Letter of Intent:

Optical fiber distribution of Radio Frequencies to remote locations with tens of femtoseconds of timing jitter.

Team Members

1. **Jun Ye, Dr**
   JILA, University of Colorado and NIST
   Box 440 UCB Boulder CO 80309-0440
   Ph 303 735 3171
   Fax 303 492 5235
   ye@jila.colorado.edu

2. **Mark Notcutt, Dr**
   As above
   Ph 303 492 0667
   notcutt@jilau1.colorado.edu

3. **Kevin Holman, Mr**
   As above
   Ph 303 492 0667
   kevin.holman@colorado.edu

4. **David J Jones, Dr**
   Department of Physics and Astronomy
   University of British Columbia
   6224 Agricultural Rd
   Vancouver BC V6T 1Z1
   Canada
   Ph 604 822 2754
   Fax 604 822 5324
   djjones@physics.ubc.ca

Motivation

Precision timing is of paramount importance to the next generation advanced light sources. In particular, in order to fully utilize the projected performance of the LCLS and realize femtosecond resolution in experimental investigations, tight synchronization of the X-ray pulse with endstation pump/probe lasers is required. Moreover, reducing the timing jitter will also improve the performance of the accelerator itself by possibly assisting in shortening the generated X-ray pulse. Present jitter in existing systems is ~1 ps. With future X-ray pulse lengths of ~250 fs and possibly significantly less, improving the technology of timing transfer to the level of tens of fs or less is essential.

Description of Proposed Research

Introduction/Background

We propose to develop an optical fiber-based RF distribution system based on a mode-locked (ML) laser. The pulse repetition rate of the ML laser will serve as the oscillator with a high harmonic of the laser's repetition rate equal to the standard LCLS clock frequency of 2.8 GHz. Output from the ML laser will be distributed to multiple locations up to a distance of 1500 m (and further if needed) through an optical fiber network. Low timing jitter will be achieved with precise feedback control of the group delay between the master oscillator and remote node(s). The phase error accumulated in the fiber network along the path length(s) of interest will be servo controlled to the noise floor of the detection system. Methods of improving the discrimination of the detection and stabilization system will be investigated while simultaneously seeking to minimize the system complexity. This system would serve as the basis of a high precision timing distribution system and be able to synchronize critical parts of LCLS (seed lasers, linacs, beamline endstation pump/probe lasers, etc) in order to obtain ~10 fs of timing jitter between the electron bunch, x-ray pulse and pump/probe lasers.

There are three critical components of the high precision timing system: spectral purity of the master clock, detection and minimization of noise added during propagation through the fiber network and the measurement of the timing signal itself, and synchronization of lasers to the clock signal. Our proposed work will address all of these aspects.

Current Results

Frequency Transfer through optical fiber:

The transfer of an (unmodulated) optical carrier over a fiber with milliHerz error was demonstrated by Ma et al [1], and is routinely used in laboratories for the transfer of optical frequency standards. The transfer of timing signals with RF amplitude modulation of an optical carrier (with two way transfer and feedback to stabilize the optical path) has been implemented over 16 km at JPL and Goldstone [2] (Allan deviation of ~3 $10^{-14}/\sqrt{\tau}$) and between Phoenix and Tuscon [3] with 0.5 ps RMS jitter (the bandwidth of this signal is not stated, probably 10 s averaging time). The time constants of the controllers for both these was 10 s or greater. Ye and Peng [4] stabilized the optical path length of a 6.9 km fiber between JILA and NIST for the simultaneous measurement of the frequency of an Iodine-stabilized Nd:YAG in the two laboratories and later the transfer of a maser-derived RF sinusoidal amplitude modulation (without control of the fiber group delay).

Holman [5] has recently demonstrated that the transfer of RF signals is more accurately done by using a modelocked laser. This system has the benefits of having very low phase noise as an oscillator, high signal to noise ratio of the detected RF harmonics, and (in the time domain) steep pulse flanks for triggering. Results for passive transfer across 6.9 km of installed fiber connecting JILA with NIST Boulder Labs using a mode-locked pulse train were an Allan deviation of 3 10^{-14} at 1s and an integrated jitter of 1 ps in a bandwidth of 25 MHz, 300 fs in 100 kHz. These experiments used a 1550 nm modelocked fiber laser with 100 fs pulse width and a 100 MHz repetition rate. It was found that pulse broadening was responsible for severely degrading the performance [5]. In recent experiments the ML fiber laser pulses have been transmitted down a 4 km spool of zero-dispersion fiber, with a jitter of 100 fs when integrated to a Fourier frequency of 10 MHz. A diagram of the experiment is shown below. Active control of the group delay of the

4 km long zero dispersion fiber has been demonstrated with a loudspeaker coil actuator, giving a reduction in the phase noise of > 20 in a bandwidth of 10 Hz. Experiments in progress will increase this bandwidth to tens of kHz, reducing the phase noise of the propagated pulse to the noise floor of the measurement system.

