Application Note 1768: Oct 21, 2002

Tracking Advances In VCO Technology

Tracks the history of voltage-controlled oscillators (VCOs) since approximately 1910. Provides examples of VCO integration in RF ICs. Presents technology, performance and size evolution to the present date. Based on history and technology, future trends are projected.

Voltage-controlled oscillators (VCOs) are commonly found in wireless systems and other communications systems that must tune across a band of frequencies. VCOs are available from a wide range of manufacturers in a variety of package styles and performance levels. Modern surface-mount and radio-frequency-integrated-circuit (RFIC) VCOs however, owe their heritage to engineering developments that began almost a hundred years ago. Improvements in VCO technology have continued throughout that time, yielding ever smaller sources with enhanced phase noise and tuning linearity.

Oscillators have been essential components from the time Edwin Armstrong discovered the heterodyne principle[1]. In this application, an oscillator feeds sinusoidal signals to a nonlinear mixing element to effect frequency translation by multiplying the oscillator's signals with other input signals. Of course, Armstrong realized that what he needed to control the frequency translation was an electrical circuit which produced a stable sinusoidal time-varying voltage (or current) with a corresponding frequency. He discovered around that same time that an Audion (an early vacuum tube) could be configured to produce an oscillation, and he effectively devised the first electronic oscillator[2] (rather than the crude spark-gap oscillators used in early wireless transmitters).

In retrospect, Armstrong started a revolution in oscillator technology that quickly made spark transmitters obsolete, leading to the development of high-performance radio receivers. From the time of Armstrong's discoveries in the 1910's to the modern era, VCO technology has progressed from vacuum tube oscillators to transistor oscillators to oscillator module solutions and finally to today's RFIC-based oscillators. The face of VCO technology is again rapidly changing and soon in many systems will only resemble early oscillators in basic topology and/or mathematically.

Armstrong's discovery was soon improved upon by Rober V.L. Hartley, with the invention of his oscillator circuit topology (Figure 1). Hartley made use of improvements in vacuum-tube technology and devised a oscillator circuit in which the vacuum tube acted as an amplifying device with inductive feedback applied to create a regenerative oscillation. The frequency of oscillation was established by the coil inductance and the circuit capacitance. This circuit was a breakthrough in the generation of a sinusoidal signal; it provided a much greater range of possible frequencies simply by varying the value of the coil or capacitor. The Hartley oscillator circuit was popular in transmitters and was quickly adapted for use in World War I. Both transmitters and receivers made use of the new tube-based oscillators circuit. Oscillator circuit innovations proliferated, giving rise to the predominant circuit topologies still in use today, such as Hartley, Colpitts, Clapp, Armstrong, Pierce, and other topologies.

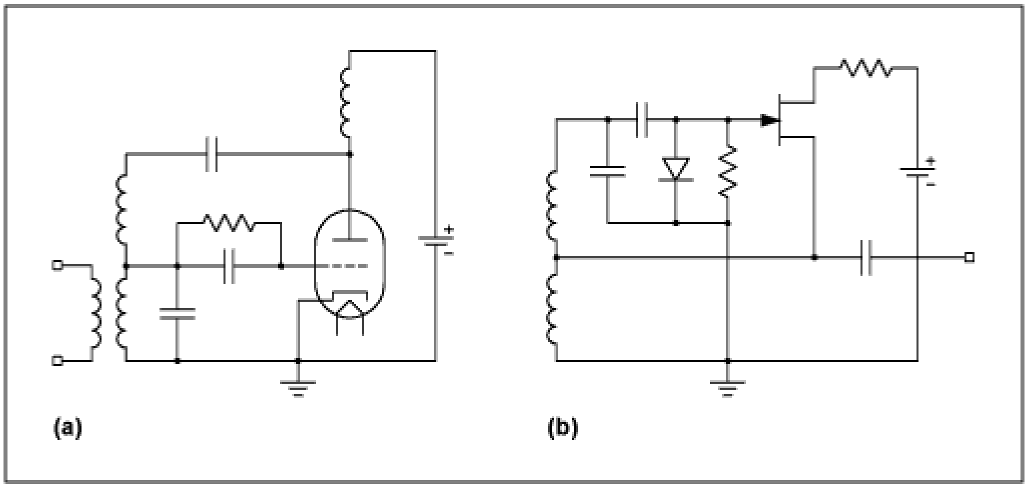

Figure 1. Examples of the Hartley oscillator; (a) triode implementation (b) JFET implementation

