A Review of the Timing and Filtering Technologies in Smartphones

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***Abstract*- The explosive growth of the smartphone market especially in supporting LTE (Long Term Evolution) to meet continuous demand for more and faster data transfer has drawn interest from many who want to know how timing and filtering components are used in smartphones to support the crowded spectrum and their future market opportunities. Known to many, the timing and filtering functions in smartphones have been diligently supported for many years by some "physically moving" electromechanical components based on piezoelectric materials- quartz-based crystal, lithium tantalate- and lithium niobate-based surface acoustic wave (SAW) RF filter, and aluminum nitride-based bulk acoustic wave (BAW) RF filter. This paper reviews the current timing and filtering technologies in smartphones and discusses the possible trends.**

***Keywords*- timing, filtering, quartz crystal, SAW, BAW, FBAR, SMR**

I. Introduction

The explosive growth of the smartphone market especially in supporting LTE (Long Term Evolution) to meet continuous demand for more and faster data transfer has drawn interest from many who want to know how timing and filtering components are used in smartphones to support the crowded spectrum and the future market opportunities. A smartphone is unequivocally a brilliant product and necessity of the digital age. However, its timing (frequency generation) and filtering (frequency control) functions still have to be processed by analog timing and filtering components. At the smartphone RF front-end (RFFE), a clock is needed to set the frequency such that the "door" is opened at the right position in the RF spectrum (Fig. 1). Then a filter is needed to ensure the "door" has the right width to pass the needed bandwidth. Both timing and filtering functions are important.

Known to many, the timing and filtering functions in smartphones have been diligently supported for many years by some "physically moving" electromechanical components based on piezoelectric materials- quartz-based crystal, lithium tantalite (LT)- and lithium niobate (LN)-based surface acoustic wave (SAW) RF filter, and aluminum nitride (AlN)-based bulk acoustic wave (BAW) RF filter (Table 1).

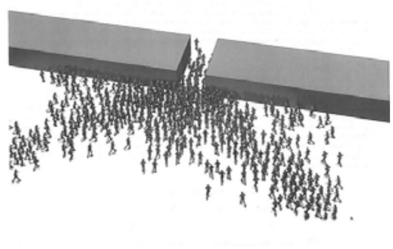


Fig. 1 Timing and Filtering

Crystal-based (<MHz ~ 200 MHz)	SAW-based (<50 MHz ~ 3.5 GHz)	BAW-based (1.5 ~ 5 GHz)
Tuning Fork and Crystal	SAWR	
MCF	SAWF	(FBAR/SMR)Filter
XO	SO	"FBAR Oscillator"
VCXO	VCSO	"VCFO"
TCXO	TCSO	"TCFO"
OCXO	OCSO	"OCFO"
Timing Module (TM)	Timing Module (TM)	☐ In Smartphones
		" " Not Productized Yet

Table 1 Crystal, SAW, and BAW for Timing and Filtering

Due to its intrinsic high quality factor Q and high temperature stability, quartz is currently the only material that can support different timing functions in smartphones. Q determines the timing accuracy and higher Q in general also means less power is needed to sustain vibration. Quartz can support 32 kHz ($32{,}768=2^{16}$ Hz) real time clocking (<150 ppm) using the X-Cut tuning fork and 10-50 MHz applications (<50 ppm) using AT-Cut crystal (Fig. 2). The weak coupling factor (a measure of electrical-mechanical energy conversion efficiency) of quartz also allows frequency pulling using load capacitors to set final frequency to within a few ppm. (At the time when a superheterodyne front-end for mobile phones was used, quartz was also the choice material for IF SAW channel filter.) The crystal timing industry is experiencing challenges in the smartphone market which include- size reduction seemingly near its end based on its traditional packaging

Invited Paper- IEEE International Frequency Control Symposium, May 9~12, 2016, New Orleans, USA

technique, rapid average selling price drop as second and third tier suppliers can now support some of the smallest crystals and crystal oscillators (XOs), threats from MEMS oscillators (MOs), and with no clear indication more timing components will be needed.

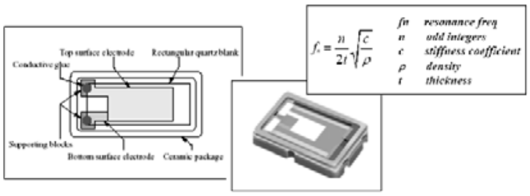


Fig. 2 SMD MHz Crystal

LT- and LN-based SAW filters have been supporting RF filtering functions in mobile phones since the early 90s. Later on AlN-based FBAR (film bulk acoustic resonator) filters joined by AlN-based SMR (surface mounted resonator) filters successfully took hold to compete with SAW filters. BAW meant crystal in the early days. The author prefers to group both FBAR and SMR under BAW (Fig. 3).

