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Femtosecond synchronization of a 3 GHz RF oscillator to a mode-locked Ti:sapphire laser

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Abstract

We have synchronized a 3 GHz electronic oscillator to a 75 MHz femtosecond self-mode-locked Ti : sapphire laser with a relative root-mean-square phase-jitter of less than 20 fs in the frequency range of 0.05 Hz–100 kHz and a drift of 20 fs/h. The jitter has been measured by time and frequency domain analysis. Potential applications include synchronization of lasers and RF power sources in particle accelerator experiments and high-resolution pump–probe experiments using, e.g. electrons and lasers. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

As the use of ultrafast lasers becomes more and more common, the ability to synchronize them to other sources becomes a key issue. For example, in high-resolution pump–probe experiments the accuracy of the time information is directly related to the synchronism between pump and probe. One of the great challenges in accelerator physics is the generation of femtosecond electron bunches using photocathode RF electron guns driven by mode-locked lasers. The generated electrons can be used to generate femtosecond pulses of radiation enabling pump–probe experiments on materials on the time scale of the motion of atoms [1]. Both for the acceleration of the electron bunches and for high-resolution pump–probe experiments with the generated radiation, a high degree of synchronization is required between the laser and the RF acceleration field. In this paper we report on the synchronization of a 3 GHz electronic oscillator to a 75 MHz mode-locked Ti : sapphire laser. The electronic oscillator is meant to drive an RF amplifier (klystron), which will be used to set up an acceleration field in an electron accelerator. The Ti : sapphire laser will be used to drive the photocathode of this accelerator [2].

In previous experiments mode-locked lasers have been synchronized to other lasers, to electronic oscillators [3] and, recently, to a free electron

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laser [4] with subpicosecond jitter. In these experiments the frequency of the laser is adjusted by changing the cavity length, to follow a master oscillator. In case the master oscillator is a stable crystal oscillator the advantages are obvious: the absolute (long term) jitter approaches the jitter of the crystal oscillator which is usually much better than the jitter and drift of a laser oscillator. However, in many experiments it is of greater interest how well the two sources are synchronized, i.e. the relative jitter counts and not the absolute jitter. In pump–probe experiments, for instance, it is the delay between the pump and the probe which is of prime importance, irrespective of the absolute timing with respect to some external reference. In these cases changing the frequency of the oscillator with the highest control bandwidth is to be preferred, because in a stable well-designed feedback system this bandwidth will determine the residual jitter. The control bandwidth of electronic oscillators often exceeds the control bandwidth of laser oscillators by more than three orders of magnitude. In our case the control bandwidth of the 75 MHz laser oscillator is of the order of 1 kHz compared to 12 MHz for the 3 GHz electronic oscillator. By making the laser the master oscillator we were able to improve the relative phase-jitter by almost two orders of magnitude, resulting in 18 fs rms jitter. In this paper we will first describe the experimental setup used for the synchronization, then we will discuss the different contributions to the total jitter together with the experimental results.

2. Experimental setup

A schematic layout of the synchronization system is given in Fig. 1. The Ti : sapphire laser (Femtolasers GmbH, Vienna) delivers 10 fs, 5 nJ pulses at a repetition rate of 75 MHz. The repetition rate is inversely proportional to the cavity length and can therefore be changed by moving one of the end mirrors. A piezo-electric transducer (PZT) is used to displace this mirror. The characteristics of the piezo together with the mass of the mirror limit the maximum frequency for displacement to about 1 kHz. The electronic oscillator operates at a frequency of 3 GHz (CTI, Type DRO-33XX). Its frequency is voltage

