

# A Review of the Recent Development of Temperature Stable Cuts of Quartz for SAW Applications

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Abstract- Quartz continues to be used widely in frequency control applications due to its high Q and temperature stable characteristics. In specific, ST-cut quartz provides the best performance in narrow band SAW filter, SAW resonator, SAW oscillator, clock and data recovery unit, frequency translator, etc. for many years. Since the discovery of the even more temperature stable LSAW quartz LST-cut quartz in 1985, a few more new quartz cuts based on regular SAW, LSAW, SH-type SAW, HVPSAW, etc. were introduced. Some of them are being used in commercial SAW products. This paper reviews the development of these temperature stable quartz cuts for SAW applications and discusses possible future development.

Keywords- quartz, SAW, SAW oscillator

## 1. Introduction

Quartz continues to be used widely in frequency control applications due to its high Q and temperature stable characteristics. From the early application of ST-cut of quartz for Surface Acoustic Wave (SAW) products, many more new temperature stable quartz cuts have been introduced. In 2004, the author reviewed the subject by first discussing the linkage of BAW (Bulk Acoustic Wave) and SAW through the discussion of singly-rotated AT-cut quartz plate, doubly-rotated SC-cut quartz plate, SAW on ST-cut quartz wafer, and STW on singly-rotated quartz wafer.<sup>[1]</sup> The paper then discussed the development of the LST-cut, K-cut and in-plane rotated 33° Y-cut of quartz. It concluded with the discussion of the development of HVPSAW on quartz. The paper generated some interesting discussions from Weihnacht in 2005.<sup>[2]</sup> In this paper, the author broadens the review, includes the development of temperature stable SH-type quartz SAW cuts, and discusses some new exciting recent development.

## 2. BAW and SAW

For many years, researchers of acoustic wave devices for electronics applications seem to be separated into two camps- the BAW group (or sometimes called the “crystal” group) and the SAW group, and they don’t seem to “mingle.” BAW researchers are most familiar with the AT- and SC-cut thickness-shear quartz resonators. The author noted some in the industry (to the chagrin of many quartz crystal engineers) began to use the term BAWR to mean FBAR (film bulk acoustic resonator). The BAW technology in this paper retains its conventional meaning. AT-cut is a singly-rotated

Y-cut quartz plate (a Y-cut plate has its normal axis parallel to the Y-axis) with  $\theta \cong 35.25^\circ$  (Fig. 1). SC-cut, mainly for OCXO (oven-controlled crystal oscillator) applications, is a doubly-rotated Y-cut with  $\theta \cong 33.93^\circ$  and  $\Phi \cong 21.93^\circ$ .

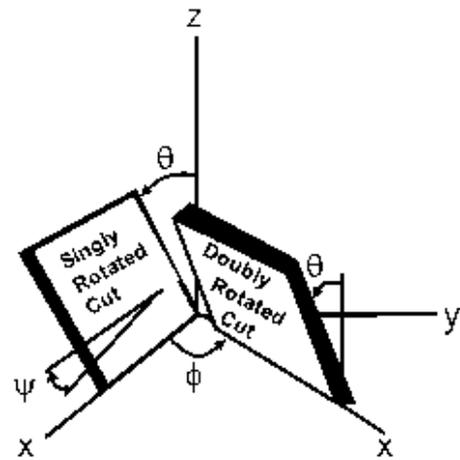


Fig. 1 Singly- and Doubly-Rotated Y-Cut Quartz Plates

In a way, one can use the “BAW Angles” ( $\Phi, \theta, \psi$ ) to describe exactly a BAW plate.  $\psi$  is in general meaningless to a BAW plate as its vibration is “bulk” in nature (frequency  $\propto 1/\text{thickness}$ ) with wave traveling across the thickness and the particle motion is in the X-axis direction. SAW researchers are most familiar with using the Euler Angles ( $\lambda, \mu, \theta$ ) to describe specific SAW cut and propagation direction. The most popular quartz cut is the ST-cut (ST = Stable Temperature) which has Euler Angles ( $0^\circ, 132.75^\circ, 0^\circ$ ). It is sometimes referred as the “X-propagation rotated Y-cut quartz”. The Euler Angles ( $\lambda, \mu, \theta$ ) can be related to the “BAW Angles” ( $\Phi, \theta, \psi$ ) by

$$\begin{aligned}\lambda &= \Phi \\ \mu &= \theta + 90^\circ \\ \theta &= -\Psi\end{aligned}$$

And so ST-cut quartz for SAW is basically an “AT-cut BAW plate” with  $\theta = 42.75^\circ$  and the SAW propagates in the X-axis. The BAW Angles are ( $0^\circ, 42.75^\circ, 0^\circ$ ). Any off X-axis SAW propagation can then be described by a non-zero  $\Psi$ . For example, one NSPUDT (Natural Single Phase Unidirectional transducer) cut of quartz has  $\Psi \cong \pm 25^\circ$ . Understanding the relationship between the BAW Angles and the Euler Angles allows one intuitively to link the BAW and SAW technologies.

