Cover Feature
Invited Paper

State of the Art in Microwave VCOs

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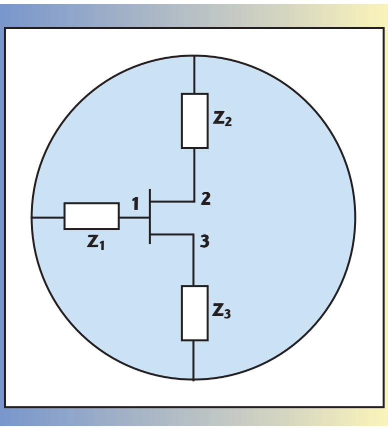
Microwave oscillators are at the heart of all RF and microwave systems from wireless communications, radar and navigation, military and aerospace to vital test equipment. Voltage controlled oscillators (VCO) represent the most common form of oscillators that tune across a band of frequencies specific to applications. VCOs have come a long way from the vacuum tube based components of 85 years ago to present fully integrated ICs. Stand-alone VCOs are commercially available in various SMT packages, hybrid coaxial modules, raw die, as well as part of higher-level mixed-signal ASICs. Improvements in VCO technology have continued throughout that time, yielding ever-smaller sources with enhanced performance. This article will cover basic topology, applications, evolution, specifications and future trends of VCOs based on three terminal devices.

VCO BASICS

A typical block diagram for a basic VCO is shown in ***Figure 1***. A three-terminal active device is the oscillation device that is enabled to oscillate at the desired band of frequencies with the help of a series feedback circuit on one port and a voltage tunable resonator or capacitor on the second port. A matching circuit on the third port is used to extract power typically into 50 ohms.



▲ *Fig. 1 Block diagram of a VCO.*

The large signal oscillation condition for this topology is given by:[1]

$$[S][S']=[I] \qquad (1)$$

where [S] represents an active matrix, and [S'] represents a passive matrix. In simplified form, this condition can be presented as follows:

$$S''_{11}\Gamma_1=S''_{22}\Gamma_2=S''_{33}\Gamma_3=1 \qquad (2)$$

where S''_{11} is the modified reflection coefficient at port 1 with ports 2 and 3 loaded by impedances corresponding to reflection coefficient Γ_2 and Γ_3.

A VCO is a type of oscillator which commonly uses a varactor diode to tune its frequency. The tuning range of VCOs can vary from a tiny 0.1 percent to more than an octave band. Other types of microwave oscillators include dielectric-resonator oscillators (DRO), YIG-tuned oscillators (YTO), surface acoustic-wave (SAW) oscillators, and transmission-line oscillators among others. ***Table 1*** compares these oscillators.

While there are many types of VCOs, it is their application that determines their desired characteristics. VCOs are a key part of test instruments and are used as a basic source of RF energy in signal generators, synthesizers as well as vector network analyzers. In spectrum analyzers and vector signal analyzers, VCOs are used in the generation of wideband local oscillators. In most cases, VCOs are converted to synthesized sources using PLL techniques and a low phase noise reference oscillator.[2] In these applications, phase noise, switching time and compact size are critical requirements.

Another VCO application is transmitter and receiver local oscillator synthesizers for wireless communications, digital radios, satellite terminals and satellites for both down-converter and up-converter application. These systems provide voice, data or video transmissions. VCOs are also an essential part of radars and military electronic systems where, in addition to phase noise, fast-frequency settling characteristics are important requirements. In threat simulator and EW jamming systems, signal responses of sub-microseconds are vital.

VCOs are directly used in FM communication systems where modulation frequency is applied to their tuning ports. In these applications, tuning

TABLE 1							
COMPARISON OF COMMON TYPES OF OSCILLATORS							
Type	**Tuning Range**	**10 GHz Phase Noise @100 kHz offset**	**Switching Speed**	**Hysteresis**	**Size inch cube**	**Relative Cost**	**Power Consumption**
VCO	Octave	-110 dBc/Hz	1 µsec	Low	0.001	1	Low
YTO	Decade	-120 dBc/Hz	1 msec	High	1.0	10	High
DRO	1%	-120 dBc/Hz	N/A	N/A	0.5	5	Low

linearity and modulation bandwidth are challenging specifications in the design of the VCO. In a specific requirement of an FMCW radar used in radio altimeters or collision avoidance systems, tuning linearity is directly linked to the accuracy of the measurement.

All modern digital and optical communications systems need a basic clock that is generally a low noise VCO. Clock frequencies have been continuously increasing and are currently in the range of tens of GHz. A clock frequency of more than 40 GHz is used in 40 Gb/s telecommunication systems. These clocks demand very low jitter performance.

