TCXO Product Overview

Application Note

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OVERVIEW OF THE TCXO

A TCXO [Temperature Compensated Crystal Oscillator] device is used when temperature stability requirements are beyond the reach of standard crystal clock oscillators [XO] or voltage controlled crystal oscillators [VCXO]. A TCXO provides a means of counteracting the frequency change caused by temperature change in a crystal oscillator which ultimately changes the output frequency.

TCXOs supply the design engineer with a device that bridges the stability gap between standard XO or VCXO and an OCXO [Oven Controlled Crystal Oscillator], sometimes equaling the performance of a low grade OCXO design. Today's TCXO designs offer lower power consumption and small package sizes than OCXOs. This technical summary will help the user understand the basic functions and attributes of a TCXO, and discuss common applications and marketplaces where they are found.

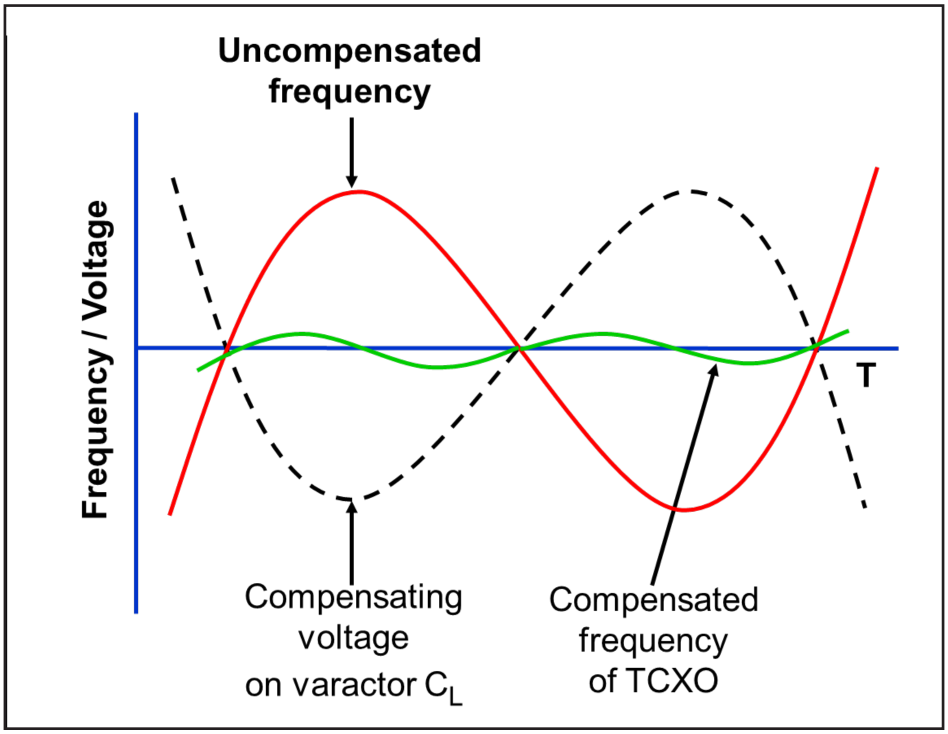

Figure 1: Frequency vs. Temperature Compensation *Source: John R. Vig Tutorial, J.Vig@IEEE.org. Approved for Public Release. Distribution unlimited.*

APPLICATIONS & MARKETS REQUIREMENTS

TCXOs are widely used in telecommunications applications, GPS positioning, navigation and timing systems for tighter temperature stability which cannot be reached by a standard XO or VCXO. They are a bridge between a VCXO and OCXO, which can be more expensive and consumes more power than a typical oscillator.

The push in technology is towards lower power consumption and of course lower cost, so TCXOs offer a good mid-range solution to power and cost sensitive applications. Applications that are exposed to dynamic changes of environments while require to maintain continuous lock to a network reference or perhaps transmit wirelessly or in high speed digital router, must maintain frequency monotonic behavior that may demand compensation of a TCXO.

The demand for TCXOs greatly increased with the development of the personal portable devices because of stability, size requirements and battery operation. TCXO was the ideal solution. A cellular telephone is a good example of a device that is exposed to temperature variations over its lifetime while keeping locked to a given network and never affect its data exchange performance. The radio in a given smartphone device is subjected to changes of weather, shock & vibrations, external interference as it maintains operation.

With the user desire for more data, next generation Wi-Fi and 5G mobile networks will need to handle much greater data volumes than at present with even higher speeds. To meet such demand and the need to penetrate buildings with error free signal levels, small cells will be used to enable greater distribution of communication data reducing potential loads on individual stations.

Small cell is a miniature base station that has all the performance features of a cell tower with simplicity and low power but can also rival the stability and accuracy cell tower systems. Small cells encompass picocells, microcells, femtocells and can comprise of indoor/outdoor systems. Oscillator used for this purpose will need even higher temperature resistance, lower phase noise and lower power consumption. In this context, demand for TCXO with such outstanding characteristics is expected to increase.

TEMPERATURE STABILITY AND COMPENSATION

Temperature stability is a measure of how much the oscillator's frequency varies over a specified temperature range. A temperature compensated oscillator uses a compensation network to adjust for temperature variations. It should be noted that the frequency versus temperature characteristic of a TCXO is not linear.

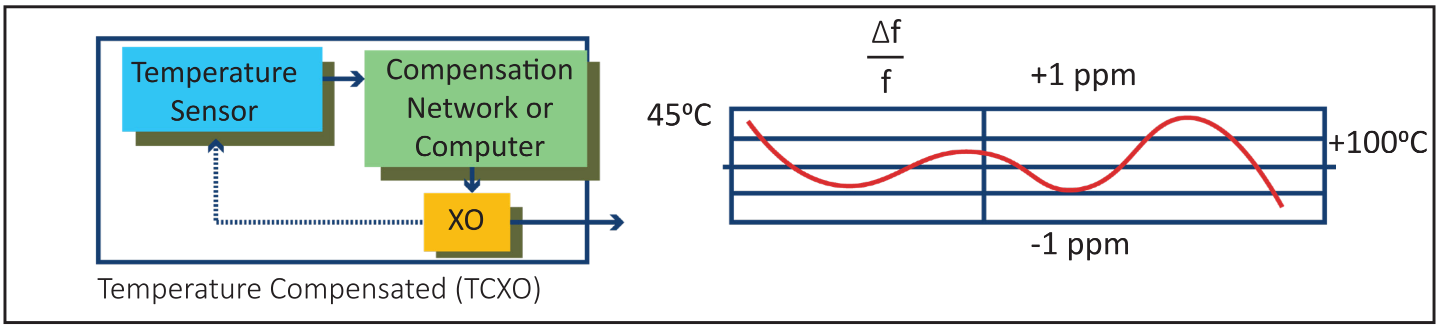

Figure 2: Frequency vs. Temperature *Source: John R. Vig Tutorial, J.Vig@IEEE.org. Approved for Public Release. Distribution unlimited.*

