Ultrafast Low-Noise Yb: fiber Laser for Precise Femtosecond-Level Synchronization Applications

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ABSTRACT

We present a robust, ultra-low-noise Yb: fiber femtosecond laser that delivers 100 mW average power and 140 fs transform-limited pulses at a 40 MHz repetition rate. The free-running repetition-rate drift remains below 0.25 ppm for more than 12 hours with the laboratory temperature stabilized within ±0.5 °C, enabling straightforward and highly precise synchronization to either an identical unit or to our in-house low-noise Er-doped femtosecond laser. Synchronization is achieved using custom high-sensitivity balanced optical cross-correlator modules. With only a 3 kHz PID locking bandwidth, we demonstrate 2 fs relative timing jitter on short time scales and 1.3 fs RMS timing drift over hundreds of hours of operation in a standard laboratory environment without enclosure and vibration isolation of the experimental setup. To our knowledge, this is the first demonstration of >140 hours long-term laser-to-laser synchronization using exclusively in-house technologies under uncontrolled environmental conditions. Owing to its intrinsically low noise performance, the system requires neither fast nor complex feedback for long-term stabilization. This laser platform enables true plug-and-play operation for experiments requiring high-precision timing control, such as pump-probe measurements in large-scale free-electron laser facilities for studies of ultrafast atomic dynamics.

Keywords: Ytterbium, femtosecond laser, timing jitter, low-noise, transform-limited, Synchronization, BOC

1. INTRODUCTION

Stable, low-noise Yb: fiber femtosecond lasers are in high demand at large-scale laser facilities such as free-electron laser (FEL) centers [1,2] and Extreme Light Infrastructure (ELI) sites, as well as in advanced research laboratories performing time-resolved spectroscopy, pump-probe measurements, and attosecond science [3]. Many of these applications rely on precise timing distribution and synchronization across multiple laser subsystems. However, commercially available Yb-doped femtosecond lasers operating below the 100 MHz regime often lack the combination of reliability, low noise, and straightforward synchronization capability required for continuous operation over hundreds of hours in realistic laboratory environments. Maintaining sub-femtosecond timing stability typically demands complex high-bandwidth feedback electronics or environmentally controlled enclosures, which limits usability and increases system overhead.

In this work, we introduce a new Yb:fiber femtosecond laser (SONATA) specifically engineered to address these challenges. The laser provides an exceptionally clean optical spectrum and delivers transform-limited pulses with outstanding power and repetition-rate stability. Its intrinsically low-noise performance enables ultra-low long-term repetition-rate drift even without dedicated actuators or elaborate stabilization schemes. When combined with our highly sensitive balanced optical cross-correlator (BOC) modules, the system supports robust laser-to-laser synchronization and can be locked either to an identical unit or to our in-house low-noise Er-doped femtosecond laser (SOPRANO). Using only a 3 kHz feedback bandwidth, we achieve 2-fs residual timing jitter (0.1 Hz–5 MHz) and 1.3-fs RMS timing drift over more than 140 hours, demonstrating that precise and durable synchronization can be realized with a compact, user-friendly architecture built entirely from in-house technologies.

2. LASER OUTPUT PARAMETERS AND FREE-RUNNING STABILITY

The laser [Fig. 1(a)] features a Gaussian-shaped spectrum centered at 1.03 μm with >14 nm bandwidth [Fig. 1(b)] at a 40 MHz repetition rate. It offers two outputs: (a) a 100-mW free-space beam with <150 fs transform-limited pulses [Fig. 1(c)], and (b) a ~10 mW fiber output with >3 ps chirped pulses. This configuration makes this laser ideal for seeding

high-power MOPA systems and enables precise synchronization via the BOC modules using the free-space output. At ±0.5 °C room temperature stability, the free-running repetition rate drift remains below 0.25 ppm over 12 hours [Fig. 1(d)] and under 0.05 ppm for 10 minutes [Fig. 1(e)]. Output power stability is better than 0.05% STD-CV over 150 hours [Fig. 1(f)]. The clean and ultra-stable laser output supports robust synchronization by one-click.