Commercial availability of fundamental stand-alone VCOs are presently limited to K-Band. Higher-frequency sources are generated using frequency multipliers, which add harmonic-related products that require filtering at the output. However there has been rapid technological progress in semiconductor integration of VCO circuitry. The semiconductor industry has demonstrated VCOs with frequencies higher than 200 GHz.[3]

VCO EVOLUTION

Two-terminal VCOs started as early as the 1960s and provided low phase noise tunable signals to over 100 GHz. Nevertheless, because of their size, high power consumption and cold start issues, their applications were limited to high-end uses until three-terminal devices capable of signal generation in microwaves started showing up in the 1970s. Silicon bipolar and GaAs FET devices were the first to be exploited in VCOs. X-Band VCOs were a reality by 1975 using GaAs FETs.[4] Silicon bipolar-based X-Band VCOs were introduced soon after. While silicon bipolar devices had an advantage of lower phase noise, GaAs FETs were able to deliver more power and higher frequencies of oscillations. Silicon bipolar devices ultimately were able to cover VCOs up to Ku-Band[5] and thus became the technology of choice, especially because of good phase noise and low power consumption. Silicon bipolar-based VCOs typically had a close-in phase noise of about 10 dB better than a GaAs FET device in X-Band, for example. GaAs MESFET devices made discrete VCOs up to 40 GHz by the early 1990s. Silicon bipolars with an f_{max} of 35 GHz and oscillation capability to 18 GHz as VCOs and 22 GHz as YTOs were reported.[5,6] f_T of GaAs FET devices continued to increase to beyond 100 GHz.

The availability of frequency-tuning element varactors made a large impact on VCO technology. Note that abrupt-junction varactor diodes were initially used; however, their frequency bandwidth was limited. Hyperabrupt-varactor diodes with higher capacitance variation ratios were made available in the 1970s resulting in wideband VCOs with better linearity. Both silicon bipolar as well as GaAs diodes are now commonly used. GaAs diodes typically have a higher Q but do not necessarily have better phase noise because of up-converted surface noise caused by lack of passivation. The thermal-oxide passivation of silicon varactors provide better 1/f noise and hence better phase noise. Another reason for choosing silicon is the poor frequency stability record of GaAs diodes. Because of the higher thermal resistance of gallium arsenide, GaAs diodes do not settle as fast as silicon diodes in fast VCOs, and the high surface state density in GaAs results in significant long-term drift compared to silicon. GaAs hyperabrupt diodes do offer better tuning ranges at higher frequencies due to their lower capacitances, higher Qs and higher capacitance ratios.

In the 1970s, microwave VCOs used bare die and thin film technology with chip-and-wire assembly techniques. These VCOs were packaged in metal housings (see ***Figure 2***). Soon, SMT parts were available and VCOs were also made available in SMT packages for direct attachment onto the PCB in the 1980s. MMIC VCOs entered the market in the 1990s and changed the landscape. Using silicon and GaAs technologies, IC VCOs were the only way to meet cost targets of emerging wireless markets. VCO functions quickly integrated into higher level ICs to meet the challenge.

STATE OF THE ART

With time, new semiconductor technologies were introduced for three-terminal active devices and were experimented within their application with VCOs. Some of those technologies, which provided good phase noise, became popular, including SiGe and InGaP HBTs. These devices not only offered higher frequency operation but also very low phase noise, comparable to Si BJTs at lower frequencies.

Commercially available SiGe discrete devices have a f_T of greater than 80 GHz but are available only in SMT form, which limits their use in Ku-Band applications as the SMT packages become parasitic. However, SiGe IC devices have been steadily making strides in high performance VCO functions up to mmWave frequencies. A wideband VCO with 30 percent bandwidth has been reported at 80 GHz using SiGe technology with +12 dBm of power and phase noise of -97 dBc/Hz at 1 MHz offset. Multiple varactors were used in achieving this bandwidth.[7]

GaAs FET and PHEMT devices have proven to be excellent devices for higher power at higher frequencies as wideband amplifiers. However, these devices fall short in phase noise performance due to high 1/f noise. HBT structures on GaAs offer significantly superior 1/f noise due to the vertical current flow. GaAs HBT, InP HBT and more commonly InGaP HBT became the technology of choice in the early part of the century, which were able to combine high frequency potential with low 1/f noise.[8] Technology improvements were able to reduce the base-emitter distance to 0.5 µm and helped increase f_{max} to close to 200 GHz. Using a push-push configuration, an 8 percent tuning range VCO was realized at 77 GHz (see ***Figure 3***) with a decent phase noise of -92 dBc/Hz at 1 MHz offset.[9] It is important to note that InGaP HBT technology has been the technology of choice for low noise discrete VCO MMICs for over a decade. Narrow or wideband VCO MMICs using InGaP HBTs are presently commercially available up to 20 GHz.