Temperature stability is commonly described as "± ppm" [parts per million]. For example, a common stability is ±0.28 ppm over operating temperature range -40°C to +85°C, and will be referenced to the frequency value at +25°C. The frequency reading at +25°C is referenced to the nominal frequency desired by the end user, and the devices frequency will deviate above or below that nominal frequency no more than 0.28ppm over the temperature range -40°C to +85°C. Frequency-temperature hysteresis limits the ultimate attainable stability of a TCXO. The crystal resonator is a primary source of this hysteresis, which can be minimized but not eliminated.

ANALOGUE VS. DIGITAL COMPENSATION

A variety of techniques are used to provide the temperature compensation. The temperature compensation configuration of a TCXO can be either a direct or indirect analog-based compensation method.

Analogue TCXO

This compensation method has been widely used in cell phone applications. Analogue technology provides temperature correction to the oscillator and it has the advantage that changes take place slowly and no phase jumps are experienced as occurs with some all-digital types. The expanding capabilities of large-scale integration made it possible to include more of the functions required for temperature compensation into a single IC.

This has led to development of the new generation of ASICs that allow construction of precision analog TCXOs with just two components - the ASIC and the quartz crystal resonator.

The compensation IC generates an analog compensating error voltage that ultimately translates to a fitted 5th order polynomial smooth curve applied to the oscillator's frequency steering section for the crystal to be compensated. Stabilities of better than ±0.1ppm can be achieved over temp ranges as wide as -40°C to +105°C.

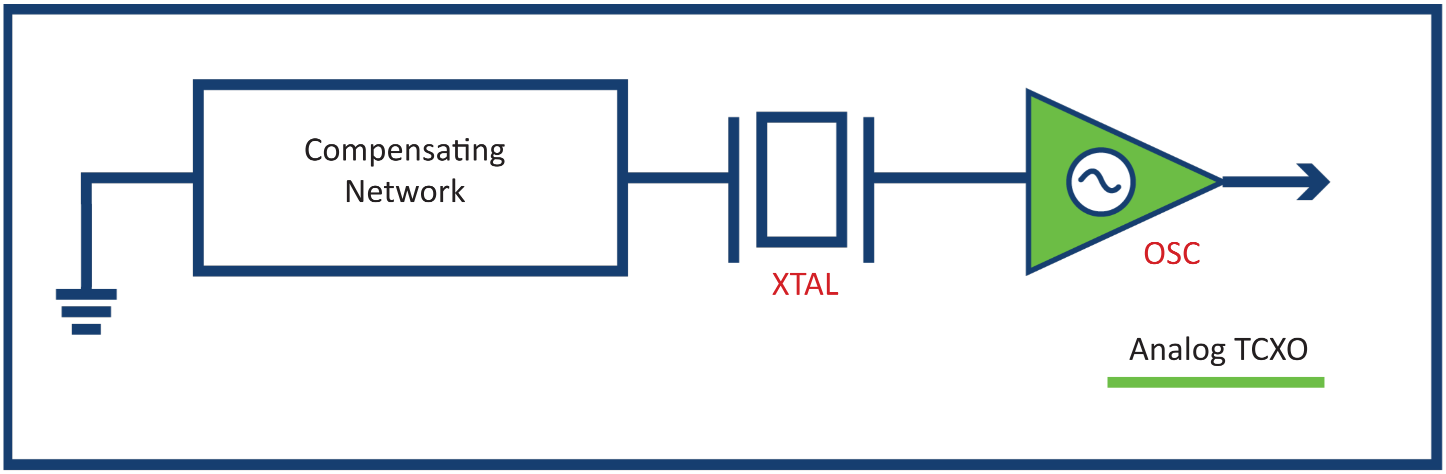

Figure 3: Analog TCXO *https://www.rfwireless-world.com/Terminology/Basics-and-Types-of-TCXO.html*

Digital TCXO

This method uses a temperature sensor, a microcontroller applying mathematical calculation functions, and digital circuitry containing a look up table. The result translates to a digital correction figure that is converted to an analogue signal using a digital to analogue converter [DAC]. High performance microcontroller compensation scheme applies polynomial approximation and digital calculation that translates to analog voltage error values.

