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Understanding the Basics of RF Signal Generation

RF signal generators have been a staple in test and measurement for more than a half century. During that time, they have evolved in countless ways, but the underlying principles have remained the same. This article will provide an overview of the basic construction of an RF signal generator and the associated figures of merit.

Whether an RF signal generator is used to generate continuous wave (CW) signals or includes analog and/or digital modulation, it has three fundamental architectural elements: a reference section, synthesis section, and output section – See Figure 1. Each section will be described below.

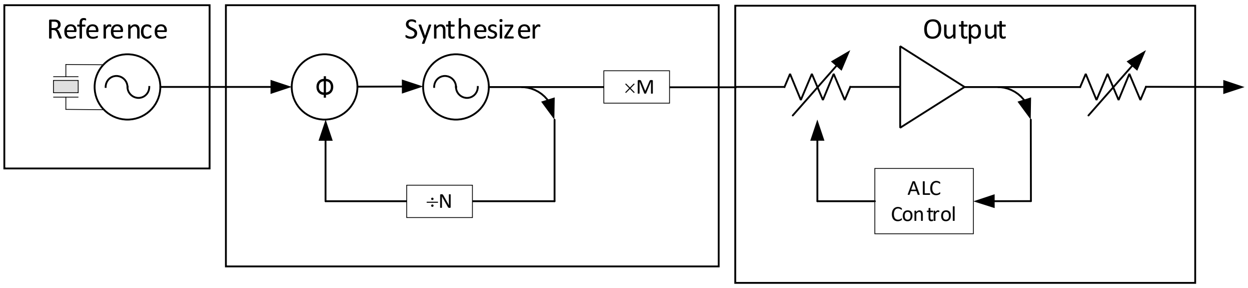

Figure 1. Three architectural elements of an RF signal generator.

The reference section is a key factor in determining the accuracy of the output frequency. At its core is a reference oscillator that must be extremely stable as well as cost-effective for inclusion in a test instrument. Many RF signal generators rely on the electrostriction (or inverse piezoelectricity) property of crystalline quartz as a reference oscillator (also known as an XO) to produce a reference frequency. Its stability will ensure that the frequency output of the source remains accurate between calibrations. The important characteristics are the short-term stability (phase noise), and the long-term stability (or aging rate), both of which can be influenced by temperature. To limit the variations in frequency due to temperature, oscillators may include **t**emperature **c**ompensation (referred to as a **TC**XO) or be placed in a temperature-controlled (**o**ven-**c**ontrolled) package, which maintains a constant temperature (referred to as an **OC**XO).

The synthesis section of a signal generator uses one or more reference oscillators, directly or indirectly to produce the desired frequency range of operation. There are two types of direct synthesis: analog and digital – see Figure 2.

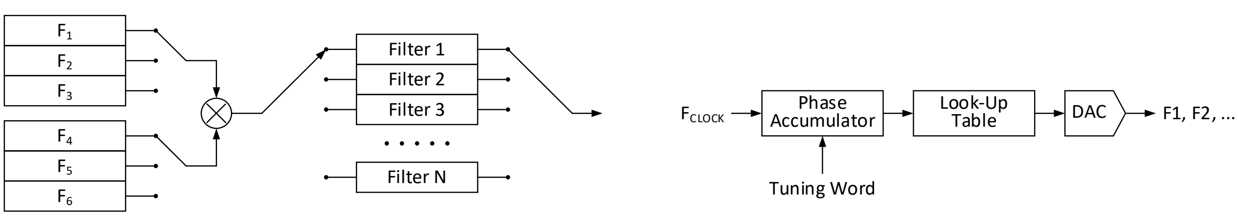

Figure 2. Direct analog synthesis (left) and direct digital synthesis (right)

Direct analog synthesis (DAS) utilizes an array of oscillators that are multiplied, divided, mixed, and then filtered to produce a range of output frequencies. The advantages of a DAS architecture are that users can change between frequencies very quickly (often in nanoseconds) and the output has very low phase noise. The disadvantage is a DAS design often utilizes many components which can increase cost, form factor and power dissipation, and reduce reliability. With all the multiplication, division, and mixing, it can also be difficult to mitigate all the undesired frequency mixing products (or spurious emissions).

