Low-noise X-band Oscillator and Amplifier Technologies: Comparison and Status[1]

(INVITED)

D. A. Howe and A. Hati

National Institute of Standards & Technology (NIST), Boulder, CO, USA

Abstract **- This study compares the phase noise of different classes of oscillators and amplifiers that work at X-band. Best-in-class results are presented based on recent measurements at NIST. In particular, comparisons are made between mature technologies of multiplied quartz, sapphire dielectric in whispering gallery mode (WGM), and air-dielectric-resonator stabilized RF oscillators in contrast to various configurations of optical electronic oscillators (OEO), cavity-stabilized, and atom-stabilized optical-domain oscillators and femtosecond-laser-comb frequency synthesizers. This study also reports the status of classes of low-noise X-band amplifiers, since high-spectral-purity oscillators are constrained by amplifiers to varying degrees. Best-available low-noise X-band commercial amplifiers are compared with new feedforward, feedback, and array-gain test devices. Straight HBT (heterojunction bipolar transistors) and SiGe HBT technologies are compared in terms of phase noise. Results are for an operating frequency of 10 GHz.**

I. INTRODUCTION

The goals of NIST's Time and Frequency Metrology Group are to: (1) support activities that lower undesirable time (or phase) residual noise on signals in electronics, (2) contribute to fundamental improvements in spectral purity of oscillators and frequency synthesizers, and (3) provide certified state-of-art PM and AM noise-measurement capabilities to U.S. industry and the military [1,2]. Central to these goals, this paper summarizes "best in class" PM noise results of X-band *amplifiers* and *oscillators*. The primary goal of this paper is for a reader to understand various X-band technologies and their key aspects, and to quickly compare PM noise results associated with these technologies. Most of the results are obtained from recent measurements performed at NIST. All measurements are normalized to an operating frequency of 10 GHz.

Amplifier PM noise is always a concern, since all signals must invariably be sent to one or more other locations, and this usually involves at least one amplifier. More critically, the impact to oscillator noise from amplifier loop (or feedback) noise is often much larger than the intrinsic noise of a frequency determining element in the loop [3] or passive component noise in regenerative division [4-8] that, to be versatile, demands very low amplifier PM noise over a wide frequency range [9].

The following X-band amplifier technologies are represented in this paper:

- SiGe with feedback noise suppression (feedback amplifier, FBA)
- Commercial amplifiers with feedforward noise suppression (feedforward amplifier, FFA)
- Array of parallel commercial amplifiers with uncorrelated noise
- Typical commercially available amplifiers

PM-noise measurements of the following classes of X-band oscillators are presented:

- Typical low-noise quartz oscillator, multiplied to 10 GHz
- Optical Electronic Oscillator using fiber-delay-line resonator
- Dielectric Resonator Oscillator (DRO)
- Sapphire-loaded cavity stabilized oscillator (CSO) using interferometric carrier suppression
- High-power (>2 W drive) air-dielectric CSO using impedance-controlled carrier suppression
- Optical femtosecond-comb divider with calcium-stabilized reference oscillator

II. SELECTION CRITERIA

The list of classes of amplifiers and oscillators used in the paper is by no means complete. The list is focused on relevant, promising X-band technologies. In the case of oscillators, the X-band PM noise is expected to be better than the PM noise from a low-noise quartz oscillator multiplied to 10 GHz. In particular, additional value of these classes are based on the following criteria:

- Room-temperature operation does not require cryo-cooled augmentation,
- Frequency selectability (the ability to fabricate to desired frequency) is simple,
- Frequency range of operation is possible over at least one octave with the same set of components,

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- ○ Methodology can be reproduced by other manufacturers or organizations,
- ○ Noise models are understood and thorough enough that PM noise of devices are consistent with their models.

In oscillators, there is unquestionable value from (1) small size and low cost, comparable to current quartz, (2) operation at exceptionally high frequencies substantially above X-band, (3) mass production with good yield, and (4) the ability to withstand harsh environments, exceeding that of SAW oscillators. The context of this paper is not focused on these areas. The candidates in this paper lie between a prototype and a production device in the sense that the devices are working and that signals are characterized but devices may not necessarily be ready for field use.

