Optical-to-RF Frequency Synthesis: Application Priorities for Ultra-low Phase Noise

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***Abstract* - We describe operational challenges and progress of optical frequency-comb dividers (OFDs) that synthesize RF signals from the optical domain. Our priorities include: (1) ultra-low phase-noise, (2) continuous operation, and (3) broadly low Allan deviation.**

***Keywords* - Oscillator; phase noise; stability; accuracy; frequency synthesizer; optical frequency divider; optical atomic standard.**

I. INTRODUCTION

A key challenge for atomic clocks whose frequencies are based on optical transitions is that they must be able to convert these optical signals to usable common radio frequency (RF) ranges of 5 MHz to tens of gigahertz with minimal noise degradation. Optical standards achieve extremely low frequency uncertainty in tenths of seconds signifying ultra-low phase noise (ULPN). Many have unprecedented levels of accuracy as determined by calibrations against references traceable to Cesium standards [1]. Exploiting optical ULPN for making fast high-accuracy microwaves is best done by using an optical frequency divider (OFD), since accuracy is defined by a microwave transition in Cesium and OFDs minimally degrade the phase stability in the conversion to microwaves from optical signals ~500 THz. Current applications that utilize microwave ULPN are in:

1. Relief of wireless communications congestion [2] [3] [4]
2. Hi-throughput, secure data communications [5] [6]
3. Radio geolocation [7] [8]

Highly stable optical-to-RF ULPN frequency synthesizers and phase-noise measurements using OFDs is an important technology for the above items. This paper discusses three prominent priorities and challenges for the use and measurement using OFDs: (1) frequency-uncertainty ADEV that assure traceable accuracy to connect long-term averaging times needed for Cs to the very good short-term stability of optical-atomic secondary standards, (2) a strategy to obtain ULPN optical-to-RF frequency synthesis, and (3) continuous operation of ULPN references to use and measure long-term stability. Section II defines how flicker-FM noise is a power-law noise type needed to maintain frequency-uncertainty as part of efficient, traceable accuracy of an optical-atomic secondary standard to Cs. Section III outlines the use of OFDs for obtaining ULPN frequencies for synthesis that meet traceability criteria of Section II by starting with a NIST-designed state-of-the-art divider chain from optical to 5 MHz. Section IV describes our initial stages of adapting our OFD and its various electronic controls so that it can operate continuously.

II. STABILITY CRITERIA FOR TRACEABLE ACCURACY

A broadly low frequency uncertainty as determined by the Allan deviation (ADEV) or similar statistics is one without substantial variations above a consistently low level that is a "not-to-exceed" performance criteria, mask or, in this case, noise maximum. In essence, a maximum of arbitrary level will be consistent with an upper limit on a flicker-FM (FLFM) process, that is, one with a constant uncertainty. For example, figure 1 on its left shows ADEV denoted as FLFM (i) with a ceiling level of 1×10^{-15} as a realistic, attainable level. The phase-noise modulation (PM noise) that corresponds with FLFM (i) is shown on the right and follows a $1/f^3$ behavior until reaching an approximate thermal white-noise floor. Note that FLFM (i) is lower in short-term than other PM noises of three best-in-class oscillating

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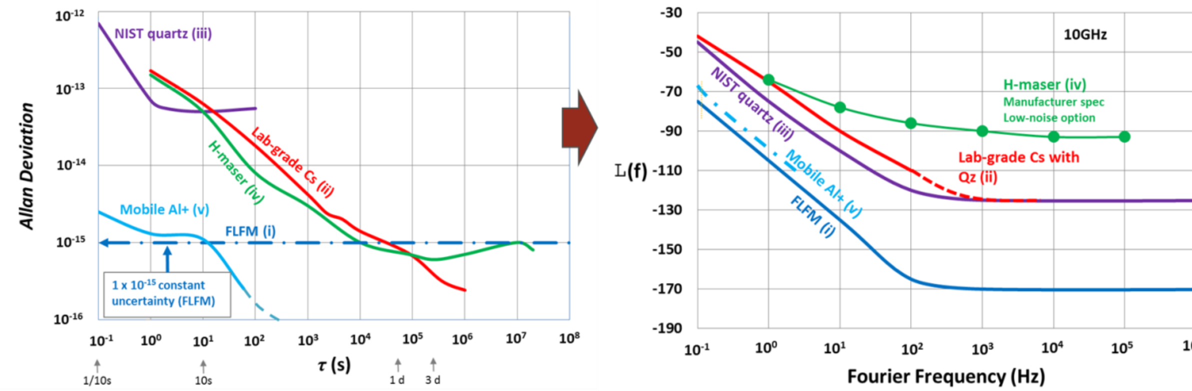

Fig. 1. Flicker-FM (FLFM) level of 10^{-15} means that frequency uncertainty is constant from short- to long-term τ-values, as shown as the constant uncertainty on left, as FLFM (i) maps to a very low level of phase noise shown on right for a 10 GHz oscillating signal. Best NIST Cesium fountain (ii), quartz oscillator (iii), and H-maser (iv), are also shown on left and the corresponding higher phase noises on right. A next-generation mobile Al+ cooled trapped-ion clock is also shown (v) to compare its very low relative phase noise and short-term stability [9].