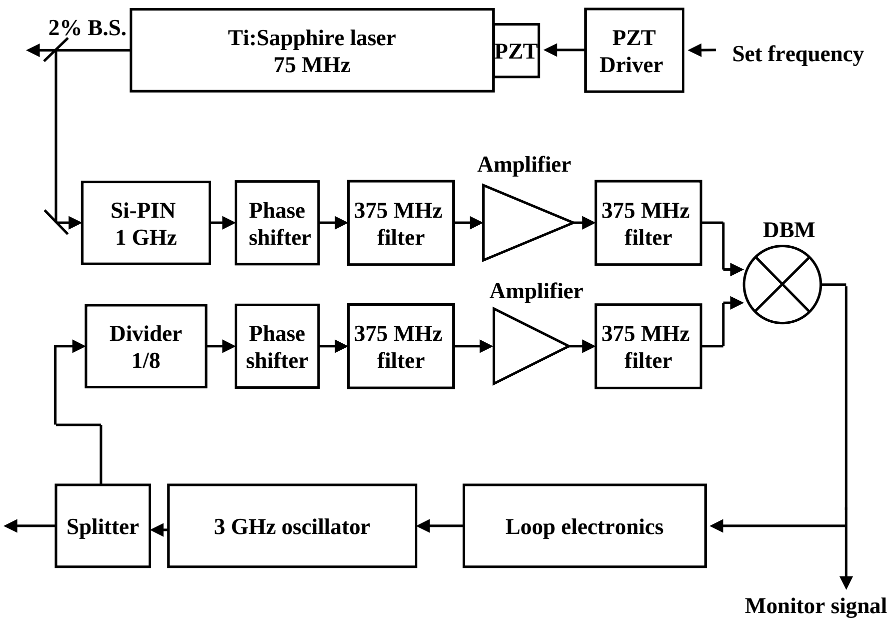

Fig. 1. Block diagram of the electronics used to phase lock the electronic oscillator to the laser.

controllable with a bandwidth of 12 MHz. The 75 MHz optical pulse train from the Ti : sapphire laser is monitored with a fast Si-(PIN)-photodiode. A narrow-band filter is used to select the 5th harmonic of this signal at 375 MHz. As phase-jitter increases at higher harmonics the use of the 5th harmonic increases the sensitivity of the loop. An added advantage of using the 375 MHz frequency band is the availability of reliable and cheap components such as amplifiers and filters. To compare the phase of the laser with the phase of the electronic oscillator the 3 GHz RF signal is divided by 8 and subsequently filtered to remove the higher harmonics. The narrow-band filters are passive bandpass devices having a bandwidth of 16 Mhz. The filters behind the amplifiers are used to remove spurious amplifier outputs. The amplifiers (mini-circuits, ZFL-500LN) are wide-band with 24 dB gain, and a specified noise figure of 2.9 dB. To avoid phase errors by temperature changes the two signal paths to the inputs of the mixer are constructed fully identically. A double-balanced mixer (DBM) is used to measure the phase difference of the two amplified signals. The DBM output signal is used by the loop electronics to change the frequency of the electronic oscillator. The loop continuously adjusts the phase of the electronic oscillator to match the phase of the laser oscillator, thereby reducing the relative phase fluctuations to a value determined by: (1) the non-ideal characteristics of the DBM, (2) the added noise in the phase-detection system, and (3) the limited bandwidth and gain of the feedback loop. These contributions have been measured and will be discussed.

3. Jitter contributions

3.1. Mixer-related jitter

The main mixer-related limitation in the synchronization is the conversion of amplitude-jitter to phase-jitter by the DC-offset of the mixer. Ideally, the mixer should give zero output if the two inputs are in phase (or 90° out of phase, depending on the type of mixer used), but due to slight mismatches in the diodes and imperfect balance in the transformer windings of the mixer a small DC-offset will be left. The feedback loop will subsequently adjust the oscillator phase to null the offset. For perfectly stable input amplitudes this results in a perfectly stable phase offset. However, if the amplitudes of the input signals are not stable this offset gives rise to a fluctuating output signal, even if the input signals are perfectly in phase. Because the control action of the loop minimizes the output of the mixer by adjusting the oscillator frequency, this amplitude-jitter will be converted into phase-jitter. If $A(t)$ is the normalized amplitude-jitter of the input signal then, for small $A(t)$, the resulting phase-jitter $P(t)$ is given by [3]

$$P(t) = \frac{-A(t)V_{\text{off}}}{K\omega_0} \qquad (1)$$

where K is the sensitivity of the mixer in (V/rad), ω_0 the frequency and V_{off} the offset voltage. The mixer used in this experiment is a double-balanced (Minicircuits, MPD-21) diode ring-type mixer with a quoted offset of $V_{\text{off}} = 0.5$ mV. The normalized pulse energy fluctuations $A(t)$ of the diode-pumped Ti : sapphire laser have been measured on an identical system, where a rms value of 0.2% (0.06 Hz–1.5 MHz) was found [5]. Together with a mixer sensitivity $K = 1$ V/rad at a frequency $\omega_0/2\pi = 375$ MHz this leads to a mixer-related jitter of 0.5 fs. As will be discussed in the next section this jitter is negligible compared to the added jitter in the rest of the phase-measurement system.

