CHASING FEMTOSECONDS – HOW ACCELERATORS CAN BENEFIT FROM ECONOMIES OF SCALE IN OTHER INDUSTRIES

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Abstract

Building accelerators we frequently push the limits of what is possible in terms of performance. When trying to solve a very challenging engineering problem, we normally resort to specialization; we narrow our focus. This talk suggests a possible alternative path. Huge benefits and great results can be achieved by combining creative ideas and approaches with ideas and solutions borrowed from the economies of scale like telecommunications. The aim of the talk is to show possibilities for combining ideas, technologies and components from different industries into innovative products.

TIMING ACCURACY: JITTER & DRIFT

One of the design requirements of modern particle accelerators is precise timing and synchronization of the machine components and user experiments at different physical locations. Before designing a high-accuracy timing system, some basic definitions and limitations need to be considered first to select the most suitable technology for a certain task.

Timing accuracy includes at least two different specifications:

- Short-term inaccuracy described as phase noise or jitter .
- Long-term inaccuracy described as wander or drift.

Jitter

Jitter is mainly caused by random noise added to the timing (clock) signal as shown in Figure 1.

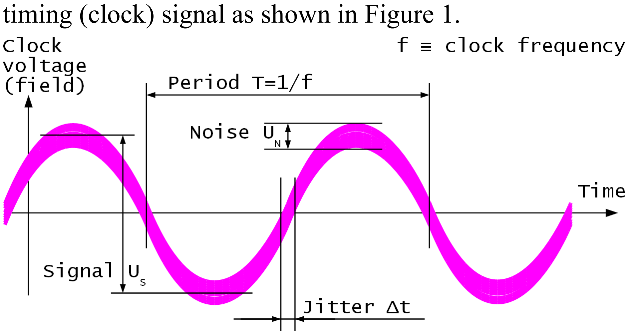

Figure 1: Signal-to-noise ratio & timing jitter.

The resulting jitter Δt is a function of the clock period T (or frequency f) and the signal-to-noise ratio (1).

$$\Delta t = \frac{T}{2\pi} \cdot \frac{U_N}{U_S} = \frac{1}{2\pi \cdot f} \cdot \sqrt{\frac{P_N}{P_S}} \qquad (1)$$

Please note that the signal-to-noise ratio may be expressed in many different physical quantities. Voltages are usually used for electrical signals. Signal and noise powers have a more general meaning.

Noise may come from many different sources. Natural noise sources like thermal noise or quantum noise shown in Figure 2 can not be avoided.

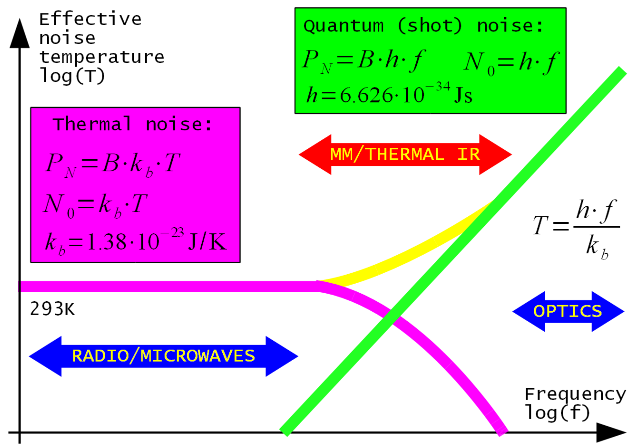

Figure 2: Thermal and quantum noise.

Noise power is usually reduced by narrow-band filtering with resonators having a quality Q. The filter bandwidth B=f/Q is orders of magnitude smaller than the clock frequency f. In narrow-band systems the noise power is simply described by its spectral density N_0.

In an electrical timing system operating in the radio/microwave frequency range, natural noise is manly thermal noise. The resulting jitter is inversely proportional to the square root of the frequency (2).

$$\Delta t = \frac{1}{2\pi} \cdot \sqrt{\frac{k_b \cdot T}{f \cdot Q \cdot P_S}} \qquad (2)$$

Therefore the performance of such a timing system improves at higher frequencies provided that all of the remaining design parameters remain the same.

In an optical timing system operating at visible light or near IR, natural noise is mainly quantum (shot) noise. The resulting jitter is frequency-independent (3).

$$\Delta t = \frac{1}{2\pi} \cdot \sqrt{\frac{h}{Q \cdot P_S}} \qquad (3)$$

Please note that the resonator Q is limited by its mechanical stability and thermal drift in all cases. Therefore there is no particular theoretical advantage in using optical or even higher frequencies for timing. The only real optical advantage is that reliable hardware for the millimeter-wave and thermal (long-wave) IR frequency ranges is almost unavailable!