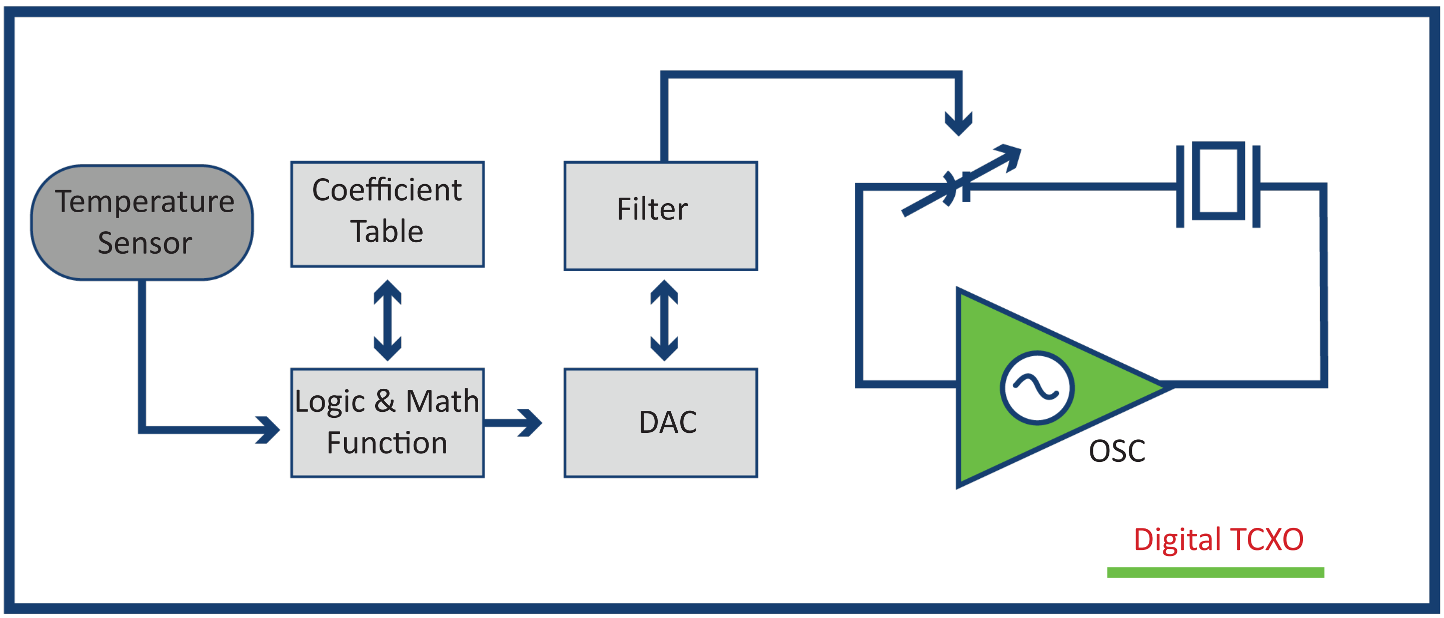

Figure 4: Digital TCXO *https://www.rfwireless-world.com/Terminology/Basics-and-Types-of-TCXO.html*

DC-TCXO, though offers tight frequency stability, isn't used in noise sensitive applications in general due to the abrupt frequency jumps in short temperature intervals. Micro-jumps also referred to as phase jumps are phenomenon where the frequency of the oscillator changes suddenly. These jumps are often random and non-repeatable.

The nature of the micro-jump can cause system related problems, especially in phase locked applications.
The figure 5 shows comparison between Analog and Digital TCXO. Micro-jumps can be seen in the DC-TCXO throughout the test.

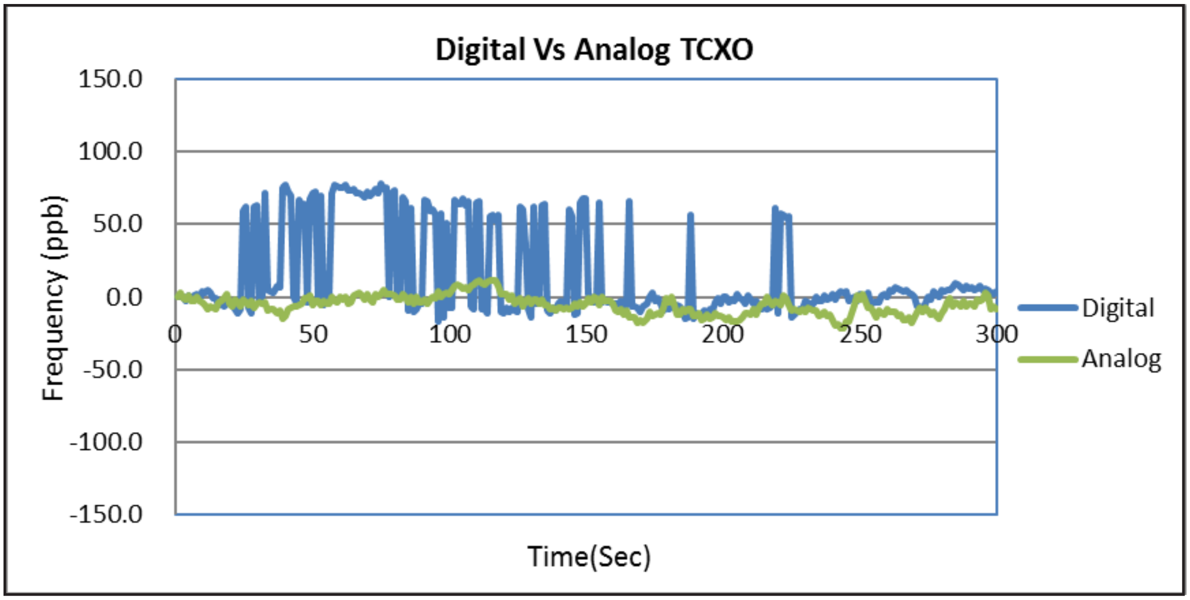

Figure 5: Digital vs. Analog Compensation *Digital Vs. Analog TXCO*

Over the years, other digital compensation implementations have been developed, many with embedded computing power as a means of facilitating calibration and system operation.

CLIPPED SINE VS. HCMOS OUTPUT

With many TCXOs being used for driving digital circuits, the Clipped Sine waveform is the most popular output option for TCXOs. The clipped-sine waveform has one major advantage over other waveforms: current draw. The typical current draw for clipped sine is <2mA maximum at +3.3V.

Here are advantages of clipped sine output.

- Low power consumption for improved thermal characteristics
- Better aging and frequency stability performance
- Better phase noise performance than CMOS Output
- Battery Power for handheld Applications

Clipped sine wave output can also be used in conjunction with an oscillator IC to generate a square wave output for the chip set. Clipped sine signal is perfect for driving PLL multiplier ICs directly providing a low current solution. To convert the clipped sine waveform to a square waveform signal such as CMOS, an input buffer is necessary.

Advantage of using HCMOS [High-speed Complementary Metal–Oxide–Semiconductor] output is high noise immunity. Noise is an unwanted disturbance in an electrical signal. In communication systems, noise translates to error or undesired random disturbance that can corrupt a data packet.

CIRCUIT DESIGN – DC-CUT CAPACITOR REQUIREMENTS

Two capacitors are usually needed for a TCXO. One is at the input side for AC decoupling to ensure pure DC supply and one is at the output side for DC blocking to ensure the output is pure AC signal. These 2 capacitors are built inside TCXO, for larger packages [i.e.: 7.0mmx 5.0mm]. For smaller packages with Clipped Sine output, a DC-Cut capacitor [typically 1,000pF] is needed externally at the output.