In Armstrong's superheterodyne receiver principle, input signals are mixed with oscillator signals to produce a constant intermediate frequency (IF). To maintain the constant IF, the oscillator must change frequency as the input signals change frequency. With a variable-frequency oscillator is was possible to tune the frequency translation circuit to a wide range of input RF signals and therefore enable multichannel communications, such as amplitude-modulated (AM) radio. Such variable-frequency oscillators were an adaptation of the basic resonant-circuit oscillators, in which one of the resonant elements (an inductor or capacitor) would vary. Most often, it was the capacitor that was varied. High-quality variable capacitors were constructed from ganged multi-plate metal air-gap capacitors. As radio technologies advanced, a tremendous amount of innovation took place in the implementation of oscillator circuits. Engineers devised countless types of coils, variable capacitors, feedback techniques, and vacuum tubes to implement oscillator and frequency-conversion circuits. Many elaborate and elegant schemes were devised to provide precise, high quality tuning of the oscillator frequency via a mechanical dial on the front on the radio. Figure 2 is a picture of a re-created vintage 1929 Hartley style transmitter (as re-creaed by Ham radio enthusiast W9QZ). Like many early implementations of electronics, the circuit was bulky and expensive and required high supply voltages.

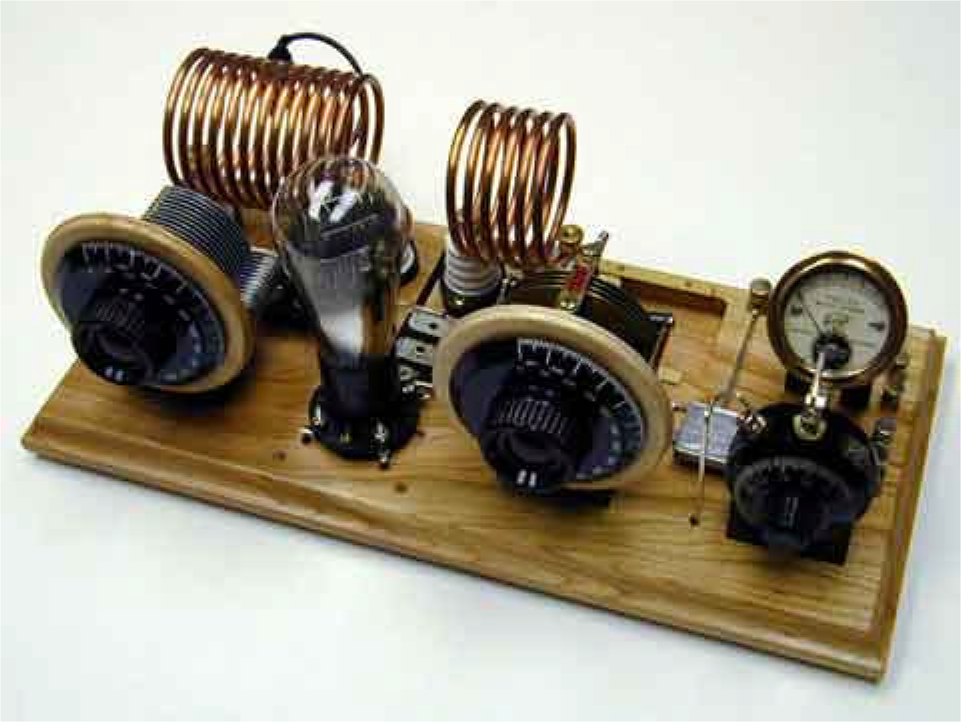

Figure 2. Vintage 1929 Hartley style transmitter

The vacuum-tube oscillator was widely employed for many years in commercial and military radio receiver applications, such as AM and frequency-modulated (FM) radios, television, and military voice communications. However, the discovery of semiconductor amplifying devices, such as the transistor and the varactor diode, led to the next dramatic change in VCO technology. The first bipolar transistor was discovered in the late 1940's at Bell Laboratories (Holmdel, NJ), and transistors became available in the 1950's as replacements for vacuum tubes. The new transistors were smaller and consumed less power than tubes, with lower operating voltage requirements and ultimately lower cost. The transistor became a replacement for the vacuum tube as the active element in oscillators and significantly changed the practical implementation established oscillator topologies.

