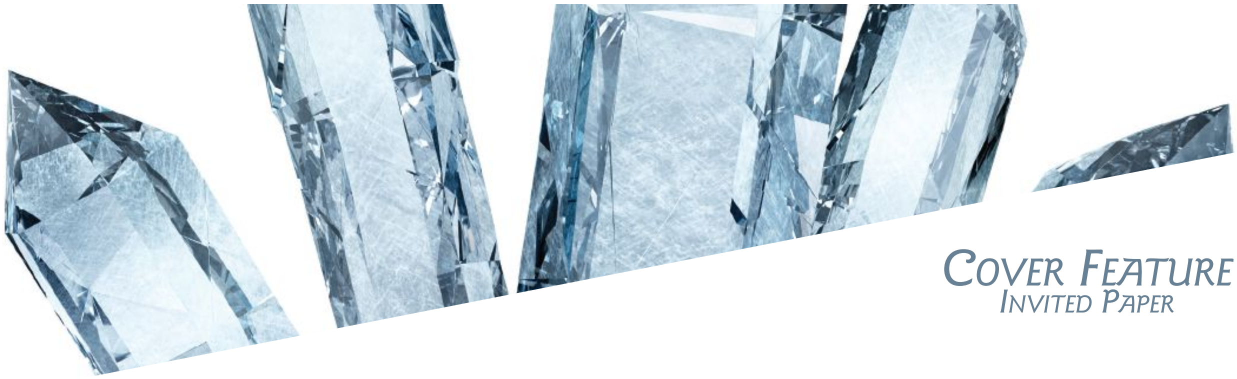

COVER FEATURE
INVITED PAPER

Oscillators Enable Conversion at X-Band

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Direct microwave conversion utilizing extremely high speed analog-to-digital converters (ADCs) and digital-to-analog converters (DACs), enable systems with increased bandwidth, more capabilities and better performance. X-Band DACs can drive radar arrays directly or through single-stage up-conversion, which adds near real-time beam steering and nulling capabilities. ADCs can sample microwave signals directly, improving bandwidth and real-time analysis. ADCs and DACs only exhibit phase noise contributions from the noise floor and 1/f noise. However, if maximum system performance is required, this places quite a burden on the phase noise requirements of the oscillator.

This article provides a summary of the oscillator types available for local oscillator (LO) generation, or clocking, at X-Band frequencies and above, along with the best applications for each type of oscillator. These technologies can also be combined in a multi-oscillator approach to achieve both short-term and long-term stability requirements. A phase-locked loop (PLL) is required in these system architectures but an in-depth analysis of PLLs is outside the scope of this article. A good overview of what to consider when selecting phase-locked oscillators is in the reference section.[1] The phase noise plots presented in the article come from multiple sources and vendors. They are meant to provide a qualitative comparison of high performance representative devices.

Figure 1 is a plot of the residual phase noise of a 10.24 GSPS high speed DAC with an output at 1 GHz. This phase noise profile is compared with a high-quality 100 MHz oven controlled crystal oscillator (OCXO) that is ideally multiplied to 1 GHz and a sapphire-loaded cavity oscillator (SLCO) from Saetta Labs that is ideally divided from 8 GHz to the 1 GHz output. This result is normalized to show the performance of the DAC if it were ideal. The total noise will be the RSS of the oscillator and DAC. The curves show that this new generation of DACs has exceptionally low phase noise, but a careful choice of LO generation is critical to achieve the desired performance.

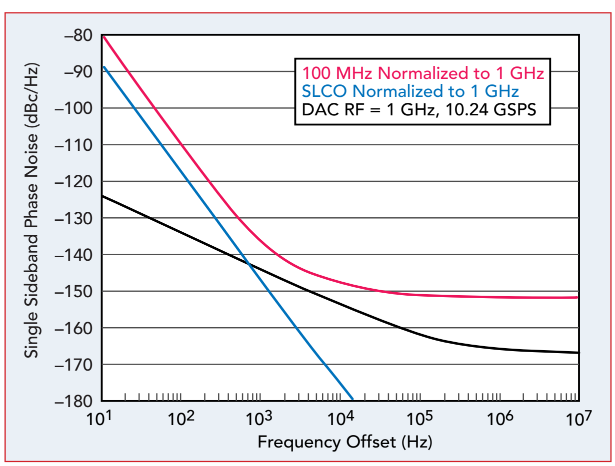

Fig. 1 **Single-sideband phase noise versus frequency.**

DATA COMMUNICATION SYSTEMS AND RADAR

High data rate communications systems and radar applications have significantly different phase noise requirements. Two important requirements for communications systems are long-term stability for signal acquisition and tracking, along with good phase noise performance at frequency offsets from the carrier where most of the data information is contained. Offsets in the frequency range from 20 kHz to

> 50 MHz may be of the most interest to optimize.