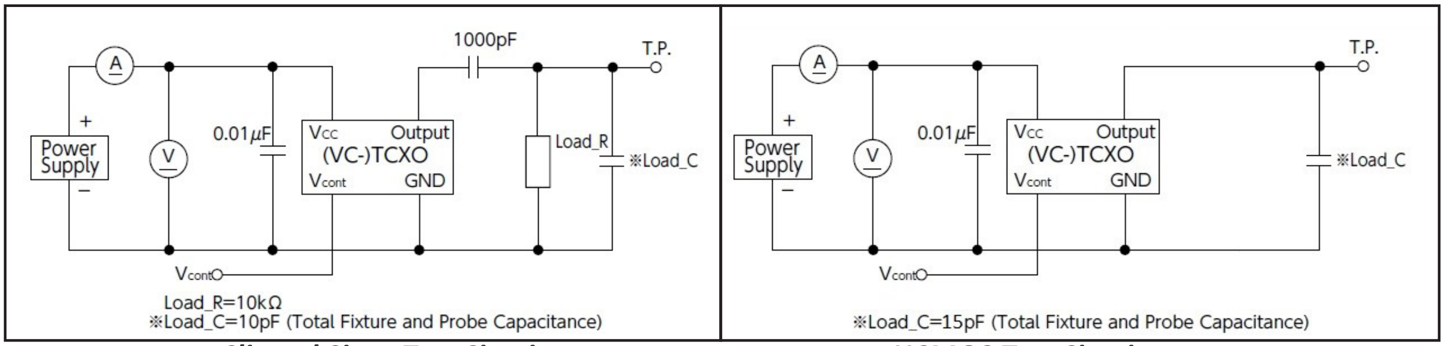

Figure 6. ***Clipped Since Test Circuit*** ***HCMOS Test Circuit***

Dependent on the RF chipset used and the board layout, customers may add additional capacitance at the output side to minimize mismatches between oscillator driver and the load.

PERTURBATIONS

Crystal perturbations are considered very significant contributors that affect frequency stability over operating temperature range. It may cause phase shift in Radio Applications and a loss of lock in PLLs.

Perturbations in the crystal characteristics (activity dips) make it virtually impossible to guarantee exceptional stability on a per degree basis in TCXOs. TCXO crystals have historically been plagued with anomalies in their temperature performance caused by blank design or imperfections in the processing and manufacturing of the crystal.

Marginal blank geometry can lead to coupling of other modes of oscillation that may be close to the frequency of the desired mode. These modes can interfere with the oscillator frequency at various temperatures causing increases in the crystal resistance or "activity dips" and resulting frequency excursions. These perturbations typically occur over a narrow temperature band. It is possible that the circuit may cease to oscillate at these points or may not start when power is applied.

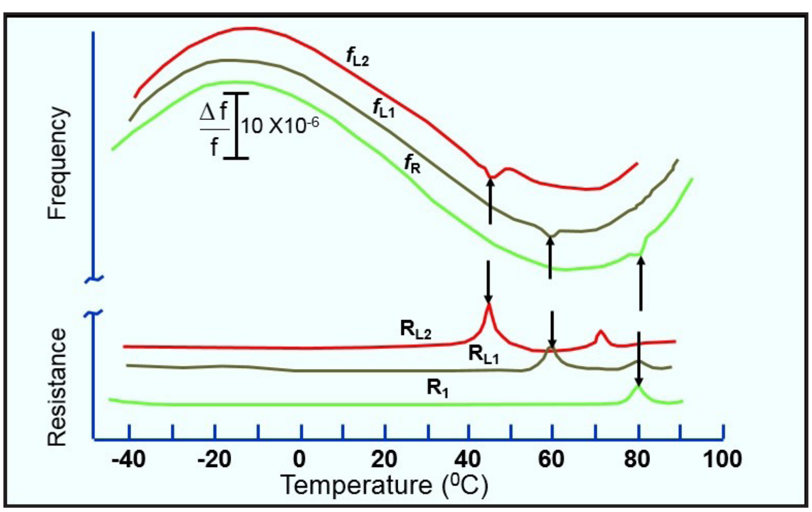

Figure 7: Activity Dip *Source: John R. Vig Tutorial, J.Vig@IEEE.org. Approved for Public Release. Distribution unlimited.*

MICRO-JUMPS

Another inconsistency that may occur over temperature is a jump or step offset in frequency. These offsets are small and often are not observed under normal TCXO testing. In most manufacturing conditions, TCXOs are tested at six or eight points over the temperature range.

Under these conditions, many perturbations and jumps [Figure -8] will go undetected. In applications where these irregularities are critical to system performance, the oscillators should be tested over additional predetermined temperature points. For the greatest confidence, the frequency of each oscillator should be continuously monitored as the temperature is ramped from one extreme to the other and back. This type of test guarantees that any perturbation or micro-jump that is present will be captured. Figure 8 is an example that utilizes an AT-cut strip crystal and shows no perturbations yet exhibits some small micro-jumps throughout the test.

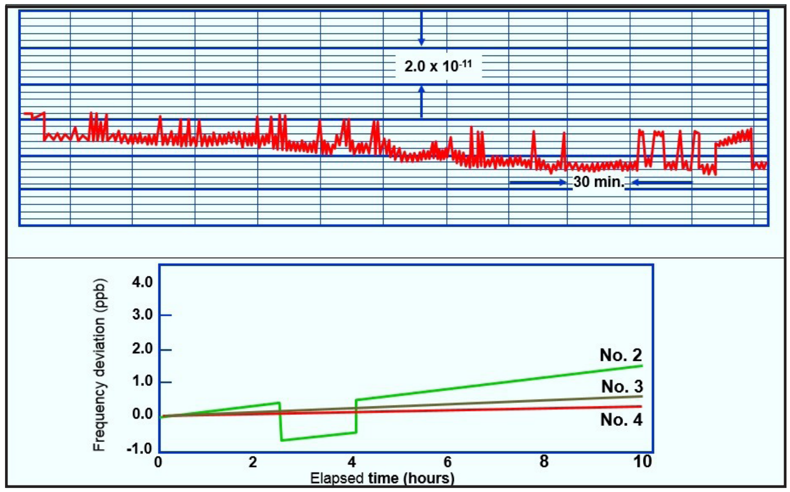

Figure 8: Frequency Jump *Source: John R. Vig Tutorial, J.Vig@IEEE.org. Approved for Public Release. Distribution unlimited.*

G-SENSITIVITY

Defined as a change in frequency resulting from exposure to an acceleration force applied to a given oscillator, expressed in ppb/g. When an oscillator is used in environment conducive to vibration, the frequency of the vibration will modulate the carrier frequency degrading the phase noise performance of the oscillator. This phenomenon is similar for both random and sine vibration and is also very deterministic, meaning the magnitude of the induced phase noise degradation can be calculated if the G-sensitivity of the oscillator is known.

