CW LASER BASED PHASE REFERENCE DISTRIBUTION FOR PARTICLE ACCELERATORS

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Abstract

We present a cost-effective solution for the synchronization of RF signal sources separated by tens of kilometers with the femtosecond accuracy. For the synchronization a phase reference distribution system (PRDS) is developed, which is comprised of a CW optical transmitter connected via single mode fiber-optic links to remote receivers. This technique enables to use only one transmitter for multiple receivers and removes the necessity of active stabilization units (e.g. piezo-driven fiber stretchers or laser wavelength tuning), which reduces considerably the system cost.

The concept of the new RF reference distribution, parameters of crucial components, phase drift detection and correction techniques are introduced, which lead to low noise and long-term stable PRDS operation. Detrimental effects of various linear and nonlinear fiber impairments are discussed. One of the most important elements is the phase detector, which is based on a direct RF-sampling ADC and it features a femtosecond measurement precision over 2π phase change. Finally, the long-term performance of the designed PRDS is shown, which was evaluated with a 500-m single-mode fiber and an RF signal of 1.3 GHz.

INTRODUCTION

Modern RF linear accelerators to fulfill high requirements in terms of energy gain per meter must be made much more effective. The accelerator performance is considerably affected by the phase reference distribution system (PRDS), which synchronizes various remote subsystems with femtosecond precision.

In this paper, a prototype of a PRDS is presented, which provides the timebase for the spatially distributed devices with the sub-100 fs pk-pk precision at the distance of a few km over several hours. The designed optical distribution makes use of standard components developed for the telecommunication industry and applies a distribution method that avoids complexity or expensive elements, which cause it attractive for a variety of applications.

Optionally, this PRDS can be also used for the transmission of low jitter RF signals to distant locations with the residual phase jitter lower than 10 fs rms. The transmitted RF signals can substitute local high performance RF sources, which leads to the considerable cost reduction.

The PRDS can be implemented in facilities using different reference signal frequencies ranging from about 100 MHz to up to several GHz, and the distance between the synchronized remote devices can reach dozens of km.

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NEW CW OPTICAL DISTRIBUTION CONCEPT

The simplified block diagram of the designed PRDS is shown in Fig. 1. The system is comprised of a CW optical transmitter connected via single mode fiber-optic links to multiple receivers (one is shown in the picture). The optical transmitter is a single-mode laser intensity modulated with an RF reference signal using a Mach-Zehnder modulator (MZM). Optical signal linewidth is broadened by applying a phase modulator to mitigate Rayleigh and Brillouin scattering detrimental effects in optical fibers, which is discussed further in the text below. The modulated laser signal is amplified by a high power erbium doped fiber amplifier (EDFA), and then split to dozens of optical fiber links utilizing a multichannel optical splitter. In a receiver a fraction of the modulated light is coupled out to a photodetector "3" and converted into an RF signal, which is further used for the synchronization of a local RF source to the reference oscillator.

Environmental conditions like temperature, humidity, vibrations or air pressure have the considerable influence on the stability of the distribution system. The major phase drift sources are the optical fibers connecting the transmitter with the remote receivers, which experience mechanical tensions and refractive index changes due to environmental variations [1]. The temperature and humidity sensitivity of a standard SMF28e amounts to 40 fs/K/m and 2.5 fs/%RH/m [2], respectively. Hence, time delay variations in a few kilometer optical fiber can equal even a couple of hundreds ps. However, these variations can be measured using the feedback signal reflected by a mirror located at the end-station. Optical signals propagating forward and backward the SMF experience the same conditions and the delay variations are almost symmetrical in both directions.

To measure time delay fluctuations of the optical fiber, a small fraction of the optical beam is reflected back to the transmitter applying e.g. a Faraday rotator mirror (FRM). In the transmitter, the reflected light is separated from the forward propagating light using e.g. a circulator, then converted into an RF signal by a photodector "2". One channel of the optical splitter is directly connected to the photodetector "1" to measure phase drifts of the components in the transmitter, which are not temperature and humidity stabilized, e.g. Mach-Zehnder modulator or EDFA (see Fig. 1).

