Low-Jitter Laser Synchronisation and ECOPS

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Introduction

For various applications it is necessary or desirable to synchronise ultrafast laser pulses to the pulses or the frequency of an other instrument. In time-domain terahertz spectroscopy for example it is common to split the laser beam in-two and use one beam for generating the terahertz pulses and the other for electro-optic sampling of the terahertz pulses. The sampling consists of superimposing the laser beam and the terahertz beam on the detector and sweeping the timing of the laser pulses with respect to the terahertz pulses with the help of a mechanical delay line with moving parts. In their various designs these solutions are always accompanied by difficulties concerning mechanical vibrations, varying spot sizes and pointing instabilities. It is therefore more convenient to use two lasers: one for the terahertz generation, the other for the sampling. The lasers run at the same pulse repetition frequency, yet the relative timing is varied in a controlled way with the ECOPS technique. Time-domain terahertz spectroscopy with ECOPS thus makes use of two FemtoFiber lasers where one is equipped with the FFS-SYNC option such that it can be phase-locked to the other laser with the FFS-PLL electronics. Optical sampling with ECOPS not only avoids the difficulties of mechanical delay lines, it also allows for fast sweeping without loss of timing accuracy. Also in experiments where the FemtoFiber laser is synchronised to for example a free-electron laser or a synchrotron, the ECOPS technique greatly simplifies the scanning procedure.

Quite a different example is frequency combs. The broad, apparently continuous spectrum of a femtosecond laser consists in

Definitions

The **FFS-SYNC** option comprises adaptations to the FemtoFiber laser oscillator enabling modulation of the cavity length. It includes a fast Piezo-electric transducer and a motorised translation stage

The **FFS-PLL** option consists of phase-locked loop electronics which controls the cavity length so that the pulses of the FemtoFiber laser run synchronously to a reference clock signal. The combination of intrinsically stable FemtoFiber technology, the FFS-SYNC option with fast Piezo actuator and state-of-the-art FFS-PLL electronics result in the lowest time jitter values for commercial femtosecond laser systems. This option includes a laptop computer.

ECOPS, the acronym for Electrically Controlled OPtical Sampling, is an excellent method for performing optical sampling or pump and probe experiments without a moving optical delay line. With a voltage applied to the repetition frequency phase input connector, e.g. from a function generator, the user controls the timing of the FemtoFiber laser pulses with respect to the reference clock signal. The dynamical range is as large as that of a 12 cm-long translation stage.

reality of many equidistant lines which are spaced by the pulse repetition frequency. From the fact that the total spectrum interferes every laser period to produce a femtosecond pulse we can infer that the lines of the comb are locked in phase. This still holds true when the range of this frequency comb is extended by means of supercontinuum generation. One application is making single-frequency lasers mutually coherent. This is achieved by phase-locking the two CW lasers to different lines of the comb. The two lasers are now phase coherent, even when their wavelengths are for example hundreds of nanometers apart. The FFS-SYNC and FFS-PLL options allow the user to lock the comb line spacing to a clock frequency. Like this the frequency difference between the CW lasers is under control. Furthermore, the user can control the absolute position of the comb lines by applying a voltage to the pump power modulation input connector of the FemtoFiber laser oscillator.

Variable cavity length

For illustration we imagine we want to synchronise a FemtoFiber laser to another laser which has a repetition frequency of 100.0 MHz, in other words a pulse period of 10.00 ns. Suppose we adjust the optical path length of the FemtoFiber ring oscillator such that it is equal to that of the other laser to within 3 nm. This would imply that the roundtrip times of the lasers would differ by 0.01 fs. Although this is a tiny amount, after 1 billion roundtrips, i.e. after 10 seconds, the timing difference between the two lasers would accumulate to 10 ns, the time between consecutive pulses. In other words, every 10 seconds the pulses of the one laser would overtake the pulses of the other. In terms of the phase difference between the repetition frequencies of the two lasers, it runs through

