Attosecond active synchronization of passively mode-locked lasers by balanced cross correlation

T. R. Schibli, J. Kim, O. Kuzucu, J. T. Gopinath, S. N. Tandon, G. S. Petrich, L. A. Kolodziejski, J. G. Fujimoto, E. P. Ippen, and F. X. Kaertner

Department of Electrical Engineering and Computer Science, Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

Received January 2, 2003

A balanced cross correlator, the optical equivalent of a balanced microwave phase detector, is demonstrated. Its use in synchronizing an octave-spanning Ti:sapphire laser and a 30-fs Cr:forsterite laser yields 300-attosecond timing jitter measured from 10 mHz to 2.3 MHz. The spectral overlap between the two lasers is strong enough to permit direct detection of the difference in carrier-envelope offset frequency between the two lasers.

OCIS codes: 320.7090, 320.7110, 320.7100.

It has long been recognized that single-cycle optical pulses may be achievable through phase coherent superposition of several spectrally overlapped few-cycle lasers. The synchronization of pulse trains from independent mode-locked lasers with subcycle timing fluctuations is the most important step in this process of synthesis. Ideally, the relative timing jitter should be less than a tenth of an optical cycle for a high-quality synthesized pulse stream. At a wavelength of 1 μm, a timing jitter of 330 attoseconds (as) or less, measured over the full Nyquist bandwidth, i.e., half of the laser repetition rate, is required. Several groups of researchers have investigated the possibility of active[1] and (or) passive[2,3] synchronization of multiple lasers. However, subfemtosecond timing jitter over the Nyquist bandwidth has not to our knowledge been achieved.

In this Letter a new method of synchronization is demonstrated in which the timing jitter between two passively mode-locked lasers is detected by a balanced cross correlator (see Fig. 1), which is the optical equivalent of a balanced microwave phase detector. The signal is then fed back via an electronic control loop to keep the two lasers synchronized. This method results drift-free and temperature-independent synchronization between two individual lasers, a task that is difficult to achieve with all-electronic schemes. To ensure the long-term stability of the system, the two laser beams are combined inside the control loop. This combination of beams ensures the stability of the output for an arbitrarily long time scale. To further improve the stability of the system we used prismless lasers to generate the corresponding parts of the continuum. Because the resonator dispersion in a prismless cavity does not rely on alignment of the cavity, stable long-term mode locking can be obtained even in an octave-spanning Ti:sapphire laser for which precise dispersion compensation over a large bandwidth is crucial.[4] Even for our octave-spanning laser, the cavity typically does not require realignment for several weeks, and mode locking can be sustained over extended periods of time. Because fine tuning of the dispersion in such a cavity can be achieved by insertion of a thin wedge of glass into the cavity, the operation of these lasers is significantly easier than of lasers with additional intracavity prism pairs. In Ref. 5 it was shown that it is possible to generate ultrabroad spectra with high conversion efficiencies in purely double-chirped mirror–compensated Ti:sapphire lasers. To obtain a spectral overlap between the Cr:forsterite laser and the Ti:sapphire laser we used a prismless version of the laser described in Ref. 4, employing only double-chirped mirror pairs for ultrabroadband dispersion compensation and BaF_2 wedges for dispersion control.[6] The repetition rate (Rep. Rate) of the laser is 82 MHz, and it emits ~100 mW of mode-locked power through a 1% output coupler when it is pumped with 3.8 W of 532-nm light. The Ti:sapphire crystal was cooled to 16 °C.

To improve stability and mode locking in the Cr:forsterite laser we used a novel broadband InGaAs saturable absorber on a large-area, high-index contrast $AlGaAs/Al_xO_y$ mirror.[7] Because of the high index contrast between AlGaAs and Al_xO_y, the mirror's reflectivity extends from roughly 1100 to 1500 nm, which enables sub-30-fs pulses to be generated at

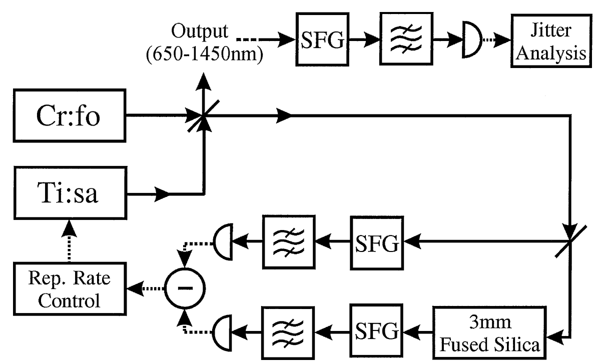

Fig. 1. Experimental setup of the synchronized lasers: Cr:fo, passively mode-locked Cr:forsterite laser; Ti:sa, passively mode-locked Ti:sapphire laser; SFG, sum-frequency generation. All bandpass filters transmit only the sum frequency (1/496 nm = 1/833 nm + 1/1225 nm). Each of the two beam splitters consists of a thin fused-silica glass substrate coated with a semitransparent metal film. The third correlator is used to generate the graphs shown in Fig. 4 below.