III. LOW-NOISE MICROWAVE AMPLIFIERS AND MEASUREMENTS

Two general strategies are used to achieve low residual phase noise in amplifiers. The first calls for use of devices or technologies that have inherently low 1/f noise, that is, low-frequency, near-DC, noise [10]. To the extent that low-frequency noise is reduced, one can expect reduced noise at Fourier (offset) frequencies near the carrier frequency of an X-band oscillating signal. Generally, heterojunction bipolar transistors (HBTs) have smaller low-frequency, near-DC noise than field-effect transistors (FETs).

The second strategy calls for uses an amplifier design technique that achieves highly linear operation. 1/f noise multiplies up into near-carrier noise due to amplifier nonlinearities and parametric effects [11,12]. Suitable amplifier design techniques to lower this multiplicative noise include feedback, feedforward, parallel HBT's, predistortion, and linear amplification using non-linear components (LINC) [13]. The last two design techniques (predistortion and LINC) are primarily aimed at amplifier efficiency and are not considered in this writing because both introduce substantial device noise at X-band. While the usable frequency range over which these two last techniques significantly reduce distortion and noise is increasing, practically speaking, the range is only to a few hundreds of MHz. In particular, LINC is limited by sampling speeds that are traded against accuracy of aperture sample-hold circuitry [13].

A. Feedback Amplifier (FBA)

It has been long known that RF negative feedback (either closed-loop or degenerate) suppresses noise and distortion as the ratio of open-to-closed loop amplifier gain [14]. Microwave amplifiers in which the noise is actively reduced by feedback have shown the best performance from near-DC up to offsets of 1 MHz [15]. Dielectrically isolated, silicon-based processing with germanium added to the base region (silicon-germanium, or SiGe, HBT technology) greatly increases carrier mobility and leads to extremely fast transient response. For very wide frequency ranges, the effectiveness of the technique is linked with high f_t (unity gain bandwidth) and the stability of feedback, that is, the unity-gain bandwidth of an amplifier along with phase dispersion [16]. Commercial suppliers generally strive for higher f_t's and low dispersion through the use of ever-finer processing techniques, because this focus is consistent with a market seeking wide operating frequency range of amplifiers [17-19]. Also in general, the higher the f_t, the lower the throughput phase dispersion, and, hence, the better the closed-loop amplifier stability for obtaining reduced amplifier noise and distortion over the widest frequency range [20,21]. Amplifiers with f_t's over 300 GHz have made possible the use of liberal RF negative feedback at X-band, with the added benefit of wide operating frequency range within this band [22].

The PM-noise measurements to follow show that the sample of SiGe FBA amplifiers were, in general, no better than straight HBTs at offset frequencies around 1000 Hz and below–the so-called 1/f flicker noise region. However, this 1/f behavior persists so that above 1000 Hz, these amplifiers had the lowest PM noise of all others. Thus, SiGe FBA amplifiers are desireable in applications that demand fast response times and low jitter such as in high-speed, high-resolution data converters and the amplifiers used to drive them. The near-DC noise of the SiGe FBA amplifier under test made it less desirable as an oscillator loop amplifier, where near-DC noise is critical to system performance.

B. Feedforward Amplifier (FFA)

The feedforward technique is well known for increasing the linearity of amplifiers, particularly when operating near saturation [23-26], but is also stressed as a means to reduce amplifier and oscillator residual noise [27-29]. Hybrid MIC feedforward amplifiers at X-band have been demonstrated to have excellent residual phase noise performance. Up to 20 dB of noise suppression has been achieved by use of feedforward operation versus operating the same (main) amplifier in a conventional manner [30].

In FFAs, an interferometer suppresses the carrier, leaving amplifier noise sidebands that serve to cancel the signal's noise sidebands at the output. Carrier and noise suppression factors are significantly affected by amplifier gain ripple and deviation from linear phase, and also by any leakage signals that may be present at the outputs of the combining couplers of each interferometer. For this reason, FFA's achieve their best suppression of distortion and noise in a relatively narrow frequency range in X-band, usually only ± 5 % of a carrier frequency. Additional aspects of FBA and FFA methodologies are nicely summarized in ref [14].

