Characterization of timing jitter in ultrafast fiber and Ti:S lasers

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Abstract

The timing jitter of erbium doped, fiber optic and Titanium:Sapphire lasers, both passively mode-locked ultrafast lasers at 80 MHz, is measured with unprecedented resolution and bandwidth. Using the balanced optical cross-correlator timing detector, we found a total integrated timing jitter of 2.2 fs rms [100 Hz, 1 MHz] for the fiber supercontinuum and only 55 as rms [100 Hz, 10 MHz] jitter for the Ti:S laser. This measurement of fiber laser jitter is an absolute measurement, since the jitter of the fiber laser was measured against the Ti:S laser, which is negligible.

1. Introduction

Ultrafast mode-locked laser oscillators hold tremendous promise as ultra-low noise optical and microwave signal sources [1]. Ultrafast optical pulse trains with extremely low timing jitter are used for femtosecond-level timing distribution for next-generation X-ray free electron laser facilities [2], as well as for high-speed, high-resolution photonic analog-to-digital conversion [3]. To this end, we aim to better characterize and understand the timing jitter of low-noise, femtosecond sources, such as fiber lasers and Ti:S lasers.

2. Experimental Technique

We measure the timing jitter with attosecond precision with an all-optical technique based on balanced optical cross-correlation (BOC), whereby a time-domain cross-correlation is performed between two pulses in a non-linear crystal [4]. The sensitivity of this balanced approach far exceeds that of microwave mixers and photodetectors, and is not prone to amplitude noise [5].

A heterodyne jitter measurement is implemented by measuring the timing jitter between two lasers. Since the jitter of the Ti:S laser is exceptionally low, it is necessary to build two identical Ti:S [6], and measure the jitter between them. Assuming that the noise properties are approximately identical, the jitter density of a single laser is simply half the measured value.

The Ti:S heterodyne jitter measurement for characterizing the timing jitter of the Ti:S laser is shown in Fig. 1. The pulse timing between the lasers is coarsely synchronized with the signal from the BOC, via feedback on an intracavity piezo, to keep the pulses within the linear measurement range of the BOC transfer function, only a few femtoseconds. The free running timing jitter can then be measured outside the loop bandwidth of about 2 kHz.

For this measurement, the BOC is built from a single Type-II phase matched BBO crystal. The output of both Ti:S lasers is orthogonally polarized, and combined on a beam splitter, before being focused into the BBO. Also, a static group delay between the backward and forward passes through the BBO is provided by a 2.2 mm fused silica substrate.

Since the Ti:S is now known to have negligible jitter compared to the fiber laser, it is possible to directly measure the jitter of the fiber laser against the Ti:S. This yields an absolute measurement of the jitter of the fiber laser. Therefore, we have the benefit of not needing to assume that the actual fiber laser jitter density is simply half the measured value. We measured the timing jitter of our fiber supercontinuum system, as shown in Fig. 2, using a cross-correlator similar to that previously described. The pumping oscillator is a stretched pulse, erbium doped, additive pulse mode-locked design [7]. The supercontinuum is coupled out with a parabolic mirror and compressed with a prism compressor to 8 fs duration, with a spectrum spanning 950 – 1400 nm [8]. However, the cross-correlator, in this case, is designed with Type-I phase matched LBO crystals since the fiber supercontinuum is at a different center wavelength than the Ti:S laser. The sum frequency generated light, at 500 nm, is filtered and detected on the balanced photodetector. Again, it is necessary to coarsely lock the pulse timing of the fiber laser to the Ti:S, to keep the BOC in the linear region.

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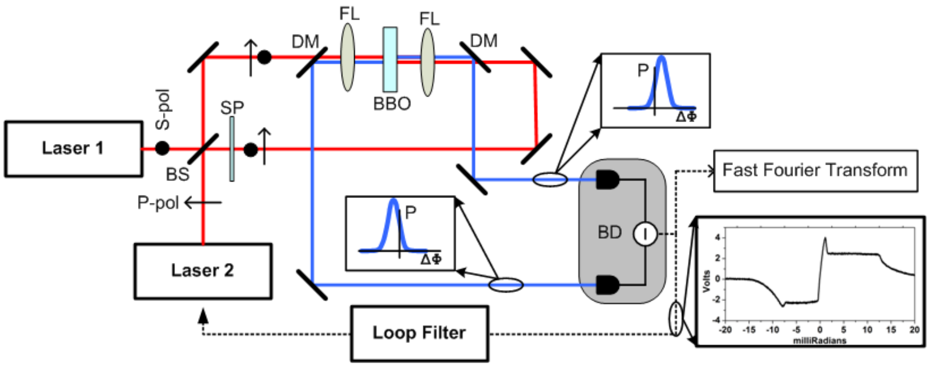

