# FIBER TRANSMISSION STABILIZATION BY OPTICAL HETERODYNING TECHNIQUES AND SYNCHRONIZATION OF MODE-LOCKED LASERS USING TWO SPECTRAL LINES

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*Abstract*

Stabilization of the transit time through a glass fiber using an optical heterodyne technique promises to provide jitter reduction down to the few femtosecond level using inexpensive commodity hardware. An acousto-optical frequency shifter provides the optical frequency offset that is used to downconvert phase shifts at optical frequency to equivalent phase shifts at radio frequency which are used to close a phase-lock loop driving a piezoelectric phase shifter. Using the stabilized fiber transmission medium, two spectral lines of a mode locked laser lock two low-power CW lasers which are transmitted to a receiver which phase locks the same spectral lines of a second mode-locked laser to the first. The optical transmission system operates at low power and is linear, providing excellent signal-to-noise ratio and alows many signals to be transmitted without mutual interference. Experimental results will be presented.

## INTRODUCTION

The transmission of precise frequency and timing signals over distances of 100 meters to kilometers, stabilized to a few femtoseconds or a few parts in $10^8$ is accomplished by measuring the fiber transit time and actively compensating differences with, say, a piezoelectric phase modulator. Previous experiments [1] reflected a 1 GHz RF signal off the far end of the fiber and measured the phase shift of the return signal with respect to the original RF signal, applying the phase difference error signal to a piezoelectric phase modulator in series with the 100 meter fiber. This technique allowed stabilization down to about 200 femtoseconds but further improvement was considered marginal due to the small phase differences measured at radio frequencies relative to the desired femtosecond resolution.

An optical heterodyne technique using frequency offsets, used at the Atacama Radiotelescope Facility of NRAO [2] provides five orders of magnitude more sensitivity to phase differences in the reflected signal than an RF-based system. Phase differences at RF are optically downconverted to 110 MHz, where the phase detection is carried out. As phase information is preserved during the heterodyning process, phase differences at optical frequency is reflected at radio frequency, so conventional electronics may be used to detect the phase differences at RF rather than at optical frequencies. All operations at the 110 MHz radio frequency become non-critical, using inexpensive off-the-shelf components.

## OPTICAL HETERODYNE

Figure 1 shows the application of the frequency-offset method in a practical fiber-based transmission system to carry a precise timing or frequency signal from one point to another. A narrow-band CW laser signal is launched through a directional coupler, used to provide a local sample, and into a piezo phase modulator and the 100 meter fiber to be stabilized. At the far end of the fiber, an acousto-optical frequency shifter shifts the optical carrier up by 55 MHz, which is then reflected by a Faraday rotator mirror, and again shifted up 55 MHz back through the frequency shifter, and sampled at the near end of the fiber. The resulting 110 MHz beat between the shifted and original laser frequency is phase compared with the 110 MHz reference and is used to correct transit time jitter with a piezo phase modulator. Since the heterodyning process preserves phase, phase shift of the 110 MHz reference frequency is equivalent to the phase shift at optical frequency. Thus the 55/110 MHz reference need not be provided at the far end of the fiber at femtosecond accuracy, as one degree error at 110 MHz corresponds to 1 degree optical or 0.014 fsec. The fiber and electrical circuits beyond the point of mixing the return and reference optical signals do not significantly add to timing error. Also, providing the 55 MHz signal to the acousto-optic modulator at the far end of the fiber does not require a strongly stabilized transmission medium and may be done over conventional copper coaxial cable in many instances.