C. Parallel HBT Amplifier (Array Amplifier)

HBT amplifiers that are graded for low 1/f noise and that are operated in parallel (called an array), once phase-balanced, have demonstrated outstanding low-PM noise over large frequency ranges at X-band. Because these so-called array amplifiers use a power-split input and power-combined output scheme, they show improved linearity over that of a single amplifier, particularly when operating at full-power output, meaning at the threshold of power-supply clipping. We note that this desirable, full-power property is not associated with FBAs and FFAs.

The device under test (DUT) in this paper consists of a custom-built array of eight two-stage HBT amplifiers. The methodology is that an input signal is sent to an eight-way power splitter that then feeds eight separate amplifiers. The outputs of the amplifiers are phase-matched and recombined in an eight-way combiner. If the noises from each of N amplifiers are independent, then they add as rms, while the signal through each amplifier adds directly, so the signal-to-noise ratio is improved by √N, or, in the case of eight amplifiers here, by a factor of 2.8 (9 dB in usual logarithmic terms).

D. Amplifier PM-noise Measurements

Figure 1 shows L(f) plots of our sample of high-performing FBA, FFA, and array amplifiers. We have also plotted a sampling of the best performances from conventional HBT commercial amplifiers. The design of each amplifier calls for input power (P_{in}) of 0 dBm, and gain is nominally 14 – 18 dB. The sampling of commercial amplifiers operated with P_{in} of +2.57 dBm and +3.7 dBm for lowest overall noise.

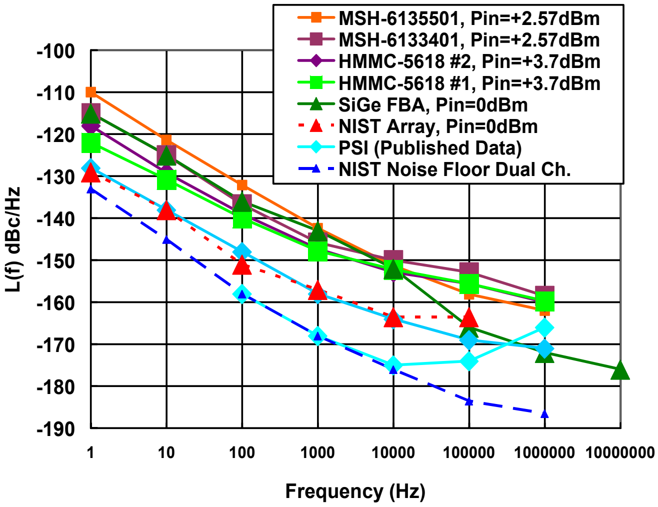

Figure 1: Results of a sampling of nine measurements of residual amplifier PM noise. Except for the commercial amplifiers designated by MSH and HMMC, the plots represent various noise-suppression schemes.

IV. LOW-NOISE MICROWAVE OSCILLATORS AND MEASUREMENTS

Microwave oscillators of the highest spectral purity are required as a local reference, or clock, signal in secure communications protocols, very-high-speed, jitter-sensitive modulation-demodulation schemes, and high-resolution digital signal processing applications such as imaging radar. Low-noise microwave amplifiers are critical in establishing the noise performance of oscillators by Leeson's noise model [3]. Basically, all such oscillators rely on a frequency-determining element (resonator) along with a positive-feedback gain element (amplifier) creating a so-called loop oscillator to generate an oscillating signal. Phase perturbations inside this oscillating loop are integrated. Thus, we have the unfortunate situation that moderate white or flicker PM noise in the loop becomes higher random-walk or random-run PM noise respectively at the output of the oscillator. In addition to this, near-DC (baseband) noise sources acting on the loop are upconverted by loop nonlinearity, either by the amplifier or by resonator parametric effects.

Next, we discuss and report the commendable PM noise performance of the classes of oscillators listed in Section I.