Arguably, the introduction of the varactor diode (with a voltage-variable capacitance arising from a reverse-biased PN junction) had a greater impact on the direction of VCOs than the transistor. In the early 1960's, a great deal of research was performed on varactor technology, and varactors rapidly displaced mechanically adjustable components as the variable-capacitance element in VCOs. Varactors proved invaluable in the development of phase-locked-loop (PLL) circuits for precise electronic control of frequency sources. The rapid growth of television during that time contributed greatly to the migration to varactor- and transistor-based VCOs. Cost-effective, low-power, high-quality VCOs with inherent electronic tuning and easily reconfigurable frequency ranges were now possible. Discrete-transistor and varactor-based VCOs dominated electronic designs of the 1960's through 1980's. But, in the 1980's two new technologies impacted VCO developments: modular approaches and monolithic VCO integrated circuits (ICs). Figure 3 shows a timeline illustrating the development of VCO technologies over the past 80 years.

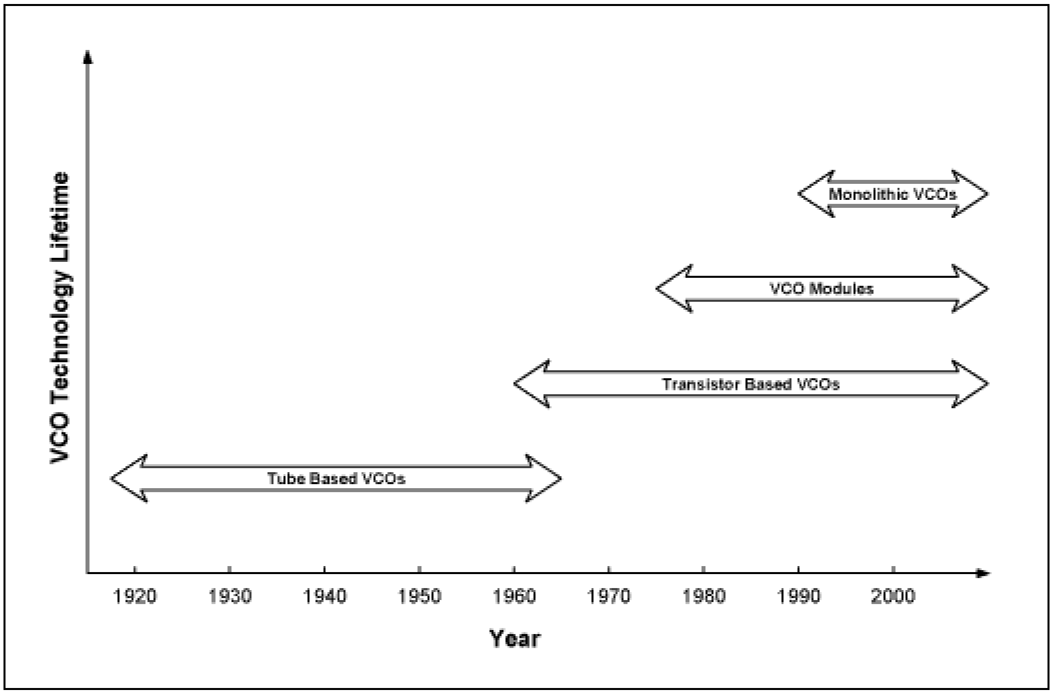

Figure 3. Chart of VCO technology lifetimes versus year

The shrinking sizes of varactors, capacitors, and inductors made possible VCOs in module form. A VCO module is essentially a miniature version of a discrete-component oscillator constructed on a substrate that is mounted into a metal housing. The module is self-contained and requires only connections to ground, the supply voltage, the tuning voltage, and the output load. Such modules first appeared in the 1960's primarily for military applications. They were fairly large (several square inches) and relatively expensive. Discrete transistor and varactor implementations of VCOs were still used in commercial products. It was not until the emergence of mobile telephony that a commercial market emerged for VCO modules.