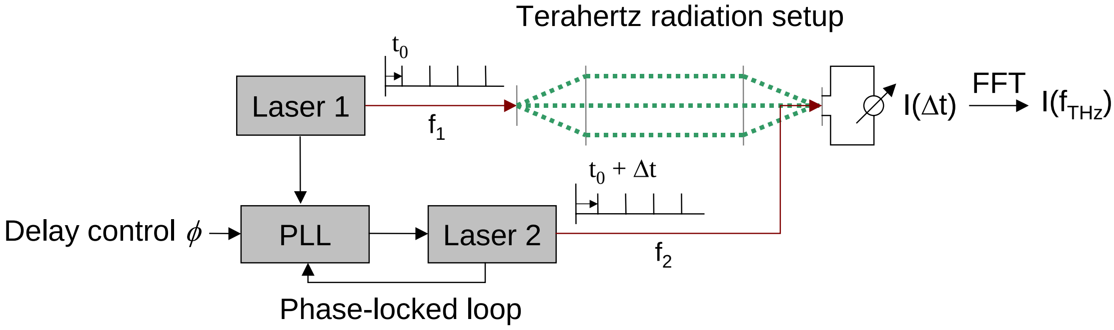
Complete FemtoFiber laser system with power supply (lower electronics rack) and SYNC-PLL option (upper electronics rack, laptop computer with software and drivers, Piezo-electric actuator and motorised translation stage inside laser head)

Special features

- Computer control and monitoring
- Jitter < 100 fs
- ECOPS

Applications areas

- Terahertz spectroscopy
- Accelerators
- Frequency combs
- Synchronisation to laser amplifiers
- Pump and probe (with other lasers, synchrotrons, pulsed magnets, etc.)

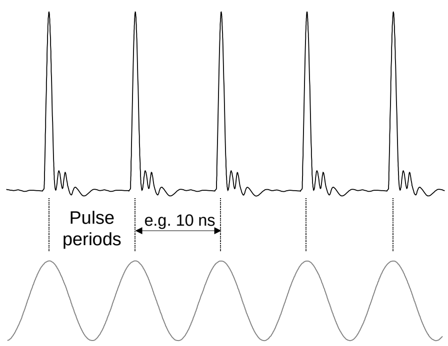


ECOPS is highly suitable for time-domain terahertz spectroscopy a complete 2π cycle every 10 s. Indeed, as the value of 10 s suggests, the 3 nm difference in optical path length corresponds to 0.1 Hz difference in pulse repetition frequencies.

Although outside influences such as varying temperature will easily introduce optical path length differences larger than 3 nm, we would of course wish to keep the phase difference between the repetition frequencies of the two lasers constant for extended periods of time and with the highest possible degree of accuracy. We therefore require an active control of the cavity length with an accuracy preferably on the nanometer scale and with as many corrections to the cavity length per second as possible.

The FFS-SYNC option therefore consists of a fast Piezo actuator inside the fiber ring oscillator of the FemtoFiber laser. The actuator is kept as light as possible such that its inertia remains small and it reacts very quickly (within 1 millisecond) to commands for changing the cavity length. By their nature the fastest Piezo crystals are very small and their maximum stroke is therefore only a few micrometers. Since this is not enough to compensate for slow temperature-induced changes in the cavity lengths, the FFS-SYNC option is also equipped with a motorised translation stage. When the Piezo actuator threatens to reach the end of its range, the motor makes a course correction, such that the Piezo actuator can operate again at the center of its range. The influence of this correction on the quality of the synchronisation is negligible since the Piezo is much faster than the motor.

Photodiode signal

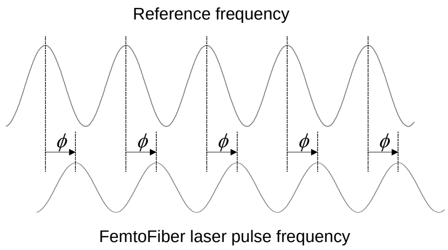


Pulse repetition frequency, e.g. 100 MHz

With filtering, the pulse train from the photodiode is transformed into a clean RF signal at the pulse repetition frequency. Whilst the fast photodiode of the FemtoFiber laser has a speed (bandwidth) of 10 GHz, the dynamics of the photodiode signal shown above is limited by the speed of the 350 MHz oscilloscope. In fact, the sub-100 fs laser pulses are four orders of magnitude shorter than the peaks on the oscilloscope.