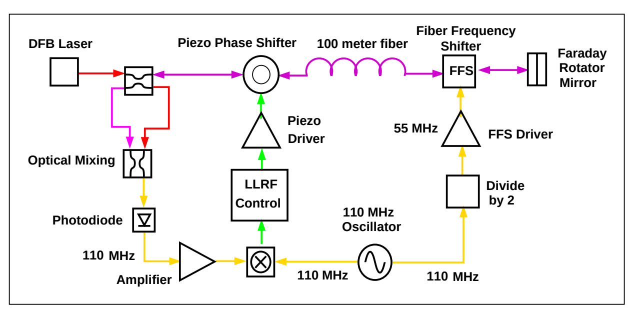


Figure 1: (color) Basic Optical Stabilizer

To transmit radio frequencies over the stabilized fiber, a wide-band zero-chirp Mach-Zehnder amplitude modulator may be used to modulate a standard frequency onto the CW laser signal that will be recovered at the far end of the fiber with a photodiode. To transmit optical frequencies a wavelength division optical multiplexor is used at each end. Radio frequencies may be transmitted optically through two optical carriers spaced by the radio frequency which are then optically mixed at the receiving end, producing a beat frequency in the RF domain. The transmitted signal loss from beginning to end is low, typically through two 3 dB directional couplers.

*Note that this is a linear system.* Signals modulated onto the CW laser carrier at the fiber entrance do not intermodulate with each other. The optical power level is significantly below any non-linear threshold in the fiber. The stabilization method does not use nonlinear optical elements and is therefore relatively independent of the laser power and intermodulation between different laser lines transmitted through the system is minimized. Reflections along the fiber, unlike in the RF-based system, do not introduce error, as they have not been upconverted by the 110 MHz RF offset frequency necessary to produce a beat note in the photodiode.

## MEASUREMENTS

Performance measurements were performed on the configuration shown in simplified fashion Figure 2.

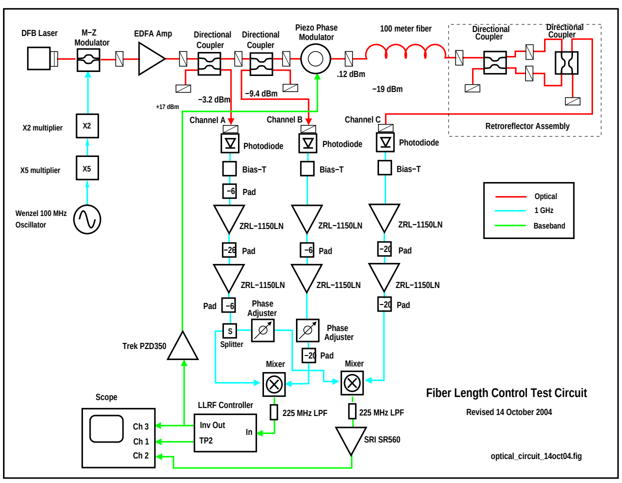


Figure 2: (color) Stabilized Transport with Optical Test Signal

A Koheras 15 milliwatt erbium-doped CW fiber laser with a 2 kHz linewidth (greater than 25 km coherence length) provides the optical carrier. The fiber stabilization system relies optical interference between a local sample and the signal reflected at the far end of the fiber, where about $10^8$ fringes exist along the length of the fiber. The laser frequency itself must be stabilized to this level as one fringe is equivalent to a time shift of 5.18 fsec. The laser itself is locked to a 1530.3714 nm absorption line in a 20 Torr acetylene cell by a piezo actuator to provide an accurate frequency reference. The absorption line is 0.005 nm wide, and and the lock system is stable to a few percent of the absorption line width.

To simulate a real-world environment, 100 meters of optical fiber is strung around the laboratory room. The group velocity temperature coefficient of 100 meters of fiber along with the 40 meters of fiber in the piezo controller is 6 picoseconds per degree centigrade. In addition, sub-acoustic pressure variations in the room modulate the transit time by several hundred femtoseconds.