Phase drifts between the reference oscillator and a remote RF source are determined using three phase detectors denoted as PD1, PD2 and PD3, which measure the relative phase drifts ϕ_1, ϕ_2 and ϕ_3, respectively. The phase of a remote RF source should be shifted by ϕ_{drift} given by

$$\phi_{drift} = \phi_1/2 + \phi_2/2 + \phi_3 \quad (1)$$

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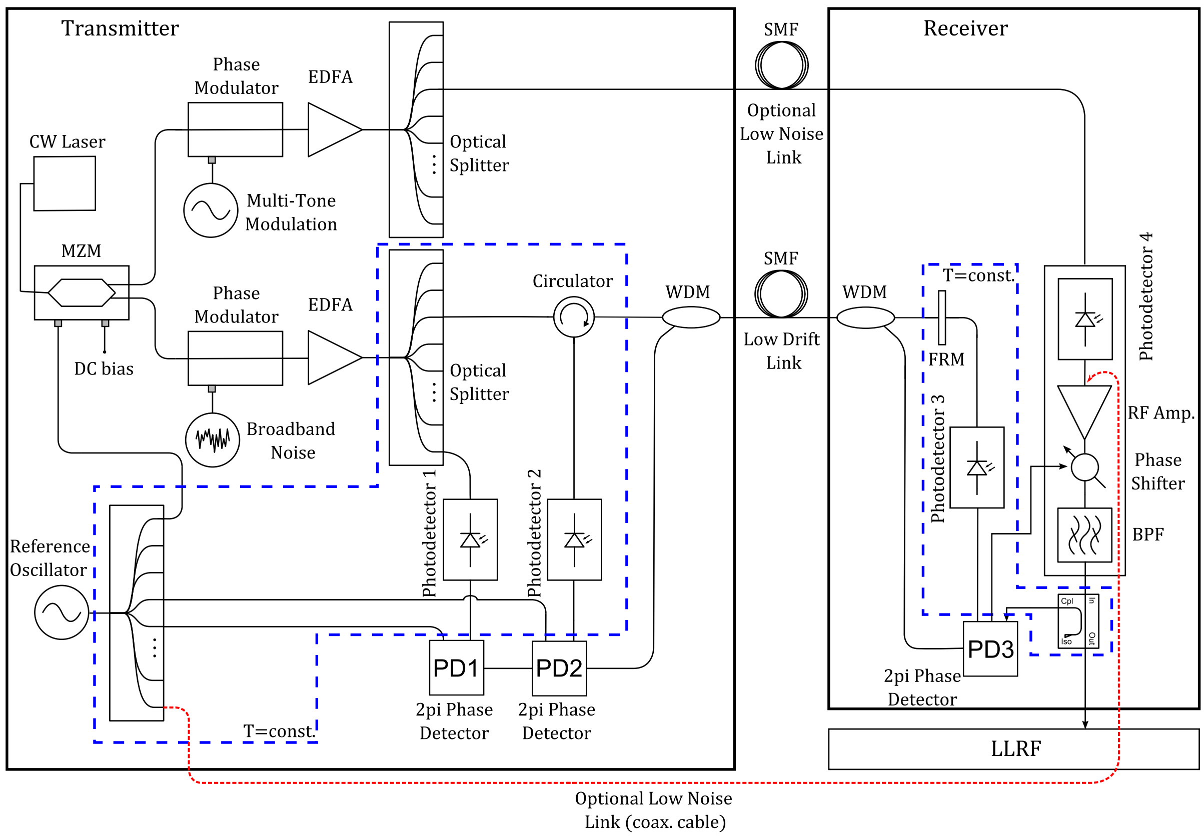

Figure 1: Simplified block diagram of the designed CW optical distribution system.

to be in the synchronization state with the reference oscillator. The drift values are sent digitally from the transmitter to each receiver over the SMF involving the WDM technique.