Though limited to low frequency applications, AT- and SC-cuts exhibit cubic frequency change vs temperature ( $\Delta f/f$  vs T) behavior. Depend on the temperature range of operation, AT- and SC-cut resonators can offer  $\Delta f/f$  stability anywhere between 10 to 100 ppm without any compensation. ST-cut exhibits quadratic  $\Delta f/f$  vs T behavior with a 2<sup>nd</sup> order temperature coefficient of  $\sim -0.034(T-T_0)^2$  where  $T_0$  is the turnover temperature (TOT). Assuming the temperature range of operation is  $-40$  to  $85^\circ\text{C}$  and the TOT is well centered at  $22.5^\circ\text{C}$ , the  $\Delta f/f$  is at least  $\sim 130$  ppm. Changing the angle  $\theta$  in Fig. 1 (away from  $42.75^\circ$ ) can shift the TOT but it doesn't improve the temperature coefficient. In the mid-70's, SAW researchers noted Surface Skimming Bulk Wave (SSBW) with horizontal shearing particle motion can be efficiently excited with SAW transducers aligned with  $\theta \cong 36^\circ$  and  $\psi = \pm 90^\circ$  equivalent to Euler Angles ( $0^\circ, 126^\circ, \pm 90^\circ$ ). It is also referred as the "Z'-propagation rotated Y-cut quartz". SSBW becomes Surface Transverse Wave (STW) when well trapped by the periodic structure of the transducers. This wave travels at  $\sim 1.6$  times of the ST-cut's SAW velocity such that it is convenient for high frequency operation. Unfortunately, the quadratic  $\Delta f/f$  vs T has higher 2<sup>nd</sup> order temperature coefficient of  $\sim -0.052(T-T_0)^2$ . Hence for many years, SAW technology though can be used in high frequency products, it doesn't offer as good temperature stable characteristic as the BAW technology.

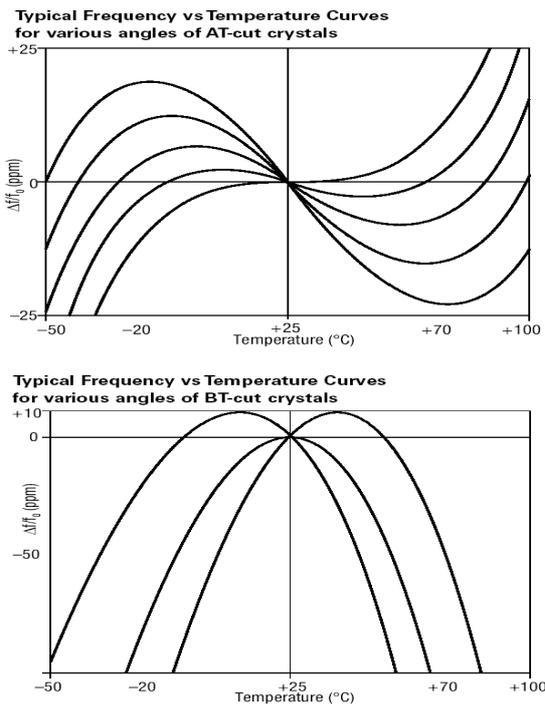


Fig. 2  $\Delta f/f$  vs T of AT- and BT-Cut Quartz

BAW researchers are also familiar with the BT-cut of quartz with BAW Angles ( $0^\circ, -49^\circ, 0^\circ$ ). Since its thickness-shear velocity is lower than that of the AT-cut, BT-cut is sometimes used when one prefers to process thicker plate of the same frequency. BT-cut doesn't have as good frequency-temperature performance since its  $\Delta f/f$  vs T is quadratic (Fig. 2). Fig. 3(a) depicts the BT-cut for BAW

operation and the  $36^\circ$  for STW operation (noted that the angle difference is  $\sim 90^\circ$ ). The thickness-shear BAW and the surface wave STW both propagate in the Z'-axis direction. The particle motion is in the X-axis direction for both cases. One recalls both operations exhibit quadratic  $\Delta f/f$  vs T. Fig. 3(b) depicts the AT-cut and the arrow indicates the thickness-shear BAW propagation direction. The particle motion is again in the X-axis direction. Based on what we observed in Fig. 3(a), one may ask "Is there a SAW or STW cut at  $\sim 90^\circ$  away from the AT-cut which exhibits cubic  $\Delta f/f$  vs T? If not, why not?"<sup>[3]</sup>

