Synthesis of ultrastable femtosecond pulse trains from an optical reference oscillator

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Abstract: We phase-lock the repetition rates of two Ti:sapphire femtosecond lasers to an optical reference oscillator at their 456,000th harmonic and achieve sub-femtosecond timing jitter. A system that can be continuously stabilized for periods approaching one day is demonstrated.

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1. Introduction

Recently, atomic clocks based on an optical frequency standard have been demonstrated [1,2]. A key element in these clocks is a femtosecond laser that downconverts the petahertz oscillation rate into countable ticks at 1 GHz. When compared to current microwave standards, these new optical clocks are expected to yield an improvement in stability and accuracy by roughly a factor of 1000. Furthermore, we envision that the lowest noise microwave sources will soon be based on atomically-stabilized optical oscillators that have their frequency converted to the microwave domain via a femtosecond laser. Here, we present a test of the ability of femtosecond lasers to transfer stability from an optical oscillator to their repetition rates. We phase-lock two lasers to a common stabilized laser diode and compare the relative timing jitter in their pulse trains. It is important to distinguish our technique from previous work where a femtosecond laser has been stabilized to a microwave standard [3]or a second femtosecond laser [4].

2. Synchronization of the femtosecond lasers

The different femtosecond lasers (referred to with index i=1,2) have been described elsewhere [5,6]. One of the lasers employs microstructure fiber to create an octave-spanning spectrum, while the second laser emits such a spectrum directly. Their repetition rates $f_{R,i}$ are both ≈1 GHz. We phase-lock the carrier-envelope offset frequencies $f_{0,i}$ (see references [7,8] for experimental details) to a synthesizer that is referenced to a hydrogen maser. Subsequently, we heterodyne a stabilized single-frequency laser diode (f_{LD}≈456 THz) with the neighboring components of both frequency combs (with mode numbers n_i, both ≈456,850) to generate beat signals at frequencies $f_{b,i}=f_{LD} - (f_0+n_i\times f_{R,i})$. These beat signals are also phase-locked to synthesizers. The repetition rates of both lasers are thus independently phase-locked, i.e. synchronized to f_{LD} as $f_{R,i}=n_i^{-1}\times(f_{LD} - f_{0,i} - f_{b,i})$. It can be shown that, within our measurement resolution, the pulse trains now derive their frequency stability entirely from the optical frequency reference. In fact, the phase-locked frequency spectra of $f_{0,i}$ and $f_{b,i}$ can both be at the millihertz linewidth level, indicating excellent coherence for the entire octave spanning comb.

3. Results and discussion

To characterize the phase-noise of the pulse trains relative to the optical reference oscillator we use an optical nonlinear cross-correlation technique (described e.g. in reference [4]). The measured single-side-band phase-noise spectrum L(f) of the pulse trains at 1 GHz is displayed in Fig. 1. It is approximately 30-50 dB better than that of high quality synthesizers and quartz oscillators and comparable to the best sapphire microwave oscillators. The excess-noise in the range from 0.1 – 1 kHz is attributed to not yet compensated mechanical vibrations in the lasers and the measurement system. From L(f) we extract the timing jitter of the pulse trains relative to f_{LD} and find it to be 0.45 fs in a passband from 1 – 100 Hz, increasing to 1.5 fs in the full available bandwidth of 100 kHz. Although no specific measures towards vibration isolation of the lasers have been taken our result is comparable to what has been achieved previously by employing microwave-domain phase-locking techniques only but with use of elaborate vibrational damping [4].

Our laser that emits a broadband continuum circumvents many of the common problems with spectral broadening in microstructure fibers regarding long-term operation. This laser enables us to establish a phase-coherent optical-to-microwave link that operates continuously for a period approaching one day. As a demonstration, we count f_0, f_b and f_R simultaneously with frequency counters at 10 s gate time. The offset of the counter readings from their preset values is displayed in Fig. 2 for all three channels. The dataset shows uninterrupted and hands-off operation of the f_0-lock for more than 20 hours until we turned the system off. The phase-lock on f_b operated for ≈14 h with only one detected cycle-slip at ≈4 h, i.e. ≈10 h of cycle-slip free data are contained. The reason for the failure at ≈14 h is not clear, although it is likely related to the stabilization of f_{LD} and not the femtosecond laser itself. As f_R actually presents a measurement of f_{LD} relative to our hydrogen maser, the time record of the offset of f_R from 998,092,449.54 Hz has been multiplied with the mode number n=456,857 to give an estimate of the temporal drift of the Fabry-Perot cavity used to stabilize f_{LD} on the right axis of the graph in Fig. 2c). The cycle slip in the f_b feedback loop does not appear in the f_R record because the effect of the 120 mHz excursion in f_b results in an error of 260 nHz in f_R which is below our measurement limit.

4. Conclusion

In conclusion, we have synchronized two femtosecond lasers to an optical reference oscillator with a timing jitter as low as 0.45 fs in a passband from 1 – 100 Hz. The presented method should provide the means to exploit the stability of low-noise optical frequency standards for the synthesis of microwave signals with a stability superior to that of current microwave sources. We are able to maintain a phase-coherent, cycle-slip free link between an optical oscillator and the repetition rate of our laser for 10 h. In other words, we have the ability to count 1.6×10^{19} optical cycles at 456 THz without ever losing track of the oscillation. We can carry out an optical frequency measurement relative to a microwave frequency standard for an uninterrupted period of 14 hours. This ability is important for frequency measurements where long averaging and/or recording times are necessary to attain useful data as well as to test the ultimate stability limit of optical frequency standards.

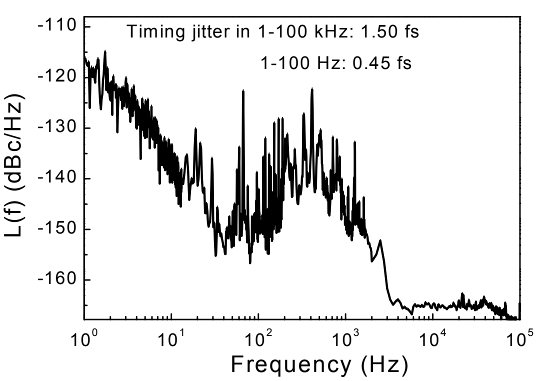

Figure 1: Phase-noise spectrum of the 1 GHz pulse trains. The timing jitter for two different pass-bands as extracted from the phase-noise plot is given.

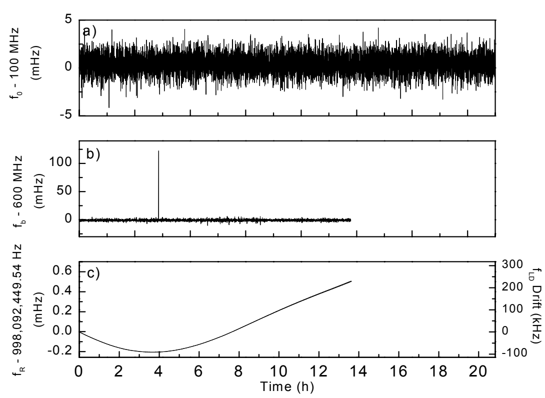

Figure 2: Panel a): record of counter readings for f_0. 100 MHz has been substracted. Panel b): offset of f_b from 600 MHz. Panel c): time record of the offset of the laser repetition rate from 998,092,449.54 Hz (left scale) translated into the drift of f_{LD} (right scale).

5. References

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