To monitor the effectiveness of the fiber stabilization system, both an RF-based and an optical-based system were used. The RF-based system modulated onto the optical carrier with a zero-chirp Mach-Zehnder fiber modulator signals ranging from 300 MHz to 18 GHz, which were then monitored at the far end with a fast photodiode. A very clean 300 MHz signal was demodulated at the far end and observed with a spectrum analyzer. When compared with the 300 MHz signal directly, no increase in signal width or baseline was observed over the -95 dBc noise floor of the analyzer. Signals up to 18 GHz, generated with a network analyzer were modulated onto the optical carrier and detected with the same fast photodiode, using the network analyzer as a phase detector to record phase shifts over the stabilized fiber. The noise floor of the phase detector of the network analyzer at 18 GHz is about 0.5 degree, which was the observed phase jitter, or about 77 fsec. Neither of these measurements were sensitive enough to determine the ultimate performance of the stabilized fiber.

Therefore, an optical measurement was performed by taking a sample of the reflected optical signal at the far end, reflected by the mirror and transformed up 110 MHz, and optically beating it with a sample of the CW signal out of the laser itself in a channel identical to the stabilization control channel. (The near and far ends of the fiber were brought into close proximity.)

With an electronic chart recorder, the room temperature, the error signal fed to the phase modulator piezo and the monitor error signal were recorded over several day intervals. The lock-in range of the system is about 1.5 psec, and the temperature variation in the room oscillates over a two-hour cycle by about 1 degree centigrade. Thus, over the temperature extreme, there will be about four lock jumps, as the one-way transit time varies by 6 psec.

The critical items in the stabilization loop itself are located in two small regions: the fiber in the acousto-optic frequency shifter and Faraday rotator mirror, and the fiber between the directional coupler tap-off at the sending end and the directional coupler optical mixer before the control signal photodiode. (The temperature coefficient of 1 meter of fiber is 50 fsec per degree centigrate, and therefore these components contribute significantly in the present setup.) The optical measurement of the transit time drift, including the errors introduced by the presently thermally uncontrolled directional coupler and Faraday rotator mirror is 20 fsec. The critical components will be stabilized with small thermo-electric controlled chambers to 0.001C to reduce the drift caused by these two items.

Additional lock-in range must be provided. To artifically increase the lock-in range for this test, a variable optical delay line was inserted in series with the piezo phase shifter and manually adjusted over one cycle of the room temperature variation to keep the correction within the lock-in range of the piezo controller. In this case, the maximum observed time shift of the time-corrected 100 meters of fiber is also about 20 femtoseconds, due mainly to the partially-controlled components mentioned above. To provide additional lock-in range, the 40 meters of fiber in the piezo phase shifter will be thermally coupled to a thermal-electric cooler which will provide a 2 psec per degree centigrade slow control along with the kiloHertz bandwidth of the piezo itself within its 1.5 psec lock range. This will extend the lock-in range to 10 psec or more. Manually introduced short-term errors with the variable optical delay of 1 picosecond result in substantially less than 1 femtosecond measured transmission error, indicating that the loop correction gain of about 90 dB is more than sufficient and that the presently-observed 20 femtosecond errors are due to slow temperature variation of the critical components mentioned above.

The fast jitter of the transmitted CW laser signal was measured by observing the wideband (25 MHz) signal from the 110 MHz phase detector. The peak-to-peak noise level is 45 degrees of 110 MHz, corresponding to 45 degrees of the 1530 nm laser frequency, or 0.6 femtosecond (0.25 fsec rms). A major source of jitter was found to be white noise in the high-voltage piezo drivers exciting resonance peaks in the piezo correctors and was eliminated by high-level filtering and is now undetectible.

## STABILIZATION SYSTEM DISCUSSION

We have demonstrated an optical stabilization system, using inexpensive off-the-shelf components capable of stabilizing 100 meters of optical fiber down to the 20 femtosecond level at present, and will be improved with the addition of temperature control of small local components. The optical signal levels are in the milliwatt range, avoiding nonlinear effects in the fiber itself, and all the optical components are linear, avoiding cross-modulation effects when multiple optical or RF signals are sent along the fiber. The frequency offset technique avoids interference from reflections by imperfections along the fiber, and the optical heterodyning technique relieves stringent requirement on all RF components. Information to be transmitted may be RF-modulated onto the optical carrier with a Mach-Zehnder optical modulator and recovered with a photodiode, or optically combined with frequency-division optical multiplexors directly onto the laser carrier. The transfer of the phase measurement from the RF to the optical frequency domain results in five orders of magnitude better phase sensitivity, and non-critical RF components may be used. Stabilization of the laser frequency by a molecular absorption line in acetylene is easily implemented and provides the primary wavelength reference.

