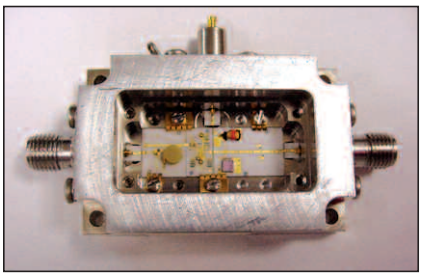
Microwave Journal

Microwave Oscillators: The State of the Technology

Demand for higher bandwidth and frequencies in wireless and wireline applications continues to climb. This is increasing the pressure on the RF industry to deliver higher performance, higher functionality, smaller size, lower power consumption, lower cost, and faster new designs of RF and microwave components. Oscillators are the key components for virtually any communications, navigation, surveillance or test and measurement system. They provide a critical clocking function for high speed digital systems, generate electromagnetic energy for radiation, enable frequency up and down conversion when used as local oscillators, and are used as a reference source for system synchronization. The market forces are motivating designers and developers to improve the performance of microwave components up to millimeter waves. This article reviews some of these developments in the field of microwave oscillators. A short recent history is presented. Present state-of-the-art is addressed and a brief look at the future is included.

Fig. 1 A 12.5 GHz GaAs FET dielectric resonator oscillator (1.6" × 1" × 0.6").



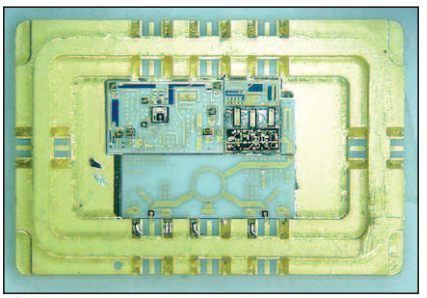


Fig. 2 A differential 43 GHz SMT source using a 10.75 GHz low noise Si-bipolar VCO (0.68" × 0.45" × 0.17").[12]

EVOLUTION

Microwave oscillators started with vacuum tubes and pretty much ruled this field for three decades starting from 1940. Reflex klystrons were a common way to generate low or moderate powers at X- or Ku-band right into the 1970s. The signal generation circuit, consisting of a klystron and its power supply itself used to be the size of some small test equipment of today, consumed greater than 20 W of DC power and used 800 V of power supply to provide 10 mW at X-band. However, it provided a clean signal due to the inherent high Q cavity used. By the late 1970s transistor dielectric resonator oscillators[1] could provide clean 10 mW of power at X-band using 5 V and 30 mA in about one cubic inch of volume (see ***Figure 1***). More recently, surface-mount hybrid oscillators (see ***Figure 2***) and complete MMIC solutions (see ***Figure 3***) are able to provide necessary performance occupying much less volume and at a fraction of the cost.

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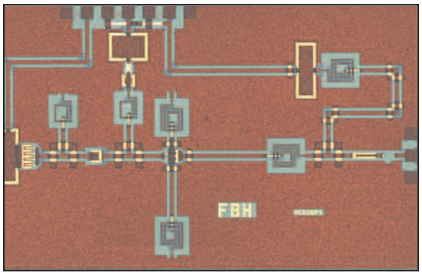
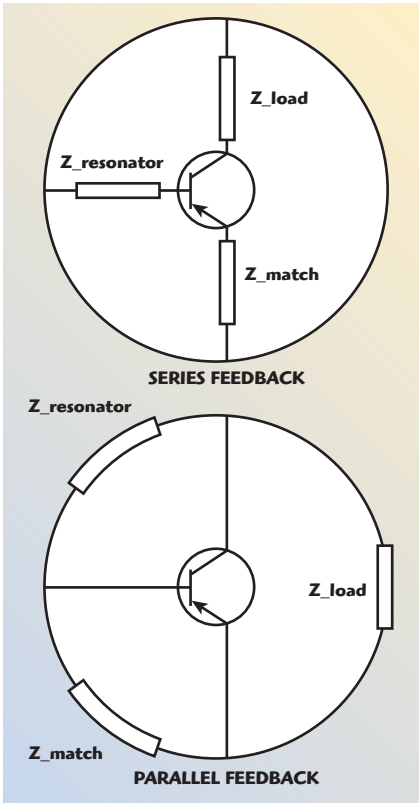
With the advent of solid-state devices, new devices started playing a role in signal generation solutions before 1970. Gunn and IMPATT diode oscillators dominated signal generation applications before the three-terminal devices took over in the mid-1970s. Gunn diodes generate microwave energy using the negative resistance characteristics of bulk semiconductor devices requiring standard, low impedance, constant voltage power supplies. Gunn diodes offer low phase noise, low power oscillators from 4 GHz to greater than 100 GHz. Gunn oscillators are still used at mm-wave frequencies and utilize GaAs or InP materials depending upon the frequencies and power required. Power output of greater than 20 dBm can be obtained at 40 GHz with efficiency in the range of 2 to 3 percent. Gunn diodes are still effectively playing at mm-wave frequencies where phase noise performance is difficult to achieve otherwise.



