A Brief View of the Current State of the Development and Aging Performance of Fixed Frequency Surface Acoustic Wave (SAW) Oscillators

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Abstract- The recent rapid expansion of optical fiber networking market fuels the demand for accurate 100~400 MHz fixed frequency oscillators based on surface acoustic wave (SAW) technology. Nowadays, several suppliers can offer small size and cost efficient SMD single-end and differential SAW oscillators (SOs) with very good phase jitter performance. Selective customers prefer SO solution as it is free of the unsettling problems from some crystal oscillator (XO) solutions- high cost of high frequency fundamental (HFF) and inverted mesa (IM) crystal blanks, spurious modes, frequency jumping, drive level sensitivity, high cost of phase lock loop (PLL) die, etc. This paper is to provide a brief view of the current state of the development of fixed frequency SOs. Based on the aging data of more than 20,000 hours at 125ºC, the authors also comment on the SO aging performance fabricated using different SAW wave-types.

Keywords- SAW, Oscillator, Quartz Crystal, Aging

1. Introduction

The recent rapid expansion of optical fiber networking market fuels the demand for accurate 100~400 MHz crystal oscillators (XOs). High frequency fundamental (HFF)-, third overtone (3OT)- and inverted mesa (IM)-based XOs can handle the 100~220 MHz frequency range and meet at ease the commonly accepted phase jitter specification of <1 ps (12 KHz to 20 MHz). One of the first successful commercial deployments of high frequency fixed frequency oscillator based on surface acoustic wave (SAW) technology was the HO-series differential dual-in-line (DIP) SAW oscillators (SOs) by RF Monolithics for the then Digital Equipment Corporation Alpha Microprocessor in the mid 1990's. Nowadays, several suppliers can offer small size and cost efficient SMD single-end and differential SOs with very good phase jitter performance to complement the XOs mentioned above. Selective customers prefer SO solution as it is free of the unsettling problems from XO solutions- high cost of HFF and IM crystal blanks, spurious modes, frequency jumping, drive level sensitivity, high cost of PLL die, etc. This paper is to provide a brief view of the current state of the development of fixed frequency SOs. Based on the aging data of more than 20,000 hours at 125ºC, we also comment on the SO aging performance fabricated using different SAW wave-types.

2. High Frequency XOs

The meaning of the term "high frequency" in the quartz crystal industry changes as time progresses. Nowadays quartz crystal companies can routinely slice, lap, and polish fundamental quartz crystal blanks to 70 MHz with effort working toward 120 MHz. Such blanks can of course be used also in 3OT mode which results in high frequency operation from 210 to 360 MHz. Advanced etching and handling techniques can push the IM quartz crystal blanks to 125~167 MHz with high yield. It's projected that soon it will reach 220 MHz.

Fig. 1 HFF (left) and IM (right) Quartz Crystal Blanks

These HFF and IM quartz crystal blanks (Fig. 1) are ideal for Voltage Controlled Crystal Oscillator (VCXO) applications for its low capacitance ratio which allows wide pulling. The earlier IM quartz crystal blanks were of large sizes.[1] Some quartz crystal oscillator suppliers can now offer single-end XO to the small size of 2.5mm x 2.0mm using very small either HFF or IM quartz crystal blanks up to 167 MHz.[2] (The smallest single-end XO in sampling stage is now of the 1.6mm x 1.2mm size). These XOs offer phase jitter easily meeting the SONET/SDH phase jitter requirement of <1 ps (12 KHz to 20 MHz). Indeed, this tight phase jitter requirement may not be needed for data communication standards like PCI Express, Ethernet, Fiber Channel, and SATA.[3] Unfortunately equipment suppliers pertinent to these standards in general still demand all oscillator solutions (XO, MEMS Oscillator, etc.) to meet this requirement.[4]