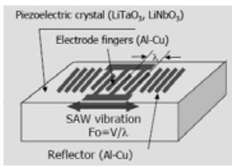


Fig. 3a SAW[1]

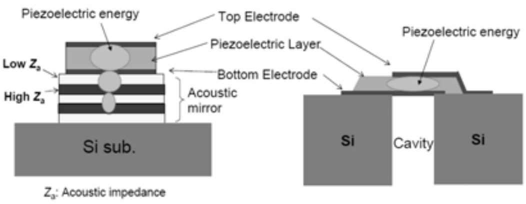


Fig. 3b BAW- SMR & FBAR[1]

It is expected that more SAW- and BAW-based filters will be needed to support the increasing number of RF bands (700 to 3500 MHz) based on the LTE initiative in the transceiver and diversity paths. Downlink and uplink carrier aggregation (CA) will also demand higher performance filters. Unlike the timing components, opportunities seem to be more abundant for the filtering components in the smartphone market. Overall performance, size, and cost will determine the competitiveness of the filter suppliers.

II. Crystal and Crystal Oscillator for Timing

The author reported in 2008 [2] the minimum sizes of 32 kHz crystal (2012 size = 2.0mmx1.2mm), MHz crystal (2016 size), and MHz TCXO [3] (temperature-compensated crystal oscillator, 2016 size) in volume production then (Figs. 4 and 5). In that year a major smartphone company launched its second generation smartphone. Based on some teardown reports later on, it was revealed that the earliest generations of smartphones from the company likely had the following crystals and crystal oscillators inside for timing purposes- two 2012 size 32 kHz crystals for baseband and power management respectively, one 2016 size 24 MHz crystal for CPU, one 2016 size 37.4 MHz crystal for WiFi/Bluetooth®/FM, one 2520 size 33.6 MHz TCXO for GPS (<0.5 ppm), and one 2016 size 26 MHz TCXO for transceiver (<2.5 ppm).

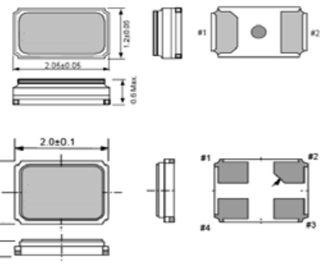


Fig. 4 Smallest 32 kHz and MHz Crystals in the Late 2000s[2]

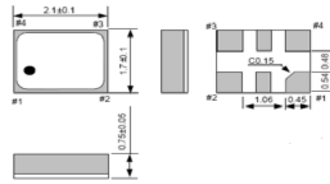


Fig. 5 Smallest 12~52 MHz TCXO in the Late 2000s[2]

After seven years, the smaller 1610 size 32 kHz crystal is now available from selected suppliers. It finds some specialty applications (e.g. possibly in some newest Bluetooth®-compatible hearing aids) but it seems to be not yet adopted in smartphones. The smaller 1612 size MHz crystal is in volume production and is used by smartphones. Further size reduction effort for 32 kHz and MHz crystals is on-going. Higher equivalent series resistance (ESR)- >60kΩ for 32 kHz and >80Ω for MHz) and lower drive level DL) allowance may likely limit their usage in smartphones and wearables to come (Table 2) [4]. Recently there was innovative effort reported in reducing the energy loss through the MHz crystal anchor by applying phononic crystals [5].

As for TCXO, some smartphone companies are now using cellular transceiver chips with a built-in GPS receiver and self-compensating algorithm that needs only a single thermistor-inside crystal off-chip (Fig. 6) [6]. A thermistor is needed to achieve the <0.5 ppm GPS TCXO requirement. In summary, the size trend of kHz crystal, MHz crystal, and TCXO for smartphones is depicted in Table 3.

