NEXT GENERATION CW REFERENCE CLOCK TRANSFER SYSTEM WITH FEMTOSECOND STABILITY

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Abstract

Present and future fourth generation light sources, such as the Swiss FEL, are placing strict requirements on current CW reference clock transfer systems. Both the added jitter and the long-term stability criteria need to be in the range of a few femtoseconds. In order to meet these requirements, the existing Libera Sync CW transfer system has been redesigned. All of the aspects of the system design have been revised and improved, from new measuring methods and better evaluation of components to careful pre-design testing and simulation. New fiber link topology, new approaches in thermal stabilization, improved power supply distribution and interconnection of carefully selected electrical and state-of-the-art optical components has led to a significant reduction in added jitter and excellent long-term stability of the system. Measurements repeatedly show the jitter performance to be below 6 fs_{rms}, integrated over the frequency range of 10 Hz to 10 MHz. Preliminary measurements of the long-term stability place the system in the range of a few tens of femtoseconds peak-to-peak of drift per day.

INTRODUCTION

Free Electron Lasers (FEL) require high performance synchronization throughout the entire machine; otherwise, its performance may be degraded or even fail. Typically, this high performance synchronization system is composed of two key subsystems. One is the source where a Reference Master Oscillator (RMO) is used. Its frequency range spans from a few 100 MHz to a few GHz. It has high close-in spectral purity and extremely stable frequency. The other extremely important element is the reference clock transfer system. Its goal is to deliver the reference signal to the users in either the optical or electrical domains while preserving initial reference clock signal purity and stability.

Typical requirements in terms of added jitter and long-term phase stability are below 10 fs for jitter and below 40 fs for phase stability per day [1]. For distances greater that 100m, the use of optical fibers as a transmission media is recommended since they exhibit low insertion loss, are insusceptible to EM interference and are reasonably inexpensive. Within the optical domain, two approaches are available.

The first is a pulsed-based system that uses the Michelson interferometer to detect optical path changes. The benefit of this approach is excellent long-term stability.

The other approach is based on a continuous wave (CW) modulation of an optical carrier in which phase detection and stabilization are done in the radio frequency (RF) domain. It offers the advantage of a system restart without re-tuning, high reliability and lower cost [2].

The Libera Sync 3 transfer system presented in this article is based on the CW modulation scheme.

THEORY OF OPERATION

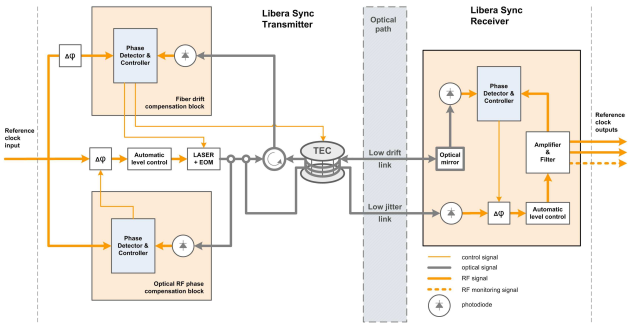

Figure 1: Block diagram of the system

The figure above is a block diagram of the system that shows the basic principle of operation. The system is composed of a transmitter and a receiver units connected by two optical fiber links. The transmitter input signal is the CW RF reference clock signal coming from the RMO. This signal modulates the 1550 nm optical carrier through an electro-optical modulator. The optical signal is then split and fed into two separate paths. One of the signals along with the on-board control circuitry is used for link phase drift compensation and is partly reflected back at the receiver side. The other path is used for transfer of the low-added jitter signal. In the receiver, both incident optical signals are demodulated back into the RF domain.

In the transmitter unit, the fiber drift compensation is done by comparing the demodulated reflected signal phase with the phase of the input reference signal. The optical path compensation is provided using two principles. The slow changes are compensated by cooling or heating a fiber spool. The temperature of the fibers on the spool is changed in the opposite direction from the temperature change on the optical path between the transmitter and the receiver. Faster changes are compensated by changing the laser source temperature and thus the optical carrier wavelength. In this manner, the optical path is artificially extended or shrunk by taking advantage of the chromatic dispersion in the interconnection fiber.