▲ *Fig. 3 A 36 GHz InGaP/GaAs HBT MMIC VCO (2.1 × 1.3 mm sq.).[21] (courtesy of FBH, Berlin, Germany)*



▲ *Fig. 4 Generalized oscillator configurations using three-terminal devices.*

IMPATT diodes were another early form of solid-state device generating high power microwave energy with efficiencies of 10 to 20 percent and covering frequencies up to and beyond 100 GHz. IMPATT diode oscillators, however, have about 10 dB higher phase noise and offer a narrower tuning band than Gunn diode oscillators. IMPATTs find their application in higher powers at higher frequencies. Depending on the frequency and power needed, Si or GaAs IMPATT diodes are used. Greater than 1 W of power can be obtained at 40 GHz. The use of both Gunn and IMPATT diodes in microwave signal generation applications has been on the decline since three-terminal devices made their debut in microwave frequency ranges around 1975. From then on it was like a revolution the way junction bipolar transistors and field-effect transistors took over the microwave active circuits domain enabling many new applications. It is interesting to note, however, that even though newer technologies made great headway in microwave signal generation, even today two-terminal solid-state devices are being used effectively due to the performance edge these devices have in certain areas.

Transistor oscillators have made great strides in the last quarter of a century. Silicon bipolar junction transistors have dominated the oscillator field until recently. With low 1/f noise characteristics, Si BJT discrete devices have produced excellent results both in fixed tuned and tunable oscillators at frequencies exceeding 20 GHz. GaAs FET and HEMT devices on the other hand have been demonstrated to oscillate at frequencies beyond 100 GHz as fundamental oscillators. Typically, in an oscillator, Si BJT devices offer about 10 dB better phase noise close to the carrier compared to GaAs FET devices. Versatility and diversity of the three-terminal devices have produced a large number of techniques to optimize different parameters in various applications. Multi-frequency oscillators, push-push oscillators, quenchable oscillators, optically controlled oscillators, injection-locked oscillators, self-oscillating mixers and regenerative frequency dividers are some of the examples.

Oscillators provide the heartbeat of all RF and microwave systems irrespective of their application. In most cases performance of the oscillator determines key characteristics of the subsystem. At the low end of the microwave frequency spectrum, cellular and emerging wireless communications are the driving force behind the development of microwave oscillators. On the high end of the spectrum, automotive radars, broadband radios and high speed optical communications are fueling the need for volume. Special and very high performance oscillators are never lacking in demand to perform so called 'out of the ordinary' functions.

OSCILLATOR TOPOLOGIES AND TYPES

Oscillators are also regarded as DC-to-RF converters. A typical oscillator consists of an active device and a passive frequency-determining resonant element. The active device can be a two-terminal device like a Gunn or IMPATT diode or more commonly a three-terminal device including a junction bipolar transistor, metal semiconductor FET or more recent devices using newer semiconductor materials. In order to generate a high frequency signal an active device with sufficient gain to compensate for feedback loop losses is necessary. Oscillation conditions need to be satisfied for the circuit containing the active device and passive element. Two different topologies are used for this purpose, as shown in ***Figure 4*** in their generalized form. A parallel feedback oscillator is the one in which the frequency-determining element is used as a feedback element between the input and output in order to generate necessary instability and a negative resistance oscillator is the one in which reflection gain at a given terminal is used to satisfy the oscillation condition when connected to a frequency-determining element with the proper phase condition.[2]