A. Opto-electronic Oscillator (OEO)

The opto-electronic oscillator (OEO) implements a low-loss optical fiber as a delay-line resonator [31,32]. The lowest noise at 10 GHz has been achieved by use of a single-loop delay as shown. A single fiber of length 16 km comprising four 4-km spools spliced in series with 100 mW 1310 nm laser, electro-optic modulator (EOM), and photo detector comprised a 10 GHz optical modem for a high-order-mode, delay-line resonator. Three X-band array amplifiers in cascade formed the loop amplifier with a total gain of ~40 dB to obtain oscillation. A narrow-band filter was used to select the oscillating mode at 10 GHz [33]. In a delay-line resonator, modes exist at frequencies ~c/nL, where c is the speed of light, and n and L are respectively the index of refraction and length of the transmission line. For the 16 kM length used here, spurious modes appear in the oscillator output signal with a spacing of ~19 kHz. While these modes appear in the results to be shown, strategies exist for significantly suppressing them [34-36]. Results of a dual-fiber, injection-locked OEO developed by Army Research Laboratory (ARL) illustrate that spurs are eliminated at high offset Fourier frequencies while preserving low PM noise [36]. The example data will show that OEO noise closely matches, and in some cases outperforms, the best room-temperature cavity-stabilized microwave RF oscillators discussed next.

B. Dielectric Resonator Oscillator (DRO)

Dielectric resonators, in particular ceramic dielectric resonators, are a popular frequency-determining element in microwave oscillators (DROs), due to their ruggedness, low cost, and small size [37-40]. This class easily satisfies all of the selection criteria of Section II. The PM noise of DROs has progressively been reduced as resonator loaded Q has increased and loop-amplifier noise has decreased [41-43].

C. Sapphire Loaded Cavity Direct Feedback Oscillator

As mentioned, oscillators use a direct feedback loop amplifier to produce an oscillating signal at one frequency ν_{res} determined by the mode of a resonator, in this case, an RF cavity. A dramatic improvement in the oscillator's spectral purity uses a technique in which phase noise that is offset from ν_{res} by Fourier-frequency f is detected by a sensitive phase discriminator and subsequently suppressed by another feedback or feedforward loop. The method of *detection* and strategy for *suppression* vary, but these two functions comprise a *cavity-stabilized* methodology and implemented in the best microwave RF oscillators. Novel techniques have been devised to reduce the near-DC noise of microwave oscillators [44-46]. The technique relies on a microwave frequency determining element with a high Q factor, in this section, a sapphire loaded cavity in whispering gallery mode (WGM) [47]. This cavity is integrated as a part of the feedback loop of the microwave oscillator and so is deemed an oscillator whose direct feedback loop is stabilized by a high Q cavity oscillator. An "interferometer" arm was introduced for increasing carrier suppression of the reflected signal from the cavity [48,49]. This arm vectorially adds to the already suppressed reflected signal (using a power combiner) a portion of the input signal fed into the cavity with the same amplitude as but opposite phase to that of the reflected signal. Carrier suppression of the reflected signal from the high Q reference cavity results in reduction of multiplicative noise introduced in an amplifier before a phase-detector mixer that comprises the phase discriminator, resulting in overcoming the mixer noise.

In the case of the direct feedback oscillator, the feedback is used to modulate the oscillator loop phase shift with a voltage controlled phase shifter. The data presented here are those of a commercial product using a sapphire loaded cavity direct feedback oscillator [40].

D. Cavity Stabilized External Oscillator

The cavity mentioned above can be used to clean up an external noisy oscillator locked to it. In the data to be presented here, the external oscillator is a DRO stabilized by an air-dielectric cavity. Basically, the feedback from a phase detector using a high Q cavity as the reference modulates an external oscillator's frequency by use of a voltage-controlled tuning port of the oscillator. Dick and Santiago [46] coined the term STALO (stabilized local oscillator) to describe this methodology. Here, the free-running DRO PM noise is suppressed because the cavity, acting as a frequency discriminator, converts noise-induced frequency fluctuations from components ahead of the discriminator into corresponding phase variations of a signal reflected from it. An amplifier and double-balanced mixer are configured as a sensitive phase discriminator that converts the phase to voltage fluctuations, which are then suitably fed back to the DRO to correct its frequency fluctuations.