Drift

Drift is mainly caused by temperature and other environmental variations, by power-supply variations, by component imperfections like AM-to-PM conversion, by component degradation & aging etc. Drift is not directly related to the theoretical design parameters of a timing system like its clock frequency. On the other hand, drift is related to the technologies used and in particular to their state of maturity.

COMPONENT TECHNOLOGIES

Over the last two or three decades, many different changes happened in electronic and/or electro-optical circuit and system design. 30 and even 20 years ago electronic and optical components were rather simple. Using these simple building blocks, an engineer could build almost everything including computers in a relatively short amount of time.

If a particular component was missing or not available at all, it was obvious to design and build such a specialized component. This was common in military and aerospace projects. Even industrial electronics frequently used specialized, low-production-volume parts. Most components were manufactured in three quality grades: consumer, industrial and military/aerospace.

20 or 30 years ago it was considered that component reliability could be designed into the component itself by very simple means. For example by choosing the right manufacturing process or better packaging for industrial-grade parts. Additional inspections and screening was used for military/aerospace-grade parts.

Economies of scale first hit the personal-computer market. A hobby electronic designer could certainly do better than the 1990-personal-computer design. In just 10 years, the personal computer evolved in a top-technology item in 2000. After 2000 inexpensive personal computers quickly displaced much more expensive workstations and other computing hardware.

A quality quantum leap was achieved in mobile telephony. While a defective consumer appliance like a TV set only bothers its owner, a defective mobile phone might disrupt the whole mobile network. Highly-reliable mobile phones had to be manufactured in large volumes at consumer prices but respecting industrial or military quality standards. The distinction among consumer, industrial and military grades suddenly disappeared!

The reliability of modern electronic and optical components is no simple matter. The most obvious example are the failure mechanisms of semiconductor lasers. Individual component screening like performed on military-grade parts many years ago does not help! The correct answer is learning from mass production in million series and correcting the manufacturing process all of the time. This simply means that specialized components can no longer be produced, at least not at the reliability levels that are obvious today.

An increasingly important component issue is complexity. Component complexity is not limited to software, although the latter is the most obvious complexity issue. The hardware design of most electronic and optical components has become so complex that the design of specialized components can no longer be afforded by a small group of engineers, especially not in the limited amount of time allowed by practical projects.

Finally, a completely new problem appeared in the 21st century called component obsolescence. Economies of scale also dictate that the production of a particular component is dropped as soon as the latter becomes obsolete. Due to the component complexity it is usually difficult to have it manufactured at a different location or find similar plug-in replacements.

Technology SUCCESSES:	Technology FAILURES:
Analog radio/microwave electronics	Millimeter-wave electronics
High-speed digital electronics	Micro-electro-mechanical devices (MEMS)
(Electronic) digital signal processing (DSP)	Long-wave (thermal) IR optics
Silica-glass optical fiber (waveguide)	Fiber-optic LASER sources (oscillators): CW, pulsed, mode-locked
Semiconductor lasers, modulators and photo-detectors	Optical signal processing (holography, nonlinear optics)
Erbium-doped fiber LASER amplifier (EDFA)	Optical computing

Figure 3: Technology successes and failures.

As shown in Figure 3, a design engineer has to be extremely careful while choosing the technologies for a new product. While there are some mass-produced and inexpensive components with fantastic performance, there are many technology failures as well. The support to some frequency ranges and applications may be missing. Even successful technologies may be affected by component obsolescence!

FIBER-OPTIC TECHNOLOGY

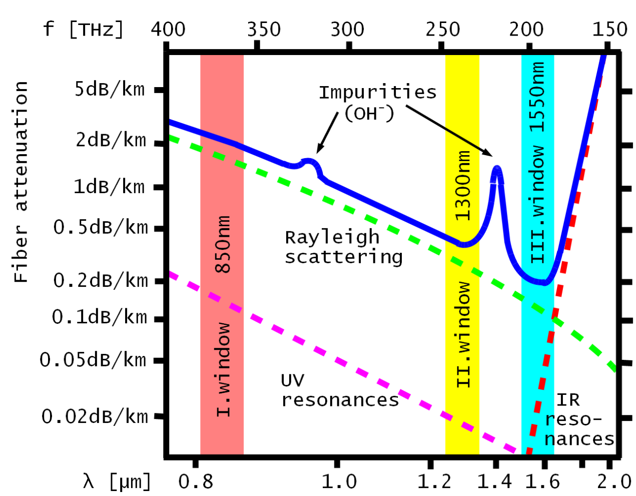

Figure 4: Silica-glass fiber attenuation.