3.2. Jitter introduced by the phase-measurement system

To measure the added jitter in the phase-measurement system, the inputs of the system are connected to the same oscillator and the output of the phase detector is measured in open loop. To minimize temperature-related drift the system is temperature stabilized within 0.1°C. Ideally, no signal is expected because both inputs exhibit the same amplitude and phase fluctuations. Fig. 2 shows the measured output signal as function of time. This signal has been measured, after amplification, with a 12-bit ADC-card. The

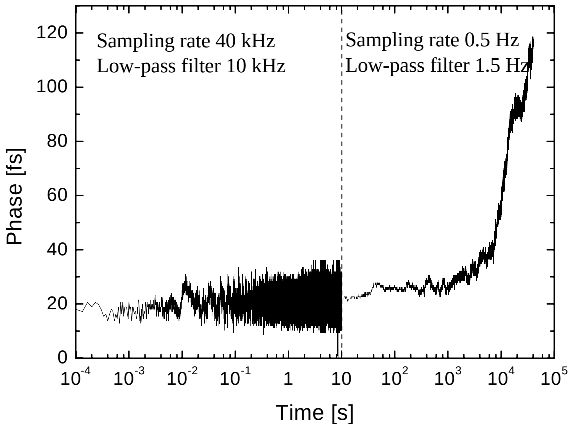

Fig. 2. Typical time evolution of the output signal of the phase-measurement system if both inputs are connected to the same oscillator.

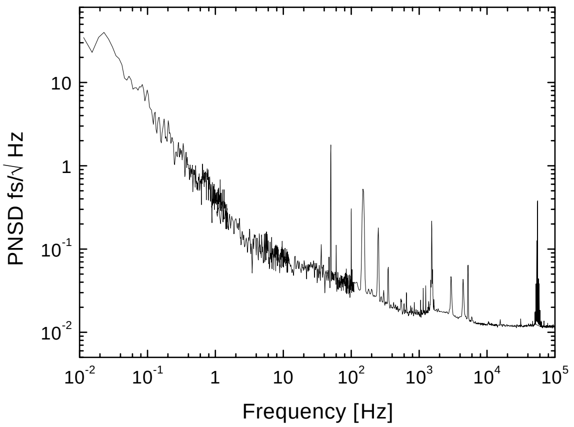

Fig. 3. Phase-noise spectral density with both inputs of the phase detector coupled to the same oscillator.

resolution of the measurement system was 1 fs, limited by the amplifier noise and the digitizing noise. The first part of the graph has been measured with a sampling rate of 40 kHz and an anti-aliasing filter of 10 kHz. To limit the amount of data, the second part was measured with a lower sampling rate of 0.5 Hz and a filter of 1.5 Hz. Because of this filter higher frequencies are averaged and only the long-term drift is left. Clearly, the phase measurement is not perfect:

Table 1
The rms phase-jitter for different frequency ranges

Frequency range (Hz)	Phase detector (fs)	Closed loop (fs)
0.05–10	2.5	0.028
10–1k	2.2	0.29
1–100k	10	15
0.05–100k	11	15

although the input signals are perfectly synchronous, the detector indicates phase-jitter and drift. In closed loop this output signal will degrade the synchronization because the part of the signal which is in the control range of the loop will be inverted and fed back to the controlled oscillator. The resulting jitter and drift can be calculated from the graph. For example, the rms jitter from 10^{-4} to 0.1 s is 3.4 fs. The drift calculated from the second part of the graph is approximately 20 fs/h. Without temperature stabilization the drift is approximately 4 times worse. A similar analysis can be made in the frequency domain. Fig. 3 shows the phase-noise spectral density (PNSD), i.e. the distribution of the phase fluctuations over frequency, as measured with a spectrum analyzer. By integrating in Fig. 3 from 10 Hz to 10 kHz a rms phase-jitter of 3.1 fs is obtained, in good agreement with the time domain result. Rms values for different frequency bands are given in Table 1. The distinct spikes in the spectrum at 50 Hz, its higher harmonics, and at 50 kHz are introduced by the power supplies. Particularly the peak at 50 kHz contributes significantly ($\sim$30%) to the jitter. Additional filtering may therefore lead to further improvement of the phase-detector-induced jitter.