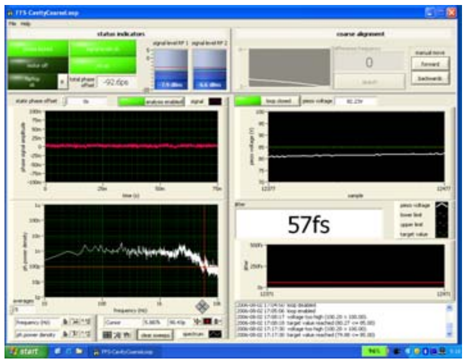
Principle of phase locking

In order to synchronise the FemtoFiber laser to the reference frequency, the pulse repetition frequency must be made available as a sine wave. This is accomplished with a photodiode and an RF filter which selects the pulse repetition frequency from the photodiode signal. The reference signal too should be turned into a sine wave if it is not already so. Both frequencies are fed into the FFS-PLL phase detector module where they are further filtered and amplified to the appropriate levels. The output of the phase detector is proportional to $\cos(2\pi f_1 t + \phi_1 - 2\pi f_2 t - \phi_2)$, i.e. the cosine of the difference between the time-dependent phases of the two waves on its input. The FFS-PLL feedback-loop module will modulate the cavity length of the FemtoFiber laser in order to steer the output of the phase detector to zero and keep it there. This implies that the frequency of the FemtoFiber laser is now the same as the reference frequency, i.e. $f_1 = f_2$, and that the phase between the two frequencies, i.e. $\phi_1 - \phi_2$, is fixed at 90 degrees. The feedback strengths of the proportional, integral and differential parts (PID) of the feedback loop are optimised to the specific reference signal. When the user applies a voltage to the RF phase input connector of the FFS-PLL phase detector module, the feedback loop will maintain the phase difference $\phi_1 - \phi_2$ at a constant value, whilst f_1 and f_2 remain equal. Like this it is possible to set the phase between the laser pulse frequency and the reference frequency to angles other than 90 degrees or to do ECOPS.



When the FemtoFiber laser is synchronised there is a constant phase difference between its pulse repetition frequency and the reference frequency.

The phase locking is supervised by a software routine on the laptop computer which is included in the FFS-PLL option. The graphical user interface displays for example the signal levels of the laser repetition frequency and the reference frequency. Also the frequency values themselves are shown. At the start of the locking procedure, the software automatically adjusts the laser repetition frequency to within the catch range of the PID feedback loop. Manual adjustment by mouse click is possible as well. The software further supervises the Piezo actuator and makes corrections with the translation stage when necessary. The rms jitter is displayed numerically as well as graphically in order to show its evolution during the experiment. The fast Fourier transform (FFT) spectrum of the jitter assists in eliminating sources of noise in the laboratory.

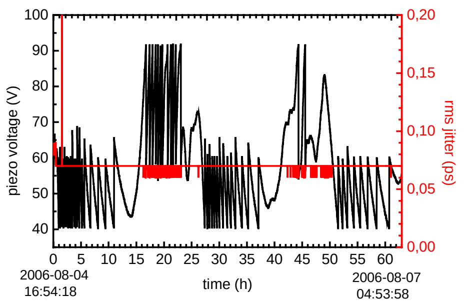


The PLL option is controlled through a graphical user interface on the laptop computer. Important diagnostic parameters are shown graphically and numerically.

Jitter

The jitter is the time difference between the desired arrival times of the laser pulses and the actual arrival times. Once the synchronisation is established, the phase detector whenever it detects a value different from the set-point, will initiate a correction to the cavity length through the process of negative feedback. Clearly the jitter cannot indefinitely be reduced to zero, since this would imply that the laser had become perfectly synchronous to the reference signal without the need for further corrections. Sooner or later the phase detector will produce a value different from zero and again initiate a correction. The phase detector is therefore also a jitter detector. For diagnostic purposes, the jitter is stored in memory every 10 microseconds (100 kHz) and every 0.1 second (10 Hz) the root-mean-square average of these numbers is calculated. The rms jitter is given in units of femtosecond with a specified range 10 Hz – 100 kHz.