One of the most important achievements of the last three decades is fiber-optic technology. As shown in Figure 4, a rotationally-symmetric dielectric waveguide in the form of an optical fiber can achieve extremely low transmission loss in some frequency bands in the visible and near-infrared spectrum. Such a waveguide is physically very small and it is manufactured mainly of silica glass, a very stable chemical compound with excellent mechanical, chemical, electrical and optical performance.

The availability of inexpensive optical fiber triggered the development of all related components: splices, connectors, LED and LASER transmitters, modulators, isolators, circulators, PIN and avalanche photo-diode receivers and even Erbium-doped fiber-optic LASER amplifiers.

All these new components changed the meaning of the word optics. Traditionally, optics meant bulk optics with lenses, mirrors and various cumbersome components on optical benches in clean-room environments, requiring precise handling and extremely sensitive to dirt, moisture and vibration. On the other hand, optical fiber and all fiber-optic components are designed right from the beginning for simple handling, stable and reliable operation in the most unforgiving environments ranging from the ocean floor up to the geostationary orbit.

Yet optical fiber does have some limitations that have to be understood in order to design a successful system. The most obvious limitation is the frequency or wavelength range. Silica glass only works in the visible and near-infrared range. Other optical-fiber limitations are shown in Figure 5.

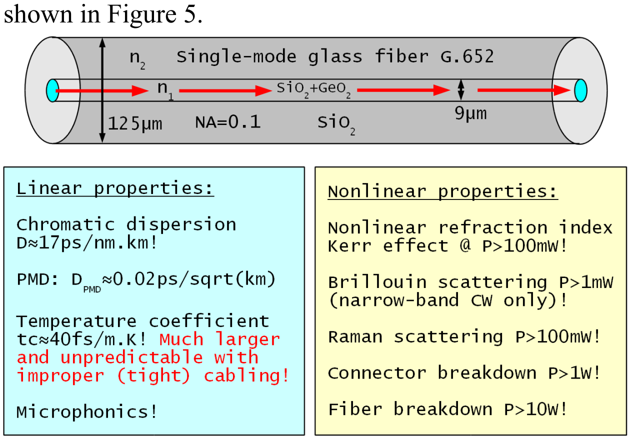

Figure 5: Single-mode optical-fiber properties.

Standard Telecom G.652 single-mode optical fibers have chromatic dispersion due to both waveguide and material effects. Rotationally-symmetrical fibers do not maintain polarization. The random coupling between the two degenerate fundamental modes causes Polarization-mode dispersion (PMD). The refractive index of silica glass has a large temperature coefficient. The latter may become unpredictable and up to an order of magnitude larger due to improper (tight) cabling like used in patch-cords or FTTH cables. Although much less sensitive to vibration than bulk optics, microphonics may still represent a problem in high-accuracy fiber-optic systems.

A major disadvantage of fiber-optic technology is fiber non-linearity. Although silica glass is a very linear material, the size of the fiber core is very small. Tens of milliwatts may already cause a breakdown in air due to the high electric field at the fiber end. A few watts of optical power may cause an electrical breakdown and melt the fiber core. In most cases the fiber signal power is limited to about 100mW due to both Kerr and Raman effects. Coherent systems using very narrow-band optical signals may be limited to power levels below 1mW due to Brillouin scattering.

OPTICAL TIMING SYSTEMS

The typical distance to be covered by a timing system in a particle accelerator ranges from a few hundred meters to a few ten kilometers. At these distances coaxial cable becomes bulky and lossy as the clock frequency is increased to improve accuracy. Optical fiber is an excellent substitute offering low loss at light-wave frequencies. Usually, no amplification is required in an optical-fiber system up to at least 50km.

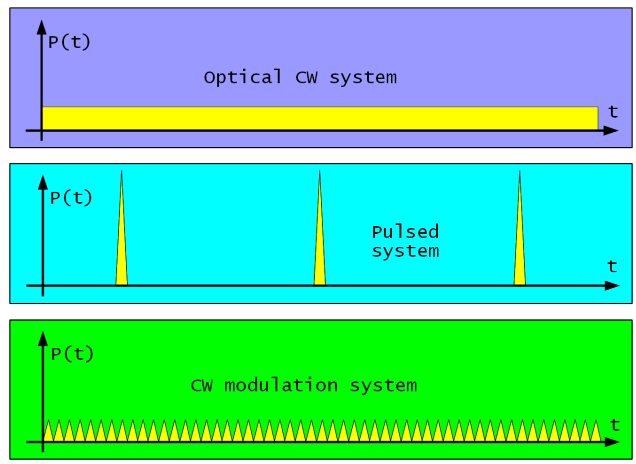

Figure 6: Optical timing systems.

