TWO COLOR BALANCED OPTICAL CROSS CORRELATOR TO SYNCHRONIZE DISTRIBUTED LASERS FOR SHINE PROJECT*

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Abstract

The planned Shanghai high repetition rate XFEL and extreme light facility (SHINE) generate X-ray light pulses in femtosecond range. For photoinjector drive laser, seed laser, and time resolved pump-probe experiments it is crucial to synchronize various slave laser oscillator to the master reference laser with a long term stability of better than 10 fs. For this purpose two color balanced optical cross correlator for locking slave laser to master laser is under developing.

In this paper, we report on the progress of the development of a background free two color balanced cross correlator (TCBOC) to synchronize 800 nm slave laser to 1550 nm master laser. The synchronization system is being tested by linking a commercial Ti:sapphire oscillator to a locally installed timing reference source.

INTRODUCTION

At present, FELs are the only facilities that can generate bright, coherent hard X-ray pulse with temporal durations below 100 fs and up to 10^{13}photon per pulse [1]. High precision timing synchronization systems are critical for FELs because X-ray temporal duration is highly sensitive to the overall synchronization between the injector laser, the Linacs, and the bunch compressors. Moreover, for the seeded FELs, timing jitter between the seed laser and the electron bunch must be minimized. Finally, the relative timing jitter between the FEL output and the pump laser must be controlled with a precision better than the FEL pulse duration for pump probe experiments aiming high temporal resolution [2].

The optical synchronization system for SXFEL and under consideration for the SHINE is based on an ultra-stable mode locked master laser locked to a low noise RF oscillator generating hundreds of fs light pulse of 1550 nm. The master laser is phase locked to the low noise RF master oscillator of the accelerator to ensure stable operation and small jitter. The timing information is contained in the precise repetition frequency of 238 MHz of the pulse train and distributed via actively length stabilized fiber links to remoted locations.

Recently, one scheme has been demonstrated that pulsed-optical timing stability distribution system using polarization maintaining fibers can deliver sub femtosecond timing stability over kilometer-scale distances [2]. One of the key components of the synchronization system is the two color balanced cross correlator (TCBOC) which provides a method to lock slave laser systems to the timing reference with less than 10 fs accuracy [3]. This balanced

optical cross correlation scheme was firstly suggested by Franz X. Kärtner group to perform pure timing measurements in the optical domain [4], and have been developed to achieve sub femtosecond precision [5-7].

PRINCIPLE OF TWO COLOR BALANCED CROSS CORRELATOR

FH: Fundamental harmonics of input pulses; DM: Dichroic mirror; HM: high reflective mirror; GVD: Silica slab for group velocity delay.V1 and V2: output voltage from photodetector.

The principle of two color balanced cross correlator is shown in Fig. 1. Two optical pulses with different central wavelength are input to a BBO crystal in a forward pass and reverse pass configuration, where one pulse is from the master laser and the other pulse is from slave laser. A third light pulse of their sum frequency will be created when they overlap spatially and temporally. As they propagate through the BBO crystal, they walk through each other due to different group velocity. Therefore, different amount of sum frequency light is generated depending on their temporal overlap in the forward and reverse pass. The generated sum frequency pulses are separated from input pulses by dichroic mirror and measured by two identical channels of a balanced photodetector. Therefore, the difference of the sum frequency pulse cancels the intensity fluctuations of input pulses, and the generated voltage signal is only proportional to the time separation of input pulses. Base on this principle, one can detect timing fluctuations significantly smaller than the pulse duration itself. Another advantage it that this method is immune to temperature variations due to the timing detection is performed directly in the optical domain.
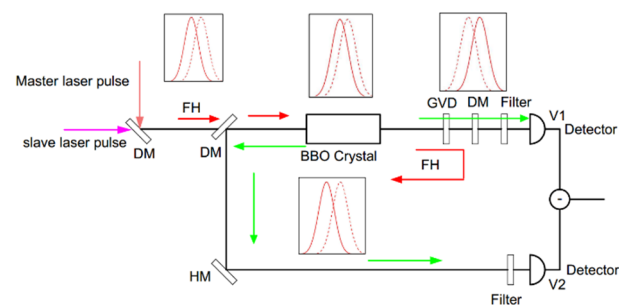

Figure 1: Principle of timing detection using TCBOC.

