9. Saw-Based Frequency Control Product Applications

Introduction

In the first half of this paper, several SAW-based frequency control products which find applications in modern telecommunication systems like Synchronous Optical Network (SONET), Synchronous Digital Hierarchy (SDH), and Asynchronous Transfer Mode (ATM) will be presented. They play the important role of frequency synthesis, frequency translation, data and clock recovery, and clock signal distribution to ensure low bit error rate transport of signals in high frequency optical telecommunication equipment up to 2.5 Gb/s.

In the second half of this paper, the applications and the availability of low-loss RF and IF SAW filters for existing and emerging wireless systems, the competing technologies, the challenges to enter the market, and the applications of conventional high-loss and high-selectivity SAW filters in equipment based on the Code Division Multiple Access (CDMA) technique will be reviewed.

1.1 SAW-Based Timing Recovery Unit

The SAW-based timing recovery unit (TRU600) regenerates data and clock signals from corrupted NRZ digital data streams, such as those encountered in fiberoptic data link and telecommunication applications. Although there are many suppliers providing discrete SAW filters for timing recovery applications, the TRU600 allows an easy drop-in solution for users. SAW-based timing recovery scheme offers the best jitter performance in many situations[1]. One example is in a SONET/SDH/ATM network interface card application situation where TRU600A can be used between the O/E converter and a serial to parallel chip[2]. A summary of the specification follows:

Supply Voltage	**5 V**
Acquisition Time	**<2 ms**
Output Clock Random Jitter	**10 ps rms**
Power Consumption	**325 mW**

The TRU600 features a high-speed bipolar ASIC and a SAW filter in a hermetically sealed, 28-lead ceramic surface mountable package (18.5x10.5x3.4 mm3). To extract a clock signal from the input data, the data is first passed through a prefilter and frequency doubler stage. This generates pulses containing significant spectral energy at the input data rate. A precision narrow-band SAW filter, centered at the clock frequency, substantially suppresses jitter by rejecting other frequencies. The extracted clock is then accurately aligned with the incoming data signal at the input of a decision circuit which then retimes the data.

In addition to producing outputs with very low jitter, the TRU600 has excellent stability, fast acquisition time, and robust operation. It is available with standard SONET/SDH/ATM frequencies at 155.52, 311.04, and 622.08 MHz. Additional frequencies (124.416, 125, 139.264, 200, 265.625, and 278.528 MHz) for FDDI, ESCON, Fiber Channel, ISDN (CEPT 4), and other applications are also available.

To prepare for the increasing capacity demand in the tele/data communication market, a similar device which works up to the STS-48/STM-16 rate (2488.32 MHz) is being developed. Such a SAW-based clock and data recovery module is preferred in the emerging high speed optical communication receiver application[4].

1.2 Discrete SAW Filters for Timing Recovery

For customers who prefer to build their own timing recovery path on their SONET/SDH/ATM boards, we offer discrete SAW filters to perform the clock extraction function. They are available at 155.52, 622.08, and 2488.32 MHz. A summary of the specification follows:

Frequency (MHz)	**155.52**	**622.08**	**2488.32**
Insertion Loss (dB)		**17**	**15.5**
19.5			
3-dB Q	**420**	**800**	**750**
Phase Slope (°/KHz)	**0.72**	**-0.33**	**-0.07**

The 155.52 MHz SAW filter is available in a standard 14-pin, metal dual-in-line package (20.3x12.7x7.4 mm^3). The 622.08 MHz SAW filter is available in a low-profile, 22-pin, metal surface mountable package (15.9x13.6x3.2 mm^3). The 2488.32 MHz SAW filter is available in a compact, surface mountable microwave package (11.4x10.7x2.1 mm^3). The 155.52 , 622.08, and 2488.32 Mhz timing recovery SAW filters are also available in the 9mmx7mm, 9mmx5mm, and 9mmx7mm leadless chip carrier surface mountable packages (LCC SMPs) respectively.

1.3 SAW-Based Voltage-Controlled Oscillator

The SAW-based voltage-controlled oscillator (VCO600)

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is a highly integrated device which uses an ASIC with an on-chip phase shifter for frequency pulling and a SAW delay line with a typical 3-dB Q of 400. The VCO600 has an ECL output and is available with standard SONET/SDH/ATM frequencies at 155.52, 311.04, and 622.08 MHz. Additional frequencies at 278.528 and 368.64 MHz are also available. The VCO600 is housed in a hermetically sealed, 28-lead ceramic surface mountable package. Typical applications are data retiming and synchronization as part of a PLL, as well as frequency synthesis and frequency translation. The VCO600A also has a unique output disable and clock through feature which improves board-level testing. A summary of the specification follows:

Absolute Pull Range	**±50 ppm**
Supply Voltage	**-5 V**
Control Voltage	**-0.5 to -4.5 V**
Linearity	**±3%**
Spurious Output Suppression	**-60 dB**

2.1 SAW Filters for Wireless Applications

Wireless communication systems available include mobile cellular, cordless phones, paging services, Specialized Mobile Radio (SMR), mobile satellite and Wireless Local Area Network (WLAN). In Europe, the analog cellular system (ETACS) is being displaced by the new Global System for Mobile digital communication system (GSM). The Personal Handyphone System (PHS) and Personal Digital Cordless system (PDC) are gaining momentum in Japan (Table 1).

