Development of Miniaturized Analog and Digital Temperature Compensated Crystal Oscillators
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Abstract
In today's highly packed RF spectrum, accurate frequency synthesizing in mobile handsets is important to ensure precise allocation of available radio channels. For a synthesizer to achieve its best performance, an accurate and stable reference clock source is a must. Temperature-Compensated Crystal Oscillator (TCXO) of size 5x3.2x1.5mm³ with better than ±2.5ppm stability over an operating temperature range of -30 to 85°C is being used in almost every single handset in the market disregarding the interface- may it be TDMA, GSM, CDMA, W-CDMA, PDC, PHS, etc. This paper addresses the continuous effort in miniaturizing the TCXO for handset application.

I. Introduction
In today's highly packed RF spectrum, accurate frequency synthesizing in mobile handsets is important to ensure precise allocation of available radio channels. For a synthesizer to achieve its best performance, an accurate and stable reference clock source is a must. Temperature-Compensated Crystal Oscillator (TCXO) offers the accuracy and stability and is being used in almost every single handset in the market disregarding the interface- may it be TDMA, GSM, CDMA, W-CDMA, PDC, PHS, etc.

Fig. 1 5x3.2x1.5mm³ TCXO

Nowadays, handsets have shrunk to sizes so small that they were unthinkable a few years ago. However, the continuous size shrinking needs to take into account the ergonomic limit set by the average distance between the human ear and mouth. The failure of marketing the Dick Tracy’s type of wristwatch handset by a manufacturer a few years ago demonstrated a sample fact- it was not practical. Instead the trend is to pack more functions into a handset. Most recently is the inclusion of digital camera function and it has proven to be highly successful. The trend is that handset will stay small enough but more functions will be added into the handset. This puts tremendous pressure on component suppliers to continue to shrink the size of components used in a handset. TCXO of size 5x3.2x1.5mm³ using dedicated IC with better than ±2.5ppm stability over an operating temperature range of -30 to 85°C first appeared a few years ago (Fig. 1). It is still being widely used though smaller sizes like 4x2.5x1.2mm³ and 3.2x2.5x1.2mm³ became available recently (Fig. 2).

This paper addresses the continuous effort in miniaturizing the TCXO for handset application down to 2.5x2mm² footprint from the viewpoints of compensation methods, IC availability, diebonding methods, quartz crystal resonator requirements, additional passive component requirements, traditional packaging methods, and novel packaging methods.

II. Compensation Methods
The temperature compensation configuration of a TCXO can be either direct or indirect analog-based compensation method (Fig. 3). In the direct configuration, the compensation circuit is imbedded inside the oscillator circuitry. TCXO for handset application uses the indirect configuration exclusively. The indirect configuration compensation circuit generates a temperature dependent DC-voltage which in turn pulls the oscillator frequency back to its nominal value through a variable capacitance diode. The circuit can be implemented with discrete components and such TCXO type is called “Discrete Type” as depicted in Fig. 2. The frequency drift of a AT-Cut quartz crystal resonator over temperature follows the cubic curve where $T_0$ can be any reference temperature-

$$\frac{df}{f}(T) = A(T-T_0) + B(T-T_0)^2 + C(T-T_0)^3.$$ 

The inflection temperature $T_i$ can be calculated as-

$$T_i = -\frac{B}{3C} + T_0$$

and $\frac{df}{f}$ can now be rewritten as-

$$\frac{df}{f}(T) = A_0(T-T_i) + C_i(T-T_i)^3.$$ 

A DC-voltage can now be applied to the oscillator based on reversing the $\frac{df}{f}$ cubic curve-
\[ V(df/f) = V_0 + E(df/f) + F(df/f)^2 + G(df/f)^3 \]

and it can be expressed as a function of T:

\[ V(T) = V_0 - E[A(T-T_i) + (C_1(T-T_i)^3)] - F[A(T-T_i) + (C_1(T-T_i)^3)]^2 - G[A(T-T_i) + (C_1(T-T_i)^3)]^3. \]

\( V(T) \) can be expressed up to the 9th power of T. Most compensation schemes take into account up to the 3rd power. Recent development took into account up to the 6th power of T. Such 7x5\( \text{mm}^2 \) TCXO offers exceptional stability and it suits telecom applications.