By contrast, radar has more stringent phase noise requirements for the low- to mid-frequency offsets. Tracking radars measure the Doppler shift of an incoming target in addition to time-of-flight ranging. Airborne targets may be traveling at rates from subsonic to hypersonic speeds. Using an 8 GHz X-Band radar as an example, a target traveling at 5x the speed of sound, or approximately 1700 m/s at sea level, has a received Doppler shift of about 95 kHz offset. A target moving at half the speed of sound has an offset of about 10 kHz and a slow-moving target or lower frequency radar, would want to be optimized for phase noise at less than 10 kHz offset.

STABILITY AND PHASE NOISE

The usefulness of an oscillator links strongly to a single performance attribute: stability. Stability is broadly categorized into short-term and long-term stability metrics. Long-term stability is described in terms of drift, measured in parts per million or parts per billion and it may also be characterized by a metric known as Allan deviation. Short-term stability is phase noise. The crossover point between categorizing stability as long-term or short-term is typically around one second. The difference between short-term and long-term stability is analogous to the differentiation between precision and accuracy.

Long-term stability is accuracy. If the frequency of an oscillator is measured every second over an hour, a day, a week or a month, the repeatability and accuracy of the frequency is typically quantified as Allan deviation. This is a measurement of stability in parts per million (ppm) or parts per billion (ppb). In most systems, this is dominated by a quartz crystal oscillator with a typical reference frequency of 10 MHz. This 10 MHz frequency may be locked to a very accurate source. This is typically accomplished with a frequency-locked loop that locks directly to an atomic clock reference or to GPS, which indirectly locks to an atomic clock.

Short-term stability is precision. It is a measure of the oscillator phase repeatability over a short period. This is measured as phase noise. Phase noise theory is another subject that cannot be addressed comprehensively in this article. Simply put, phase noise is a power spectral density at a frequency offset from the carrier relative to the carrier power. It can also be viewed as the probability of phase fluctuations from ideal.

The preceding discussion has been theoretical, but there are practical implications. A microwave LO designed to drive a DAC or an ADC must strike a balance. It is typically a combination of a high frequency oscillator with good phase noise or short-term stability phase-locked to an oscillator with good long-term stability or drift.

OSCILLATOR FUNDAMENTALS

To a first order, an oscillator fundamentally has only two components that contribute to and affect phase noise and short-term stability. These components are the amplifier and the resonator. Control tuning circuitry and thermal performance are also contributing factors, but they are second-order. Thermal performance is a significant issue for a long-term reference. Leeson's equation, shown in Equation 1, is a relatively simple equation that describes the phase noise of an oscillator based on amplifier and resonator parameters. There is an excellent summary of some of the work in this area in the reference section.[2]

SSB ↓ ; 10 dB/dec Amplifier Flicker Noise ↓

$$L(f_m) = 10\log\left[\frac{1}{2}\left(\left(\frac{f_0}{2Q_l f_m}\right)^2 + 1\right)\left(\frac{f_c}{f_m} + 1\right)\left(\frac{FkT}{P_s}\right)\right] \quad (1)$$

↑ 20 dB/dec Resonator f_m<1/2 bw of Resonator ; ↑ -177 dBm-P_S+NF White Noise of Amplifier

Where:[3]

f_0 is the output frequency
Q_l is the loaded quality factor
f_m is the offset from the output frequency (Hz)
f_c is the 1/f corner frequency
F is the noise factor of the amplifier
k is Boltzmann's constant in joules/kelvin
T is the absolute temperature in kelvin
P_s is the available power at the sustaining amplifier input.

Figure 2 shows a generic oscillator block diagram. The phase shifter satisfies the oscillator stability criteria of a positive feedback loop at 360 degrees. The oscillator operates in a compressed amplifier state when the open loop gain is assumed to be greater than one. From Leeson's equation, the phase noise is dominated by the Q-factor of the resonator.

