Microwave generation with low residual phase noise from a femtosecond fiber laser with an intracavity electro-optic modulator

William C. Swann,* Esther Baumann, Fabrizio R. Giorgetta, and Nathan R. Newbury
National Institute of Standards and Technology, 325 Broadway, Boulder, Colorado 80305 USA
*swann@boulder.nist.gov

Abstract: Low phase-noise microwave generation has previously been demonstrated using self-referenced frequency combs to divide down a low noise optical reference. We demonstrate an approach based on a fs Er-fiber laser that avoids the complexity of self-referenced stabilization of the offset frequency. Instead, the repetition rate of the femtosecond Er-fiber laser is phase locked to two cavity-stabilized cw fiber lasers that span 3.74 THz by use of an intracavity electro-optic modulator with over 2 MHz feedback bandwidth. The fs fiber laser effectively divides the 3.74 THz difference signal to produce microwave signals at harmonics of the repetition rate. Through comparison of two identical dividers, we measure a residual phase noise on a 1.5 GHz carrier of $-120$ dBc/Hz at 1 Hz offset.

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References and links


1. Introduction

Microwave signals with high spectral purity are of interest in diverse fields such as clocks, communications, radar, fundamental measurements, and other applications. However, it is challenging to generate microwave signals with low phase noise, particularly at Fourier offset frequencies close to the carrier, because of upconversion of the ever-present 1/f noise in experimental systems. Cryogenic sapphire microwave oscillators can successfully generate microwaves with extremely low close-to-carrier phase noise [1, 2], but they are physically large systems that require cryogenic temperatures. An alternative approach uses frequency
combs to divide a very quiet optical oscillator down to the microwave domain [3–13]. A Ti:Sapphire comb frequency divider has produced microwaves with an absolute phase noise rivaling, and at some offset frequencies surpassing, cryogenic microwave oscillators [3]. Fiber comb-based frequency dividers have the potential to provide a relatively compact and less expensive system [3–13]. Indeed, the absolute phase noise of a fiber comb-based system has been shown to be comparable to the Ti:Sapphire comb-based system [11].

Although these comb-based systems do not require the cryogenic temperatures of a state-of-the-art sapphire oscillator, they are otherwise complex. The microwave generation requires a cw laser phase-locked to a state-of-the-art optical cavity, whose output is transmitted through a Doppler-cancelled fiber link to the frequency comb. The comb itself is a complex system, regardless of whether it is based on a fiber or Ti:Sapphire laser, comprising a femtosecond (fs) laser followed by supercontinuum generation to allow for a self-referenced “f-to-2f” phase lock of the offset frequency [14, 15] and a second phase lock of one comb tooth to the transported cavity-stabilized light. The final step in the microwave generation is the photodetection of a harmonic of the stabilized comb repetition rate, which should be a divided-down replica of the original cw laser light, subject to limitations imposed by the photodetection [12, 16, 17]. These full comb-based systems are appropriate for metrology laboratories, but some simplification is warranted for portable or field-deployable systems.

Fig. 1. (a) Concept for microwave generation directly from a fs Er fiber laser. (b) Frequency-domain illustration of the stabilization of the fs laser repetition rate, or tooth spacing, through stabilization of the 3.74 THz (30 nm) wide output comb of the fs fiber laser. PDH: Pound-Drever-Hall lock

In this paper, we explore a simpler system design, illustrated in Fig. 1. The basic concept follows standard comb-based approaches; namely we stabilize the repetition rate of a fs fiber laser to a cavity-stabilized cw laser. However, standard comb-based dividers phase lock only one comb tooth to a cw laser and phase lock a second tooth near zero frequency, i.e. the offset frequency, to an rf reference. Here, instead, we phase lock one comb tooth to a 1565 nm cw cavity-stabilized laser and a second comb tooth to a 1535 nm cw laser stabilized to the same cavity. Although a second cw fiber laser has been added, the system is otherwise considerably simplified. First, it does not require an octave-spanning supercontinuum, eliminating the need for a dispersion-compensated Er-doped amplifier, highly nonlinear fiber, and various polarization controllers. Second, it does not require an f-to-2f interferometer or the phase-locking electronics to stabilize the offset frequency. (It requires only a single phase lock on the difference between the heterodyne beat at 1535 nm and 1565 nm.) Third, we use commercially available, compact fiber lasers that are compatible with a compact, fiber-optic based Pound-Drever-Hall (PDH) cavity lock. Finally, there is no need for a Doppler-cancelled fiber link as the entire setup for the phase locks of the cw lasers to the optical cavity and the phase locks of the comb to the cw lasers easily fits onto a single vibration-isolation platform.