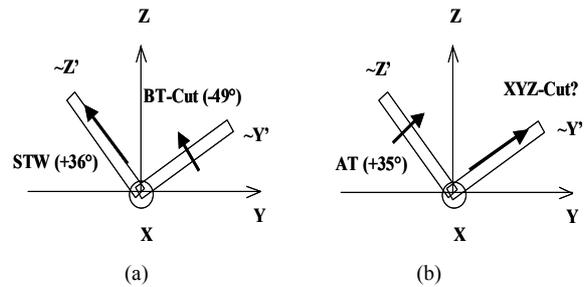


Fig. 3 AT- and BT-cut of Quartz and STW Operation<sup>[3]</sup>

In the past many years, SAW researchers discovered other SAW quartz cuts which offered good frequency-temperature performance<sup>[4,5]</sup>. However, many of these were doubly-rotated Y-cut quartz with Euler Angles ( $\lambda \neq 0^\circ, \mu \neq 0^\circ, \theta$ ). These cuts are difficult to be processed from quartz stones as two angles needed to be held. They are also expensive (similar to the SC-cut in BAW applications) and do not see commercial acceptance.

### 3. Past Development of LST-Cut Quartz

The SAW and STW (well trapped SSBW) on quartz described in the previous section are true (no leakage) generalized surface wave and slow-shear surface wave, respectively. It is well known that generalized SAW has a surface wave velocity lower than that of bulk slow shear wave (Fig. 4). The STW has a surface wave velocity close to that of the bulk slow shear wave.

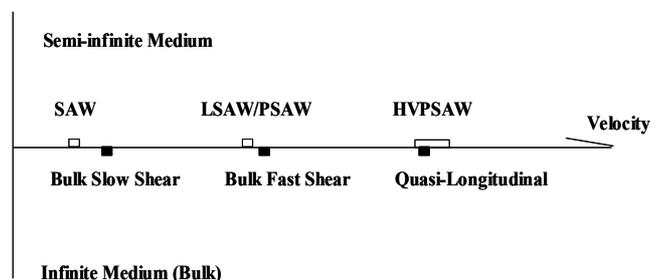


Fig. 4 Bulk and Surface Waves

In 1985, Shimizu et al.<sup>[7,8]</sup> discovered a new cut of quartz with exceptional frequency-temperature performance (Fig. 5). The cut has Euler Angles ( $0^\circ, \sim 15^\circ, 0^\circ$ ) with X-axis propagation. The wave type is leaky surface acoustic wave

(LSAW) which leaks energy into the bulk as it traverses. And so this cut of quartz was named LST-cut (leaky stable temperature cut). The leakage for this cut was found to be small ( $\sim 0.0026$  dB/ $\lambda$ ). LSAW in general has higher velocity than that of the bulk slow shear wave and lower than that of the bulk fast shear wave (Fig. 4) and its particle motion is shear predominant. The velocity of the LST-cut is  $\sim 25\%$  higher than that of the ST-cut.

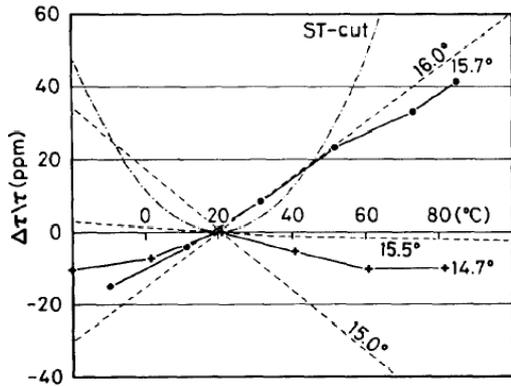


Fig. 5  $\Delta\tau/\tau$  vs T for ST- and LST-Cut Quartz<sup>[7]</sup>

Table 1 lists the comparison of the key parameters of these two cuts. It is noted that in special case where leakage is zero and velocity is above the bulk slow shear wave, the term pseudo surface acoustic wave (PSAW) is sometimes used to describe such wave type which is true surface wave.

