Synchronization of a femtosecond modelocked Ti:sapphire laser to the Stanford SCA/FEL

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Abstract

We have synchronized a modelocked ultrahast Ti:sapphire laser to the Stanford picosecond free electron laser (FEL) by frequency locking the lasers using a phase lock loop. The jitter between the infrared FEL and the near-ir Ti:sapphire laser has been obtained by optical cross correlation. Synchronization is typically better than 3 ps over periods of hours. We have implemented a drift correction scheme to remove long term temporal drift due to temperature changes during operation.

1. Introduction

The Stanford superconducting accelerator/free electron laser (SCA/FEL) is configured to produce radiation from 3-10 μm in 0.7-3 picosecond pulse widths with 1 μJ of energy per pulse, resulting in 0.3-1.4 MW of peak power. These peak powers in the mid-ir make the SCA/FEL an ideal pump source for studies of vibrational relaxation and dephasing in, for example, condensed phase systems or proteins [1,2]. Currently, these experiments have been performed using the FEL as a one-color tunable source, with both pump and probe restricted to the same wavelength. Obviously, the range of potential experiments would be greatly expanded if two-color pump-probe experiments could be performed with two independently tunable lasers. Such experiments require the synchronization of an external laser to the FEL. The timing jitter, over a particular bandwidth, is a measure of how well the lasers have been synchronized and effectively determines the time resolution of these two-color experiments. The timing jitter requirements are particularly demanding for pump-probe experiments since data acquisition times are often many minutes, i.e., sub-Hertz frequency measurement regime (similar requirements exist when utilizing ultrafast lasers to drive photocathodes in linear accelerators (linac)). As a prelude to such experiments we report what we believe to be the first synchronization of an FEL with an ultrafast laser with jitter of a few picoseconds, as determined by optical cross correlation measurements.

2. Synchronization scheme

The synchronization scheme is shown in block form in Fig. 1. In the SCA/FEL, the electron beam is produced by a superconducting linac that operates at 1.3 GHz, derived from a master oscillator (HP 8660C). Electron bunches repeating every 110 linac cycles (11.818 MHz) are accelerated to relativistic energies and channeled into the wiggler. These electron bunches are guided through a wiggler/optical resonator to produce coherent radiation. Because of thermal loading constraints, the cavities are pulsed on for 1-5 ms at a 10 Hz rate. Thus the laser produces a string of picosec-
FEL/Ti:S Synchronization Scheme

Fig. 1. Block diagram of the synchronization scheme. The FEL reference signal input to the Ti:S PLL is derived from the 1.3 GHz oscillator through a series of phase locked loops (FEL PLL). The Ti:S reference signal is derived optically from a special photodiode/filter amplifier inside the Ti:S laser head. These two signals are phase locked in the Ti:S PLL to provide an error signal to the PZT driven cavity mirror inside the Ti:S laser. Long term drifts which are invisible to both PLLs are corrected for by using a stepper motor driven retroreflector under computer control.

Second pulses ("micropulses") which are separated by $T_{\text{micro}} \sim 85$ ns in "macropulses" of 1–5 ms in duration which are separated by $\sim 100$ ms. The macropulse repetition rate (10 Hz) is locked to the 60 Hz line. The optical output of the wiggler is thus locked to the master oscillator of the linac, which therefore becomes available as a reference source with which to phase lock another oscillator (or laser).

A regeneratively initiated self mode-locked Ti:sapphire (Ti:S) laser (Spectra Physics Tsunami) was used as the second laser source, which provides a highly stable pulse train. For high mechanical and thermal stability, it uses a rigid Invar resonator. Since it is passively mode-locked, the laser repetition rate is determined by the cavity length. By carefully controlling the cavity length, it can be frequency locked to a reference oscillator, as demonstrated by Spence et al. [3].

An optically derived reference signal from the FEL was not possible due to the micro/macropulse structure of the FEL. However, since the FEL optical beam is phase locked to the electron beam, an electronic reference signal was obtained by phase locking an 82.7 MHz oscillator to the 7th harmonic of the 11.818 MHz input. (Reference cabling consists of $\sim 76$ m of RG-8, which runs through regions of the SCA/FEL facility which are not temperature controlled. This fact becomes important as discussed below.) The output of the FEL PLL was attenuated to 0 dBm and used as the reference signal for the Ti:S PLL electronics (Spectra Physics Model 3930). The Ti:S laser produced $\sim 80$ fs pulses at 800 nm with an output of $\sim 1$ W when pumped with 6–8 W from a Spectra Physics 2080 BeamLok argon ion laser. The ion laser had active noise cancellation circuitry (SilentLite) to minimize low frequency power-line related noise and reduce amplitude to phase noise (timing jitter) conversion in the Ti:S laser. A special photodiode and filter/amplifier inside the Ti:S laser provides the Ti:S PLL electronics with an optically derived sinusoidal reference signal.