While both techniques are commonly used for microwave signal generation, the parallel feedback approach is more suitable for narrowband, lower noise tunable oscillators and the nega-

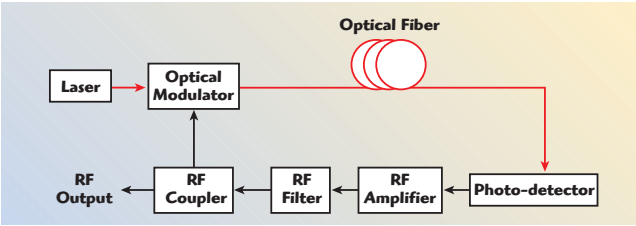


Fig. 5 Block diagram of an opto-electronic oscillator.

tive resistance configuration is used for wideband tunable oscillators.

Microwave oscillators can be divided into many different types based on frequency bandwidth, type of resonator used or type of active device used. Resonators largely determine frequency tuning range, stability and noise performance of the oscillator, and are commonly used to define different types of oscillators.

FIXED TUNED OSCILLATORS

Fixed tuned oscillators are generally required for many applications including as reference sources, fixed local oscillators and radars. These oscillators are generally characterized by low frequency drift and low phase noise. A high Q resonator is the key element for this type of oscillator. A wide range of resonators with varying Q factors are presently available. From low Q planar transmission line resonators to the highest Q sapphire loaded resonators, there are a number of different types of resonators.

Metallic cavity resonators have long been used as high Q elements for filters and low noise oscillators. High temperature stabilities were achieved using Invar. The impractical size of these cavities, however, restricted their application in signal generation. Excellent phase noise performance of –180 dBc/Hz at 10 kHz has been reported at 10 GHz using an air dielectric resonator cavity for stabilization using a noise detection and suppression technique.[3]

Dielectric resonators are made of low loss, temperature stable, high permittivity and high Q ceramic material in a regular geometric form. Common examples of the materials are $BaTi_4O_9$ and $ZrSnTiO_4$.[6] The material resonates in various modes determined by its dimensions and shielding conditions. $TE_{01\delta}$ mode is used for the optimum temperature stability and Q. The practical frequency range for these resonators lies between 2 and 40 GHz while the Q factor typically reduces linearly with increasing frequency. A Q of 10,000 at 4 GHz is representative of commonly used materials. Because of its small size, low price and excellent integrability in MICs, DRs are very commonly used in active and passive microwave components up to mm-wave frequencies. Development of temperature stable dielectric resonators dates back to the late 1970s, soon after the introduction of three-terminal devices in the main stream of microwaves. The marriage between these two elements has produced a wide variety of much needed microwave sources with excellent performance in terms of phase noise and temperature stability with desired compactness and cost. Dielectric resonator oscillators (DRO) are most commonly used for fixed tuned or narrowband tunable configurations to phase lock or frequency modulate for numerous applications. A well-known high volume application for these oscillators in recent history has been in the Ku-band DBS applications. Recently, when there was a large telecom demand ahead of availability of fully integrated ICs, these sources were employed in volume for the 10 Gb/s high speed optical communications market. With the increased bandwidth requirements of microwave communication systems today, complex modulation schemes using 64QAM or higher are commonly used. This order of complexity requires very low close-in phase noise in order to keep the bit error rate (BER) in the digital communication systems under check. Electronically tunable phase-locked DROs are today the backbone of the majority of microwave communication systems requiring very high performance in a small size and reasonable cost. DROs are now commercially available with better than ±1 ppm/°C and/or with a phase noise of better than –120 dBc/Hz at 100 kHz at X-band.[2]

The sapphire-loaded cavity resonator oscillator (SLCO) is another type of low noise oscillator that utilizes sapphire, a low loss dielectric material. Using whispering gallery modes with a Q factor > 200K, and noise detection and suppression circuits, phase noise as low as –160 dBc/Hz at 10 kHz offset at 10 GHz has been reported.[4,5]

Ceramic coaxial resonator oscillators are fixed or narrowband tunable oscillators based on high Q ceramic resonators. The resonator is a silver-plated length of temperature-stable ceramic shorted on one end. Using these resonators in a negative resistance oscillator configuration, phase noise of better than –120 dBc/Hz at 10 kHz is now commercially available up to 4 GHz. Coaxial resonator oscillators (CRO), however, offer a practical low cost solution for frequencies between 1 and 5 GHz.