As shown in Figure 6, optical timing systems include:

- Optical CW systems,
- Pulsed systems and
- CW modulation systems.

Optical CW Systems

Optical CW systems should offer the highest resolution and accuracy due to the high clock-signal frequency. Unfortunately the resulting 5.16fs timing ambiguity at 194THz is too small for practical applications. Vibrations might cause cycle slips and the system phase can never be recovered after any power down. The extremely narrow-band optical signal causes interferometric noise and triggers Brillouin scattering. Polarization changes and PMD in optical fibers are a big problem. Last but not least, no user equipment is currently available that could use the timing information of an optical carrier directly.

Pulsed Systems

Pulsed systems use an optical carrier while the timing information is carried in the pulse envelope. The spectrum of the latter may extend in the millimeter/long-wave IR to offer precise timing and avoid phase ambiguity at the same time. Unfortunately, pulsed systems are affected by fiber non-linearity, chromatic dispersion and PMD. Compensation of the fiber thermal coefficient is very difficult. Pulsed systems are well understood by the user community although optical signal processing is not here yet and the electrical signal-to-noise ratio from a photo-detector may be poor.

CW Modulation Systems

Replacing a few large pulses with many more smaller pulses results in a CW modulation system. Fiber non-linearity can be avoided due to the lower peak power. The signal distortion caused by chromatic dispersion and PMD is much less critical than in pulsed systems. Standard, mass-produced, inexpensive, high-performance and high-reliability Telecom components may be used. The electrical input and output of CW modulation systems interface to user equipment directly just like coaxial cable.

Unfortunately, the timing jitter of CW modulation systems is rather poor. Most of the signal-to-noise degradation comes from the impedance mismatch between the photo-diode and following electrical amplifier as shown in Figure 7.

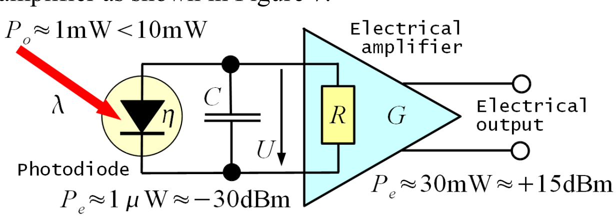

Figure 7: Photo-diode receiver.

Assuming an electrical noise temperature of T=300K and a parasitic capacitance of C=1pF (sum of photo-diode and amplifier input) results in a noise voltage of $U_{neff}=25.7\mu V_{eff}$ (4) independent of the frequency range!

$$U_{Neff} = \sqrt{\frac{k_b \cdot T}{2\pi \cdot C}} = 25.7\,\mu\,\text{V}_{\text{eff}} \tag{4}$$

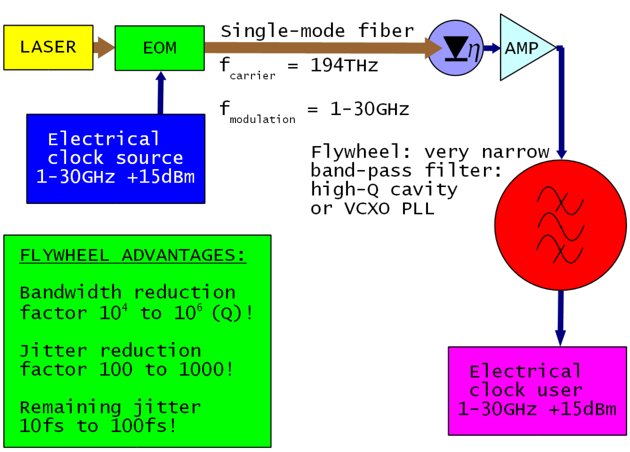

Figure 8: CW modulation system with flywheel.

The timing jitter can be reduced by averaging many small pulses. In other words, each small pulse just adds a small amount of momentum to a large flywheel. In electrical terms the flywheel is a narrow band-pass filter.

The electrical flywheel is built as a high-Q resonator or VCXO PLL as shown in Figure 8.