Suppliers	1210	1612	2016	2520	3225
A		30~54 MHz	24~54 MHz	12~48 and 52 MHz	12~60 MHz
		50/100 µW	100 µW	100 µW	10~100 µW
		30~32 MHz 200Ω	24~26 MHz 80Ω	12~16 MHz 150Ω	12~13 MHz 100Ω
		32~36 MHz 100Ω	26~54 MHz 60Ω	16~25 MHz 80Ω	13~20 MHz 80Ω
		36~54 MHz 80Ω		25~30 MHz 60Ω	20~25 MHz 60Ω
				30~35 MHz 50Ω	25~30 MHz 50Ω
				35~48 MHz 40Ω	30~60 MHz 40Ω
B	In Development	26~60 MHz	18~60 MHz	16~60 MHz	10~60 MHz
	30~60 MHz	10,20 µW	30 µW	30 µW	30,50 µW
	100 µW typical	60~200Ω	60~300Ω	60~80Ω	10~13 MHz 30~200Ω
	300Ω				13 to 60 MHz 120Ω
C		26~80 MHz	24~80 MHz	16~80 MHz	12~150 MHz
		200 µW	200 µW	200 µW	200 µW
		26~32 MHz 150Ω	24~26 MHz 80Ω	16~20 MHz 80Ω	12~13 MHz 100Ω
		32~38 MHz 100Ω	26~40 MHz 60Ω	20~30 MHz 60Ω	13~20 MHz 80Ω
		38~80 MHz 80Ω	40~80 MHz 50Ω	30~35 MHz 50Ω	20~54 MHz 50Ω
				35~80 MHz 40Ω	40~100 MHz 140Ω
					100~150 MHz 100Ω
D		30~60 MHz	18~60 MHz	13.56~60 MHz	12~54 MHz
		100 µW	100 µW	100 µW	100 µW
		30~40 MHz 200Ω	18~26 MHz 150Ω	13.56~16 MHz 200Ω	12~13 MHz 200Ω
		40~60 MHz 100Ω	26~36 MHz 80Ω	16~19.2 MHz 100Ω	13~15 MHz 150Ω
			36~40 MHz 60Ω	19.2~26 MHz 80 Ω	15~16 MHz 100Ω
			40~60 MHz 50Ω	26~30 MHz 60Ω	16~20 MHz 80Ω
				30~60 MHz 50Ω	20~26 MHz 50Ω
					26~54 MHz 40Ω
E	In Development	30~80 MHz	18~80 MHz	13.5~80 MHz	10~60 MHz
	36~80 MHz	100 µW	100 µW	200 µW	200 µW
		100 Ω	18~20 MHz 300Ω	13.5~16 MHz 300Ω	10~16 MHz 200Ω
			20~25 MHz 200Ω	16~20 MHz 150Ω	16~30 MHz 100Ω
			25~40 MHz 100Ω	20~30 MHz 100Ω	30~60 MHz 50Ω
			40~80 MHz 60Ω	30~80 MHz 60Ω	
F		24~54 MHz	20~54 MHz	12~54 MHz	10~54 MHz
		200 µW	200 µW	100 µW	100 µW
		24~30 MHz 100Ω	20~30 MHz 100Ω	12~13 MHz 150Ω	10~16 MHz 100Ω
		30~54 MHz 80Ω	30~54 MHz 80Ω	14~30 MHz 100Ω	16~20 MHz 80Ω
DL is Max.				30~54 MHz 60Ω	20~54 MHz 60Ω

Table 2 MHz Crystal ESR and Maximum Drive Level[5]

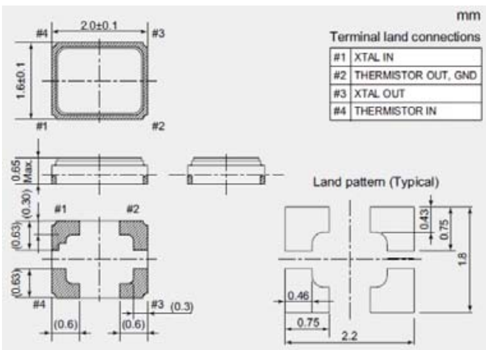


Fig. 6 Thermistor-Inside Crystal[6]

Crystal								
32 kHz Crystal	Various Molded Sizes	4115	3215		2012	1610 Sampling	?	
MHz Crystal	7050 6035	5032 4025	3225	2520	2016	1612	1210 Sampling	1008?
TCXO								
MHz TCXO (Analog)	7050	5032	3225	2520	2016	1612 Sampling	1210?	

Table 3 Size Trend of kHz Crystal, MHz Crystal, and TCXO

III. MEMS Oscillators for Timing

The strong push for MOs to compete in the crystal timing market more than ten years ago suffered some false starts [2]. The earliest MO had inadequate performance and was only able to marginally compete with the then programmable crystal oscillator (PXO) which though was a small segment of the overall XO market. In addition, the bulk of the crystal timing market is still crystal. There are still no commercial oscillator ICs to support MEMS resonators (MRs) whch can be non temperature-compensated, DC biased (electrostatic), and DC driven (electroresistive). It is the author's opinion that the early MO startups unfortunately didn't understand the crystal timing industry well enough to compete in it.