Supposing two Gaussian-shaped input pulses with their intensities $I_1(t)$ and $I_2(t)$, the intensity of generated sum frequency light is expressed by the convolution of the two input pulses:

$$I_{sum}(t) \propto \int_{-\infty}^{\infty} I_1(\tau)I_2(t-\tau)d\tau \qquad (1)$$

Where τ is the time delay between the two input pulses. Eq. (1) can be described by

$$I_{sum}(t) = \frac{1}{\sqrt{2\pi(\sigma_1^2+\sigma_2^2)}} exp\left\{-\frac{(t-\Delta t)^2}{2(\sigma_1^2+\sigma_2^2)}\right\}, \qquad (2)$$

where $I_{sum}(t)$ is highly sensitive to variation of relative timing Δt between the two input pulses. Therefore, intensity changes of sum frequency pulse is a measure for the timing changes.
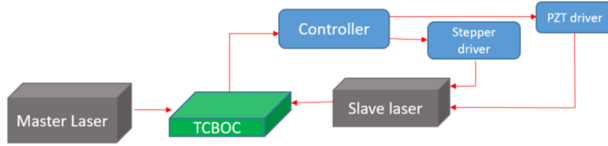

Figure 2: Schematic of TCBOC feedback control system to synchronize the pulse trains of two ultrafast laser at different wavelength.

In order to synchronize Ti:sapphire laser oscillator to the master laser, an feedback control loop is developed as described in Fig. 2. The TCBOC is used as high precision timing detectors. The voltage signal generated from the TCBOC is used as a feedback signal to control the frequency of the slave laser oscillator via its step motor and intra-cavity PZT shown in Fig. 3. Once the feedback control is running, it will pull the frequency of the slave laser f_S oscillator closer to that of the master laser f_M which will stretch the period response curve in time. As shown in Fig. 3, once frequency difference Δf is sufficiently small ($\Delta f \ll f_M$), the phase lock loop will operate in the linear region of the detector output and lock the slave oscillator's frequency by suppressing the error voltage as tightly as possible to zero. Once a stable locking is achieved, the TCBOC output will be a DC voltage.
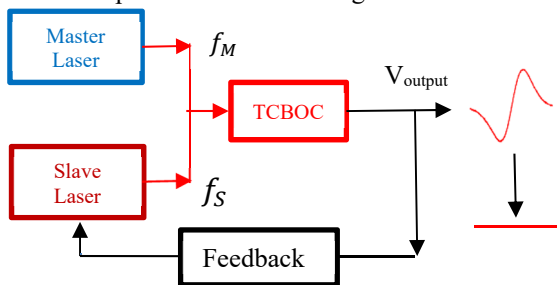

Figure 3: Operating principle of frequency synchronization using TCBOC.

As shown in Fig. 3, pulse trains from the master laser and slave laser with small repetition rate difference ($\Delta f \ll f_M$) are sent to the TCBOC to measure their relative timing error. The repetition period difference ΔT between the two pulse trains can be expressed as

$$\Delta T = \frac{1}{f_M} - \frac{1}{f_M+\Delta f} = \frac{\Delta f}{f_M^2 + f_M\Delta f} \approx \frac{\Delta f}{f_M^2} \qquad (3)$$

Eq. (3) shows that the pulse trains temporally move with respect to each other by ΔT in every time period T_M of