To overcome optical limitations, two fibers are used, the first one for the transfer of a low-noise signal and the second one for the transfer of a low-drift reference signal.

This combination yields ultra-low added jitter and low drift.

Design approach and implementation

In order to meet the tight performance requirements, a new development approach has been followed. Theoretical knowledge with simulations has been combined with prototyping and measurements of the individual components. Based on those results, a careful selection process has been commenced for both electrical and optical components.

Vital subsystems, such as the power supply distribution network, control system, temperature stabilization, mechanical layout and optics, have all been subject to prototyping, testing and tuning before being integrated into the final design.

The power supply subsystem proved to be as vital, and it has been specially developed to provide a low noise power rail for the RF circuitry especially the RF amplifiers.

The environmental conditions inside the box must be kept as constant as possible. In this context, a new temperature stabilization subsystem has been devised in which the temperature is kept stable to within 0.001°C.

The mechanical layout has been specifically designed to facilitate the environmental stabilization system inside the unit while simultaneously ensuring ease of manufacturing.

The RF amplifiers were tested and tuned in order to achieve low noise and low phase noise, respectively.

The layout of the fiber interconnections within the system is as symmetric as possible (temperature/humidity drift compensation). Using one single instead of two different fibers for drift stabilization guarantees independence from dispersion tolerances, as the laser's emission wavelength is varied to correct the link group delay. Rayleigh backscattering noise [3] increases the low-frequency phase noise as well as the phase noise floor in this bi-directional transmission. By reducing the coherence of the reflected light, the first effect can be minimized. To dispense with the added noise floor, a second uni-directional "low-noise" link, that is phase-locked to the first "low-drift" link and "cleaned", transmits the same signal but without backscattering noise. The stability of the "low-drift" link is further increased by operating photodiodes (out-of loop) in low AM-to-PM conversion operating points and by stabilizing the optical power. Furthermore, the optical power has been chosen to be sufficiently large so that the resulting shot noise limit enables achieving the envisaged phase noise floor.

Following that, all of the electronics have been integrated onto a single printed circuit board (PCB), thus allowing for better manageability and greater reproducibility.

Finally, the hardware platform is complemented with a software control system that monitors over 120 different parameters, from environmental data (temperature, humidity and pressure) to electronics and optics (phase detectors outputs, RF power levels, photodiode currents, laser temperature, etc.).

RESULTS

Jitter frequencies below 10 Hz are classified as wander and frequencies at or above 10 Hz as jitter [4]. Measuring these two parameters with a resolution of a few femtoseconds proved to be a challenge. Special measurement techniques along with specially developed equipment have been used.

Jitter performance

In our case, the added jitter has been measured at offset frequencies ranging from 10 Hz to 10 MHz. The figure below shows the added jitter measurement of the Libera Sync 3 prototype.

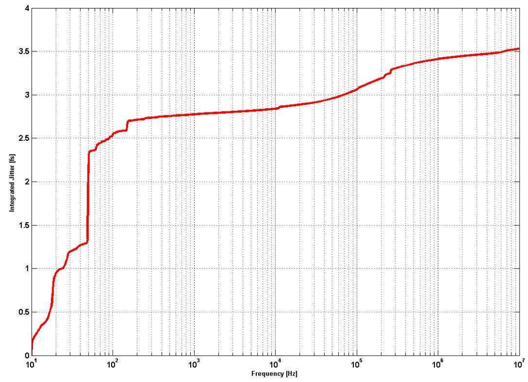

Figure 2: Integrated added jitter

The majority of the jitter is concentrated in the lower frequency region between 10 Hz and 110 Hz. This has been attributed to mechanical vibrations and the coupling of the 50 Hz frequency component present in the environment at the time of the measurements. The total integrated jitter is slightly over 3.5 fs. This is a preliminary measurement and can be subject to change in the final implementation of the system. However, we do not expect a significant degradation.

