SYSTEMS DESIGN CONCEPTS FOR OPTICAL SYNCHRONIZATION IN ACCELERATORS

R. B. Wilcox, J. W. Staples, LBNL, Berkeley, CA 94720, USA

Abstract

Development of accelerator-based light sources is expanding the size of femtosecond laser systems from tabletop devices up to kilometer-scale facilities. New optical techniques are needed to maintain temporal stability in these large systems. We present methods for distributing timing information over optical fiber using continuous optical waves, and how these can be employed in advanced accelerators requiring less than 100fs timing stability. Different techniques combine to form a tool set that can provide for synchronization down to a few femtoseconds. Practical examples are given for timing systems applicable to FELs now under construction, with experimental results to show these systems can be built with required performance.

TRANSMISSION FORMATS

Timing transmission systems consist of some signal to be transmitted, a fiber transmission medium, a receiver, and a delay stabilizer. There are several formats now in use for sending time information: 1) a train of short pulses, 2) an RF signal modulated onto a continuous wave (CW) laser signal, 3) optical phase information from a CW laser signal.

Pulse Trains

A train of pulses can be used to control other devices in several ways, including optical-to-electrical conversion in a photodiode (from which a harmonic series of RF frequencies is derived), cross-correlation with another train of short optical pulses (yielding a signal proportional to the temporal overlap of the pulses), electro-optic sampling of an RF signal (using the short pulses to interrogate an RF zero crossing)[1], passive optical control of a modelocked laser (using nonlinear optical effects to control pulses in the laser cavity)[2], or direct seeding of an amplifier (where the delivered pulse train is conditioned before being amplified).

RF Modulation

An RF modulated CW signal can be detected on a photodiode directly (in the case of amplitude modulation), or via an interferometer and photodiode (for frequency modulation). In this case the optical bandwidth is not fully utilized, and synchronization of below 100fs but more than 10fs is typical. However, for many applications this is sufficient, and the low cost of the detector is attractive. Figure 1 shows jitter observed on a 2.5GHz RF signal transmitted through a commercial RF-over-fiber link (Microwave Photonics). RMS jitter is 15fs from 1kHz to 40MHz, while the source itself is 12fs over the same interval. Longer term drift can be adversely affected by optical amplitude-to-phase conversion in the photodiode, although some types of detectors exhibit a nonlinear phase versus amplitude response, which can be exploited to reduce amplitude sensitivity. In addition, a simple optical power regulator can be added to make amplitude effects negligible.

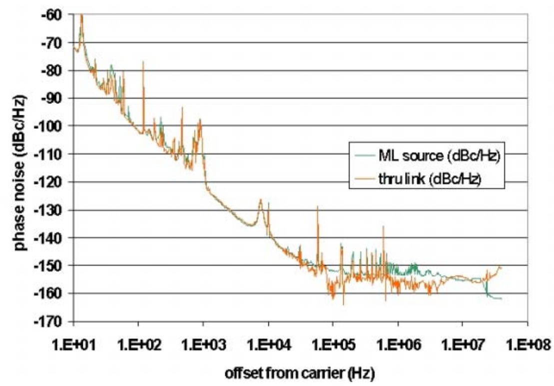

Figure 1: Phase noise of 2.5GHz source and after transmission through AM fiber link.

Amplitude modulation and photodiode detection has also been used to transmit high stability radio frequencies over long fibers. Daussy demonstrated 100MHz transmission over 86km with $3x10^{-14}$ frequency stability, integrated for one second [3].

Optical Phase Transmission

An unmodulated carrier can transmit time information using only the optical phase (analogous to RF transmission via waveguides at much lower frequencies) which can be detected interferometrically. These signals can be used to control timing of modelocked lasers. One method is to first stabilize the envelope of the laser pulse train with respect to the optical carrier, such that the phase of the carrier within each pulse is determined. A single optical frequency can then be interfered with the carrier, yielding a beat signal that can be used to stabilize their relative phase. The phase of the carrier and the pulse repetition rate are thus locked to the phase of a CW optical signal. Two modelocked lasers can be synchronized by being locked to the same CW signal, as in the work of Bartels et al [4], demonstrating sub-femtosecond synchronization of two titanium sapphire lasers.

