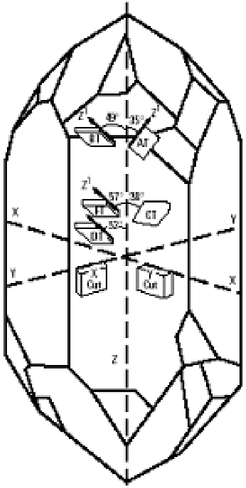

Integration of SAW and BAW Technologies for Oscillator Applications

International Workshop on SiP/Soc Integration of MEMS and Passive Components with RF ICs
March 2, 2004
Chiba University, Japan

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Contents

BAW* or SAW

BAW Development

SAW Development

BAW and SAW

Some Interesting Thoughts

* Conventional Crystal Technology and not FBAR as in-

	Ceramic	SAW	BAW
Size	Large	Small	Small
Selectivity	Worst	Best	Good
Power handling	Best	Fair	Good
Integration potential	No	Multi-Chip modules	System on chip-full integration possible
Manufacturability	Mature	Mature	In progress

Unaxis

BAW or SAW

- BAW or SAW: Two "schools" of trainings, two types of companies, …

  General Understanding

  BAW: quartz exclusively, temperature stable and low frequency.

  SAW: quartz, $LiNbO_3$, $LiTaO_3$, … high frequency and temperature not as stable

- In general, BAW folks don't know SAW, SAW folks don't know BAW, …

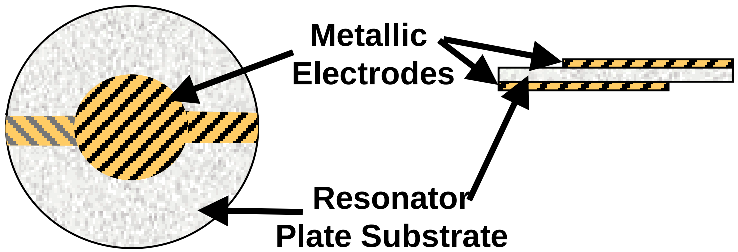
- In general, IC folks else don't know much about BAW and SAW, …

- TriQuint's acquisition of SAWTEK (SAW)

  ICS's acquisition of MicroNetwork/Andersen Labs (SAW)

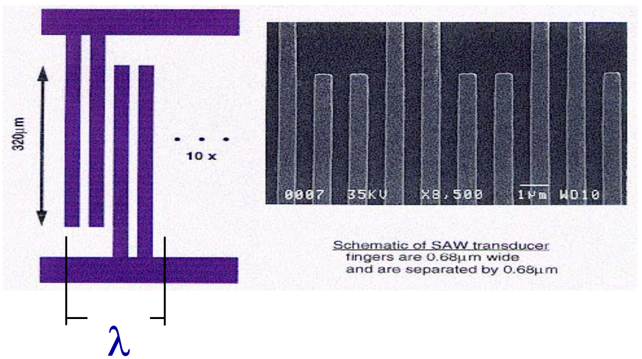
  Pericom's acquisition of SaRonix (BAW)

BAW or SAW



$$f_n = \frac{n}{2t}\sqrt{\frac{c}{\rho}}$$

fn	*resonance freq*
n	*odd integers*
c	*stiffness coefficient*
ρ	*density*
t	*thickness*

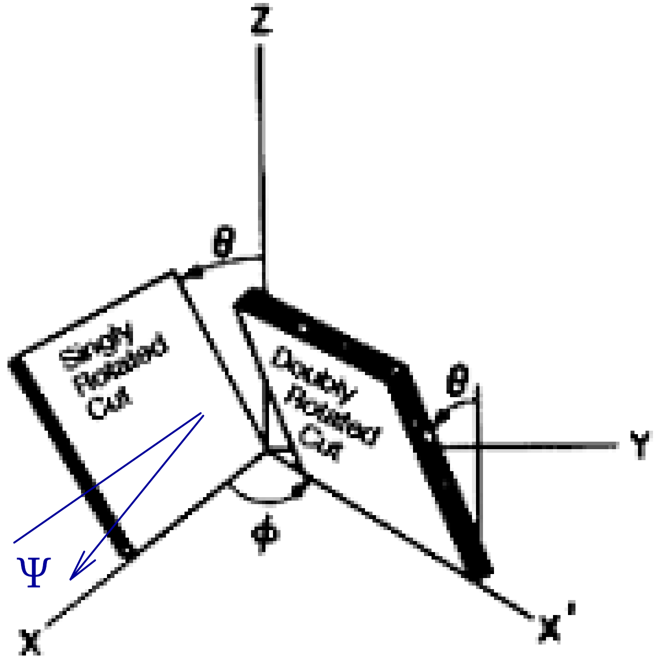


Frequency (f) = Velocity (V) * Wavelength (λ)

BAW and SAW Cuts

BAW Angles (Φ, θ, Ψ)

AT-cut is typically with θ of ~35.25º
SC-cut is typically with θ of 33.93º and Φ of 21.93º



SAW Euler Angles (λ, μ, θ)

ST-cut quartz has Euler Angles (0º, 132.75º, 0º)
XY112 LiTaO3 has Euler Angles (90º, 90º, 112º)

$\lambda = \Phi$
$\mu = \theta + 90^{\circ}$
$\theta = -\Psi$

Frequency Control Products

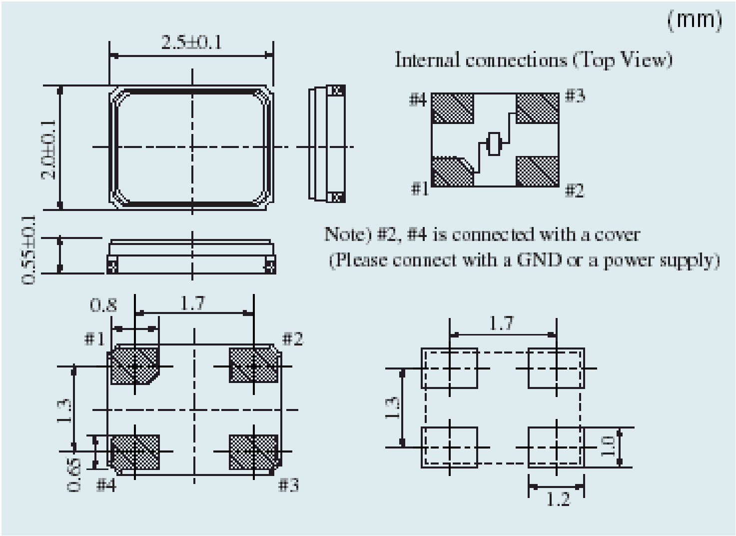
***BAW*-based (<MHz ~ 200 MHz)**	***SAW*-based (<50 MHz ~ 5 GHz)**
Passives-	
Tuning Fork and Crystal Resonator	**SAWR**
MCF	**SAWF**
CXO	**CSO**
Oscillators-	
VCXO (Voltage-Controlled)	**VCSO**
TCXO (Temp. Compensated)	**TCSO?**
OCXO (Oven-Controlled)	**OCSO?**

Where BAW and SAW May Meet to Provide the Performance

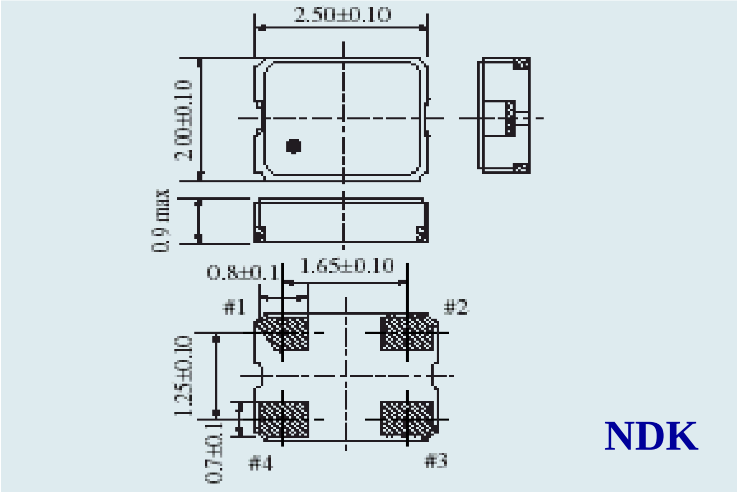
Timing Modules-	
Clock Data Recovery (CDR)	**Clock Data Recovery (CDR)**
Clock Smoother (CS)	**Clock Smoother (CS)**
Frequency Translator (FX)	**Frequency Translator (FX)**
….	**….**

BAW Development- Smaller

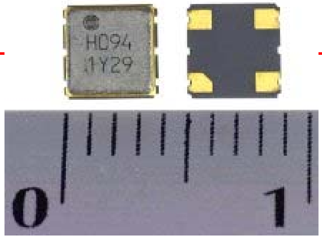
Smallest Crystal- 2.5x2mm^2
(2x1.6mm^2 is coming?)



