Long term (>300 seconds) phase coherence of a train of ultrashort pulses

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Abstract. The carrier-envelope phase of the pulse train emitted by a 10-fs mode-locked laser has been stabilized such that phase coherence is maintained for at least 300 seconds as measured both in-loop and out-of-loop.

Following the recent demonstrations [1-4] of stabilizing the relative pulse-to-pulse phase between the carrier wave and the pulse envelope (carrier-envelope phase) generated by mode-locked femtosecond (fs) lasers, effort has focused on measuring and increasing the coherence time of this phase stability. Carrier-envelope phase stabilization is an important advance for fs technology, as the advent of few-cycle pulses makes it possible to study processes that are directly sensitive to the electric field of each pulse, rather than just the intensity envelope [5,6]. In order for most of these physical processes to be experimentally investigated it is of interest to extend the time period (i.e., the coherence time) over which phase coherence of the carrier-envelope phase is maintained. In this paper we present measurement of the lifetime of the carrier-envelope phase > 300s on the output of a phase stabilized 100 MHz, 10-fs mode-locked laser.

The frequency spectrum emitted by a mode-locked laser is a series of lines with optical frequencies $\nu_n = nf_{rep} + \delta$, where n is a large integer, f_{rep} is the laser repetition rate, and δ is the comb-offset frequency. The offset frequency is the result of the difference between group and phase velocities in the cavity and is thus related to the carrier-envelope phase by $\Delta\phi_{CE} = 2\pi\delta/f_{rep}$ modulo 2π. Stabilization of the ratio δ/f_{rep} allows for coherence of the carrier-envelope phase between adjacent pulses to be established.

The comb-offset frequency is measured using an f-to-$2f$ interferometer as discussed in prior publications (e.g. [1]). The input to the interferometer is continuum spectrum, spanning an optical octave, generated via external broadening of Ti:sapphire pulses in microstructure fiber [7]. The output of the interferometer is the interference between comb lines on the high frequency end of the continuum with frequency doubled light on the low frequency end of the spectrum. Given that spectral overlap exists, this yields a heterodyne signal which is proportional to $Cos(2\pi\delta t + \phi_{CE}(t))$, where $\phi_{CE}(t)$ represents jitter in the carrier-envelope phase. Once determined the offset frequency is stabilized to an rf signal derived from the laser repetition rate, f_{rep}, as measured on a fast Si photo-detector.

Stabilization of δ is then obtained via negative feedback to the laser by tilting the laser end mirror using a fast (~30 kHz bandwidth) piezo-electric actuator [refs. within 1]. Feedback in this work can also be realized using an acoustic-optic modulator (AOM) to modulate the pump laser [3]. Both schemes yield similar performance.

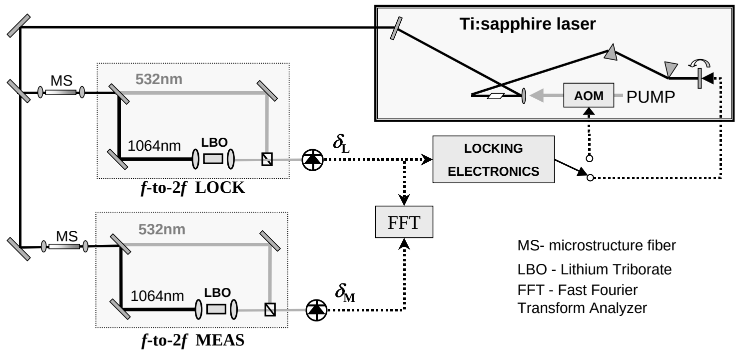

Fig. 1 Schematic of the two *f*-to-2*f* interferometers used for phase stabilization and measurement of the comb-offset frequencies. δ_L and δ_M are the in-loop and out-of-loop comb-offset frequencies, respectively, whose phase power spectral densities and linewidths are measured on a fast Fourier transform spectrum analyzer (FFT).