![Temperature compensation network](image)

**Fig. 3** Compensation Methods

The indirect compensation scheme can also be embedded in a single IC along with the oscillator circuit. This is in general being done “digitally” by storing the voltage value for each temperature step (1-bit) or polynomial coefficient as a table in a PROM. This type of TCXO is still analog-based but the compensation scheme is implemented digitally and it is the focus of discussion in this paper (IC Type as in Fig. 2). Note that automatic frequency control (AFC) is needed to allow on board frequency pulling at handset assembly stage and aging compensation later on. And so such TCXO is in fact a VC-TCXO. Typical performance of TCXO for handset application using such sort of IC is:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>13–26 MHz</td>
</tr>
<tr>
<td>Supply Voltage</td>
<td>2.3–3.3V</td>
</tr>
<tr>
<td>Temp. Stability</td>
<td>±2.5ppm</td>
</tr>
<tr>
<td>Temp. Range of Operation</td>
<td>-30 to 85°C</td>
</tr>
<tr>
<td>Output</td>
<td>Clipped Sinewave</td>
</tr>
<tr>
<td>Load</td>
<td>AC Coupled to 10kΩ/10pF</td>
</tr>
<tr>
<td>Current Drain</td>
<td>~1.5 mA</td>
</tr>
<tr>
<td>AFC</td>
<td>±7–16ppm</td>
</tr>
<tr>
<td>Aging</td>
<td>&lt;±1ppm/year</td>
</tr>
<tr>
<td>Phase Noise</td>
<td>&lt;130 dBc/Hz at 1 KHz</td>
</tr>
</tbody>
</table>

High performance microprocessor-controlled compensation scheme can be used to compute the voltage values by polynomial approximation. Voltage values can be resolved with 8- to 10-bit/0.25°C accuracy. This is the conventional “digitally controlled TCXO (DC-TCXO)” which consistently offers better than ±1ppm stability over wide temperature range of operation. DC-TCXO, though offers tight frequency stability, isn’t used in handset application in general due to the abrupt frequency jumps in short temperature intervals. One example is a 16.8 MHz 5x3.2\( \text{mm}^2 \) DC-TCXO which achieves ±0.2ppm over a -30 to 85°C temperature range (Fig. 4) which finds application in the digital radio trunk TETRA system.

![Temperature Stability of 3 Units of DC-TCXO](image)

**Fig. 4** Temperature Stability of 3 Units of DC-TCXO

### III. IC Availability

Commercial ICs for miniaturized TCXO are now available from a few suppliers for application in mobile phone systems and cordless phone systems like PHS. They are based either on EPROM, EEPROM, fusible link, or other techniques in programming the compensation parameters. IC chip size is down to 1.85x1.4\( \text{mm}^2 \). As small as 1.2x1.2\( \text{mm}^2 \) is being introduced. A single 6” wafer can have more than 8,000 chips. This further reduces the IC cost. Wafer thickness is now also down to 135\( \mu \text{m} \) which allows further reduction in device height. Frequency divider is also becoming available in the IC.

### IV. Diebonding Methods

Conventional diebonding of IC followed by wirebonding provides the cheapest and most reliable solution. However, wirebond pads in the package take up area beyond the IC occupied space. Flipchipping the IC is one diebonding method that saves space and it can be cost effective. However, to flipchip IC reliably is proven to be challenging. Nowadays most 5x3.2\( \text{mm}^2 \) TCXOs in the market use either conventional diebonding or flipchip method. To move on to 3.2x2.5\( \text{mm}^2 \) or 2.5x2\( \text{mm}^2 \) footprint, flipchip method may be needed.

### V. Quartz Crystal Resonator Requirements

Due to the limitation of compensation presented by most commercial ICs, the AT-cut quartz crystal resonator used in a TCXO should have tight df/f spread. This can usually be achieved by controlling the angle of the crystal to within a
fraction of a minute. To ensure good aging, the quartz crystal resonator in also has to have gold base plating which adds to the cost. Good control of angle and baseplating will also result in consistent motional parameters. In addition, the quartz crystal resonator has to exhibit no activity dips and suppressed close-in spurs. Furthermore, the best performance TCXO in general has the quartz crystal resonator individually encapsulated as described in Section VII below.

