Long-Term Stable Microwave Signal Extraction from Mode-Locked Lasers

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Abstract: Long-term synchronization [13-fs (10 Hz-10 MHz), <50 fs (for one hour)] between two 10.225-GHz microwave signals at +10 dBm referenced to a 44-MHz repetition rate mode-locked fiber laser is demonstrated using balanced optical-microwave phase detectors.

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Mode-locked lasers have a great potential to generate ultralow-jitter microwave signals encoded in its pulse repetition frequency. However, it is a highly nontrivial task to transfer the low noise properties in the optical domain to the electronic domain, and extract a drift-free, ultralow-jitter microwave signal from an optical pulse train. For high-precision optical-to-RF synchronization [1] as well as microwave signal readout from atomic optical clocks [2], it is crucial to convert the optical pulse train into a drift-free, low-jitter microwave signal with a satisfactory power level in a long-term stable way. One of the major limitations in direct photodetection for the microwave signal extraction is amplitude-to-phase conversion in the photodetectors [3]. The intensity noise and fluctuation can be converted into a significant amount of excess timing jitter and drift.

To circumvent the amplitude-to-phase conversion and also to ensure long-term stable operation, a balanced optical-microwave phase detector is proposed and demonstrated [4]. It is based on the precise phase detection in the optical domain using a differentially-biased Sagnac fiber loop and synchronous detection. Because the phase error between the optical pulse train and the microwave signal is detected in the optical domain before the photodetection is involved, it is robust against drifts and photodetector nonlinearities. More detailed information on the balanced optical-microwave phase detector can be found in Ref. 4.

In this paper, we measured the out-of-loop performance between two optoelectronic phase-locked loops (PLLs) using balanced optical-microwave phase detectors. The measurement result shows 12.8 fs relative jitter between two 10.225-GHz microwave signals integrated from 10 Hz to 10 MHz. In addition, the long-term drift measurement shows that the drift in microwave signal extraction is within 50 fs over one hour time scale. Note that the long-term measurement is mainly limited by the drift of the mixer and amplifier used in the out-of-loop characterization setup, which drifts up to 50 fs even when the temperature of the characterization setup is actively stabilized.

Figure 1: Experimental setup for long-term out-of-loop relative timing jitter measurement between two microwave signals referenced to a mode-locked laser. DBM: double-balanced mixer, LPF: low-pass filter, PLL: phase-locked loop, VCO: voltage-controlled oscillator.

Figure 1 shows the schematic of the experimental setup for long-term out-of-loop relative timing jitter measurements between the two 10.225-GHz microwave signals referenced to a 44-MHz, 1550-nm Er-doped fiber mode-locked laser. Two nearly identical optoelectronic PLLs based on balanced optical-microwave phase detectors were built with 10.225-GHz VCOs (PSI DRO-10.225). The input optical power to each phase detector is 5 mW, and +4 dBm of VCO output power is used to close the PLL. From each VCO, +10 dBm of 10.225-GHz microwave signal can be extracted. To evaluate the out-of-loop relative timing jitter between the two extracted microwave signals, the outputs from the locked VCOs are mixed in quadrature. The baseband phase error signal is amplified by a low-noise amplifier and monitored by a vector signal analyzer for spectral phase noise density measurements and a data acquisition system for long-term drift measurements. The resolution of the out-of-loop characterization is about 0.8 fs at 10.225 GHz, which is determined by using two correlated microwave signals generated by a microwave signal generator and a splitter. Note that only the out-of-loop mixer is temperature-stabilized to enable a long-term measurement, while both PLLs are not temperature-stabilized.

Figure 2: (a) Phase noise spectra at 10.225 GHz from 10 Hz to 10 MHz. The out-of-loop measurement shows 12.8 fs relative jitter between two extracted microwave signals. (b) Long-term out-of-loop drift measurement between two locked VCOs shows that the timing drift is within 48 fs over one hour. The data was taken at every 5 seconds. (c) Long-term baseline measurement of the out-of-loop characterization setup. The same 10.225-GHz signal is applied to both inputs of the mixer. Although the characterization setup is temperature-stabilized, timing drift up to 50 fs is observed over 500 minutes. The data was taken at every 1 minute.

Figure 2 summarizes the measurement results. Figure 2 (a) shows that when both VCOs are locked, the out-of-loop timing jitter between two extracted microwave signals integrated from 10 Hz to 10 MHz is 12.8 fs. Figure 2 (b) is the long-term timing drift measurement result when both VCOs are locked. The relative timing between two microwave signals drifted within 48 fs over one hour. Note that although there was no temperature stabilization for the PLLs, when we intentionally blew hot air over the entire experimental setup at $t = 57$ min (which caused ~ 5 °C temperature increase), the timing was immune to such temperature change. In fact, the baseline measurement in Figure 2 (c) shows that the characterization setup itself may contribute up to 50 fs drift. To evaluate the out-of-loop characterization setup, we applied the same 10.225-GHz signal to both mixer inputs and measured the timing drift over 500 minutes. Even though the temperature of the mixer is stabilized within 1 °C, up to 50 fs drift was observed. Therefore, the drift measurement result in Figure 2 (b) is already limited by the characterization setup itself.

In summary, we have demonstrated long-term stable microwave signal extraction from a mode-locked laser using balanced optical-microwave phase detectors. The relative out-of-loop timing jitter integrated from 10 Hz to 10 MHz is 12.8 fs, and the drift is within 50 fs in one hour.

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