One concern in this approach is that the effective “moment arm” for the stabilization of the comb repetition rate is reduced from ~200 THz to 3.74 THz (see Fig. 1). As a result, the sensitivity to excess phase noise on the optical locks is degraded by a factor of (3.74 THz/200 THz)² ≈1/2500. Therefore, we do require much tighter optical phase locks to reduce excess noise, which is realized here by including an intra-cavity electro-optic modulator (EOM) within the fs laser [11, 18–20]. While inclusion of a free-space bulk lithium niobate EOM within the fs laser cavity can achieve feedback bandwidths of 100’s of kHz, the complete advantage of an intracavity EOM is only realized with a fiber-coupled waveguide modulator,
where MHz feedback bandwidths are possible [19, 21]. Here we achieve bandwidths of 2 - 4 MHz, limited by the electronic bandwidth of our phase-locked loop.

We compare two identical frequency comb dividers, both phase-locked to the same optical cavity, and find a residual microwave phase noise of $-120$ dBc/Hz at 1 Hz offset from a 1.5 GHz carrier, which scales to $-103.5$ dBc/Hz at 10 GHz and is comparable to phase noise achieved by other comb-based dividers. The phase-noise floor at high offset frequencies is limited to $-140$ dBc/Hz by am-to-pm noise conversion of the fiber-laser relative intensity noise (RIN). However, this noise floor could be substantially suppressed through the recent techniques of Refs [12, 13, 22]. Alternatively, the system could be combined with a low phase noise dielectric oscillator at high offset frequencies. In this work, we examine the suitability of our scheme for low phase noise microwave generation exclusive of any reference cavity noise and, as such, we compare two separate microwave generating systems locked to a common cavity. Ultimately (and the subject of future work) these systems would be decoupled and locked to separate cavities, and the absolute microwave phase noise, including the effects of cavity noise, quantified.

2. Experimental setup

The overall system is illustrated in Fig. 2. All "out-of-loop" optical paths that could contribute to phase noise, including the entire optical paths for photodetection, stabilization of the cw lasers to the cavity, and stabilization of the comb to the cw lasers, are located on a single vibration isolation table. This approach eliminates the need for a separate Doppler-cancelled fiber link between the cw lasers and the comb, both of which lie adjacent to the isolation table. It also reduces $1/f$ noise as the critical "out of loop" optical paths mentioned above are short and are contained within the low-vibration environment of the isolation table. Below, we first describe the stabilization of the cw lasers and then the stabilization of the fs fiber lasers.
The wavelengths, 1535 nm and 1565 nm, of the cw fiber lasers are chosen to match the wings of the fs fiber lasers’ spectra. The cw lasers are locked to an optical cavity constructed of two silica mirrors optically contacted to a 10-cm ULE glass spacer, giving a free spectral range of 1.5 GHz and finesse of 200,000. The cavity is in a vacuum enclosure and has a single layer of temperature control. The locks are implemented with the Pound-Drever-Hall (PDH) technique [23] after first polarization multiplexing both lasers onto a polarization maintaining (pm) fiber. A few percent of the combined light is coupled into the cavity. Light reflected from the cavity is polarization de-multiplexed, detected, and the resulting two signals fed back to their respective lasers.

Both fs lasers are of a fiber ring design [24] containing Er-doped fiber as a gain medium, pumped at 1480 nm, and include intracavity fiber-coupled waveguide EOMs. The lasers operate in the “stretched-pulse” regime with a net cavity dispersion of ~0.006 ps², repetition rate of ~100 MHz, and output power of ~60 mW. One “all-fiber” laser (fs laser #1) uses only fiber-optic components and one “tunable” laser (fs laser #2) contains a free-space section so its repetition rate can be tuned to exactly match fs laser #1. The RIN at high frequency offsets (10’s of MHz) is ~152 dBc/Hz. As shown in Fig. 2, the output of each fs laser is split. A portion is detected by a commercial high-bandwidth photodetector, followed by a narrow (±25 MHz) rf bandpass filter (BP) to select the microwave harmonic of interest, and then amplified through a low 1/f noise amplifier. The other half of the fs laser output is directed to a polarizing beam splitter, where it is combined with the two cavity-stabilized cw lasers. The combined light is spectrally filtered and the respective heterodyne beat signals at 1535 nm and 1565 nm detected, each with a signal-to-noise ratio of ~35-45 dB in a 300 kHz bandwidth. The two heterodyne signals are then used in a phaselocked loop to stabilize the fs laser.