## SYNCHRONIZING MODELOCKED LASERS

Our scheme to synchronize modelocked lasers over hundreds of meters of optical fiber is based on transmission of two optical frequencies from a master clock laser and

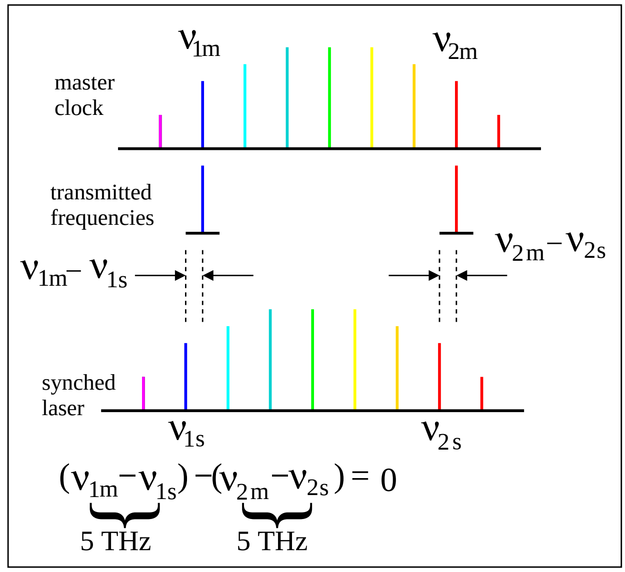


Figure 3: (color) Basic Concept

interferometric locking of the phase of comb lines of the synched laser. The basic concept is illustrated in Figure 3. In order to determine the frequency and phase of the repetition rate of a modelocked laser, it is sufficient to specify the frequency and phase of the difference between any two of its comb lines. Our application is not sensitive to the phase of the carrier with respect to the pulse envelope, so a frequency offset between the combs of the two modelocked lasers is ignored. Two single frequencies locked to two lines of the clock are transmitted and compared with the comb lines of the synched laser, so that the repetition rate of the synched laser is locked to that of the clock. Figure 4 shows the arrangement of lasers in this scheme. The reference clock is a modelocked laser with one of its comb lines locked to a stabilized, single longitudinal mode CW laser. A second CW laser is locked to another comb line, at a large frequency offset from the first. Two single-frequency lasers now can transmit phase information about the clock laser via fiber to a remote modelocked laser. This synched laser has two of its comb lines interferometrically compared with and locked to the two transmitted frequencies, fixing the phase of its repetition rate. The error signal that controls the repetition rate is derived so that an offset in the entire frequency comb of the synched laser from the clock is not detected.

Previous experiments are similar in general principle. Shelton et al [3] used a 14GHz harmonic of the basic reprate to synchronize two lasers to within 1.75fs over a 2MHz bandwidth. In this case the reference frequency was the 140th harmonic of the reprate. Bartels et al [4] synchronized two carrier-envelope stabilized lasers to a 456,000th harmonic in the optical regime, using a single frequency laser at 456THz as a reference, obtaining 1.5fs over 100kHz with better immunity to environmental perturbations. In both cases, the reference frequency is the