A high-Q resonator allows a bandwidth reduction in the range between 10^4 and 10^6. The jitter reduction goes with the square root of the bandwidth reduction, resulting in a jitter reduction factor between 100 and 1000.

In a CW modulation system, the optical carrier is not coherent with the timing modulation. Therefore the optical carrier frequency may be modulated to avoid Brillouin scattering. Even more important, changing the optical carrier frequency together with the fiber chromatic dispersion can be used for small adjustments of the group velocity and overall system delay.

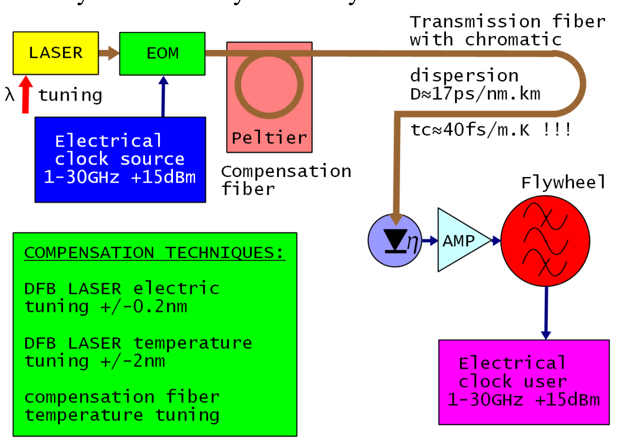

Figure 9: Delay-variation compensation techniques.

As shown in Figure 9, delay-variation compensation can be achieved in different ways. Fast variations like vibrations can be compensated by electrically tuning the DFB LASER over a restricted bandwidth of just +/-0.2nm in a very fast way (τ=1µs). Medium-speed variations can be corrected by thermally tuning the DFB LASER over +/-2nm (τ=1s). Slow variations like temperature changes of the transmission fiber can be adjusted by heating or cooling a spool of compensating fiber (τ=100s).

PROTOTYPE COMPENSATED CW MODULATION SYSTEM

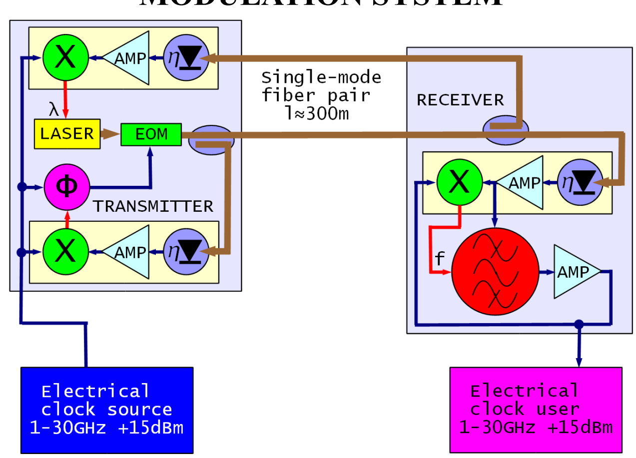

Figure 10: Compensated CW modulation system.

A prototype CW modulation system Libera Sync was built by Instrumentation Technologies for the accelerator

"FERMI" distributing a 3GHz clock over distances up to 300m. A fiber pair made of two identical optical fibers in the same cable was used for clock distribution. In this way the actual delay could be measured at any time and any variations compensated immediately.

The block diagram of the 3GHz compensated CW modulation system is shown in Figure 10. A flywheel resonator with the Q≈10^4 was used to reduce the timing jitter. The phase noise of the 3GHz signal source is plotted blue in Figure 11 in the frequency range from 100Hz to 10MHz. The phase noise after Libera Sync is plotted red in the same graph. The integrated jitter increases from 12.4fs at the system input (source+SSA) to 13.4fs at the system output (source+Libera Sync+SSA).

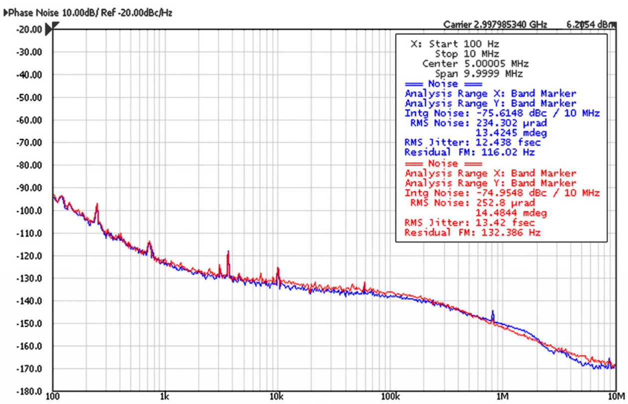

Figure 11: Measured phase noise & jitter at 3GHz.