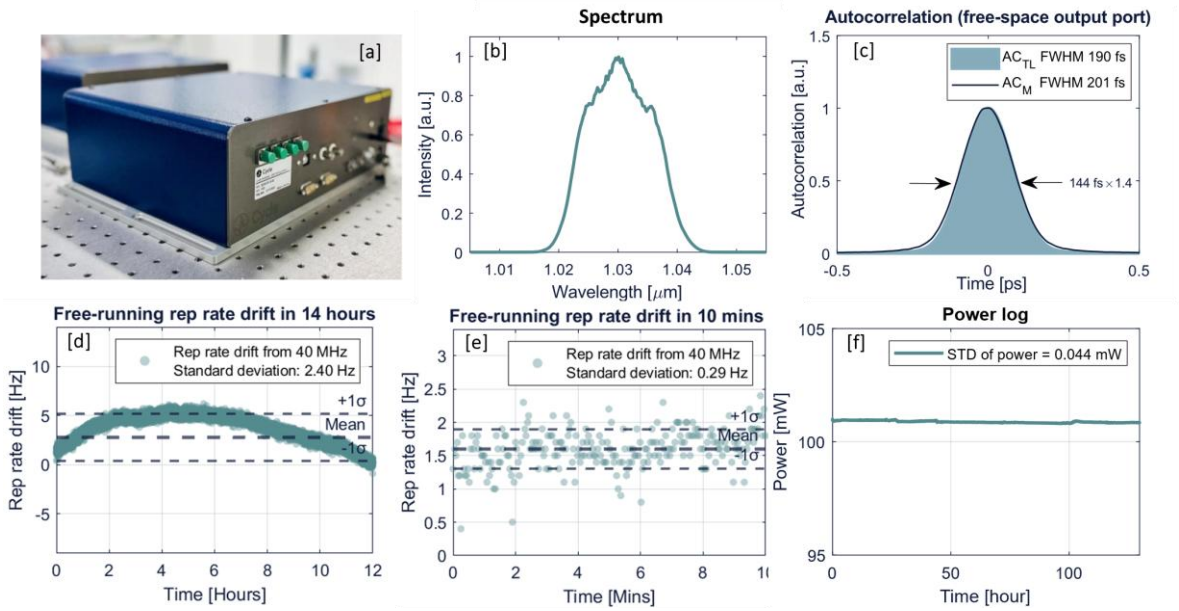

Figure 1. (a) Yb:fiber femtosecond laser. (b) Output spectrum; (c) Autocorrelation trace from free-space output. (d) Laser free-running rep. rate drift for 12 hours.(e) Laser free-running rep. rate drift for 10 mins. (f) Output power log for 150 hours.

3. LASER TIMING JITTER AND DUAL-COLOR LASERS SYNCHRONIZATION

To evaluate the absolute timing noise of the laser, two identical Yb:fiber laser units were synchronized using the Cycle 1-µm BOC and the E-Sync module, which integrates the PID controller and PZT actuator [Fig. 2(a)]. A feedback bandwidth of only 3 kHz was employed to allow a large out-of-loop measurement range. The BOC S-curve, shown in Fig. 2(a), provides a timing sensitivity of 1.92 mV/fs. The residual relative timing jitter spectral density between the two synchronized 1-µm lasers is plotted in Fig. 2(b). The integrated out-of-loop jitter is 2.5 fs (3 kHz–2 MHz). The shaded dark-green region indicates the 3 kHz locking bandwidth, within which the timing noise is actively suppressed by the control loop.