Phase drifts of a few components, located in blue, dashed frames in Fig. 1, can not be measured and calibrated. Any asymmetric timing variations between output signals of the electrical and optical power splitters lead directly to the synchronization inaccuracies. Phase drifts in the circulators, FRMs and photodetectors result in the PRDS performance degradation as well. Therefore, these components are located in a sealed housing that is actively temperature controlled using a Peltier thermoelectric module and passively humidity stabilized using silica gel beads.

PHASE DETECTOR

The phase detector, discussed in detail in [3] and shown schematically in Fig. 2, is based on a direct RF-sampling dual-channel analog-to-digital converter (ADC) and it features a femtosecond measurement precision over 2π RF signal phase change. Hence, the propagation time can be determined with high precision at all times and sent to a remote receiver where the phase of e.g. a remote RF source can be corrected. Phase correction of the remote RF source can be implemented electronically e.g. by tunning the oscillator frequency or by shifting phase involving a phase shifter or a vector modulator. Alternatively, if no direct phase correction is required, e.g. in digital RF control systems of particle accelerators, the correction can be applied digitally. This advantageously gets rid of the need of cost intensive active link techniques compensating the fiber drift, e.g. piezo-driven fiber stretchers.

A non-I/Q algorithm is used to calculate phase from the RF signal samples. The I/Q demodulation consists of three main steps: down-mixing, low-pass filtering and decimation. The real-valued RF signal is multiplied ("mixed") with two sinusoid signals with 90° phase difference. After down-mixing the signal is low-pass filtered using a FIR filter. The filter bandwidth limits the phase correction bandwidth, which is usually set to be below 10 kHz due to slow phase variations caused by environmental changes.

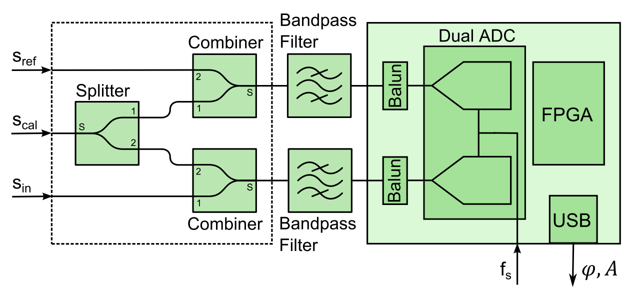

Figure 2: Simplified scheme of the 2π phase drift detector with a two-tone calibration circuit.

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Phase detectors are used to measure relative phase drift between the measured signal s_{in} and the reference signal s_{ref}. Since the relative phase drift is measured, the absolute stability of each detector channel is not critical. The developed phase detector uses a dual channel ADC having both analog-to-digital converters implemented on the same semiconductor substrate. Inside of a single chip temperature variations and ADC input clock changes are common for both channels, which allows for ultra-stable phase difference measurements.

Temperature and humidity drifts of the ADC front-ends comprising attenuators, band-pass filters, RF transformers and microstrip lines (or RF wires) are not perfectly correlated and they decrease long-term measurement stability. To eliminate these potential drifts a two-tone calibration method described in [4] was implemented. For drift calibration a special circuit (a head) with a power splitter and two combiners is applied, which is located in a temperature and humidity stabilized housing. Second RF signal (second tone) s_{cal}, which is synchronized with the signals s_{in} and s_{ref} is fed to the calibration circuit. The combiners are used for combining the measured signal s_{in} and the reference signal s_{ref} with an RF calibration signal s_{cal}. Since the calibration unit can be built drift free, errors in the analog front-ends can be detected through the second tone and digitally corrected.

DISTRIBUTION OF LOW PHASE NOISE RF SIGNALS

RF signals at the remote locations do not have to be generated locally, which is not cost-effective due to the considerable cost of a high performance RF source, but they can be generated once in the transmitter and sent to the distant devices applying coaxial cables or optical-fiber links. The simplest way for the RF signal transmission is the connection of the reference oscillator with the remote electronics via a long coaxial cable that is shown in Fig. 1 (red, short-dashed line). However, coaxial cables have a few disadvantages in comparison to optical fibers like high insertion loss (increasing fast with the frequency), high-cost and the connection of distant devices can cause large ground loops. Therefore, the coaxial cables are usually used to transmit low-noise RF signals up to several hundred meters with the maximum frequency of a few GHz.

