Ultra-low Phase Noise Frequency Synthesis from Optical Atomic Frequency Standards

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***Abstract*— We discuss frequency synthesizer needs and recent phase noise results of a multi-level frequency divider that are consistent with the phase noise of new high-accuracy optical atomic standards. Optical atomic standards achieve extremely low frequency uncertainties in less than hundreds of seconds due to their unprecedented phase stability and accuracy. The desire for low white-FM noise that ordinarily required days of averaging for laboratory standards to attain full accuracy has been shifted to a need for low flicker-FM noise to maintain long-term frequency uncertainty with only seconds of averaging. This imposes new requirements for low levels of phase noise realizable by laser stabilization by a hi-Q optical cavity of a phase-coherent optical frequency comb. The multi-level frequency divider serves as a tool for synthesizing many low-phase noise frequencies.**

Keywords—accuracy; atomic; frequency synthesizer; optical atomic standard; optical frequency divider; oscillator; phase noise; stability

I. Introduction

Applications increasingly need ultra-low phase noise (ULPN) synthesizers in the most common radio frequency (RF) range of 5 MHz to tens of gigahertz (GHz). These needs affect metrology labs that must make phase noise measurements and/or test devices in emerging areas that include:

1. Wireless standards that manage and relieve spectral congestion [1-3]
2. Hi-speed communications [4-5]
3. Wireless geolocation [6-7]

This short list by no means represents the vast number of applications. Such applications require low phase noise or high phase stability of oscillators, synthesizers, and synchronization to achieve the best performance. We note that upgrades or redesigns in these and other applications often involve the replacement of low size, weight, and power (SWaP), low-accuracy quartz-based oscillators with better ones.

For these and many in-the-field applications, high-accuracy ULPN oscillators primarily mitigate problems in the following areas: (a) corruptions/disruptions and excessive lag time due to phase noise, and (b) system synchronization due to and frequency drift/uncertainty. It is apparent that atomic clocks with low SWaP that simply replace quartz oscillators to attain accurate timekeeping may typically exhibit white-FM (WHFM) noise of $10^{-13}/\sqrt{\tau}$ at 1 s. The fastest accuracy is attained, however, by flicker-FM (FLFM) noise as discussed next.

II. Fundamental Change in Approach

The new breed of oscillators will be based on laboratory standards that target frequency accuracy of 10^{-15}; attainable in averaging times of tenths of seconds. The most promising reference-oscillator and clock technology to meet desirable specifications are based on: (1) laser trapping and confinement of atoms/ions, cooling and/or use of slow beam with optical quantum resonances that have high contrast and low systematic frequency-accuracy uncertainty (Type B) [8], and (2) optical frequency combs that have enabled frequency intercomparisons at the 10^{-19} level and that translate the ultra-low-noise performance of optical atomic frequency references to RF microwave. In the clock community, tenths of seconds is essentially "instant" compared to the usual days and weeks of averaging for attaining this same accuracy. If the desired frequency stability is 10^{-15}, this maps a level of required phase noise that is significantly lower than that available from mainstream atomic clocks and oscillators as illustrated in Fig. 1. As one can see, the noise type for the lowest and broadest range of frequency instability is shown as FLFM (i). The goal of 1×10^{-15}, $0.1\ \mathrm{s} < \tau < 10^{8}$ s is attained by an ideal FLFM noise, i.e., one with constant uncertainty. In contrast, WHFM noise that is typical of atomic frequency standards [9] shows a substantial rise in instability as the averaging time gets shorter, increasing as $1/\sqrt{\tau}$. Furthermore, FLFM < 10^{-15} is consistent with 10^{-15} frequency accuracy for all averaging times. The desired property of FLFM noise represents a paradigm shift to designs of atomic-based oscillators that produce ULPN RF outputs without necessarily exhibiting WHFM.

FLFM design criteria changes the need to verify WHFM as an underlying noise type in ultra-stable, accurate optical frequency standards. The "Need" phase noise in Fig. 1, left, is based on the expectation of WHFM, and the new FLFM (i) goal actually relaxes the close-in phase noise while making the requirement lower and more stringent for measurements far from carrier. The development of ULPN synthesizers at frequency accuracy of 10^{-15} gives rise to improved performance of the applications mentioned in Section I.

