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# A FEMTOSECOND-LEVEL FIBER-OPTICS TIMING DISTRIBUTION SYSTEM USING FREQUENCY-OFFSET INTERFEROMETRY\*

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## Abstract

An optical fiber-based frequency and timing distribution system based on the principle of heterodyne interferometry has been in development at LBNL for several years. The fiber drift corrector has evolved from an RF-based to an optical-based system, from mechanical correctors (piezo and optical trombone) to fully electronic, and the electronics from analog to fully digital, all using inexpensive off-the-shelf commodity fiber components. Short-term optical phase jitter and long-term phase drift are both in the femtosecond range over distribution paths of 2 km or more.

## Future Accelerator Timing Requirements

The next generation of accelerators, spread over an area measured in kilometers, will require femtosecond-level synchronization of RF cavities, lasers, photoinjectors and diagnostic devices. Phase-stabilized optical fiber is well-suited for this, along with its immunity to electrical interference, gigaHertz bandwidth, low loss and easy installation in wireways.

Commodity-level single-mode glass fiber, such as Corning SMF-28, optimized for 1300-1550 nm wavelength, exhibits about the same phase velocity dependence on temperature as copper, although the mechanism is temperature dependence of the glass dielectric constant. All fiber components used are inexpensive off-the-shelf devices developed for the telecommunications industry.

The stabilization system developed at LBNL uses the technique of frequency-offset interferometry.

As shown in Figure 1, the optical output of a 1550 nm CW laser is split between the short arm of a Michelson interferometer and the long fiber to a remote receiver. The short arm of the interferometer is temperature-controlled to a variation of less than 0.01 C. At the end of the long fiber arm, an acousto-optical modulator (AOM) excited at 50 MHz up-shifts the 195 THz laser frequency by 50 MHz, where it is then reflected by a 50% Faraday rotator mirror. The shift of the laser frequency is phase coherent with the 50 MHz RF drive of the AOM. The reflected laser signal is again upshifted by 50 MHz by its return passage through the AOM, resulting in a 100 MHz total frequency shift where it returns along the long fiber, and combines with a sample of the original laser frequency from the interferometer short arm in the splitter.

The variation of the phase length of the fiber is phase coherent to the phase variation of the 100 MHz upshifted return signal. The original laser frequency, from the short

arm and the upshifted laser frequency are transmitted along a second fiber, the error signal fiber, to a photodiode at the stabilizer where they produce a 100 MHz beat note which is compared to the 100 MHz reference oscillator. Any change in the phase length of the long fiber is reflected in a phase shift of the 50 MHz signal to the AOM, derived from the 100 MHz reference oscillator, which adds or subtracts the same number of optical cycles in the AOM. The resulting error signal is integrated, the integral representing the change of phase length of the fiber, which shifts the phase of the 50 MHz drive signal to the AOM. All these functions are combined in a single chip field-programmable gate array (FPGA) controller.

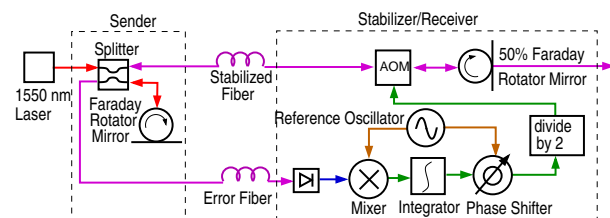


Figure 1: Frequency-Offset Stabilizer Configuration

The fiber that carries the error signal to the stabilizer needs no stabilization itself, as it is providing optical phase information down-converted to 100 MHz. The 100 MHz beat note is phase-coherent with changes in optical phase in the stabilized fiber, but the frequency ratio of 195 THz (1550 nm wavelength) and 100 MHz is  $2 \times 10^6$ , so a 1 nanosecond change in the error signal fiber produces an error of only 0.5 femtosecond to the correction.

In previous implementations of the stabilizer, the AOM phase was fixed, and mechanical phase shifters (piezo and motor-driven optical trombone) were placed in series with the stabilized fiber. These suffered from a finite range of correction and the usual problems with devices using moving parts. The transition to an all-electronic system significantly simplified the system with a smaller parts count, essentially unlimited range of correction, and increased reliability.

The frequency reference for the system is the 195 THz laser frequency itself, which must be stabilized to 1 part in  $10^9$  for the system to provide 1 femtosecond stability with variations of the long fiber of 1 nanosecond. The CW laser is stabilized by taking a sample of the laser, doubling its frequency, and locking it to a saturated absorption line in a Rubidium cell using a Pound-Drever-Hall (PDH) [2] stabilizer configuration. To verify its operation, two independent PDH-stabilized 1550 nm lasers were beat against each other with measured drifts in the 200 kHz range.

