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Optical phase-noise dynamics of Titanium:sapphire optical frequency combs

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ABSTRACT

Stabilized optical frequency combs (OFC) can have remarkable levels of coherence across their broad spectral bandwidth. We study the scaling of the optical noise across hundreds of nanometers of optical spectra. We measure the residual phase noise between two OFC's (having offset frequencies $f_0^{(1)}$ and $f_0^{(2)}$) referenced to a common cavity-stabilized narrow linewidth CW laser. Their relative offset frequency $\Delta f_0 = f_0^{(2)} - f_0^{(1)}$, which appears across their entire spectra, provides a convenient measure of the phase noise. By comparing Δf_0 at different spectral regions, we demonstrate that the observed scaling of the residual phase noise is in very good agreement with the noise predicted from the standard frequency comb equation.

The development of stabilized optical frequency combs (OFC) allows for straightforward schemes for comparisons of optical frequencies which are separated by 100's of terahertz. When OFC's are referenced to stable atomic transitions, the OFC provides a bridge to evaluate relative instabilities based on different atomic frequency standards [5,6,9,10]. In such an atomic-optical 'clockwork', the fractional instability of the (stabilized) OFC must be sufficiently low that it does not degrade the measurement of the stability of the atomic transition. In fact, recent work has shown that the frequency instability of OFC can achieve levels of 10^{-19} at averaging times of 500 s (when compared against another stabilized OFC [9]). Building on previous work with Titanium:sapphire [1,17,19], which showed phase-coherence across the optical spectrum, here, we focus on the optical phase-noise dynamics on shorter times scales ($100\ \mathrm{ns} \le \tau \le 1\ \mathrm{s}$). We explore factors that limit the noise floor and demonstrate that the measured scaling of the phase-noise exhibits the scaling expected from the simple frequency comb equation.

To determine the optical phase-noise attributable to the OFCs we lock two independent OFCs to the same cavity-stabilized CW optical frequency reference and measure the residual phase-noise between the two combs (Fig. 1(a)). Alternatively, one could use two highly stabilized optical frequency references to measure the phase fluctuations of individual comb modes. That approach would add a source of phase noise not attributable to the combs. Such a scheme is used for comparisons of optical atomic clocks [16], spectroscopy [3] and for frequency comparisons [4], in which high levels of long-term coherence have already been demonstrated. While comparing two free-running frequency combs [18] give some measure of phase-noise, locking the frequency combs allows one to robustly quantify the noise across a broad spectral region and compare with theoretical predictions. The excellent stability of the comb [9] makes it an excellent reference tool in spectral regions from microwave and terahertz to optical domains [14].

Our apparatus consists of passive two mode-locked titanium: sapphire (TiS) ring lasers having a pulse repetition rate of 1 GHz. These self-referenced lasers have been discussed in detail elsewhere [1] and employ piezoelectric actuators for cavity repetition rate stabilization. The offset frequency of both OFC's stabilized with an 2f-to-3f technique [15] which requires less than an octave of optical bandwidth, in our case, from approximately 600–1150 nm. The nth optical frequency mode is identified as

$$\nu_n = n f_{\mathrm{rep}} + f_0 \tag{1}$$

where f_{rep} is the repetition rate and f_0 is the offset frequency [20] and n indexes an optical mode and is an element of the integers of order 10^5. However, when an OFC is referenced to a stable optical source with frequency ν_0 (at 657 nm), we can also

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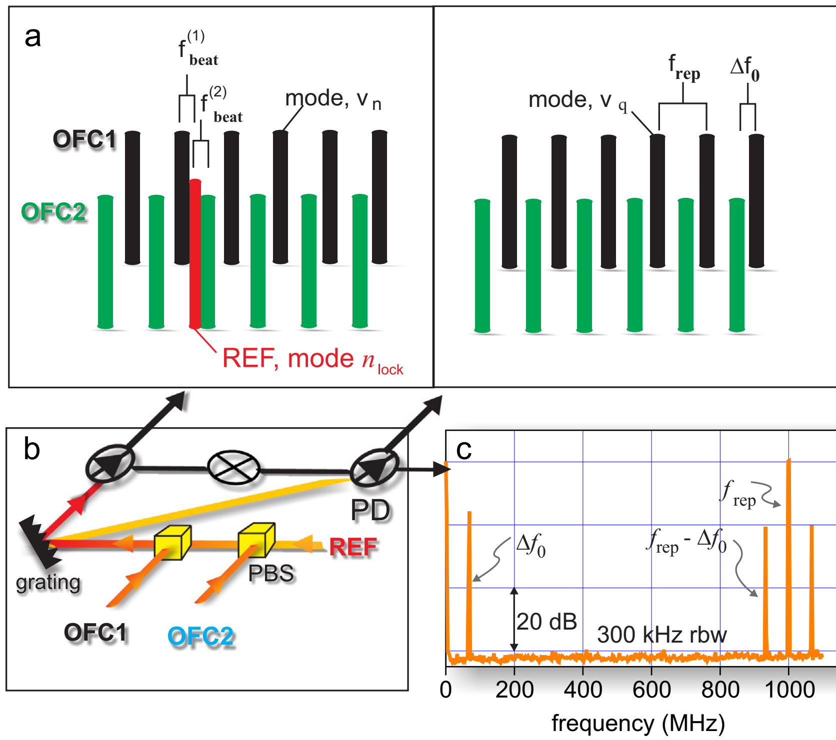