The performance of both CMOS and SiGe HBTs, as measured by f_T,

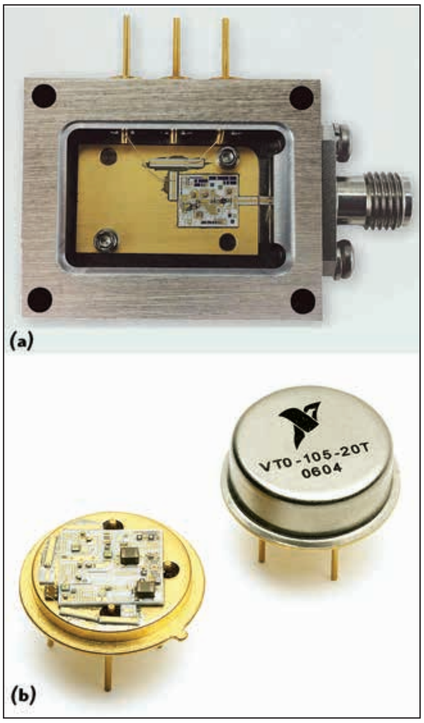


Fig. 2 VCOs in a metal housing (a) and TO-8 cans (b).

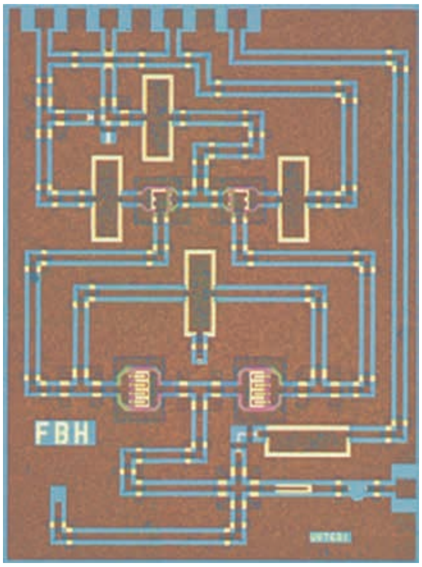
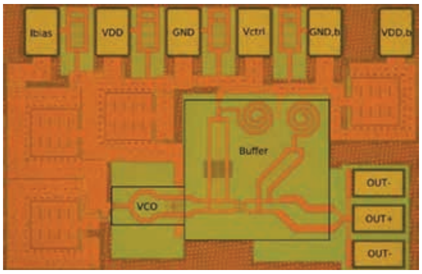


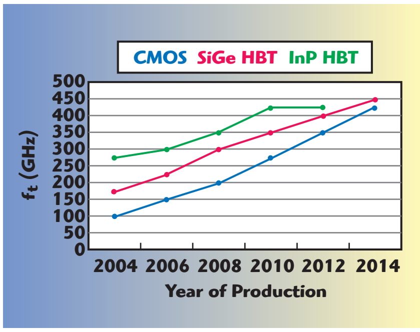
Fig. 3 77 GHz VCO with 8% tuning range and phase noise of -92 dBc/Hz at 1 MHz offset. ©2003 IEEE. Reprinted with permission from IEEE Proceedings, June 2003.

f_{max}, or NF_{min}, has dramatically improved with geometry scaling and technology enhancements. These silicon technologies are able to implement large amounts of digital logic in a given area, enabling the on-chip integration of control logic and digital signal processing. The combination of mm-scale wavelengths, low cost, and the ability to integrate make these technologies an attractive solution for transceiver topologies being implemented on a single die.

CMOS has made significant inroads into microwave and mmWave VCO functions as part of a higher-level mixed-signal IC. CMOS is key to achieve low cost integrated circuits at frequencies approaching 100 GHz and enable the rapidly growing needs of communications and radar applications. A 118 GHz VCO with 8 percent bandwidth and -83 dBc/Hz at 1 MHz phase noise has been reported using CMOS (shown in ***Figure 4***.)[10] Low level oscillations up to 300 GHz have been reported using 65 nm CMOS.[3] CMOS and SiGe technologies are both in use presently, but CMOS is expected to take the lead with the new 0.1 µm technology, which will enable it to perform at the new emerging applications in 5G as well as collision-avoidance radar frequencies covering 30 to 86 GHz.



▲ *Fig. 4 118 GHz VCO with 8% bandwidth and phase noise of -83 dBc/Hz at 1 MHz offset. ©2011 IEEE. Reprinted with permission from IEEE Proceedings, June 2011.*



▲ *Fig. 5 Evolution of f_t for various technologies over the years.*

Figure 5 shows the evolution of f_t for CMOS, InP HBT and SiGe technologies. Conventional CMOS is now rapidly reaching its fundamental limits of silicon performance despite ever decreasing transistor line widths and use of highly complex architectures. It may be noted that for purely RF devices, III-V implementations may turn out to be a lower cost solution under certain conditions when use of existing designs and time-to-market are taken into account. However, as the world moves towards integration of RF with digital and control functions for high volume applications, CMOS has a clear advantage.