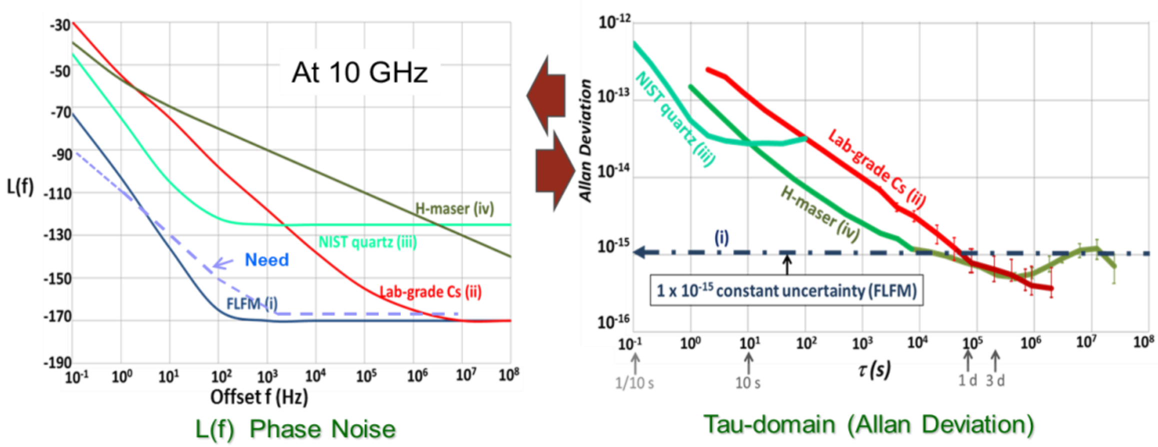

Fig. 1. The need is for white-FM substantially below lab cesium and may exhibit flicker noise as FLFM (i) at a level of phase noise shown on left for a 10 GHz oscillating signal. A FLFM (i) floor yields a desirable constant uncertainty in frequency of 10^{-15} from very short- to long-term tau, as shown as on right, thus accuracy of 10^{-15} would be available instantly compared to any other of the best oscillators. Phase noises of the best cesium fountain F1 (ii), quartz oscillator (iii), and commercial H-maser (iv), are also shown on left and the corresponding Allan deviation on right.

It also produces strategies in applications, such as Global Navigation Satellite System (GNSS) [10] and frequency difference of arrival (FDOA) geolocation [11], that will now enable "fast accuracy." Fast accuracy in the time domain maps to phase noise levels and measurement requirements at new, unprecedented-low-noise levels that still quite often must be made at virtually any frequency with traceable accuracy [8].

III. Optical ULPN Atomic Oscillators

ULPN atomic oscillators provide a very important property, dissemination of frequency, in the following way. Since quantum energy levels of atoms are related to the transition frequency ω by E = ħω, these frequencies occur naturally and are regarded as non-dissipative with spectral-noise distribution that is white (constant except at exactly ω) without frequency aging or drift. The energy difference ΔE = ħΔω possesses a finite lifetime with reciprocal value that therefore gives ω a finite, or non-zero, bandwidth Δω. An expected normalized frequency of 1 + Δω/ω is accessible and reproducible in any location at any time, in perpetuity. It is easy to show that fractional-frequency accuracy $\Delta\omega/\omega = \Delta\tau/T_{\mu}$, where Δτ is some required timing accuracy and T_{μ} is the time-update interval. The operating frequency ω should be as high as possible, thus the interest in shifting to optical wavelengths, while Δω = 1/(lifetime) should be as small as possible by using narrow linewidth resonances. This reproduction can be regarded as "frequency dissemination." The degree of phase alignment (synchronization) can be done very infrequently, ideally only once at the beginning, the so-called "time origin," of many long-duration missions. Synchronization updates relate directly to frequency reproducibility and less than 100 ps holdover for a day is possible. Schemes using Ca magneto-optical traps (MOTS) and beams [12-13] achieve a high 10^{-15} accuracy. Better than 10^{-15} accuracy has been successfully attained for several years at NIST and other research using Yb and Sr [14] lattice clocks as shown in Fig. 2. Results show the possibility of attaining 10^{-15} stability [15]. We note that cavity-stabilized lasers are used to interrogate the optical atomic transitions. Given that most applications require accuracy and stability on RF rather than optical signals , this paper now will address work on low-noise frequency conversion, or synthesis, to RF from cavity-stabilized lasers that are locked to optical atomic transitions.