Although discrete VCOs could be custom designed to any frequency and tuning range, they typically required labor-intensive production adjustment of the frequency-setting elements to compensate for component variations. In addition, discrete VCOs needed good shielding to minimize emissions and reduce pulling effects. But with the growing sales of mobile telephones in the late 1980's and early 1990's, demand increased for "canned" oscillator modules. Some Japanese companies, being increasingly proficient in miniaturization, developed small, cost-effective VCO modules for mobile telephones. As new wireless application arose, VCO module manufacturers developed products with frequency plans unique to each application. As surface-mount components became progressively smaller (1206, 0805, 0603, 0402, 0201), new smaller, lower cost VCO modules were developed. Figure 4 illustrates the size reduction over time of the "typical" state-of-the-art commercial VCO module. Today, these improvements have culminated in compact (4 x 5 x 2mm) modules that sell for close to $1.00 (US) in high volumes. This 15 year cycle of shrinking VCO module volume was a truly amazing reduction in size and satisfied the tough space constraints imposed by the new mobile wireless devices, such as cellular phones. Yet, an even smaller and more cost-effective VCO technology would emerge by the end of the 1990's; monolithic VCO IC technology.

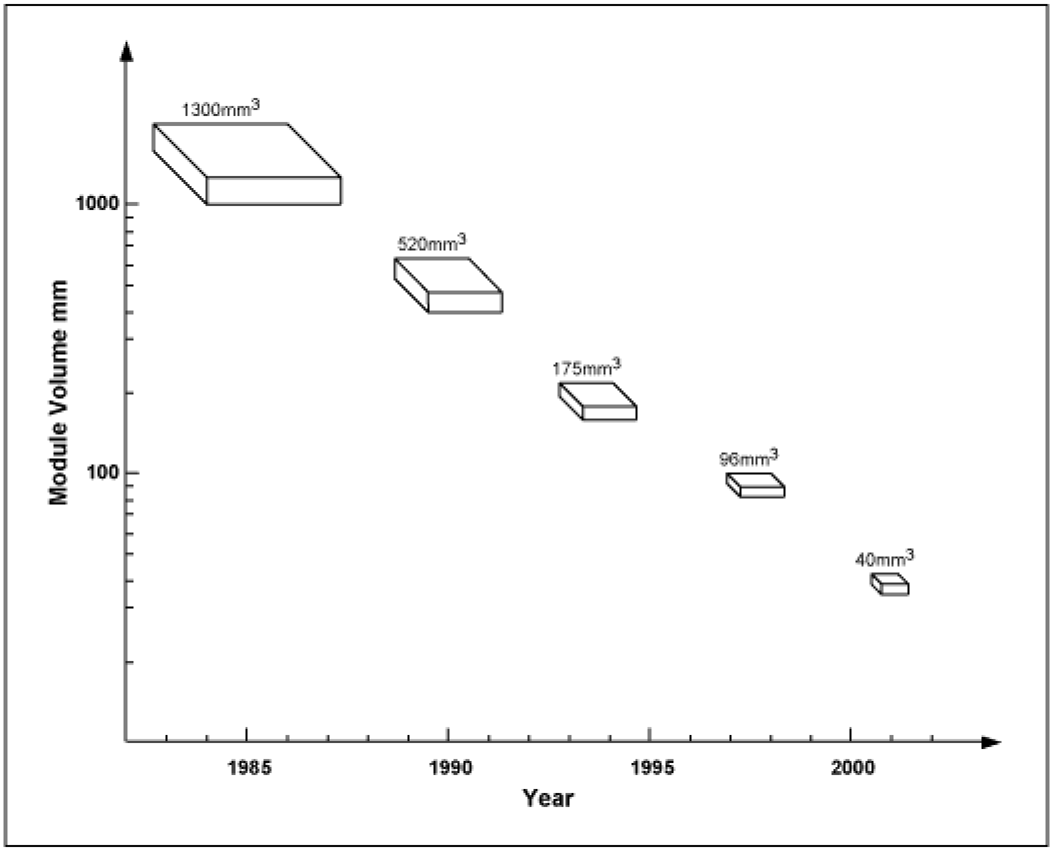

Figure 4. VCO module size scaling versus time

Monolithic IC VCO technology is defined as a VCO implementation in which all the circuit elements of an LC VCO: transistors, capacitors, resistors, inductors, and varactor diodes; are integrated on one chip. As in a VCO module, the devices are configured to form a complete VCO, requiring only connection to the power supply, ground, output, tuning input and any digital control lines. (Note that voltage-controlled ring oscillator circuits have been excluded from this definition of VCOs, given that their phase noise is much poorer and eliminates its use in most radio systems.) The first instance of a monolithic VCO IC coincided with the development of Gallium Arsenide (GaAs) IC technology and monolithic microwave integrated circuits (MMICs). The monolithic VCO emerged in the literature [1,2] in the early 1980's during a period of intense research into commercial and military applications for MMICs (funded largely by the US DARPA MIMIC program). Early MMIC VCOs were fabricated with GaAs IC processes, using 2-in.-diameter wafers, although the MMIC VCOs were not particularly area efficient and therefore were not cost effective. Generally, these VCOs operated at multi-GHz frequencies consistent with the target applications, satellite receivers and radar systems.