Among other emerging technologies, GaN is a promising one for high power and high frequency signal sources. GaN's potential to generate directly multi-watts of RF power at S- and C-Bands is unmatched in the solid-state industry. Almost 50 W of RF power has been realized at 2.45 GHz.[11]

With commercial availability of GaN amplifier MMICs in the mmWave frequencies,[12] oscillators exceeding 100 GHz using GaN are not far behind. A W-Band VCO MMIC has been realized using 0.1 µm AlGaN/GaN HEMT technology. Covering 85.6 to 92.7 GHz, it provided better than +10 dBm power output (see ***Figure 6***). Phase noise of the VCO varied between -80 to -90 dBc/Hz at 1 MHz offset from the carrier.[13]

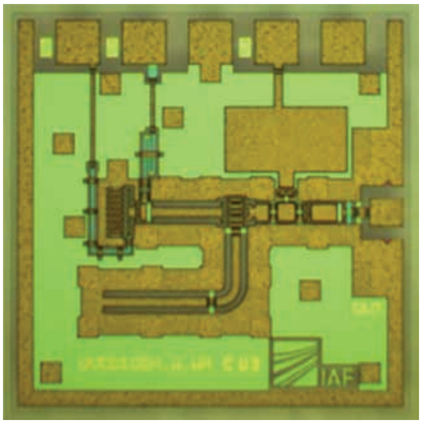
VCO PERFORMANCE PARAMETERS

The importance of VCO characteristics depends upon its applications. In addition to basic parameters like frequency range, RF power output, harmonics, spurious and power consumption, there are a number of special parameters that determine the quality of the operation of the system. These include tuning linearity, frequency pushing, load pulling, frequency settling, modulation bandwidth, phase noise and jitter. Some of these parameters are outlined below:

Frequency Range

The output frequency of a VCO can vary over a wide range depending on the tuning varactor, active device and architecture. Frequency bandwidth is defined as:

$$\text{Bandwidth}=(f_{max}-f_{min})/f_{center} \qquad (3)$$



▲ *Fig. 6 W-Band VCO MMIC using AlGaN/GaN HEMT technology with better than +10 dBm power output. ©2014 IEEE. Reprinted with permission from IEEE Proceedings, June 2014.*

In this formula, f_{max} is the maximum tuning frequency, f_{min} is the minimum, and f_{center} is the center of the frequency range. Frequency bandwidths of up to 100 percent have been reported; up to 67 percent (an octave bandwidth) are commercially available up to K-Band.

Output Power

The output power of a fundamental RF VCO can vary from less than 0 dBm for a small low noise device to greater than a watt from a power device. However, since the required RF power can typically be achieved by using amplifiers at the output of VCOs, the VCO design is optimized more for parameters other than power output. Output power flatness in ± dB over the frequency band is another important parameter that reflects the output impedance match of the VCO to the load.

DC Power Efficiency

Since a VCO is a DC-to-AC converter, its DC power efficiency is one of the measured characteristics. It is measured as the ratio of RF power output to DC power input. At microwave frequencies a typical efficiency of about 10 percent is achieved. Load coupling/isolation is one of the factors that impact power efficiency.

Frequency Pushing

Effect of DC bias voltage variation is related to pushing figure. Pushing figure is defined in Hz/V and is measured by varying DC bias in steps of not more than 0.1 V.

$$\text{Frequency Pushing} = \Delta f / \Delta V \qquad (4)$$

In a typical VCO, pushing figure is related to the resonator quality factor and is sometimes used to measure quality of the oscillator. In view of the fact that it is a means to change the frequency, this characteristic has been used for narrowband FM or phase locking for VCOs that present a linear or monotonic relationship between voltage and frequency.

Harmonic Suppression

Harmonic signals represent frequencies that are integer multiples of the fundamental or carrier frequency and are generally measured in dBc with respect to power in fundamental frequency. An oscillator inherently being a nonlinear device will always have harmonics. However, the level of harmonics are generally affected by the design and are commonly rejected by using an external lowpass filter.

Spurious Response

Spurious outputs are the undesired signals in the output of a VCO, which are not harmonically related to the fundamental frequency. One of the causes of close-in spurious is from the ripple in the power supplies, i.e., 60 Hz and its harmonics. It is a low frequency modulation effect produced by the pushing characteristics of the VCO. Another type of spurious is caused by multiple instabilities in the active device causing low-level signals almost anywhere in the useful frequency range of the active device. Careful design can avoid these spurious. It is important to note that spurious performance over temperature can vary due to gain variation of the active device. It is not uncommon to find spurious only at cold temperatures.