Rough cavity length adjustment of the Ti:S laser ($\pm 1$ mm) to the FEL linac frequency is provided by a stepper motor attached to the end high reflector mirror. Fine adjustment of the cavity length ($\pm$ ca. 6 μm) is facilitated by a fold mirror in the cavity mounted on
a piezoelectric translator (PZT) which is driven in response to the error signal generated by the Ti:S laser PLL. Once the lasers are within 150 Hz of each other, the PLL is activated, frequency locking the lasers; however for alignment purposes it is more efficient to leave the lasers offset by several hundred Hertz. In this way, the laser pulses sweep by each other periodically, making optimization of the optics relatively straightforward. Once a cross correlation signal is obtained the two lasers are phase locked by activating the Ti:S PLL. After this step, it is necessary to zero the phase shift between the two lasers to zero (temporal overlap). This is done in two stages, first by changing the cable length of the Tsunami (or external) reference signal to reduce the phase shift to <2 ns. Secondly, fine control of the phase is adjusted using an electronic phase shifter inside the Ti:S PLL, which has a range of 2 ns.

The optical cross correlation was performed by sum frequency mixing of the two laser beams in LiIO₃ in a non-collinear geometry. The two beams were focussed into a 1 mm LiIO₃ type I crystal using a 25 cm f.l. CaF₂ lens. The laser beams and sum frequency signal were recollimated using a second 25 cm f.l. lens. The sum frequency signal at 670 nm was isolated by an iris and filtered using a 20 nm bandwidth interference filter centered at 670 nm. It was detected using a variable gain/bandpass Si photodiode (PD, New Focus 2001). The bandwidth of the detector was set to 30 kHz to match the bandwidth of the data acquisition electronics. Data acquisition was performed using a 100 kHz data acquisition card (Data Translation DT2812). Typically the detector output was digitized at 50 kHz. Optical delay of the Ti:S laser was provided by a galvanometer driven retroreflector (Clark ODL-150) under computer control.

3. Results

By digitizing the cross correlation signal over the entire macropulse as a function of optical delay a contour map (Fig. 2a) may be obtained showing the dynamical response of the synchronization scheme. To obtain reasonable S/N, three macropulses were averaged for a particular optical delay so that the time necessary to map out the cross correlation was about 1 minute. It is obvious that to obtain best possible performance the cross correlation should be stable both over the macropulse and relative to the optical delay.

We now examine the factors which influence the behavior of the cross correlation in this parameter space.

The contour plot shows that the lasers are very well synchronized; slices through the contour for a particular macropulse time yields cross correlations of <2 ps.
for a FEL pulse width (fwhm) of 0.8 ps (Gaussian pulse shape assumed, see below), but that the centroid of the contour (solid line) has a slew over the macro-pulse. Indeed, integration of the contour over the macropulse gives a fwhm of 6.74 ps. The presence of the phase slew indicates an undesirable trade-off between time resolution and duty factor (signal to noise) of the synchronized system.

Since the measurement took place over many macropulses the apparent phase slew is locked to the 10 Hz macropulse trigger. It remains to be seen whether the phase slew is a result of some sort of modulation of the period of the FEL optical pulse train or whether the slew occurs because of line-locked noise entering one of the phase lock loops which provides the reference signals for the generation of the PZT error signal. Both the Ti:S laser and FEL electronics have noise components which are locked to the line phase. This is verified when the FEL phase is shifted slightly relative to line phase. Fig. 2b shows the resulting contour plot. Integration as above gives a fwhm of 1.84 ps, increasing the time resolution of the apparatus by nearly a factor of four while increasing the duty factor (usable macropulse). The timing jitter is then 1.66 ps = (1.84 ps² - 0.8 ps²)¹/², about twice the FEL pulse width.

An analysis of the PZT error signal shows that the position of the centroid along the macropulse correlates primarily with noise in the reference signal from the FEL PLL. If we assume that these noise sources are the major source of broadening in the 1.84 ps cross-correlation, then we can obtain a cross-correlation free from these artifacts by using the centroid as the zero of time for integration along the macropulse. When this is done, we obtain a value of 1.45 ps, a 25% reduction in the timing jitter from the uncorrected value above.

The second parameter of interest is the stability of the cross correlation centroid with respect to the optical delay axis. This was investigated by measuring the centroid position periodically over a long time period. Cross correlations consisting of 5 scans each were taken at 0, 17, 42, and 82 minutes during which time the system was left alone. The centroid drifted monotonically at a rate of ~ 10 ps/hr (data not shown). We believe this behavior is due to length changes in the 76 meters of FEL reference coaxial cable (RG-8) resulting from ambient temperature changes. Specifications for coaxial cable designed to reduce temperature effects, such as Adams Russell FN19TX Type C, can be used to estimate a lower limit on the temperature dependent phase shift [4]. FN19TX Type C has change in the velocity of propagation of 5.5 ppm/°C from 15.5–21.1 °C. Assuming the velocity of propagation is 0.67c, we calculate a lower limit of 2.1 ps/°C phase shift for this length of cable. RG-8 is likely to have 3–5 X worse performance than this best case calculation.