references: quartz, H-maser, and laboratory-grade Cs. We show here just one recent example of ~1× 10^{-15} frequency stability that is obtained from a compact (mobile) Al+ cooled trapped-ion clock [9]. This ADEV is based on a larger research device. The downward trend in ADEV for sample times beyond tens of seconds is, in some sense, not essential since its accuracy is traced to a definition based on Cs with an accuracy in the mid-10^{-16} regime. There are, of course, possible applications for the excellent long-term stability from Al+ not necessarily tied to Cs accuracy, but the authors purport that any atomic standard meeting just FLFM (i) level continuously for months and years would be of substantial benefit to vast numbers of uses.

III. Frequency Synthesis

A fundamental building block for synthesis schemes is a ULPN divider chain that is driven by a stable reference operating at a frequency higher than any desired operating or output frequency. The high reference frequency allows synthesis by a combination of divisions and heterodynes that avoids frequency multiplication that commonly introduces more noise than regenerative dividers. The NIST Time and Frequency Metrology Group currently holds the world record for the lowest-noise frequency divider chain using for its source the pulse repetition rate of an optical frequency divider that starts at ~200 THz by a stable, optical cavity [10].

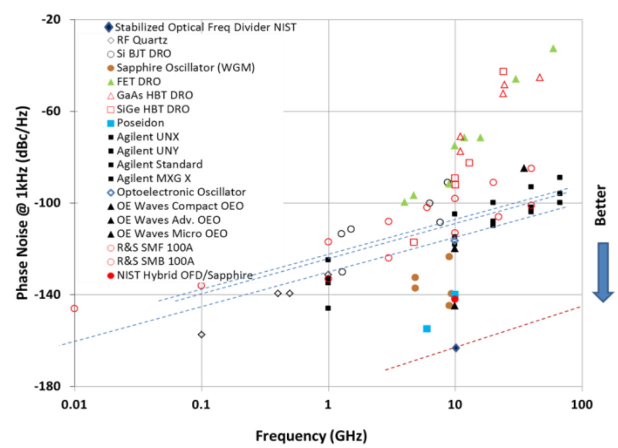

Fig. 2. Phase noise at 1 kHz offset of state-of-the-art oscillators and technologies at ambient temperature. Various dashed lines are along a noiseless frequency-synthesizer line-of-comparison that translate frequencies from one RF oscillator type and carrier frequency to another. Manufacturers are shown. Many manufacturers exist, no endorsement is implied. The lowest line intersects a cavity-stabilized optical-frequency division (OFD) to attain RF output at 10 GHz [10].

Frequency synthesizers that generate $\omega_{out} = [M \div N]\omega_{in}$, are the most straightforward for coarse translations from one frequency to another. M and N are integers and are multiplication and division factors, respectively. An ideal phase noise transformation due to $[M \div N]$ is given by, $L(f)_{\omega out} = L(f)_{\omega in} + 20\log[M \div N]$. Fine, or high resolution, translations can introduce noise, usually from non-ideal divider and multiplier residual noise. In this we provide result of the coarse frequency translations (Fig. 3), the primary resource being extremely low-noise division from ULPN optical carriers to RF. For example, $N = 10^8$ for division from 500 THz to 5 MHz.

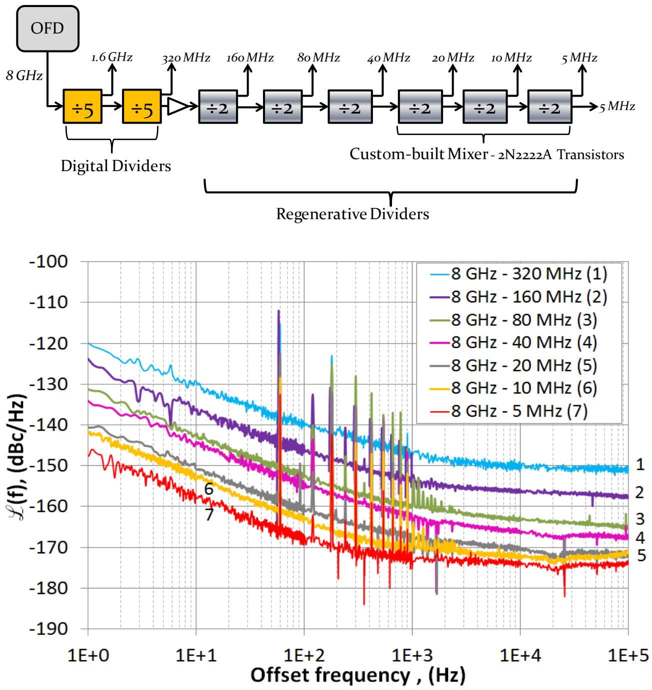

Fig. 3. Frequency synthesizer starts with the output of an optical frequency divider (OFD) and a combination of digital dividers and analog regenerative frequency dividers (RFDs) as shown at the top [10]. The input signal at 8 GHz is generated from a cavity-stabilized, self-referenced, 1 GHz Ti:sapphire 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.

