TIMING DISTRIBUTION IN ACCELERATORS VIA STABILIZED OPTICAL FIBER LINKS*

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Abstract

We present progress on fiber-optic based systems for highly stable distribution of timing signals for accelerators. This system has application for linac-based sources of ultrafast radiation which require sub-100 fsec synchronization or for very large accelerators such as the linear collider. The system is based on interferometrically stabilized optical fiber links with RF and timing signals distributed as modulations on the optical carrier. We present measurements of the stability of this link over distances of several hundred. This work was supported by the Director, Office of Science, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

INTRODUCTION

The requirements of future accelerators for stable timing are expected to increase substantially. For example, the next generation of high brightness ultrafast x-ray sources driven by free electron lasers has typically sub-100 fsec requirements on the distribution of RF signals to accelerator components and laser systems. These requirements are expected to tighten as these facilities become operational for users. Another example is the ILC, which does not have timing requirements as strict but rather must maintain good timing stability over distances greater than 10 km.

To satisfy this need, we have been developing timing distribution systems based on stabilized fiber optic transmission lines. Although this technology significantly increases the complexity of the timing distribution, it allows the possibility of femtosecond level synchronization between various accelerator and laser systems by taking advantage of advances in optical communication technology and metrology. This paper provides a description of the system and progress over the past year.

SYSTEM CONCEPT

A schematic of the concept for transmission of an RF signal is shown in Fig. 1. The RF modulates the amplitude of an optical carrier of a frequency-stabilized Koheras 15 milliwatt erbium-doped CW fiber laser with a 2 kHz linewidth (greater than 25 km coherence length.) The RF signal is demodulated at the far end with a photodiode.

The fiber stabilization system relies on maintaining constant the relative optical phase between the forward optical carrier and the signal reflected at the far end of the fiber in an unequal arm Michelson interferometer configuration, consisting of the transmission fiber (long arm) and a reference fiber (short arm). At the receiver end of the fiber an acousto-optic frequency shifter doubly shifts the retroreflected optical carrier (and AM sidebands) by 55 MHz. When the long and short arm signals are superimposed on a photodiode, a beat at 110 MHz is seen, which can be compared in phase with a 110 MHz reference oscillator. When these 110 MHz signals are stabilized in relative phase, the optical phase delay of the transmission fiber is constant with respect to the reference. This technique is called optical heterodyning[3]. Note that this technique allows sensitivity to the optical delay at a fraction of the optical period of 5.2 fs. This feature is used to advantage but also presents a number of technical challenges because of the sensitivity to a variety of effects such as humidity, acoutic energy, etc. that can usually be neglected.

The relative phase error signal is processed by a digital low-level RF controller[4] and controls it by driving both a motor-driven optical line stretcher for slow phase shifts and a piezoelectric phase shifter for faster phase shifts. At relatively large gain, the effective bandwidth of the feedback is about 1 kHz. All fibers in the interferometer not stabilized electronically are stabilized in temperature to 0.01 degree C.

RESULTS

Optical RF Transmitter

We have demonstrated low phase noise RF transmission using amplitude modulated CW light using a commercial RF-over-fiber link consisting of a transmitter and receiver connected by a short fiber, with no fiber length drift compensation. A low noise RF source was constructed by detecting the pulse train of a modelocked laser with a photodiode, bandpass filtering at 2GHz and amplifying in a low noise amplifier. The integrated jitter of the source from 1kHz to 40MHz was 11fs RMS, limited by the photodiode shot noise at around –150dBc. This RF signal was input to the link transmitter and the received signal was observed, with an integrated jitter of 15fs RMS from 1kHz to 40MHz, as shown in the Fig. 2.

No additional phase noise added by the link could be observed from 10Hz to 10kHz. RF power loss through the link is about 20dB, with the input to the link at 5dBm and its output at –16dBm. Differences in signal levels into the noise analyser may account for the link output noise being lower than the input noise at some frequencies, an apparent experimental error. Minimizing acoustic noise in the lab improved the measurement by tens of femtoseconds. We conclude that this approach is viable for timing transmission systems with less than 100fs integrated jitter.