Direct digital synthesis (DDS) instruments use a reference oscillator to clock a digital circuit, which includes a digital-to-analog converter (DAC) to directly generate the desired output frequency. This architecture provides fast switching speeds (often in microseconds) and fine frequency generation resolution, but DAC technology can be limited in frequency and typically have high spurious content.

Indirect synthesis utilizes a voltage-controlled oscillator (VCO) or a Yttrium iron garnet (YIG) tuned oscillator (YTO) to generate the desired output frequency. A VCO produces an output frequency from an input voltage. The output frequency can be changed or tuned varying the voltage using a varactor, which is a voltage-variable capacitor commonly made from a reverse-biased p-n junction diode. YTOs exploit the principle of magnetic resonance to generate very low phase noise signals over broad tuning ranges (e.g., 2-18 GHz). VCOs are smaller and less expensive than YTOs, and can change frequency faster, while YTOs have better spectral purity and a wider tuning range.

For instrumentation purposes, VCOs and YTOs lack sufficient frequency accuracy and stability. Many signal generators employ phased-locked loops (PLLs) to improve performance. In a PLL, the VCO or YTO output frequency is divided down and compared to the reference using a phase detector. If there is a difference, an error signal is produced. If either oscillator drifts upwards (or downwards), the error signal at the output of the phase detector will adjust the VCO/YTO output downwards (or upwards) to maintain a stable frequency output. The rate at which the corrections occur is the PLL loop bandwidth. Because of the limited frequency ranges, especially of VCOs, the synthesizer output is often followed by a frequency multiplier to achieve higher desired frequencies.

The output section of a signal generator maintains the desired output amplitude by measuring the output power and compensating for deviations from the set power level. An automatic level control (ALC) circuit samples the signal generator output power and adjusts gain or attenuation to maintain the user-intended output power. The ALC circuit provides a nominal amplitude tuning range that can be extended with adjustable attenuators. There are two types of attenuators that are commonly used: mechanical and solid state.

Mechanical attenuators introduce very little loss between the output of the power amp and the output connector. However, they have finite lifetimes, lower repeatability, slower switching speeds, and can introduce phase shifts. A typical mechanical attenuator may be specified for one to ten million cycles. For an ATE application in which the power level is changed every second for 8 hours per day on weekdays for 50 weeks, the attenuator could fail in a matter of months. Solid state attenuators have much longer life spans, do not introduce phase shifts, and switch much faster. However, they may have increased insertion loss and temperature drift, more limited attenuation, and narrower frequency range.

The architectural trade-offs described above will affect the signal generator performance. The key figures of merit can be placed in three categories: frequency and amplitude control, spectral purity, and power delivery efficiency. Maximum power delivery efficiency occurs when the impedance of the signal generator output matches the impedance of the input of the device-under-test (DUT). When there are mismatches, standing waves are created. The standing wave ratio (SWR) specification describes the SWR that would result if the signal generator was presented with a DUT having a perfect 50-ohm impedance.

For frequency and amplitude control, the aspects of importance are range, accuracy, stability, resolution, and switching speed. Most of these are fairly self-explanatory, but switching speed has some variability and nuance. Switching speed can refer to the time it takes to switch to a specific frequency or power level, to sweep through a range of frequencies or power levels with a fixed increment/ decrement, or to execute a list of frequency and power level changes. The nuance has to do with determining when a signal generator has arrived at a specific frequency or power level. The change is considered complete when the updated frequency or power satisfies a defined “settled” criterion. For example, an amplitude change for the SGX1006 is considered complete when the output amplitude has settled within 0.1 dB of its intended value. Of note, the frequency switching speed for signal generators utilizing PLLs will be impacted by the loop bandwidth. In contrast, signal generators using DAS or DDS architectures will not incur this effect.

