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 periodically poled KTiOPO₄ 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 m long optical fiber link for timing distribution with long-term stable 10 fs precision. © 2007 Optical Society of America

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 and phased-array high-precision synchronization, for example, seeded tions is important for large-scale facilities requiring Precise optical timing distribution to remote locations. As a first application of this single-crystal balanced cross correlator, we stabilized a 310 m long optical fiber link for timing distribution with long-term stable 10 fs precision. © 2007 Optical Society of America

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 vanishes. 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 near 1550 nm.

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

$$\eta_{\text{opt}} = \frac{8\pi^2Z_0d_{\text{eff}}^2}{\lambda^3} \frac{n^3}{3} \frac{5.68l}{\sqrt{2}},$$

where $Z_0 = \sqrt{\mu_0/\varepsilon_0}$ is the free-space characteristic impedance, $\lambda$ is the wavelength of the input, $d_{\text{eff}}$ is the effective nonlinear coefficient, $n$ is the refractive index of the nonlinear crystal, $l$ is the walk-off length, and $P_{\text{peak, in}}$ is the peak power of the input pulse. For input pulses with 200 fs pulse width and 77 pJ pulse energy at 1550 nm, the optimum conversion efficiency of PPKTP is calculated as $\eta_{\text{opt, PPKTP}} = 8 \times 10^{-3}$. The measured efficiency with a 4 mm long PPKTP crystal with a poling period of 46.2 μm is $\eta = 60 \mu W/15 mW = 4 \times 10^{-3}$, which shows 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 beam splitter that 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 backreflected pulses is separated by the dichroic beam splitter 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 4 mm long PPKTP crystal (poling period=46.2 μm).

Figure 2 shows the schematic for a 310 m timing stabilized link using the single-crystal balanced cross correlator. A 194 MHz soliton Er-doped fiber laser is used as the optical pulse source. The output power is 40 mW and the pulse width is 200 fs. Part of the input pulse train is tapped off by a polarizing beam splitter cube (PBC 1 in Fig. 2) to the out-of-loop characterization setup. The other part of the light is transmitted through a 310 m long dispersion-compensated fiber link containing a piezostretcher. The fiber link is composed of ~40 m of dispersion-compensating fiber (DCF) \((D_2=-114.3 \text{ ps/km/nm})\) and ~270 m of SMF-28 fiber \((D_2=+17 \text{ ps/km/nm})\). Half of the link-transmitted pulses are backreflected 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 of 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 with the input pulses. To compensate those losses in the transmission, we used an Er-doped fiber amplifier at the end of the fiber link. The reflected pulse (measured pulse width ~420 fs) is combined with the fresh pulse directly from the laser at the polarizing beam-splitter 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 piezostretcher in the link via a high-voltage piezodriver. 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 piezostretcher. 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 m 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 fs/√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 jitter corresponds to 8.2 fs. The top trace of Fig. 3(b) shows the long-term out-of-loop timing jitter trace over 100 s 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 lower noise balanced photodetec-
tors, it is clearly possible to improve the locking performance as well as the measurement resolution. The bottom trace of Fig. 3(b) shows the displacement of the piezostretcher 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 piezostretcher we used (\(700 \mu \text{m}, \text{corresponding to } 2 \times 10^{-6} \text{ length fluctuation of the whole fiber link}\)). With additional manual adjustment of the translation stage, we could keep the lock for more than 1 h. To the best of our knowledge, this result is the first long-term 10 fs level stabilization of a 310 m fiber link. The potential applications of the single-crystal balanced cross correlator include drift-free subfemtosecond 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.\(^5\) 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.

In summary, we have demonstrated a self-aligned, single-crystal balanced cross correlator. As a first application of this single-crystal balanced cross correlator, we demonstrated long-term 10 fs precision stabilization of a 310 m fiber link. The potential applications of the single-crystal balanced cross correlator include drift-free subfemtosecond 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.\(^5\) 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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**References**