OPTICAL COMB AND INTERFEROMETER DEVELOPMENT FOR LASER SYNCHRONIZATION IN FEMTOSECOND FELS*

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Abstract

We describe a method of synchronizing lasers in FELs to potential sub-femtosecond precision using interferometry and optical clock techniques, and show supporting experimental results. This precision is needed for pump/probe experiments in ultrafast FELs. The proposed system consists of carrier/offset phase stabilized, pulsed lasers synchronized via a single optical frequency delivered over fiber, analogous to RF oscillators synchronized with a reference frequency, but at 200 to 400THz. Our tests of modelocked lasers, interferometers and stabilized CW lasers show that subsystems can perform to the required precision. We have synchronized fiber lasers to less than 10fs jitter using two different frequency comb line locking schemes, and demonstrated interferometers in a working FEL with less than 100as jitter over 150m fiber. Based on these tests and published work by others, we calculate the performance of an optimized, integrated timing system to be less than 1fs in the short term. Long term stability is maintained by feedback from X-ray/optical cross-correlation at the experiment.

LASER SYNC IN FEL FACILITIES

Newly developed X-ray free-electron lasers (FELs) will produce sub-femtosecond light pulses due to their high carrier frequency and large fractional bandwidth, compared with optical lasers transform limited to few-fs pulses. These FELs are typically a few hundred meters in scale. Ultrafast pump/probe experiments using these X-ray sources will require synchronization of modelocked lasers to sub-fs precision over hundreds of meters of distance. This can be achieved using recently developed techniques for controlling the optical frequency comb of modelocked lasers.

The Overall Problem

Synchronization of pump and probe signals in a large facility requires that all relevant signal paths are stable or have measured temporal delay. Besides the transmission of master clock signals to modelocked laser oscillators there are beam paths through amplifiers, beam transport optics, the FEL modulator (in the case of seeding), the FEL itself and X-ray transport to the experiment. For the purposes of this paper we assume seeding so that there is a strict temporal relationship between a modulating laser signal and the X-ray pulse.

Figure 1 shows a block diagram of a seeded FEL with synchronization between seed and experiment lasers. Different means of measuring and/or controlling the signal paths are suggested, although it remains a research topic to determine what techniques will be optimal. The aim of the current paper is to establish that synchronization of modelocked oscillators to sub-femtosecond precision is feasible given current techniques of laser frequency and time stabilization.

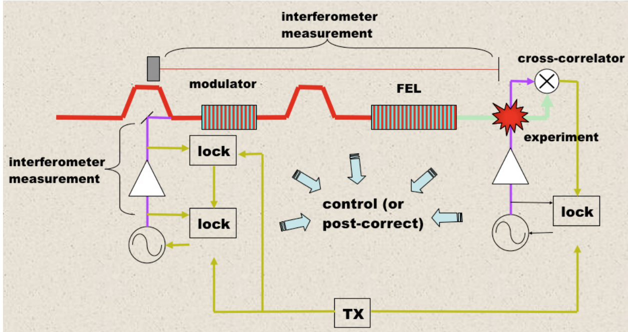

Figure 1: Temporal signal paths in a seeded FEL.

CW OPTICAL SYNC SCHEME

The proposed method of synchronizing lasers is shown in block diagram form in Fig. 2. Here, a master clock laser generates a frequency comb which provides several spectral lines which can be selected. This first comb laser may be frequency locked to an RF source which is the machine clock rate. If the master laser is a carrier/envelope phase (CEP) stabilized laser, the optical frequencies will be integer multiples of the repetition rate and thus also multiples of the RF clock. Thus, the optical frequency which will be used to temporally stabilize other modelocked oscillators is related to the original clock for the rest of the accelerator.

Synchronizing other CEP-stabilized lasers to this master laser is accomplished by transmitting a single spectral line through fiber and interfering this CW signal with the equivalent spectral line of the synchronized lasers. This fixes the frequency and phase of one line of the synchronized laser. Since the spectral line is also determined by being an integer multiple of the repetition rate, the frequency and phase of the repetition rate is therefore fixed. Equivalently, in the time domain the transmitted CW signal is interfered with the carrier of the synchronized laser. Since this carrier is fixed in phase with respect to the envelope the envelope is therefore fixed in time. Since the frequency at which the phase lock operates is hundreds of teraHertz, moderate phase error becomes a very small temporal error. All components of this system can be shown to have sub-femtosecond error.

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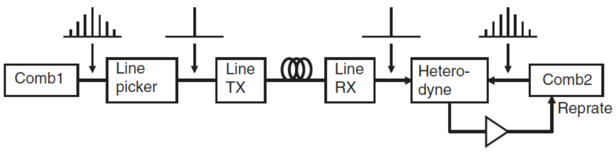

Figure 2: Synchronizing CEP-stabilized lasers by transmitting a single comb line.

