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Mode-Locked Fiber-Laser Repetition-Frequency Stabilization using a Low-cost FPGA board

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Abstract: We demonstrate repetition frequency stabilization of a mode-locked laser using an FPGA board and open-source software. The stabilized repetition frequency exhibited low timing jitter and an Allan variance of 8×10^{-12} at 100 s gate time.

1. Introduction

Mode-locked lasers (MLLs) have enabled such applications as ultrafast time and frequency-resolved measurements, precision timekeeping, high-resolution spectroscopy techniques and optical ranging [1,2]. However, the utilization of MLLs for such applications demand full stabilization of lasers. Conventionally, analog proportional-integral (PI) servos have been employed for achieving MLL stabilization [3]. Recently, digital PI servos based on embedded systems using field-programmable gate arrays (FPGAs) have been used for this purpose due to their advantages like customizability, flexibility, integrability and superior performance [4,5]. Despite several reports on using FPGA-based PI servos [6], such systems remain out-of-reach of many applications due to high cost and sophisticated programming requirements.

Here, we demonstrate repetition frequency stabilization of a commercial fiber MLL using a low-cost FPGA-based embedded computer and a versatile open-source firmware/software. We use a Red Pitaya† (RP) 125-14 as an FPGA (also called STEMlab 125-14) and an open-source software named PyRPL to function as a PI servo [7, 8]. The residual phase noise and long-term frequency stability of the stabilized signal exhibited comparable performance to that of the frequency reference, which was synchronized to maser, without any significant limitations imposed by our stabilization scheme.

2. Experiment

Figure 1 shows the schematic of experimental setup. The output of a mode-locked fiber laser is fed to a fast photodiode which detect the laser pulses with 100 MHz repetition frequency. The 10th harmonic of the repetition rate at 1 GHz, is bandpass filtered and amplified before mixing down using a radio-frequency (RF) reference of 1 GHz. The down-converted signal is applied at an analog input channel of the FPGA and an analog output of the FPGA is applied to the modulation input of a high-voltage (HV) amplifier. The FPGA is programmed and controlled as a PI servo using open-source software. The amplified output of FPGA is added to the DC bias of the HV amplifier to modulate the laser cavity length for correcting repetition frequency fluctuations. The cavity length is controlled via a piezo-electric transducer (PZT). A 1% tap on the MLL (~0.35 mW) is used to analyze phase noise with a signal analyzer and Allan variance using a frequency counter.

In brief, the RP is an embedded system which contains an FPGA, two RF inputs with two 125 MS/s 14-bit analog to digital converters and two RF outputs with two 125 MS/s 14-bit digital to analog converters [7]. It also has 16 digital input/output (I/O) pins connected to the FPGA for I/O programming. Though we use RP as a PI servo by using only one pair of RF input and output it can also be used as two PI servos either for stabilizing two MLLs useful in dual-comb experiments or for full stabilization of a frequency comb laser [6] utilizing both pairs of RF I/O.

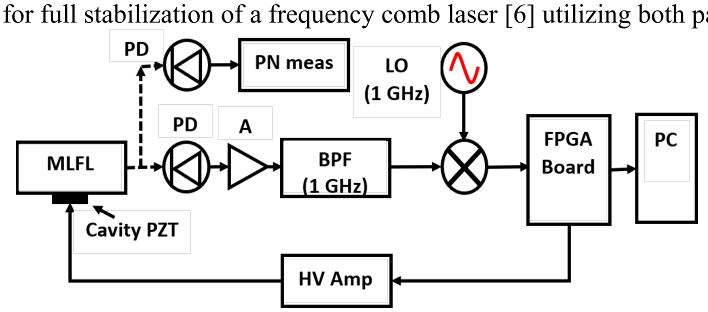

Fig 1: Schematic of experiment. MLFL: mode-locked fiber laser; PD: photodiode; A: amplifier; BPF: bandpass filter; LO: local oscillator; PC: computer; PN meas: phase noise measurement.