The rms jitter of the synchronisation which can be achieved will depend on the intrinsic jitters of both the reference signal and the FemtoFiber laser. With intrinsic jitter is meant the deviation from a perfectly periodic signal. When the periodicity of the reference signal changes not too fast, the Piezo actuator can alter the cavity length such that the FemtoFiber laser periodicity will follow. Also the length of FemtoFiber laser cavity may unintentionally change. Again, as long as these changes are not too fast, the Piezo actuator can compensate for these. However, random variations on a time scale significantly shorter than one millisecond cannot be compensated.

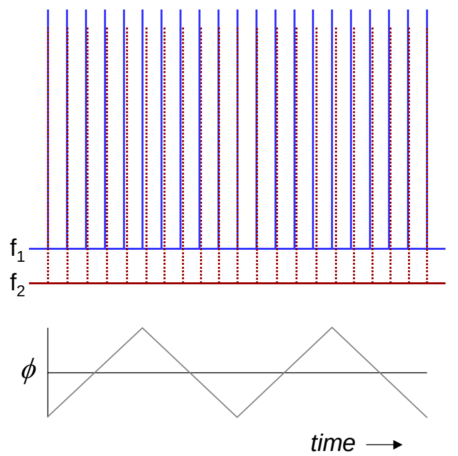


Two FFS lasers were synchronised without interruption for >60 hours. The black curve shows the voltage on the Piezo, which is kept between 40 and 90 Volts by making corrections with the translation stage when necessary. The red curve shows the rms-jitter, it had a value of app. 70 fs.

When two FemtoFiber lasers are synchronised to each other, the rms jitter as described above is smaller than 100 fs. Optical cross-correlation measurements have confirmed the correctness of this value. The same low rms jitter value is obtained with other reference frequencies when their intrinsic jitter allows it.

Pump-probe with ECOPS

Let us imagine two lasers that are being used for pump-probe spectroscopy with ECOPS. In the beginning f_1 and f_2 are both exactly 100 MHz and the pump-probe delay is zero. Then, we make the ring oscillator of the probe laser 300 nm longer (in air): f_2 = 99,999,990 Hz. This starts a pump-probe sweep. Every roundtrip the pump-probe delay increments by 1 fs. After 500,000 roundtrips (5 milliseconds) the pump-probe delay has accumulated to 500 ps. Thereafter we make the probe laser oscillator 300 nm shorter than the other oscillator: f_2 = 100,000,010 Hz . The pump-probe delay sweeps back again, until after another 5 ms the delay has returned to zero and the lasers are in sync again. Thus, by stepping between +300 and -300 nm in intervals of 5 ms, the pump-probe delay makes a triangular scan from zero to 500 ps and back.



Principle of pump and probe spectroscopy with ECOPS. In reality there will be millions of laser pulses in a sweep.

In practice, we do not measure the lengths of the cavities, but we measure and control the phase between the two repetition frequencies. So, if we apply the voltage to the phase input connector as a triangular function, the phase-locked loop takes care that the one oscillator is alternately longer and shorter than the other oscillator by tiny steps.

The actual delay between the pump and probe pulses when they arrive at the experiment can be adjusted as usual by changing the optical path lengths of the laser beams. Another method is changing the length of the cables that feed f_1 and f_2 to the PLL module.

Advantages of ECOPS

Although ECOPS eliminates the disadvantages of a moving optical delay line, fortunately it preserves the advantages. With ECOPS one can choose very slow sweeps or one can dwell at fixed delay times if one chooses. One can even change the sweep speed in the middle of a sweep: go slowly at delay times with high information content, go faster at delay times with little information. A further advantage of ECOPS is the adjustability of the sweep range. One may sweep the delay from 0 – 100 ps, but also from 0 – 10 ps, or from 0 – 1 ns. It is not even necessary to always start at zero delay. ECOPS is therefore just as flexible as a classical setup with moving optical delay line.

Specifications

FFS-SYNC	
Tuning range Piezo actuator	~ 100 Hz for 100 MHz oscillator
Resonance frequency Piezo actuator	> 5 kHz
Tuning range motorised translation stage	> 200 kHz for 100 MHz oscillator

FFS-PLL	
Rms jitter	< 100 fs (10 Hz – 100 kHz)
Delay range ECOPS	800 ps for 100 MHz oscillator or user-defined
Size electronics rack	w × h × d 355 × 132 × 360 mm^3