SUBSYSTEMS AND MEASUREMENTS

Synchronizing Comb Lasers

The basic method of synchronizing two CEP-stabilized lasers with a CW reference has been demonstrated with titanium sapphire lasers [1]. Fiber lasers have been tested in a similar arrangement but not their temporal synchronization has not been directly measured [2]. We synchronized two Er fiber comb lasers to a CW reference at ~1550nm and measured the relative timing on a cross-correlator, as depicted in Fig. 3.

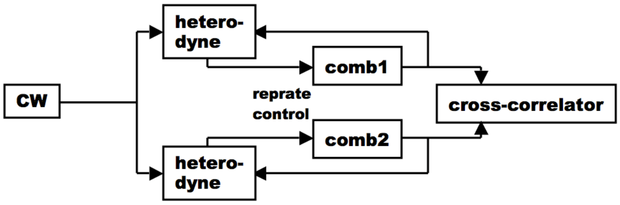

Figure 3: Oscillator synchronization experiment.

Experimental results are shown in Fig. 4 as the integrated RMS cross-correlator error versus frequency. We calibrated the cross-correlator by introducing a precise offset frequency into one laser's repetition rate, to scan relative timing. Pulse widths from the lasers were about 100fs FWHM. As shown, the jitter is 8fs, although if each laser's excess jitter is uncorrelated (which it must be to show up on the cross-correlation), the actual jitter of each laser with respect to the CW signal is less than 6fs. We expect that with ~1MHz bandwidth intracavity phase control (via EO modulator), the loop bandwidth should increase to ~100kHz, decreasing RMS jitter to ~1fs.

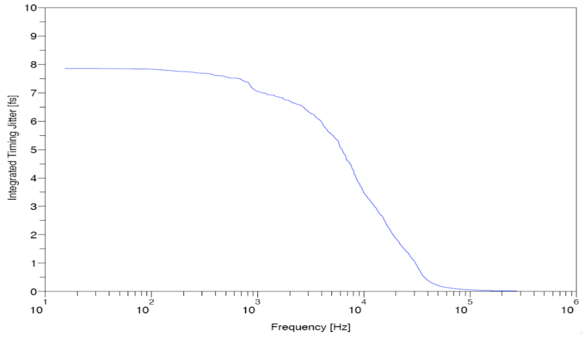

Figure 4: Oscillator Synchronization Results.

Transmitting Stable Optical Phase

To transmit the CW synchronization signal with low phase jitter, we use a scheme similar to systems designed to transmit a stable optical frequency [3]. A heterodyne Michelson interferometer maintains one arm (the transmission fiber) stable with respect to a thermally-stabilized reference arm, by changing the RF phase of the 50MHz signal driving a frequency shifter. Our scheme is unique in that the digital phase controller is located at the receiver end, thus simplifying the transmitter when multiple channels are implemented.

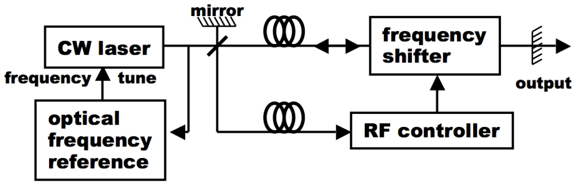

Figure 5: Interferometer for stably transmitting optical phase information.

We implemented this heterodyne interferometer in an operating FEL (LCLS), stabilizing optical phase over a 300m fiber loop. Results are shown in Fig. 6, as the integrated in-loop jitter versus frequency when the stabilization is locked (black curve) versus unlocked (gray curve). When locked, the jitter from 10Hz to 100MHz is 50as. The loop bandwidth is about 40kHz, determined by the averaging time for the digital phase controller.

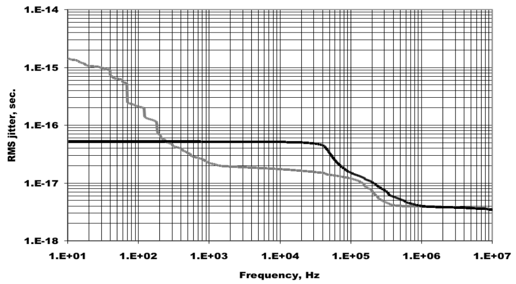

Figure 6: Integrated in-loop error for interferometer transmitting through 300m fiber. Gray trace: unlocked. Black trace: locked.