Most of the early monolithic GaAs VCOs were developed as part of the DARPA MIMIC research, with little impact on commercial markets. Silicon IC technology was still relegated to low frequencies during the 1980's, and lacked the bandwidth needed for gigahertz-frequency monolithic VCOs. But by the 1990's, silicon IC technology had been developed with sufficiently high transition frequencies (f_T) and suitable monolithic components (high-Q inductors and high-frequency capacitors and varactor diodes) to enable development of higher-frequency silicon monolithic VCOs. And wireless markets had emerged with sufficient size and growth potential to spur the demand for low-cost VCOs in the 800 to 2500MHz bands.

Prior to this, most commercial radio systems operated at frequencies sufficiently low as to make construction of a monolithic VCO IC impractical; on-chip inductor values were simply too large. The first apparent instance of a silicon monolithic VCO IC in the literature is from the University of California at Berkeley in 1992[3]. The VCO employed a unique, unorthodox topology in which the frequency was varied by electrically "interpolating" between two separate resonant circuits, even though it was still technically an implementation of monolithic silicon VCO IC technology. Arguably, this work and further research by Professor Robert Meyer and his graduate students at the University of California at Berkeley appears to have ushered in a period of increased research on monolithic VCOs.

By 1995, work on silicon monolithic VCO ICs was being reported in the technical literature by researchers at leading universities[4,5]. In these reports, researchers disclosed some of the first examples of modern, monolithic LC (inductance-capacitance) resonator VCO ICs. In 1996 to 1997, a tremendous number of papers appeared describing work on different implementations of monolithic VCOs[6-12]. This period effectively marked the emergence of the commercially viable monolithic VCO ICs. The monolithic VCO ICs were being developed in both high-frequency bipolar transistor IC technology and silicon CMOS IC technology. Academic researchers typically used CMOS technologies to take advantage of the widespread availability of the IC technology, while industrial researchers used RFIC-specific bipolar/BiCMOS process technology. Figure 5 shows a typical monolithic VCO circuit implemented in both CMOS and bipolar/BiCMOS process technology.