One approach for laser stabilization is to phase lock one heterodyne signal (say at 1565 nm) by feeding back to the laser’s repetition rate using the PZT and EOM and the other heterodyne signal (say at 1535 nm) by feeding back to the power of the 1480 nm pump diode through its current supply [25]. In that case, both degrees-of-freedom of the fiber comb are phaselocked and the entire comb should have very narrow linewidths [26]. Figure 3 shows an example of the relative optical linewidth and phase noise between the two fs lasers when locked with this approach. The small servo bump at 2 MHz indicates the EOM feedback bandwidth, which is set by accumulated rf phase shifts in our discrete rf bandpass filters and in the loop filter rather than by the EOM itself. As in Refs [19, 20], the phase noise and residual optical linewidths are significantly lower than they would be without the EOM.
Fig. 4. (a) In-loop measurement of the rf spectrum for the phase-locked difference signal for fs laser #1 (purple) and #2 (blue) for a 200 kHz span and 10 Hz resolution bandwidth (RBW). The inset is at a 2.5 kHz span and 300 mHz RBW. (b) Corresponding in-loop measurement of the phase noise. The servo bump at 2 MHz on fs laser #1 results from the EOM phase-locked loop (PLL). For fs laser #2, a similar servo bump is observed at 4 MHz (offscale). The integrated phase noise from 1 Hz to 100 kHz is 3.2 mrad and 3.9 mrad for fs lasers #1 and #2, respectively. The group of spurs starting at 60 Hz are harmonics of the 60 Hz power line. The servo bump at 2 kHz on fs laser #2 results from the intracavity PZT. The larger increase at ~80 kHz appears to be related to unsuppressed residual phase noise between the cw lasers and the optical cavity and could be further suppressed by a tighter PDH lock.

While individually stabilizing both degrees of freedom using feedback to the EOM / PZT and to the pump power is appropriate for generating optical comb teeth with narrow residual linewidths, it is not necessarily ideal for microwave generation for the following reasons. Although it is tempting to consider the EOM and PZT as applying the same correction signal to the cavity length, in fact they are quite different. The EOM actually has a very different “fixed point” than the PZT [27, 28] (defined as the effective tooth about which the comb expands and contracts as the EOM control voltage is changed). Through the technique of Ref [28], we measure a fixed point for the EOM actuator of 90 THz and 55 THz for fs lasers 1 and 2, respectively. For comparison, the expected fixed point for the PZT actuator is ~2 THz and the fixed point for pump power is 155 THz and 177 THz. As the fixed point for the EOM feedback lies uncomfortably close to that of the pump power feedback, it will also significantly modify the offset frequency as well as the repetition rate. Feedback to the pump current can overcome this additional modulation to stabilize the offset frequency, but only at the cost of additional amplitude modulation, which in turn can increase the microwave phase noise through am-to-pm conversion in the photodetection. Either this additional amplitude noise must be removed through external power stabilization [10], or, as we do here, one can avoid the problem by forgoing stabilization of the offset frequency altogether, as it is not needed for microwave generation.

Therefore, for the microwave phase noise discussed in the remainder of the paper, we rearrange the phase locking to stabilize only the difference frequency between the heterodyne beat frequencies at 1535 nm and 1565 nm by feedback to only the EOM and PZT. This feedback stabilizes the comb repetition rate and therefore its harmonics, but allows the offset frequency to change. Indeed, the individual heterodyne signals are observed to move on MHz
scales due to uncontrolled noise on the offset frequency, but nevertheless their difference is tightly phase-locked to a narrow rf signal, as shown in Fig. 4. This approach avoids imposing additional am noise on the laser from pump current modulation and also has the advantage of a single phase lock for the comb. We note a similar approach can be taken with a self-referenced comb by taking the difference of the offset frequency and optical beat [7].

