Broadband phase-coherent frequency synthesis with actively linked Ti:sapphire and Cr:forsterite femtosecond lasers*

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Abstract: We report a scheme to generate a phase-coherent optical frequency comb extending from 0.6 µm to 1.4 µm wavelength by actively linking the Ti:sapphire and Cr:Forsterite femtosecond lasers.

Extremely broadband femtosecond pulse sources with well defined carrier-envelope phase evolution have been a field of intense research over the past years [1-3]. The time-domain motivation for the push towards increased bandwidth is the generation of optical pulses that approach the single-cycle regime and can be used for phase-sensitive nonlinear experiments [4]. The frequency-domain motivation is the interest in extending the bandwidth over which optical frequencies can be precisely synthesized and subsequently used for absolute frequency measurements or comparisons [1,5,6]. Nonlinear frequency conversion is one route to overcome the bandwidth limitations of current systems based on *one* Ti:sapphire laser. A second attractive route is linking *two* femtosecond lasers with overlapping emission spectra. Phase-locking the repetition rates of two femtosecond lasers with different gain media has recently been demonstrated [7]. Here, we additionally link the absolute position of the frequency combs emitted by a Ti:sapphire and a Cr:forsterite laser. The laser repetition rates are phase-locked by using a nonlinear cross-correlation technique. The difference $\Delta f_0 = f_{0,Ti} - f_{0,Cr}$ between the carrier-envelope offset frequency of the Ti:sapphire laser, $f_{0,Ti}$, and that of the Cr:forsterite laser $f_{0,Cr}$ is measured by beating the portions of the their spectra around 1.1 µm wavelength against each other. Finally, the frequency $F_0 = |2f_{0,Cr} - f_{0,Ti}|$ is measured, which is necessary to perform a phase sensitive measurement or an absolute frequency measurement with the combined comb[1].

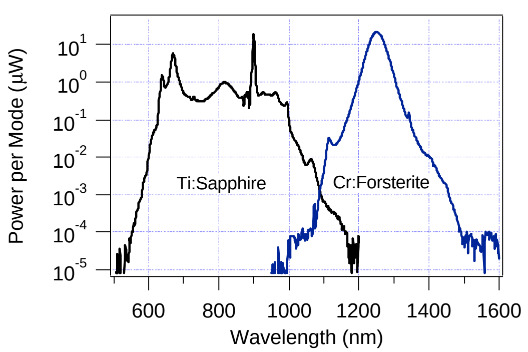

Fig. 1: Output spectra of the Ti:sapphire laser and the Cr:forsterite laser.

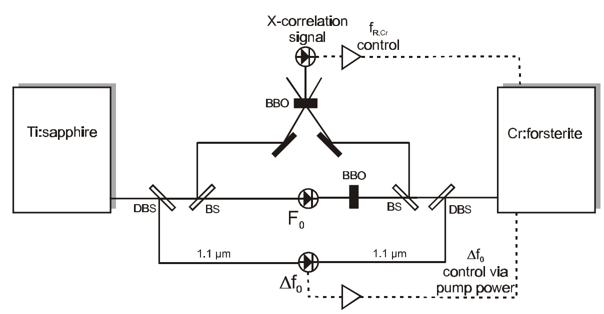

Fig. 2: Sketch of the setup for linking the Ti:sapphire and Cr:forsterite lasers. DBS and BS are dichroic beamsplitters and 50% beamsplitters, respectively. A cross-correlation signal and the second harmonic of the Cr:forsterite laser are generated in BBO crystals. Polarization optics and the out-of-loop cross correlator are omitted for clarity.

The broadband Ti:sapphire laser and the Cr:Forsterite laser we employ have been described elsewhere [8,9]. Their output spectra are shown in Fig. 1. The combined coverage extends from 0.57 µm to 1.45 µm at a power level of 1 nW per frequency mode[2]. It is important to point out that the spectra overlap without the

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[1] F_0 is identical to the carrier envelope offset frequency of the combined frequency comb when Δf_0 is stabilized to 0 Hz.

[2] 1 nW per mode is the approximate power that is necessary to achieve a sufficient signal-to-noise ratio for a beatnote against a single mode cw-laser at a mW power level and thus perform a frequency measurement.

necessity for external spectral broadening. Both ring oscillators are configured to have a repetition rate of 433 MHz. Their output powers in modelocked operation are both approximately 500 mW.