Smallest CXO- 2.5x2mm^2
Under Development



BAW Development- Higher Frequency

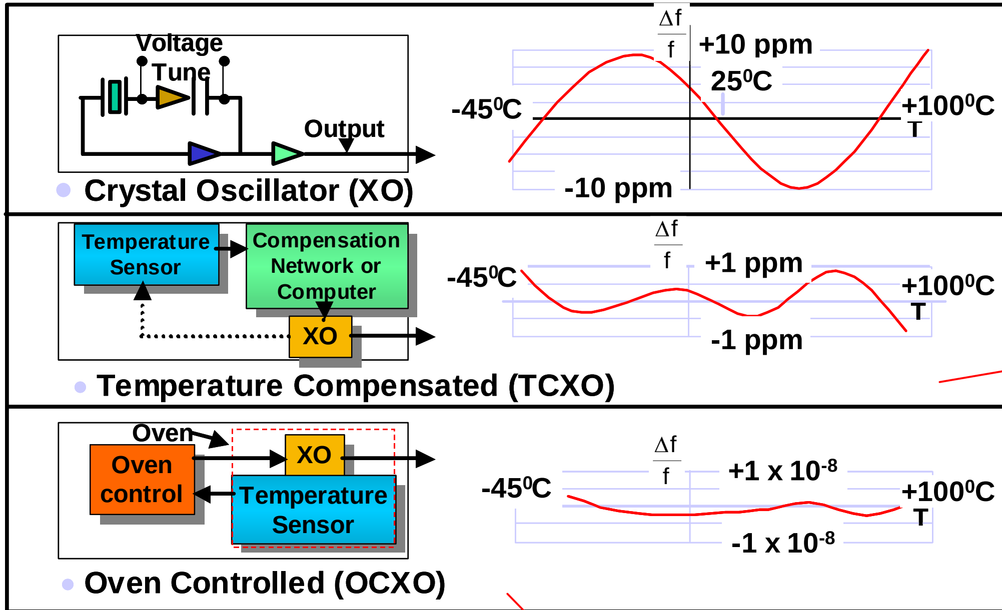


60 to 200 MHz Inverted Mesa Quartz Resonators

No.	Parameters	Requirements
1	Nominal frequency	60 to 200 MHz
2	Mode of vibration	AT-Cut fundamental
3	Package type	SMD package (3.8x3.8x1.0mm^3)
4	Load capacitance	Series
5	Drive level	100 μW max
6	Frequency tolerance	±30.0 ppm (at 25±3 °C)
7	Operating Temp. range	0 to 85 °C
8	Resonance resistance	30 Ohms max
9	Motional capacitance(C1)	TBD (4 to 7 fF)
10	Re-flow soldering	±5 ppm max (260 °C peak)
11	Frequency stability	±15 ppm (Operating Temp. Range, Ref. 25 °C)
12	Frequency Discontinuities	±2 ppm/°C max (Frequency Perturbation)
13	Aging	±10 ppm/20years (25±3 °C)

Toyocom 2002

BAW Development- More Stable



Smaller- 2.5x2 mm^2 (TEW)

Smaller- 20.8x13.2x7.6 mm^3 (VI's EMXO) Evacuated.

SAW Development- History

	Segments	*Frequency Range*	*ASP (US$)*	*Leaders*
60's on	Conventional high-loss TV-IF SAWFs incl. 480 MHz for digital satellite broadcast, etc.- 1st Wave	30 to 50 MHz	0.2~0.5	MuRata, Hitachi, Epcos, et al.
70's on	SAWRs for remote control, keyless entry, etc.- 1.5 Wave	300 MHz to 1 GHz	0.3~0.8	RFM, Epcos, et al.
70's on	Medium to high-loss IF SAWFs for general IF filtering, VSAT, basestations, repeaters, routers, GPS, etc.	100 to 600 MHz	1.5~50	Epcos, SAWTEK, VI, ICS, Temex, et al.
70's on	SAW oscillators for frequency sources, computer servers, IFF, telecom equipment, etc.	100 MHz to 1.1 GHz	3~300	ICS, SAWTEK, Epson, et al.
80's on	SAWFs for clock and data recovery applications, etc.	100 MHz to 2.5 GHz	5~100	Hitachi, VI, et al.
90's on	Low-loss IF and RF SAWFs for mobile phones, cordless phones, WLAN cards, handheld GPS Rx, etc.- 2nd Wave	50 MHz to 5 GHz	0.2~1.0	Epcos, Fujitsu, SAWTEK, MuRata, Temex, VI, et al.
Mid 90's on	VCSOs for telecom equipment, etc.	150 MHz to 2.5 GHz	20~300	VI, ICS, Epson, SAWTEK, et al.
Y2K on	3rd Wave? Application will have to be closely related to daily living like TVs (1st Wave) and cell phones (2nd Wave).			

SAW Development- Selecting SAW Substrates

V_f (m/s)	**SAW Velocity**
k^2	**Electromechanical Coupling Constant ($k^2 = -(\Delta v/v)$)**
TCD (ppm/°C)	**Temp. Coefficient of Delay (TCF = 1/TCD)**
PFA (°)	**Power Flow Angle**
Leakage (dB/λ)	**For LSAW and HVPSAW**
Penetration Depth (xλ)	

SAW Development- SAW Substrates

Established (3”~4”)

Quartz (SiO_2)
Lithium Niobate ($LiNbO_3$)
Lithium Tantalate ($LiTaO_3$)
Lithium Tetraborate ($Li_2B_4O_7$)
ZnO/Glass

Available but either Limited Supply or Not Widely Used (2~4”)

Bismuth Germanium Oxide ($Bi_{12}GeO_{20}$)
Langasite ($La_3Ga_5SiO_{14}$)
ZnO/Diamond
Gallium Phosphate ($GaPO_4$)