### 3. Results

Because only one high-finesse cavity was available, the measurements were limited to residual phase noise between the two fs fiber lasers, both locked to the same pair of cavity-stabilized cw lasers through separate optoelectronic systems. The relative phase of the 15th harmonic at 1.5 GHz of the two photodetected microwave signals was adjusted so that the signals were in quadrature at the mixer (see Fig. 2). The mixer output was then a direct measure of the relative phase noise, which is shown in Fig. 5. A $-3\text{dB}$ correction was applied to account for the fact that there were two oscillators.

![Phase Noise Measurement](image)

**Fig. 5.** Residual phase noise at the 1.5 GHz carrier between the output of the two phase-locked fs fiber lasers (black line) along with the measurement noise floor (gray line). The spikes are at harmonics of 60 Hz and appear on both the measured phase noise and the measurement noise floor. The measured phase noise is $-120 \text{ dBc/Hz}$ at 1 Hz offset.

The phase noise shows the typical $\sim 1/f$ falloff to a white phase noise floor. In particular, note the absence of excess phase noise at acoustic frequencies of 100 Hz to 10 kHz, which we attribute to the tight phase locking of the combs to the cw lasers through the EOM actuator and to the minimal free-space path lengths in the overall system. The $1/f$ phase noise is $-120 \text{ dBc/Hz}$ at 1 Hz offset. In fact, the measured $1/f$ noise falls on top of the mixer noise floor, and is an upper limit to the residual phase noise of the microwaves. An alternative dark-fringe detection [10, 29] was implemented at a lower harmonic and indicated the residual noise was at best a few dB below this mixer noise floor. However, the mixer approach provided greater flexibility and was used for these measurements. The white noise floor at $-140 \text{ dBc/Hz}$ is dominated by either thermal noise or am-to-pm conversion of the laser RIN, depending on the power incident on the detector. There are a number of clever techniques to push this white noise floor further down, including operating the system at a power level where the am-to-pm conversion is zero and/or repetition-rate multiplication through cascaded Mach-Zender interferometers to lower the pulse energy [12, 13, 22].
We next compare the measured residual phase noise to predictions. The excess phase noise involved in the generation of microwaves by a comb-based frequency divider has been well explored in a number of papers [3-5, 7, 9–13, 17, 22, 30]. The expected residual single-sided phase noise on the microwave signal at $f_{rf}$ is

$$L_p(f) = \frac{1}{P_{rf}} \left[ \frac{qI_{dc}R}{4} + \frac{NFK_BT}{2} \right] + \frac{\alpha^2}{2} RIN(f) + \left[ \frac{f_{rf}}{\Delta f_{opt}} \right]^2 L_{locks}(f) + L_{other}(f). \quad (1)$$

where $P_{rf}$ is the rf power at the harmonic (equal to $I_{dc}R^2/2$ in the absence of saturation) and we assume a matched 50 $\Omega$ impedance at the photodetector and amplifier. The first term is the shot-noise contribution defined in terms of the electron charge, $q$, dc photodetection current $I_{dc}$, and resistance, $R = 50 \Omega$. The second term is the thermal noise floor from the rf amplifier, defined in terms of the amplifier noise figure, $NF$, Boltzmann’s constant, $k_B$, and temperature $T$. The third term is the amplitude-to-phase noise conversion in the photodetection, defined in terms of a highly system-dependent coefficient $\alpha$ and relative intensity noise (RIN) [12, 17]. $\alpha$ is zero at low pulse energies, increasing with power to $\sim$1 rad or more and then oscillating with pulse energy above detector saturation [12, 17]. The fourth noise term is the divided-down noise on the difference phase lock, which spans $\Delta f_{opt}$. Finally, the last term is a general placeholder for other potential noise terms such as fiber thermal noise.