Tuning Sensitivity and Linearity

Tuning sensitivity or modulation sensitivity describes the monotonic relationship between the tuning voltage and VCO frequency. Measured as Hz/V, it represents the differential of the tuning voltage curve. Many applications require linear tuning characteristics or constant tuning sensitivity. Linear tuning is affected by the type of varactor diode and oscillator architecture. Hyperabrupt varactor diodes offer better linearity for example. Special profiles for the varactors have been made available for linearity. Another influencing parameter is the VCO circuit itself, which can be optimized for linearity. In certain applications ADC and ROM devices can be used to digitally enhance the linearity of VCO tuning characteristics.

Modulation Bandwidth

Modulation bandwidth is the speed at which a VCO frequency can be changed. In reality, the VCO acts as a frequency modulator where frequency can be modulated using an AC voltage on the tuning port. Higher modulations help with wideband FM systems.

In a VCO, if the amplitude of the modulating signal and modulating frequency (f_m) are proportionally increased, the modulation index and the amplitude of the carrier plus the sideband signals will remain constant up to a point and will start decreasing after that. When the effective deviation of the modulating signal is 0.707 of the initial value, that modulating frequency is known as the 3 dB modulation bandwidth. Modulation bandwidth is a function of the tuning port impedance as well as the modulating source impedance. Generally, high frequency VCOs have higher modulation bandwidths. Typical bandwidths are between 10 and 20 MHz. Using optimized circuits, tuning bandwidths of greater than 100 MHz have been achieved at X-Band as shown in ***Figure 7***.

Slew Rate

Slew rate is the rate of change of VCO signal and is of significance in VCOs used as clocks in digital circuits and is presented in V/sec. In a sinusoidal source, it can be estimated by:

SR = 2 π f Vpk, where Vpk is the peak amplitude of the sine wave clock.

Frequency Settling and Post Tuning Drift

When a VCO frequency is switched from one point to another, it takes a finite amount of time to settle to the new point within the frequency range. Settling time is defined as the interval between the time when the input tuning drive waveform reaches its final value and the time when the VCO frequency falls within a specified tolerance of a stated final value at a particular time. Frequency settling refers to close-in settling (typically up to 1 msec) (see ***Figure 8***). Post tuning drift, on the other hand, represents the frequency settling characteristics between two points in time typically between 1 msec and 1 minute or more. Time references are generally

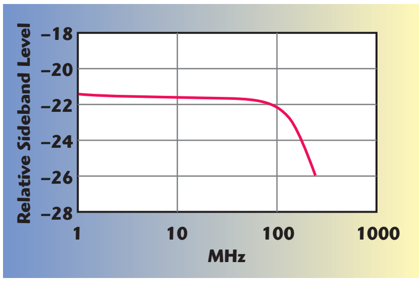


Fig. 7 Modulation bandwidth of a 10 GHz VCO.

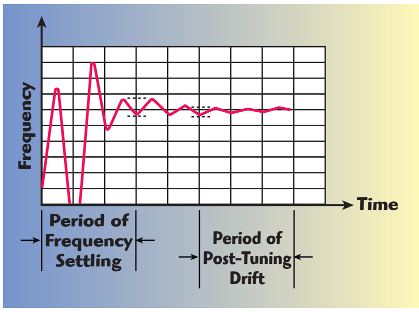
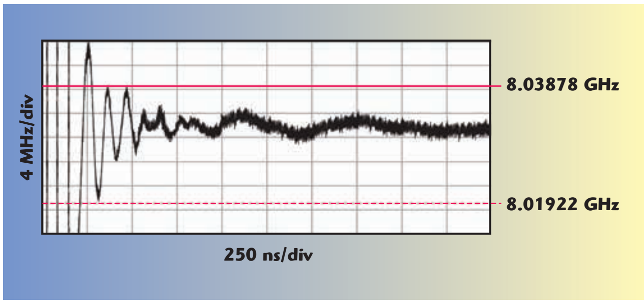


Fig. 8 Frequency settling and post tuning drift diagram.



▲ *Fig. 9 Frequency settling from 6 to 8 GHz using LeCroy LabMaster 10 Zi 36 GHz/80 Gs/s oscilloscope.*

application specific.