Leeson's equation can be separated into independent contributions from the amplifier and the resonator, as shown in Equation 1. The two last terms, as indicated in Equation 1 apply to the amplifier. The term, FkT/P_s defines the signal-to-noise ratio of the amplifier and the noise floor. This quantity can be measured independently and under oscillation with a typical value of around 3 dB in compression.[4,5] The first term of the amplifier portion of Lesson's equation is the 1/f noise. Different technologies have different 1/f corner values, but most X-Band oscillators will use a SiGe, GaAs or InGaP HBT process with 1/f corner frequencies between 10 kHz and 100 kHz. The loop is multiplicative, so all the amplifier noise is multiplied in positive feedback with the resonator. The noise floor of an amplifier can be estimated by taking the single-sideband PM noise

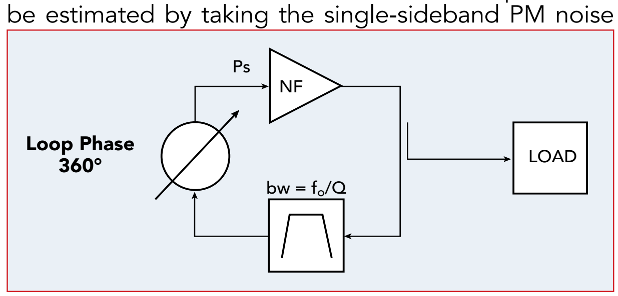

Fig. 2 Oscillator block diagram.

floor due to thermal noise, which is -177 dBm, then subtracting the input power and adding the NF.

As an example, a medium power amplifier with 14 dB of gain, 16 dBm of output power and an NF of 5 dB results in a P_s, the input power to the amplifier in a compressed state of about 5 dBm, assuming 3 dB compression. In practice, the NF typically increases by a few dB under compression, so the assumption is that the NF increases to 8 dB. Plugging in these values (-177-5+8) yields a -174 dBc/Hz noise floor, which is the thermal noise floor in a 50 Ω system. This means that each oscillator is bound by the same amplifier condition theory and the noise floor will be similar among all oscillators.

The first term in Leeson's equation, shown in Equation 1, relates to the resonator. Resonators have a particular loaded Q-factor that depends on the technology choice and integration. The equation can be rewritten to show the $f_0/2Q_l$ term is the half bandwidth frequency of the resonator and the resonator does not affect the noise at offsets greater than this frequency. At higher offsets, the only noise contribution comes from the amplifier. At frequencies below this half bandwidth frequency, the term follows a second-order system and it can be shown as a Bode diagram increasing at 20 dB per decade.

Phase noise is a single-sideband measurement, so half the power is taken. ***Figure 3*** is Leeson's equation as a phase noise plot with the values of a typical dielectric resonator oscillator (DRO). The properties of each component of Leeson's equation are shown graphically. The amplifier is plotted separately on the bottom and then summed on a log scale with the resonator for the total phase noise. The phase noise plot identifies the 20 dB per decade phase noise characteristic of the resonator, along with the 30 dB per decade sections that result when the 1/f and resonator phase noise profiles overlap due to the multiplicative effect of the positive feedback loop. From this chart, Q, noise floor and 1/f can be estimated for any oscillator.

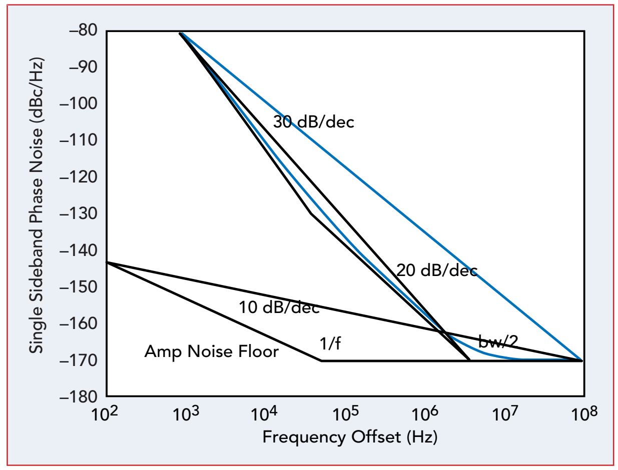

Fig. 3 **Phase noise plot of Leeson's equation.**

LOWER FREQUENCY OSCILLATORS: LONG-TERM STABILITY

Quartz Crystal Oscillators

Quartz crystals satisfy the medium- to long-term stability requirements of most microwave systems.[6] Quartz is a bulk electroacoustic element. While crystal oscillators operate at 10 to 100 MHz, they resonate acoustically. Two properties make quartz an advantageous material: it has high Q values, typically between 10,000 in small low-cost variations to about a million in very expensive versions and quartz has a flat frequency versus temperature plateau, as shown in ***Figure 4***.