In the US, the existing analog cellular systems (AMPS) is being converted gradually into dual mode analog/digital systems (IS-54). Digital cellular system (IS-95) using the CDMA is also available in some metropolitan areas. These systems operate at the 800 MHz bands and claim to support more subscribers and provide better services. Non-licensed digital cordless phones using frequency hopping spread spectrum (FHSS) technique at the ISM-15 902-928 MHz band are in the market. They provide more secure services in the crowded consumer market of cordless phones. Paging companies are now providing two-way paging services. In-flight Air to Ground Telephony (AGT) service operating in the 849-851 MHz & 894-896 MHz bands is becoming more popular with the option to route ground to air calls. Wireless data transfer equipment (e.g. WLAN operating at the non-licensed ISM-15 2400-2483.5 MHz band) is now available[6]. SMR is changing into the enhanced version (ESMR) to support digital data/voice transport. Low/Medium Earth Orbit (LEO/MEO) Mobile Satellite Services like[5] IRIDIUM (Motorola), ARIES (Constellation Communication, Inc.), GLOBALSTAR (Loral & Qualcomm), ELLIPSAT (Ellipsat Corp.), Odyssey (TRW), and Teledesic (Microsoft et al.) will make "calling anyone, anytime, and anywhere" a reality. In addition, equipment using the Global Positioning System (GPS) technology is now available in the commercial (automobiles, aircrafts, ships, etc.) and consumer market (handheld receivers). Tremendous efforts are being put into developing low-power front end and baseband chips sets, longer life batteries, etc. In the RF and IF sections of the portable and stationary equipment of these systems, low-loss SAW filters and conventional high-loss and high-selectivity SAW filters have become and will continue to be the vital components[6]. Most European, US, and Japanese manufacturers of SAW filters are adding equipment and expanding their facilities to accommodate the business opportunities.

Standard	Rx MHZ	TX MHz	#Users	RF BW MHZ	IF BW MHz
Analog Cellular (FDMA)					
AMPS	869-894	824-849	832	25	30
ETACS	916-949	871-904	1240	33	25
NTACS	860-870	915-925	400	10	12.5
NMRT450	463-468	453-458	200	5	25
NMT900	935-960	890-915	1999	25	12.5
Digital Cellular (TDMA)					
IS-54/-136	869-894	824-849	832X3	25	30
IS-95 (CDMA)	869-894	824-849	20X798	25	1250
GSM	935-960	890-915	124x8	25	200
PDC	810-826	940-956	1600x3	16	25
	1429-1453	1477-1501	1600x3	24	25
Digital Cordless/ PCN (TDMA/TDD)					
CT2 & 944/948	864/868 & 40		4	100	CT2+
DECT	1880-1990		10X12	110	1728
PHS	1907	1895	300X4	12	300
DCS1800 (FDD)	1805-1880	1710 1785	750X16	75	200

Table 1. World wide Wireless Telecommunication Standards

Continued

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Standard	Rx MHZ	TX MHz	#Users	RF BW MHZ	IF BW MHz
Wireless Data-WAN/LAN (TDMA)					
CDPD	869-894	824-849	832	25	30
RAM	935-941	896-902	480	6	12.5
	403-470		450	67	12.5
Ardis	851-869	806-824	720	18	25
IEEE (US/Europe)	2400-2483	FHSS/79	83	1000	802.11
(CSMA)	2470-2499	DSSS/7	29	10000	(Japan)
Emerging Personal Communication System (PCS)					
	1930-1990	1850 1910		60	
High Tier)Larger Cel)					
PCS TDMA (based on IS-136 celluler)			Ericsson, AT&T, Hughes		
PCS CDMA based on IS095 cellular)			Qualcomm, AT&T, Nokia		
PCS 1900 (based on GSM cellular)			Nortel, Ericsson, Nokia, Alcatel, Motorola, MCI, Pacific Telesis		
Wideband CDMA			InterDigital, OKI Low Tier (Small Cell)		
PACS (based on PHS Cordless)			Motorola, Panasonic, NEC, Hitachi Hughes, Bellecore		
DCT-U (based on DECT cordless)					
Composite CDMA/TDMA		Omnipoint			

Table 1. World wide Wireless Telecommunication Standards

2.2 Low-Loss SAW Filters for Front-End RF Applications

The RF bandwidth in Table 1 shows the minimum bandwidth requirement for the front-end filtering in both the transmitting and receiving paths of different wireless systems. For many years, dielectric resonator filters (2 to 3 poles) have been widely used especially for the terminals. They are low cost, rugged, and easily implemented. In addition, they can handle high power. Though they were bulky, it was not a problem since early wireless terminals were mostly mobile but stationary (e.g. mounted in cars). However, the current trend of wireless equipment is moving toward more and more portable, and component size is one of the many factors that designers of terminals are concerned with.