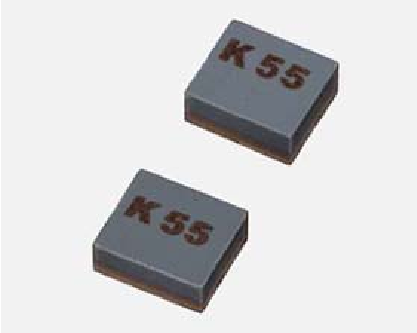
At R&D Stage

Potassium Niobate ($KNbO_3$)
ZnO/Sapphire
AlN/Sapphire
SiO_2/$LiNbO_3$
Others

SAW Development- Smaller

World's Smallest CSP RF SAW Filter

1.6 x 1.4 x 0.6 mm^3

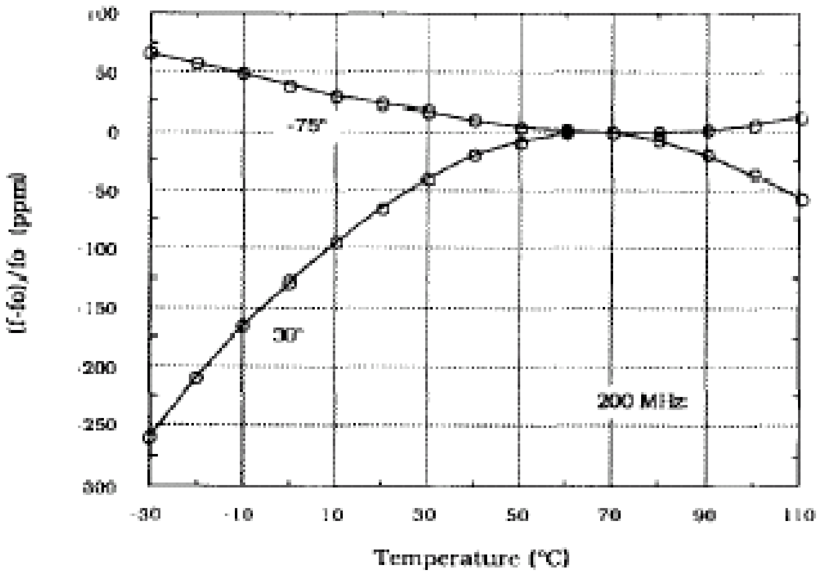


Kyocera 9/2003

Type	PCS Rx SF16-1960M5UB01	Cellular Rx SF16-0881M5UB01	GPS Rx SF16-1575M5UB01
Center Frequency (MHz)	1960	881.5	1575.42
Insertion Loss (dB)	4.1	3.0	1.8
Ripple (dB)	2.0	1.5	0.7
VSWR	2.5	2.5	2.5
Rejection (dB)	DC-1850MHz 30	DC-824MHz 30	DC-1475MHz 30
	1850-1910MHz 15	824-849MHz 30	1475-1525MHz 10
	2040-2200MHz 25	915-960MHz 23	1625-1675MHz 10
	2200-2800MHz 30	960-3000MHz 40	1675-3155MHz 30
	2800-3400MHz 30		3155-6000MHz 20
	3400-6000MHz 20		
Amplitude Imbalance (dB)	+/- 1.0	+/- 1.85	+/- 2.0
Phase Imbalance (deg)	+/- 15	+/- 10	+/- 20
Impedance (ohms)	50 Unbalance Input // 100 Balance Output		

SAW Development- More Stable Cut

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



Bell Labs 1989

SAW Development- CSO to Compete with CXO

SAW Oscillator with K-Cut of Quartz with Euler Angles (0º, 96.5º, 33.8º)

Epson's EG2001 (106~170 MHz).

5x7mm^2 ceramic package.

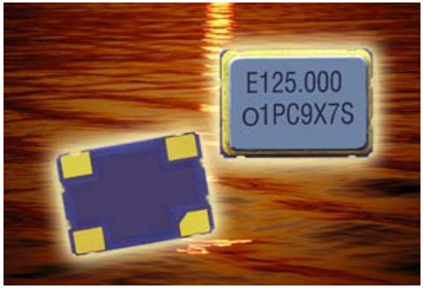
CMOS output.

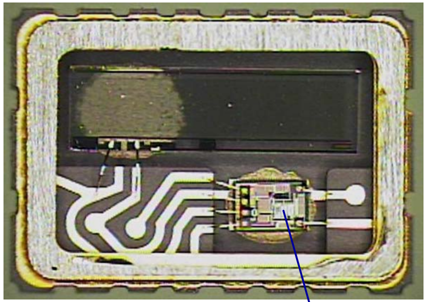
106.25 to 170 MHz.

3ps period jitter.

±100 ppm stability including 10 years aging.

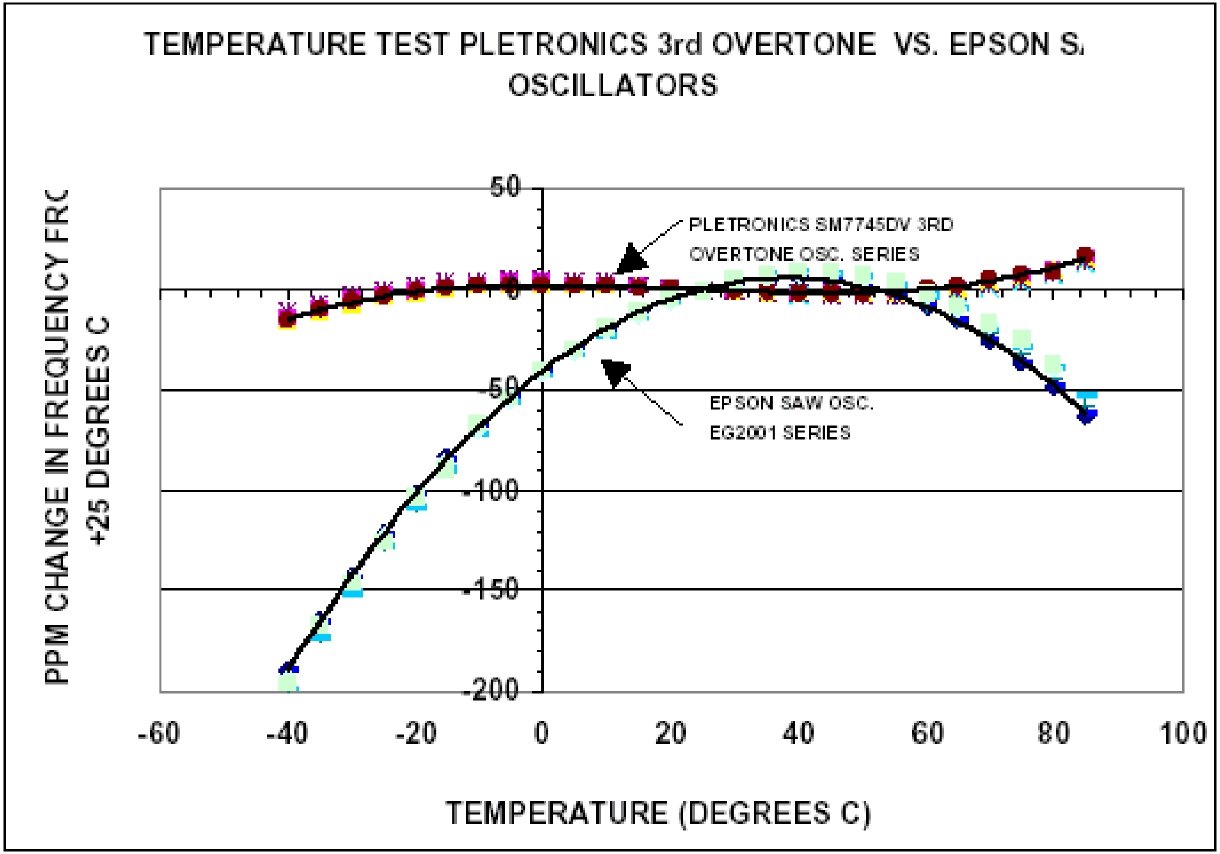
Applications- Gigabit Ethernet, Fiber Channel, SONET/SDH.





NPC CXO IC

SAW Development- CSO Compared with CXO



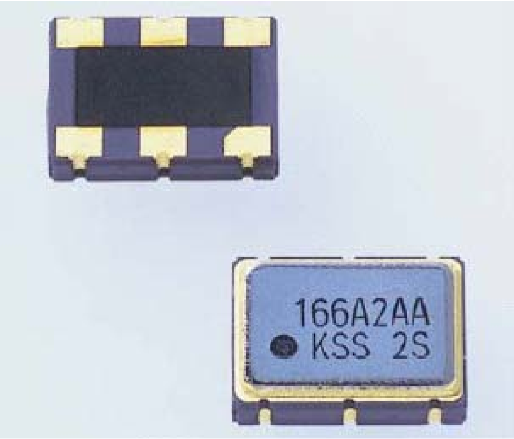
SAW Development- CSO to Compete with CXO

May, 2003

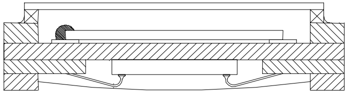
KSS's TSO-1 (LVPECL 50~300 MHz) and FSO-2 (CMOS 100~170 MHz).

5x7mm^2 ceramic package.

±100 ppm total stability (0 to 70 °C).