The data presented here are from the latest version of the NIST low-noise microwave reference using an air dielectric cavity resonator. An air (or vacuum) dielectric has unique, ideal properties as a discriminator [50,51]. Of all the possible types of resonators that can be used as a phase detector, conventional air-dielectric high-Q cavities are most ideally suited for handling large power levels without difficulty and do not exhibit flicker-noise behavior. NIST's configuration presently drives the cavity resonator with 2 W and does not require the use of an interferometric arm [52].

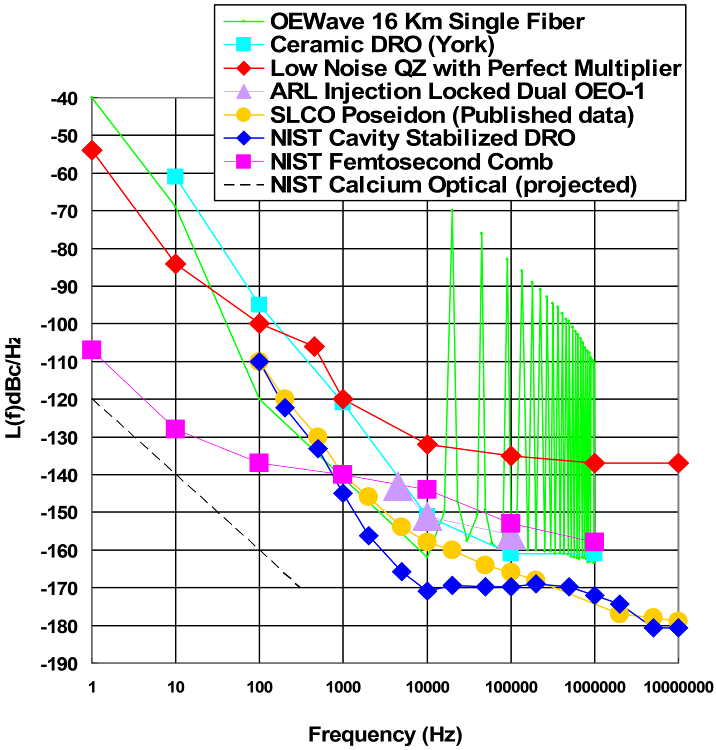

Figure 2: Eight L(f) plots of different classes of oscillators with a normalized frequency of 10 GHz. The "NIST Calcium Optical" plot is based on theory, while the others are based on actual measurements.

E. Optical Femtosecond-comb Divider with Stabilized Laser

While the idea of using mode-locked laser combs as a resource for optical frequency measurements originates in the 1970's [53-55], a significant re-introduction of mode-locked laser combs for absolute measurements came in 1999 [56] and low-noise frequency synthesis and division using the so-called femtosecond divider quickly gained popularity for metrology applications [57,58]. This divider is central to exploiting the exceptional accuracy and stability of extremely high Q atomic resonances at optical frequencies [59]. While prototype designs for generating low-phase noise microwave signals are not yet fieldable as the other oscillators, we include optical femtosecond-comb synthesis data in this report due its very desirable feature of near-continuous tunability in the microwave band of a signal with 10,000 times lower near-DC phase noise compared to the best of the other classes of oscillators. A summary of features and properties is contained in [60] and [61].

F. Oscillator Measurements

Figure 2 shows L(f) characterizations of the classes of oscillators described in the just-prior subsections A – E. The range of Fourier (offset) frequencies were chosen as the important range of interest or applicability for the DUT. We note that specialized quartz oscillators with very low near-DC phase noise can cost $20,000 or more, therefore, the data shown are for comparison only and typifies high-quality devices but not the absolute best-attainable devices. There is a vast literature on quartz oscillators to which the reader should refer if this is of primary interest.

V. SUMMARY

We present a compilation of PM noise from relevant amplifier and oscillator technologies. The primary goal is for a reader to quickly compare PM noise results associated with these technologies. It would be impossible to include all classes of technologies, many of which provide important value to several specialized applications. Selection criteria for this paper attempt to be broad enough in scope to be useful, focusing on as many aspects as possible. The following areas are deemed important: (1) room-temperature operation, (2) frequency range of operation possible over one octave or greater of frequency range in one device, (3) simple frequency selectability, (4) mature methodology with results that can be reproduced by other manufacturers or organizations, and (5) noise models thorough enough that PM noise of devices are consistent with their models.

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