Long-term femtosecond timing link stabilization using a single-crystal balanced cross-correlator

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We demonstrate a self-aligned balanced cross-correlator based on a single type-II phase-matched PPKTP crystal. The birefringence of the crystal generates a walk-off between the two orthogonally polarized pulses. This enables the balancing of the cross-correlator with input pulses at the same center wavelength. As a first application of this single-crystal balanced cross-correlator, we stabilized a 310-meter long optical fiber link for timing distribution with long-term stable 10-fs precision.

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Precise optical timing distribution to remote locations is important for large-scale facilities requiring high-precision synchronization, for example, seeded x-ray free electron lasers [1] and phased-array antennas [2]. It is also crucial for the optical time/frequency standard distribution over long distances [3-5]. Acoustic noise and thermal drifts introduced to the fiber involved in the distribution must be cancelled by a proper feedback loop. So far, electronic techniques based on high-speed photodetectors and microwave mixers are used to stabilize fiber links on a rather short-term time scale [6,7]. The limited timing resolution as well as thermal drifts of microwave components makes it difficult to stabilize links better than 100 fs in a long-term stable way.

To overcome these limitations set by the performance of microwave components and techniques, it is highly desirable to use optical cross-correlation techniques [8] for high-resolution and drift-free detection of timing errors between two optical pulses. In particular, a balanced cross-correlation configuration [9] is preferred to suppress the laser amplitude noise. Previously, a balanced cross-correlator for long-term (>12 hours) sub-fs synchronization of two independently mode-locked lasers operating at different center wavelength was demonstrated [9,10]. However, this method is limited to the case of optical pulses with different center wavelengths because the delay between the two input pulses is generated by group delay dispersion (GDD). It is not applicable to the case when the two optical pulses have the same center wavelength, such as the timing link stabilization or synchronization of the two lasers operating at the same center wavelength.

In this Letter, a single type-II phase-matched PPKTP crystal is used to construct a compact and self-aligned balanced optical cross-correlator for precise timing detection. We use the timing error signal generated from this balanced cross-correlator, which is robust against intensity noise

and temperature drifts, to stabilize a 310-meter long fiber link. In a first experimental demonstration, long-term 10-fs level stabilization is achieved.

The balanced cross-correlator presented in this Letter consists of (a) generation of a group delay difference between two orthogonally polarized – otherwise identical – pulses, and (b) broadband second-harmonic generation (SHG) by a type-II phase-matched nonlinear crystal. Using the group delay resulting from the birefringence between the two orthogonal polarizations in the crystal enables the implementation of balanced cross-correlation at the same wavelength. The detected signal is background free, i.e., if the pulses do not overlap in time, the detector signal is vanishing. Moreover, the group delay and the SHG functions can be combined in a single nonlinear crystal. For construction of a cross-correlator at 1550 nm, the use of a PPKTP crystal is especially advantageous because of the extended phase-matching bandwidth of 100 nm centered at 1550 nm [11].

For collinear type-II phase-matched SHG under optimum focusing conditions, we obtain the following optimum conversion efficiency:

$$\eta_{opt} = \frac{8\pi^2 Z_0}{\lambda^3} \frac{d_{eff}^2}{n^3} 5.68 \cdot l \cdot \frac{P_{peak,in}}{\sqrt{2}}$$

where $Z_0 = \sqrt{\mu_0 / \epsilon_0}$ is the free-space characteristic impedance, λ is the wavelength of the input, d_{eff} is the effective nonlinear coefficient, n is the refractive index of the nonlinear crystal, l is the walkoff length, and $P_{peak,in}$ is the peak power of the input pulse. For input pulses with 200-fs pulsewidth and 77-pJ pulse energy at 1550 nm, the optimum conversion efficiency of PPKTP is calculated as $\eta_{opt,PPKTP} \approx 8 \times 10^{-3}$. The measured efficiency with a 5-mm long PPKTP crystal with a poling period of 46.2 μm is $\eta \approx 60 \mu\text{W} / 15 \text{mW} = 4 \times 10^{-3}$, which shows a fairly good agreement with the optimum theoretical efficiency.

Figure 1 (a) shows the operation of the single-crystal balanced cross-correlator. The input pulses are transmitted through a first dichroic beamsplitter which transmits the input pulses but reflects the SHG of the input pulses. The pulses are focused into a type-II phase-matched PPKTP crystal. The generated SHG component is transmitted through the second dichroic mirror and detected by photodiode 1 in the balanced detector. The remaining fundamental input pulses are reflected from the dichroic mirror and again focused into the PPKTP crystal. The SHG component generated by the back-reflected pulses is separated by the dichroic beamsplitter and detected by photodiode 2 in the balanced detector. At the balanced detector output, a signal proportional to the relative position between the two input pulses is extracted. Figure 1 (b) shows the measured autocorrelation trace of a 77 pJ, 200-fs pulse at 1550 nm using a balanced cross-correlator with a 5-mm long PPKTP crystal (poling period = 46.2 μm).

