FEMTOSECOND-STABILITY DELIVERY OF SYNCHRONIZED RF-SIGNALS TO THE KLYSTRON GALLERY OVER 1-km OPTICAL FIBERS

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Abstract

We present our recent progress in optical frequency comb-based remote optical and RF distribution system at PAL-XFEL. A 238 MHz mode-locked Er-laser is used as an optical master oscillator (OMO), which is stabilized to a 2.856 GHz RF master oscillator (RMO) using a fiber-loop optical-microwave phase detector (FLOM-PD). We partly installed a pair of 1.15 km long fiber links through a cable duct to connect and OMO room to a klystron gallery in the PAL-XFEL Injector Test Facility (ITF). The fiber links are stabilized using balanced optical cross-correlators (BOC). A voltage controlled RF oscillator (VCO) is locked to the delivered optical pulse train using the second FLOM-PD. Residual timing jitter and drift between the two independently distributed optical pulse train and RF signal is measured at the klystron gallery. The results are 6.6 fs rms and 31 fs rms over 7 hours and 62 hours, respectively. This is the first comb-based optical/RF distribution and phase comparison in the klystron gallery environment.

INTRODUCTION

Time-resolved X-ray-optical pulse pump-probe experiments with femtosecond time resolution and sub-nm spatial resolution can reveal molecular dynamics and accelerate natural and medical science. Therefore, the future most advanced X-ray Free Electron Lasers (XFELs) require femtosecond-precision synchronization of several lasers and RF signals in tens of accelerator units over km length scale [1]. In the last decade, optical timing and synchronization techniques, based on CW lasers or pulsed mode-locked lasers, have been intensively investigated.

Optical pulsed fiber link stabilization technique based on a balanced optical cross-correlator (BOC) resulted in unprecedented performance. Sub-10 fs in rms long-term stability and short-term jitter were achieved for standard single mode fiber link stabilization in well-controlled laboratory environment [2]. This technique has been already installed in operating FEL facilities (such as FERMI and FLASH), and currently shows <100 fs in peak-to-peak long-term stability over several hours [3,4]. This amount of drift is caused by the polarization mode dispersion (PMD) of the fiber link. Recently, in order to deal with the PMD problem, a polarization maintaining (PM) fiber link was used, and sub-femtosecond long-term timing link stability [5] and remote optical-to-optical synchronization [6] in the laboratory environment was reported.

Synchronization techniques of local RF signals to a mode-locked laser have been also developed in the last decade. A balanced optical-microwave phase detector (BOM-PD) with sub-10 fs long-term stability and short-term jitter was demonstrated [2]. It detects timing error between optical pulse trains and RF signals directly in the optical domains based on electro-optic sampling in the fiber Sagnac-loop interferometer. The BOM-PD is being used in FEL facility (FERMI) for the mode-locked laser stabilization to the RF master oscillator in the well-controlled laser room [3]. In 2012, a fiber-loop optical-microwave phase detector (FLOM-PD) was developed with both sub-femtosecond short-term jitter and long-term stability [7]. It showed ultra-low short-term residual phase noise floor (-158 dBc/Hz) between two 10 GHz microwave oscillators which were locked to a common mode-locked laser locally [8]. The basic principle of the FLOM-PD is very similar with the BOM-PD, but the FLOM-PD is based on balanced photodetection instead of synchronous detection, and it is much simpler and easy to build.

The combination of these two modular methods (BOC + BOM-PD or BOC + FLOM-PD) may lead to a great performance in remote RF transfer or remote synchronization between a mode-locked laser and a RF oscillator. However, the full implementation of such remote laser-RF synchronization has not been demonstrated so far.

In this paper, we show remote synchronization between a 238 MHz mode-locked laser and a 2.856 GHz RF source by combining FLOM-PD-based local laser-RF synchronization units and BOC-based stabilized fiber links in the real accelerator klystron gallery environment [9]. We installed a pair of 1.15 km long fiber links in an accelerator building and measured the relative phase drift between the optical pulse train and the RF signal at the link outputs in a klystron gallery, which resulted in 6.6 fs and 31 fs rms timing drift maintained over 7 hours and 62 hours, respectively [9]. To our knowledge, this is the first demonstration of maintaining few-fs-level drift over hours of operation in the remote synchronization between a femtosecond mode-locked laser and a RF source over a kilometer in distance. This shows the possibility to distribute RF signals, all tightly locked to a master mode-locked laser, to remote locations with femtosecond stability, not only in the well-controlled laboratory but also in the accelerator environment.