Frequency settling is determined by a number of factors including type of active device, varactor diode, thermal management as well as quality of die attaching. During the interval, when the VCO is being tuned, the junction temperature of both the transistor and the varactor are changing due to changes in RF circuit efficiency and loading. This causes impedance changes that result in frequency shift. The time interval during which this happens is dependent on the thermal impedance of the devices. The varactor used in the VCO is a significant factor for frequency settling caused by the choice of passivation. Ceramic-to-glass passivation is usually superior to thermal oxide or silicon dioxide passivation in terms of post tuning drift. However, devices with thermal oxide passivation usually have more stable settling-time performance over time and temperature. Another parameter affecting frequency settling is chip thickness. In general, thinner is better because of less resistance in series as well as lower thermal resistance. The varactor and the active device are the two components where the most thermal sensitivity occurs and dominates this performance; hence, any long thermal time-constant associated with either of these components can cause pronounced frequency settling effects.

There are a number of measurement methods for frequency settling characteristics. Use of a frequency discriminator at the final frequency or at a down-converted frequency is a common method. With recent advances in technology, new approaches have become possible. Modern digital oscilloscopes are handy tools for making time-domain measurements, and they have recently become available to work at microwave and mmWave frequencies. Newly released high frequency oscilloscopes are already able to analyze signals up to 100 GHz,[14] providing microwave engineers with a tool for time-domain measurements. High frequency scopes make a number of VCO measurements possible including frequency, power output, jitter, modulation bandwidth and frequency settling characteristics. ***Figure 9*** shows a settling time measurement of a 6 to 8 GHz VCO using a silicon bipolar active device and a silicon hyperabrupt varactor. It shows that the VCO frequency settles within ± 4 MHz in less than 750 nanoseconds.

Frequency Load Pulling

VCO frequency also is affected by the load impedance. Variation in load magnitude and phase will change the frequency of the VCO as a function of the oscillator quality factor. Frequency pulling, generally in MHz, is measured at a frequency by changing the phase of a known return loss through 180 degrees. Typically, a 12 dB return loss or a 6 dB attenuator is used as shown in ***Figure 10***.

Load pulling is also used to test whether the VCO is falling out of oscillations at a given frequency when expected worst-case load return loss is rotated through 180 degrees. In reality, VCOs are rarely used directly in high VSWR loads. Isolation between load and VCO is generally achieved by using an isolator or a buffer amplifier.

Power Load Pulling and Output VSWR

Power load pulling is the variation of VCO power output with the magnitude and phase of a known load return loss. Power load pulling is measured in a way similar to frequency pulling (see Figure 10). Care is taken to place the attenuator after the directional coupler and use a coupler with very good directivity at the frequency of measurement. Peak-to-peak power variation is typically measured into a 6 dB attenuation representing a 12 dB return loss. From the power variation (ΔP) and return loss, output VSWR or return loss of the oscillator can easily be calculated using:

$$VSWR = (5 \times 10^{\Delta P/20} - 3)/(5 - 3 \times 10^{\Delta P/20})$$

An interactive web flash tool can perform this equation as well.[15]

Hysteresis

Hysteresis represents the maximum difference in VCO frequency measured at the same tuning voltage when the oscillator is tuned slowly through the specified tuning range from low end to high end and vice versa. Unlike YTOs, VCOs present a very low hysteresis. However, poor thermal management, where slow frequency drift over a long period is present, can result in adverse hysteresis.

Phase Noise and Jitter

Phase noise is an important characteristic of a VCO. It represents short-term stability of the device. Oscillator power is distributed in spectral distributions known as noise sidebands on opposite sides of the carrier. Phase noise can be analyzed as FM phenomenon that describes short-term random frequency fluctuations of a signal. It is measured in dBc/Hz at a particular offset from the carrier. The phase noise of a VCO is determined by a number of factors including resonator quality factor, type of varactor or the active device used, power supply noise, tuning voltage supply noise as well as the circuit design of the oscillator itself. Once DC power supplies are quieted, phase noise depends mainly upon the overall quality factor of the circuit and noise properties of the semiconductor devices. Higher Q means lower bandwidth and vice versa. For better phase noise, therefore, one can combine multiple narrowband VCOs rather than using a single wideband VCO. Regarding semiconductor technologies, silicon bipolar, SiGe HBT and InGaP HBTs are the technologies of choice and are used as demanded by frequency and other features desired.

A graphical representation of phase noise is shown in ***Figure 11***. The various noise sources inside and outside the transistor modulate the VCO, resulting in energy or spectral distribution. More noise from various noise sources degrades the phase noise of the VCO. A number of methods are used to measure phase noise. An old trusted method has been the one which uses a frequency discriminator at the final frequency, requiring complex calibration. Automated phase noise measurements are now the norm allowing engineers more time to design and less time measuring. ***Figure 12*** shows a phase noise plot of a 10 GHz narrowband VCO and a wideband VCO using a silicon bipolar transistor.

