COMPARATIVE STUDY OF DIGITAL AND ANALOG SYNCHRONIZATION TECHNIQUES FOR LASERS IN ACCELERATORS

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Abstract

Pulsed laser systems play an important role in present and future light sources. These lasers need to be synchronized very precisely to the accelerator RF. One approach is using an analog controller, which offers low-noise performance and has been demonstrated to achieve sub-50 fs stability. A digital controller based on a high-performance FPGA offers more flexibility, for instance the possibility to implement notch filters to evade the limitations by resonances of the piezo crystal used to adjust the laser cavity length. This paper presents results obtained with both approaches.

INTRODUCTION

A mode-locked laser serves as an ultra-stable laser master oscillator (LMO) for the proposed optical synchronization system for the European XFEL, which will be tested at the FEL facility FLASH [1]. Fiber lasers are well suited to realize such an optical master oscillator, because of the ease of coupling to the fiber distribution system, their excellent long-term stability, and the well-developed and mature components that are available at the optical communications wavelength of 1550 nm. A detailed description of the laser master oscillator can be found elsewhere [3]. Erbium-doped fiber lasers exhibit an extremely low phase noise at high offset frequencies making these lasers competitive with the best low-noise microwave oscillators around. Environmental effects like microphonics and vibrations cause excessive low-frequency phase noise, which can be significantly reduced by phase-locking the fiber laser to a ultra-low noise reference oscillator. Due to the extremely high upper state life time of erbium (1 ms), noise for frequencies above 1 kHz, due to for instance the pump laser, is suppressed.

SETUP OF THE LMO SYSTEM

A schematic of the setup of the LMO system is shown in Figure 1. Two fiber lasers run at a repetition rate of 54 MHz, which is the 24th subharmonic of the accelerator RF frequency of 1.3 GHz. Part of the laser pulse train is detected using a high-bandwidth photodiode. In frequency domain, the ultrashort pulses consist of harmonics of the repetition rate with equal energy and a spacing of the repetition frequency. Using a bandpass filter of appropriate

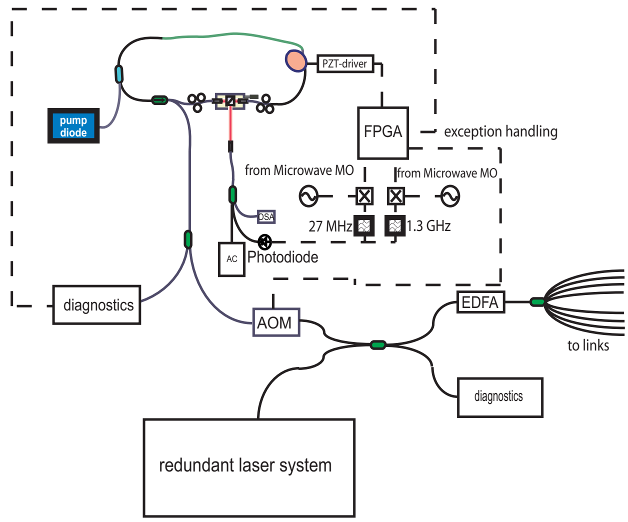

Figure 1: Schematic of the proposed FLASH LMO system.

bandwidth, the 23rd harmonic is selected and amplified to a level of around 5 dbm. The reference signal comes from a low phase noise RF oscillator at 1.3 GHz. Both signals are fed to a analog double-balanced diode ring mixer. The resulting error signal is now amplified by the loop filter, which is either a digital or analog proportional-integral controller. The proportional and integral part are in parallel, so the advantages of an integrator at low frequencies can be obtained without compromising the phase margin at higher frequencies. After being amplified to higher voltage levels to fit the range of piezo crystals, the signal is fed to a piezo-based fiber stretcher, onto which a substantial part of the optical fiber making up the laser cavity is wound. This adjusts the repetition rate of the LMO.

To achieve the required uptime of the LMO system, it is built redundant. Both lasers run continuously and should one of the lasers fail, the backup unit will take over. To enable an ultra-low residual jitter performance, the highest possible comparison frequency is selected which is 1.3 GHz in our case. This however leaves 24 possible positions where the PLL can catch. If the phase-lock of a failed unit is reestablished, it cannot be guaranteed that the laser pulse position is identical to the one of the backup laser which is now seeding the synchronization system. The solution to this problem is the introduction of a second PLL into the system. It runs at a comparison frequency which is equal to the repetition rate of the LMO. This leaves only one zero-crossings where the PLL can catch per revolution of the laser pulse inside the cavity. The lower frequency PLL catches first and thus selects the phase of the laser pulse. Once the lock is established, the second PLL running at 1.3 GHz will take over.