Master pulse [2]. As a result of this temporal pulse "sliding", the TCBOC generates a cross correlation signal every time the pulses coincide. Therefore, the output signal of TCBOC can be recorded by an oscilloscope and measure the slope of the cross correlation at the zero crossing point with unit mV/s. However, the recorded time scale has to be converted to the relative time scale between the pulses, which can be expressed as

$$\xi = \frac{\Delta f}{f_M} \qquad (4)$$

EXPERIMENT SETUP

As shown in Fig. 4, the 1550 nm $\pm$ 10 nm pulses with a repetition rate of 238 MHz and power of 17.7 mW is from a stabilized polarization maintaining fiber link, which is provided by Cycle company. The 800 nm $\pm$ 40 nm pulse is from Ti:sapphire laser oscillator(Micra, Coherent) which has a repetition rate of 79.33 MHz and 45 mW power. In order to reduce the fiber dispersion influence, 800 nm pulses is reflected into the TCBOC system through free space. Beta barium borate (BBO) with a thickness 5 mm was chosen for the generation of 527 nm sum frequency signal. The phase match angle is calculated to be 22.2° according to Sellmeier equation for the used collinear type-I configuration(ooe) [8]. A free space balanced amplified photodetector (PDB210A/M, Thorlabs) with gain of 500×10^3 V/A was chosen for measure the sum frequency signal and corresponding signal difference. This detector acts as balanced receivers by subtracting the two optical input signals from each other, resulting in the cancellation of common mode noise, which allows small changes in the signal path to be extracted from the interfering noise floor.
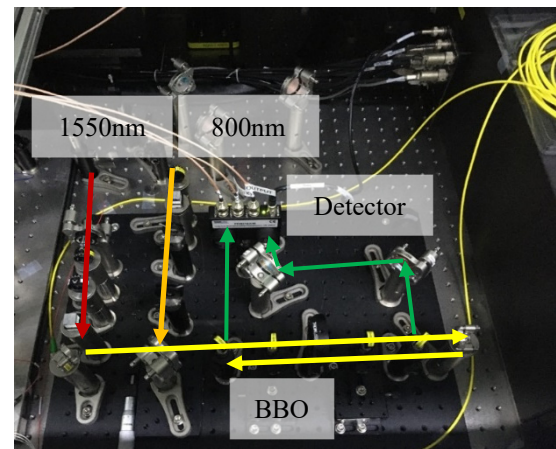

Figure 4: Experimental setup of two color balanced cross correlator.

MEASUREMENT RESULTS AND DISCUSSIONS

When two input pulses are combined and propagate through the BBO crystal in forward direction, 527 nm sum frequency signal is produced shown in Fig. 5 red curve. As the two pulses are reflected back and propagate through the

BBO crystal again, 527 nm sum frequency signal is generated shown in Fig. 5 blue curve. The real time scale in Fig. 5 is obtained by multiplying the time scale of the oscilloscope by a ratio of the repetition rate difference 3.3 Hz to the repetition rate of the master laser 238 MHz.
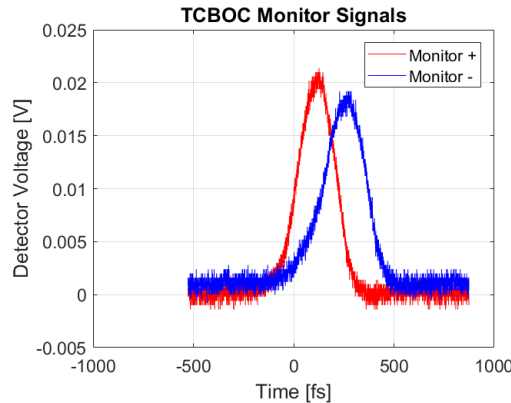

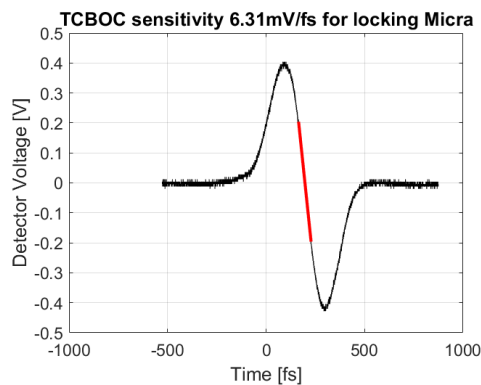Figure 5: Measured 527 nm sum frequency signal intensity on a balanced detector.