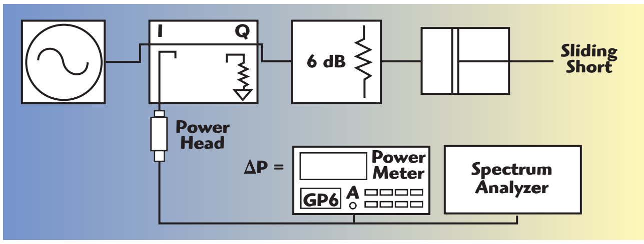


Fig. 10 Frequency pulling and output VSWR measurement setup.

Jitter is another measure of short-term stability, which is used more in the digital world. A perfect sinusoidal output of an oscillator would have identical time between subsequently measured zero crossings along the time axis. Any deviation from this time is defined as a phase fluctuation and is known as jitter. Jitter is responsible for causing bit errors. In other words, jitter is a time-based phenomenon in which the edges of waveform transitions arrive early or late with respect to the clock that is latching the signal. If, for instance, the data edge arrives after its companion clock edge, then a bit that was supposed to be latched as high will be latched as low. Wrong edge timing causes incorrect latching which causes bit errors.

A low jitter clock source is an essential requirement for a low bit error rate digital communication system. Jitter in digitizer circuits deteriorates the signal-to-noise ratio. With ever increasing data rates both in the wireless and wired world, digital clocks have entered the microwave and mmWave region. While Gb/s data is entering the wireless world, optical communication systems are knocking at the terabit rate door. These clocks are nothing but microwave VCOs

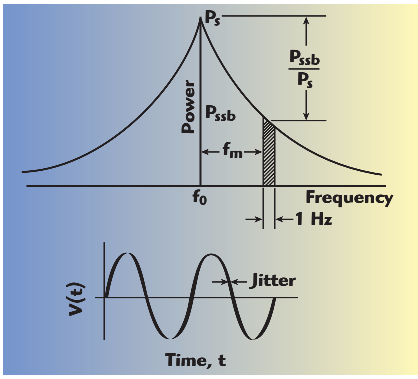


Fig. 11 A graphical representation of phase noise.

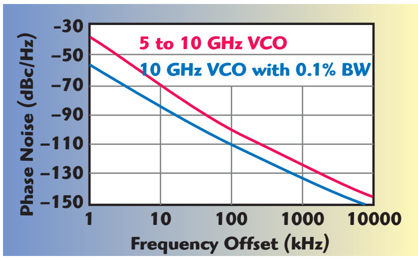


Fig. 12 Phase noise of silicon bipolar VCOs, one narrowband and one octave band.

with special features. As an example, clock sources need to have differential outputs, achieved in VCOs by using a balun in the output or having a differential output oscillator. Instead of power output and phase noise, clocks are characterized by p-p voltage and jitter. Jitter and phase noise both represent phase fluctuations and are related through simple equations. Jitter is calculated by integrating phase noise over a specified offset range and converting to appropriate units. A simple interactive graphical tool is also available[16] online. Jitter is represented in different ways including radians, degrees, time in seconds as well as unit interval.

CONCLUSION

RF and microwave VCOs have come a long way in the past few decades. Progress in semiconductor IC technology has made these key functions ever so small that they have humbly lost their identity and have merged into a small corner of large mixed-signal ICs. Even when it is hard to see these master functions physically, they continue to provide vital control functions for communication, navigation and radar.

It seems that progress in VCO technology has slowed in the last decade. Technologies of choice for low phase noise, for example, remain silicon-bipolar devices, SiGe HBTs, and InGap HBTs.[17] Gradually, the f_T of these processes is expected to increase to a region where it will be hard to find more applications. Future challenges then will be more focused on cost and volume. Work on CMOS technology in this field will go into high gear. With the promise of low cost and a high level of RF analog and digital-integration capabilities, future consumer electronics applications in microwave and mmWave will see more of this CMOS technology. GaN semiconductor technology is also expected to move into practical use at microwave and mmWave frequencies with necessary cost reduction. Once it reaches high volume production capability, it has the potential to offer a serious challenge to GaAs.

Conventional CMOS may no longer be capable of continuing Moore's law. The ever increasing cost of narrowing line widths with diminishing returns calls for a paradigm shift. A potentially optimal solution is III-V compound semiconductors fully integrated on a silicon platform. Focus is expected to shift to this process in order to exploit the advantageous electronic, optical and power-handling properties of compound semiconductors while continuing to use the scale and cost structure of existing silicon semiconductor fabs. Recently, GaN on silicon was demonstrated on an 8" wafer.[18]

A wide variety of other compound semiconductor combinations could be realized as part of the full array of compound semiconductor on silicon technologies. Mixed-technology ICs are also expected to meet certain custom requirements that were not possible using a single technology. Design libraries will need to be developed in order to enable widespread adoption of these technologies across multiple applications. Improvements in 3D EM simulation software will continue to make the RF designer's job easier with more and more accurate results.