Recently, Watanabe et al. [1] used doubly-rotated quartz crystal resonator near the FC-cut region in a discrete type 26 MHz 4x2.5x1.5mm³ VC-TCXO. Due to the high inflection temperature of the cut, only low-temperature compensation was needed which resulted in less part number count (Fig. 5). Better than a ±2.5ppm df/f was recorded over an operating temperature of -30 to 75°C. However, it is well known that processing doubly-rotated strip-type quartz crystal resonator is no trivial matter.

VI. Additional Passive Component Requirements

Two capacitors are usually needed inside 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. Tiny 0402 type (1x0.5x0.35mm³) multilayer SMT ceramic capacitors are usually used. Dependent on the RF chipset used and the board layout, customers may add additional capacitance off-chip at the output side. In general, the two built-in capacitors are always needed which somewhat hinders the miniaturization effort.

VII. Conventional Packaging Methods

Nowadays, two packaging types are widely used for the 5x3.2mm² and 3.2x2.5mm² TCXOs. They are the piggyback type and the H-type (Figs. 6a and 6b). Both allow the quartz crystal resonator encapsulated in individual cavity so to separate it from the IC and other passive components to improve aging performance.

The piggyback type TCXO composed basically of two packages- one quartz crystal resonator package and one IC holder. Recently, many chipset suppliers began to offer GSM RF transceivers with built-in TCXO circuit [9]. Such transceivers need only an off-chip 13 or 26 MHz discrete quartz crystal resonator. Suppliers of piggyback type TCXO can then offer both the discrete quartz crystal resonator and the complete TCXO to respective customers. The single-type package (Fig. 6c) offers ease in fabrication as it is similar to that of the conventional XO, VCXO, etc. with both the quartz crystal resonator and the IC in a single package. Achieving good aging performance is still proven challenging.

VIII. Novel Packaging Methods

In the past few years, quartz crystal resonator itself saw continuous size reduction. 5x3.2mm² one is in mass production for many applications including that for the handset. 3.2x2.5mm² production is ramping up especially for the digital camera market and Bluetooth equipment. The general rule of thumb is that it is more and more difficult to build low frequency quartz crystal resonator (e.g. <13 MHz) as the package size gets smaller. This is due to the fact that crystal beveling and vacuum sealing are needed for low frequency quartz crystal resonator in order to maintain modest crystal impedance.

One innovative 5x3.2mm² VC-TCXO marketed couple of years ago used a 3.2x2.5mm² packaged quartz crystal resonator mounted directly on a populated PCB (Fig. 7). The first plastic molded VC-TCXO was introduced in 2003 (Fig. 8) [7]. These two TCXOs have to use individually encapsulated quartz crystal resonator of smaller size compared to that of the TCXO.
To allow the miniaturization being only limited by the size of the quartz crystal resonator package, one can consider removing the sidewalls of the IC holder. One technique being considered is a stacked structure (Capillarity And Surface Tension = CAST) as shown in Fig. 9. The IC can be either wirebonded or flipchipped. The space between the IC holder and the cover plate are held together by Kovar blocks or other structures. IC overcoat is dispensed through the hole of the covering plate. Capillarity effect traps the overcoat within the boundaries as demonstrated in an experiment using H₂O shown in Fig. 10.

IX. Discussion

The size of TCXO for handset application continues to shrink to 3.2x2.5x1.2mm³ and smaller. The price also continues to fall. The authors believe this will impact the conventional low frequency clock oscillator market in the future since TCXO offers much better frequency-temperature performance and tight set frequency tolerance.

References


5. RF Transceivers for Handset Applications. Examples- Skyworks’ CX74063, Hitachi’s BRIGHT, Silicon Labs’ Aero+, Infineon’s SMARTi, GCT’s GRF6201, and Motorola’s i250.

6. MuRata’s Product Announcement Sept. 30, 2002, HFX323 Series 5x3.2x1.2mm³ VC-TCXO.

7. Epson’s Product Announcement Sept. 24, 2003, TG-5000/5001LA Series 5x3.2x1.15mm³ VC-TCXO.