Figure 6: Measured difference signal by two color balanced optical cross correlator. The slope of red part curve is 6.31 mV/fs around zero crossing.

Figure 6 shows the difference signal generated from TCBOC. The sensitivity of the curve is calculated by selecting the red part of the curve, which given a voltage difference 0.4 V and time difference 63.3 fs. Therefore, we extract a slope around the zero crossing of 6.31 mV/fs, which is sufficient for the feedback control loop.

Further investigation of this will include careful characterization of all the input pulse length in the setup and changing the group delay glass accordingly.

CONCLUSION

An two color balanced cross correlator was developed and tested, which will be used to phase lock two individual laser systems operating at different center wavelength and different repetition rates. The repetition rate between the master laser and the slave laser has to be a harmonic of the other's. At present, difference signal of sum frequency have been obtained, which shows a sufficient slope around zero crossing for phase locking. The next step is to make short and long term stability measurements with an identical out of loop TCBOC.

In the future, this TCBOC system will be reassembled and upgraded from breadboard setups to a professionally engineered version, which promises long term stability, user friendly operation and low maintenance.

The same type of two color balanced cross correlator can be used for laser system of SHINE project, such as drive laser, seed laser as well as pump probe laser, which presumably only requires BBO crystal with different cutting angle.

ACKNOWLEDGEMENTS

REFERENCES

[1] Kemal Safak *et al*., "A pulsed-optical timing distribution system for LCLS-II", in *Proc. Conference on Lasers and Electro-Optics (CLEO'20)*, Washington, DC, United States, May, 2020. doi:10.1364/CLEO_SI.2020.SM2N.5

[2] Kemal Shafak, "Large-scale laser microwave synchronization for attosecond photon science facilities", Ph.D. thesis, Universität Hamburg, Hamburg, Germany, 2017.

[3] S. Schulz *et al*., "An optical cross correlation scheme to synchronize distributed laser systems at FLASH", in *Proc. 11th European Particle Accelerator Conf. (EPAC'08)*, Genoa, Italy, June, 2008, paper THPC160, pp. 3366-3368.

[4] T. R. Schibli *et al*., "Attosecond active synchronization of passively mode-locked lasers by balanced cross correlation", *Opt. Lett.*, vol. 28, no.11, pp. 947-949, 2003.

[5] J. Müller *et al.*, "Large-scale optical synchronization system of the European XFEL", in *Proc. 29th Linear Accelerator Conf. (LINAC'18)*, Beijing, China, September, 2008, paper MOPO121, pp. 253-256.

[6] Ming Xin *et al*., "Sub femtosecond precision timing synchronization systems", *Nuclear Inst. and Methods in Physics Research, A*, vol. 907, pp. 169-181, 2018.

[7] Kemal Safak *et al*., "Large-scale turkey timing distribution system for attosecond photon science facilities", in *Proc. Conference on Lasers and Electro-Optics (CLEO'17)*, San Jose, CA, United States, May, 2017. doi:10.1364/CLEO_AT.2017.JTu4L.3

[8] C. L. Li, L. Feng, B. Liu, X. T. Wang, and W. Y. Zhang, "Measurements of Ultraviolet FEL Seed Laser Pulse Width Broading in Thin ß-BBO Crystals", in *Proc. 9th Int. Beam Instrumentation Conf. (IBIC'20)*, Santos, Brazil, Sep. 2020, pp. 140-144. doi:10.18429/JACoW-IBIC2020-WEPP20