H-Package



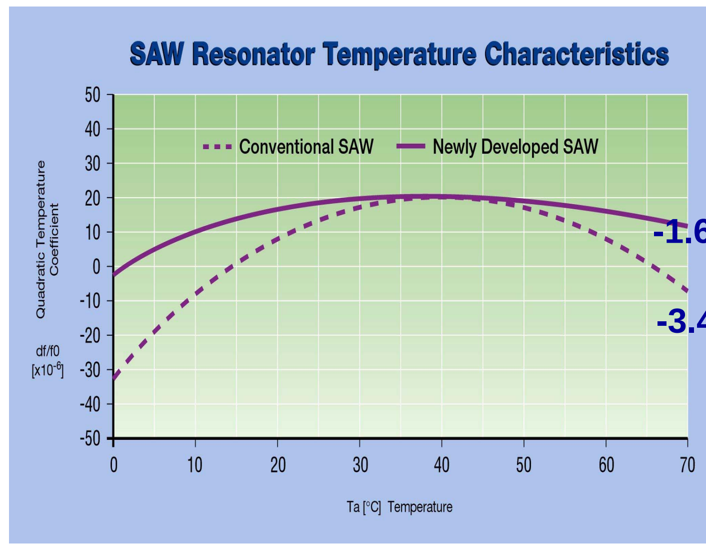
SAW Development- More Stable CSO

Size : 7x5x1.4 mm^3

EG-2102CA

Low Jitter High Frequency SAW Oscillator

- **Low jitter oscillator which adopted the direct oscillation**
- **Ceramic package with 1.4mm thickness**
- **Excellent shock resistance and environmental capability**
- **LVPECL output**
- **Provided with output enable function (OE)**
- **Frequency Range : 100.0000 to 700.0000 MHz**
- **APR : $\pm$100 x 10^{-6}**
- **Power : 3.3$\pm$0.3 V**

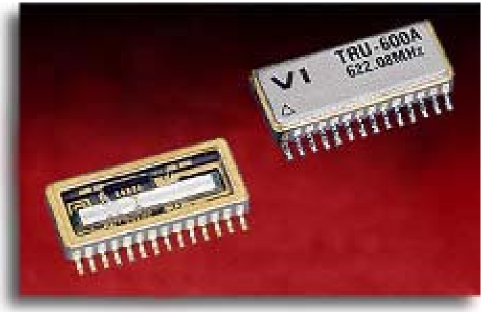


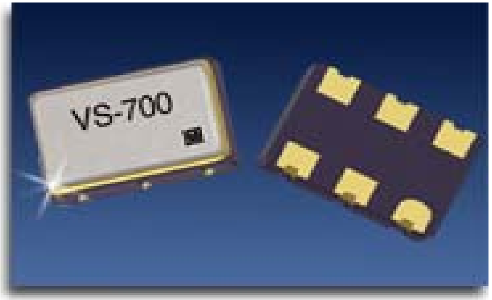
$-1.6\times10^{-8}/^{o}C^{2}$

$-3.4\times10^{-8}/^{o}C^{2}$

SAW Development- VCSO

VI (Up to 800 MHz)





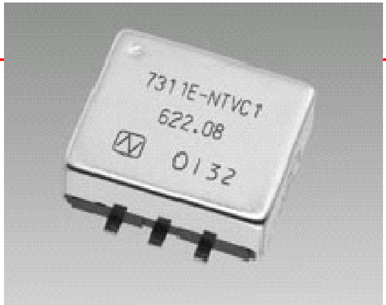
1993- 18.5x10.5 mm²

2000- 14x9x4.5 mm³

2003- 7x5x2 mm³

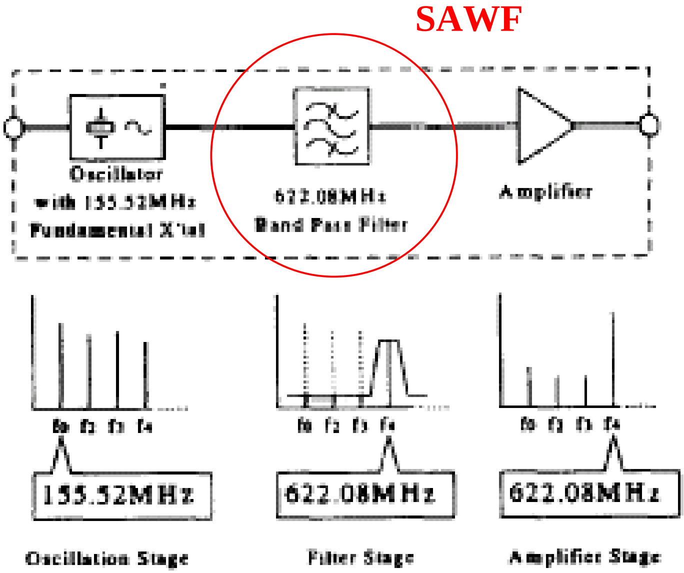
To Compete with VCXO

622 MHz VCXO with SAW Content

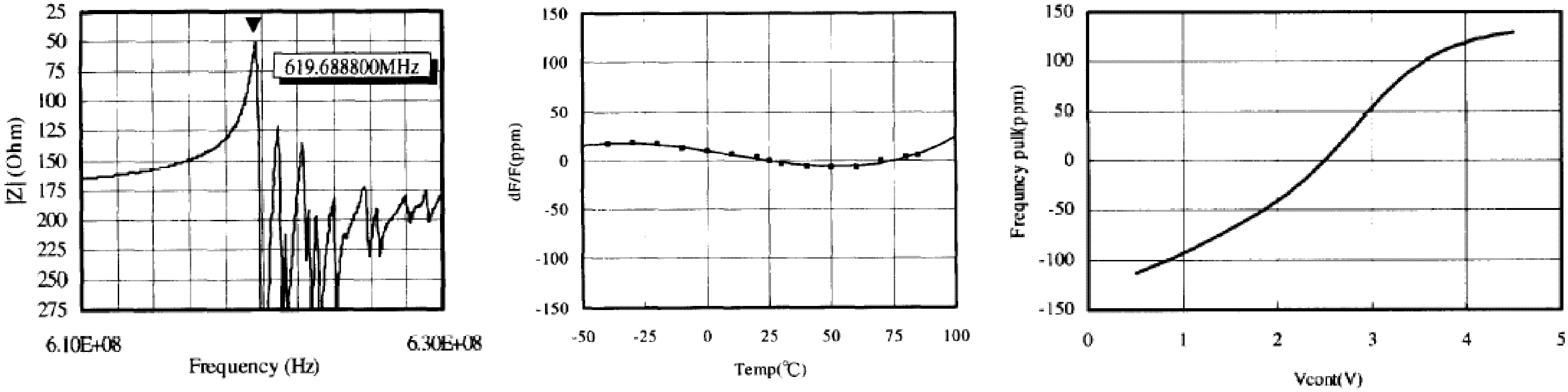


11.4x9.6x6.9 mm^3 (NDK)

Item	Spec.
Nominal Frequency	622.08MHz
Supply Voltage	+3.3V
Control Voltage	+1.65±1.5V
Load	50ohm
Operating. Temp. Range	-10 to +70deg.C
Freq. Stability	±50ppm max.
Freq. Trim Range	±100ppm min.
Output Level	1mW min.
(Sub-) Harmonics	-20dB
Dimension	11.4x9.6x4.5mm
Jitter	16ps rms max.



622 MHz VCXO Using 622 MHz HFF



Yamada et al. 2002

SAW Development- Diamond SAW based VCSO

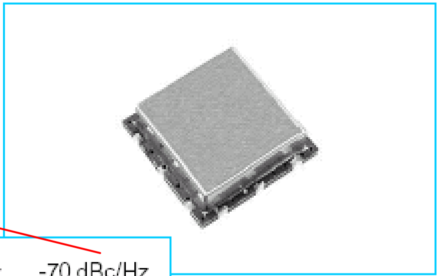
Synergy 2001

622.08 & 2488.32 MHz

0.625x0.625x0.25 in^3

Tuning range ±100 ppm

Power 5V



@ 100 Hz offset	-80 dBc/Hz	-70 dBc/Hz
@ 1 kHz offset	-110 dBc/Hz	-100 dBc/Hz
@ 10 kHz offset	-135 dBc/Hz	-122 dBc/Hz
@ 100 kHz offset	-155 dBc/Hz	-142 dBc/Hz
@ 300 kHz offset	-162 dBc/Hz	-155 dBc/Hz

Epson 2004

2~3 GHz (2488.32 MHz)

10.0x10.0x3.8 mm^3

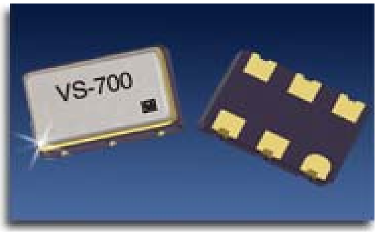
APR ~ ±50 ppm

Power 3V

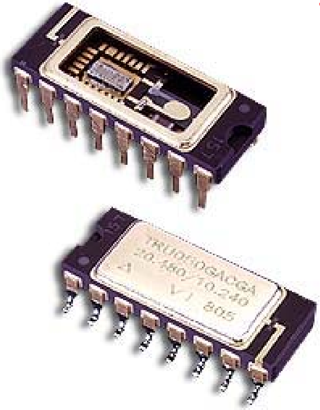
What the Market wants w.r.t. Oscillators?