Another way to use optical phase to synchronize modelocked lasers is to compare two frequencies in their respective "combs." The Fourier transform of a train of optical pulses is a series of discrete frequencies separated by the repetition rate. If one can specify the phase of two frequencies in this comb, one can fix all other features such as the phase of the repetition rate, which is the timing of the pulses. Thus, if two combs from two lasers are compared at two widely spaced frequencies, information about their relative timing can be derived and used to synchronize them. In figure 2, two CW lasers are interferometrically compared with two frequencies in the comb emitted by a modelocked laser at left. The CW frequencies are locked to their respective comb lines, and are then transmitted to a receiver. There, the CW frequencies are compared with the comb lines of the laser to be synchronized. Mixing first optically then electronically, an error signal proportional to the difference in repetition rate phase is derived, and used to control the second laser. Phase coherence from transmitter to receiver is maintained with an interferometer as described below.

Figure 2: Two-frequency laser synchronization scheme. ML=modelocked laser. CW=CW laser.

A simplified experiment has been done to test the concept [5], where parts of the combs of two lasers are selected by 0.8nm bandpass filters, separated by 40nm. The lasers were adjacent and separated by only a few meters of fiber, with synchronization observed on a cross-correlator. Short term jitter was 6fs RMS, as shown in figure 3.

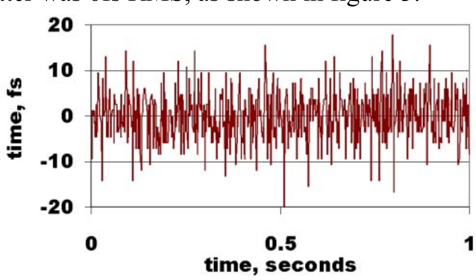

Figure 3: Relative timing jitter of two lasers synched with two-frequency scheme.

DELAY STABILIZATION

Perturbations of time delay through the transmission fiber due to temperature and mechanical vibration need to be counteracted by a control system which monitors the delay. If timing information is transmitted as an envelope modulating an optical carrier (as with pulses or modulated CW), the group delay through the fiber must be stabilized. The transmitted signal is retroreflected from the receiver back to the transmitter, where a timing detector monitors the roundtrip delay and applies a correction to the optical path length or by electronically controlling the phase of the transmitted signal.

Pulse Trains

Using photodiode detection of the pulse train, Hudson synchronizes modelocked lasers over 7km of fiber to 19fs RMS from 1Hz to 50MHz [6]. Kim demonstrates a cross-correlation delay detection scheme, stabilizing 310m of fiber to 9.7fs RMS over 100 seconds [7].

RF Modulation

Frisch uses retroreflected amplitude modulation at 11.4GHz to stabilize short term jitter to 46fs, in a 15km fiber [8].

Phase Stabilization

Transmission of phase information of a single optical frequency can be stabilized using interferometry. A frequency-shifting Michelson interferometer is typically used, which interferes a shifted, retroreflected signal with a stable reference. The CW laser must have long coherence length and good absolute stability, derived from a molecular or atomic absorption line. We have demonstrated an interferometric stabilizer with 0.25fs RMS jitter and 4fs p-p drift over 10 hours (phase translated to time), through 3km of fiber, 2km of which was ordinary LAN fiber around the Berkeley lab site [9]. The laser frequency was controlled to less than a part in 10^9 by locking to a molecular absorption line in acetylene. Similar short term jitter results have been achieved by Coddington [10] and Grosche [11]. Shillue transmits RF by beating two CW frequencies, and stabilizes resultant 20GHz phase to 41fs RMS over 10km of fiber [12].

It is possible to stabilize group delay of RF transmitted over fiber by detecting changes in phase delay. The main long term perturbation of fiber delay is temperature, with temperature coefficients of the group and phase indices differing by about 1.6%. Using the interferometric phase controller described above, we can measure the total correction applied to maintain constant phase as the fiber changes temperature. Feeding forward a 1.6% correction to either the fiber length or the RF phase, the group delay can be stabilized. Figure 4 shows results of measuring the error in group delay (RF phase) as phase delay through a 2km LAN fiber is held constant. A correction for thermal coefficients is added to the data (along with a constant drift correction for the RF oscillator aging) to produce the orange trace, simulating a feedforward corrector. With 95ps of phase correction over one day, group delay can be stabilized to 36fs RMS.