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TEST OF REMOTE LASER-RF SYNCHRONIZATION IN ACCELERATOR ENVIRONMENT

In order to assess the feasibility of applying remote laser-RF synchronization in a real large-scale scientific facility outside the well-controlled laboratory, we installed a pair of 1.15 km dispersion compensated fiber links in an accelerator building [Injector Test Facility (ITF) in the Pohang Accelerator Laboratory (PAL)]. Figure 1 shows the schematic of the experiment at the PAL-ITF.

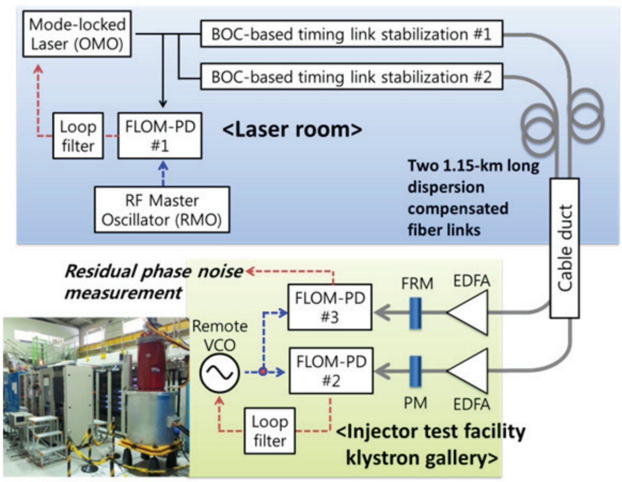

Figure 1: Remote laser-RF synchronization test set-up in an accelerator building (PAL-ITF). BOC, balanced optical cross-correlator; FLOM-PD, fiber-loop optical-microwave phase detector; FRM, Faraday rotating mirror; PM, partial mirror; VCO, voltage-controlled oscillator [9].

In a laser room, a 238 MHz repetition rate, 120 fs pulsewidth, soliton mode-locked Er-laser (OneFive, Origami-15) is stabilized to the 2.856 GHz RF master oscillator (Agilent, N5181B) with 6 kHz locking bandwidth using a fiber-loop optical-microwave phase detector (FLOM-PD) for a long-term stable operation. The 6 kHz feedback bandwidth is selected, because the laser phase noise is higher than the RF master oscillator phase noise below the 6 kHz Fourier frequency region. The output from the laser is split into two independent fiber links. Each link is composed of 1.05 km standard SMF-28 fiber and 100 m DCF (OFS LLWB), and part of each fiber link is installed in a cable duct between the laser room and the klystron gallery. The outputs of the fiber links are installed in an instrument rack in the klystron gallery (photograph in Fig. 1). Part of the delivered optical pulse trains is reflected back, and is applied to the balanced optical cross-correlator (BOC) in the laser room. The detected fiber link timing fluctuations are compensated by a pzt fiber stretcher and a fiber coupled motorized stage. In the klystron gallery rack, a 2.856 GHz voltage-controlled RF oscillator (VCO, INWAVE AG, DRO-2856A) is synchronized with the output from one link using the FLOM-PD (FLOM-PD #2 in Fig. 1). Finally, to assess the out-of-loop synchronization performance between the locked VCO and the delivered pulse train via the other fiber link, another FLOM-PD (FLOM-PD #3 in Fig. 1) is used. Thus, we can evaluate the relative phase stability between the RF signal regenerated from a fiber link output and the optical pulse train from another independently timing-stabilized fiber link output.

Figure 2 shows the residual phase noise measured in the klystron gallery rack. The rms timing jitter between the RF source and the optical signal is 7.3 fs integrated from 1 Hz to 10 MHz. The VCO is locked to the delivered optical signal with 300 kHz bandwidth. Outside the locking bandwidth, the VCO phase noise follows the free-running VCO absolute phase noise itself. Note that the measured VCO absolute phase noise data from the vendor was limited by a measurement instrument at the high offset frequency (>300 kHz). To figure out the residual phase noise floor inside the locking bandwidth, we also measured the residual phase noise between the two delivered fiber links output optical pulse trains using an out-of-loop balanced optical cross-correlator (BOC). The result shows that the BOC is more sensitive to the gallery environment than the FLOM-PD, because the residual phase noise measured by the BOC is even higher. Thus, the origin of the -128 dBc/Hz noise floor below 1 kHz offset frequency measured by the FLOM-PD was not revealed yet. However, it might be caused by the link stabilization performance. In fact, the noise floor from 30 kHz to 100 kHz is the balanced photodetector voltage noise floor of the in-loop BOC for the fiber link stabilization.