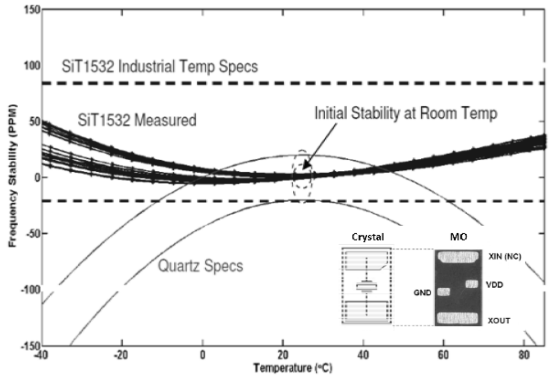


Fig. 7 32 kHz MO[7]

In the past few years MO companies, based on lessons learned, have made tremendous progress in MR, oscillator circuit, and PLL (phase locked loop) technologies such that the current generation of MO can compete in the commodity and some commercial XO market segments. As can be seen in Table 3, the smallest 32 kHz crystal in volume production now is 2012 size and a 1610 size is in development. One MO supplier has developed very low power 2012 and 1508 (~1610) size 32 kHz MOs with low temperature drift and set tolerance to compete head-on with the 32 kHz crystal [7]. For the 2012 size, customers can use the same 32 kHz 2012 size crystal footprint. Customers do need to add pins to drive and ground the MO but will save board space as load capacitors are no longer needed.

IV. The "Future" of Timing in Smartphones

As stated in Section III, a major smartphone company used four crystals and two TCXOs in its earliest generations of smartphone in the late 00s. Teardown reports indicate the 2014 generation of smartphone from this company had only four crystals- one 2012 size 32 kHz crystal for baseband, one 1612 size 24 MHz crystal for CPU and near field communication (NFC), one 1612 size 37.4 MHz crystal for WiFi/Bluetooth®/FM, and one 2016 size 19.2 MHz thermistor-inside crystal for transceiver and GPS. The author notes the following that may be the norm in the future for some advanced smartphones- no more TCXO; less number of crystals even though smartphones have become more sophisticated; single crystal supporting multiple functions; and more difficulty in crystal size reduction. Crystal blanks are processed mostly one at a time (singulate). Crystals are also encapsulated in high temperature co-fire ceramic leadless chip carrier (HTCC LCC) with a metal lid one at a time and are 100% frequency trimmed (ion beam milling). Smaller size crystals need more costly miniature HTCC LCC. Seam seal metal lid tacking is no longer feasible for small size crystals and a more costly solder sealing method like AuSn is needed. Some crystal companies are using "MEMS" technique to process crystal blanks from rectangular quartz wafers [8]. The finished crystal blanks still have to be encapsulated in HTCC LCC one at a time. Some crysal companies use metal dome lid to enclose crystal blanks on low cost wired ceramic. The resulting crystal, however, may not be as hermetic as required by many applications [9]. Some crystal companies are also investigating 6" Si wafer level packaging WLP) but face many challenges like cost, flatness, parallelism, through silicon via (TSV), trimming, etc [10]. It is not really WLP though because the cystal blanks are still processed discretely and mounted onto a silicon base wafer. In the meantime, MO technology continues to improve. MR and the associated oscillator+PLL IC are processed in wafer form. MO cost is expected to go lower as it gets smaller. Using MO to replace kHz crystals as mentioned in the previous section may continue into the future covering also MHz.

V. SAW and BAW Filtering

In the early 90s, SAW filters based on impedance element filter (IEF = ladder type), coupled resonator filter (CRF = double mode SAW (DMS)), and interdigitated interdigital transducer (IIDT) were used in mobile phones covering the single-band analog systems (AMPS, ETACS, NTACS, NMT450, NMT900) and digital systems (IS-54/136, IS-95, GSM, PDC) [11] were encapsulated in HTCC LCC packages (5050/3838/3030) similar to those used by crystals.