What?	*Level?*	*BAW*	*SAW*
Frequency	Higher	Overtones, analog multiplier, inverted-mesa (HFF), FBAR, …	STW, LSAW, HVPSAW, …
Activity Dip/Spurious	Absence	Better crystal design tools, …	N/A
Drive Level Dependence	Low	Cleaner process, …	N/A
Short Term Stability	Better	Inverted-mesa, less components, cleaner process, …	Less components, cleaner process, …
Long Term Stability	Better	TCXO, OCXO, …	TCSO? OCSO?
Functions and Integration	More	Synthesizing, programmable, multi-output, …	
Output and Power	Lower	CMOS, LVPECL, LVDS, 3.3V, 2.5V, 1.8V, …	
Cost	Lower	Lower materials/labor cost, plastic package, better yield, …	
Size	Smaller	IC-based, novel packaging, LTCC, CSP, flipchip, …	

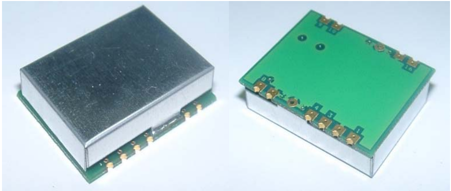
Packaging



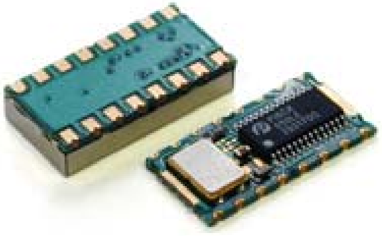
VI's VS-700
VCSO
w/ Bare SAW Delay Line



VI's TRU-050
CDR/FX/CS
w/ Bare Crystal Resonator



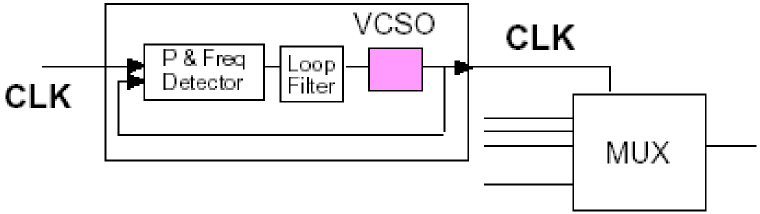
TXC's FX61
Frequency Translator
8 KHz In 77.76 MHz Out
w/ UM1 77.76 MHz Crystal



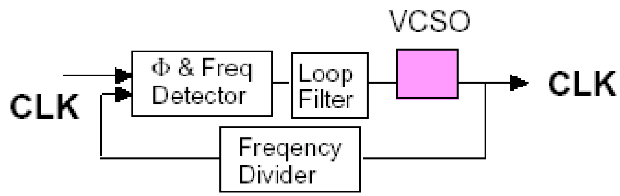
Pericom's SCR-050
CDR/FX/CS
w/ VCXO

The Basis of Most Clock Data Recovery (CDR)units, Clock Smoother (CS), Frequency Translator (FX), Timing Modules (TM), …

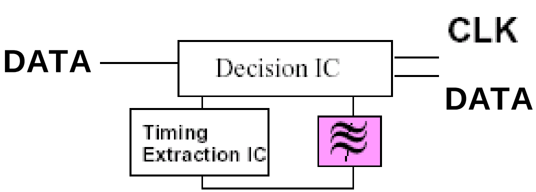
Clock Jitter Filter



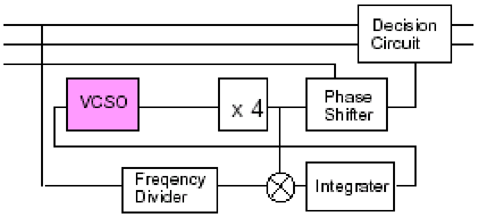
Frequency Translator



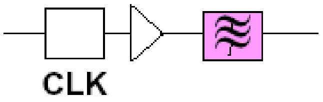
Clock Data Recovery using Retiming filter



Clock Data Recovery using PLL circuit

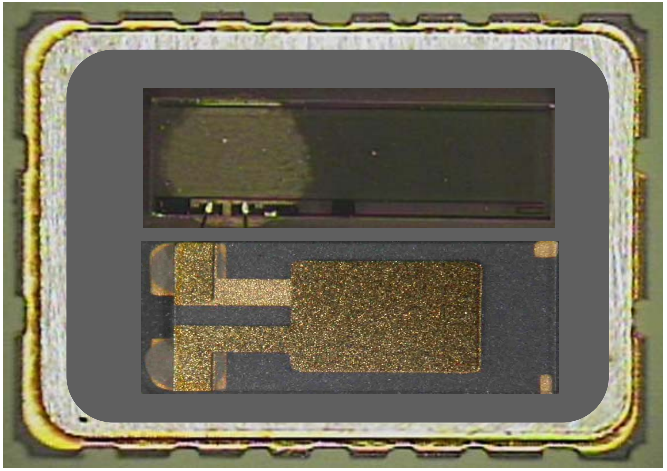


Clock Spurious cut



SMI

BAW and SAW Components in the Same Package



Possible application in frequency synthesizer-

BAW to provide the frequency source and SAW to provide the frequency output.

BAW and SAW components can be put in the same package and frequency trimmed with Au addition.*

* "In-Situ Frequency Trimming of SAW Resonator Using Conventional Crystal Resonator Fine Tuning Method with Gold Thin film Addition," 2003 Proc. IEEE Int'l Ultrasonics Symposium.

Interesting Thoughts

Many inventions/discoveries happened by accident.

What was bad then may be very useful now.

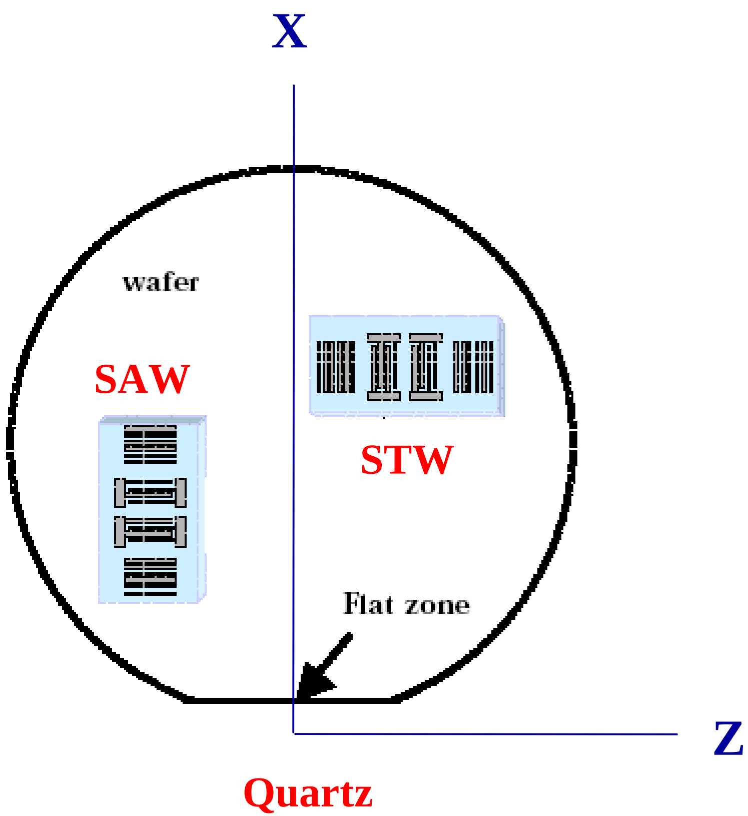
What was impractical then may become very useful now.

Did we miss anything? May be it's time to slow down and look back.

