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This work was supported by the Director, Office of Science, Office of Fusion Energy Sciences, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

Locking Lasers to RF in an Ultrafast FEL

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Abstract: Using a novel, phase-stabilized RF-over-fiber scheme, we transmit 3GHz over 300m with 27fs RMS error in 250kHz bandwidth over 12 hours, and phase lock a laser to enable ultrafast pump-probe experiments.

OCIS codes: (060.2360) Fiber optics links and subsystems; (060.5625) Radio frequency photonics

Free-electron lasers (FELs) are capable of producing short-duration (<10fs), high-energy X-ray pulses for a range of scientific applications. The recently activated Linac Coherent Light Source (LCLS) FEL facility at SLAC will support experiments which require synchronized light pulses for pump-probe schemes. We developed and operated a fiber optic RF transmission system to synchronize lasers to the emitted X-ray pulses, which was used to enable the first pump-probe experiments at the LCLS.

The principles of the fiber timing system have been previously described in detail [1]. Referring to figure 1, an RF signal input to the transmitter at 2856MHz is amplitude modulated onto a CW laser signal, which is then photodetected at the receivers. We have shown that these LBNL-developed, low-noise digital RF phase detectors can compare two signals at this frequency with 15fs RMS uncertainty in 250kHz bandwidth, or <5fs uncertainty in 2kHz bandwidth. In order to compensate for drifts in timing due to the fiber's temperature coefficient of delay, the optical phase delay through the fiber is sensed via a heterodyne interferometer using the carrier of the modulated CW signal [2]. The two arms of this Michelson interferometer are the transmission fiber 1 in the figure, and a short, temperature-controlled arm local to the transmitter, both terminated in Faraday mirrors. The CW laser oscillator is frequency locked to a saturated absorption line in rubidium in order to achieve the needed stability [3]. Information from the interferometer is returned to the receiver via fiber 2, and is used to electronically correct phase errors in the received RF due to changes in fiber delay. In this feedforward compensation, the difference between the temperature coefficient of group and phase delay [4] is taken into account, using a concept different from that of reference 2. All delay correction is applied in software after the incoming RF signal is digitized. This allows the laser timing to be digitally controlled, rather than using optical trombone delays for coarse timing. To add channels, a splitter is put into the temperature controlled box, after the amplifier in the transmitter (triangle in the figure), and all parts to the right are multiplied.

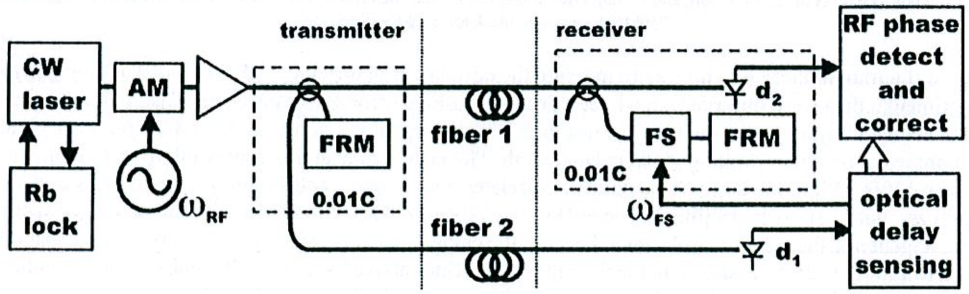

Figure 1. One channel of the RF transmission system. AM: amplitude modulator. FS: frequency shifter. FRM: Faraday rotator mirror. Dotted lines indicate boxes temperature controlled to 0.01 degree.

To test the system, both receivers were placed next to each other. One receiver tuned a low-noise voltage-controlled oscillator (VCO) which was phase locked to the reference signal from the transmitter propagated through 300m loop of installed fiber. The VCO was controlled using the receiver error signal averaged over 0.5ms (2kHz bandwidth). The other receiver compared the output of the VCO with the transmitted reference (over 2m of fiber), and the output of this receiver was the data shown in figure 2. Over 12 hours, the RMS variation was 16fs in 2kHz bandwidth, with 13fs uncertainty over shorter periods. In 250kHz bandwidth, the RMS variation is 27fs, indicating the noise power drops rapidly with frequency. The 30fs peak-to-peak long term drift is probably due to a 1m (5ns delay) coaxial cable connecting the two receivers. Temperature fluctuations in the room were around 1 degree C peak-to-peak, predicting 50fs delay change, which is close to what is observed. The drift also correlates with the delay correction of the short fiber arm in the same thermal environment as the coax cable.

