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Extremely low noise microwave signals synthesized from stable CW lasers with femtosecond laser frequency combs*

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Abstract: A femtosecond laser frequency comb transfers the low phase and frequency noise of a cavity-stabilized CW laser to the microwave domain. Phase noise of –115 dBc/Hz at 1 Hz offset from the1 GHz carrier is achieved.
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Continuous wave (CW) lasers stabilized to isolated Fabry-Perot optical cavities with high quality factors ($\sim 1\times10^{11}$) can result in visible single-frequency radiation with sub-hertz linewidths [1] and fractional frequency instabilities ($\Delta f/f_o$) near or below 1×10^{-15} at 1 s [1,2]. Such stabilized lasers are some of the best oscillators in any region of the electromagnetic spectrum, surpassing the performance of most microwave standards by several orders of magnitude. In this paper, we demonstrate the generation of extremely low noise microwave signals at 1 GHz that are down-converted from two cavity-stabilized CW lasers using independent femtosecond laser frequency combs (FLFC). The single-sideband phase noise is as low as –115 dBc/Hz at 1 Hz offset from the 1 GHz carrier, decreasing as approximately 1/f. The associated fractional frequency instability is $\leq 5\times10^{-15}$ at 1 s of averaging, which is 1-2 orders of magnitude better than what is typically achieved with conventional microwave oscillators. Transferring the phase and frequency properties of high performance optical oscillators to the microwave domain should impact a variety of technologies that require extremely low-noise oscillators. Applications include atomic frequency standards, high-bandwidth communications systems, optical A/D conversion, radar, remote sensing, and navigation systems.

The FLFC has recently been introduced as a tool for optical-to-microwave frequency transfer [3,4]. The FLFC can be phase locked to the CW laser oscillator such that the repetition rate f_r (or equivalently the mode spacing) is a subharmonic of the optical frequency[5]. Earlier experiments have demonstrated that the stability properties of the CW laser can be effectively transferred to all elements of the FLFC. However, it was also found that the fractional frequency stability of the generated microwave signals were degraded by at least a factor of 10 from that of the optical signals [6]. This degradation has been attributed in part to excess noise that arises in photodetection[7]. For the present experiments, we use broadband FLFC's [8] that do not require nonliner microstructure fiber for the determination of the carrier-envelope offset frequency f_0 [9] and we have improved the performance of the optical phase-lock loops in addition to the environmental isolation of the FLFC's.

With previously-developed techniques[5,6,8,9], we phase-lock one broadband FLFC to a cavity-stabilized CW laser diode at f_{LD} = 456 THz (657 nm) that has 1-s fractional frequency instability $\sim 3\times10^{-15}$. A second broadband FLFC is phase-locked to a cavity-stabilized dye laser at f_{DYE} = 532 THz (563 nm), having 1-s fractional frequency instability $\sim 5\times10^{-16}$. The two fully-independent stabilized CW lasers are located in separate labs and their outputs are delivered to the femtosecond laser lab via optical fibers of 30 m and 250 m in length, respectively. Doppler cancellation servos are used to eliminate excess noise introduced by these optical fibers.

The infrared portions of the spectra from each of the FLFC's illuminate highspeed InGaAs PIN photodiodes. The 1 GHz harmonic of the photocurrent from each photodiode is filtered, amplified, and then sent to a mixer. By adjusting the phase-lock frequencies, we can make f_r from each of the two FLFC's equal, or alternatively offset by a few kilohertz. With Δf_r = 0 and the relative phases set in quadrature, the output of the mixer is a voltage proportional to the relative phase fluctuations between the two independent 1 GHz signals. The voltage fluctuations are measured with a FFT spectrum analyzer to produce the single-sideband phase noise spectrum L(f) shown as curve (i) in Fig. 1(a). It is important to note that this spectrum represents an upper limit of the down-converted 1 GHz phase noise of one system as is contains contributions from the two CW lasers as well as the two FLFC's. Locking both FLFC's to f_{LD} allows us to measure the contribution of a single FLFC as it synthesizes the 1 GHz signal, which is shown as curve (ii) of Fig. 1(a). The 1/f dependence and subsequent flattening above 1 kHz for both curves (i) and (ii) leads us to believe that these present results are still limited by noise in the photodiodes, amplifiers or measurement system. The noise-level set by the phase-locks of the FLFC's is shown in curve (iii) of Fig 1(a), implying that significant gains can still be attained, provided the noise level of the CW laser is low enough. Also shown in Fig. 1(a) are the phase noise spectra of a high-quality quartz-based 1 GHz oscillator and a sapphire microwave resonator.