Low-loss RF SAW filters (as low as 2.5 to 4 dB) between 800 and 1500 MHz are now available in LCCs as small as 3.8x3.8x1.6 mm^3 for AMPS, GSM, PDC, and other applications and the trend is moving toward 3.0x3.0x1.0 mm^3 for PCS, WAN, and WLAN, and other applications at 1.8 to 2.5 GHz band[7,8]. There are many suppliers of these devices from and Europe. Some of these companies offer robust products in this 800 to 1500 MHz range and are developing devices toward the 1.8 to 2.5 GHz range with the goal to attain even lower insertion loss. The popular designs are In-Line Coupled Resonator Filter (In-Line CRF, Figure 1) and Impedance Element Filter (IEF, Figure 2). The latter does not offer as good ultimate rejection and it can only be slightly improved by adjusting the capacitance ratio of the parallel and series arms. It does hold a good prospect in offering insertion loss lower than 2 dB with high frequency operation. Table 3 compares their applications and performance. Almost all low-loss RF SAW filters for mobile applications use $LiTaO_3$, $LiNbO_3$, or $Li_2B_4O_7$ as the substrate materials in order to provide the wide bandwidth requirement (up to 6%)[9].

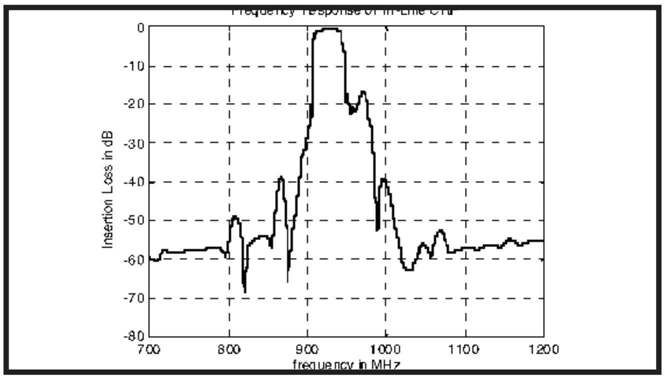


Figure 1. In-line CRF Design for RF Applications

One Japanese supplier recently announced the availability of SAW-based duplexers at the 800 MHz band has put itself as the leader of the pack[10]. They have succeeded in overcoming one major obstacle- power handling requirements for the transmission path in duplexer applications. In North America, only two suppliers manufacture RF SAW filters for cellular terminals and/or digital cordless phones (e.g. CT-2) and they are primarily captive.

Most low-loss RF SAW filter suppliers consider they have shrunk the footprints of the devices to small enough sizes. The trends are to put in efforts to reduce the package height possibly through flip-chip method[12] and, more importantly, to develop ways to further reduce the insertion loss to below 2 dB. The latter is to compete with the dielectric resonator filters

9. Saw-Based Frequency Control Product Applications

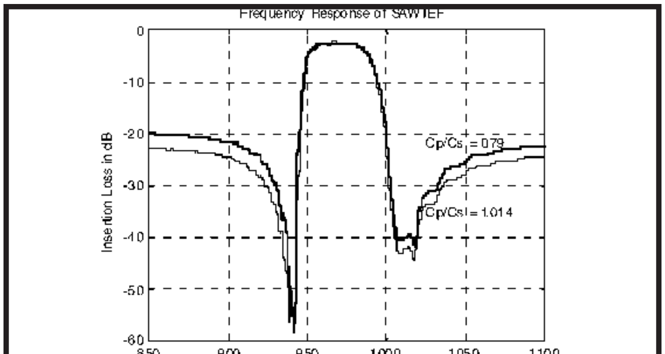


Figure 2. Impedance Element Filter Design for RF Applications

which now have 1.3 to 3 dB insertion loss.

Many suppliers provide dielectric resonator filters, SAW filters, and chip monolithic LC-type filters to meet the frequency and bandwidth requirements for RF filtering. These devices are primarily different in insertion loss, attenuation, price, and size. Major progresses have been made in the development of chip monolithic LC-type RF filters and dielectric resonator filters[11]. The former has comparable size and insertion loss as SAW filters except they do not offer as good attenuation. Suppliers have also shrunk the size of dielectric resonator filters significantly in the last couple of years and it is a formidable competitor especially in the >2 GHz RF applications[12]. Table 2 depicts the generic comparison of these RF filter technologies.