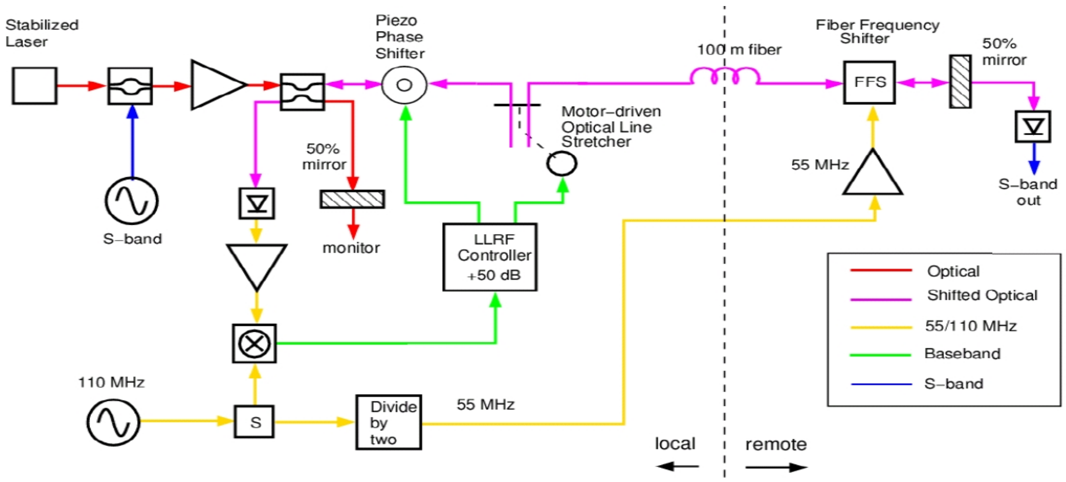

Figure 1: Schematic diagram of RF transmission via amplitude modulation of an optical carrier on a stabilized fiber optic transmission line.

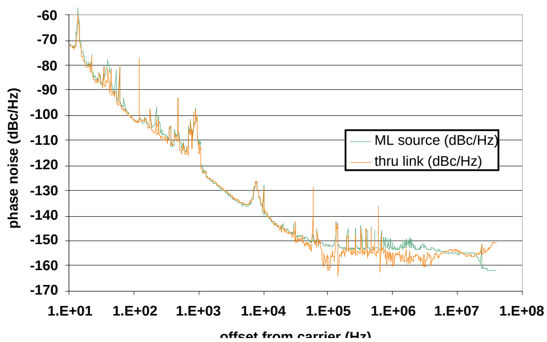

Figure 2. Phase noise of 2GHz source and signal transmitted through a modulated CW fiber optical link measured on an Agilent 5052.

Laser Frequency Stablization

Because the line stabilization technique described above operates by maintaining constant the number of optical periods ($<1\times10^8$ over 100 m), it is critical to stabilize the optical wavelength to better than this. Note that this requirement increases linearly with line length. We initially stabilized our CW laser by side locking 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 the lock system is stable to a few percent of the absorption line width. This translates to an instability of 15fs over a 300m fiber.

We have adapted a modification to this based on the Pound-Drever-Hall technique where a sample of the CW laser output is phase modulated at 500 MHz. The laser carrier frequency is tuned to the peak of an absorption line in the acetylene cell. Any shift in laser carrier frequency results in a conversion of phase to amplitude modulation, which is detected by a photodiode. The phase and amplitude of the modulation with respect to the 500 MHz reference gives the error signal, which is filtered, amplified and fed back to a piezo in the laser. This approach promises to reach wavelength stability of a part in 1×10^9.

Relative Drift and Jitter Measurements

Figure 3 shows results of stabilizing a 100m fiber strung around the walls of our lab, to pick up low frequency acoustics due to airflow. We monitor the stability of a single transmission line and the operation of the control loop via another interferometer, in this case a Mach-Zehnder using the stabilized long fiber as one arm, and a temperature controlled fiber as the other. The monitor channel does the same phase comparison as the control channel, providing us an out-of-loop measurement with high precision.

The phase comparison in Fig. 3 from the monitor channel (Mach-Zehnder interferometer) was made using a digital phase detector (an up/down counter with 128pi range). The drift rate is 0.13fs per hour, with a superimposed sinusoidal variation of 1fs peak-to-peak due to air conditioning cycling. Higher frequencies are controlled well below a fs.

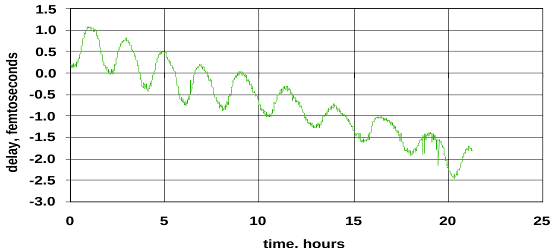

Figure 3. Delay variation of a stabilized fiber, measured using a second interferometer over a period of one day.