Associated stability measurements are made by slightly offsetting f_r from each of the two FLFC's by a few kilohertz. The mixer output at this offset frequency was then measured with a high-resolution counter. From a series of counter measurments, we calculate the Allan deviation, which is a measure of the fractional frequency instability. This is plotted as the triangles in Fig. 1(b) for various gate times of the counter. Small drifts between the two optical reference cavities are responsible for the flicker-like behavior at averaging times >3 s. Nonetheless, the 1-s Allan deviation is $\sim 5\times 10^{-15}$, significantly below that of the best quartz oscillators which have 1-s Allan deviations of $\sim 7\times 10^{-14}$. Again, this represents an upper bound as it contains contributions from the two CW lasers as well as the two FLFC systems. The squares of Fig. 1(b) are the Allan deviation f_{LD} and were obtained from the heterodyne beat between f_{LD} and of one tooth of the FLFC that is stabilized by f_{DYE} and represent the instability of the optical frequency comb components. The difference between the two data series in Fig. 1(b) is representative of the excess noise that remains in the extraction of the 1 GHz microwave signal from the optical pulse train.

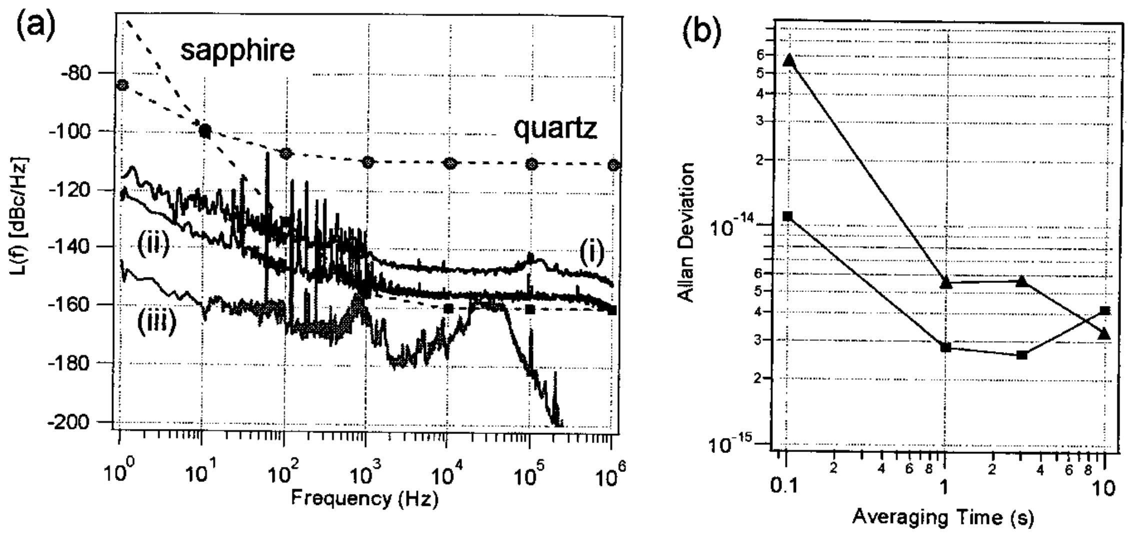

Figure 1. (a) Curve (i): Measured phase noise between two 1 GHz signals generated by down-converting independent optical frequency oscillators using two FLFC's. Curve (ii): Measured phase noise of a single FLFC. Curve (iii): Noise level set by the phase-lock loops of the FLFC. The dashed curves are the phase noise of 1 GHz signal derived from a quartz oscillator (circles) and a sapphire microwave resonator (squares). (b) triangles: Allan deviation (fractional frequency instability) of 1 GHz microwave signals generated by down-converting independent optical frequency oscillators using two FLFC's. squares: Allan deviation of f_{LD} determined via heterodyne with the FLFC that is stabilized by f_{DYE}.

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