The second method for transmitting a low-jitter RF signal is the fiber-optic link. Due to the low loss of SMFs, the relatively high bandwidth of optical components and immunity to electrical interference, RF signals with frequencies up to dozens of GHz can be sent for distances of tens of km applying the RF-over-fiber technique that is shown in Fig. 1. The intensity-modulated light is coupled from the dual output MZM to the multi-tone phase modulation unit for the reduction of Rayleigh and Brillouin scattering. Next, the light is amplified in the EDFA and split to multiple fiber-optic links transmitting optical signals to remote receivers. After direct demodulation in the photodetector "4", the electrical signal is amplified and further its phase is corrected to be constant in relation to the reference oscillator. Next, the RF signal is bandpass filtered using an ultra-narrowband filter to remove harmonics/intermodulation products and to decrease the noise floor. Residual timing jitter of the transmitted RF signals depends on the fiber length and the signal frequency. It was measured that the residual timing jitter is lower than 10 fs rms (integrated from 10 Hz to 1 MHz) for the distances up to 10 km and for the RF signal frequency of 1.3 GHz, which is shown in Fig. 3.

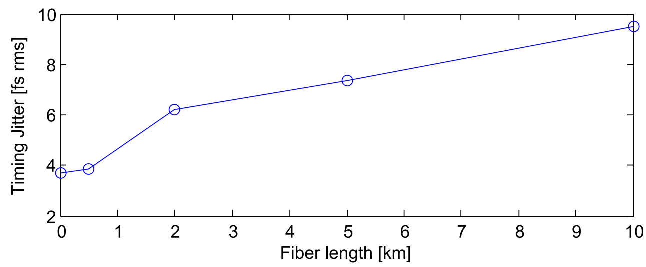

Figure 3: Residual timing jitter integrated from 10 Hz to 1 MHz versus optical fiber length measured with an RF signal of 1.3 GHz.

DESIGN ISSUES FOR ACHIEVING HIGH PRDS PERFORMANCE

In the text above, the new concept of the distribution system for synchronizing remote devices is described. However, to fulfill stringent long-term and short-term stability requirements several engineering and scientific issues had to be considered. Some of them are shortly introduced in this section, but the detailed description is going to be publish elsewhere.

Signal-to-noise ratio (SNR) of the RF signal at the output of the fiber-optic link is decreased by several noise sources like thermal noise of resistive components, shot-noise of photodiodes, relative intensity noise (RIN) of active optical devices (laser source, EDFA). The trade-offs had to be found between the noise reduction and the cost-intensity (or the complexity). The model of the RF-over-fiber link was developed to optimize the performance of the transmitted microwave signals.

Another noise source is the optical fiber, which is susceptible to various linear and nonlinear impairments. The most important linear impairments are chromatic dispersion, polarization mode dispersion (PMD), polarization dependent loss (PDL) and Rayleigh scattering. The nonlinear effects depend on the light intensity and they lead to the generation of new optical frequencies. The potential nonlinear timing error sources in the designed PRDS are stimulated Brillouin scattering (SBS) and self-phase modulation (SPM).

Rayleigh scattering is the scattering of light from non-propagating density fluctuations (molecular vibrations of material), which cause slight modulation of the refractive index [5]. Double backscattered light, called double Rayleigh backscattering (DRB), interferes with the forward propa-

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gating light and due to optical signal phase noise is interferometrically converted to intensity noise, which is called interferometric phase-to-intensity noise conversion. This noise is effectively reduced by wideband and multi-tone modulation of an optical carrier, which lead to the redistribution of noise energy from baseband to higher frequencies [6]. At high frequency, noise is removed by filtering.

