FEMTOSECOND SYNCHRONISATION OF ULTRASHORT PULSE LASERS TO A MICROWAVE RF CLOCK

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Abstract

A precise synchronization between the laser repetition rate and the linac RF is mandatory for electro-optic sampling or pump-probe experiments. The level of stability is usually determined by measuring the spectral noise power density of the feedback signal when the system is locked. However, an independent measurement is needed to confirm this. In this paper, we present an approach exploiting electronic techniques to synchronize a TiSa laser to the RF of the DESY VUVFEL with sub-70 fs rms stability. The remaining time jitter is measured by an RF monitoring system independent of the locking PLL.

INTRODUCTION

Ultrashort pulse lasers have become increasingly valuable diagnostic tools for linear accelerators. Their applicability ranges from electro-optic sampling (EOS) [Win04] to determine the bunchlength of the electron beam to pump-probe experiments with free electron laser (FEL) radiation [Bri02]. All these applications can tolerate different levels of timing jitter between repetition rate of the optical pulse train of the laser and the main radio frequency used in the machine ranging from sub 50 fs to several ps. Whereas the latter is readily achieved using electronic techniques, the first requirement pushes the capabilities of electronics to the limit. For the electro-optic sampling experiment at the VUVFEL at DESY [Ste05], an untrashort pulse laser with a repetition rate of 81 MHz had to be synchronized to the linac RF with a stability of sub 100 fs in the frequency range of mHz to 40 MHz. Furthermore, the experiment requires that the phase between the laser pulses and the linac RF is electronically adjustable over several ns with a precision in the order of 50 fs. The repetition rate lock is achieved by a phase-lock-loop (PLL), keeping the phase between the pulse train and the linac RF constant. Since the repetition rate depends on the cavity length of the laser, the PLL will act on a piezo crystal, which moves one of the mirrors inside the cavity.

The stability of synchronisation setups is usually monitored by observing the jitter of the phase detector output when the system is locked. However, accurate monitoring can only be accomplished with an out of loop measurement, i.e. a phase detection which is not used to lock the system but exclusively for jitter observation. This is done here by using a second phase detection circuit operating at a frequency of 10.4 GHz.

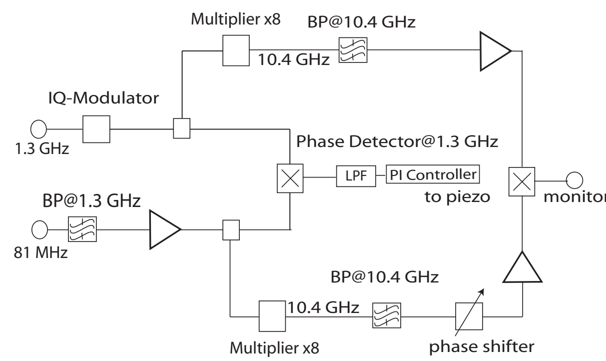

Figure 1: Schematic of the synchronization electronics

EXPERIMENTAL SETUP

The experimental setup is shown in Figure 1. Part of the laser pulse train is deflected onto 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. The repetition rate of the laser was chosen, such that the 16th harmonic of the laser is equal to the linac RF (1.3 GHz). Using a bandpass filter of appropriate bandwidth, the 16th harmonic is selected and amplified to a level of around 0 dbm. The reference signal from the VUVFEL master oscillator is fed to a vector modulator, which makes it possible to introduce a phaseshift proportional to an external voltage. This enables a computer controlled scanning of the phase between laser and RF synchronous to the machine trigger, which is mandantory for EOS. Both signals are fed to a digital phase detector, which converts the phase difference of the two input signals to a voltage error. The resulting error signal is now amplified by the loop filter, which is a 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 the piezo, the loop is closed by feeding the signal to the piezo.
If stability of sub-100 fs is desired, the total integrated error signal will be in the range of 100 μV. In order to increase the sensitivity of the phase detector, a higher comaprison frequency is desired. To enable a better monitoring of the system performance, part of both the reference signal and the filtered laser diode signal are multiplied by eight in a multiplyer chip, amplified and compared in a mixer. This will increase the time equivalent of a degree of phase by a factor of eight. As the resolution of mixers and digital phase detectors are very similar, the gain in resolution is expected to be a factor of eight. However, additional noise introduced by the multiplier circuit limits the gain in performance, as will be explained below.
To minimize drifts, the whole setup is temperature stabilized to a level of 0.1 degrees C.