In order to compensate for long-term variations and/or drift, Libera Sync includes three identical receiving blocks. The first receiving block is located in the transmitter to compensate for any phase-shift changes in the transmitter. The second receiving block is also located in the transmitter to compensate for transmission-line-delay variations. Finally, the third receiving block is located in the receiver and compensates for any delay variations of the flywheel resonator.

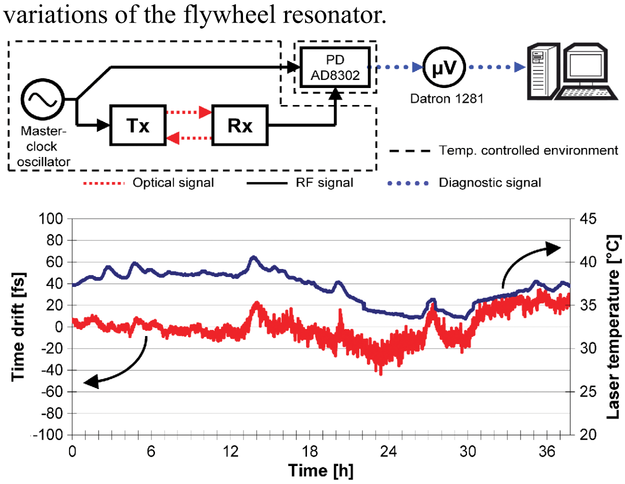

Figure 12: Measured long-term drift at 3GHz.

All three receiving blocks are built using matched components kept in precisely-controlled environments. Further there is a spool of two identical compensating fibers for the forward and backward signal paths that is omitted on figure 10 for simplicity. The spool is heated or cooled by a Peltier heat pump. The measured long-term drift is shown in Figure 12. The measured drift is 9.5fs_{RMS} in 24h and 13.4fs_{RMS} in 38 hours for an installed fiber length of 360m in the FERMI accelerator tunnel.

FURTHER FIBEROPTIC DEVELOPEMENTS

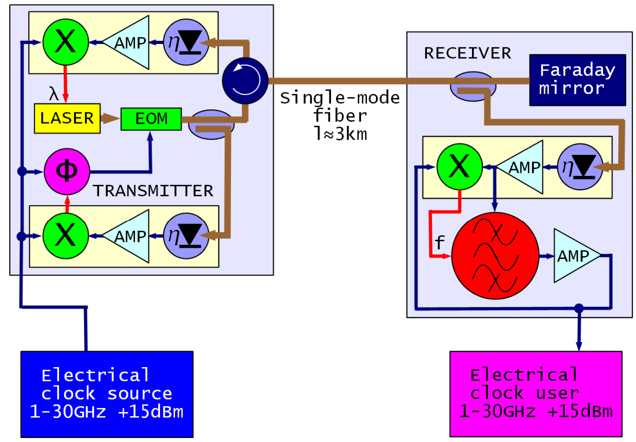

Figure 13: PMD compensation with a Faraday mirror.

The initial Libera Sync prototype was designed for short distances up to about 300m, where fiber-to-fiber matching is excellent and PMD is not an issue. At longer distances (3km to 10km) a Faraday mirror becomes necessary to use a single fiber and compensate PMD precisely as shown in Figure 13.

Finally, the same design and control technologies can be used to design a top performance, extremely low phase noise master oscillator as shown in Figure 14. The combined effect of the fiber delay and flywheel resonator is an effective Q in the range between 10^5 and 10^7!

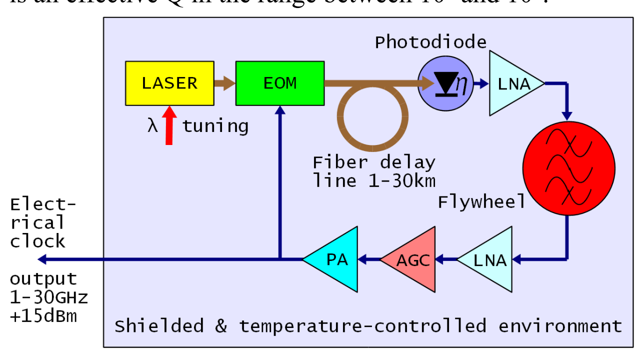

Figure 14: Electro-optical master oscillator.