Long-term phase stability

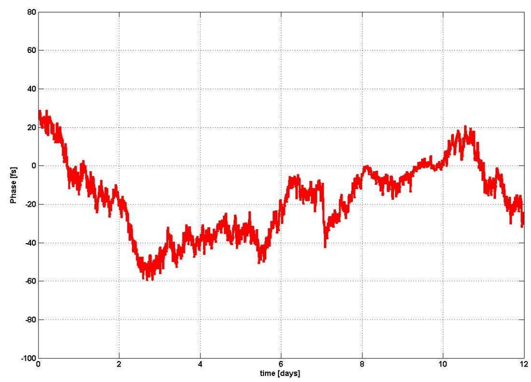

Figure 3: Phase drift

Phase drift, like jitter, is the undesired variation of the phase of an otherwise periodic signal. However, these variations happen at much lower frequencies and are regarded as a time variable phase offset in relation to an initial arbitrary phase. In our case, the measurement was done over a period of 12 days. The following figure shows phase drift stability of the Libera Sync 3 prototype in relation to a phase stable reference.

The maximum peak-to-peak phase drift has been measured at 88.7 fs while the average day-to-day phase drift has been calculated to be around 30 fs with a standard deviation of 8.9 fs.

Measurement techniques

In order to measure added jitter in the femtosecond range, a differential technique (saturated mixer) has been used. In this case, the reference signal is split into two branches. One is used as the reference signal while the other contains the device under test (DUT). If the two signals are driven in a quadrature phase relation at the mixer input ports, the resulting baseband output difference signal is 0 V plus a small phase modulation of the carrier, which is regarded as the residual phase noise of the DUT. This residual phase noise is sampled and digitized by a signal source analyzer (SSA). The jitter is calculated by integrating the digitized phase noise spectrum over the offset frequency range and is normalized to the original carrier frequency. Despite limitations induced by non-symmetries and non-linearities of the mixer, the resolution of the measurement can be estimated to be on the order of 0.1 fs [5].

Phase drift measurements have been performed by using a phase detector unit specifically designed for this application. The detector unit has been built by following the same design steps and implementing the same technology that has been used for the Libera Sync 3 system itself. The phase drift measurement is based on the AD8302 integrated circuit (IC). When thermally stabilized and driven with proper RF power levels, this IC exhibits minimal phase drift. Combined with thermally stabilized splitters and special RF cables, the setup can reach an accuracy of about 10 fs of phase drift per day.

DISCUSSION

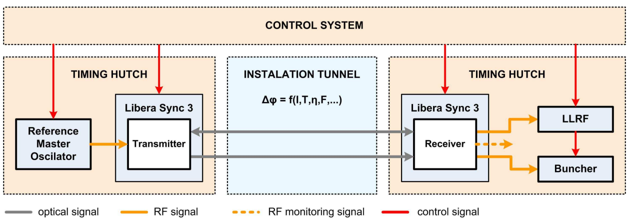

Figure 4: Example of use an accelerator environment

Figure 4 shows an example of how the Libera Sync 3 transfer system can be integrated into an accelerator environment. The interconnecting RF cables from and to the transmitter and receiver units respectively as well as the fiber cables between them are also vital parts of this system, which require careful consideration.

The use of temperature-compensated RF cables with low temperature coefficients in the range of a few fs/mK is mandatory [6].

Phase drift in the optical fiber depends on link length, temperature and relative humidity variations, mechanical stress etc. Deviations of a few degrees in temperature and some tens of a percentage in relative humidity can contribute high phase drifts in the fiber link. The current Libera Sync 3 prototype provides a phase compensation range of approximately 360 ps. Therefore, if long distance operation is to be achieved, special care in selecting the fiber cable needs to be taken. Only loose type cabling preserves the temperature coefficient of the silica glass optical fiber in the range of 40 ps/kmK. In cases in which the estimated phase drift of the optical path exceeds the phase compensation range of the Libera Sync 3, the use of phase stable optical fibers is mandatory [7].

Finally, the Libera Sync 3 provides a user interface that can be operated manually or remotely. Manual operation is done by accessing the front panel controls along with the display, which is ideal for data examination and link tuning. Remote operation is done using SCPI commands over a standard 10/100 Mbit Ethernet connection, which is ideal for integration into the control system.

The current prototype works on a fixed frequency of approximately 3GHz. Future upgrades include extended operation range and support for other frequencies (6 GHz).

CONCLUSION

The new Libera Sync 3 transfer system integrates a novel approach with state-of-the-art technologies, ultimately providing outstanding performance, high reliability and reproducibility as well as ease of use.

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