Fig. 1. (a) Schematic of the optical frequency comb (OFC) output of two 1 GHz repetition rate TiS mode-locked lasers. One optical mode of each OFC is referenced, using a phase-locked loop (PLL), to a cavity-stabilized narrow linewidth CW source (REF) at 657 nm, (b) schematic of the setup used to compare $\Delta f_0 = f_0^{(2)} - f_0^{(1)}$ derived from two spectral regions, ν_n and ν_q. Polarizing beam splitters (PBS) and a waveplate (W) are used to obtain spatial and polarization overlap and (c) photodetected heterodyne beat of Δf_0 from one spectral region.

identify the optical mode as $\nu_n = \nu_0 + f^i_{beat}$, where the RF heterodyne beatnote between a mode from OFC1 (OFC2) and the CW reference is denoted by $f^{(1)}_{beat}$ $f^{(2)}_{beat}$ or f^i_{beat} (where i=1,2). Solving for the repetition rate we have, $f^i_{rep} = (\nu_0 + f^i_{beat} - f^i_0)/n$.

When we tune the repetition rates of two OFC's to be equal, we have a uniform frequency shift ($\Delta f_0 = f_0^{(2)} - f_0^{(1)}$) between all of the modes of the two combs (Fig. 1(a)). Here, we are interested in the scaling of the phase noise away from the optical lock point at 657 nm (that is, from an imposed fixed point [2] of the comb). At the lock point, we measure Δf_0 within a small bandwidth about 657 nm and then compare it with Δf_0 measured at another spectral region (Fig. 1(b)). We observe excellent signal-to-noise ratios (SNR) on the Δf_0 signal because 1 nm of optical bandwidth corresponds to $\sim$1000 modes contributing to the measured beatnote. Fig. 1(c) shows the measured RF heterodyne signal from OFC1 and OFC2 which are spatially, spectrally and temporally combined.

To calculate the residual phase noise, we begin by expressing each optical mode in terms of the laser's free parameters, f_0 and f_{beat}, to obtain: $\nu^i_n = r_n(\nu_0 + f^i_{beat}) + (1 - r_n) f^i_0$ (where $r_n = n/n_{lock}$ and n_{lock} indexes the mode nearest the CW optical reference) [11]. The optical phase-noise signal between OFC1 and OFC2 for the spectral region n may be expressed as $\delta\nu_n = \nu^{(2)}_n - \nu^{(1)}_n$,

$$\delta\nu_n = r_n(\Delta f_{beat} - \Delta f_0) + \Delta f_0 = r_n \Delta f_{rep} + \Delta f_0 \quad (2)$$

where $\Delta f_{rep} = f^{(2)}_{rep} - f^{(1)}_{rep} = 0$. A similar equation may be written for the spectral region around the lock point at 657 nm, and this is denoted by $\delta\nu_q$. The relative phase noise power spectral density (PSD) $S_\Phi(f)$ away from the lock point is calculated from the variance of $\delta\nu_n - \delta\nu_q$, scaled with respect to the noise bandwidth, giving

$$S_{\Phi,n,q}(f) = (r_n - r_q)^2 [S_{\Phi f^{(2)}_{beat}}(f) + S_{\Phi f^{(2)}_0}(f) + S_{\Phi f^{(1)}_{beat}}(f) + S_{\Phi f^{(1)}_0}(f)], \quad (3)$$

where $S_{\Phi f^{(1)}_{beat}}(f)$ and $S_{\Phi f^{(1)}_0}(f)$ denote the PSD of the electronic locks and where we have neglected all cross terms [such as $S_{\Phi f^i_0}(f) \otimes S_{\Phi f^j_{beat}}(f)$]. Phase noise on the relative offset frequency Δf_0 is a measure of the combs' residual optical phase noise. The residual phase noise is the remaining phase noise between the two combs after common mode noise has been subtracted. Notably, both OFCs are locked to a common CW reference to better ensure that noise on the beat between the two OFCs (Eq. (2)) yields noise of one comb with respect to the other and not simply a measure of different CW references. Regarding coupling between an individual OFC's two parameters of f^i_0 and f^i_{beat}, we note that the two OFCs have independent pump lasers and phase-locked loops so ideally there should be little correlation between the two noise sources on each OFCs. Some coupling between f^i_0 and f^i_{beat} is evident and enhanced by amplitude noise on the pump source of the Ti:S modelocked laser. Phase-locking f_0 with an acousto-optic or electro-optic transducer in the pump beam path significantly reduces the coupling [13].

We measure the relative optical phase noise across the comb (Eq. (3)) by using the setup shown in Fig. 1(b) to extract Δf_0 from the spectral region around 800 nm and compare that against Δf_0 extracted from near the lock point at 657 nm. We observe that the optical phase noise increases with increasing frequency range away from the lock point (Fig. 2). The data in Fig. 2 is integrated from 1 Hz to 1 MHz, where we obtain 1.4 radians for the 800 nm data (the lock point contribution to this value is 0.9 radians). In order to obtain high resolution across all the Fourier frequencies from 0 Hz to 1 MHz, the phase noise traces shown in this work were taken by stitching together traces from smaller frequency spans where the spans initially extended less than 1 kHz and ended at a 1 MHz span.

We can also simply measure the noise of each lasers' lock to the reference separately (left-hand side of Eq. (3)). Once we measure f^i_0 and f^i_{beat}, we can use Eq. (3) to predict the phase noise of comb