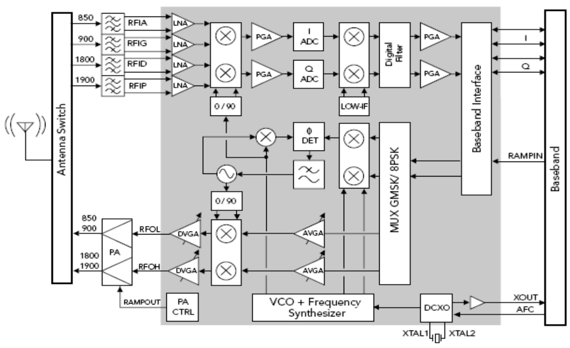


Fig. 8 GSM Transceiver Chipset with On-chip DCXO[2]

The author reported in 2008 [2]- "…GSM transceiver chipsets with on-chip digitally-compensated crystal oscillator (DCXO) circuit began to appear. TCXO is no longer needed to pair with these transceiver chipsets. However, an off-chip quartz crystal was still needed…" The figure used (Fig. 8) also represents the advanced cellular transceiver technology then in supporting multi-band GSM-850, EGSM-900, DCS-1800 and PCS-1900 in 3GPP (equivalent to band 5, band 8, band 3, and band 2 in LTE) [12]. Filtering for the former two were supported by SAW filters. Filtering for the latter two were supported by both SAW and BAW filters.

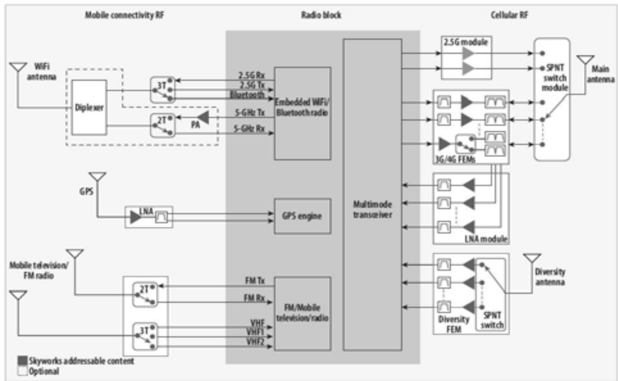


Fig. 9 Typical Smarphone Architecture[13]

The current generation of LTE smartphones supporting multi-mode multi-band (MMMB) has very complicate front-ends between the transceivers and the antennas (Fig. 9) [13]. It is becoming quite difficult for smartphone companies to populate discretely the many filters, duplexers, switches, PAs, matching circuits, etc. Front-end modules (FEMs) are now available from some suppliers [14,15]. These <1mm thick multi-chip module (MCM) FEMs include-

Front-End Module (switches+duplexers/filters)
PA-Inside-Module (switches+PAs+duplexers/filters),
Diversity Module (switches+LNAs+filters),
WiFi/BT/FM Module (some with crystal inside),
GPS Module (some with LNA, filter, and TCXO inside).

To support these modules, SAW/BAW filter/duplexer packaging (Fig. 10) also moves to chip scale packaging (CSP), wafer level chip scale packaging (WLCSP), and wafer level packaging (WLP) [16].

For filtering, both Q and coupling factor are important. Q determines the filter insertion loss and filter roll-off sharpness. Coupling factor determines the sustainable filter bandwidth. The two widely used SAW cuts are 42YX-LT (leaky SAW, higher Q, lower TCF) and 128YX-LN ("Rayleigh" SAW, lower Q, higher TCF). Another important factor is temperature coefficient of frequency (TCF). Lower TCF means filter passband drifts less over temperature. In recent years, temperature-compensated SAW (TC-SAW) filters have become available. The two widely used TC-SAW configurations are LT/Si (or LT/Sapphire) and SiO2/LN. With the right SiO2 thckness to SAW period ratios, the Q of SiO2/LN can be improved along with reduced TCF (Fig. 11).

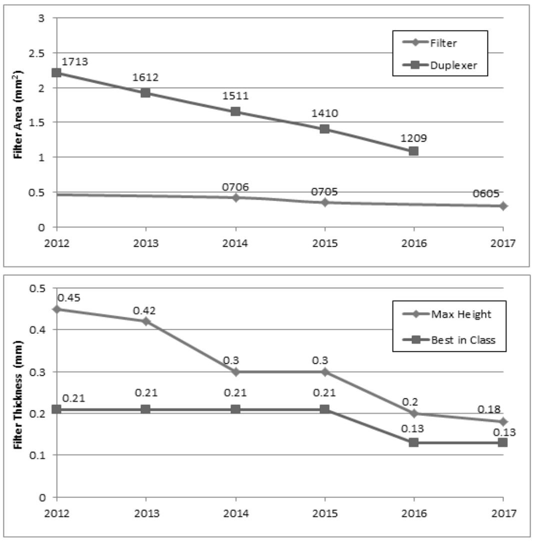
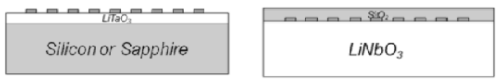