A better measure of the performance of this approach is the relative drift of two independent lines. To test this, we built two independent interferometrically stabilized lines, using both of them in a Mach-Zehnder arrangement. Each line was stabilized using an unequal-arm Michelson scheme described above, using light from the same laser. The two frequency shifters apply a shift of opposite sign, so that the optical wave is upshifted by 55MHz in one arm and downshifted by 55MHz in the other. Light transmitted through the two arms is combined in a directional coupler and the beat between the two waves observed on a photodiode. Thus we can observe relative phase shifts between the two.

With 100m of fiber in each stabilized line, the relative phase between the Mach-Zehnder output and a reference oscillator was recorded using a vector voltmeter. Data from a 35 hour run is shown in Fig. 4. There is about 3fs p-p drift due to temperature cycling. The larger temperature-induced variations in this experiment may be due to a different heatsinking scheme for the temperature-stabilized boxes that contain the Michelson interferometer reference arms. Measurement of a single line may underestimate the effect of temperature drift, as the reference arm for the Mach-Zehnder monitor interferometer is in the same box as the Michelson reference arm, and they drift together. The longer term variation seems to be diurnal, possibly due to changes in humidity, which we have reduced in earlier experiments by dehumidifying the reference arm box.

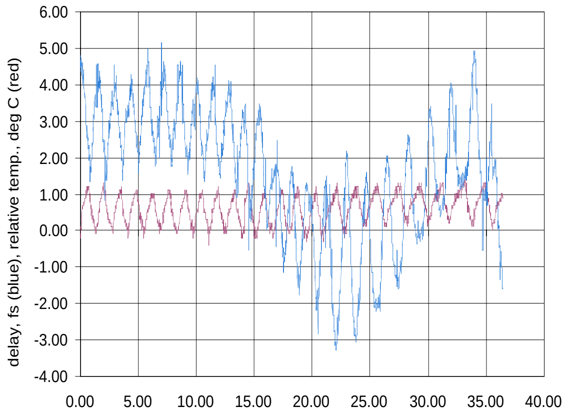

Figure 4. Relative temporal drift of two 100m lines (blue), compared with temperature (red). Vertical scale is in femtoseconds, horizontal in hours.

GROUP DELAY COMPENSATION

Though we precisely stabilize the optical phase delay using an interferometer, the group delay is what is important for AM transmission. The group or phase delay in the fiber will be the fiber length divided by the speed of light times the group or phase refractive index. The phase and group indices are related by

$$n_g = n_p + \omega \frac{dn_p}{d\omega}$$

If all the terms in the above equation had the same temperature coefficient, or if dispersion was constant with temperature, a constant correction could be added to the group or phase delay to compensate delay variation with temperature. Unfortunately, dispersion has a different temperature coefficient, which makes compensation more complicated. Over a small enough range, the difference in temperature compensation for group or phase delay can be approximated by a constant multiplication factor which can be found by measurement of the fiber. Measurements made of several different fibers have allowed us to estimate that the temperature coefficients of group and phase index differ by a few percent. In one case, the difference was around 2%. For a 200m fiber, there is 7ps per degree C of phase delay drift. If group delay was uncompensated, the delay error could be 140fs per degree.

This implies a possible compensation scheme. If the total phase delay correction to the interferometer is known, the variation in phase index is also known. An additional correction is then applied to compensate the group delay variation instead. The group delay is thus controlled by measuring changes in the phase delay. All computations can be done by the digital controller. If the compensation scheme is able to reduce the error by a factor of ten, errors due to group versus phase index can be reduced to less than 20fs per degree. If the fiber is routed in the linac tunnel, the temperature excursions will be within ~1 degree due to the temperature stability requirements of the other equipment.

CONCLUSION

We have shown that independent stabilized fiber optic transmission lines can be synchronized to within a few fsec. This was achieved primarily by the following: careful feedback control of the fiber length, temperature control of optical and RF components outside the feedback loop, and stabilization of the laser wavelength. We would like to thank Franz Kaertner, Mario Ferianis, Miltcho Danailov, and Axel Winter for many useful discussions. This work was supported by the Director, Office of Science, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

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