To maintain stable timing, the interferometrically stabilized optical signal must also be stable in frequency. With a CEP-stabilized optical clock, the frequencies of the optical lines are exact integer multiples of the repetition rate, which can be locked to a GPS-referenced, low noise RF source. If time stability of 0.1fs is to be maintained over 100m of fiber delay, the optical frequency stability must be better than 2x10^-10. This is well within the long term stability of stabilized RF sources, specified at 5x10^-12. In previous systems not using comb lasers, we have stabilized the optical frequency of a CW laser to a Rb reference cell, to 5x10^{-10} without difficulty.

Picking a Single Comb Line

It is necessary to select one comb line of the master laser to transmit. This is done by locking a low noise CW laser to the comb line using a phase-locked loop (PLL) with an error signal derived from the heterodyne beat between the two optical signals. We tested the scheme of Fig. 7, where one comb line is selected, transmitted via an interferometer and interfered with the original comb. Here, the CW laser is locked with an offset frequency of 20MHz with respect to the original line. Since we use a heterodyne interferometer which introduces a 50MHz frequency shift, a second frequency shifter is used to subtract this shift before the CW frequency is again interfered with the comb. Also, we speed up control of the CW phase by adding a frequency shifter after the CW. This shifter is controlled by a VCO which receives the same error signal as the piezo frequency control.

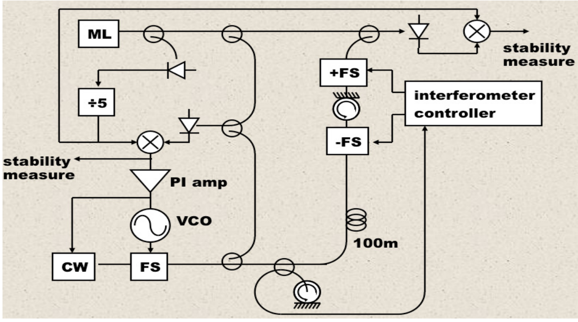

Figure 7: Line picking and transmitting experiment.

Results are shown in Fig. 8. The in-loop error of the CW lock loop is 0.95fs RMS, while the out-of-loop comparison with the original comb line is 1.0fs. Subtracting the errors yields the lower trace, which has an RMS of 0.41fs. This amount of added error is larger than that observed in the 300m experiment described above, although the uncertainty may be larger in this experiment due to lower signal levels. Still, the interferometer only contributes 5% to the overall error.

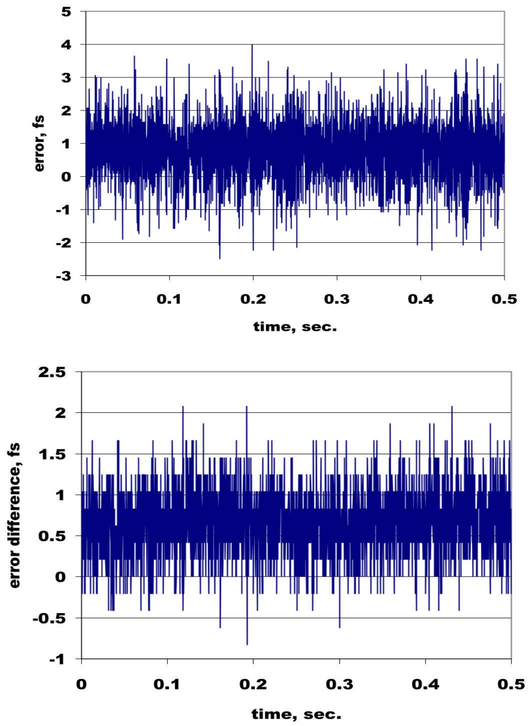

Figure 8: Line picking experiment results. First graph: in-loop error for CW laser lock loop, 0.95fs RMS. Second graph: jitter added by the interferometer, 0.41fs RMS.

ESTIMATING PERFORMANCE

It is possible to estimate the performance of a laser synchronization system like that shown Fig. 2, comprised of the sort of components described in the sections above, by adding the square of their RMS temporal errors and taking the square root. This simple estimate will not include correlated errors (such as common acoustic noise or thermal drift), and makes the assumption that the errors are normally distributed, although the error spectra are typically not Gaussian. Still, it is worth calculating the summed errors to find the contributions of different subsystems, and to determine which subsystems require the most effort.

Table 1: Estimated Performance

Subsystem	**Meas. error**	**Best pub. error**
Laser lock to CW	8fs	1fs
Line picker	1fs	53as
Interferometer	410as	50as
Opt. freq. error	250as	100as
Overall error	8fs	1fs

CONCLUSIONS

State of the art stabilized lasers, interferometers and frequency references enable the development of ultra stable laser timing. The key element needing development is the locking of the lasers to a CW signal, as the other elements are much more stable. Improvement of the laser lock is more of an engineering task than a physics one, given the performance of high stability lasers in other applications.

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