Sub-hertz stabilization of femtosecond laser frequency combs[1]

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Abstract: Femtosecond laser frequency combs can have sub-hertz linewidths when phase-locked to a similarly narrow reference laser. Long term coherence is verified by high-contrast interference between two combs with integration times up to 10 s.

OCIS codes: (140.7090) Ultrafast lasers, (320.7160) Ultrafast technology, (120.3940) Metrology

Young *et al.* have demonstrated a visible continuous-wave (CW) laser with a sub-hertz linewidth[1]. Subsequently, it was shown that the frequency stability of such narrow-linewidth CW lasers can be transferred to a broad comb of optical frequencies ($f_n = nf_r + f_0$) or to a microwave signal with high precision when a femtosecond laser is used as an optical frequency synthesizer [2,3]. Here, we show that the components of a femtosecond laser based frequency comb (FLFC) can also have sub-hertz linewidths at optical frequencies when phase-locked to a similarly narrow reference laser. Phase noise measurements yield a coherence time of 5 seconds for the FLFC. This is verified by high contrast spectral interferograms between two FLFCs locked to a common optical oscillator with integration times of up to 10s.

Using previously-developed techniques[2-5], we phase-lock two broadband FLFCs (referred to with indices 1 and 2) to a cavity-stabilized CW laser diode at f_{LD}=456 THz (657 nm). To achieve this, we phase-lock heterodyne beats $f_{b,1}$ and $f_{b,2}$ between f_{LD} and the same mode from each FLFC (i.e. $n_1=n_2=N\approx456{,}000$) to a stable RF signal. The offset frequencies $f_{0,1}$ and $f_{0,2}$ of the FLFCs are also locked to a second RF signal such that the repetition rates are $f_{R,i}=(f_{LD}-f_{b,i}-f_{0,i})/N$ with i=1,2. The dominant source of noise for such a phase-locked FLFC is that of f_{LD} [3-6]. However, if we chose $f_{0,1}+f_{b,1}=f_{0,2}+f_{b,2}$, then $f_{R,1}= f_{R,2}$ and the noise of the laser diode largely cancels out in the following experiments, which are rigorous measurements of the excess phase-noise of the stabilized FLFC itself.

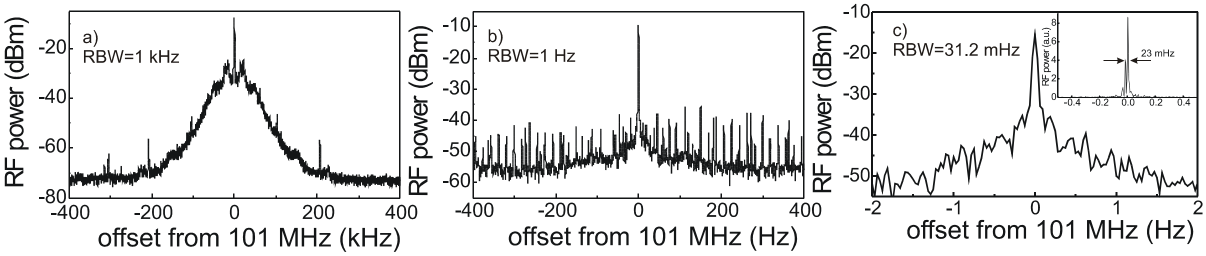

Fig. 1. Optical heterodyne beat notes between the two femtosecond lasers near 333 THz [$f_{R,1}=f_{R,2}$ and $\Delta f_0=f_{0,1}-f_{0,2}$=101 MHz] a) Measurement with an RF-spectrum analyzer at 1 kHz RBW, b) at 1 Hz RBW, c) measurement of the beat mixed to 10 Hz with an FFT-spectrum analyzer having 31.2 mHz RBW (inset: 3.12 mHz RBW).