Many Types of SAW- Some with BAW Content

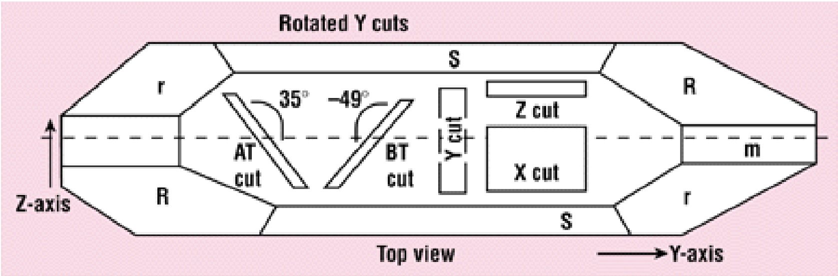
Many inventions/discoveries happened by accident.

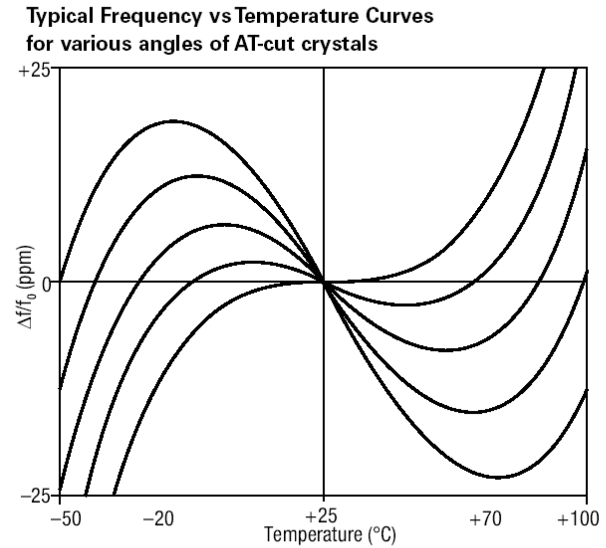
- SAW
- Rayleigh Wave
- Lamb Wave
- Love Wave
- SSBW
- STW
- LSAW
- PSAW
- HVPSAW
- BGS Wave
- Stoneley Wave
- Sezawa Wave
- ……

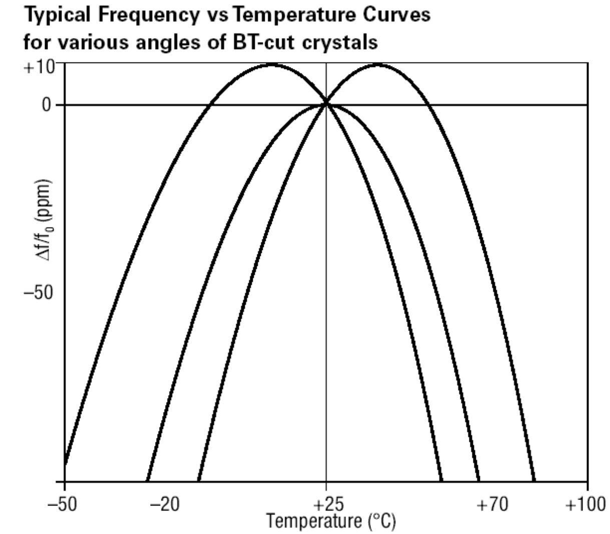


AT-Cut and BT-Cut Crystal Resonators

Did we miss anything? May be it's time to slow down and look back.

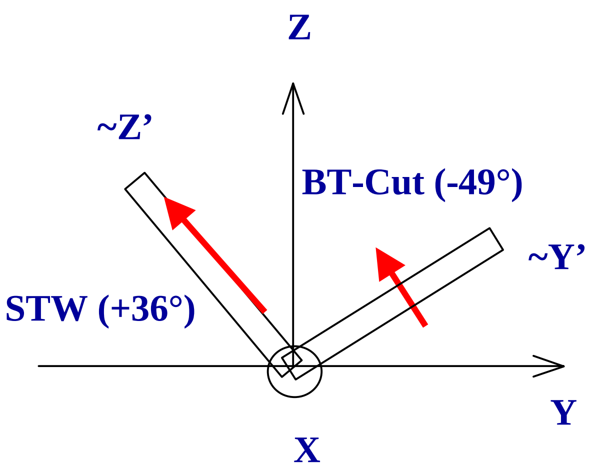






STW and BT-Cut Quartz Resonator

Did we miss anything? May be it's time to slow down and look back.

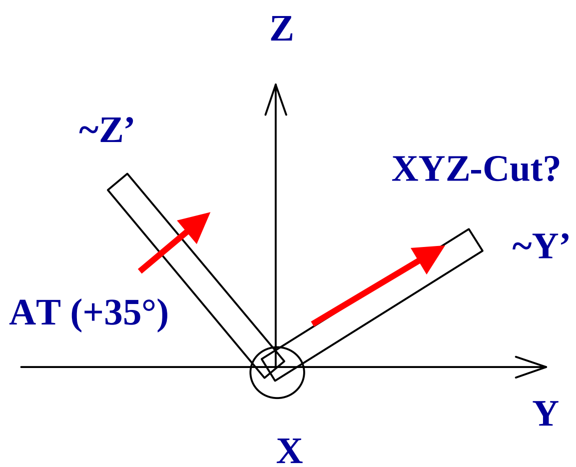


Both STW and BT-Cut have-

~Z' direction wave propagations.

X direction particle motions.

Quadratic df/f vs T.



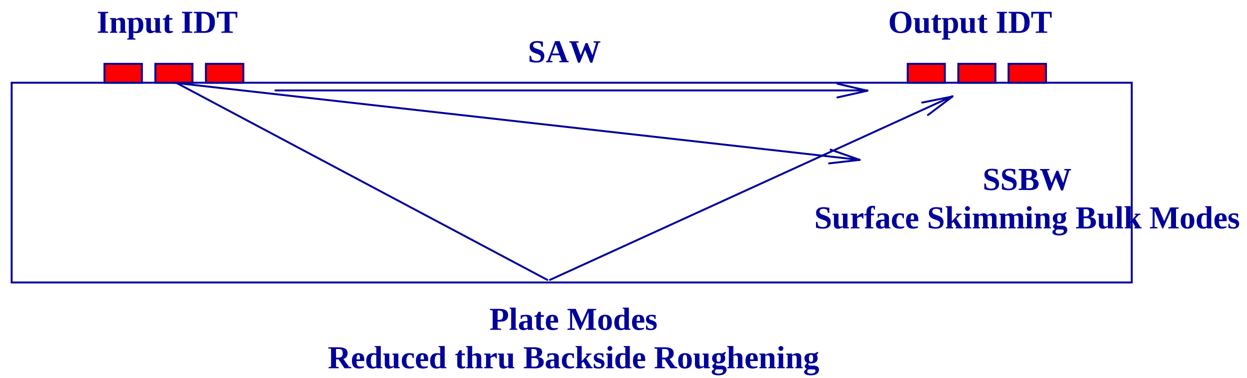
AT-cut has Y' direction wave propagation, X direction particle motion, and cubic df/f vs T.

Is there a ~Y' direction propagating SAW with predominating X direction particle motion and cubic df/f vs T?

If not, why not?