Fig. 1. Output from each Ti:Sapphire laser is split into the two arms of the cross correlator. Dichroic mirrors remove the light converted in the BBO since the counter propagating beams passing through the BBO crystal are only offset for clarity. As shown in the inset graphs, converted second harmonic power(P) in each arm is related the phase offset between the two pulses (~10 µW peak). A 2.2 mm thick phase plate (SP) is inserted into one arm of the cross correlator to introduce a stable phase delay between the two pulse trains. Resulting voltage output from the balanced detector is plotted vs phase error. Once the loop is locked, the output of the balanced detector is analyzed by a commercial fast Fourier transform analyzer (Agilent 89410A). BS – 50:50 beamsplitter; DM – dichroic mirror; FL – focusing lens; BBO – beta barium borate crystal; BD – balanced detector; SP – Sapphire plate.

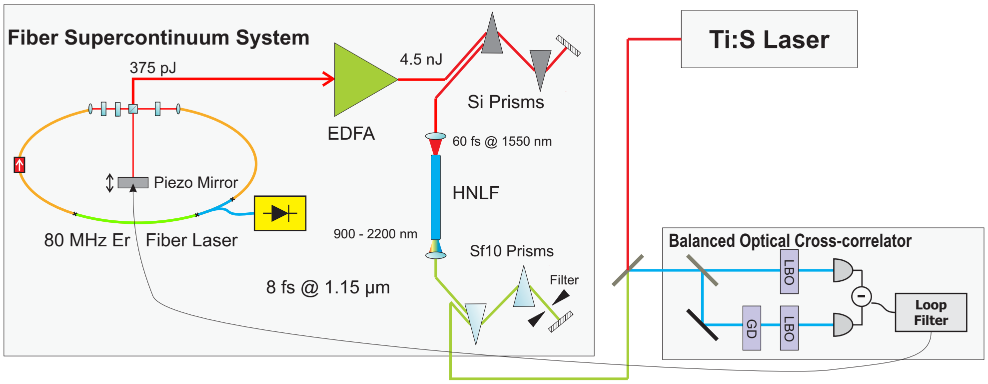

Fig. 2. Schematic of erbium fiber laser supercontinuum system, which is pulse timing locked to the Ti:S laser with a balanced optical cross-correlator using a piezo mirror in the cavity of the fiber laser. The supercontinuum produces 8 fs pulses centered at 1150 nm. GD, group delay element of 3 mm fused silica. HNLF, highly non-linear fiber [8].

3. Results

The measurements show that both fiber lasers and Ti:S lasers have low noise properties, while Ti:S lasers in particular offer exceptional performance. The total integrated timing jitter of the fiber supercontinuum source was found to be 2.2 fs rms [100 Hz, 1 MHz]. Since the measured jitter is very close to that previously reported value, of 2.6 fs rms, for the two identical fiber oscillators of this type, this measurement confirms both the validity of the heterodyne technique and that this supercontinuum system adds negligible timing jitter [9]. Moreover, this measurement represents an absolute jitter measurement of a passively mode-locked, ultrafast fiber laser.

While the jitter of the fiber laser is quite low, the Ti:S laser jitter is nearly two orders of magnitude better. This is thought to largely be due to the much higher pulse energy (and shorter pulse duration) in the free space laser, which is approximately 40 times greater than for the fiber laser. From 100 Hz to 10 MHz, the total integrated jitter of the Ti:S laser is only 55 as, demonstrating that these lasers provide readily available ultralow noise sources. Fig. 3 shows the measured jitter spectral density of the Ti:S lasers, scaled to that of a single laser, along with the integrated timing jitter. Also shown is a measurement of the timing jitter of a single Ti:S laser made with a commercial Agilent 5052 phase noise analyzer. Since the Ti:S jitter is significantly lower than that of the microwave Agilent 5052, the device cannot measure the real timing jitter.