There are two fundamental approaches which can be considered for the controller of this system. One choice is to use a conventional analog controller. It has been shown, that excellent synchronization performance can be achieved using such a system [4]. The limits of an analog controller lie in the flexibility it can offer. It is very difficult to realize more complex transfer functions than that of a simple PI controller. One aspect of where this is helpful is the implementation of a notch-filter to counteract the effects of the resonance of the piezo crystal in the fiber stretcher to obtain a higher gain in the PLL. Furthermore the switching of two PLL's is significantly easier using a digital controller which will be described in the next section.

DIGITAL CONTROLLER

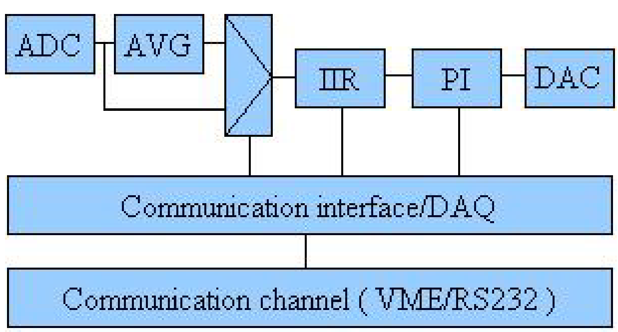

Figure 2: Schematic of the digital controller architecture.

The digital PI controller was implemented using an in-house developed controller board for the low-level RF control, called SIMCON 3.1[5]. The application utilizes the Virtex 2 Pro FPGA, located on the controller. The internal structure of the controller is shown on Figure 2. The digital controller offers the same functionality as its analog pendant, namely a parallel PI-controller with an optional second order infinite impulse response low-pass filter. The error signal from the double balanced mixer is sampled with a sampling frequency of 50 MHz. Then the data is decimated to provide one valid sample every 1 μs. Optionally averaging of 50 samples of the error signal can be used to reduce the ADC noise. The controller transfer function is applied to the resulting digital signal which is then converted with a DAC and fed to the piezo driver. For diagnostic purposes, a flexible data acquisition system was used. It saves 16 signals over 64 ms (64000 samples of each signal) to the external SRAM memory of the SIMCON controller. Two forms of communication were were implemented: a VME interface and an RS232 serial link.

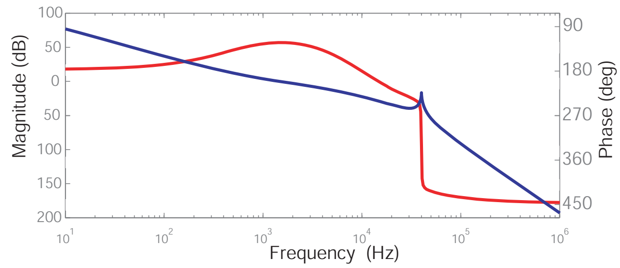

Figure 3: Bode Plot of the open loop transfer function (magnitude - blue, phase - red).

All the controller's parameters can be set with MATLAB software using a channel independent interface [6].

CONTROLLER TYPE AND SIMULATION

The feedback acts on the cavity length through the piezo which stretches the optical fiber. Care has to be taken not to disrupt the laser dynamics through introduced birefringence which occurs if the fiber is bent. The fiber stretcher is constructed such that bending is avoided and only the length of the fiber is varied by the piezo. Hence laser dynamics will to first order not be influenced and the laser will in terms of phase act as an integrator with the transfer function $G_l = \frac{k_l}{s}$, where k_l is the gain of the piezo inside the laser cavity (in our case is 0.35 $\frac{Hz}{V}$). Mechanical resonances of the piezo have to be considered (~ 40 kHz), which can be modeled by a harmonic oscillator. This yields a transfer function of $G_{piezo} = \frac{(2\cdot\pi\cdot f_{res})^2}{s^2+4\pi\gamma f_{res}\cdot s+(2\pi f_{res})^2}$ which ultimately limits the achievable gain of the PLL. A linear response is assumed for the phase detector around the locking point, which is valid for analog mixers around the zerocrossing, i.e. $\Delta\phi = 0, \pi, 2\pi \ldots$. The controller consists of a PI-controller ($G_{PI} = K_P + \frac{K_I}{s}$) and an optional low pass filter with a corner frequency of $f_{lp} = 10$ kHz.