	ST-Cut	LST-Cut
Rotated Y-Cut (°)	42.75	$\sim -75$
Velocity (m/s)	3158	3960
Coupling Constant ( $k^2$ )	0.0016	0.0011
Attenuation (dB/ $\lambda$ )	0	0.0026

Table 1 Comparison of ST- and LST-Cut Quartz

LST-cut quartz attracted much attention as it offered good frequency-temperature performance. The study of it continued for a few years including using gold film as the metallization.<sup>[9,10]</sup> LST-cut also saw some real applications<sup>[11,12]</sup> in the late 80's and early 90's. However, researchers were not able to resolve some critical issues- high sensitivity to metallization thickness, cut angle tolerance, increase of leakage as temperature rises (Fig. 6), etc.<sup>[13-15]</sup>

Study of this cut subsided almost for the rest of the 90's. Interesting enough, the first reporting of leakage-temperature<sup>[13]</sup> relationship for LSAW in the early study of LST-cut quartz proved to be partially responsible for the industry's abandoning of the conventional 36° YX LiTaO<sub>3</sub> LSAW cut for RF SAW filters in mobile handsets in the late 90's and the beginning of using 42° YX LiTaO<sub>3</sub> which was found to offer optimal performance (steeper skirt and lower insertion loss) over temperature.<sup>[16]</sup>

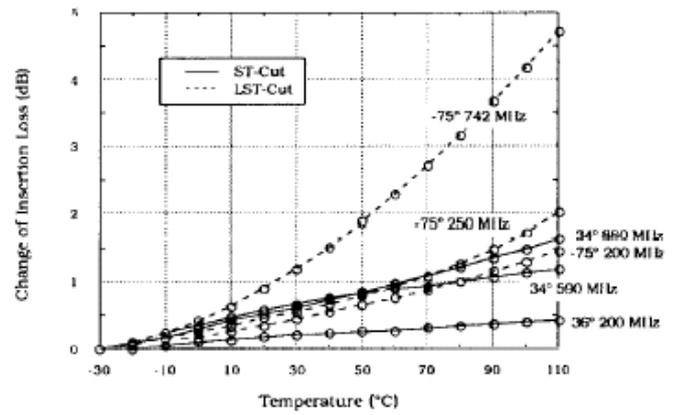


Fig. 6 Leakage Increase vs T for LST-Cut Quartz<sup>[13]</sup>

#### 4. Recent Development of LST-Cut Quartz

Since the late 90's and early 00's, renewed interest in LST-cut quartz began to appear. This was partly due to the increase in market demand of higher frequency oscillators with stable frequency-temperature performance. In 1999, Yong et al. began to use finite element analysis (FEA) tool to study LST-cut quartz (Fig. 7).<sup>[17]</sup> Yong proposed an elegant parameter "mean attenuation factor" which was defined as the ratio of the root mean square of the displacement in the top half of the substrate to that of the bottom half. It was a relative measure of the "leakiness" of the LSAW modes. A LSAW mode with its energy well confined near the top surface would have a higher mean attenuation factor. A BAW mode would have a mean attenuation factor close to one, while the bottom LSAW mode would have a mean attenuation factor much less than one. In 2003<sup>[18]</sup>, Yoon also used commercial FEA tool to study the effect of the finite thickness of LST-cut quartz substrates on the dispersion of LSAW.

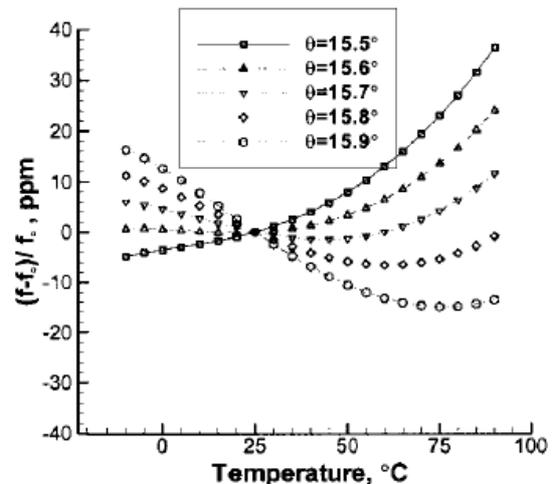


Fig. 7 FEA Results of  $\Delta f/f$  vs T for LST-Cut Quartz<sup>[17]</sup>

In 2002, Watanabe, one of the discoverers of the LST-cut quartz in 1985, maintained his passion toward this cut and developed innovative multi-wire-sawing method to slice

LST-cut SAW wafers from lumbered quartz Z-bar. It was believed, by bringing the tolerance of LST-cut angle at  $16.2^\circ$  to within  $\pm 0.2^\circ$ , the frequency variation and insertion loss change could be held to minimum.<sup>[19]</sup> In the same year, Watanabe demonstrated a raised-transducer structure (Fig. 8) on LST-cut quartz so to remove the electrode film thickness dependency.<sup>[20]</sup> The change of frequency for a 200 MHz device was within  $\pm 20$  ppm in a temperature range of  $-30$  to  $110^\circ\text{C}$  (Fig. 9). The insertion loss change was under 0.5 dB.