To create a combined phase-coherent frequency comb from the two lasers we employ the scheme sketched in Fig. 2. The mode spacings of the combs are equalized by phase-locking the repetition rate of the Cr:forsterite laser, $f_{R,Cr}$, to that of the Ti:sapphire laser $f_{R,Ti}$. The phase lock is based on a nonlinear cross-correlation signal between the laser outputs that is generated in a type-I phase matched BBO crystal in a non-collinear configuration. The cross-correlation signal is offset from zero, filtered, amplified and fed back to a piezoelectric transducer behind a cavity mirror of the Cr:forsterite laser to lock its cavity length. Thus, the cross-correlation signal is locked to a non-zero value and the timing between the two laser pulse trains is precisely stabilized. The advantage of this method over conventional methods employing photodetection of the pulse trains and phase-locking electronic microwave signals at the repetition rate or their harmonics is that it has an inherently more effective phase-sensitivity at the lock point and thus allows for tighter phase-locking. A timing-noise spectrum of the two lasers as measured with an out-of-loop nonlinear cross-correlator is shown in Fig. 3. It exhibits a pronounced contribution around 30 kHz that cannot yet be canceled by our feedback loop due to the limited bandwidth of the employed PZT. The integrated timing jitter in a bandwidth from 1 Hz to 100 kHz is 20 fs. This is sufficient to keep the pulses overlapped to a large enough fraction at all times such that the following steps are feasible.

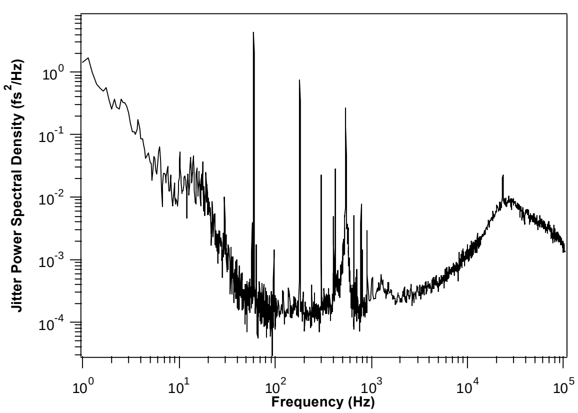

Fig. 3: Power spectral density spectrum of the timing jitter between the two lasers when phase-locked. The timing jitter integrated over the full bandwidth is 20 fs.

With the repetition rates of the two lasers locked, we are able to measure the difference of the lasers' carrier-envelope-offset frequencies Δf_0, equal to the amount by which the now equally spaced frequency combs are offset from each other. We pick the overlapping portions of both lasers around 1.1 µm wavelength with dichroic beamsplitters that transmit the remainder of the spectra and generate a heterodyne beat with frequency f_b on a low-noise InGaAs photodiode. The beam from the Cr:forsterite laser is transmitted through an acousto-optic modulator that is driven with a frequency of f_{AOM}=75 MHz before it impinges on the photodetector in order to offset the beat signal at frequency f_b from Δf_0 by f_{AOM}. In a later step this allows us to phase-lock Δf_0 to 0 Hz by phase locking f_b to f_{AOM}, which makes it possible to circumvent problems related to the low-frequency noise floor of the photodetector. The estimated power that contributes to the beat signal is 10 µW from each laser. A radio frequency spectrum of the signal at f_b is shown in Fig. 4 (left panel). The signal-to-noise ratio is 35 dB in 300 kHz resolution bandwidth. So far, we have only been able to realize a loose frequency lock of f_b to 75 MHz and thus to equalize $f_{0,Ti}$ and $f_{0,Cr}$ on average. In this loop, we act on a different acousto-optic modulator in the pump laser of the Cr:forsterite laser to control $f_{0,Cr}$ such that it tracks $f_{0,Ti}$. Tight phase-locking remains to be demonstrated and the most serious difficulty appears to be cross-talk between the loops controlling $f_{R,Cr}$ and $f_{0,Cr}$.

The phase-lock ofs the repetition rates and the availability of a countable signal representing Δf_0 readily make it possible to measure frequency differences across the entire combined frequency comb. To facilitate an absolute frequency measurement, however, F_0 needs to be measured. To do so, we employ the conventional "f-2f" self-referencing method. A portion of the Cr:forsterite laser is frequency-doubled in a type-I phase matched BBO crystal and beat against the spectrally matching portion of the fundamental Ti:sapphire spectrum to generate a signal at F_0 (see radio-frequency spectrum in Fig. 4b). The power contributing to this beat is approximately 1 mW for each laser and thus a signal-to-noise ratio exceeding 40 dB in 300 kHz resolution bandwidth is achieved.