Surface acoustic wave (SAW) oscillators utilizing high Q lithium niobate devices enable the circuit to achieve low phase jitter performance over a wide operating temperature range. SAW oscillators have long filled the need for very low noise oscillators at RF frequencies up to 2 GHz. These oscillators have been extensively used as clocks in wired applications including optical communications, Gigabit Ethernet communications, storage circuits, etc. Sonet applications at 622 Mb/s, 2.488 Gb/s use these oscillators extensively. Very low phase noise has been demonstrated using SAW devices and optimized active devices. A frequency multiplied SAWO at 8 GHz was reported using a high quality SAW resonator at 500 MHz in the parallel feedback of a low noise amplifier, with a phase noise of –140 dBc at 10 kHz.[6] The practical frequency range for a SAWO is typically between several hundred megahertz to about 2.5 GHz.

Bulk acoustic wave resonator (BAW) oscillators are a recent introduction in the field of fixed frequency oscillators. The resonator, more commonly known as FBAR, is a three-layer structure with the top and bottom electrodes of molybdenum sandwiching a middle layer of oriented piezoelectric aluminum nitride. These resonators are practical for use in the frequency range of 500 MHz to 5 GHz. An air interface is used on both outer surfaces to provide high Q reflectors at all frequencies. When RF signals are applied near the mechanical resonant frequency the piezoelectric transducer excites the fundamental bulk compression wave traveling perpendicular to the films.

These tiny chips with a size of 40 × 40 mils possess a quality factor of greater than 500 at 2 GHz.

FBAR oscillators have demonstrated phase noise of better than –112 dBc/Hz at 10 kHz at 2 GHz.[7] Even though FBAR filters are already being used in large volume in cellular phones, improvements in the Q and temperature stability (5 to 10 ppm/°C presently) will be required before FBAR oscillators can be exploited commercially.

Optoelectronic oscillators (OEO) are a recent addition to achieve high frequency sources. These oscillators employ an elegant opto-electronic feedback loop approach to the generation of microwave frequencies. The OEO is a generic architecture consisting of a laser as the source of light energy. The laser radiation propagates through a modulator and an optical energy storage element, before it is converted to electrical energy with a photo-detector (see ***Figure 5***). The electrical signal at the output of the modulator is amplified using an RF amplifier and filtered before it is fed back to the modulator, thereby completing a feedback loop with gain, which generates sustained oscillation at a frequency determined by the filter. The OEO enjoys extremely high Q-factors of its optic resonator system suitable for the low phase noise RF signal generation. A 10 GHz oscillator with the phase noise of –160 dBc/Hz at 10 kHz offset has been reported.[3] The main advantage of the OEO is its phase noise frequency independence that enables the generation of a low phase noise signal from microwaves to upper millimeter-wave frequencies. A disadvantage in its simple form is its natural multimode operation resulting in gaps in the frequency coverage as well as relatively high spurs. A YIG filter has been used to extend the tunability of the OEO, while the spurious problem has been addressed in a multiloop design capable of undesired mode suppression.[8,9]

FREQUENCY TUNABLE OSCILLATORS

Wideband tunable oscillators are necessary components for ECM, ESM and test instrumentation, as well as many communication systems. These are characterized by the tuning bandwidth and linearity, phase noise, settling time and post tuning drift. The needs for the specific characteristics depend upon the application. Compromises are called for in view of the fact that all of these parameters cannot be achieved using a single technology or technique. In order to achieve oscillations over a wideband the active device needs to possess negative resistance over the band and the frequency tuning element needs to tune over the band. Design techniques are then used to satisfy oscillation conditions over the band while optimizing one or more desired parameters. Phase noise being a function of the carrier frequency and tuning bandwidth, care should be taken while comparing frequency tunable oscillators.