The quartz crystal resonator is cut as either AT or stress-compensated (SC). AT is the room temperature cut used in temperature-compensated crystal oscillators (TCXOs). This type of oscillator has very little frequency change versus temperature around 25°C. Additional compensation circuitry can extend this useful plateau significantly. The SC cut has a higher Q and a flat frequency-to-tempera-

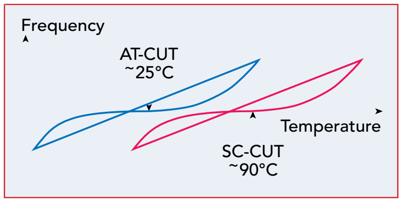

Fig. 4 **Quartz crystal oscillator frequency stability versus temperature.**

ture plateau around 90°C. Instead of temperature compensation, the SC crystal is used in an OCXO device, held at a constant temperature in an oven, to achieve even greater stability than is achievable in a TCXO.

A disadvantage of quartz-based crystal oscillators is their performance degrades at frequencies above about 100 MHz. To utilize a quartz-based oscillator in X-Band requires multiplication and this approach adds a 20log10(N) noise multiplier, where N is the frequency multiplication factor. ***Figure 5*** shows a 10 MHz and 100 MHz high-quality OCXO and their noise after ideally multiplying to 8 GHz. The 10 MHz device will almost always outperform a 100 MHz device at 1 to 100 Hz offsets. However, the 100 MHz oscillator will perform better at higher frequencies because it has been optimized for a better noise floor farther from the carrier. High performance systems may integrate and phase-lock both oscillators for the optimum phase noise and stability performance.

SAW

A SAW oscillator is a surface acoustic device with a good Q-factor and small size. They operate from around 300 MHz to 2 GHz and serve as an intermediate oscillator to lock while multiplying OCXOs higher in frequency. These devices can sometimes replace a 100 MHz OCXO or a DRO. The performance of the SAW oscillator sits between the DRO and the OCXO in frequency and the material has significant size advantages. SAW oscillators require frequency multiplication for operation at X-Band and above.

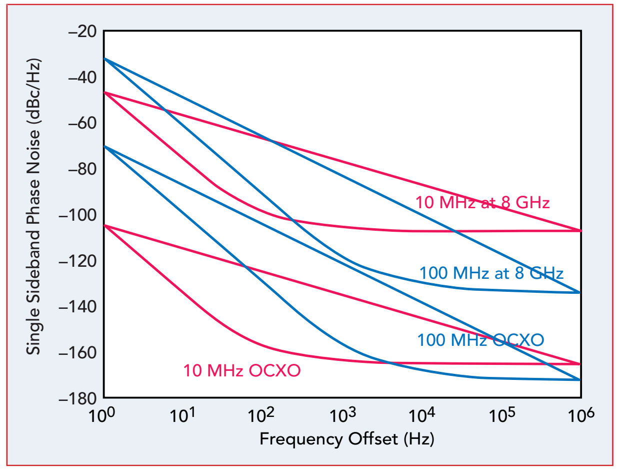

Fig. 5 **Comparison of 10 MHz and 100 MHz OCXOs at 8 GHz.**

X-BAND OSCILLATORS: SHORT-TERM STABILITY

Oscillators operating fundamentally at X-Band will have better phase noise than a quartz oscillator at offsets far from the carrier. ***Figure 6*** is a phase noise plot showing the quantitative performance of OCXO, voltage-controlled oscillator (VCO), DRO and SLCO designs at 8 GHz. As discussed, the Q-factor is the main performance difference in these oscillators. The Q-factors range from about 10 to 100,000, depending on the resonator technology. Size and cost are usually related to the Q-factor.