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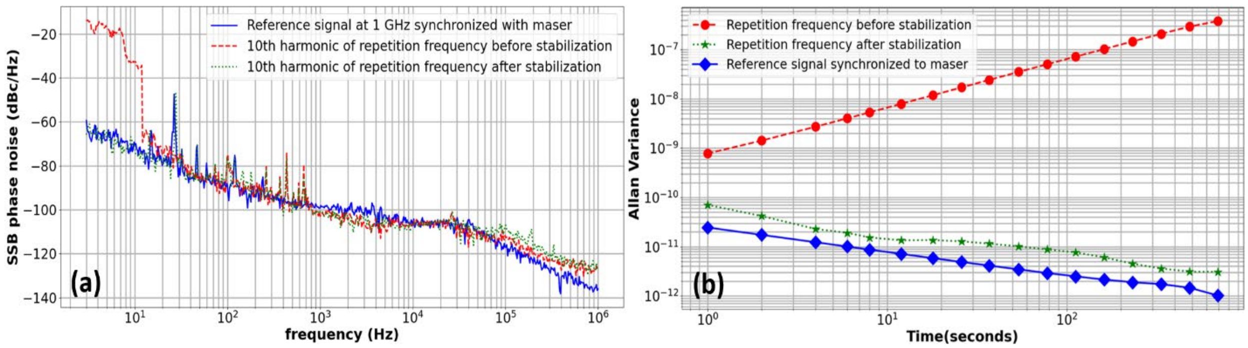

Fig. 2: Results of stabilization showing comparison of (a) single sideband (SSB) phase noise and (b) long-term frequency stability of the repetition frequency before and after stabilization with the frequency reference.

The RP has been programmed as a PI servo using an easy to use and open-source software package called PyPRL [8]. In short, PyRPL is a versatile open-source software with graphical user interface (GUI) that allows one to use FPGA boards with analog interfaces for measurement and control of real-world devices by providing many test and measurement instruments. Here, we used the PI servo and oscilloscope tools of PyRPL.

2. Results

Figure 2 shows the results of stabilizing the 10th harmonic of repetition frequency with a 1 GHz reference which is synchronized to the maser frequency reference [9]. In Fig. 2(a), solid (blue), dashed (red) and dotted (green) traces represent the phase noises of the reference signal, repetition frequency before stabilization and repetition frequency after stabilization, respectively. It can be clearly seen that the phase noise of repetition frequency signal improved greatly after stabilization and it's stability is reference-limited which can be further improved by employing an optical clock as a reference instead. In particular, the calculated root-mean-squared (RMS) timing jitter in the 3 Hz to 100 Hz region is lowered from 62.190 ps to 293 fs demonstrating excellent stabilization capability of RP-based PI servo. The diveregence in phase noise of the repetition frequency signal from the reference signal beyond 500 kHz may have stemmed from pump laser noise.

Figure 2(b) depicts the performance of long-term stabilization. The solid (blue), dashed (red) and dotted (green) traces in Fig. 2(b) show Allan variance of reference signal, repetition frequency before stabilization and repetition frequency after stabilization, demonstrating the improvement in long-term stability after stabilization. For example, the the Allan variance improved from 5×10^{-8} to 8×10^{-12} at 100 sec gate duration. The stabilized repetition frequency also closely tracks the long-term stability of the reference for all gate times from 1 sec to 700 sec, demonstrating the efficacy of long-term stabilization.

It should be noted that we have fed back to the PZT for stabilizing relatively fast fluctuations of the laser cavity. However, if long-term stability over several hours is desired then the temperature of cavity can be controlled too.

3. Conclusion

We have stabilized the repetition frequency of a mode-locked laser to a radio-frequency (RF) reference using a low-cost (< 350 USD) FPGA based embedded system as a PI servo. The stabilization scheme followed the conventional scheme except it utilizes a Red Pitaya 125-14 FPGA board running on a versatile open-source software in place of an analog servo. The demonstrated stability is ultimately limited by the stability of RF reference. Importantly, using FPGA-based servos allows the ability to remotely control and stabilize the laser for field use [10]. We anticipate this report will accelerate the use of such digital locking scheme without compromising intended performance.

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†We identify brand names in this paper only to explain the experimental conditions. NIST does not endorse commercial products. Other products may work as well or better.