The simulated open loop transfer function is shown in figure 3. The unity gain bandwidth is at 1 kHz which is in good agreement with the experimental results. It can be seen from Figure 5, that the phase noise spectra of the locked laser and reference oscillator start deviating just above 3 kHz which is the point of unity gain.

RESULTS

The first step to compare the performance of the two systems was to lock one LMO to a 1.3 GHz reference and evaluate the residual jitter. Figure 4 shows the power spectral density of the error signal when the system is locked for both analog and digital controller. The integration of these signal yields the respective residual jitter for either the analog or the digital controller. It amounts to 74 fs for the analog controller and 107 fs for the digital controller, both in a bandwidth from 1 Hz to 112 kHz. The difference in performance of the two controllers is almost entirely due

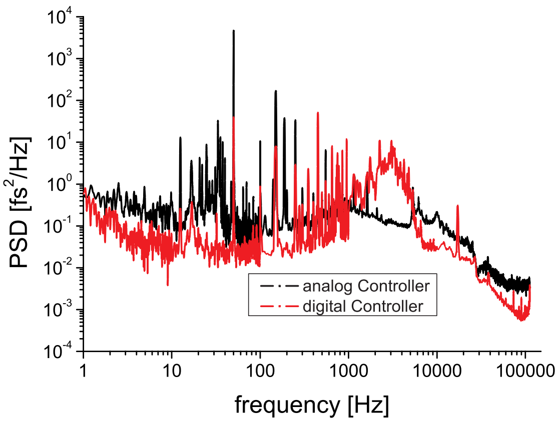

Figure 4: Power spectral density of the closed-loop error signal for both analog (black) and digital (red) controllers.

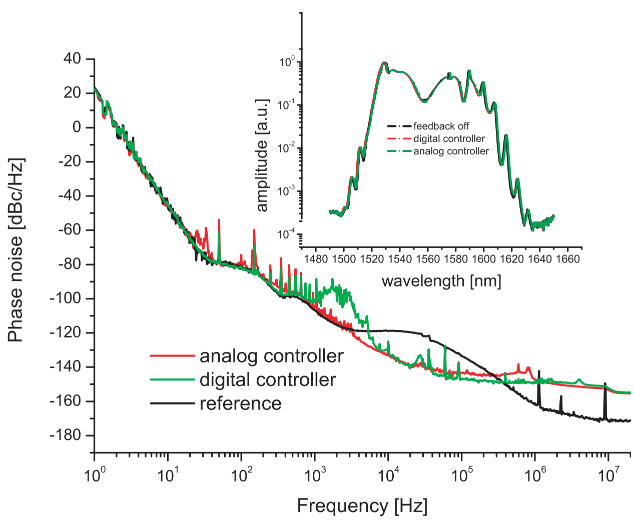

Figure 5: Phase noise for the locked fiber laser with both analog (red) and digital (green) controllers and the reference (black). Insert: Optical spectrum of the fiber laser without feedback (black), with digital controller (red) and analog controller (green).

to the PLL peaking of the digital controller. This is due to a slightly higher proportional gain which limits the phase margin of the system and leads to the power spectral density increase around 2 kHz. Reducing the proportional gain will yield a comparable result to the analog controller. It should be noted, that a significant part of the jitter in the digital controller is due to the 50 Hz line. The magnitude of this perturbation does not change with proportional and integral gain settings of the controller, making a crosstalk from the power supply to the DAC a likely candidate for the cause. It can possibly be improved in the next redesign of the digital controller board. An advantage of the digital controller is the possibility to average the ADC data. The sampling rate of the ADC is a lot higher than needed for the regulation (60 MHz), so an average was employed reducing the sampling rate to 1 MHz. This reduces the uncorrelated noise of the ADC by a factor of almost 8.

It is important, that the activated PLL does not increase the phase noise at higher offset frequencies. The measured phase noise with and without feedbacks is depicted in figure 5. There is no significant increase in the high frequency phase noise when locking with either system.

A further important issue is the possible change of the optical properties of the laser pulses due to the phase locking. The insert to Figure 5 shows the optical spectrum of the fiber laser without any feedback and with either controller. No significant change was observed for either feedback option.

CONCLUSION AND OUTLOOK

An optical master oscillator system requires a precise phase-lock of the fiber lasers to an external RF clock. This can be achieved by either using a digital or an analog controller. The measured performance for either system was comparable. No significant differences in the high frequency phase noise or the optical spectrum could be observed. This indicates that the more flexible approach using an FPGA as a digital loop filter is feasible without compromising the locking performance.

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