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To measure the effectiveness of the stabilizer itself, two independent stabilizers were built, operating from a common laser, and the out-of-loop optical beat note measured between the outputs of the 50% Faraday mirrors at the far end of the long fibers of the independent stabilizers. The AOMs may operate by shifting the laser light either upward or downward, so one channel has an up-shifting AOM and the other uses a down-shifting AOM, giving a 100 MHz difference in the laser light between the two channels (the one-way shift in each channel is up or down 50 MHz). The resultant difference in optical frequency of the laser light exiting each of the 50% Faraday mirrors in the independently stabilized channels is then compared directly to the 100 MHz reference oscillator and represents the residual differential optical phase error between the two channels.

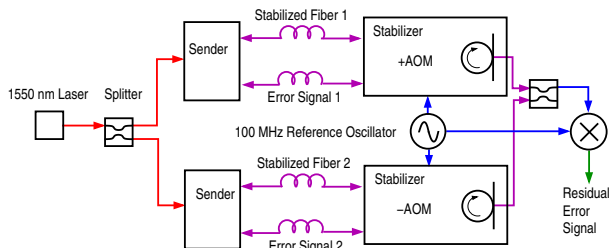


Figure 2: Two independent channels with out-of-loop monitor.

We tested the stabilizer performance in two venues: the long fiber at LBNL is a 2 km loop, part of the LBNL data network backbone which runs under roads and through several buildings, and a 2.8 km fiber loop in the SLAC klystron gallery, exposed to full ambient temperature variation and the acoustic perturbation of the klystron modulators. Measurement were taken with a stabilized reference short fiber in one channel and the long fiber in the other. Figure 2 shows a block diagram of the differential phase measurement setup, with a long fiber in channel 1 and a short fiber in the channel 2. Figure 3 shows the results for a 232 hour data run of the 2.8 km fiber in the SLAC klystron gallery. The black trace shows the phase length change of the gallery fiber, 2184 picoseconds peak-to-peak due to diurnal temperature variation, and the red trace is the residual error after correction, drifting 31.5 femtoseconds in 232 hours, or less than 0.14 fsec per hour. The p-p short-term jitter is less than 2 femtoseconds.

Figure 4 shows the noise spectrum on the stabilized klystron gallery fiber, measured on the 50 MHz drive to the AOM, from 10 Hz to 100 KHz with the loop open (red) and closed (black). The noise suppression at 10 Hz is 60 dB. The feedback loop consists of a simple integrator with a  $1/f$  gain curve. As the correction is phase-coherent to the optical frequency, the integration of the power spectrum from 10 Hz to 1 MHz gives an rms jitter of the optical carrier of 0.95 femtosecond.

Fiber Transit Time Variation (psec) and Differential Error Timing (fsec)

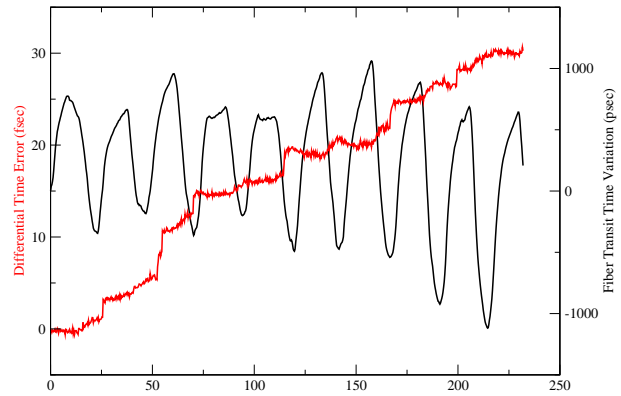


Figure 3: 2.8 km SLAC klystron gallery phase variation (black trace, right-hand scale), and residual error after correction (red trace, left-hand scale) for a 232 hour data run.

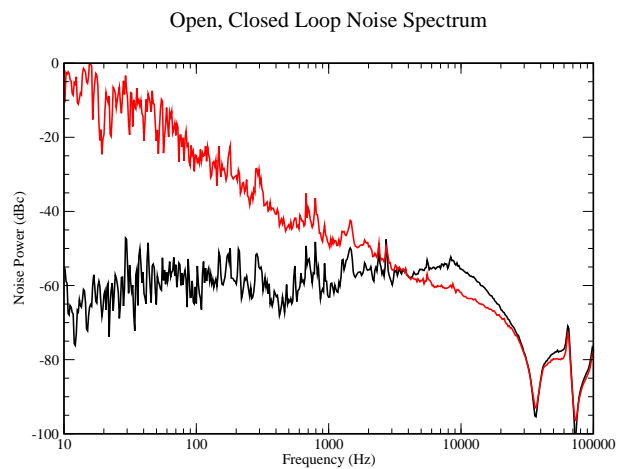


Figure 4: Loop noise with control loop open (red) and closed (black).

### Group-Phase Velocity Correlation

The system corrects the *phase* variation of the fiber. To transmit a stabilized RF signal, the *group* velocity must also be stabilized. There is a monotonic relationship between the two, which is experimentally determined. This requires the modulation of the laser by RF, recovery of the RF at the far end of the fiber with a photodiode and measuring the group velocity variation, and comparing it to the optical phase velocity variation of the fiber. The optical level to the photodiode is set to the level that minimizes the phase-amplitude characteristic of the photodiode itself. The ratio of group velocity to phase velocity variation of the fiber due to temperature variation is approximately 1.02.