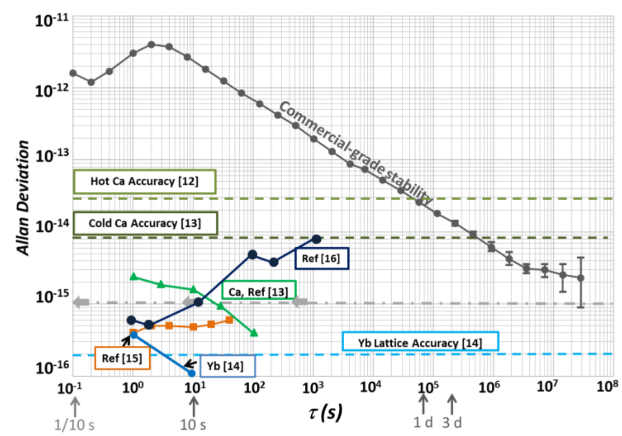

Fig. 2. Optical atomic oscillator stability achieves $<10^{-15}$, 1 s < τ_s < 100s [12] [13] [14][15]. The cavity-stabilized OFD is shown in dark blue [16]. Note that commercial-grade Cs does not reach 1×10^{-15} (gray plot) and that NIST F1, lab-grade Cs, requires 1 d of averaging for 1×10^{-15} (see Fig. 1). A FLFM floor yields a desirable constant uncertainty in frequency of 10^{-15} for all tau, thus accuracy of 10^{-15} would be available faster, essentially instantly, compared to any other of the best oscillators. Lower phase noise, consistent with optical atomic oscillator stability in order to be usable at RF, requires ULPN synthesizers, the basis for which is a ULPN divider-chain.

IV. Frequency Synthesis

$\mathscr{L}(f)$ is defined as the single-sideband phase noise whose plots have $\mathscr{L}(f)$ and f axes on log-log scales so that power-law noise-identification corresponds to a slope β given by power-law f^{β}, $-5 < \beta < 0$, β integer. Frequency synthesizers that generate $\omega_{out} = [N \div M]\omega_{in}$, where N, M are integers, usually provide the lowest-noise, most straightforward for coarse translations from one frequency to another. One can see that N and M are multiplication and division factors, respectively, and ideal phase noise transformation is given by, $\mathscr{L}(f)\omega_{out} = \mathscr{L}(f)\omega_{in} + 20\log[N \div M]$. Fine, or high resolution, translations can introduce noise, usually from non-ideal divider and multiplier residual noise. This paper addresses the coarse translations, the primary resource being noise-free division from ULPN optical carriers to RF. For example, $M = 10^8$ for division from 500 THz to 5 MHz. Fig. 3 shows various best-in-class oscillators operating at essentially their lowest-noise, RF carrier frequencies. The phase noise noise at an offset frequency of 1 kHz, is shown for quick comparisons and the fact that 1 kHz is a frequency that impacts most applications. The dashed lines in Fig. 3 indicate how $\mathscr{L}$(1 kHz) would change with "noiseless" frequency synthesis to another RF carrier frequency. The dashed lines-of-comparison follow a slope of +6 dB per octave of frequency change. The list of oscillators and synthesizers used in Fig. 3 is a sampling of best-in-class commercial and laboratory oscillators. Virtually all of the oscillators and synthesizers can be measured against an optical frequency divider that is stabilized by an optical cavity or, for high accuracy, an atomic resonance, as discussed earlier.

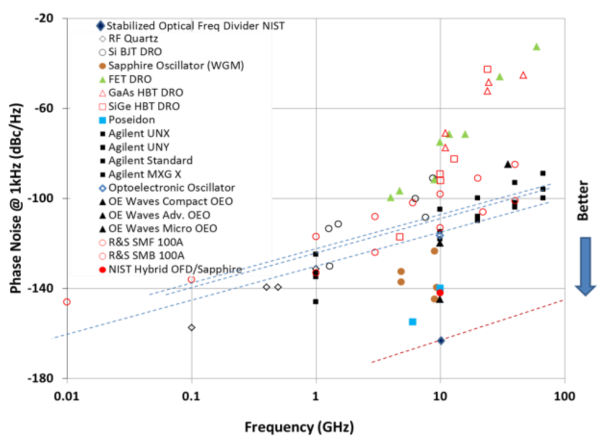

Fig. 3. Phase noise comparison at 1 kHz offset of state-of-the-art oscillators and technologies at ambient temperature. Dashed lines are along a noiseless frequency-synthesizer line-of-comparison that translate frequencies from one RF carrier frequency to another. Manufacturers are shown. Many manufacturers exist, no endorsement is implied. The lowest line intersects a cavity-stabilized optical-frequency division (OFD) to attain RF ULPN output at 10 GHz [16].