In regards to frequency tuning and

resonator elements new technologies including MEMS and substrate integrated waveguide are expected be used in addition to the standard varactor diode variations. On chip, narrowband but higher Q resonator switching may be used to achieve wider band low phase noise VCOs.

VCOs on MICs will continue to play a vital role in custom, lower volume requirements for defense, instrumentation and higher end communication systems. The speed and cost to develop signal sources with specific optimization of one or more features including power, frequency range, phase noise, settling time and power consumption will continue to count on MIC-based VCOs. Among test equipment, more automation and use of more modular instruments in place of benchtop equipment is expected.[19] High frequency real-time oscilloscopes will start playing a bigger role in characterizing VCOs up to mmWave frequencies. In spite of the slowdown in the rate of innovation, there will be many challenging and interesting opportunities for signal source designers. ■

References

1. A.P.S. Khanna and J. Obregon, "Microwave Oscillator Analysis," Microwave Theory and Techniques, *IEEE Transactions*, Volume: 29 Issue: 6, pp. 606–607, June 1981.
2. "A Compact Synthesizer Module Offers Instrument Grade Performance and Functionality," *Microwave Journal*, Vol. 54, No. 2, pp. 34–38.
3. Razavi Behzad, A 300 GHz Fundamental Oscillator in 65-nm CMOS Technology, *IEEE Journal of Solid-State Circuits*, Vol. 46, No. 4, April 2011.
4. R. A. Pucel et al., "Experiments on Integrated Gallium Arsenide FETs at X-Band," *Electronics Letters*, 1975, 11 (10), pp. 219–220.
5. A.P.S. Khanna, "Fast-Settling, Low Noise Ku-Band Fundamental Bipolar VCO," *Microwave Symposium Digest*, MTT-S International, pp. 579–581, June 1987.
6. A.P.S. Khanna and J. Buenrostro, "2-22 GHz Low Phase Noise Silicon Bipolar YIG Tuned Oscillator Using Composite Feedback," *Microwave Symposium Digest*, IEEE MTT-S International, pp. 1297–1299, June 1992.
7. "SiGe Bipolar VCO With Ultra-Wide Tuning Range at 80 GHz Center Frequency," *IEEE Journal of Solid-State Circuits*, Vol. 44, No. 10, pp. 2655–2662, 2009.
8. Herbert Zirath, Rumen Kozhuharov and Mattias Ferndahl, "A Balanced InGaP-GaAs Colpitt-VCO MMIC With Ultra-low Phase Noise," Chalmers University of Technology, Microwave Electronics Laboratory, MC2, SE-412 96, Göteborg, Sweden *12th GaAs Symposium*, Amsterdam, 2004.
9. F. Lenk, M. Schott, J. Hilsenbeck, J. Würfl and W. Heinrich Ferdinand-Braun-Institut für Höchstfrequenztechnik (FBH), "Low Phase-Noise Monolithic GaInP/GaAs-HBT VCO for 77 GHz," D-12489 Berlin, Germany, *Proceedings IEEE IMS 2003*.
10. Wouter Volkaerts, Michiel Steyaert and Patrick Reynaert ESAT/MICAS, Katholieke Universiteit Leuven, Belgium, "118 GHz Fundamental VCO with 7.8% Tuning Range in 65 nm CMOS," *IEEE Radio Frequency Integrated Circuits Symposium (RFIC)*, 2011.
11. Sang Hoon Kim et al., "Combined Power Oscillator using GaN HEMT," Kwangwoon University, Seoul, Republic of Korea, 2011 *IEEE MTT-S International Microwave Symposium*.
12. V. Radisic et al., "80 GHz MMIC HEMT VCO," *IEEE Microwave and Wireless Components Letters*, Vol. 11, Issue 8, pp. 325–327.
13. R. Weber, D. Schwantuschke, P. Brueckner, R. Quay, F. van Raay and O. Ambacher, "A 92 GHz GaN HEMT Voltage-Controlled Oscillator MMIC," *International Microwave Symposium*, June 2014.
14. Peter J. Pulpalaikis et al., "Technologies for Very High Bandwidth Real-time Oscilloscopes," IEEE Bipolar/BiCMOS Circuits and Technology Meeting 2014.
15. Oscillator Output VSWR Measurement: http://bit.ly/vcovswr
16. Phase Noise to Jitter Conversation: http://bit.ly/pn2jitter
17. A.P.S. Khanna, "Microwave Oscillators–The State of The Technology," *Microwave Journal* April 2006.
18. www.iqep.com/news-2014/Mar_31_14.asp, news release
19. www.ni.com/white-paper/4426/en