Once stabilized the coherence time of the carrier-envelope phase is determined from the comb-offset frequency's linewidth. This relationship exists because jitter in the carrier-envelope phase results in phase noise sidebands on δ. Integration of these phase noise sidebands, otherwise known as the phase power spectral density (PSD) of the noise, $S_\phi(\nu)$ in rad^2/Hz, reveals the RMS phase jitter in the carrier-envelope phase:

$$\Delta\phi_{RMS}\ |_{\tau_{obs}} = \sqrt{2\int_{-\infty}^{1/\tau_{obs}} S_\phi(\nu)\, d\nu} \tag{1}$$

In the Eqn. 1 τ_{obs} is the observation time and ν is an offset frequency relative to the carrier. In the above expression only the lower sideband is integrated. The observation time over which $\Delta\phi_{RMS}$ accumulates ~1 radian is generally taken to define the coherence time, $\tau = 1/(2\pi\tau_{obs})$. $\Delta\phi_{RMS}$ is obtained via measurement of the phase PSD both within the stabilization loop (in-loop), and out-of-loop using a second *f*-to-2*f* interferometer as shown in Fig.1. The in-loop measurement determines the effectiveness of the stabilization circuitry while the out-of-loop measurement determines the effect of the extra-cavity phase noise on the useful output of the laser. This latter step is crucial as it gives an indication of the coherence of the pulses emitted directly by the laser (rather than the pulses exiting the fiber used for the *f*-to-2*f* lock).

Using the above procedure we measure an accumulated phase jitter of 0.12 rad (0.80 rad) present in-loop (out-of-loop) via integration of the phase PSD displayed in Figure 2 a). This phase was accumulated over the frequency range

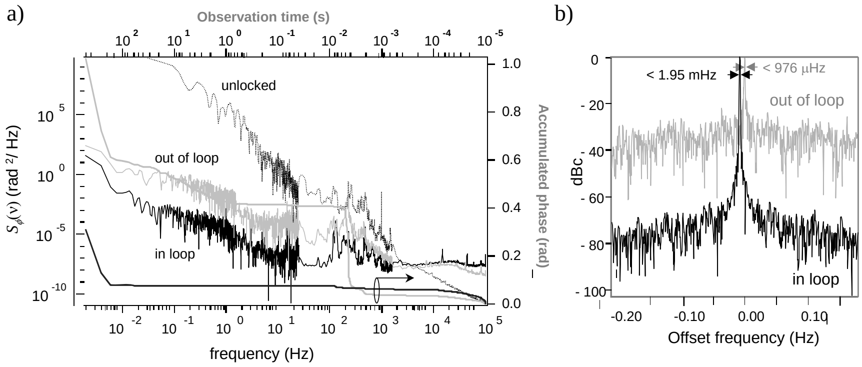

Fig. 2 a) Phase PSD, $S_\phi(\nu)$, of the carrier-envelope phase (left axis) vs. frequency and the accumulated phase jitter, $\Delta\phi_{RMS}$ (right axis), as the upper integration limit $1/\tau_{obs}$ approaches zero. An unlocked spectrum of δ is included to indicate the effectiveness of the stabilization loop. b) Comb-offset frequency linewidths (offset in frequency for clarity).

102kHz to 488 μHz, indicating a minimum coherence time of >300s (measurement limited), both in and out-of-loop. For the out-of-loop case, we suspect the sidebands in frequency range 100 Hz - 1 kHz which contribute the most toward $\Delta\phi_{RMS}$, are mechanical (fiber coupling) resonances common to both interferometers. We next examine the linewidth of δ which presents a more intuitive representation of the noise on the carrier. Shown in Figure 2 b), the linewidth measurements indicate the comb-offset linewidths are unresolved below 976 μHz (1.95 mHz) out-of-loop (in-loop). Prior measurements using a prismless Ti:saphire laser only achieved an in-loop resolution of 10 mHz [8] while the out-of-loop coherence time has hitherto not been measured.

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