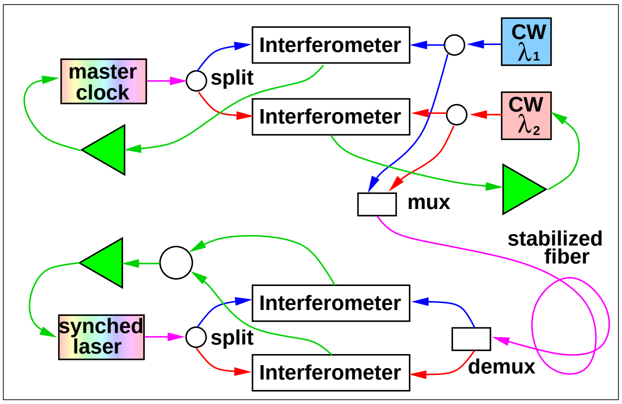


Figure 4: (color) Laser Arrangement

difference between a high harmonic of the reprate and zero frequency (as a virtual comb line). In the proposed scheme, the difference between two actual comb lines is the frequency of comparison, but the basic concept is the same. In our current design, the frequency difference between comb lines is 5THz, so we are effectively comparing the phase of two 5THz waves. If the error in phase detection was one degree, the corresponding temporal error would be 0.6fs.

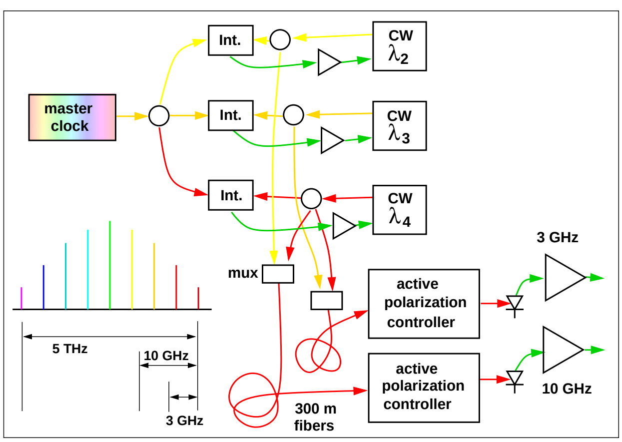


Figure 5: (color) Synchronizing Several Lasers

We also need to transmit phase information to RF cavity electronics. To do this, several CW lasers could be employed as in Figure 5. The RF frequencies are synthesized by locking single frequency lasers to selected comb lines of the clock, and transmitting them two at a time. The resulting beats generate the microwave signal [5]. This technique has been used to generate and transmit high frequency microwave signals over fiber with 33fs of jitter on an 18GHz signal [6]. An important advantage of this method is that all beats between comb lines of the clock laser have very stable relative phase which is fixed by the phase lock of the comb lines themselves, a feature of the laser modelocking phenomenon.

We are currently implementing the system in Fig 4, using two 150fs fiber modelocked lasers broadened to span greater than 5 THz bandwidth (from Menlo Systems), and two fiber DFB lasers at 1530 and 1570nm (from Koheras). A background-free cross-correlation measurement will monitor the relative temporal stability of the modelocked lasers when they are synchronized.

## REFERENCES

[1] Russell Wilcox, John W. Staples, Ronald Holzwarth, "Optical Synchronization Systems for Femtosecond X-Ray Sources", PAC2005, Knoxville

[2] Bill Shillue, Sarmad AlBanna and Larry D'Addario, ALMA Memo 483, *The ALMA 1st Local Oscillator Reference*, http://www.alma.nrao.edu/memos

[3] R. K. Shelton, S. M. Foreman, L-S. Ma, J. L. Hall, H. C. Kapteyn, M. M. Murnane, M. Notcutt, and J. Ye, Opt. Lett. 27, 312 (2002).

[4] A. Bartels, S. A. Diddams, T. M. Ramond and L. Holberg, Opt. Lett. 28, 663 (2003).

[5] S. Fukushima, C. F. C. Silva, Y. Muramoto and A. J. Seeds, IEEE J. Lightwave Technol., 21, 3043 (2003).

[6] J-F. Clich, B. Shillue, C. Latrasse, M. Tetu and L. D'Addario, Proc. of SPIE Vol. 5489, p. 1115 (2004).