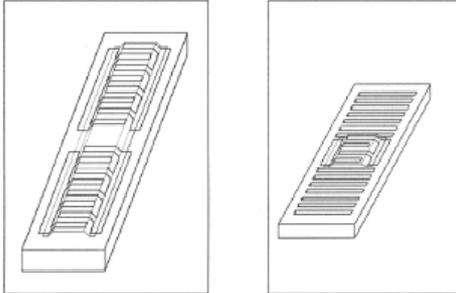


Fig. 8 Raised Transducer Structure on LST-Cut of Quartz<sup>[20]</sup>

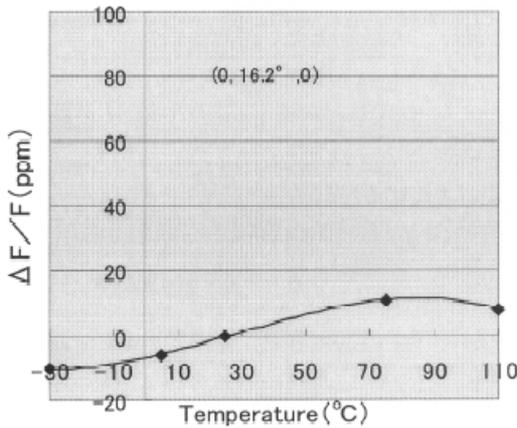


Fig. 9  $\Delta f/f$  vs T for Raised Transducer Structure on LST-Cut Quartz<sup>[20]</sup>

The best result obtained by the author as described in the 2004 review paper<sup>[1]</sup> for a 622 MHz 1-port SAW resonator using surface electrodes is shown in Fig. 10 ( $-73^\circ$  cut, mark period ratio = 0.4, and  $H/\lambda = 1.0$ ). A better than  $\pm 50$  ppm was obtained for temperature range  $-30$  to  $70^\circ\text{C}$ .

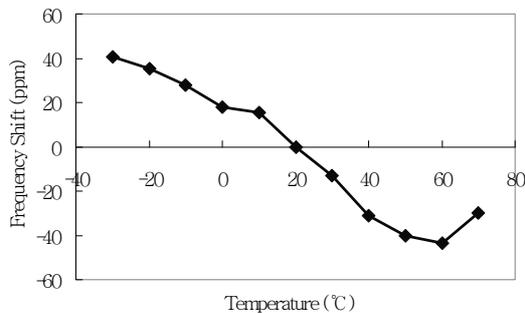


Fig. 10  $\Delta f/f$  vs T for a 622 MHz SAW Resonator on LST-Cut Quartz

In 2003, Soluch indicated that the LST-cut actually belonged to the minimal diffraction cut family and the reflection coefficient of a single aluminum electrode was about four times larger compared to that of the ST-cut.<sup>[21,22]</sup>

## 5. K-Cut Quartz

During the “siesta” of the study of LST-cut quartz in the mid 90’s, a new static and dynamic temperature stable cut of quartz was discovered. In 1996<sup>[23-25]</sup>, Takagi et al. introduced a cut of quartz with Euler Angles ( $0^\circ, 96.5^\circ, 33.8^\circ$ ) which offered better 2<sup>nd</sup> order temperature coefficient ( $\sim 0.028(T-T_0)^2$ ) than ST-cut, near to room temperature TOT ( $\theta_{\max}$ ), and a modest  $k^2$  (Table 2).

$\phi = 0$					
Name of cut	ST*	J	K	L	M
$\theta$ ( $^\circ$ )	123.0	11.25	96.51	10.46	0.00
$\psi$ ( $^\circ$ )	0.0	21.59	33.79	69.11	55.15
$k^2$ ( $\times 10^{-2}\%$ )	17	7	11	3	2
PFA ( $^\circ$ )	0.0	0.81	2.53	4.64	-5.3
$\theta_{\max}$ ( $^\circ\text{C}$ )	20.0	68.8	22.2	-25.5	-24.4
$\beta(10^{-8}/^\circ\text{C}^2)$	-3.4	-33.5	-2.78	-4.76	-4.8

ST\*: measured value.