SOURCES OF NOISE

Careful selection of all high frequency IC's is crucial to obtain best possible performance. Very high quality RF amplifiers are readily available, so they are no major concern for the overall stability. The final noisefloor however is given by the performance of the phase detector, which has an input phase noise floor at 1.3 GHz of -140 dBc/Hz with a 1/f corner frequency of 100 Hz. Taking into account the 1/f jitter for lower frequencies, this yields in our case a limit of 37 fs rms for a bandwith of 1 Hz to 40 MHz, which is the Nyquist frequency of the laser. A passive mixer does not suffer the limitation of a digital phase detector due to the noise floor, however the temperature dependent drift will ultimately limit its performance. With a typical temperature coefficent of around 2 $\frac{mV}{\deg C}$, a stability of better than 250 fs over minutes is difficult to achieve with double balanced mixers.
The benefit of the low drifts of the active phase detectors has the drawback of increased sensitivity to power supply ripples and other noise introduced to the system by e.g. stray RF. Therefore a good shielding of the whole setup and the use of lowest ripple power supplies is crucial. Thus all the electronics were built into a HF shielded 19" rack. Besides the unavoidable RF connections to and from the rack, special care was taken to avoid any other electrical connection to the system. A possible source of additional noise are the inputs needed to control the vector modulator. To avoid any additional noise coupled into the system through there, all these signals were converted into the optical domain and transmitted via plastic fiber into the rack and reconverted into the analoge control signals locally.
The multiplier chip used has a noise floor -136 dBc/Hz, which corresponds to 22 fs rms timing jitter at 10.4 GHz. Although the noise floor of the active elements at 10.4 GHz is considerably higher than at 1.3 GHz, an overall benefit is still obtained, because the phase noise for a given timing jitter scales with $20 \log N$ where N is the multiplication

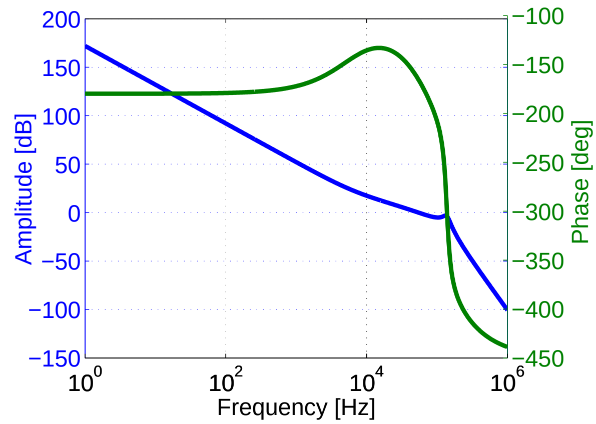

Figure 2: Bode Plot of the open loop transfer function

factor for the carrier frequency (8 in our case). Both the reference and the 16th harmonic of the laser were multiplied by the same model of multiplier chip located next to each other in the setup. This ensures that correlated effects e.g. due to temperature drifts are minimized.

SIMULATION OF THE PLL

The feedback only acts on the cavity length through the piezo. Hence laser dynamics will 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 7.5 $\frac{Hz}{V}$). Mechanical resonances of the piezo have to be considered ($\sim$ 15 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. Digital phase detectors are linear over the full range, 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 a low pass filter with a corner frequency of $f_{lp} = 14$ kHz.
The simulated open loop transer function is shown in figure 2. The unity gain bandwidth is at 9 kHz which is in good agreement with the experimental results. It can be seen from figure (3), that the phase noise spectra of the locked laser and reference start deviating just below 10 kHz which is the point of unity gain.