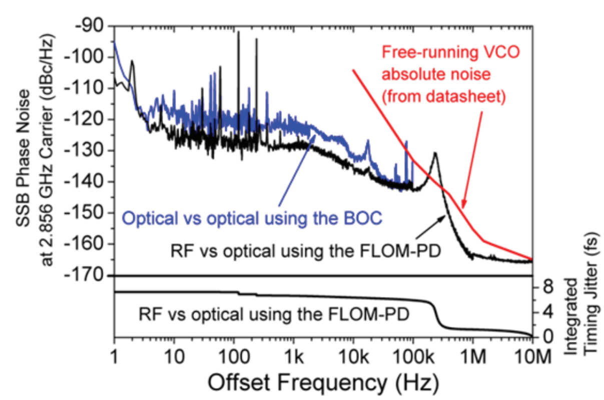

Figure 2: Residual phase noise measurement at the klystron gallery rack after transferring over 1.15 km long fiber link.

Figure 3 shows the relative phase drift measured in a klystron gallery rack. The best 7 hours result (indicated as the red box in Fig. 3) shows 6.6 fs rms timing drift integrated over 7 hours. To our knowledge, this is the first time to show that maintaining sub-10 fs long-term RF phase stability in operating klystron gallery environment is possible by remote laser-RF synchronization via

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kilometer-scale fiber links. Over the full measurement span of 62 hours, the integrated rms timing drift is 31 fs. There are several possible reasons for this drift. First reason is that the gallery temperature change by ~3 K with a period of ~1 day, which can influence the excess phase drift in FLOM-PDs themselves (note that the instrument rack used in the gallery did not have an active temperature controller in this experiment). The previously measured temperature coefficient of the FLOM-PD with an active temperature change of several Kelvin was ~20 fs/K [7]. Secondly, PMDs in the two independent 1.15 km long fiber links may have caused the relative phase drift between them that cannot be compensated by the timing stabilization method. Similar amount of PMD-limited timing drift (~100 fs) has been observed in other fiber links with hundreds meters to few kilometers scale [4,10,11]. In addition, harsh environments in the klystron gallery with high voltage, high current pulsed signals, and high vibration might lead to additional timing noise to the local laser-RF synchronization system. However, as this is a very early stage demonstration in the gallery environment, more careful investigation on the exact origins and noise-coupling mechanisms is required.

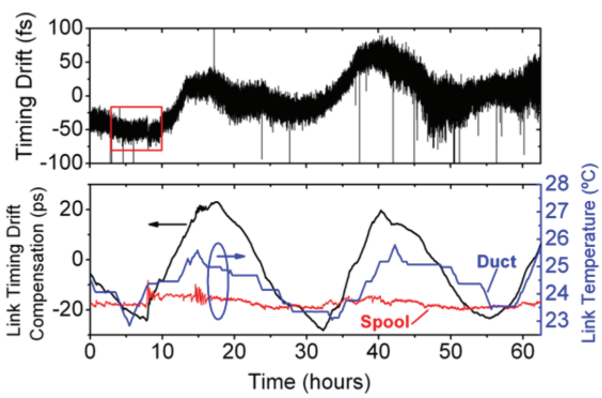

Figure 3: Residual phase drift measurement at the klystron gallery rack after transferring over 1.15 km long fiber link. The best 7 hours result (indicated by red box) shows 7.7 fs rms drift integrated over 7 hours. For the entire 62 hours measurement, 31 fs rms drift was measured [9].

CONCLUSION

We demonstrate remote fiber link-based synchronization between a mode-locked laser and a 2.856 GHz RF source with sub-10 fs rms timing drift over >7 hours, in the accelerator environment. The longer-term synchronization performance is limited to 31 fs rms drift during 2-3 days, by combined effects of the fiber link PMD, gallery rack temperature change, and harsh vibration environment. As this is a very early stage demonstration in the gallery environment, more careful investigation on the exact origins and noise-coupling mechanisms is required.

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