Attosecond-resolution timing jitter characterization of free-running mode-locked lasers

Jungwon Kim,* Jeff Chen, Jonathan Cox, and Franz X. Kärtner

Department of Electrical Engineering and Computer Science and Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA
*Corresponding author: jungwon@alum.mit.edu

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Timing jitter characterization of optical pulse trains from free-running mode-locked lasers with attosecond resolution is demonstrated using balanced optical cross correlation in the timing detector and the timing delay configurations. In the timing detector configuration, the balanced cross correlation between two mode-locked lasers synchronized by a low-bandwidth phase-locked loop is used to measure the timing jitter spectral density outside the locking bandwidth. In addition, the timing delay configuration using a 325 m long timing-stabilized fiber link enables the characterization of timing jitter faster than the delay time. The limitation set by shot noise in this configuration is \(2.2 \times 10^{-8} \text{fs}^2/\text{Hz}\) corresponding to 470 as in 10 MHz bandwidth. © 2007 Optical Society of America

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It has been shown, both theoretically and experimentally, that mode-locked solid-state lasers can generate optical pulse trains with ultralow timing jitter [1,2]. Theory predicts that the timing jitter of such lasers at high frequencies (e.g., >100 kHz) is well below 1 fs [3]. However, the characterization of timing jitter of free-running mode-locked lasers with attosecond resolution is a highly nontrivial task. The accurate measurement of the fast noise dynamics in mode-locked lasers is important for optimization of lasers for high-precision applications such as photonic analog-to-digital converters, low-noise microwave signal synthesis, large-scale optical timing distribution, and high-data-rate communications.

The most commonly used characterization technique employing a high-speed photodetector and a microwave mixer [4] suffers from excess phase noise in the photodetection process [5] and the limited timing resolution of microwave mixers. Although interferometric cross correlation [6] has been used for high-resolution timing jitter measurements, it does not measure timing jitter but rather optical phase noise, which may or may not be a consequence of timing jitter. In addition, since the measurement range is much less than an optical cycle, it is strictly not suitable for measuring the timing jitter of free-running lasers.

The use of optical cross correlation is an attractive approach in measuring timing jitter with high sensitivity and sufficient detection range. It also does not involve excess noise in the photodetection. In particular, balanced optical cross correlation [7,8] can precisely extract the timing information without conversion of intensity noise into timing jitter. Since it measures the timing fluctuations between two optical pulses, it directly and accurately determines the timing jitter. Depending on the pulse width and the delay between the two signal paths in the balanced cross correlator, the detection range can span from tens of femtoseconds to more than one picosecond, which provides enough detection range for measuring timing jitter of free-running lasers.

In this Letter, we demonstrate the characterization of the pulse timing jitter spectral density of free-running mode-locked lasers with attosecond resolution using balanced optical cross correlation. Two different methods are demonstrated. The first method, named the timing detector method, is analogous to the phase detector method [9] for phase noise characterization of microwave oscillators. It uses a low-bandwidth (kilohertz range or lower) lock between the two mode-locked lasers and measures the relative timing jitter outside the locking bandwidth with a balanced cross correlator. The second method, named the timing delay method, is the optical equivalent of the delay-line frequency discriminator method [9] used at microwave frequencies. Here, we use a timing-stabilized and dispersion-compensated fiber link as a delay line, and measure the timing jitter between the pulse reflected from the fiber end and the pulse from the laser with a balanced cross correlator. In this way, we can measure the timing jitter of the laser under test from \(f_{\text{delay}}=1/T_{\text{delay}}\) to the Nyquist frequency, where \(T_{\text{delay}}\) is the delay time between the two pulses. By combining these two methods, we could resolve the timing jitter spectral density of free-running mode-locked lasers with attosecond resolution up to 10 MHz bandwidth.

For comparison with the conventional microwave-based technique, we measured the timing jitter spectral density using a high-speed photodetector followed by a commercial signal source analyzer (Agilent E5052B). The signal source analyzer that we used has a low-noise tracking microwave oscillator synchronized to the oscillator-under-test by an internal phase-locked loop (PLL) to enable a direct noise measurement of microwave signals. Figure 1(a) shows the measurement setup, and Fig. 2(b) shows the collection of timing jitter spectral density measurements of a free-running 200 MHz Er-fiber laser (“M-Comb-Custom” from MenloSystems GmbH; “mode-locked laser 1” in Figs. 1 and 2; “laser 1” in the text) with different input optical power and instrument settings. The phase noise of the seventh har-
monic (1.4 GHz) of the fundamental repetition rate is measured. Depending on the input power and the instrument setting, the measured spectra above 10 kHz are significantly different. The high-frequency noise above 300 kHz depends on the input optical power as shown in curves (i)–(iii) in Fig. 1(b). The midfrequency (10–200 kHz) noise shows a dependence on the instrument setting as shown in curves (iii) and (iv) in Fig. 1(b). These measurements indicate that even the most sophisticated commercial microwave techniques are limited in accuracy to ∼10 fs by the combination of excess noise in photodetection, resolution of microwave mixers, and phase noise of synthesizers and PLLs.