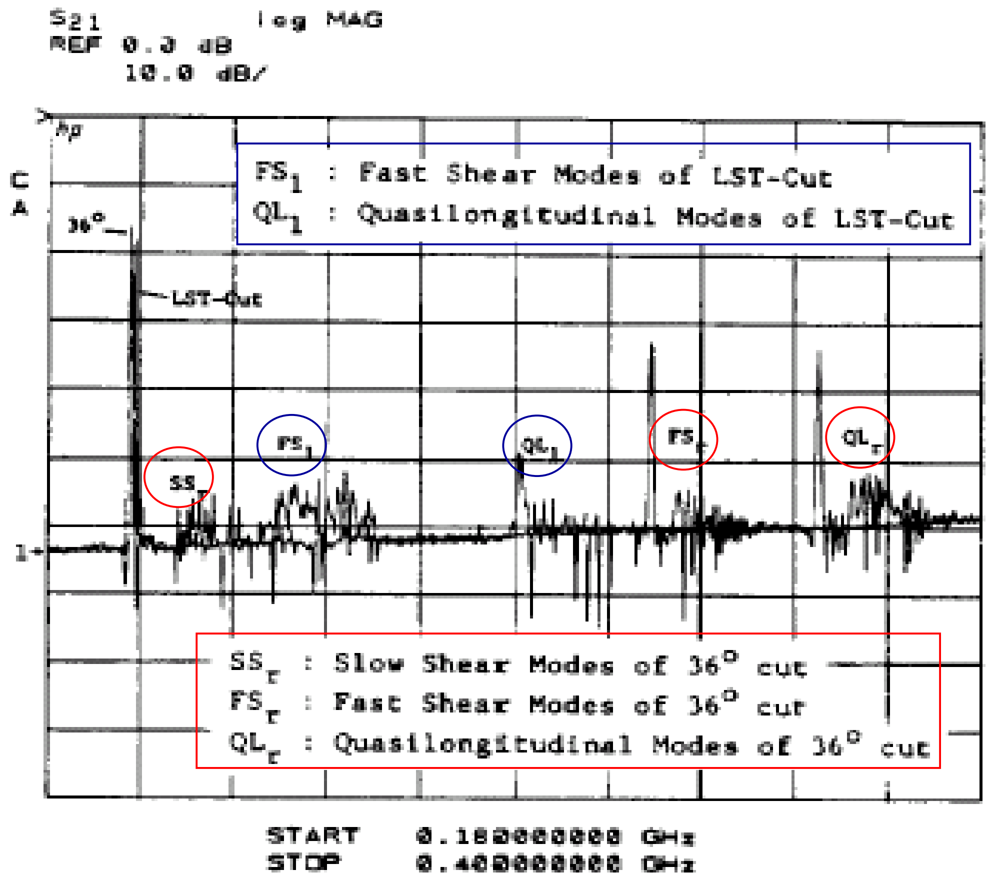
SAW/SSBW/Plate Modes

What was bad then may be very useful now.



SSBW and "Plate Modes" of ST- and LST-Cuts of Quartz

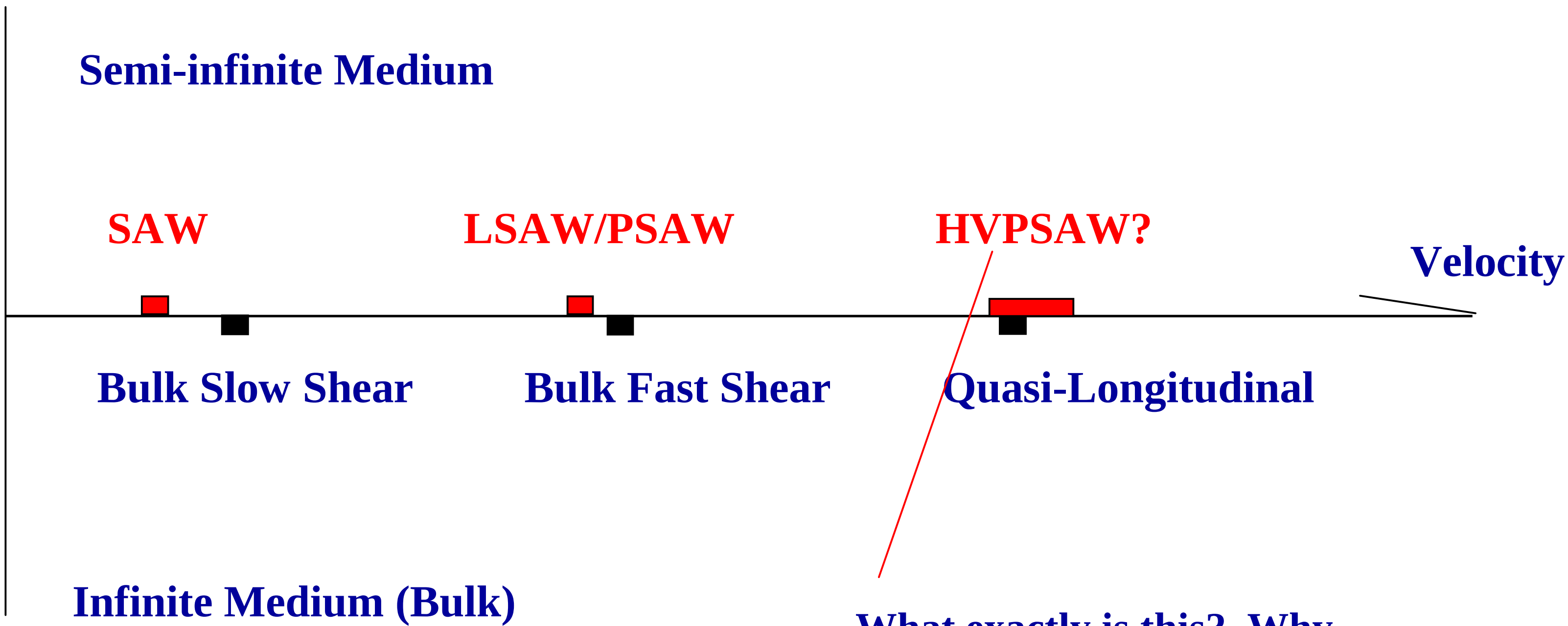
What was bad then may be very useful now.



Bell Labs 1989

More Usable Waves Out There (Faster, Zero TCD, …..)?

What was bad then may be very useful now.



What exactly is this? Why sometimes it has higher velocity than quasi-longitudinal bulk wave?

HVPSAW

Extended Investigation on High Velocity Pseudo Surface Waves

Maurício Pereira da Cunha, *Member, IEEE*

IEEE TRANSACTIONS ON ULTRASONICS, FERROELECTRICS, AND FREQUENCY CONTROL, VOL. 45, NO. 3, MAY 1998

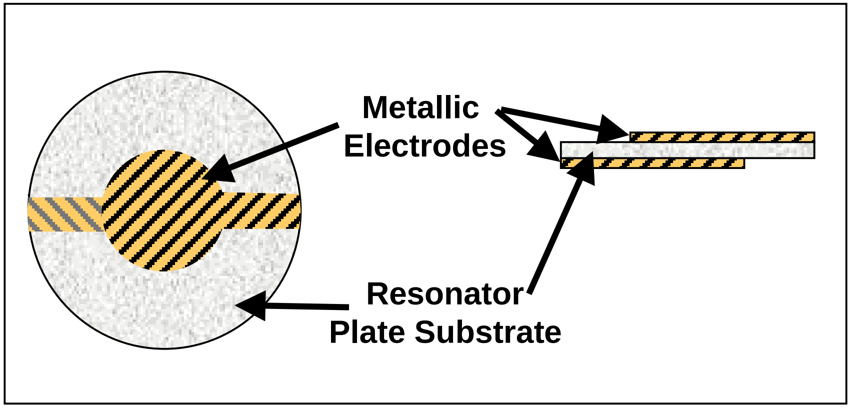
Material and orientation (Euler angles [°]) v_{BULK} [Km/s]	v_p short/open (v_{SAW}^{FREE}) [Km/s]	α short/open [dB/λ]	Fields @ $z=0$ u_x, u_y, u_z, short/open (magnitude [Km]) Symmetry type	PFA[°] short/open $2\|\Delta v_p\|/v_p$ [%]
$LiTaO_3$	6.2442	0.56	1 0.19 0.25	1.3
[90° 90° 31°]	6.3179	8.0e−3	1 0.09 0.13	3.5
[3.336 3.365 6.316]	(3.1420)		TYPE 1	2.3
36° YX-$LiTaO_3$	6.9049	0.80	1 0.11 0.60	−14.8
[0° −54° 0°]	6.9779	0.12	1 0.13 0.58	−12.0
[3.351 4.227 5.589]	(3.1252)		TYPE 1	2.09
quartz AT-X	5.7447	1.0e−2	1 0.12 0.077	−0.2
[0° −54.7° 0°]	5.7454	2.5e−3	1 0.12 0.080	−0.1
[3.298 5.100 5.744]	(3.1510)		TYPE 1	0.023
quartz ST-X	5.7446	6.0e−3	1 0.066 0.081	−0.5
[0° 132.75° 0°]	5.7449	1.2e−3	1 0.056 0.084	−0.7
[3.298 5.100 5.744]	(3.1576)		TYPE 1	0.011
quartz ST-25°	6.5262	1.8e−5	1 0.35 0.090	14.1
[0° 132.75° 25°]	–	–	–	–
[3.365 4.032 6.604]	(3.2475)		TYPE 1	–
GaAs	5.3987	1.9e−2	1 0.04 0.234	2.8
[45° −90° 25°]	5.3986	1.6e−3	1 0.04 0.233	2.9
[2.654 2.990 5.376]	(2.5339)		TYPE 1	0.004