Electromagnetic field applied to a fiber generate acoustic waves (through electrostriction), which in turn cause a periodic modulation of the refractive index. The resulting refractive index grating scatters light through Bragg diffraction [7], which is called the stimulated Brillouin scattering. The SBS is completely removed applying the same methods that are used for the reduction of Rayleigh scattering.

SMF fibers feature various deformations and experience external mechanical stress such as bends or twists. This causes birefringence - a slight difference in the propagation constants of both polarization modes, which propagate at different speeds according to a slow and fast axis. These polarization effects degrade the light transmission primarily due to two polarization phenomena as polarization mode dispersion (PMD) and polarization dependent loss (PDL) [8]. PDL causes light intensity fluctuations, which are diminished by a PID control loop involving a variable optical attenuator (VOA). Such a feedback loop is placed in front of each photodiode to reduce the AM/PM conversion (discussed below) and to get the stable amplitude RF signal at the output of the photodiode. PMD causes that light velocity is different for different states of polarization (SOP), which change randomly in time. Currently, the PMD is one of the most important factors limiting the long-term PRDS stability. For long fibers, longer than the correlation length of the birefringence, the PMD value is porportional to $D_p\sqrt{L}$, where L is the fiber length and D_p the coefficient depending on the fiber type. D_p of the best SMFs is of the order of $40\,\mathrm{fs}/\sqrt{\mathrm{km}}$ [9].

Due to the chromatic dispersion, propagation velocities of the optical signal carrier and the modulation sidebands are different, which results both in a SNR penalty [10] and the conversion of laser phase noise to intensity noise (PM-AM conversion). It was calculated that as far as the transmission distance is up to 15 km and the RF modulation frequency is below 10 GHz the SNR penalty due to chromatic dispersion is negligibly small. The discussion about the PM-AM conversion exceeds the scope of this paper - interested readers may found more information in the reference [11].

One of the challenges in the generation of low-noise and low-drift microwave signals is the conversion of optical power fluctuations into phase fluctuations of an electrical microwave signal by a photodiode [12]. However, it mainly concerns the systems in which short optical pulses are detected - a photodiode exhibits highly nonlinear operation under the illumination by high peak-power optical pulses. In the PRDS, the phase-stable conversion is possible by selecting a low AM-PM photodiode and additionally by stabilizing the optical power utilizing the feedback loop, which was already mentioned above.

For achieving the femtosecond synchronization accuracy several other issues must be considered, e.g. frequency stability of the reference oscillator, the directivity of the circulator, the reflections from various optical and electrical components, power supply noise, mechanical vibrations, etc.

EXPERIMENTAL RESULTS OF THE LONG-TERM STABILITY MEASUREMENT

The long-term stability of the PRDS prototype was evaluated using a 500-m length, 3-mm jacketed SMF spool. The transmitter and the receiver were located in a climatized laboratory, in which temperature was stabilized with an accuracy of ±0.1 °C. The sensitive components inside the blue, dashed frames in Fig. 1, discussed earlier in this paper, were additionally temperature and humidity stabilized with the accuracy of about $T = \pm 5\,\mathrm{m°C}$ and $RH = \pm 0.1\,\%$. The fiber spool was kept outside the climatized laboratory and its temperature fluctuated by about 1.2 °C. Phase drift of the RF signal at the output of the fiber link in relation to the reference oscillator equals about 24.6 ps over 50 h, which is presented in Fig. 4 a. The PRDS precision with the 500-m fiber-optic link is measured to be about 35 fs pk-pk (moving average over 1 hour) that is shown in Fig. 4 b. The phase drift reduction factor equals 703.