To overcome the limitations set by microwave techniques, balanced optical cross correlation is used to implement two independent measurement methods. The first method, the timing detector method, uses a low-bandwidth lock between the two independent lasers to measure the timing jitter spectral density outside the locking bandwidth. In this way, we can measure the sum of the free-running noise of the two lasers used. Figure 2(a) shows the schematic of the timing detector method. The laser under test is a commercial 200 MHz Er-fiber laser (laser 1). The laser used as a reference ("mode-locked laser 2" in Fig. 2; "laser 2" in the text) is a 200 MHz soliton Er-fiber laser similar to the one shown in [2]. Part of the output from each laser is tapped off and detected by a 10 GHz InGaAs photodetector. After bandpass filtering, the two 1.4 GHz signals beat with each other in a mixer, and the downconverted differential phase error is used to lock the repetition rates by a piezoelectric transducer in laser 1. By adjusting the relative delay between the two lasers, the locking point is placed at the linear detection regime of the balanced cross correlation [the inset graph in Fig. 2(a) shows the balanced cross-correlator output when the two lasers are not locked]. The balanced cross correlator is based on a single type II phase-matched periodically poled KTiOPO4 (PPKTP) crystal, which was recently demonstrated in [8]. The balanced photodetector in the cross correlator has a 3 dB bandwidth of 10 MHz. When the two lasers are locked, the voltage noise density from the cross-correlator output is measured by a vector signal analyzer. The voltage noise spectral density is converted into the timing jitter spectral density using the measured slope of the cross-correlation signal when the two lasers are not locked.

The second method, the timing delay method, is illustrated in Fig. 2(b). In the optical implementation, it basically has the same configuration as the timing link stabilization demonstrated in [8], but here we used a 10 MHz balanced photodetector in the cross correlator to monitor the noise in the high-frequency range. If the round-trip delay time of the fiber link is \( T_{\text{delay}} \), we can extract the timing jitter of laser 1 in the frequency range above \( f_{\text{delay}} = 1/T_{\text{delay}} \) from this measurement. For the experiment, a 325 m long dispersion-compensated fiber link is used. The link is timing stabilized with 1 kHz bandwidth to prevent timing drift of the fiber link.

Figure 3 summarizes the measurement results of the timing jitter spectral density. Curves (i) and (ii) show the measurement results for lasers 1 and 2, respectively, when measured by the signal source analyzer [the schematic is shown in Fig. 1(a)]. As discussed in Fig. 1(b), the result depends on the input optical power and instrument settings. For a fair comparison with the optical cross-correlator-based measurement results, in Fig. 3, the best measurement results obtained with the signal source analyzer are included. In the 10 kHz–10 MHz range, the measured noise spectra of lasers 1 and 2 are almost identical, which suggests that these results might be already limited by the instrument resolution.
In the 10–310 kHz range, we can extract the upper limit for the integrated timing jitter of laser 1 as 0.72, 1.02, and 5.19 fs in the 1–10 MHz, 100 kHz–10 MHz, and 10 kHz–10 MHz ranges, respectively. In comparison, the signal source analyzer gives 4.93, 6.10, and 8.07 fs over the same frequency ranges, respectively, which are mainly limited by the noise resolution limit at $3 \times 10^{-6}$ fs$^2$/Hz in the 1–10 MHz range.

In summary, we have demonstrated attosecond-resolution characterization techniques for measuring the high-frequency timing jitter of free-running mode-locked lasers in a simple and direct way using balanced optical cross correlation. The first measurement confirms that mode-locked solid-state lasers indeed have subfemtosecond-level high-frequency timing jitter. The demonstrated shot-noise-limited resolution is currently $2.2 \times 10^{-8}$ fs$^2$/Hz. By optimizing the cross-correlation efficiency, for example, by using aperiodically poled LiNbO$_3$ waveguides [11], the resolution can be significantly improved. Although the demonstration in this Letter is based on the Er-fiber lasers and the PPKTP-based cross correlators at 1550 nm, this technique can be extended to the characterization of other mode-locked lasers and wavelength ranges using appropriate nonlinear crystals and delay elements in the balanced cross correlator.

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References