Figure 2 shows the schematic for a 310-meter timing stabilized link using the single-crystal balanced cross-correlator. A 194-MHz soliton Er-doped fiber laser [12] is used as the optical pulse source. The output power is 40 mW and the pulsewidth is 200 fs. Part of the input pulse train is tapped off by a polarizing beamsplitter cube (PBC 1 in Fig. 2) to the out-of-loop characterization setup. The other part of the light is transmitted through a 310-meter long dispersion-compensated fiber link containing a piezo-stretcher. The fiber link is comprised of ~40 meter of dispersion-compensating fiber (DCF) ($D_2 \approx -114.3 \text{ ps}^2/\text{km}/\text{nm}$) and ~270 meter of SMF-28 fiber ($D_2 \approx +17 \text{ ps}^2/\text{km}/\text{nm}$). Half of the link-transmitted pulses are back-reflected by a 50:50 Faraday rotating mirror (FRM) at the end of the fiber link. With the FRM, the polarization state of the returning pulse is orthogonal to that of the input pulse, which enables 100 % transmission through PBC 2 (in Fig. 2). Due to the coupling loss to the collimator, the splicing loss between DCF and SMF-28 fiber and the insertion loss inside the FRM, the loss is more than

10 dB for the reflected pulses compared to the input pulses. To compensate those losses in the transmission, we used an Er-doped fiber amplifier (EDFA) at the end of the fiber link. The reflected pulse (measured pulsewidth ~ 420 fs) is combined with the fresh pulse directly from the laser at the polarizing beamsplitter cube (PBC 2 in Fig. 2). The combined pulses are applied to the balanced cross-correlator (balanced cross-correlator 1 in Fig. 2). The error signal generated from the balanced cross-correlator is regulated by a loop filter and applied to the piezo-stretcher in the link via a high-voltage piezo driver. This closes the timing stabilization loop. When it is locked, the timing fluctuation introduced to the fiber link is compensated by the counteraction of the piezo stretcher. To evaluate the out-of-loop performances, a second balanced cross-correlator (balanced cross-correlator 2 in Fig. 2) is used to compare the transmitted pulses through the 310-meter link with fresh pulses directly from the mode-locked laser.

Figure 3 summarizes the measurement result of the stabilized fiber link. Figure 3 (a) shows the out-of-loop timing jitter spectral density in units of $\text{fs}/\sqrt{\text{Hz}}$. The out-of-loop rms-timing jitter integrated from 10 Hz to 100 kHz (detector bandwidth) is 9.2 fs, where the detector background noise corresponds to 8.2 fs. The top trace of Figure 3 (b) shows the long-term out-of-loop timing jitter trace over 100 seconds measured with an oscilloscope. The rms-value of this measurement confirms the stabilization to a precision of 9.7-fs. The jitter analysis was mainly limited by the limited signal-to-noise ratio of the detection. With a higher optical power level and/or lower losses in the fiber link as well as a lower noise balanced photodetectors, it is clearly possible to improve the locking performance as well as the measurement resolution. The bottom trace of Figure 3 (b) shows the displacement of the piezo stretcher in the fiber link during the same time frame. The fiber link used in this experiment is not temperature, vibration, nor airflow stabilized, and the locking is broken purely by the limited displacement range of the piezo stretcher we used

($\sim 700\text{ }\mu\text{m}$, corresponding to 2×10^{-6} length fluctuation of the whole fiber link). With additional manual adjustment of the translation stage, we could keep the lock for more than one hour. To our best knowledge, this result is the first long-term 10-fs level stabilization of a fiber link. It also indicates that adding a motorized translation stage and polarization control at the end of the fiber will enable to maintain this level of accuracy in synchronization as long as desired.

In summary, we have demonstrated a self-aligned, single-crystal balanced cross-correlator comparing the timing between optical pulses at the same center wavelength. As a first application of this single-crystal balanced cross-correlator, we demonstrated long-term 10-fs precision stabilization of a 310-meter fiber link. The potential applications of the single-crystal balanced cross-correlator include drift-free sub-fs synchronization of two lasers operating at the same center wavelength, fiber link stabilization for large-scale timing distribution, and high-frequency timing jitter measurements of mode-locked lasers [13]. It is also possible to implement a compact balanced cross-correlator as a fully packaged waveguide device using periodically poled waveguide structures in the near future.

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Figure captions

Figure 1: (a) Operation of a single-crystal balanced cross-correlator. SHG: second-harmonic generation. (b) Balanced autocorrelation using 77 pJ, 200-fs pulses at 1550 nm. The trace is clipped by the maximum output voltage of the photodetector (4 V).

Figure 2: Schematic for timing link stabilization using a single-crystal balanced cross-correlator. EDFA: Er-doped fiber amplifier, FRM: Faraday rotating mirror, HWP: half-wave plate, PBC: polarizing beamsplitter cube, QWP: quarter-wave plate, R: reflection, SM: silver mirror, T: transmission.

Figure 3: (a) Measured out-of-loop timing jitter spectral density. The integrated rms-jitter from 10 Hz to 100 kHz is 9.2 fs. The detector noise floor corresponds to 8.2 fs jitter, which sets the limits in measurement accuracy. (b) Long-term out-of-loop timing jitter trace (top trace) and piezo stretcher displacement (bottom trace) over 100 seconds. The rms-jitter over 100 seconds is 9.7 fs.

Figure 1. J. Kim *et al.*

Figure 3. J. Kim *et al.*