To correct for this slow drift a computer controlled stepper motor driven retroreflector was put into the Ti:S beam geometry (see Fig. 1). At the end of the first scan a centroid was calculated from the raw cross correlation data and the maximum of the centroid was defined at the zero of time, t₀. Subsequent scans were treated in the same way and their centroids were compared to t₀. The retroreflector was adjusted to compensate for the movement of the centroid about t₀. The data for the scan were fitted to an adjusted timebase, assuming a linear drift given by the shift of the centroid, and averaged into the previously collected data. An example of this can be seen in Figs. 3a,b, where the optical delay was stepped at 0.084 ps per point and 19 scans were taken and averaged (approximately 5 minutes of data collection time). Fig. 3a shows a scan corrected for drift. The fwhm is 1.42 ps and the centroid (Fig. 4) shows approximately 1 ps of drift in 19 scans. In contrast, the cross correlation obtained without drift correction (Fig. 3b and Fig. 4) shows a cross correlation of 3.86 ps with the centroid having a commensurate drift. By using this method, the cross correlation nar-
Fig. 4. Position of the centroid for each individual scan taken in Figs. 3a,b. The centroids are plotted against the scan number. Slow long term drifts due to environmental influences are invisible to the PLLs and must be removed by monitoring the position of the cross correlation centroid on a scan-by-scan basis. The drift correction algorithm returns the centroid to the position measured in the first scan by moving a retroreflector via a stepper motor. With no drift correction the drift of the centroid is principally responsible for the broad cross correlation observed in Fig. 3b.

rowed approximately 25–70%, depending on the length of the scan. In spite of this, the timing jitter of \( (1.42\text{ ps}^2 - 0.9\text{ ps}^2)^{1/2} = 1.10\text{ ps} \) was slightly greater than the FEL pulse width (0.9 ps), which indicates that higher frequency components are contributing to the timing jitter.

4. Discussion

Recent theoretical work [5] on timing jitter in passively modelocked lasers predicts subpicosecond timing jitter which falls off as \( 1/f^4 \) for frequency \( f \) above a critical frequency \( f_c = 4g/3T_R\Omega_k^2 \tau \) where \( T_R \) is the pulse repetition rate, \( g \) is the saturated gain, \( \Omega_k \) is the gain bandwidth, and \( \tau \) is the pulse duration. This frequency dependence has been tested experimentally by Spence et al. using a Ti:S laser locked to the tenth harmonic of the laser cavity frequency [3]. The timing jitter was measured using a spectrum analyzer, as described by von der Linde [6]. The measurement showed the expected frequency dependence (to within their measurement signal to noise) for both unstabilized and servo loop stabilized laser cavities. In the case of the unstabilized cavity, the rms timing jitter was 3.4 ps (100–500 Hz) and 0.8 ps (500–5000 Hz). With a PLL, the jitter decreased to 150 fs (100–500 Hz) and 80 fs (500–5000 Hz). Spence et al. have synchronized two Ti:S lasers to a reference oscillator and achieved \(<0.4\text{ ps} (> 30 \text{ Hz}) \) [7]. In this case, both lasers were pumped from the same Ar+ laser and locked to the same external reference oscillator, which must play an important role in reducing timing jitter.

However, pump-probe experiments provide a much more rigorous test of timing jitter, as the timing jitter is much larger as the measurement frequency window becomes sub-Hertz (indeed, expressions for the timing jitter spectral density become singular at 0 Hz). In this light, timing jitter between the FEL and the Ti:S laser of \( \sim 2\text{ ps} \) in the \( 10^{-3}-10^{-1} \text{ Hz} \) range is rather good, especially considering the fact that these two laser systems share nothing more than a reference signal from the FEL master oscillator. Long term drift control is essential to removing phase shifts due to environmental effects. Such shifts are “invisible” to the PLL circuitry, but easily dealt with when monitoring the centroid of the cross correlation. We can expect further improvement in the timing jitter by a reduction of spurious line-locked noise introduced by the phase locked loop which locks the master oscillator to the 7th harmonic used to drive the Ti:S PLL electronics. The use of a solid-state pump laser would further reduce amplitude to phase noise in the Ti:S laser, as pointed out by Spence et al. [3].

5. Conclusions

We have successfully synchronized the SCA/FEL to a modelocked Ti:S laser with timing jitter on the order of twice the FEL pulse width, \(<2\text{ ps}\). Further refinements are possible given reduction in the amplitude noise of the Ar+ pump laser and elimination of spurious noise in the electronics. Long term drift is effectively removed by measurement and adjustment of the cross correlation centroid using a simple linear drift model. We are currently applying this new capability to the study of vibrational relaxation in various systems of interest.
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References