We measure the average frequency stability of a group of comb components around 900 nm (333 THz) by detecting a heterodyne beat between both FLFCs. This optical beat appears at frequency $\Delta f_0=f_{0,1}-f_{0,2}$ when the pulses from both lasers are temporally overlapped on the detector [see Fig. 1]. The central peak has a linewidth that is limited by the resolution bandwidth (RBW) down to 31 mHz RBW before we begin to see the real linewidth of approximately 20 mHz. Down to 31 mHz RBW, the central peak still contains about 59% of the power (from an overall 1 MHz integrated bandwidth). A more rigorous determination of the linewidth is obtained from a measurement of the spectral density of phase-noise $S_\varphi(f)$ of the beat at Δf_0 as shown in Fig. 2. The phase-noise

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integrated as $\sqrt{\int_{f_l}^{1\mathrm{MHz}} S_\varphi(f')df'}$ reaches 1 rad at f_l = 0.2 Hz, equivalent to a coherence time of 5 s for the optical comb components.

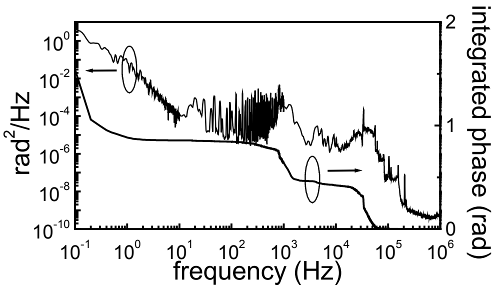

Fig. 2. (left axis) Phase-noise power spectral density of the optical frequency comb components around 900 nm, corresponding to the beat note shown in Fig. 1. (right axis) Integrated phase-noise.

To confirm the high degree of coherence of the FLFCs we measure spectral interferograms between them at wavelengths around 650 nm and 860 nm using an optical spectrum analyzer (OSA). In this case, we further require that both frequency combs overlap with $n_1=n_2$, $f_{b,1}=f_{b,2}$ and $f_{0,1}=f_{0,2}$, and the beams are spatially filtered with a single-mode fiber. Figure 3 shows interferograms with 1 s and 10 s integration time, having constant contrast of ≈50% from 650-870 nm. At 10 s integration time, high contrast interference fringes can still be detected, confirming the long coherence time discussed above. Compared to previous works [6,7], this is an increase in relative coherence time for a FLFC of at least 3 orders of magnitude.

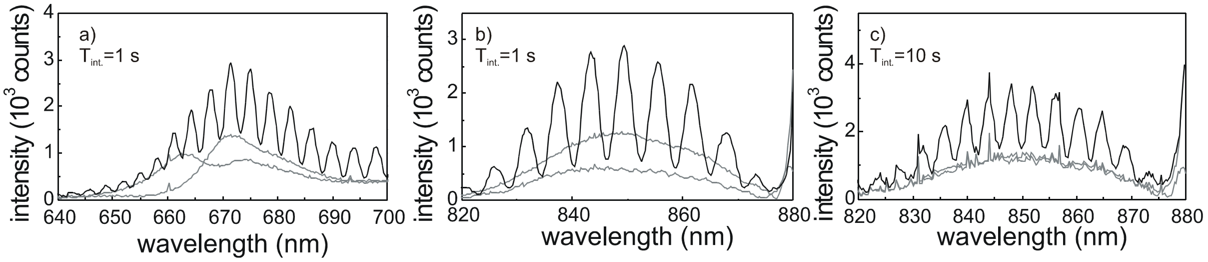

Fig. 3. Spectral interferograms (black line) between the two lasers and their individual spectra (gray lines): a) using the visible output of the lasers and the OSA integration time set to $T_{int.}$=1 s, b) using the infrared output and $T_{int.}$=1 s, c) same as b) with $T_{int.}$=10 s. The different fringe spacings are due to different time delays between the laser pulse trains. The degradation from ideal 100% contrast can be largely accounted for by the phase noise of Fig. 2 and the finite resolution of the OSA.

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