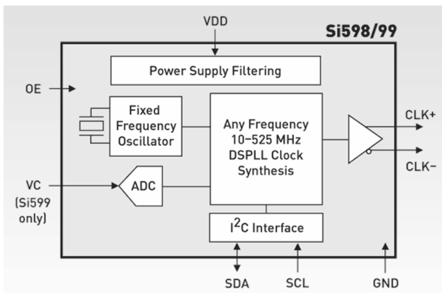

Fig. 2 Silabs DSPLL®-based XO[5]

The recent advancement of phase lock loop (PLL) technology

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has brought out families of 100 to 1,500 MHz XOs using simple tens of MHz of quartz crystals with uneven phase jitter performance from 0.3 to marginal 1 ps (Fig. 2).[5]

There is less pressure on XO miniaturization for optical fiber networking market. The bulk of that market needs 7.0mm x 5.0mm and 5.0mm x 3.2mm XOs. One of the authors wrote in [4]- *In the past, only a handful of US, European and Japanese crystal oscillator suppliers had accesses to proprietary oscillator ICs. These companies dominated the frequency control products market. Others could only participate in the low-end CMOS oscillator segment or they simply stayed with manufacturing only quartz crystal. Nowadays oscillator IC die for many low- to mid-end XO, PCXO, VCXO and TCXO are available from quite a few IC suppliers (NPC, JRC, Interchip, IDT, Phaselink, AKM, Panasonic, MAS, Glacier, KME, Pericom, Silicon Clocks, EM Microelectronics, et al.). These IC suppliers are willing to work with the crystal oscillator companies to come up with smaller and thinner value-added oscillator IC die for different applications. Many more crystal oscillator companies, especially those from Taiwan, China, and Korea, can now compete in more segments of the frequency control products market.*

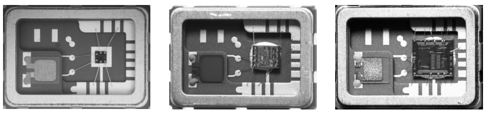


Fig. 3 7.0mm x 5.0mm XOs based on HFF/IM, 3OT and PLL[6]

Indeed, many companies can now offer single-end and differential XOs for the optical fiber networking market using the HFF/IM quartz crystal blanks, 3OT quartz crystal blanks, and PLL (Fig. 3) which enjoy the inherent good cubic Δf/f vs T stability of AT-Cut quartz crystal.[6]

3. High Frequency SOs

Interesting enough, SAW for commercial oscillator application was first used as Voltage Controlled SAW Oscillator (VCSO) up to ~700 MHz in SONET/SDH systems[7] for the simple reason that there was limited need for high frequency fixed frequency oscillators then (Fig. 4).

Fig. 4 VCO-600 (VCSO), Vectron International, Early 1990's[7]

ST-Cut quartz crystal was used for the bare SAW die inside the 18.5mm x 7.5mm gull-wing HTCC hermetic VCSO package. Adequate Absolute Pulling Range (APR) could be achieved by careful designs even though ST-Cut quartz offered quadratic Δf/f vs T stability.[8]

Bulky SOs for military, industrial, and commercial applications have been around for sometime.[9] One of the most successful commercial deployments of high frequency fixed frequency oscillator based on SAW technology was the differential dual-in-line (DIP) 300/400 MHz SOs (Fig. 5) by RF Monolithics for the Digital Equipment Corporation Alpha Microprocessor in the mid 1990's.[10] ST-Cut quartz SAW Coupled Resonator Filter (CRF) was used to achieve ±100 ppm frequency stability over 0 to 70ºC Operation Temperature Range (OTR). The SAW element was individually hermetic packaged and the circuit was discretely implemented. As it was pretty much the only high frequency accurate oscillator solution available then, the industry jokingly claimed the price for such SOs was $1 for 1 MHz.