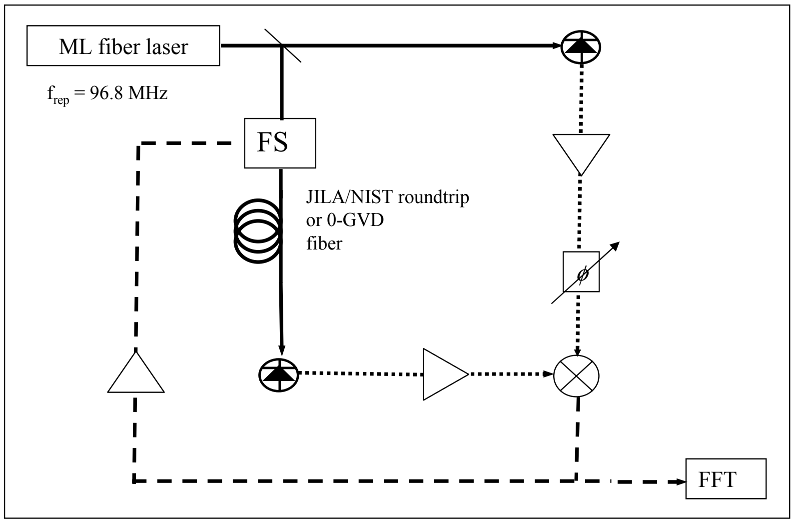

Figure 1. Schematic of the experiment: FS – fiber stretcher, FFT – Fast Fourier Transform.

Synchronization of femtosecond lasers:

Shelton [6] synchronized two Ti:sapphire femtosecond lasers with residual jitter of 0.6 fs in 160 Hz bandwidth and 1.8 fs in a 2 MHz bandwidth, using a mixer to detect the RF signals for servo control and optical cross correlation as an out of loop measurement to confirm the jitter performance. An actively mode-locked diode laser [7] and a passively mode-locked Er/Yb waveguide laser [8] (both at 1550nm) were synchronized with a Ti:Sapphire ML laser that was locked to a Iodine-based optical frequency standard and an external 6 GHz source, respectively. Results were 22 fs jitter in 100 MHz and 14 fs jitter in 375 MHz.

Proposed Work

The experimental program we are proposing aims to investigate the limits of the present experimental arrangement by extending the transmission distance and improving the S/N of the detection process. The ML optical fiber transfer experiment will also profit from developments in other ongoing laboratory experiments in the Ye and Jones labs such as the synchronization of two Ti:sapphire lasers for the generation of an ultra-wideband comb. A second goal is to increase the robustness of the system, so that it operates stably, with timing transfer over greater distances over extended time periods.

We propose the following set of experiments. Initially, work (in parallel) will concentrate on objectives 1 and 2, before moving on to items 3-5. Objectives 6 and 7 consist of more long term goals and will be pursued following completion of work on the earlier topics:

1. Turnkey, commercial passively mode-locked sources at 1550 nm will be evaluated for use as the oscillator for this experiment. Potential candidates that will be tested include an Er/Yb glass laser and a variety of mode-locked fiber lasers.

2. Extend the zero dispersion fiber experiment to a 6.9 km (round trip) length of fiber installed between JILA and NIST in Boulder. The fiber will have a dispersion compensated length added to minimize pulse spreading of the detected pulse to optimize S/N to ~ 80 dB in a 1 kHz bandwidth. Fiber stretchers will be used to control the group delay with a unity gain bandwidth of ~ 20 kHz, and faster actuators can be added as needed. The expected performance of this system can be estimated from the noise floor of the detection system with the reasonable assumption that the feedback system has sufficient gain. The noise floor has been measured by replacing the installed (or zero gvd) fiber with a short length that contributes insignificant phase noise and taking an open loop measurement. Integrating this noise floor one could expect timing jitter of ~ 10 fs in a bandwidth of 10 kHz and 100 fs up to 10 MHz, with detection at 8 GHz.

3. Optimal signal to noise in the present experiment occurs for photodetector powers of ~ 30 μW. The reason for this optimum is not yet understood, and amplitude to phase conversions are thought to be a candidate. This will be investigated with intensity stabilization of the power from the ML laser. Higher incident powers without AM/PM conversion would improve the S/N of the discriminator leading to lower jitter.

4. In the ML laser synchronization experiments of Shelton [6], sub femtosecond jitter was achieved in a 160 Hz bandwidth (14 GHz detection) with the signal/noise amplifier limited. A development of this experiment aims to reduce the timing jitter by a factor 10 by using custom lower noise amplifiers due for delivery soon. This technology will be implemented in the fiber ML detection system to bring the timing jitter of pulses transferred over the fiber network to 1 fs in a bandwidth of 300 kHz. In addition to the stabilization of group delay, this system will transfer the optical carrier with a stability of ~ 10^{-15} and below.

5. By deriving the error signal from an optical cross-correlation of the reference and measured pulses, many more harmonics of the repetition rate contribute to the signal and excess noise in the generation of the RF can be avoided [9]. We also plan to investigate alternate (and simpler) all-optical techniques in order to minimize the measurement noise floor and maximize the timing error sensitivity.

6. Testing of the long term reliability of servo loops employed to stabilize the path lengths of the fiber networks. Redundant feedback systems will be investigated for failsafe operation.

7. The output of the fiber laser will be broadened in highly non-linear fiber to produce an octave-spanning comb, allowing f_{ceo} (carrier/envelope offset frequency) to be detected and servo locked to a stable RF signal. An appropriate comb line will be phase locked to a narrow linewidth laser, for example at 1064 nm [10], which should produce an RF signal of exceptional spectral purity [9]. To ensure long-term stability, the repetition rate of the comb can be referenced to a crystal oscillator with feedback to an AOM in the cavity feedback path or pzt control of the cavity spacer length.

In summary, the timing jitter already demonstrated in fiber transfer experiments should result in jitter at the 50 fs level for bandwidths of 1 MHz. Synchronization experiments have demonstrated jitter of 2 fs in comparable bandwidths, and with custom amplifiers we expect the jitter to be improved by >10dB. The improvement of the S/N in the fiber transfer experiments to the levels of the synchronization experiments should improve the jitter of the transfer to the few fs level.

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