Varactor-tuned oscillators are voltage-tuned oscillators utilizing Si or GaAs varactors, typically a metal n-type schottky barrier, in association with the active device to generate signals over a wideband. With the available technology a little more than octave band oscillators have been reported up to Ku-band using multiple varactors.[10] At lower frequencies it is more practical to achieve an octave band. VCOs based on discrete devices have demonstrated more than octave bands with excellent phase noise up to 4 GHz. Silicon bipolar devices are the devices of choice due to their lower 1/f noise and corner frequency and are commonly used for VCOs up to X-band. Using a low noise silicon bipolar transistor with a 10 GHz f_t and 40 GHz f_{max} process and a silicon hyperabrupt varactor diode, a narrowband VCO was reported at 10 GHz with phase noise of –112 dBc/Hz at 100 kHz offset.[12] GaAs FET devices offer wideband oscillations up to mm-wave frequencies with degraded phase noise. Another technique to achieve low noise wideband signal generation at higher frequencies is the use of push-push oscillators. VCOs covering 9 to 18 GHz have been demonstrated using silicon bipolar devices.[10] VCOs exceeding octave bandwidth have been recently developed using coupled push-push technology. Phase noise of –118 dBc/Hz at 100 kHz offset was reported at 4 GHz in a 3 to 6 GHz VCO.[11]

Frequency settling time is another important characteristic required in certain military systems as well as in test instruments. This represents the speed and accuracy with which the oscillator frequency can be changed. Silicon devices once again shine in realizing fast settling VCOs. Using silicon bipolar transistors with silicon varactor diodes, settling times of better than 1 µs (for the frequency to be within 1 MHz) have been demonstrated at Ku-band.[13] In applications requiring fast on and off VCO switching, a technique of quenching the negative resistance instead of switching the bias on and off has demonstrated switching times of better than 1 µs.[14]

YIG-tuned oscillators (YTO) are used in test and measurements as well as in wideband military systems requiring multi-octave bands of tuning. YTOs are oscillators of choice when wideband tuning, high tuning linearity and good phase noise are simultaneously required. These oscillators utilize a yittrium iron garnet (YIG) ($Y_3Fe_5O_{11}$) spherical resonator placed between two poles of a cylindrically re-entrant electromagnet. The resonant frequency of the YIG resonator in a uniform magnetic field is a linear function of the magnetic field strength. YIG resonators offer a very high Q (> 4000 at 10 GHz), which linearly increases with frequency. The practical usable frequency range of YTO is between 2 and 50 GHz. While the higher frequency is limited by the magnet saturation and high power dissipation, the lower limit is governed by the saturation magnetization $4\pi Ms$.

In view of the wideband nature of these oscillators, active devices in the negative resistance configuration have been generally used. Using a low noise silicon bipolar transistor and a novel composite feedback architecture in which double coupling the YIG sphere as a series feedback for higher frequencies and as a parallel feedback for lower frequencies, a tuning range of 2 to 22 GHz has been achieved with a phase noise of better than –130 dBc/Hz at 100 kHz at 10 GHz.[15] At higher frequencies, using a single GaAs FET and a single YIG sphere frequency range coverage of 20 to 40 GHz was reported with a phase noise of better than –100 dBc/Hz at 100 kHz at 40 GHz.[16] YTOs have been commercially available up to 50 GHz. In practice it is becoming more common to achieve mm-wave frequencies by using MMIC frequency doublers with low-

er frequency YTOs or VCOs. YIG-tuned oscillators are still an attractive choice when their slower tuning speed, large size and high power consumption can be tolerated.

Permanent magnet YTOs are a narrowband tunable version of the YTO. These oscillators use a permanent magnet in place of an electromagnet significantly reducing the DC power consumption and size of the oscillator. Phase noise of –125 dBc/Hz at 100 kHz has been demonstrated using PMYTOs in X- and Ku-bands covering 20 percent bandwidth. These oscillators offer excellent tuning linearity, good frequency stability and phase lock/modulation capability as well.