Table 2 Comparison of ST- and K-Cut Quartz<sup>[24]</sup>

The cut was still a singly-rotated Y-cut (similar to the ST-cut) except with off X-axis propagation which resulted in a small power flow angle (PFA). The measured phase velocity based on a 152 MHz SAW resonator using a cut with Euler Angles ( $0^\circ, 96.5^\circ, 32.43^\circ$ ) was 3308.2 m/s. The author’s calculation (as reported in the 2004 review paper<sup>[1]</sup>) yielded the following results-

Phase velocity (shorted) = 3305.7981 m/s

Phase velocity (open) = 3307.7022 m/s

Electromechanical coupling factor ( $k^2$ ) = 0.001151

PFA =  $3.63^\circ$

The  $k^2$  and PFA were very close to those reported in Table 2. The average phase velocity was  $\sim 3306$  m/s which was  $\sim 5\%$  higher than that of ST-cut. K-cut was first considered to be deployed in 100~150 MHz fixed frequency SAW oscillators<sup>[26]</sup> to compete with BAW-based oscillators, which at such frequencies, needed to use 3<sup>rd</sup> overtone BAW AT-cut crystal resonators. Though K-cut quartz offers better frequency-temperature performance than that of the ST-cut quartz, it still can’t compete with the cubic  $\Delta f/f$  vs T of the conventional BAW AT-cut crystal resonator. The integrated phase jitter of SAW-based oscillator seems to be better than that of the 3<sup>rd</sup> overtone crystal oscillator. Arguments continue till today on which technology actually offers the better performance.<sup>[26,27]</sup> The author believes each finds its own acceptance by customers for different applications.

## 6. In-Plane Rotated $33^\circ$ Y-Cut Quartz

In 2002<sup>[28]</sup>, Kanna et al. introduced an “in-plane rotated  $33^\circ$

Y-cut quartz” which had an even smaller 2<sup>nd</sup> order temperature coefficient of  $\sim -0.014(T-T_0)^2$  (Fig. 11).

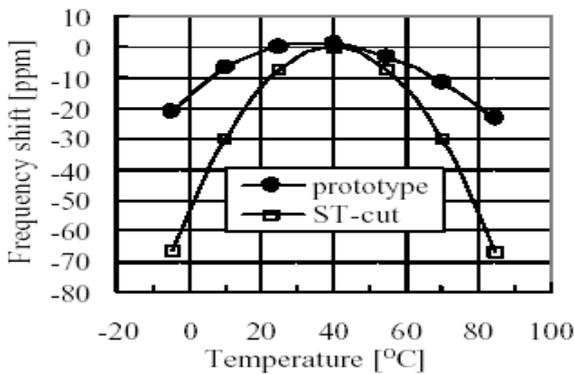


Fig. 11  $\Delta f/f$  vs T for ST- and In-Plane Rotated 33° Y-Cut of Quartz<sup>[28]</sup>

Theoretically,  $\Delta f/f$  for this cut can be as low as  $\pm 50$  ppm for a temperature range of  $-40$  to  $80^\circ\text{C}$ . The Euler Angles for this cut were  $(0^\circ, 123^\circ, 39\sim 44^\circ)$  and so it's still a singly-rotated Y-cut. Kanna demonstrated a 644 MHz SAW resonator using this quartz cut with impedance  $\sim 11\Omega$  and  $Q > 10,000$ . The SAW parameters for this cut were not revealed when it was first introduced. The author's calculation (as reported in the 2004 review paper<sup>[1]</sup>) for Euler Angles  $(0^\circ, 123^\circ, 41.5^\circ)$  yielded the following results-

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

The average phase velocity was  $\sim 3252$  m/s which was  $\sim 3\%$  higher than that of ST-cut.  $k^2$  was close to that of ST-cut and it has a small PFA. Such cut is now being deployed in high frequency SAW oscillator applications.<sup>[29,30]</sup>

### 7. SH-Type SAW

As said in Sec 2, SSBW (became STW when well trapped by the periodic structure of the transducers) with Euler Angles  $(0^\circ, 126^\circ, \pm 90^\circ)$  on quartz travels at  $\sim 1.6$  times of the SAW velocity of the regular ST-cut. High frequency STW-based SAW oscillator is a reality even though STW has higher 2<sup>nd</sup> order temperature coefficient of  $\sim -0.052(T-T_0)^2$ .<sup>[31]</sup>