![Fig. 6. Measured residual phase noise at the 1.5 GHz carrier (black) between the two fs lasers (without the $-3$ dB correction of Fig. 5) along with the contribution from shot noise (gray), thermal noise (green), the noise on the phase locks (blue and purple) for the two fs fiber lasers. Also shown are the measured RIN (orange and brown) for the two fs fiber lasers, which can be converted to residual phase noise with increasing incident power.](image)

Figure 6 compares our results with the predicted performance of Eq. (1). Typical optical power incident on the detectors is $\sim0.8$ mW. From this, we have typical dc photodetection currents of $I_{dc} \sim0.3$ mA and typical rf power of $P_{rf} \sim25$ dBm at 1.5 GHz. The amplifier noise figure of our 35 dB gain amplifiers is $NF = 3.5$ dB. From these values the thermal and shot noise of Fig. 6 are generated. The RIN varies from $\sim-130$ dBc/Hz to $-140$ dBc/Hz and is predominantly above the microwave phase noise, indicating $\alpha < 1$ rad. The phase-lock noise, $L_{locks}(f)$ from Fig. 4 are rescaled by $[f_{rf}/\Delta f_{opt}]^2 = -68$ dB to show their contribution to the microwave phase noise on Fig. 6. In general, the contribution from shot noise is negligible, as expected for dc currents below a few mA. The contribution from the phase-lock noise is also negligible, indicating that the combination of the 3.74 THz separation between lock points and direct high-bandwidth feedback to the EOM is sufficient. This contribution does increase
quadratically with increasing harmonics; at $f_r = 10$ GHz it is 16 dB higher and just reaches the white noise floor. For the parameters here, the thermal noise dominates the white noise floor. However as the incident power is increased we observe that the white noise floor stays roughly at the same level but is dominated instead by am-to-pm conversion of the laser RIN, until it increases at even higher incident powers.

The data of Figs. 5 and 6, and Eq. (1) characterize the residual noise between the two dividers; they ignore the common-mode contributions to the phase noise from the cavity itself, from residual phase noise of the cw fiber lasers versus the cavity, or from fluctuations in common beam paths. We next provide a rough estimate of these contributions.

Fiber paths can lead to significant phase noise both from environmental perturbations and from fundamental fiber noise [31–33]. As noted in Section 2, the layout ensures cw fiber laser and almost all fiber paths are within the feedback loops so as to strongly suppress excess fiber noise. “Out-of-loop” common beam paths are short, on the vibration isolation table, and mainly free-space. There are ~1 meter fiber paths to the photodetectors to avoid phase noise from pointing fluctuations. Technical noise on this fiber is reduced by attaching it to the table. The intrinsic thermal fiber noise is calculated for the carrier from Refs. [31–33] and would contribute only ~ -200 dBc/Hz at 1 Hz offset when scaled to 1.5 GHz. Also, any excess noise from these 1 m fiber paths would be observed in the measured residual phase noise.

The cw fiber lasers are locked tightly to the cavity through an AOM. We compared a cw fiber laser locked to one cavity in this way with a semiconductor laser locked to a second cavity. The residual optical noise between the lasers is dominated by excess phase noise on the semiconductor laser due to its much larger intrinsic Lorentzian linewidth of 4 kHz, but nevertheless when scaled by $(1.5$ GHz/$3.4$ THz)$^2$ results in only ~ -140 dBc/Hz at 1 to 50 kHz. (Below 1 kHz, the noise increased as $1/f^4$, presumably due to temperature drift of the cavities.) The residual phase noise on the quieter cw fiber laser should be well below this level.

The most important common mode noise is the optical cavity itself. When scaled to 10 GHz, our phase noise at 1 Hz offset corresponds to ~ -103.5 dBc/Hz; this value is equivalent to the absolute $1/f$ phase noise achieved by several frequency-comb dividers [3, 11], and comparable to that achievable for fieldable optical cavities [34] (although it is ~ -10 dB above the highest performance cavities, which can reach ~ -114 dBc/Hz when scaled to 10 GHz [35]). Therefore, our measured residual $1/f$ noise floor does appear sufficient to support the absolute phase noise achievable with current high finesse, fieldable optical cavities.

4. Conclusion

We demonstrate an optical-divider based microwave generation system with a close-in excess phase noise comparable to previous frequency comb systems. The system can achieve these low phase noise values with the use of only a EOM-based fs fiber laser and without f-to-2f detection and its associated pulse amplification, compression, and supercontinuum generation, although at the cost of a second cw fiber laser. The small system size suggests a compact cavity-stabilized reference laser [36] and the fs laser could be contained within the same environmentally-isolated enclosure to generate microwaves in a single physical unit. Here we have only explored residual noise; the ultimate performance will be established by absolute phase measurements between two fully independent cavity-comb systems.

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