MMIC-IZATION AND RECENT TECHNOLOGIES FOR MICROWAVE SIGNAL GENERATION

MMIC oscillators are now becoming more and more common. It is worth noting that microwave oscillators, due to their intrinsic mysterious nature, resisted getting converted from discrete to integrated form for much longer than their amplifier counterparts. While MMIC amplifiers started maturing in the early 1980s, the microwave industry had to wait much longer before having reliable commercially available MMIC oscillators. One of the reasons that oscillators continue using discrete devices in many applications is that the volume required for each potential model does not justify the investment for developing MMICs for each. However, once a volume application is identified, MMIC oscillators are developed systematically. In amplifiers it is easier to design wideband generic amplifiers and use them in multiple applications. Additionally, in any given system one can notice a much larger number of amplifiers compared to the number of oscillators. Volume applications of the microwave oscillators today have been converted or are in the process of being converted to stand alone integrated circuits or as a part of the complete system on a chip (SoC). As an example, the oscillator function in cellular phones today is fully integrated in the mixed signal IC.

Heterojuction bipolar transistors (HBT) inherently exhibit much lower 1/f noise levels than field-effect transistors due to their vertical current flow through the semiconductor interfaces, where the impact of surface states on the output signal is reduced. SiGe HBTs exhibits very good 1/f noise levels, but suffer from the limitation of high frequency performance as the emitter area is increased. A larger emitter area is normally required to reduce the current density, which leads to lower 1/f noise.

SiGe HBTs exhibit higher electron mobility, lower device thermal noise and lower device shot noise compared to traditional silicon bipolar transistors. These devices are very attractive for oscillators due to their wide potential bandwidths and low contributions to phase noise. Using SiGe HBTs, low noise DROs and YTOs have been reported. Recently, using a SiGe HBT device, a YTO covering 8 to 20 GHz was reported offering –130 dBc/Hz at 100 kHz offset up to 18 GHz.[17] A fixed frequency SiGe DRO at X-band is capable of providing phase noise of better than –125 dBc/Hz at 100 kHz.

With increased demand for higher frequency sources coupled with progress in MMIC technology and improved modeling and simulation techniques, significant progress on MMIC oscillators can be noticed. Silicon germanium technology devices are inherently highly linear, low phase noise and temperature stable. The key advantage of silicon germanium over many technologies is its compatibility and integrability with mainstream low cost CMOS processing. In addition, silicon germanium provides ultra high frequency capability up to and beyond 100 GHz. A fully integrated SiGe push-push VCO covering 64 to 72 GHz has shown phase noise of –103 dBc/Hz at 1 MHz at 70 GHz.[18] Using a SiGe HBT oscillator and integrated buffer amplifiers, an output power of greater than 16 dBm and a frequency range of 74 to 81 GHz was reported with phase noise of –99 dBc/Hz at 1 MHz offset at 77 GHz, intended for automotive applications.[19] Phase noise of –90 dBc/Hz was also demonstrated at 98 GHz for a VCO covering 94 to 100 GHz.

MMICs based on a GaAs InGaP HBT process have taken a performance lead in providing excellent phase noise X- and Ku-band MMIC oscillators. Using these devices, VCOs with greater than 10 percent bandwidth in X-band have been reported.[20] A Colpitts, push-push oscillator topology is selected for the VCO with a distributed tank circuit and on-chip collector-base junction varactors. The VCO draws approximately 160 mA from a 3 V supply at room temperature. The free running VCO achieves –110 dBc/Hz at a 100 kHz-offset frequency at X-band. The VCO's phase noise performance is excellent due to the use of high Q, low impedance distributed transmission lines and high power excitation. A fundamental 36 GHz VCO with 7 percent tuning bandwidth was recently reported using the InGaP/GaAs HBTs process. This VCO offers a phase noise of –85 dBc/Hz at 100 kHz.[21]