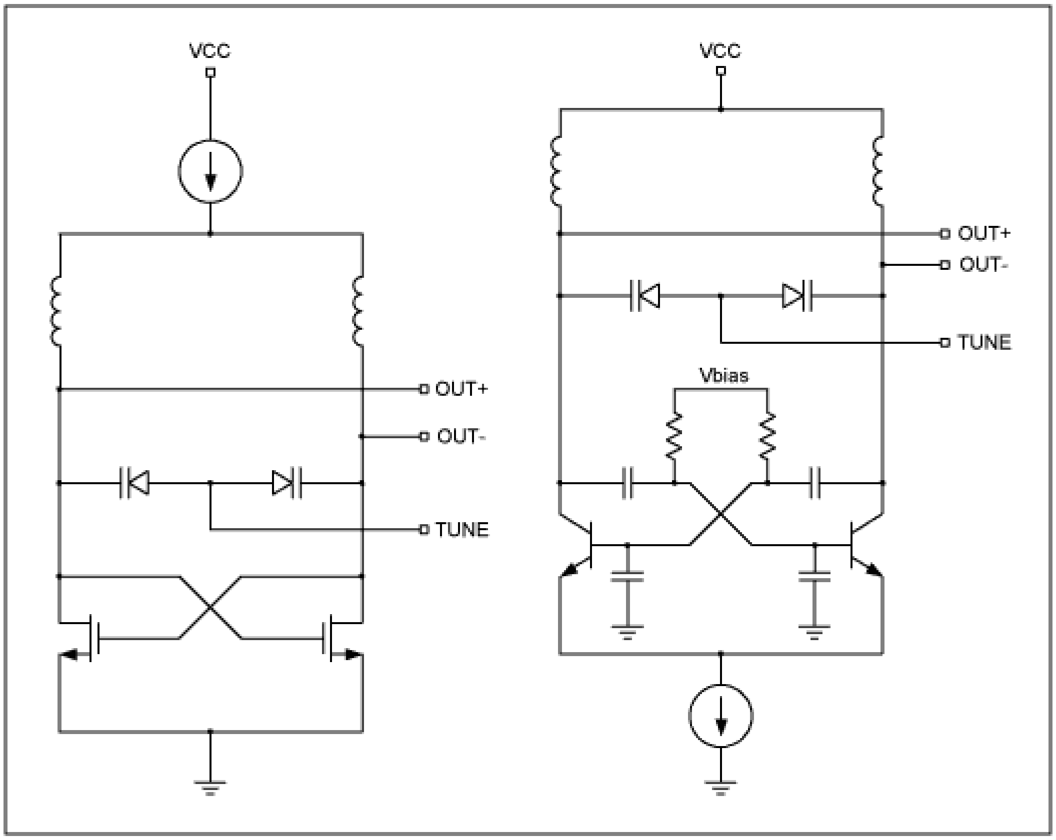

Figure 5. Typical monolithic VCO core circuit in MOS and bipolar

Generally, the overall performance of these early VCO IC implementations was inferior to discrete implementations and VCO modules. Specifically, the phase noise and tuning characteristics were poorer than what could be routinely achieved in discrete designs or VCO modules. This shortfall was principally due to the low Q inductors and crude varactor diodes commonly available in that generation of IC technologies.

However, monolithic VCOs proved to be extremely small, cost-effective, and available in the same process in which RF transceiver functions were being implemented. This meant that the VCO could be integrated with other RF and IF functions, such as the mixer, low-noise amplifier (LNA), and phase-locked loop (PLL). This capability to cost-effectively integrate the VCO with other receiver and transmitter functions helped make the monolithic VCO IC a commercial reality. A good early example of this was a commercial 900-MHz spread-spectrum cordless-telephone chipset[13].

In the late-1990's, research on VCO IC technology intensified considerably[14-20]. This was in large part due to the explosion in the wireless markets and also in the proliferation of high-frequency bipolar, CMOS, and BiCMOS process technologies. Significant research and development took place at both industrial and academic levels. Researchers focused on improving the phase-noise performance, extending the frequency of operation and adjustment of the VCO's tuning range on-chip. useful improvements in performance. These improvements achieved electrical specifications which permitted the VCOs to be use in RFICs for cordless phones, Bluetooth, WLAN , GPS and DBS applications. Table 1 shows a summary of some commercial RFICs which contain monolithic VCOs.

Table 1. Examples of monolithic VCOs integration in commercial RFICs

Unit	Frequency Range	Source	Application
MAX2622-24	855-998MHz	Maxim	general purpose 900MHz ISM
MAX2750-53	2025-2500MHz	Maxim	general purpose 2.4GHz ISM band
MAX2754	1145-1250MHz	Maxim	2.4GHz cordless phones
MAX2115	925-2175MHz	Maxim	DBS
MAX2900	902-928MHz	Maxim	900MHz ISM band (wireless meter reading)
MAX2820	2400-2500MHz	Maxim	802.11b WLAN
RF105	902-928MHz	Conexant	900MHz cordless phones
SA2400	2400-2500MHz	Philips	802.11b WLAN
BlueCore-01	2400-2500MHz	CSR	Bluetooth
TRF	2400-2500MHz	TI	Bluetooth
GRF2i/LP	1575MHz	SiRF	GPS
AR5111	5.2-5.8GHz	Atheros	802.11a WLAN