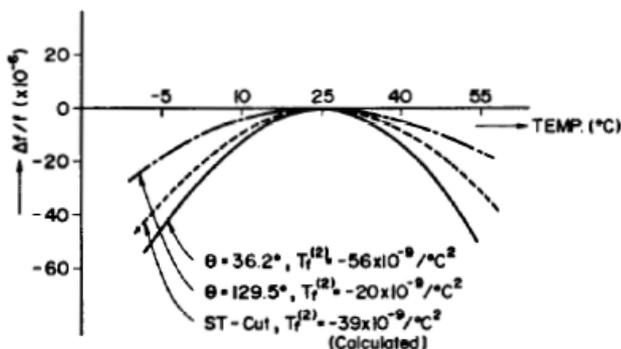


Fig. 12  $\Delta f/f$  vs T for ST- and Rotated Y-Cut of Quartz<sup>[32]</sup>

In 1980 when Nishikawa et al. studied SH-type SAW on rotated Y-cut quartz  $(0^\circ, 126^\circ, \pm 90^\circ)$ <sup>[32]</sup>, they also studied the frequency temperature characteristics of the quartz cut with Euler Angles  $(0^\circ, 50.5^\circ, \pm 90^\circ)$ . A 2<sup>nd</sup> order temperature coefficient of  $\sim -0.020(T-T_0)^2$  was obtained (Fig. 12). Nishikawa et al. also noticed the SH-type SAW at this orientation wasn't as well trapped (Fig. 13). Not as well trapped SAW in general indicates lower reflectivity and more sensitive to wafer backside surface and mounting conditions. It does have the merit of less sensitive to surface contamination (i.e. better aging).

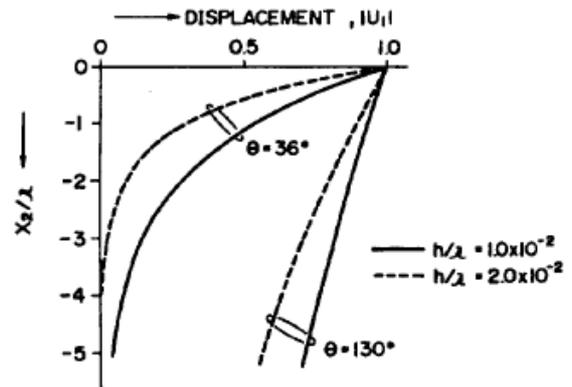


Fig. 13 Distribution of Displacement when the Surface was Layered with Aluminum<sup>[32]</sup>

Interesting enough, this cut received little attention for many years. Recently we began to see more studies on this cut near the Euler Angles region  $(0^\circ, 26^\circ\sim 51^\circ, \pm 90^\circ)$  and actual deployment became a reality.<sup>[33-35]</sup>

### 8. Quartz Cuts Employing HVPSAW

In 1988, Zaslavsky et al.<sup>[36]</sup> studied experimentally the possibility of using “longitudinal near-surface volume acoustic waves” in SAW devices. The waves were basically SSBWs with dominating longitudinal particle motions. In ST-cut quartz, it appears at around 1.8 times the generalized surface wave frequency and has always been considered as spurious. In 1979, Jhunjhunwala suggested that, since LSAW existed between the bulk slow shear and bulk fast shear waves, “secondary LSAW” could exist between the bulk fast shear and bulk quasi-longitudinal waves.<sup>[37]</sup> Jhunjhunwala predicted the velocity would be even higher than that of the regular LSAW but the wave could be of little usage because of suspected high leakage. In the mid 90's, SAW researchers began to study high velocity pseudo surface acoustic wave (HVPSAW) in some piezoelectric substrates, which seemed to offer possibly low leakage loss, strong electromechanical coupling, and low temperature coefficient. Cunha et al. summarized his study (Table 3) in 1998.<sup>[38]</sup> One quartz cut example with Euler Angles  $(0^\circ, -54.7^\circ, 0^\circ)$  that supported HVPSAW has-

Phase velocity (shorted) = 5744.7 m/s  
 Phase velocity (open) = 5745.4 m/s  
 Electromechanical coupling factor ( $k^2$ ) = 0.00023

No temperature coefficients for this cut were reported. In 2000, Yong et al.<sup>[39]</sup> used FEA tool to study HVPSAW for quartz cuts with Euler Angles (0°, 125~140°, 0°). Yong projected the electrode height played a strong role in the frequency-temperature behavior and wave attenuation of the HVPSAW mode. An optimal electrode height and cut angle could be chosen to produce low-loss temperature stable HVPSAW resonator. The author believes the full potential of HVPSAW is yet to be exploited.