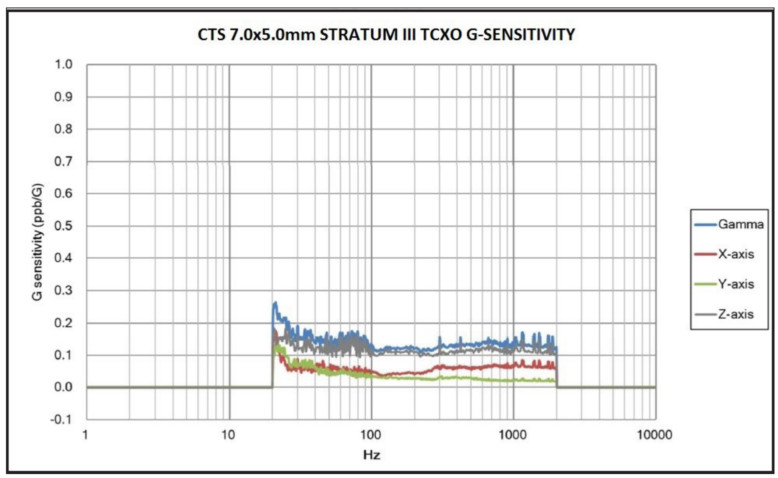

Figure 9: G-Sensitivity Example

PHASE NOISE

Phase noise is a method of describing the stability of an oscillator in the Frequency Domain. The Frequency Domain shows what the spectral [frequency] content of oscillator output looks like over a given frequency range. It can differentiate between Random [Stochastic] noise and Induced/Repetitive [Deterministic] noise.

The phase noise of oscillators can lead to erroneous detection of phase transitions, i.e., to bit errors. Phase noise performance is increasingly critical for applications delivering fast data transfer such as GPS, GSM, WCDMA and WiMAX as well as a very wide range of portable applications.

Maintaining strong frequency stability in electronic RF circuits by eliminating phase noise is important in many high-end communication applications. Typical phase noise plots of 40MHz TCXOs can be seen below.

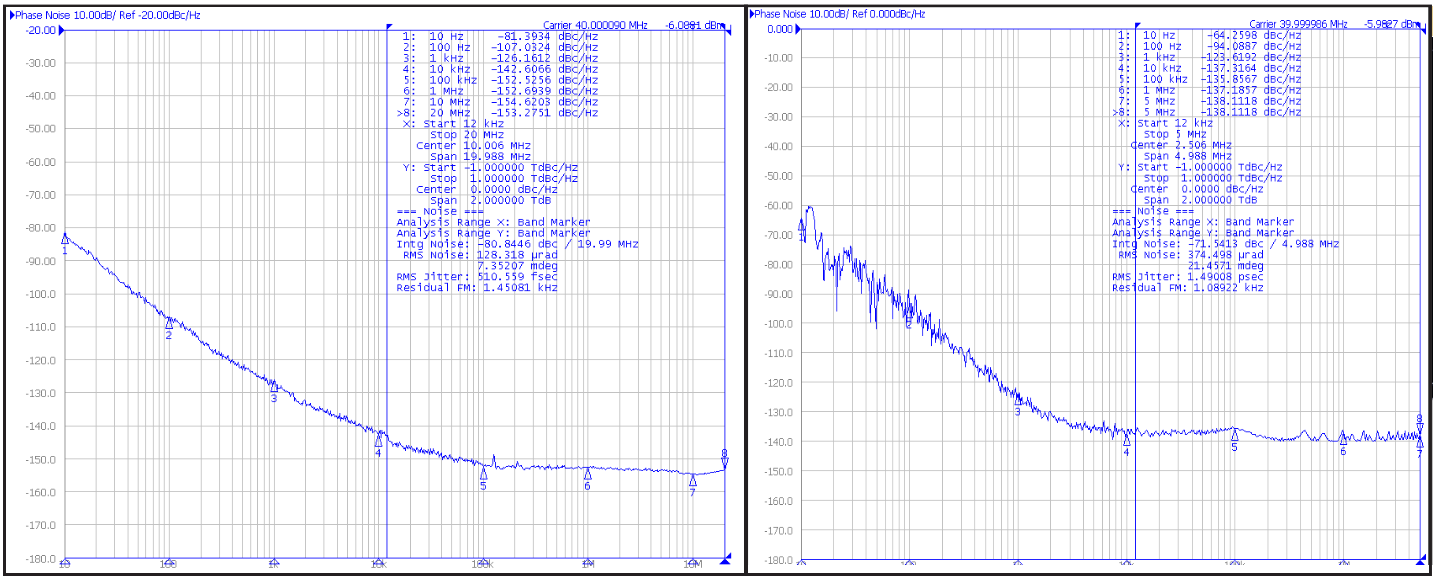

Figure 10: ***40MHz Analog TCXO*** ***40MHz Digital TCXO***

The phase noise level of a digitally compensated temperature-compensated crystal oscillator is degraded due to the numerical system of compensation.

AGING

One other parameter of concern to most TCXO users is the long-term drift of the frequency caused by aging. Although other oscillator components can contribute to aging, in a well-designed oscillator the aging is primarily due to the crystal. Changes in the crystal's resonant frequency arise because of mass transfer to or from the quartz blank. Relaxation of mounting stresses can also play a role. Advances in crystal design and processing have reduced the aging capability to under ±1 ppm per year, even for miniature packages. Long-term projections for the 10- or 20-year expected life of an oscillator can be less than ±5 ppm, as the aging rate decays with time.

Aging effects can be projected with curve-fit extrapolation using the MIL-SPEC logarithmic model below.

$$\frac{\Delta f}{f(t)} = af(x) = a_0 + a_1 \ln(1 + a_2 t)$$

t: time in days,

a_0, a_1, a_2: numerical coefficients adjusted for curve fitting to the sample data.