Fig. 2 shows various best-in-class oscillators operating at essentially their lowest-noise, RF carrier frequencies. The PM 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. 2 indicate how L(1 kHz) would change with "noiseless" frequency synthesis to another RF carrier frequency. The various dashed lines-of-comparison follow a slope of +6 dB per octave of frequency change.

The list of oscillators and synthesizers used in figure 2 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. 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. The basic coarse acquisition of ULPN frequencies can be obtained from a OFD as mentioned, an example would be where $N = 10^8$ for division from 500 THz to 5 MHz. The dividers at NIST and phase noises are shown in figure 3. 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 L(1 Hz) = -150 dBc/Hz [12]. These dividers demonstrate continuous we're pleased to report.

IV. ULPN Optical Frequency Division

Generation of ultralow phase noise microwaves from 200 MHz-10 GHz is possible with the emerging field of optical frequency division. In this technique schematically shown in figure 4, a pulsed femtosecond laser (OFD as mentioned earlier) is incident on a fast photodiode, and the repetition rate of the laser pulse train is detected with a spectrum analyzer, dividing the optical frequency (visible to near infrared) to the microwave. In order to obtain low phase noise of the microwave signal, tight control over the laser repetition rate and the carrier offset frequency of the pulse train is needed. This control can be achieved by self-referencing the frequency comb optical spectrum (f_{ceo}) and locking a single comb frequency to an optical reference (f_{beat}) [11].

For virtually all clock applications and for frequency stability measurements, we are concerned not only with the purity of the microwave signals produced, but also the

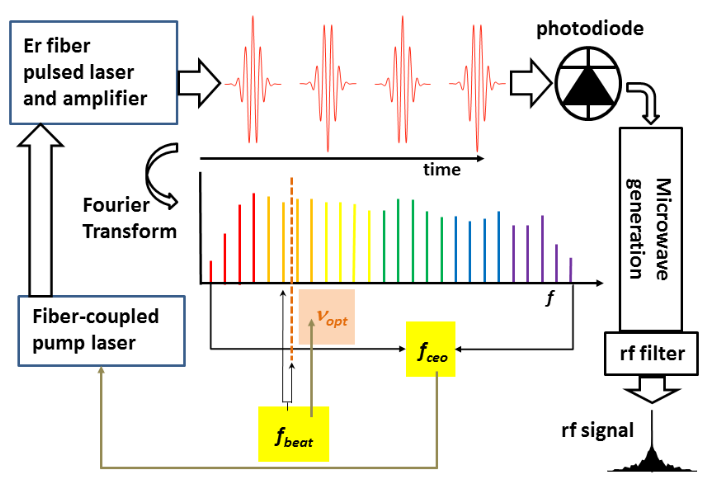

Fig. 4. Schematic of an Optical Frequency Comb divider (OFCD), consisting of an Er fiber pulsed laser incident on a photodiode to produce stable microwave pulses. The ultralow phase noise of the microwave (rf) signal is due to stabilization of two rf frequencies, f_{ceo} (the beating of two optical signals on each end of the spectrum) and f_{beat} (related to the repetition rate of the pulse train and referenced to an ultrastable optical cavity). Long term stability feeds back to the Er fiber laser pump and the cw laser used as an optical reference (ν_{opt}).

long term stability of these signals. Our goal is to construct state-of-the-art cavity stabilization + OFDs that can operate continuously as a reference standard for very long-term frequency ADEV measurements. The limits of the long term stability of the locked frequency comb conversion to microwave have yet to be fully explored. Laser drift, both the pulsed laser and the optical reference cw laser, is a major concern. To stabilize f_{ceo}, long term drift is corrected by feeding back to the laser cavity's pump diode. There is a range of pump diode current values where the laser will stay modelocked (continue to create pulses), and if the feedback loop pushes the current out of this range, the lock will fail. This effect can be minimized by carefully constructing the laser cavity to eliminate temperature and vibrational fluctuations, however, a complete understanding of these perturbations is not fully understood. Secondly, to stabilize f_{beat}, long term stability is corrected by changing the wavelength of the cw laser reference through a piezo which changes the cavity length. This suffers from similar effects as described for the pulsed laser cavity. We are focused on the limits of the long term stability of the frequency comb, generating microwave signals that are not only low noise but also able to run for days and months without interruption nor intervention by someone.

V. Conclusion

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 unprecedented 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 here our experience and results of one of the most straightforward methods that can be reconfigured easily for metrology purposes. Increased developments of optical-atomic frequency standards are resulting in levels around 1×10^{-15} accuracy for time intervals considerably shorter than the many hours associated with lab-grade Cs standards. We discuss three application priorities related to these developments: Allan deviation criteria for efficient calibrations of secondary standards, frequency synthesis using OFDs that produce a convenient range of RF frequencies, and compensation against long-term aging with sufficient resistance to environmental stress (vibration, acceleration, temperature, pressure, etc.) to obtain continuous operation.

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