3.3. Jitter due to the limited bandwidth of the feedback loop

The final contribution to the total jitter is due to the limited bandwidth of the feedback loop. First the relative phase-jitter of the two oscillators in free-running mode is measured. Both the laser and the electronic oscillater are connected to the phase-measurement system. The relative jitter is measured as side-band jitter by shifting the laser frequency by 50 kHz and subtracting the 50 kHz difference frequency (Fig. 4). The PNSD decreases with frequency, the main contributions to phase-jitter being due to frequencies below 10 kHz. To have a large suppression at 10 kHz and below, the unity gain loop bandwidth of the feedback controller was set at 1 MHz. Once the unity-gain bandwidth is chosen, the loop gain and the integration time constant of the controller can be calculated from feedback control system theory [6]. Ideally, the loop should have large gain at all frequencies where the phase-jitter is significant, but it is limited by stability constraints. The open-loop gain was set at 1.1×10^6 and the integration time constant of the controller at 4.7 μs, leading to a fast, well-damped system with a maximum overshoot of 10%. Fig. 4 also shows the relative phase fluctuations when the control loop is closed. From these data it can be seen that the noise level has been reduced by many orders of magnitude for the low-frequency range, indicating a very tight lock between the two oscillators. The inferred rms timing-jitter figures are summarized in Table 1.

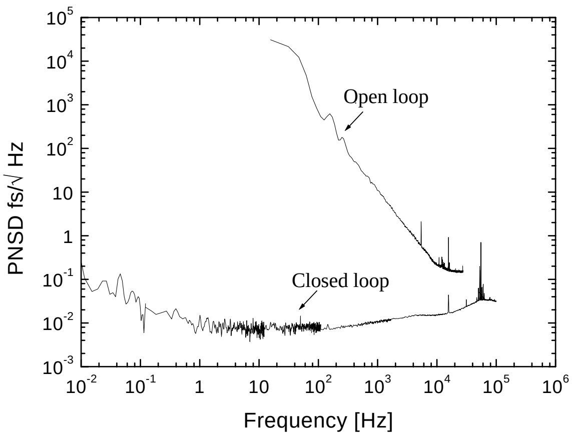

Fig. 4. Phase-noise spectral density of the laser and electronic oscillator as measured at the output of the phase detector. The "Open-loop" graph has been measured as side-band jitter by shifting the laser frequency by 50 kHz.

4. Discussion

If we compare the phase-detector-induced jitter with the jitter in closed loop (Table 1), it can be concluded that at low frequencies the residual jitter is dominated by imperfections of the phase-measurement system. At higher frequencies the suppression of the relative phase-jitter of the oscillators becomes less effective. For this reason the residual phase-jitter at higher frequencies is dominated by the relative phase-jitter of the oscillators. Combining the phase-detector jitter and residual jitter in closed loop, the total phase-jitter between 0.05 Hz–100 kHz is calculated to be 18 fs. It must be emphasized that this phase-jitter is measured directly at the output of the oscillators. In practice additional components, such as amplifiers, will add phase-jitter. For instance, the added phase-jitter of a klystron RF amplifier depends on the stability of the drive voltage. To arrive at a phase-jitter of less than 100 fs after the klystron requires, in our case, a relative voltage stability of better than 10^{-4}.

5. Conclusions

We have synchronized a 3 GHz electronic oscillator to a mode-locked Ti : sapphire laser with an accuracy of 18 fs rms (0.05 Hz–100 kHz), using a simple, large bandwidth, feedback circuit. The measured phase-jitter is completely understood in terms of the separate components. The drift is mainly determined by the phase-measurement system and is as low as 20 fs/h. The jitter is limited, for high frequencies, by the bandwidth and gain of the feedback loop and, for low frequencies, by the phase-measurement system. By improving the phase-measurement system and the bandwidth of the control loop a rms jitter below 10 fs should be possible.

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