These VCO ICs and the integrated solutions that contain them are smaller and more cost-effective than VCO modules and easier and faster to apply than discrete solutions. The monolithic VCOs provide significantly improved value over previous technologies. The performance of this generation of VCO technology is sufficient for systems like cordless phones, wireless data radios and DBS receivers; and therefore is being widely adopted for use in these systems. However, the phase-noise performance is presently insufficient (the noise is about 5 to 10dB too high) to meet the requirements of higher-date-rate mobile telephone systems (such as GSM, IS-136, CDMA, etc). Low inductor Q and excess bias noise contribute to limits for the VCO phase noise. Although some researchers had demonstrated promising results with the use of bond-wire inductors, low phase-noise performance has remained elusive and out of reach of monolithic VCO IC technology. However, this is appears to be only temporary. In the last three years (1999-2001), many significant advances in VCO design have been reported and point out some clear trends for the future.

Major Trends

Several trends are impacting the development of monolithic VCOs with improved phase noise. For example, basic RFIC process technologies are improving. The quality factors possible with semiconductor processes is increasing, and the performance of active and passive devices is improving. Even with silicon processes, transistors can now be fabricated with f_T performance exceeding 50GHz, and higher-Q varactor diodes are available with wide capacitance ratio tuning ranges (low series resistance). These processes feature lower-loss substrates with thicker metalizations and higher-Q inductors. The processes are capable of devices with reduced parasitic elements, leading to VCOs with lower phase noise, higher operating frequencies, and lower-current operation.

Design techniques are also becoming more advanced. VCO researchers are exploiting the power of IC technologies by devising more sophisticated circuits to improve performance. These researchers are introducing techniques previously impractical with discrete VCO or module VCO implementations, such as differential oscillator topologies, amplitude control, second-harmonic traps, IC transformers for improved coupling, topologies with multiple oscillators, and architectures capable of higher-frequency operation.

Design engineers are also gaining a better understanding of VCO theory. They are building upon mathematical models from the past, such as Van der Pol's and Leeson's equations, and devising new analytic expressions for oscillator behavior (such as tuning characteristics and phase-noise performance). For example, designers are on the cusp of amending Leeson's noise equations with Abidi's relationships. In addition, computer-aided-engineering (CAE) tools are growing in power and sophistication as the processing capabilities of personal and workstation computers increases, allowing engineers to experiment with VCO behavioral models to discover performance enhancements.

Monolithic VCO technology continues to appear in an increasing number of new products, with high-quality VCOs integrated with the transceiver circuitry. For example, the latest transceivers for the WLAN and Bluetooth markets integrate the VCO within the RF transceiver IC, resulting in a dramatic reduction in size compared to discrete components. In higher-performance WLAN radios (2.4-GHz IEEE 802.11b and 5-GHz 802.11a versions), system requirements call for higher-performance VCOs with the very low phase noise needed to achieve the needed packet data rates and blocking performance levels.

Improvements in RFIC VCO technology make these integrated sources ever more attractive for an increasing number of commercial RF applications, including satellite receivers, CATV set-top boxes, wireless data applications, cordless telephones, and mobile telephones. Clearly, monolithic VCOs are winning an ever-increasing share of high-volume applications compared to discrete and module VCO solutions. The time is coming very soon when monolithic VCOs will be the dominant oscillator approach in all high volume commercial wireless systems. VCOs have traversed a remarkable path from bulky tube based circuits to <1mm sq of silicon.

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Notes

1 The heterodyne principle is defined as the multiplication of two signals in the time domain in order to produce a frequency shift in the frequency domain. The principle is the fundamental basis for frequency translation of signals in wireless systems.
2 Both Edwin Armstrong and Lee DeForest were working on regenerative receiver circuits at the time. These regenerative circuit created the first oscillators.

A similar version of this article appeared in the July 2002 issue of *Microwave and RF* magazine.

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