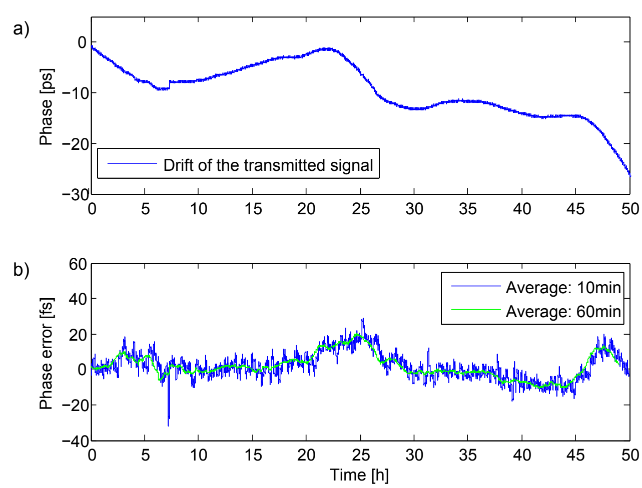

Figure 4: a) Phase drift of the 1.3 GHz signal at the output of the fiber link in relation to the reference oscillator and b) the PRDS accuracy measured with the 500-m SMF.

SUMMARY

The paper presents the cost-effective solution both for the synchronization of distant devices that can be separated by tens of kilometers and for the distribution of low-noise RF signals ranging from about 100 MHz up to several GHz. In the new concept, the intensity modulated light is split to

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many remote receivers. Since the relatively expensive components in the transmitter are used only once for multiple fiber-optic links, this solution is cost-effective and attractive for a variety of applications. Moreover, the calibrated drift-free direct RF-sampling phase detectors feature a femtosecond phase measurement precision over 2π RF phase change. Therefore, the fiber link round-trip propagation time can be determined with femtosecond precision at all times without the need of cost-intensive active link stabilization techniques.

In the paper, the new concept of the CW laser based distribution was presented. Various technical and physical issues influencing the PRDS performance were shortly introduced. The short-term and long-term stability of the built prototype was evaluated. The system can distribute microwave signals at the distance up to 10 km with the residual timing jitter below 10 fs rms. The long-term synchronization precision equals 35 fs pk-pk measured with a 500-m standard SMF.

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REFERENCES

[1] M. Bousonville and J. Rausch. Valocity of signal delay changes in fibre optic cables. In *Proc. of DIPAC09*, pages 248–250, Basel, Switzerland, May 2009.

[2] C. Sydlo et al. Femtosecond timing distribution for the European XFEL. In *Proc. of FEL2014*, pages 1–5, Basel, Switzerland, August 2014.

[3] S. Jablonski, K. Czuba, F. Ludwig, and H. Schlarb. 2π low drift phase detector for high-precision measurements. *IEEE Trans. Nucl. Sci.*, 62(3):1142–1148, June 2015.

[4] G. Huang, L. R. Doolittle, J. W. Staples, R. Wilcox, and J. M. Byrd. Signal processing for high precision phase measurements. In *Proc. of BIW10*, pages 375–378, Santa Fe, USA, May 2010.

[5] R. W. Boyd. *Nonlinear Optics*. Elsevier, 3 edition, 2008.

[6] P. K. Pepeljugoski and K. Y. Lau. Interferometric noise reduction in fiber-optic links by superposition of high frequency modulation. *J. Lightwave Technol.*, 10:957–963, July 1992.

[7] A. Yeniay, J. M. Delavaux, and J. Toulouse. Spontaneous and stimulated brillouin scattering gain spectra in optical fibers. *J. Lightwave Technol.*, 20(8):1425–1432, Aug 2002.

[8] E. Collet. *Polarized Light in Fiber Optics*. Polawave Group, New Jersey, 2003.

[9] Corning. Corning leaf optical fiber. `http://www.corning.com/WorkArea/showcontent.aspx?id=63927`, 2014.

[10] U. Gliese, S. Norskov, and T. N. Nielsen. Chromatic dispersion in fiber-optic microwave and millimeter-wave links. *IEEE Trans. Microw. Theory Techn.*, 44(10):1716–1724, Oct 1996.

[11] S. Yamamoto et al. Analysis of laser phase noise to intensity noise conversion by chromatic dispersion in intensity modulation and direct detection optical fiber transmission. *J. Lightwave Technol.*, 8:1716–1722, Nov 1990.

[12] J. A. Taylor et al. Characterization of power-to-phase conversion in high-speed p-i-n photodiodes. *IEEE Photon. J.*, 3(1):140–151, Feb 2011.

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