Fig. 5 25mm x 12.8 mm DIP SAW Oscillator[10]

Nowadays, several quartz crystal oscillator suppliers can offer small size and cost efficient fixed frequency single-end and differential SMD SOs with very good phase jitter performance to complement the XOs mentioned in the previous section. The first announcement of a compact 7.0 mm x 5.0mm single-end SO was the 3.3V ±100 ppm over 0 to 70ºC OTR EG-2001 series (106 to 170 MHz) in 2000 by a supplier in Japan.[11] It was revealed in 2002[12] (Fig. 6) that, like the XOs in Fig. 3, the SO was implemented with a single IC die (BiCMOS for high frequency up to 300 MHz) and a single resonant element- a one-port SAW resonator (SAWR). ST-Cut quartz was likely being used.

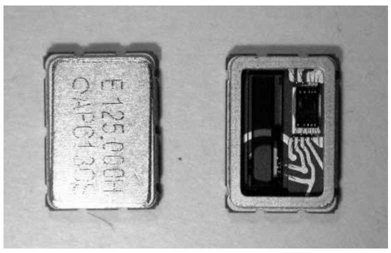


Fig. 6 7.0mm x 5.0mm SO in 2002[12]

In [12] the equivalent parameters of a 3OT quartz crystal and a one-port ST-Cut quartz SAWR were also compared (Table 1). The reason to use BiCMOS for high frequency was clearly explained via the load capacitance, motional resistance, negative resistance, gain, etc.

One of the authors discussed in detail the later on development of different quartz SAW cuts in improving the temperature stability of SOs to less than 20 ppm.[8] ST-Cut quartz based single-end and differential 2.5/3.3V of ±100 ppm over 0 to 70ºC OTR SOs in 7.0mm x 5.0mm and 5.0mm x 3.2mm packages are now available from several suppliers. Couple of suppliers can provide SOs of ±50 ppm over 0 to 70ºC and wider OTR using patented quartz SAW cuts.

	R1	L1	C1	C0
100MHz 3O.T.	18.3Ω	2.1mH	1.2fF	3.5pF
304MHz SAW	10.9Ω	90.6uH	3.0fF	4.0pF

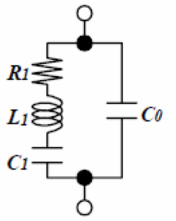


Table 1 Equivalent Parameters Comparison[11]

As said in the Introduction, selective customers prefer SO solution as it is free of the unsettling problems from XO solutions- high cost of HFF and IM quartz crystal blanks, spurious modes, frequency jumping, drive level sensitivity, high cost of PLL die, etc. The argument if XO or SO is better continues though.[13~18] We report in Table 2 the comparison of phase noise and phase jitter of our own XO solutions said in Section 2 and our own SO (ST-Cut quartz) solution said in this section (all 2.5V differential 156.25 MHz).

156.25MHz Oscillator	10Hz	100Hz	1KHz	10KHz	100KHz	1MHz	10MHz	20MHz	Phase Jitter *(pS)
IM	-51	-86	-119	-140	-145	-151	-160	-161	0.096
3OT	-70	-98	-127	-138	-144	-150	-157	-158	0.120
PLL	-68	-100	-123	-130	-135	-139	-162	-166	0.250
SAW	-68	-97	-126	-145	-146	-146	-147	-147	0.295

** The phase jitter is integrated from 12KHz to 20MHz.*

Table 2 Phase Noise and Phase Jitter Comparison of XOs and SO

4. Different SAW Wave-Types

We shall discuss the aging data of some SOs in the next section. In this section we first shall comment on the particle motions of two different SAW wave-types. It is known that the aging performance of SOs depends on many things including the penetration depth of the SAW into the substrate. The norm is that the deeper the dominant particle motion is into the substrate, the less sensitive is the SAW to surface contamination which results in lower aging. One of the authors reported in [8] that a SO Supplier X used a patented quartz cut of Euler Angles of (0°, 123°, 39~44°) to achieve ±50 ppm over wide OTR. The SAW parameters for the cut (In-Plane Rotated 33º Y-Cut quartz) were not revealed when it was first introduced. In [8], calculation yielded the following results for Euler Angles (0°, 123°, 41.5°)-

Phase velocity (shorted) = 3251.5286 m/s
Phase velocity (open) = 3253.4841 m/s
Electromechanical coupling factor (k^2) = 0.001202
PFA = 1.35º

The average phase velocity is ~3252 m/s which is ~3% higher than that of ST-Cut quartz. k^2 is close to that of ST-Cut quartz and it has a small Power Flow Angle (PFA).