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1230-nm wavelength in a self-starting configuration. This laser emits ~60 mW of mode-locked power through a 3% output coupler when it is pumped with approximately 2 W of 1064-nm light. To improve efficiency we cooled the Cr:forsterite crystal to −25 °C.

Figure 2 shows the spectrum of the two lasers (solid curve) at the output. The dashed curves indicate the extent of the individual laser spectra in the vicinity of the overlap region. The shaded region marks the spectral region that we filtered out to record the difference in carrier envelope offset frequency between the two lasers (see Fig. 3). For phase coherent superposition of the two lasers, the pulse envelopes of the two lasers must be synchronized; in addition, the difference in the carrier envelope offset frequency between the two lasers must be set to zero with a phase lock. Synchronizing the pulse trains with subcycle precision is the most challenging step in the synthesis process. Ideally, a timing accuracy of less than a tenth of an optical cycle should be achieved; this requires a timing jitter of 330 as or less, measured over the full Nyquist bandwidth. To overcome the typical problems posed by balanced microwave mixers previously used for this task[1] we employ the optical equivalent of such a device: a balanced cross correlator. As shown in Fig. 1, the outputs of the two lasers are combined on a broadband metallic beam splitter. One part of the combined beam is directed to two nearly identical cross correlators by use of 1-mm-thick lithium triborate crystals phase matched for sum-frequency generation of 833-nm light from the Ti:sapphire laser and of 1225-nm light from the Cr:forsterite crystal. The only difference between the two correlators lies in the insertion of a 3-mm-thick fused-silica window in the optical path of one of them. This glass causes a group delay of 45 fs between 833 nm and 1225 nm to offset the pulses emitted by the Cr:forsterite and Ti:sapphire lasers with respect to each other. Because of the small dependence of the chromatic dispersion on temperature (<1 as/°C), it is legitimate to use this 45-fs delay as a reference for measurement of timing offset. For small time differences between the two laser pulses the difference between the currents of the photodetectors at the ends of the correlators is nearly proportional to the time difference between the two pulses. Furthermore, in the vicinity of zero timing offset this detector acts as a balanced phase detector operating in the multiple-terahertz range if the signal amplitudes of the two correlators are balanced against each other. At the zero crossing of the difference of the photocurrents, this detector delivers a perfectly balanced signal, and, therefore, the amplitude noise of each laser does not affect the detected error signal. The output of this balanced cross correlator is shown in Fig. 4(b) as a function of the time difference between the Cr:forsterite and the Ti:sapphire pulses.

The signal from the balanced mixer is used to lock the repetition rates of the two lasers by controlling the cavity length of the Ti:sapphire laser with cavity mirrors mounted upon piezoelectric transducers in a manner similar to that described in Ref. 1; this finally closes the control loop. The first beam splitter that is used to combine the two output beams from the lasers is inside this control loop. Because the output beam shown in Fig. 1 originates from this beam splitter, temperature drifts, acoustic noise, or beam fluctuations always affect both laser beams in the same way, as they both travel along identical paths. Therefore, external noise cannot corrupt the relative jitter, and the output behaves as if it originated from the same source.

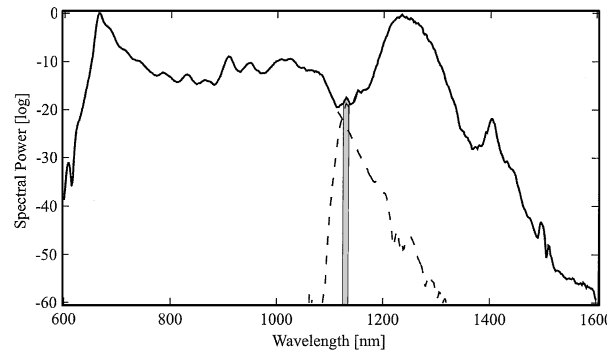

Fig. 2. Optical spectra of the mode-locked Ti:sapphire and the Cr:forsterite lasers. Dashed curves, the spectra of the individual lasers; shaded region, spectral region used to detect the difference in carrier envelope offset frequency between the two lasers shown in Fig. 3.