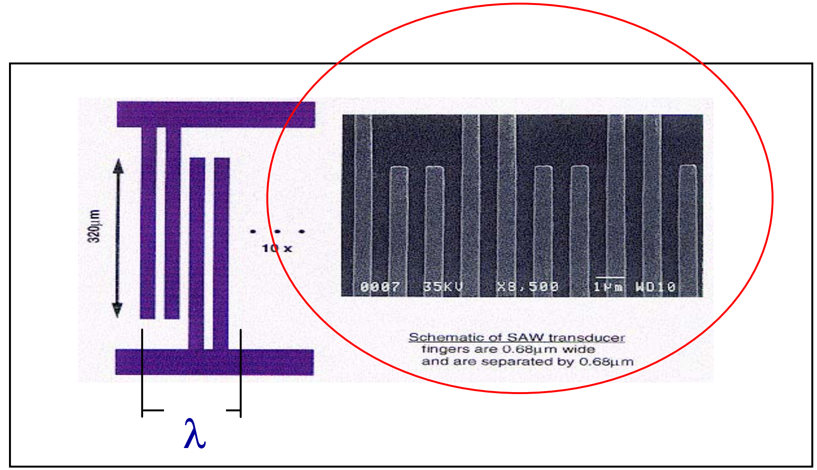
Why sometimes HVPSAW has higher velocity than quasi-longitudinal bulk wave?

BAW and SAW

What was bad then may be very useful now.

4-Finger/Period to Suppress Finger Mechanical Reflections





$$f_n = \frac{n}{2t}\sqrt{\frac{c}{\rho}}$$

fn	***resonance freq***
n	***odd integers***
c	***stiffness coefficient***
ρ	***density***
t	***thickness***

Frequency (f) = Velocity (V) * Wavelength (λ)

Low-Loss SAW Filters

What was bad then may be very useful now.

SPUDT

NSPUDT

RSPUDT

TCRF

LCRF

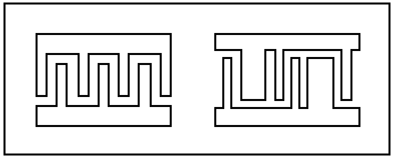
IEF

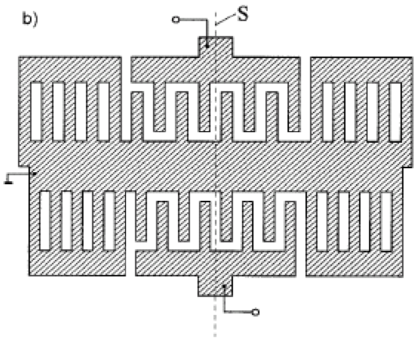
FEUDT

IIDT

……

Figure 1. Two-Focus SFIT





Can we have low-loss SAW filters without using reflections?

Answer is simply "No".

Film Bulk Acoustic Resonator (FBAR) Technology by Agilent

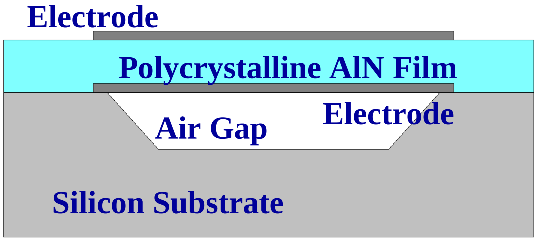
What was impractical then may be very useful now.

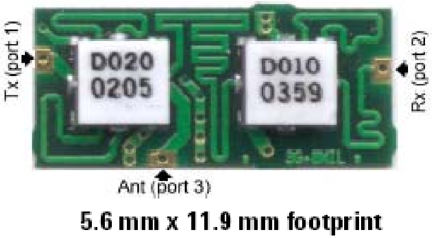
Roughly Speaking-

1980 to 1990 Hot
1990 to 1995 Quiet
1995 to Now Very Hot

Issues-

1.5 ~ 5 GHz.
A threat to SAW.
Processing yield is still low.
Integration is still far way.



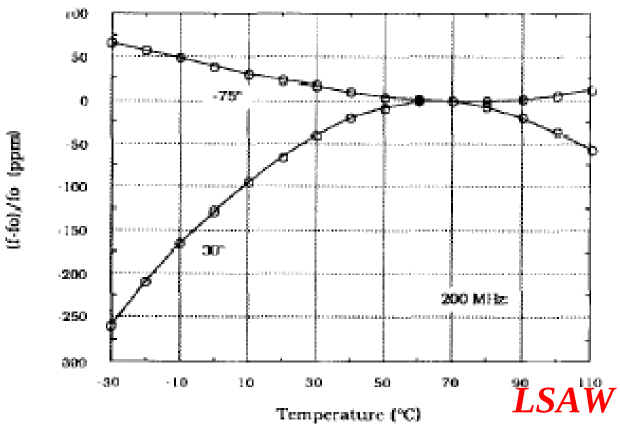


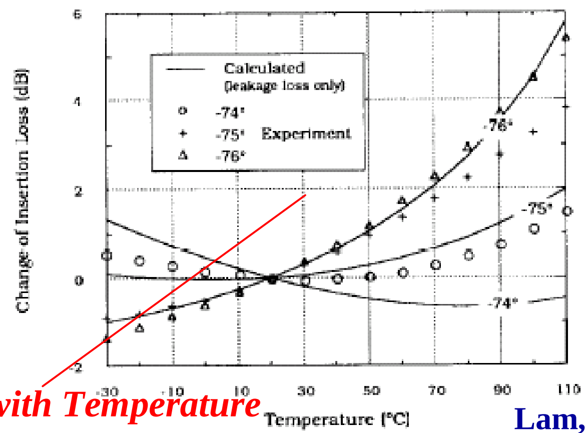
5.6 mm x 11.9 mm footprint

	Ceramic	SAW	FBAR
size (PCS duplexer)	675 mm^3	140 mm^3 (cellular band)	98 mm^3; going to 46 mm^3
electrical (I.L., roll-off)	excellent	good	excellent
power handling	best (>35 dBm @ 2 GHz)	fair (31 dBm @ 900 MHz)	good (>32 dBm @ 2 GHz)
temperature coefficient	0 to -5 ppm/C	-23 to -94 ppm/C	-20 to -30 ppm/C
frequency range filters: duplexers:	 cellular/PCS cellular/PCS	 IF-cellular-PCS cellular/PCS?	 cellular-PCS-mw cellular-PCS-mw
integration	no	Multi-Chip Module (MCM)	MCM ; future full integration

From 36° to 42° $LiTaO_3$- Fujitsu in 1997

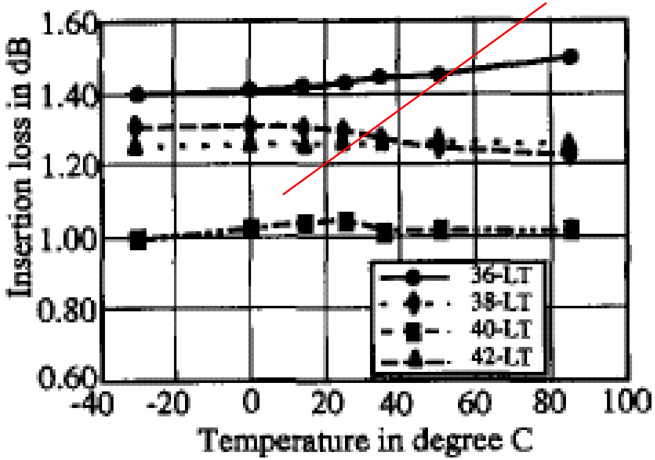
What was bad then may be very useful now.





LSAW with Temperature Dependent Bulk Wave Leakage

Lam, Holt and Hashimoto 1989



Hashimoto, Yamaguchi, et al. 1997

Interesting Thoughts

Many inventions/discoveries happened by accident.

What was bad then may be very useful now.

What was impractical then may become very useful now.

Did we miss anything? May be it's time to slow down and look back.

BAW and SAW are not totally non-related. They are contributing and will continue to contribute to the development of high performance frequency control devices and modules.