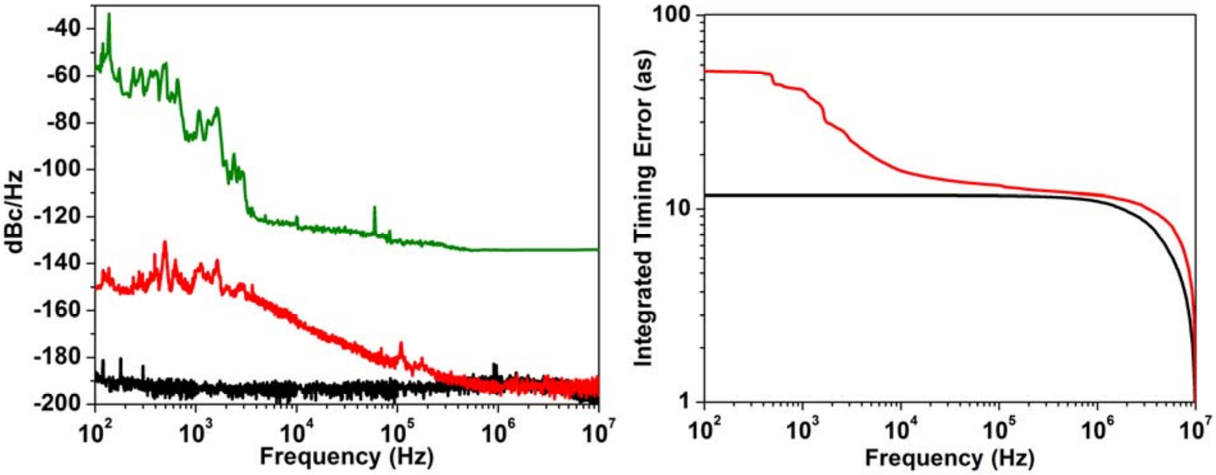

Fig. 3. Spectrum of phase error between Ti:S laser pulse trains, scaled to a 10 GHz carrier. The phase error spectrum of each laser was measured independently using an Agilent 5052, with the result of both measurements square root summed to generate the green curve. The result of the optical cross-correlator measurement is plotted in red, and in black is the noise floor of the optical cross correlator measurement. In black is the expected quantum limited phase noise of an ideal mode locked laser source, see text. (b) Integrated timing error of the corresponding phase noise spectra. Red is the integrated jitter from the optical measurement, while black is the integrated jitter from the optical measurement noise floor.

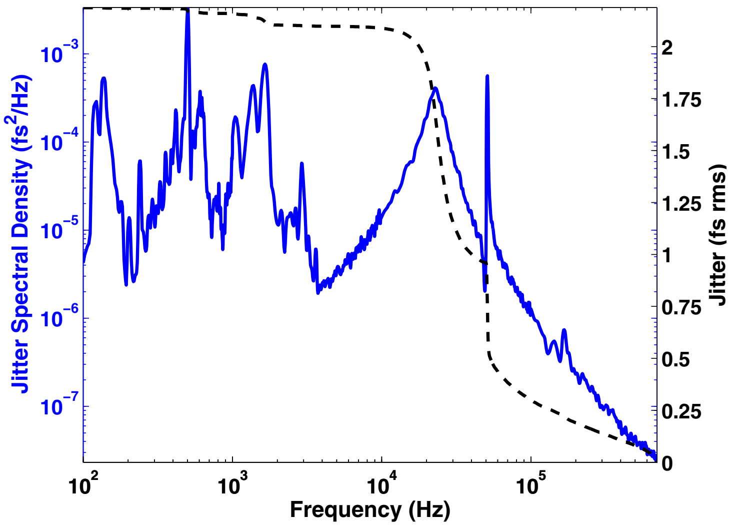

Fig. 4. Measured timing jitter spectral density, blue, and integrated jitter, dashed black, of the fiber supercontinuum source. The jitter is measured against the Ti:S laser, and provides an absolute measurement of fiber laser and supercontinuum jitter.

4. Acknowledgements

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