To allow for aging, most TCXO are made tunable over a small frequency range, using a voltage control function [VCTCXO].

VOLTAGE CONTROLLED TCXO

VCTCXO output frequencies can be adjusted with an external control voltage. This is usually done by placing varicap or varactor diodes on either side of the crystal. Varicap serves as a variable capacitor by means of applying voltage across the diodes, which "pulls" the output frequency as desired.

The amount of frequency change caused by the control voltage is called the deviation [Pullability]. The deviation verses the amount of control voltage can be graphically measured and displayed in ppm.

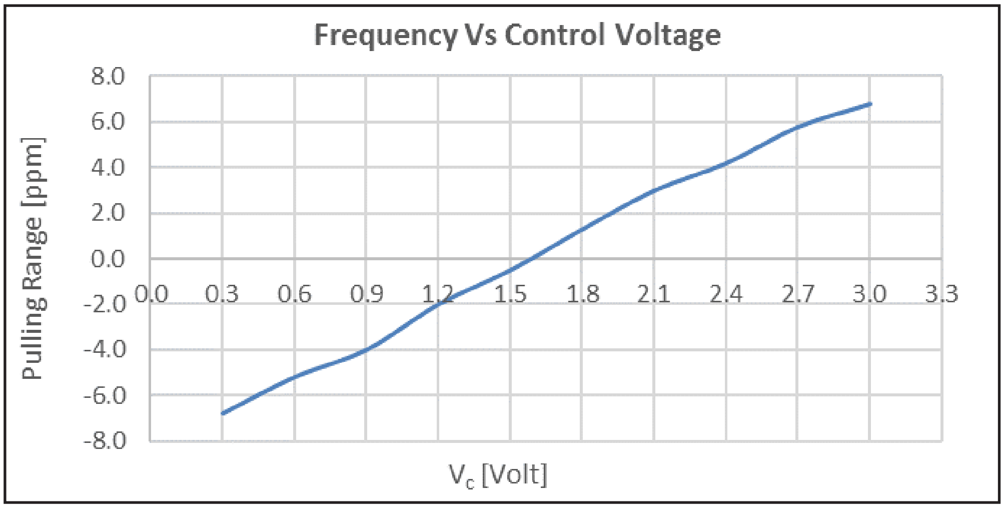

Figure 11. Frequency vs. Voltage Control

PACKAGES

TCXOs can be supplied in a variety of packages dependent upon the way they have been designed and the requirements of the end user. The most common packages widely used today are 5.0mmx3.2mm and 3.2mmx-2.5mm TCXOs.

Discrete type packages are usually used for larger sizes, i.e.: 7.0mmx5.0mm. The single-type package offers ease in fabrication as it is similar to that of the conventional XO [Crystal Oscillator], VCXO [Voltage Controlled Crystal Oscillator], etc., with both the quartz crystal resonator and the IC in a single package.

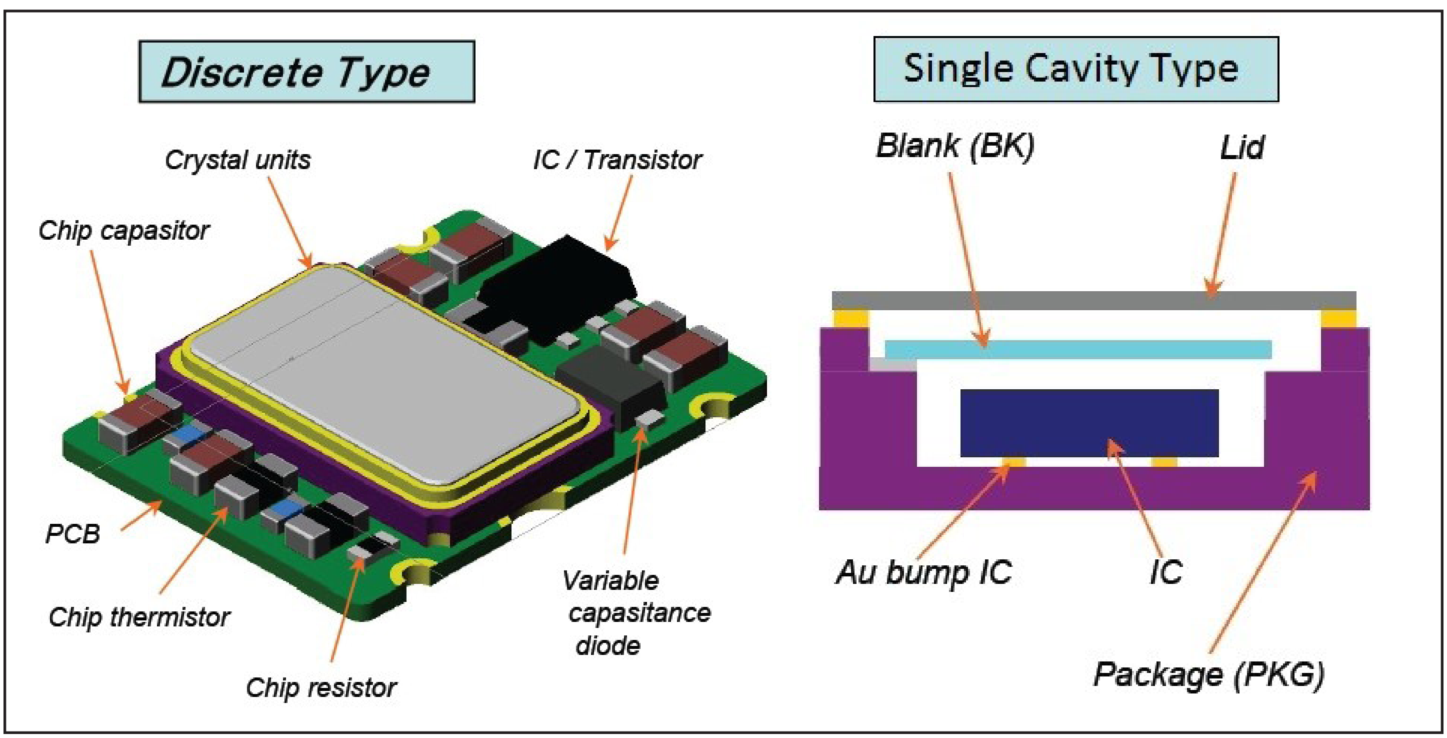

Figure 12a. Package Types

Double Decker [piggyback type] & H-type allow the quartz crystal resonator encapsulated in an individual cavity, so it is separate from the IC and other passive components to improve aging performance. This type of TCXO composed basically of two packages; one quartz crystal resonator package and one IC holder.