In this paper we plot the particle motions and the surface shorted electric potential (u_1, u_2, u_3, and ϕ) of the SAWs in the ST-Cut and the In-Plane Rotated 33º Y-Cut quartz- u_1 and u_3 are on the sagittal plane and u_1 is in the SAW propagation direction (Figs. 7 & 8).

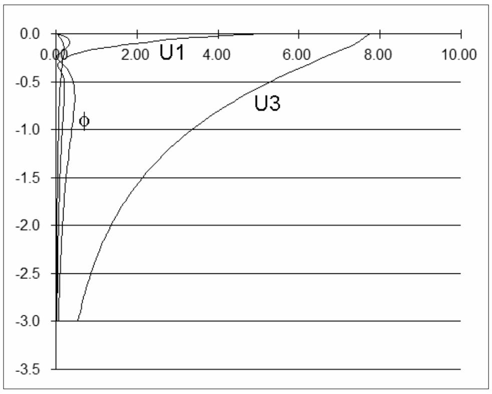


Fig. 7 ST-Cut Quartz

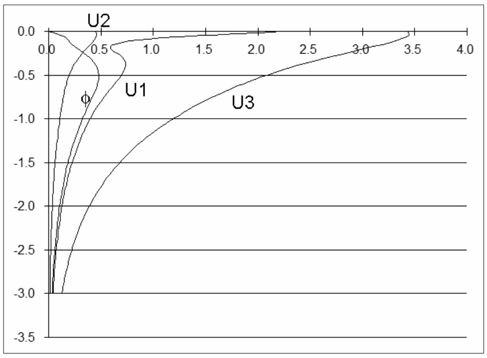


Fig. 8 In-Plane Rotated 33º Y-Cut Quartz- (0°, 123°, 41.5°)

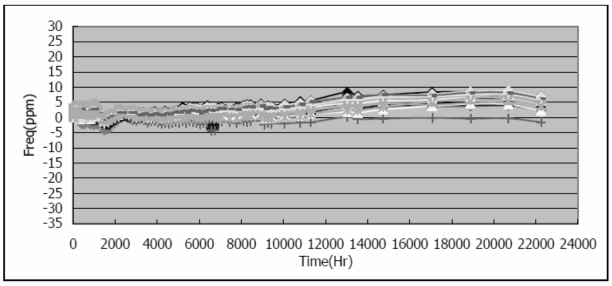
We note that the ST-Cut has a stronger u_1 and u_3 components in the surface (under the same nominal drive voltage) and u_3 also penetrates deeper. Stronger u_1 and u_3 components in the surface mean more energy is available to overcome surface abnormalities. Deeper u_3 component penetration also means more energy is inside the substrate bulk. The authors project ST-Cut SO should age less than the in-Plane Rotated 33º Y-Cut SO.

5. SO Aging

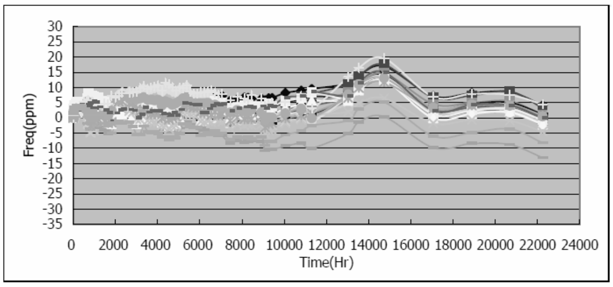
We started aging five groups (20 devices each) of 7.0mm x 5.0mm 3.3V SO and XO at 125ºC under bias more than two and a half years ago. Fig. 9 shows the aging performance of these five groups up to 22,248 hours (927 days)-