### Stabilized RF Phase Detectors

To maintain better than 10 femtosecond stability in the RF domain, phase detectors operating at S-band (2856

MHz) must have a stability of better than 0.01 degrees. In a configuration where RF is transmitted over a stabilized fiber, closed-loop controllers will include high-precision phase detectors operating in the RF domain. This requires active stabilization of the RF phase detector itself.

To maintain the high precision offered by stabilization in the optical domain, a technique that continually injects a calibration signal into the RF circuits is used [4]. As this is a CW rather than a pulsed RF transmission system, a double-sideband suppressed-carrier (DSSC) calibrate signal is injected into the RF chain, immediately following the RF recovery photodiode and carried through the entire RF closed-loop phase corrector. The frequency offset of the sidebands in an S-band system is on the order of 1 MHz.

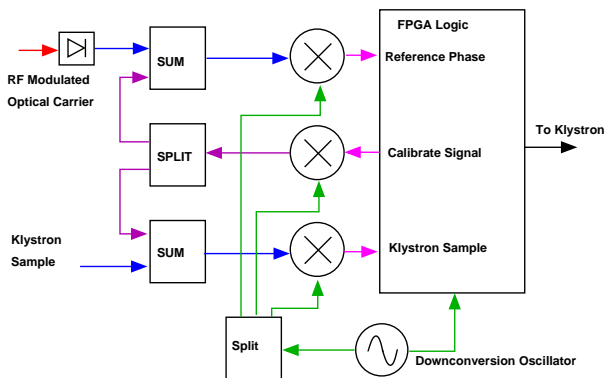


Figure 5: Phase detectors stabilized by injection of a DSSC calibrate signal.

Figure 5 shows an example where a stabilized fiber link carries an S-band modulated carrier to a photodiode, which recovers the S-band phase reference signal. The system's goal is to use the phase of that reference to stabilize the phase of the cavity field, and the feedback actuator is the phase of a klystron drive signal. The FPGA generates a DSSC signal and injects it as close to the photodiode and the cavity sensor as possible. All phase shifts (including those that vary with temperature) in the components after the summing junctions will apply equally to the reference and calibration signals, and can therefore be detected and corrected digitally by the FPGA. The downconversion mixers convert S-band signals to 50 MHz that are digitized by the FPGA circuit board.

### Modulation-Demodulation Noise Performance

The additional noise generated by the modulation-demodulation process of transmitting RF over an optical link is measured. The RF carrier is impressed onto the laser light with a Mach-Zehnder (M-Z) modulator. The AM modulated carrier is then amplified with an erbium-doped diode-pumped fiber amplifier (EDFA) and transmitted through the stabilizer. The modulation of the laser signal does not affect the operation of the stabilizer. Figure 6 shows two overlaid plots of the noise power spectrum of a

1 GHz oscillator that modulates the laser light through the M-Z modulator, and of the output of the photodiode.

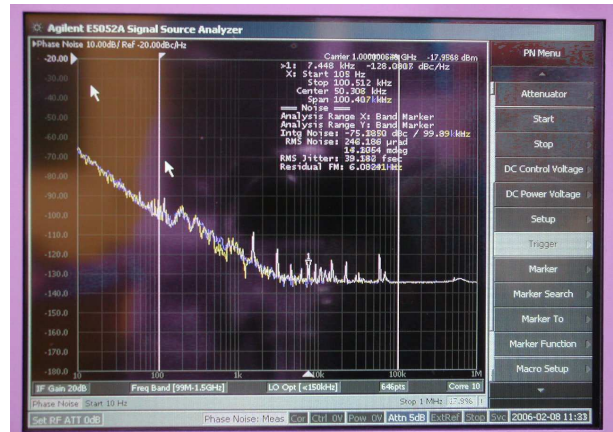


Figure 6: Noise spectrum of original RF generator (yellow), and of photodiode output of RF modulated onto laser and demodulated (blue).

In this case, the phase noise jitter of the 1.0 GHz test signal was 31 femtosecond, integrated over the range of 100 Hz to 100 kHz, as was the recovered 1 GHz signal from the photodiode. The modulation-demodulation process does not add significant phase noise to the original RF signal.

### Synchronizing Mode-Locked Lasers

This system is particularly well-suited to locking a remote mode-locked (M-L) laser to a local reference standard. Two widely separate (for example, 5 THz) comb lines of the M-L laser spectrum synchronize two CW lasers, which are each transmitted over individually stabilized fibers, which then lock the same two lines in a slave laser. This preserves the carrier-envelope-offset conditions of the slave M-L laser to that of the reference laser. In this application, only phase stabilization of the fiber stabilizers is needed, not group velocity correction as only the unmodulated optical carrier frequency is used. [5]

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