sub-fs short-term residual jitter (673 as jitter from 1 Hz to 10 MHz, see Fig. 6) and few-fs long-term drift (2.0 fs drift over 10 hours, see Fig. 6).

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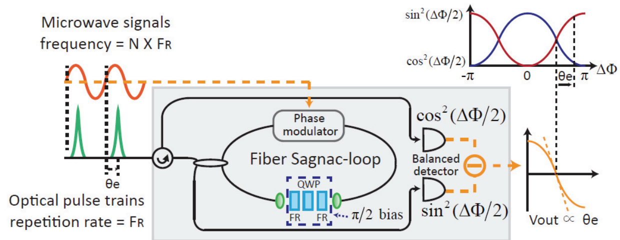

Figure 5: Schematic of FLOM-PD [6].

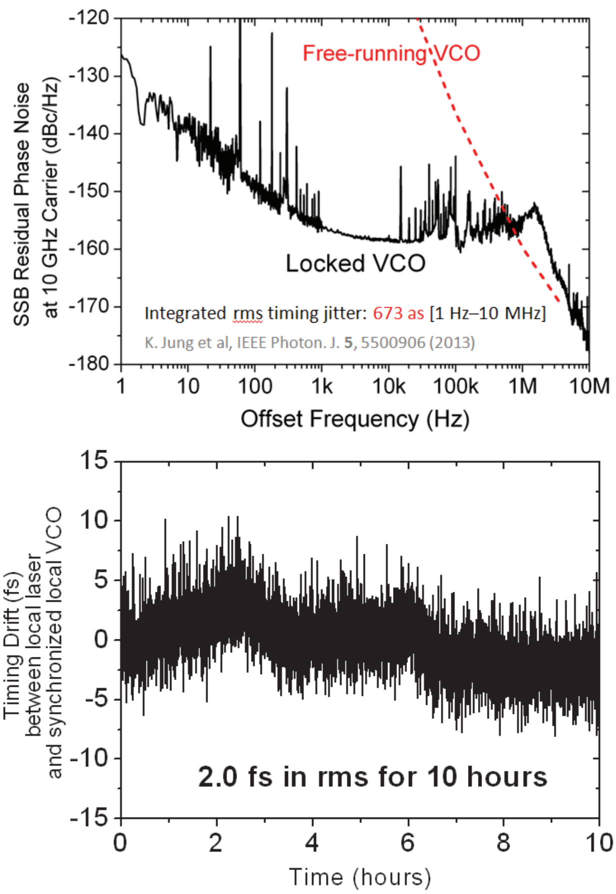

Figure 6: FLOM-PD residual timing jitter (673 as from 1 Hz to 10 MHz) and timing drift (2.0 fs for 10 h) performance data.

We further characterized the power-to-timing conversion performance of the FLOM-PD. Figure 7 shows the measurement result: 14 % input optical power change resulted in only 24 fs timing drift at 10 GHz. This is far more stable compared to the direct photodetection-based RF conversion method. With our measured power stability of OMO plus fiber link of 0.98 % peak-to-peak power fluctuation over 2.5 days, it suggests that few-fs level RF stability is obtainable in the fiber link synchronization applications.

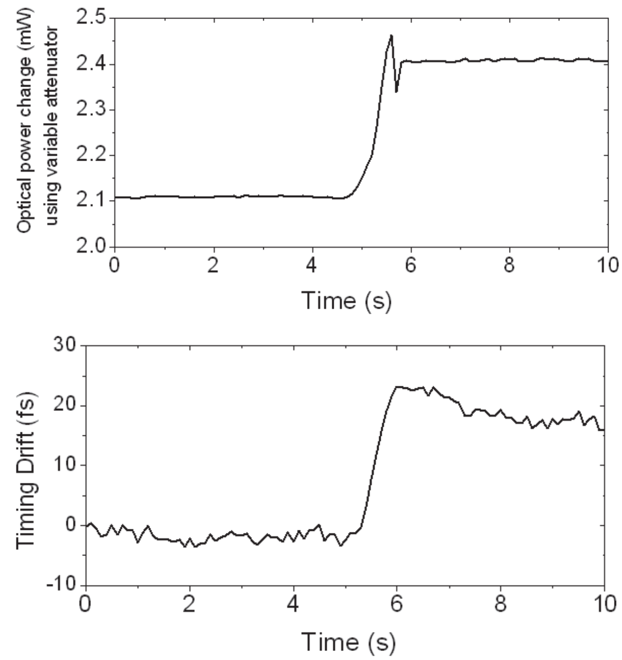

Figure 7: FLOM-PD power-to-timing conversion coefficient measurement result. 14 % optical power change results in 24 fs timing drift.

If we use this FLOM-PD (or BOM-PD as well, at the expense of more coarse short-term resolution due to higher residual phase noise floor) for timing link stabilization, we can implement the remote RF synchronization up to a few km length scale without both dispersion compensating fiber (or other dispersion compensating optical elements) and alignment-sensitive BOC, as shown in Fig. 8. In this scheme, in addition to the two optical-microwave phase detectors (as used in Fig. 1), we use one more optical-microwave phase detector for the link stabilization as well. Even we do not use the second harmonic generation-based BOC, we also anticipate that the FLOM-PD can still provide sufficient sub-femtosecond resolution, both short-term and long-term, as shown in Fig. 6 results.

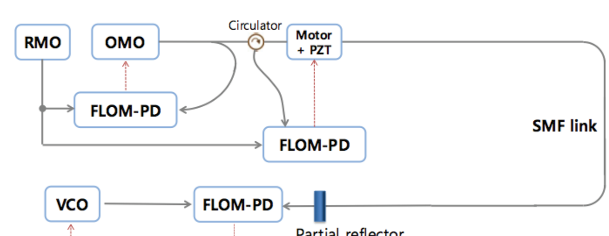

Figure 8: Proposed schematic of remote RF synchronization based on FLOM-PD-stabilized fiber link.

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SUMMARY

We showed that remote RF synchronization using a BOC-stabilized 610-m long fiber link and BOM-PDs is possible, with 2.7 fs residual rms timing drift over 7 hours between the OMO and the remote VCO demonstrated at PAL on site. We also showed our recent progress in reducing both short-term jitter and long-term phase drift in optical-RF synchronization using a FLOM-PD, and further proposed a simpler RF distribution schematic based on FLOM-PDs and standard SMF-28 fiber links.

ACKNOWLEDGMENT

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