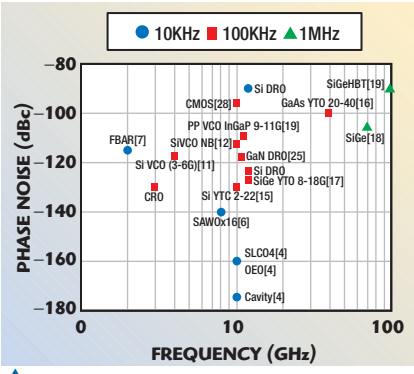
CMOS

Advances in CMOS processes are pushing low cost silicon into the signal generation turf at frequencies right into millimeter-wave applications. RF capabilities of the CMOS process were demonstrated at 1 GHz in 1995. Due to the very nature of the carrier transport in CMOS transistors taking place at the interface between the SiO_2 and Si, the 1/f corner frequency in CMOS transistors is much higher than the corner frequency for bipolar transistor typical verticle devices, with bulk carrier transport. Within a decade CMOS has proven to have useful properties up to 100 GHz. Innovative circuit and system architecture techniques have compensated intrinsic CMOS transistors' physical deficiencies by exploiting and advancing the understanding of fundamental mechanisms behind excess thermal noise and 1/f noise processes in semiconductor devices and how it affects circuit and system performance. CMOS provides a unique appeal for integration of multiple and mixed signal technologies, making it an ideal choice for radio and high speed wired applications of the future.[22] Power handling is another limitation of CMOS, and therefore long-range wireless links requiring transmitted power above 100 mW are definitely a challenge. Fortunately, trends towards higher capacity and smaller cells conspire to favor CMOS. Similarly, trends towards high data rates, large bandwidth, and package switched voice, data and video, favors CMOS by making its higher corner frequency (relative to bipolar devices) for 1/f noise become less of a problem. CMOS scaling enabled the technology to reach for higher gigahertz frequencies and higher speeds. Using a CMOS process with f_{max} of 110

TABLE I

RELATION BETWEEN Vp-p AND dBm INTO 50 Ω

*dBm = 4 +20*log(Vp-p)*		*Vp-p = 0.637*10^(dBm/20)*	
Vp-p	*dBm*	*dBm*	*Vp-p*
0.1	–16	–10	0.2
0.5	–2	0	0.64
1	4	6	1.27
5	18	15	3.58
10	24	20	6.37



▲ *Fig. 6 Phase noise comparison of different technologies.*

GHz, 100 GHz oscillations were reported in 2004 with 0.4 Vp-p output using 1 V, 30 mA.[23] More recently a 192 GHz cross-coupled push-push VCO was reported using 0.13 µm CMOS with phase noise of –100 dBc/Hz at 10 MHz.[24] CMOS is very well poised to be the enabling technology for the merging of computing and communication functionality right up to foreseeable high frequencies and speeds.

Fully integrated CMOS oscillators are of great interest for use in single-chip wireless transceivers. In most oscillator circuits reported to date that operate in the 0.9 to 2 GHz frequency range, an integrated spiral inductor is used and the final oscillator displays much superior phase noise than a ring oscillator. For lack of a good varactor compatible with CMOS technology, the integrated LC oscillator uses MOS caps instead, as another innovative circuit technique. New tuning methods using digital capabilities and MOS analog switches have been successfully demonstrated.

GaN technologies were initially developed for solid-state source amplifiers. It is only recently that capability of AlGaN/GaN HEMT transistors has been demonstrated to be suitable for frequency generation in the microwave frequencies. The low frequency noise performance and the residual phase noise of AlGaN/GaN HEMT grown on SiC is expected to have interesting applications for designing low phase noise oscillators. These devices, designed for power applications, have the potential of directly generating power levels greater than 20 dBm at frequencies higher than 10 GHz removing the need for buffer amplifiers and improving the noise far from the carrier. A 10 GHz DRO using a GaN discrete device was reported offering –118 dBc/Hz at 100 kHz.[25] InP technology is another prime candidate for low noise oscillators at microwave and millimeter-wave oscillators.

IMPACT OF INCREASING SPEEDS IN THE DIGITAL WORLD

Speeds with which digital signals are processed have been increasing at a very fast pace requiring the clocks to move up in frequency to the microwave region. Optical communication systems are now operating at 2.5 Gb/s, 10 Gb/s and 40 Gb/s requiring clocks at 10, 20 and 40 GHz. 10 Gb Ethernet is already in the main stream and standardization work is likely to start on 100 Gb Ethernet this year. A number of digital communication systems and storage systems are operating at speeds higher than 1 Gb/s. CPUs are operating at microwave frequencies. Microwave broadband radios are already providing bandwidths exceeding 1 Gb/s. Microwave component developers need to get familiar with new requirements and terminologies in the digital world. Digital engineers are also becoming more tuned to RF/microwave techniques.