RESULTS

The stability of the synchronisation was measured in two ways. The phase noise spectrum of the 16th harmonic of the laser repetition rate (1.3 GHz) was measured when the system was locked and compared to the phase noise of the reference oscillator. These plots are shown in Figure 3. The

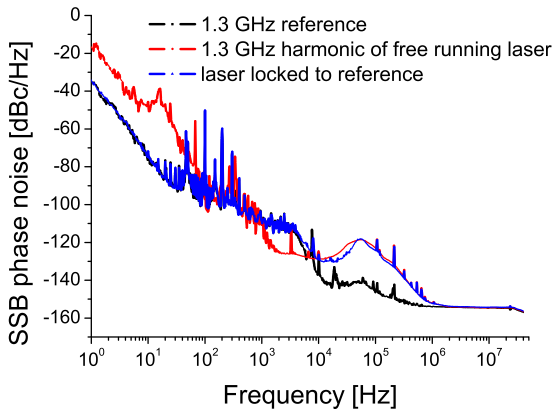

Figure 3: SSB phase noise of the 16th harmonic of the laser and the 1.3 GHz reference

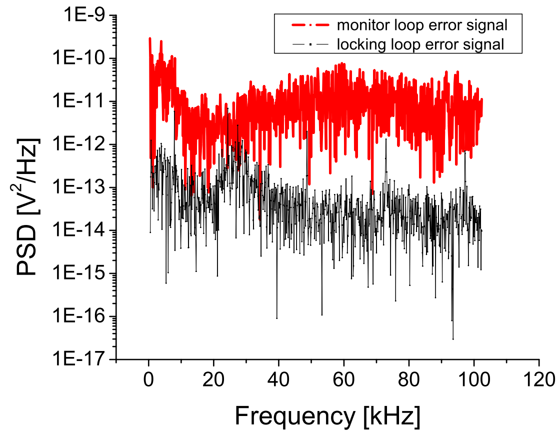

Figure 4: Noise on the error signal for locking loop and monitor loop

residual timing jitter is given as

$$\Delta t = \frac{\sqrt{\int_f L_{laser}(f')df'} - \sqrt{\int_f L_{ref}(f')df'}}{\sqrt{2}\pi f_{ref}}, \qquad (1)$$

where L is the power spectral density of the phase noise given in $\frac{\text{rad}^2}{\text{Hz}}$ and f_0 is the linac RF of 1.3 GHz. In this case the total residual jitter in a bandwidth from 1 Hz to 40 MHz amounts to 57 fs rms. The noise around 100 kHz is due to the relaxation oscillations of the TiSa laser. These numbers are obtained by a direct measurement of the timing jitter of both laser and reference frequency using an Agilent E5052 phase noise analyzer.

The other possibility is to measure the output signal of the phase detector and integrate the jitter. This was done in a range from 31 mHz to 100 kHz for both the 1.3 GHz locking PLL and the 10.4 GHz monitor loop (Figure 4). Integrating the signal and converting it into timing jitter by multiplying with the gain of the phase detector yields 62 fs rms and 67 fs rms respectively. This is in good agreement with the timing jitter obtained by measuring the phase noise directly at the carrier. The additional jitter for frequencies >100 kHz is small. Combining the low frequency jitter derived from the error signal measurements (f<1Hz) with the measurements directly at the carrier (f>1Hz) leads to a total timing jitter in the frequency range from 31 mHz to 40 MHz of 65 fs rms. This is the lowest jitter reported up to date for a synchronisation of a laser system to a microwave clock in this bandwidth.

CONCLUSION AND OUTLOOK

We have demonstrated the highest stability synchronisation to date of a ultrashort pulse laser system to an external microwave clock with a residual timing jitter of 65 fs rms in a bandwidth of 31 mHz up to the Nyquist frequency (40 MHz). To minimize drifts, special care was taken in choice of components and stabilization of the setup against temperature variations and noise coupled in via connections to the control system of the linac. In order to verify the measurements of the error signal at 1.3 GHz, a second loop was introduced, comparing reference and laser harmonic at 10.4 GHz. Measurements of the error signal at both frequencies and a direct measurement of the phase noise of the carrier gave similar results. Improvements can be made to the system by pushing the unity gain bandwidth further which requires either piezos with a higher resonance frequency or a digital control system to notch out these resonances.

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