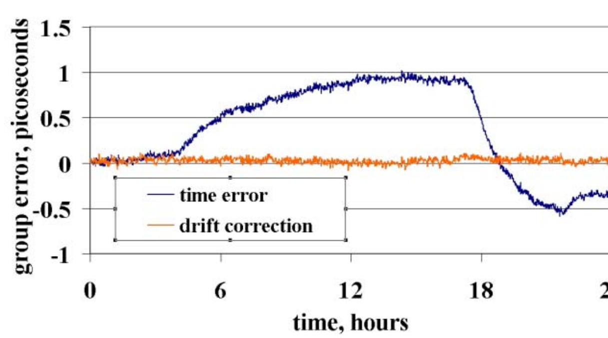

Figure 4: Group delay error of phase stabilized fiber (blue) and calculated with correction factor (orange).

CONNECTING DIFFERENT SYNCH METHODS

The transmission and synchronization devices described above can be considered as transducers between different modes of encoding time information. Depending on the device to be synchronized, different methods can be chosen for transmission and reception, as shown in table 1.

Table 1: Matrix of connections between timing devices.

From\To	RF	Pulsed laser
RF	AM or FM of CW laser	High harmonic (RF)over fiber
Pulsed laser	Diode detection/high harmonic Electro-optic sampling	Cross-correlation Direct transmission Passive optical lock
CW laser	Optical synthesis (difference frequency)	One frequency comb lock Two-frequency comb lock

For instance, an RF transmission system using amplitude modulated CW light can control pulsed laser timing by phase locking a high harmonic of the laser repetition rate (as detected by a photodiode). Conversely, a transmitted pulse train from a laser can synchronize RF through diode detection or electro-optic sampling. This “mix and match” approach allows flexibility, and optimization of the system for cost, performance, control or interface reasons.

Example Synchronization System

An example of the application of flexibility in system design is the timing and synch system for Fermi@Elettra. As shown in figure 5, a master RF clock provides a long-term stable frequency, while a pulsed laser phase locked to the clock stabilizes short term jitter. RF signals derived from the clock are used to modulate a CW laser, and transmit RF signals via fiber to low level RF systems. These control the phase of all the accelerating cavities and other devices needing stabilized RF. Time delay is stabilized in the RF transmission system using interferometric phase detection and adding a correction for group delay.

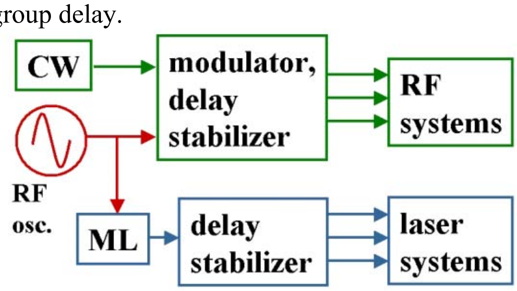

Figure 5: Interconnection of RF and laser sources in Fermi synch system.

At the same time, pulses from the master modelocked laser are transmitted via fiber throughout the facility, to either synchronize lasers at various points or deliver optical pulses to be used as a seed for laser amplifiers. Transmission time delay is stabilized by detecting retroreflected pulses using a cross-correlator. An advantage of transmitting pulses is that they can be used as optical signals directly, rather than just timing marks. When so used, the dispersion due to propagation through the fiber must be adequately cancelled.

These two systems are both stabilized to a common reference, and remain synchronized with each other despite differences in modulation format and delay stabilization. The pulse transmission system is expected to deliver sub-10fs stability, while the RF system will deliver sub-100fs stability, per spec. There are more RF clients in the system than optical ones, but the RF receivers are less expensive. The relative advantages and tradeoffs in this synch system allow the design to reflect the strengths of each synchronization method.

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