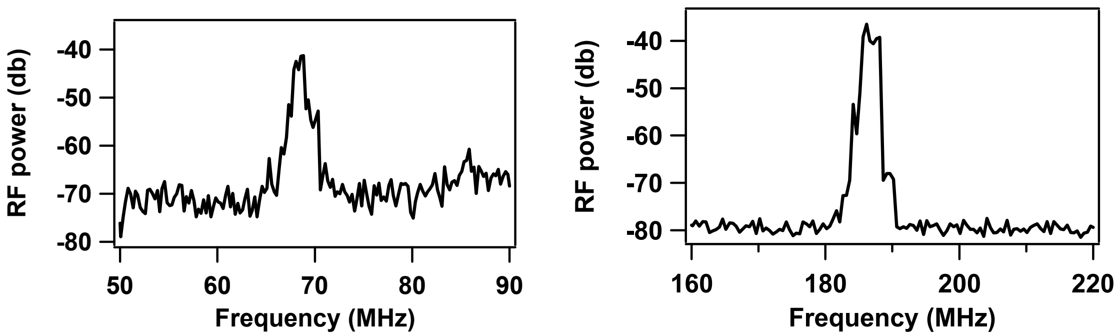

Fig. 4, left panel: RF-spectrum of the Δf_0 signal. Right panel: RF-spectrum of the F_0 signal. The resolution bandwidth for both signals is 300 kHz.

In conclusion we have tightly phase-locked the repetition rates of a Ti:sapphire and a Cr:forsterite femtosecond laser at 433 MHz. Subsequently we have measured the offset Δf_0 among the now equally spaced frequency combs and are able to stabilize its frequency to 0 Hz. Tight phase locking of Δf_0 still remains to be demonstrated. A heterodyne beat between the second harmonic of the Cr:forsterite laser and the fundamental spectrum of the Ti:sapphire laser has given us access to F_0, the carrier envelope offset frequency of the combined frequency comb. The system readily allows us to perform absolute optical frequency measurements within the combined spectrum by simultaneous counting all relevant RF-frequencies. Furthermore, all ingredients to generate a broadband, high powered and phase-coherent frequency comb from two lasers with different gain media are now available. Combining possible second harmonic generation, sum and difference frequency generation [9] as well as possible broadening in nonlinear fibers [10] our approach has great potential for phase coherent optical frequency synthesis from the ultraviolet through the visible, the telecommunications band all the way to the mid-infrared.

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References

[1] D.J. Jones, S.A. Diddams, J.K. Ranka, A. Stentz, R.S. Windeler, J.L. Hall, S.T. Cundiff, Science **288**, 635 (2000).

[2] U. Morgner, R. Ell, G. Metzler, T.R. Schibli, F.X. Kärtner, J.G. Fujimoto, H.A. Haus, E.P. Ippen, Phys. Rev. Lett. **86**, 5462 (2001).

[3] T.M. Ramond, S.A. Diddams, L. Hollberg, A. Bartels, Opt. Lett. **27**, 1842 (2002).

[4] A. Baltuska, Th. Udem, M. Uiberacker, M. Hentschel, E. Goulielmakis, Ch. Gohle, R. Holzwarth, V.S. Yakovlev, A. Scrinzi, T.W. Hänsch, F. Krausz, Nature **421**, 611 (2003).

[5] Th. Udem, J. Reichert, R. Holzwarth, T.W. Hänsch, Phys. Rev. Lett. **82**, 3568 (1999).

[6] R. Holzwarth, Th. Udem, T.W. Hänsch, J.C. Knight, W.J. Wadsworth, P.St. Russell, Phys. Rev. Lett. **85**, 2264 (2000).

[7] Z. Wei, Y. Kobayashi, Z. Zhang, K. Torizuka, Opt. Lett. **26**, 1806 (2001).

[8] A. Bartels, H. Kurz, Opt. Lett. **27**, 1839 (2002).

[9] S.M. Foreman, D.J. Jones, J. Ye, Opt. Lett. **28**, 370 (2003).

[10] I. Thomann, A. Bartels, K.L. Corwin, N.R. Newbury, L. Hollberg, S.A. Diddams, J.W. Nicholson, M.F. Yan, accepted for publication in Optics Letters.