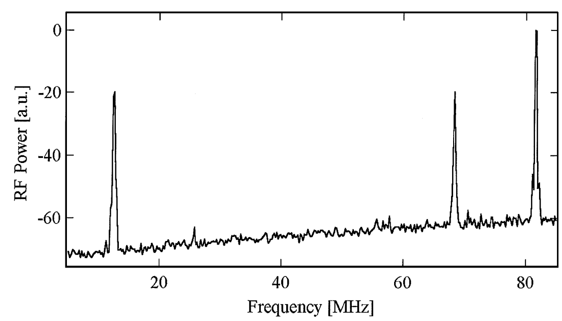

Fig. 3. Heterodyne beat between the Cr:forsterite and the Ti:sapphire lasers obtained from the spectral region shown in Fig. 2. The two beat signals below the repetition rate of 82 MHz represent the difference in the carrier envelope offset frequencies of the two lasers. The rf-analyzer filter bandwidth is 30 kHz. The noise floor is caused by the uncompensated transimpedance amplifier and poses only a technical limitation.

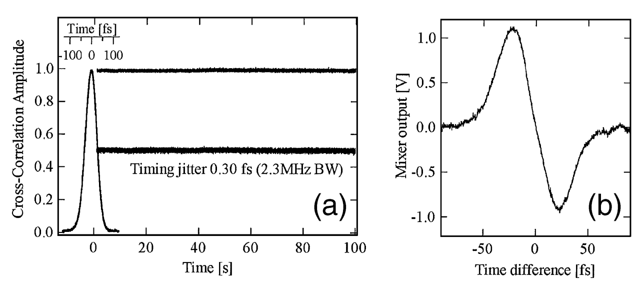

Fig. 4. (a) Timing jitter determined from the amplitude noise of the sum-frequency generation of the out-of-loop cross correlator (see Fig. 1). The time delay in the correlator was generated by a dispersive medium in front of the sum-frequency generating crystal. The rms jitter measured in a 2.3 MHz bandwidth (BW) yielded a value of 299 ± 104 as. (b) Output of the balanced cross correlator as a function of the difference in time between the two laser pulses.

Even environmental noise, which influences the optical length of the cross correlators, cannot corrupt the timing, because the group delay of the 3-mm fused silica, measured at 833–1225 nm, is the only timing reference in this system.

Figure 4(a) shows the timing jitter measurement made with the out-of-loop cross correlator shown in Fig. 2. The residual timing jitter over the detector's bandwidth of 2.3 MHz is 299 $\pm$ 104 as. The stated error is determined from the amplitude noise measured at the peak of the cross correlation. As in most passively mode-locked laser systems, the main contribution to the timing jitter has frequency components up to a few times the relaxation oscillation frequency of the laser.[8] In the current system the relaxation oscillation frequencies are roughly 70 kHz for the Ti:sapphire laser and 140 kHz for the Cr:forsterite laser. Therefore we assume that noise above 2.3 MHz is negligible.

As soon as the two lasers are locked to each other, we observe a strong beat signal in the overlap region of the optical spectrum. The beat signal shown in Fig. 3 was detected with an InGaAs p–i–n diode connected to a transimpedance amplifier. To avoid saturation of the detector we directed only a small part of the optical spectrum to the diode. The transmission of the 10-nm-wide bandpass filter is indicated by the shaded region in Fig. 2. As described in Ref. 9, the beat signal represents the difference in the carrier-envelope offset frequency Δf_{CEO} between the two lasers. In contrast to previous results, it is now possible to obtain this beat without the use of spectral broadening of the mode combs, which helps to provide an exceptionally large signal-to-noise ratio of ~50 dB in a 30-kHz bandwidth.

In conclusion, we have demonstrated the effectiveness of a balanced cross correlator, the optical equivalent of a microwave phase detector, in synchronizing two independently passively mode-locked lasers. A timing jitter as low as 300 as over the spectral band from 10 mHz to 2.3 MHz has been demonstrated. Because of the overlap of the optical spectra of the two lasers we obtained a strong beat signal when the two synchronized lasers interfered on an InGaAs p–i–n photodiode. We intend to investigate the possibility of locking Δf_{CEO} to zero and thus to generate a phase-coherent mode comb over a spectrum extending well beyond 1 octave.

The authors gratefully acknowledge very fruitful discussions with Jun Ye and David Jones and the fabrication of the broadband beam splitters by Peter O'Brien. This work was supported in part by MIT Lincoln Laboratory contract ACC-334, National Science Foundation grant ECS-0119452, U.S. Air Force Office of Scientific Research grant F49620-01-1-0084 and U.S. Office of Naval Research grant N00014-02-1-0717. T. R. Schiblis' e-mail address is schibli@mit.edu.

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