(a) 156.25 MHz LVDS SO from TXC (ST-Cut)
(b) 212.5 MHz LVPECL SO from TXC (ST-Cut)
(c) 250 MHz LVPECL SO from TXC (ST-Cut)

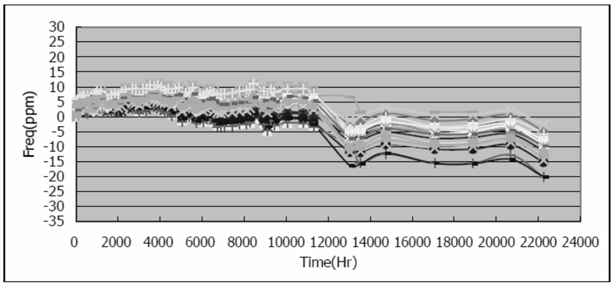
(d) 156.25 MHz LVPECL SO from Supplier X
(In-Plane Rotated 33º Y-Cut)
(e) 156.25 MHz LVPECL 3OT XO from TXC (AT-Cut)



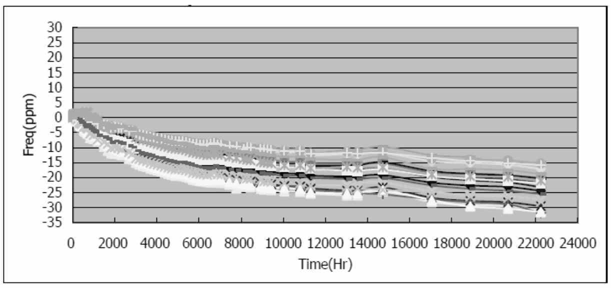
(a) 156.25 MHz LVDS SO from TXC



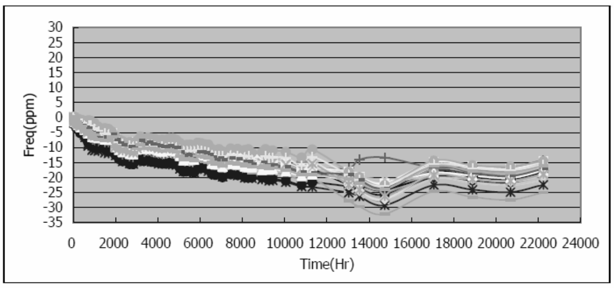
(b) 212.5 MHz LVPECL SO from TXC



(c) 250 MHz LVPECL SO from TXC



(d) 156.25 MHz LVPECL SO from Supplier X



(e) 156.25 MHz LVPECL 3OT XO from TXC

Fig. 9 Long Term Aging of SOs and XO at 125ºC.

For such a long term aging, power supply abnormalities did happen (so far six times in the past two and a half years) due to circuit break and loss of power with the most severe data distortion noted at between 11,000 and 13,000 hours and at between 14,000 and 16,000 hours. The aging trend within each group of 20 devices was though very consistent. Of all the SO groups, Supplier X's group aged the faster in the beginning but began to stabilize after ~10,000 hours. It started to age down again at ~15,000 hours. The most stable SO group is the first one which aged within ±10 ppm. The 3OT XO group aged surprisingly similar to this SO group.

6. Discussion

This paper provides a brief view of the current state of the development of fixed frequency SOs and the 22,248 hours aging data at 125ºC under bias for several groups of SO and XO. We are not aware of published high temperature aging data of SO and XO to that many hours. The integrity of SO and XO for long term operation is exceptional. We correlate the SO aging performance with the SAW particle motions. Ideally it is better to compute the energy volume ratio at different depths from the particle motions. The aging of SAW devices of course depends on many other factors- mounting adhesives, mounting position, cleanliness, burn-in, etc.[19] The authors want to thank Prof. Ken-ya Hashimoto of the Chiba University, Japan for providing the penetration depth plots in Section 4.

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