Material and orientation (Euler angles [°]) $v_{BULK}$ [Km/s]	$v_p$ short/open ( $v_{SAW}^{FREE}$ ) [Km/s]	$\alpha$ short/open [dB/λ]	Fields @ z = 0 $u_x, u_y, u_z$ , short/open (magnitude [Km]) Symmetry type		PFA[°] short/open
			$2 \Delta v_p /v_p$ [%]		
LiTaO <sub>3</sub> [90° 90° 31°] [3.336 3.365 6.316]	6.2442 6.3179 (3.1420)	0.56 8.0e-3	1 0.19 0.25 1 0.09 0.13 TYPE 1		1.3 3.5 2.3
36° YX-LiTaO <sub>3</sub> [0° -54° 0°] [3.351 4.227 5.589]	6.9049 6.9779 (3.1252)	0.80 0.12	1 0.11 0.60 1 0.13 0.58 TYPE 1		-14.8 -12.0 2.09
quartz AT-X [0° -54.7° 0°] [3.298 5.100 5.744]	5.7447 5.7454 (3.1510)	1.0e-2 2.5e-3	1 0.12 0.077 1 0.12 0.080 TYPE 1		-0.2 -0.1 0.023
quartz ST-X [0° 132.75° 0°] [3.298 5.100 5.744]	5.7446 5.7449 (3.1576)	6.0e-3 1.2e-3	1 0.066 0.081 1 0.056 0.084 TYPE 1		-0.5 -0.7 0.011
quartz ST-25° [0° 132.75° 25°] [3.365 4.032 6.604]	6.5262 - (3.2475)	1.8e-5 -	1 0.35 0.090 - TYPE 1		14.1 - -
GaAs [45° -90° 25°] [2.654 2.990 5.376]	5.3987 5.3986 (2.5339)	1.9e-2 1.6e-3	1 0.04 0.234 1 0.04 0.233 TYPE 1		2.8 2.9 0.004

Table 3 HVPSAW for Different Piezoelectric Substrates<sup>[38]</sup>

## 8. Discussion

The author commented in the 2004 review paper- *Quartz continues to be the material of choice for stable temperature SAW applications. From the early investigations of generalized surface acoustic wave (Rayleigh Wave with also off-sagittal plane particle motion), STW, and LSAW to the recent development of HVPSAW, SAW researchers continue to gain new insights in what this material can offer. In the earlier days of SAW filter development, electrode finger reflection was to be suppressed to reduce passband ripples. Finger reflection today instead is the corner stone allowing us to realise low-loss SAW filters. As in other sciences, SAW researchers sometimes need to slow down and look back what we missed in the past. What was "bad" in the past may now be important. With persistent study of this material, we shall see more surprises in the future...*

Last September Epson Toyocom Corporation surprised the industry by announcing<sup>[40]</sup>- *Epson Toyocom Corporation, the world leader in crystal devices, today announced that it has used its unique technology to achieve the world's first SAW resonator with a frequency/temperature coefficient that is represented by a cubic curve. This resonator is used in the newly developed EG-4101/4121CA (SAW Oscillator), a high-frequency, low jitter and low phase noise SAW oscillator that provides outstanding frequency stability over a wide temperature range (Fig. 14).*

The details of this patent pending technique (without oscillator circuit temperature compensation and without

resonator temperature compensation layer) shall be revealed in the forthcoming Int'l Ultrasonics Symposium.

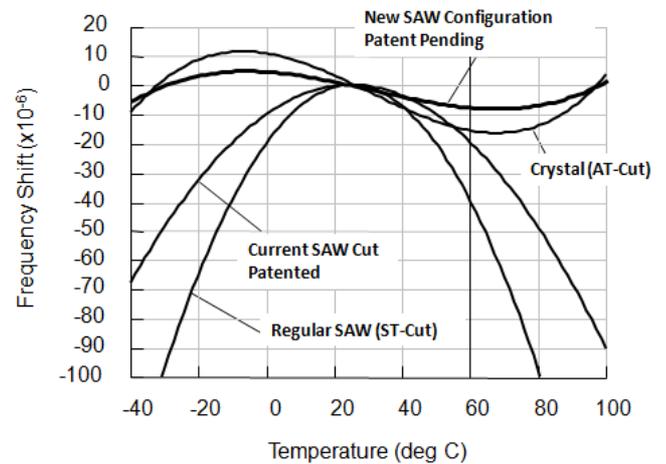


Fig. 14 New SAW Configuration of Quartz with Cubic  $\Delta f/f$  vs  $T$ <sup>[40]</sup>

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