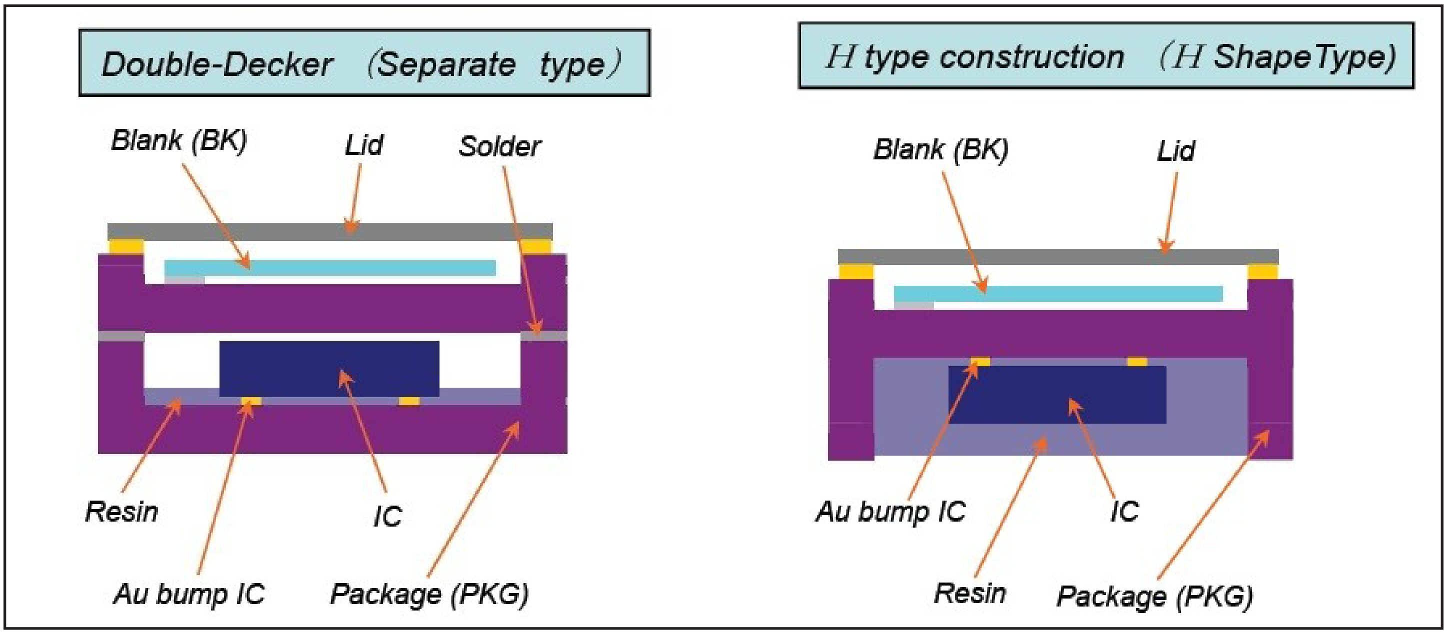

Figure 12b. Package Construction

Since the basic TCXO architecture has been integrated into a single IC, which is suitable for many applications, further reductions in the size of precision oscillators require smaller resonators. Although bulk mode quartz resonators can be made small, physical limitations preclude making usable devices below a certain size. Surface-mount packages with 3.2mmx2.5mm or smaller footprints are available with reasonable motional parameters and stabilities. To allow the miniaturization being only limited by the size of the quartz crystal resonator package and reductions much beyond this level requires advancement of resonator technologies.

STRATUM LEVEL PERFORMANCE

American National Standards Institute [ANSI] standard entitled "Synchronization Interface Standards for Digital Networks" [ANSI/T1.101-1987] was first released in 1987. This document defines the stratum levels and minimum performance requirements for digital network synchronization. The table below shows the requirements for the stratum levels which provides a comparison and summary of the drift and slip rates for the strata clock systems.

Stratum	Accuracy/ Adjust Range	Pull-In-Range	Stability	Time to First Frame Slip
1	1×10^{-11}	N/A	N/A	72days
2	1.6×10^{-11}	Must be capable of syncing to clock with accuracy of ± 1.6×10^{-8}	1×10^{-10}/day	7days
3E	1.0×10^{-6}	Must be capable of syncing to clock with accuracy of ± 4.6×10^{-6}	1×10^{-8}/day	3.5 Hours
3	4.6×10^{-6}	Must be capable of syncing to clock with accuracy of ± 4.6×10^{-6}	3.7×10^{-7}/day	6 Minutes (255 in 24 hrs)
4E	32×10^{-6}	Must be capable of syncing to clock with accuracy of ± -32×10^{-6}	Same as Accuracy	Not Yet Specified
4	32×10^{-6}	Must be capable of syncing to clock with accuracy of ± -32×10^{-6}	Same as Accuracy	N/A

CTS TCXO

CTS offer cost effective, small package solutions, along with high performance capabilities, suitable for complex electronic system requirements. Several Stratum 3 TCXO models [i.e. models 580 and 581] support a wide array of applications, covering 1588 timing and synchronous Ethernet, base stations including femtocells and microcells, networking, test and measurement, and many more. They deliver outstanding phase noise performance and a high level of frequency stability.

CTS enables 5G infrastructure through its high-performance product lines of ultra-low noise precision timing devices and RF ceramic filters that support both sub-6 GHz and mmWave wireless infrastructure. CTS' 5G product portfolio is designed to comply and support stringent performance and quality standards of networking systems' wider bandwidth and transmission rates operating at high frequencies, powering applications such as 5G mass MIMO base stations, small cells, and mmWave 5G hybrid beam forming base stations.