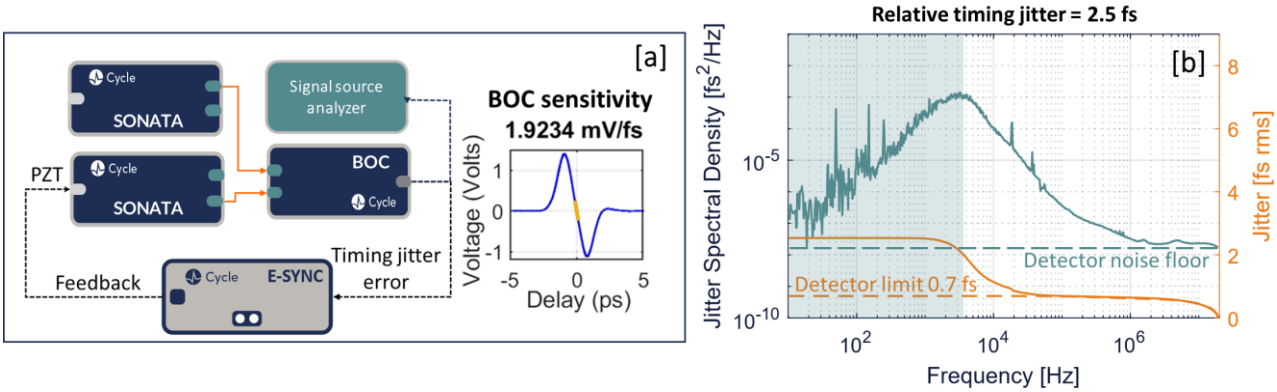

Figure 2. (a) Setup for synchronizing two identical Yb: fiber femtosecond laser. (b) Relative timing jitter power spectral density and integrated jitter between Yb: fiber femtosecond laser.

It is important to note that approximately 0.7 fs of the measured jitter at Fourier frequencies above 1 MHz originates from the detector noise floor. After subtracting this contribution, the realistic residual timing jitter between the two lasers

is ~1.8 fs. Owing to symmetry, the absolute timing jitter of each individual Yb:fiber laser is therefore ~0.9 fs (integrated from 3 kHz to 20 MHz), corresponding to half of the measured relative jitter reported in Fig. 2(b).

For many applications, ultrafast laser pulses at different wavelengths must be tightly synchronized in time, for example in pump–probe experiments, multicolor microscopy, nonlinear frequency-conversion processes such as DFG, and timing distribution for free-electron lasers (FELs). Here, we demonstrate the synchronization capability of our 1.0-µm femtosecond laser by locking it to an in-house 1.5-µm Er:fiber laser (SOPRANO), serving as a proof of principle for broader multi-wavelength synchronization applications.