VCO

A VCO is the smallest, lowest cost and most prevalent of all the X-Band oscillators. They are typically realized as a lumped-element oscillator, either discrete or integrated on-chip. Some are embedded directly into the PLL IC for the highest level of integration. The advantages of this approach are wide tuning range, fast acquisition, low power consumption and small size. The disadvantage is a relatively low Q-factor, ty ically between 10 and

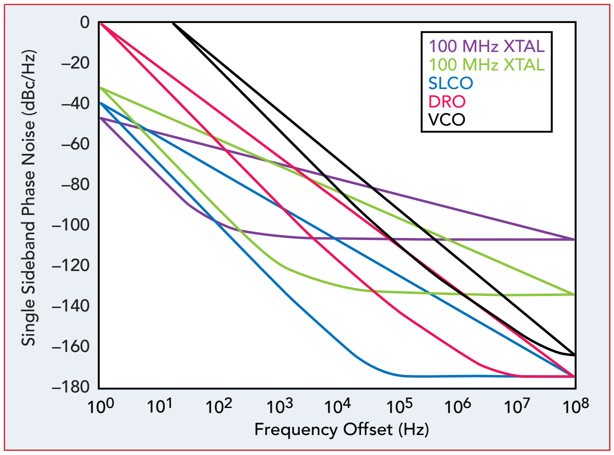

Fig. 6 **8 GHz oscillator phase noise comparison to Saetta Labs' SLCO.**

100. While this option has the lowest performance, it offers the best SWaP-C solution and the performance is often "good enough."

YIG

Yttrium iron garnet (YIG) material enables wide tuning, high Q, magnetically-tuned oscillators. The material resonates in the 3 to 10 GHz range and this range can be made wider if the material is doped. The resonance is directly proportional to a magnetic field. These oscillators have higher Q than VCOs with wide, but slow tuning. The large magnetic field results in significant power consumption and heat dissipation. These devices may be the best option when applications require a wide tuning range and better phase noise than VCOs can provide. Q-factors are in the 500 to 1000 range. YIG oscillators are significantly bigger and more expensive than VCOs and they are typically seen in higher performance systems like test equipment requiring a wide tuning range and low phase noise.

DRO

DROs are single-frequency oscillators that operate with a TM or TE electromagnetic resonance in a cylinder of high dielectric material. In a coaxial resonator oscillator (CRO), this high dielectric material is in a small coaxial cylinder. The material options range from larger dielectric pucks with high Q-factors to smaller, lower Q pucks for different applications and temperature stabilities. Unlike VCOs, they are single-frequency devices that are typically coarse-tuned mechanically and fine-tuned electrically for phase locking. DRO-based devices are about the size of a YIG but provide better phase noise performance at significantly lower operating currents. DROs are a good high performance option for architectures where fixed LOs drive ADCs and DACs. Q-factors can be around 1000, although phase noise varies greatly between manufacturers and models.

Sapphire Oscillators

Sapphire oscillators are relatively new to commercial applications. They operate as an electromagnetic device, like a DRO, but they use a different material and mode of resonance. The resonator material is sapphire and the resonance is called a whispering-gallery mode. The mode was named for the acoustic resonance in St. Paul's Cathedral in England, where the acoustic waves from a whisper travel around the perimeter of the circular hall with almost no attenuation. In a circular shape, a whispering-gallery mode can travel on the inside of two dielectric boundaries with near-perfect reflection. This removes the metallic losses inherent in DROs and cavity oscillators, improving the Q-factor from 10× to 100×. The only loss mechanism is the dielectric loss of the sapphire, which is extremely low. Sapphire oscillators have Qs around 100,000, which are like quartz but operate fundamentally at X-Band. These microwave oscillators have the lowest available noise performance but they are the largest solution and they do require power for thermal control like an OCXO. These constraints make these oscillators more expensive.

SUMMARY

Direct microwave conversion capabilities in the X-Band and above frequency range are expanding system design capabilities. The low phase noise performance of the new generation of DACs and ADCs spotlights the need for increasingly stringent clock performance requirements. In addition to improvements in materials, careful design considerations are needed to achieve the highest performance possible while still being able to accommodate SWaP-C requirements. This article has discussed oscillator phase noise and stability concerns along with the advantages and disadvantages of quartz, IC, VCO, YIG, DRO and newer SLCO technologies for designing and manufacturing oscillators that will become essential as direct conversion techniques move higher in frequency. ■

ACKNOWLEDGMENTS

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