Signal generator manufacturers often have different settling criteria. This makes is very difficult to compare switching speed specifications. Moreover, it can also lead to a misalignment between the instrument settling criteria and the requirements of the test being performed. To address this potential misalignment, many signal generators allow users to set a dwell time. A dwell time is the minimum amount of time a signal generator will stay at a specified frequency or power level before switching to the next.

For spectral purity, the aspects of importance are phase noise and the amplitude of harmonics and spurious emissions relative to the intended signal. Ideally, a signal generator would only output a CW signal at a specific intended frequency. Unfortunately, signal generators are constructed from non-ideal components that produce phase noise and signal harmonics, both of which generate intermodulation products and result in spurious emissions. Harmonics are unwanted signals that occur at integer multiples of the intended CW output signal. Frequency multipliers are often used in signal generators to extend the frequency range which can lead to the presence of sub-harmonics. Spurious emissions can come from many sources so they may occur at a wide variety of frequencies and are difficult to predict and mitigate. Fortunately, they are often much lower in amplitude than the intended CW signal and the more predictable harmonics – See Figure 3.

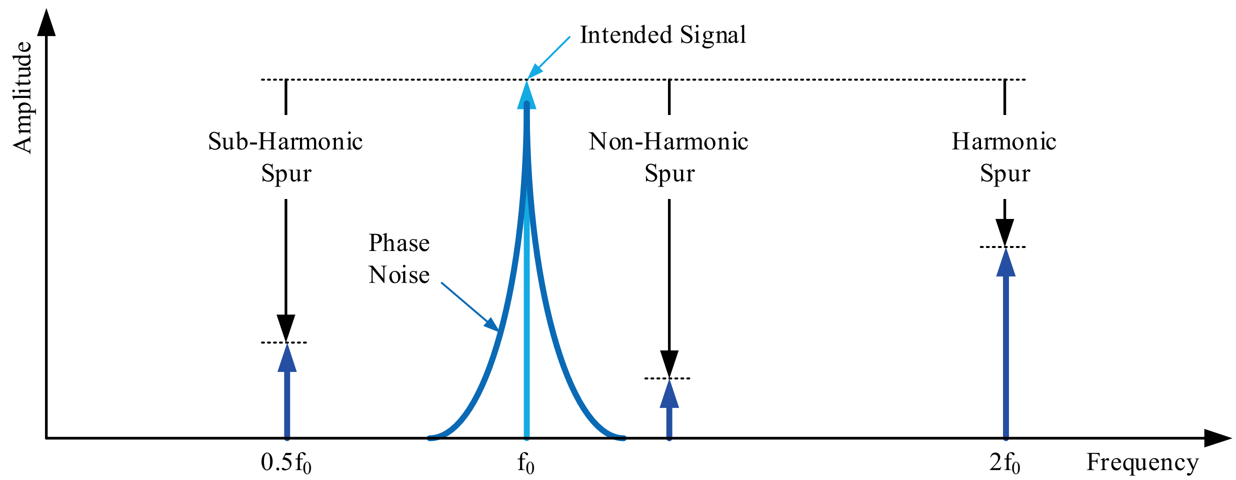

Figure 3. Measures of spectral purity

There are four main sources of phase noise in a PLL-based signal generator: the reference oscillator, the PLL phase detector, the VCO or YTO, and broadband noise. Broadband noise is primarily the result of the thermal noise within the signal generator and is independent of the operating frequency. Phase noise from the phase detector is also independent of the operating frequency. However, the phase noise is degraded by 20 log N, where N is the divisor of the dividing circuit that translates the VCO/VTO signal to the reference frequency for the phase comparison. On the other hand, the phase noise contribution of the reference oscillator and VCO/YTO does have a predictable frequency dependence, falling off at a rate of $1/f^3$ (-30 dB/decade) initially and transitioning to a $1/f^2$ (-20 dB/decade) relationship. The bandwidth of the PLL determines the point at which the VCO/YTO contribution to the overall phase noise becomes suppressed. Figure 4 illustrates how these different contributions combine to result in a signal generator phase noise plot.