Fig. 10 Size and Thickness Trend of SAW/BAW Filter/Duplexer[16]



LT on Si/Sapphire	SiO2 on LN
No Redesign Needed	Redesign Needed
4/6" Possible	4" For Now
Q Maintained	Q Improved
Zero ppm/C Not Likely	Zero ppm/C Possible
Difficult to Increase Coupling	Easy to Reduce Coupling

Fig. 11 TC-SAW Configurations

As stated in Section I, AlN-based FBAR filters joined by AlN-based SMR filters successfully took hold to compete with SAW filters more than ten years ago. FBAR and SMR structures have not changed much- polygon, "oval" shape, etc (Fig. 12) [17,18]. They remain strong especially in competing in the high frequency filter and duplexer market (Table 4).

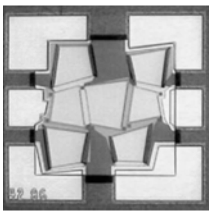


Figure 12a FBAR Filter[17]

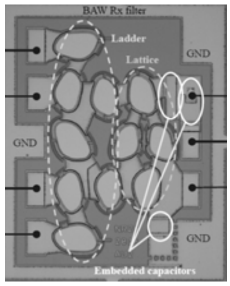


Figure 12b FBAR Filter[18]

SAW-based (<50 MHz ~ 3.5 GHz)	BAW-based (1.5 ~ 5 GHz)
-	Higher Frequency
Higher Coupling	-
-	High Power Durability
-	Higher Q
-	Lower TCF
(Low/Zero TCF TC-SAW)	(Low/Zero TCF TC-BAW)
-	Higher Power Durability
-	More Costly
Balanced/Single-End	Single-End

Table 4 SAW and BAW Comparison

VI. The "Future" of Filtering in Smartphones

The smartphone market continues to grow. The demand for smaller and thinner filters and duplexers shall continue. On the one hand, there are no clear new technologies which can replace the current "one band one filter" scheme. Tunable filtering is in development stage but it likely still follows the "one band one filter" scheme. In addition, meeting requirements on low insertion loss, high close-in attenuatons, high isolation (in duplexer), co-existence with WiFi/GPS, carrier aggregation, etc. during tuning will not be trivial [19]. On the other hand, there are also no clear new technologies to compete with SAW and BAW in performance, size, and cost.

The author believes that in the next five to ten years the filtering technology competition in smartphones will still be limited to between SAW and BAW.

SAW has made tremendous progress in the past few years and TC-SAW is one great example. SAW seems to have more "parameters" to work on to continue the improvement efforts- the substrates, the wave types (lower and higher SAW velocities), the interdigital transducer (IDT) designs, the electrode metal stacks, the compensation coating, etc [20].

BAW also has room for improvements. In a way BAW learned from the crystal industry- building a resonator with piezoelectric material sandwiched in two electrodes- thickness-entensional mode for BAW and thickness-shear mode for crystal. There may still be lessons to learn from crystal.

(In one occasion SAW learned from crystal- trimming SAW resonator using the crystal fine tuning method with a gold thin film addition [21].) Between the flexural mode kHz X-Cut tuning fork and thickness-shear mode MHz AT-Cut crystal there may be other vibration modes which BAW can use to push down frequency and to further improve Q, coupling factor, and TCF.

The evolving of hybrid SAW-BAW technology has also attracted attention. When the piezoelectric "substrate" is very thin, "SAW" IDT excites "BAW" (plate) modes efficiently [22]. This MEMS-type development is primarily for timing applications (Fig. 13). As the filter/duplexer market continues to expand, it's expected to see more development effort in this area.

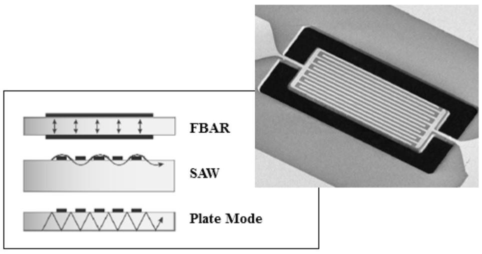


Figure 13 Plate Wave Resonator[22]

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