V. ULPN Optical Frequency Division

The RF-output frequency (comb repetition rate) can effectively divide an accurate, optical atomic transition frequency and so also divide the intrinsically low optical phase noise down to low levels of usable RF and microwave signals. While there are several ways to generate a frequency that is coherent with a reference, we present the results of one of the most straightforward methods that can be reconfigured

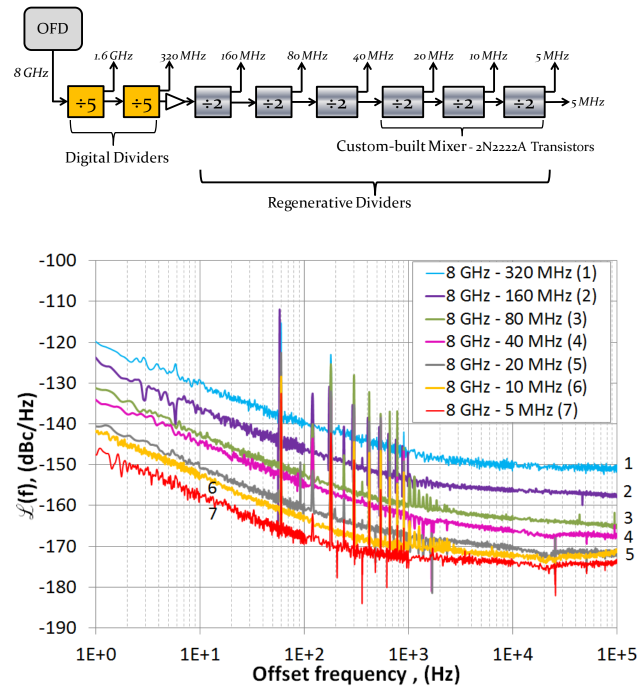

Fig. 4. Frequency synthesizer starts with the output of an optical frequency divider (OFD) [16] and a combination of digital dividers and analog regenerative frequency dividers (RFDs) as shown at the top. The input signal at 8 GHz is generated from a cavity-stabilized, self-referenced, 1 GHz Ti:sapphire mode- locked laser. Residual single-sideband phase noises of a pair of synthesizers at the seven output frequencies starting at 8 GHz (input) are shown at the bottom. For several stages, the phase noise slope between 1 Hz and 10 Hz offsets is 1- 2 dB steeper than 1/f. This is due to thermal fluctuations and vibration disturbances of the laboratory environment.

easily for metrology purposes. It is based on generating a divider-chain of cascading intermediate ULPN signals at frequencies that can be added, subtracted, multiplied, and divided for synthesizing RF and microwave frequencies suitable as reference. We start with the well-known technique of cavity-stabilized optical-frequency division (OFD) to attain RF ULPN output at 8 GHz [16].

Recent work at NIST has created two divider chains of ULPN regenerative RF dividers whose input is a cavity-stabilized OFD and whose end output at 5 MHz has a phase noise of $\mathscr{L}$(1 Hz) = -150 dBc/Hz [17]. Several frequencies are available from these chains and the measured phase noise is shown in Fig. 4. This is the best result to date towards achieving low noise frequency synthesis by frequency division from the cleanest pulsed output of a stabilized optical frequency divider.

VI. Conclusion

A formidable challenge to metrologists is synthesizing various frequencies with ultra-low phase noise (ULPN) as references for measurements of new breeds of pure signals from atomic standards. The ever-increasing requirements are in realizations of 1×10^{-15} accuracy for time intervals considerably shorter than the many hours associated with laboratory grade Cs standards. Commercial, industrial, and military sectors have sufficient markets to motivate the development and manufacture a variety of high-accuracy ULPN optical oscillators applied at RF microwave frequencies and with resistance to environmental stress (vibration, acceleration, temperature, pressure, etc.).

The current discussion has been limited to laboratory environments with slow acceleration and small changes in gravitational potential. These applications call for decentralized accuracy that approaches 1×10^{-15}, such as from a laboratorygrade Cs standard, but evaluated every few tenths of seconds rather than over days. Relativistic effects are significant here and must be taken into account, but a more important aspect of future discussion is the necessity and challenge of accurately measuring the vibration sensitivity of ULPN standards at required in-the-field levels below 10^{-11} /g at certain vibration frequencies. This topic is beyond the current paper's scope; however, we intend to devote attention to this increasingly important aspect in the metrology community.

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