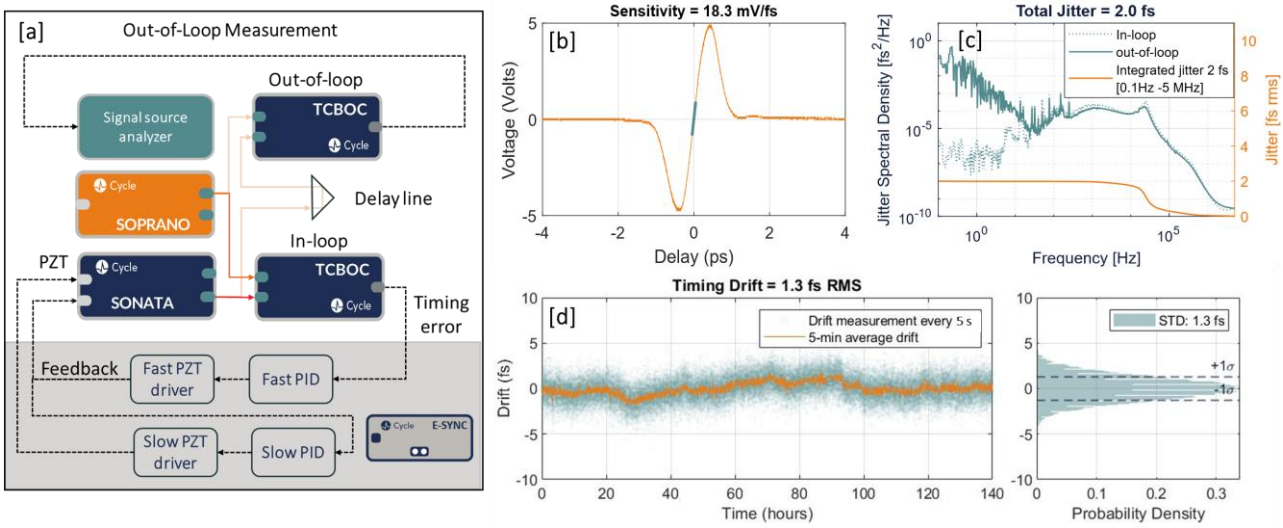

Figure 3. (a) Experimental setup for synchronizing a Yb:fiber femtosecond laser (SONATA) to an in-house Er:fiber femtosecond laser (SOPRANO), including both in-loop and out-of-loop timing jitter measurements using the TCBOC. (b) Measured TCBOC S-curve with a timing sensitivity of 18.3 mV/fs. (c) In-loop and out-of-loop timing jitter power spectral densities, together with the out-of-loop integrated jitter (0.1 Hz–5 MHz), yielding a total jitter of 2.0 fs. (d) *Left*: Long-term out-of-loop timing drift between the Yb:fiber and Er:fiber lasers, recorded over 140 hours at a sampling rate of 0.2 Hz. *Right*: Probability distribution of the long-term drift, showing an RMS drift of 1.3 fs.

In the experiment shown in Fig. 3(a), the output of the 1-µm Yb:fiber laser is split into two paths. One path is synchronized to the in-house 1.5-µm Er:fiber laser using a highly sensitive two-color BOC (TC-BOC) together with the E-Sync module, providing a feedback bandwidth of approximately 3 kHz. The second portion of the Yb:fiber laser output is combined with a partial output of the same Er:fiber laser and sent to a second TC-BOC through an optical delay line (ODL) for out-of-loop timing-jitter characterization with a signal source analyzer (SSA). The S-curves of both TC-BOCs is shown in Fig. 3(b), exhibiting a timing sensitivity of 18.3 mV/fs. The corresponding in-loop and out-of-loop timing-jitter spectral densities are presented in Fig. 3(c). Compared with the in-loop measurement, the out-of-loop trace shows increased noise from 0.1Hz to 30 Hz due to environmental disturbances not compensated by the feedback loop. Nevertheless, the integrated out-of-loop jitter (orange curve) exhibits no significant increase in accumulated jitter, and the overall timing jitter between the two color-separated lasers remains at the 2-fs level when integrated from 0.1 Hz to 5 MHz. In addition to the short-term noise analysis, a long-term drift measurement was performed over more than 140 hours. Timing data were sampled at 0.2 Hz, and the resulting drift trace is shown in Fig. 3(d) (left), while the corresponding statistical distribution is shown on the right, yielding an RMS drift of 1.3 fs. Together with the 2-fs integrated jitter measured from 0.1 Hz to 5 MHz, the long-term drift characterization provides a comprehensive view of the achievable timing stability in a standard laboratory environment without enclosures and vibration isolation of the setup. To the best of our knowledge, this represents the first demonstration of >140-hour laser-to-laser synchronization using exclusively in-house technology under uncontrolled environmental conditions.

4. CONLUSION

We have demonstrated a robust Yb:fiber femtosecond laser featuring ultra-low noise, excellent power stability, and highly stable repetition rate performance. Using a 1-µm BOC module, the laser's absolute timing jitter was measured to be ~0.9 fs (integrated from 3 kHz to 20 MHz). When synchronized to our in-house Er:fiber laser, the system achieved 2-

fs relative timing jitter together with a long-term timing drift of only 1.3 fs RMS. These synchronization results confirm the performance and reliability of the Yb:fiber laser for timing-critical applications in advanced laser-science facilities.

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