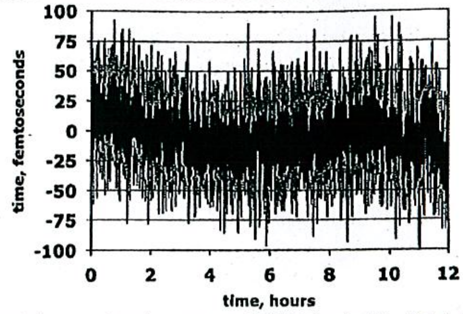

Figure 2. Results of RF transmission test. Data in gray are at 250kHz bandwidth. Data in black are at 2kHz bandwidth.

The timing system was reconfigured into the final arrangement shown in figure 3. Here, an RF signal from an electron bunch arrival monitor is used as the master clock, since this is synchronized with the X-ray pulses from the FEL. The phase-locked loop on the left of the transmitter locks the transmitted reference signal to the RF input from the master clock. The phase locked loop on the right of the transmitter locks the laser to the transmitted reference. The laser is a commercial titanium sapphire oscillator, producing pulses that are subsequently amplified and sent to the experiment. The 68MHz pulse train from the oscillator is photodetected and bandpass filtered to provide a 2856MHz RF signal to the receiver phase comparator.

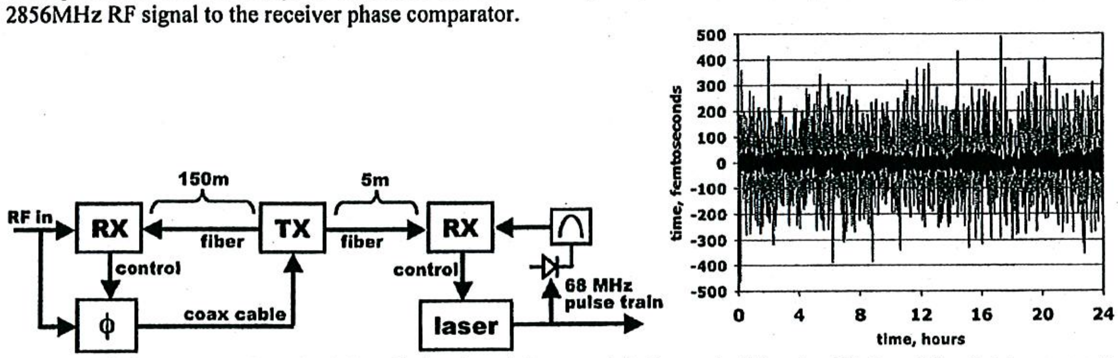

Figure 3. Timing system configuration, left, and in-loop laser timing error, right. Box marked ϕ is an I and Q phase shifter. Data in gray are at 250kHz bandwidth, black are at 2kHz bandwidth.

With this configuration, there was no way to measure the correlation between two channels of the timing system until experimental data were observed, so we recorded only in-loop error signal measurements to monitor timing. Results are shown in figure 3, for the laser control loop. The RF signal is sampled at 87.5MHz, but must be averaged to extract phase data, with a resulting 250kHz bandwidth. The error signal at this bandwidth over 24 hours is shown in gray, with 120fs RMS uncertainty. This number correlates with single-sideband noise spectra measured using a signal analyzer, with ~100fs RMS jitter between 1kHz and 10MHz. The error signal is further averaged with 2kHz bandwidth to generate the laser control signal, because the cavity control bandwidth is ~800Hz. At this bandwidth the RMS uncertainty is 25fs, as shown in black in the graph. Jitter above 2kHz could be due to a noisy pump laser, and to acoustic perturbations which can be attenuated with sound and vibration absorbers.

This work was supported by the U.S. Department of Energy under contract DE-AC02-05CH11231.

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