Oscillators perform a key "clock" function in the digital communication world in both wired as well as wireless applications. In the digital world the quality of the signal source is traditionally measured in the form of jitter instead of phase noise. In reality these clocks are microwave oscillators requiring certain features or characteristics. As an example, clocks typically require differential outputs requiring active or passive baluns in the output. We need to think in terms of p-p or rms voltage rather than dBm (see ***Table 1***). Oscillators like ring oscillators, I/Q oscillators, differential cross-coupled oscillators and multivibrators are now being used at microwave frequencies in a number of applications.

A low jitter clock source is a key requirement of modern low BER digital communication systems.[12] However, jitter and phase noise are related. Clock jitter is defined as the variation in timing of a critical instant in a periodic waveform with respect to a jitter-free reference. In interpreting the clock sources generally it is the phase jitter, which characterizes the clock.

At lower speeds oscilloscopes or communication analyzers can easily measure the jitter from the wave shape. However, at 10 Gb/s and above it is much harder to measure the clock jitter using classical methods for lack of real time oscilloscopes at frequencies high enough to capture the third and fifth harmonic of the fundamental signal. A phase noise measurement capable of measuring extremely low level instabilities is a practical tool to interpret the source phase jitter at high frequencies.

Jitter is calculated from the measurement of integrated phase noise over a fixed offset bandwidth (50 kHz to 80 MHz for OC-192, for example) and is represented in many units, including radians, degrees, time (seconds) and UI (unit interval).[2,26] Different forms of jitter including period jitter, cycle-to-cycle jitter and time interval error are in some ways related to the phase noise or frequency stability of the microwave oscillator. Oscillators required to clock analog-to-digital converters (ADC)/digitizers working at multi-gigahertz frequencies need a low noise floor in order to improve the signal-to-noise ratio (SNR) performance of the data converter. Noise generated by a clock source can add jitter to an ADC, which causes degradation of the SNR of the ADC.

CONCLUSION

Microwave oscillator technology continues to make strides in the availability of new active devices and resonator technologies. Circuit simulation and design techniques are advancing. Oscillator noise simulation techniques have matured over the last decade. One of the areas requiring more effort, however, is accurate noise modeling of

the active devices. Oscillator noise simulation is only as good as the device model. It has now been shown that low frequency current noise sources are cyclostationary and are modulated not only by the DC current, but also by the time varying, large-signal RF current.[27] Significant progress has been made in the last decade on this subject but more challenges remain for the designers of the future. ***Figure 6*** is an attempt to show some examples of phase noise performance of microwave oscillators using different technologies and techniques.

On the measurement and specifications front, a number of issues need to be addressed. As an example, there is no standard technique for the measurement of oscillator output impedance or return loss. The quality factor of the oscillator continues to be an ambiguous term. Due to the lack of standard techniques it is sometimes difficult to correlate even measurements of modulation sensitivity and bandwidth. Similar comments can be heard about frequency settling measurements as well as jitter measurements. Oscillator packaging is another area where standardization can be valuable to both vendors and users. Even though partial standardization is happening due to market forces, a concerted effort will be beneficial. In general, standardization for specifications and measurement techniques related to microwave oscillators and high speed clocks requires attention.

The future of microwave solid-state signal generation is brilliant and full of new applications. The integration wave will continue absorbing discrete oscillators in most of the volume applications. In addition to InGaP and SiGe HBT we should see good results from newer technologies including InP and GaN devices for high frequency, low noise MMIC or discrete oscillators. The fundamental frequency of operation of transistor oscillators will continue moving up with the technology. GaAs metamorphic HEMT will be a candidate to provide power and efficiency at W-band and above. High volume and consumer applications will continue to see more and more signal generation functions absorbed in a small corner of the system-on-a-chip (SoC). Gunn and IMPATT diodes will continue to be used at higher mm-wave frequencies. In addition to potential improvements in FBAR oscillators, MEMS technology will make in-roads in signal generation by providing micro-machined resonators, inductors and switches for new applications. Finally, let us not underestimate the power of RF CMOS technology, which will not only solidify its position at low freqencies[28] but also produce exciting results at frequencies beyond 100 GHz. Special applications to support unusual requirements for defense, instrumentation and the higher end of communication systems will continue to use oscillators based on discrete devices where one or more parameters including power consumption, settling time, phase noise and bandwidth can be more easily optimized. ■

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