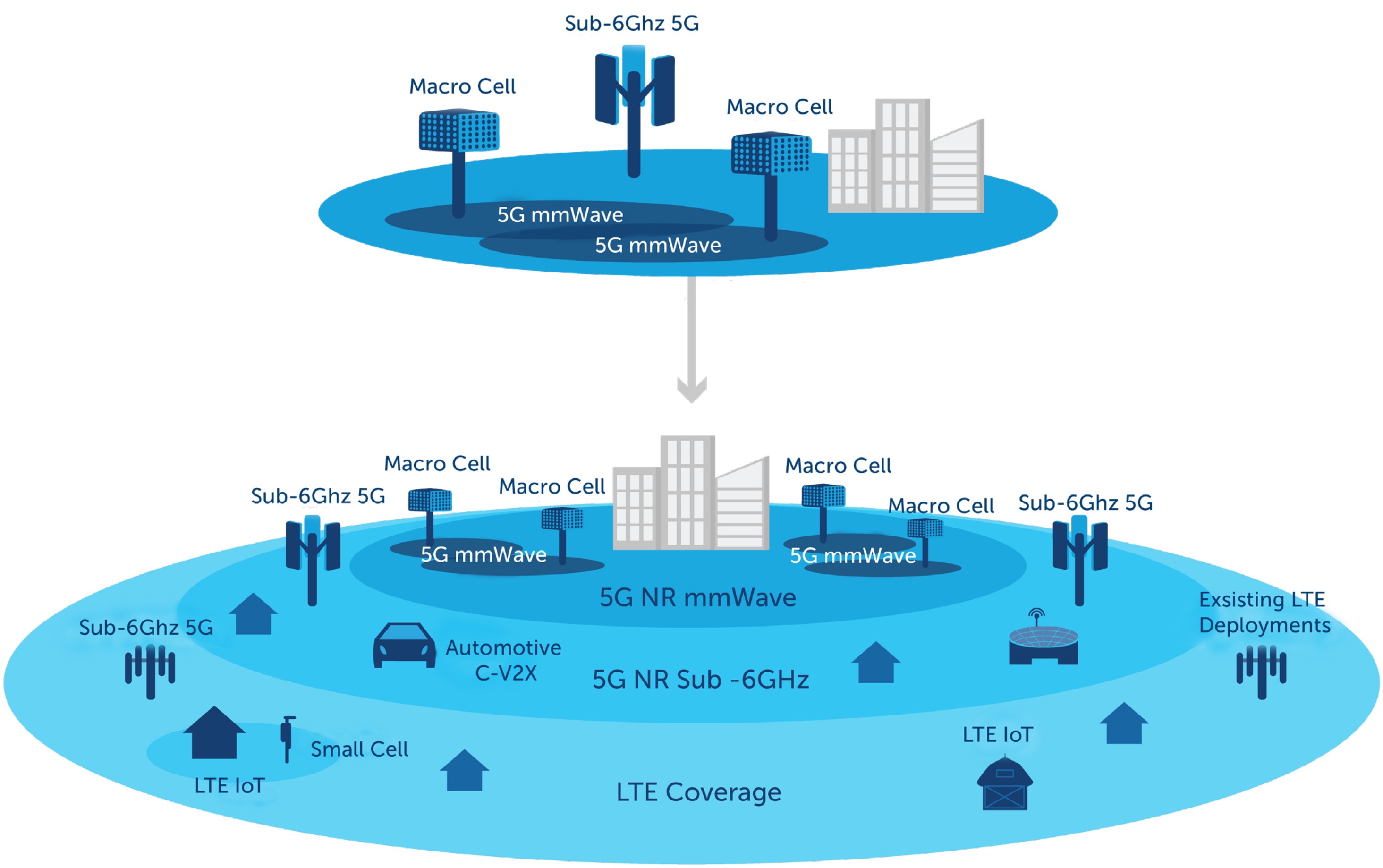

Figure 13: 5G Coverage & Support for Excel Bandwidth

CTS precision timing devices for 5G networks utilize low noise frequency synthesis techniques to clean system noise and multiply low frequency to high frequency making our technology suitable for high transmission rates. Our embedded ASIC solution and high Q crystal technology offer optimized signal to noise ratio that results in a precise and clean signal that is used for data, voice, and video transmission.
See the CTS 5G page for details

Newly released two miniature precision TCXO models, 535 and 536, provide a frequency reference with low noise, high stability performance attributes targeted for the evolving 5G New Radio [NR] standard and chipset solutions for small cells and remote radio head applications that will support 5G architecture.

The 535 and 536 have been designed to achieve low noise performance at high transmission frequency while remaining energy efficient and provide a low noise frequency reference signal, tight stability options down to ±0.1ppm, an operating temperature range from -40°C to +105°C that supports outdoor deployment and a choice between Clipped Sine or HCMOS outputs. Optional Voltage Control for frequency tuning and Output Enable function are also available. Standard product features, common market applications and new platforms are summarized below.

Product Features	
Clipped Sine or HCMOS Output	Analog Temperature Compensation Engine
Overall Frequency Stability ±4.6ppm	Fundamental Crystal Designs
Stability Options – ±0.10ppm to ±0.50ppm	Optional Enable Function Available
Temperature Range to-40°C to +105°C	Small Ceramic Surface Mount Package
Voltage Control Option for Frequency Tuning	Tape and Reel Packaging

Please refer to individual data sheets on our website to see more performance characteristics.
https://www.ctscorp.com
https://www.ctscorp.com/connect_product_line/TCXO/

AUTHORS

Aye Min Ko
Senior Engineer
Aye.Minko@ctscorp.com
T: +65 65517515
CTS Corporation – Singapore

John Metzler
Applications Engineer
John.Metzler@ctscorp.com
T: 630-577-8816
CTS Corporation - North America

Contact

CTS Corporation
4925 Indiana Avenue
Lisle, IL 60532
Web: www.ctscorp.com

Authors and Technical Contacts:

Aye Min Ko
Senior Engineer
CTS Corporation – Singapore
E-mail: Aye.Minko@ctscorp.com
Tel: +65 65517515

John Metzler
Product Engineer
E-mail: John.Metzler@ctscorp.com
Tel: +1 (630) 577 8828

Media Relations Contact:

Jackie Morris
Marketing & Communications Manager
E-mail: mediarelations@ctscorp.com
Tel: +1 (630) 577-8865

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