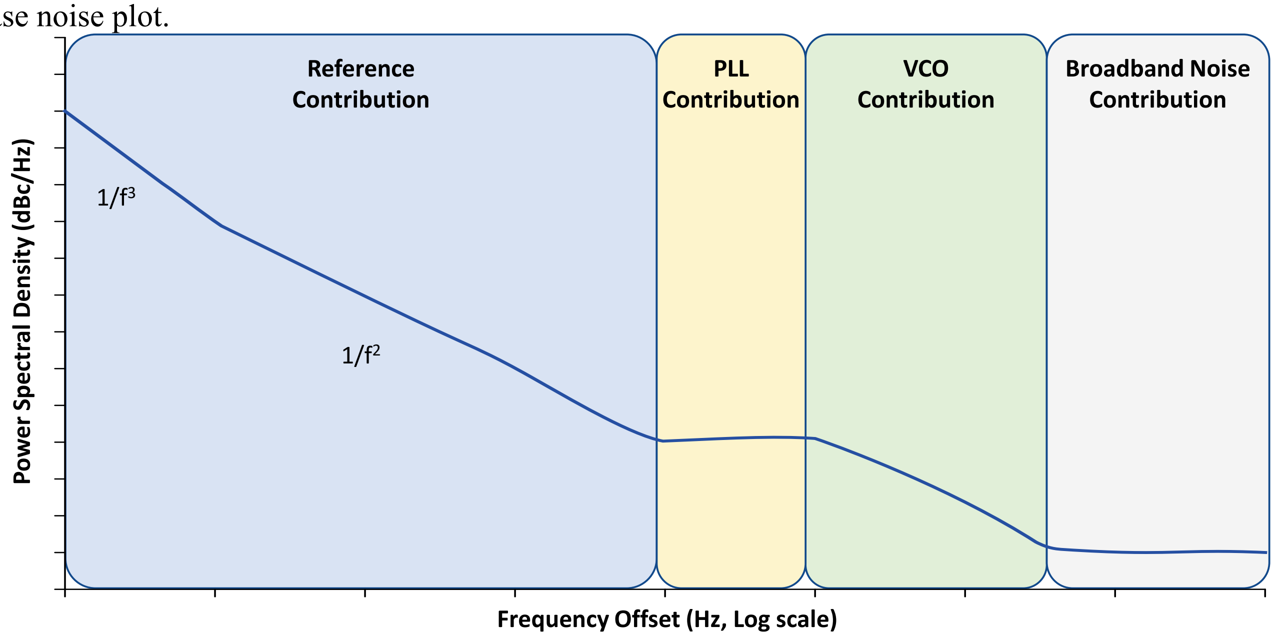

Figure 4. Phase noise contributors

To provide an example of a signal generator with various architectural optimizations and the resulting performance, consider the **Boonton SGX1000** series of signal generators. The **SGX1006 RF Signal Generator** utilizes an internal 100 MHz OCXO in a non-PLL-based proprietary blend of DAS and DDS to generate frequencies from 10 MHz to 6.4 GHz fed into a solid-state variable attenuator to deliver power levels between -50 dBm to +18 dBm. This design results in several outstanding performance specifications.

- Lightning-fast frequency switching speed — 200 µs, fully settled
- Ultra-low phase noise — -116 dBc/Hz @ 6 GHz with a 10 kHz offset
- Excellent amplitude accuracy — +/- 0.25 dB

Figure 5. Boonton SGX1006 RF Signal Generator