	Dielectric Filter	SAW Filter	LC Multilayer Filter
Loss	Best	Good	Good
Attenuation	Good	Best	Good
Size (cubic mm)	Fair	Best	Good
Design Flexibility	Good	Fair	Best

Table 2. Generic Comparison of RF Filter Technology[[11]]

2.3 High Velocity Longitudinal Leaky SAWs and High Velocity SAWs in Piezoelectric Film/Diamond Structures

One way to maintain the physical feature size of transducer fingers while pushing up the operating frequencies is to increase the SAW velocity. LSAWs with low leakage loss are being used extensively in modern low-loss RF SAW filters. Popular LSAW cuts are 36° Y-X $LiTaO_3$, 41° and 64° Y-X $LiNbO_3$ [[9]]. LSAW's velocity is in general higher than that of the Rayleigh wave, and is always sandwiched in between the slow shear and fast shear velocities. They are attractive because of its high velocity, low leakage loss, and strong electromechanical coupling. In the last several years[[13]], we have seen progresses in the study of longitudinal LSAWs which have low leakage loss, strong electromechanical coupling, and comparable temperature coefficient of delay (TCD). It is foreseeable that wafer cuts using longitudinal LSAWs will become commercially available in the future to support high frequency SAW devices.

In the past several years, the synthesizing of polycrystalline diamond films using chemical vapor deposition (CVD) has become quite successful. In 1989, Yamanouchi et al. suggested theoretically that high frequency SAW devices (>3 GHz) could be realized in a piezoelectric AlN or ZnO/diamond structure because of the hardness of diamond film (Rayleigh wave velocity could exceed 12,000 m/s)[[14]]. Extensive experimental work is being actively pursued in Japan and Russia[[15]]. It's likely we will see vendors supplying diamond film coated SAW wafers in the future.

Design	TCRF	SPUDT	In-Line CRF	IRF
Application	IF	IF	IF & RF	RF
Current Frequency Range	<600 MHz	<400 MHz	<1GHz	As high as 2.4 GHz
Insertion Loss	>3 dB	6~10 dB	>2 dB	>1 dB
Bandwidth	0.04 to 0.1%	0.3 to 5%	0.08 to 5%	up to 6%
Materials	Quartz	Quartz & $LiTaO_3$ $Li_2B_4O_7$	Quartz, $LiTaO_3$, $LiNbO_3$ &	Quartz, $LiTaO_3$., & $LiNbO_3$
Strengths	Superior near-in rejection; Low-loss.	Superior out-of-band rejection.	Small size; Wide bandwidth; Traps placing is easy; Matching is not needed.	Small size; Wide bandwidth; Matching is not needed; Excellent near-in rejection.
Weakness is critical; Matching is generally needed	Metallization usually thick and uniformity is fingers usually needed; Difficult to Synthesize/ optimize	Matching is generally needed; long chip size; </8 direct transmission.	Sidelobe on high frequency side due to transducer frequencies.	Poor out-of band rejection Varied

Table 3. Comparison of Different Low-Less SAW Filter Designs for Current Applications

9. Saw-Based Frequency Control Product Applications

2.4 Low-Loss IF SAW Filters for Very Narrow Band Applications

The IF bandwidth listed in Table 1 depicts the channel width. For many years, 20 to 45 MHz monolithic crystal filters (MCFs) of 10 to 30 KHz bandwidth (4 to 6 poles) dominated the IF filtering segments of analog cellular systems like AMPS. Nowadays, the trend is to push up the IF frequency to help to suppress images and spurs due to mixing and the continuous narrowing of the transmitting and receiving bands in the RF carriers to support more channels[16] (e.g. the expansion of AMPS bands from 20 MHz to 25 MHz several years ago and the current expansion of GSM to EGSM). MCFs above 45 MHz, in addition to being fragile, are costly to make. Only one company from Japan is persistently pushing the MCFs to higher frequencies using the inverted mesa quartz resonator technique[17].

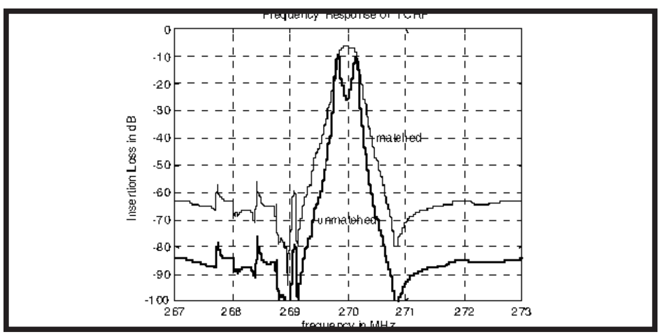


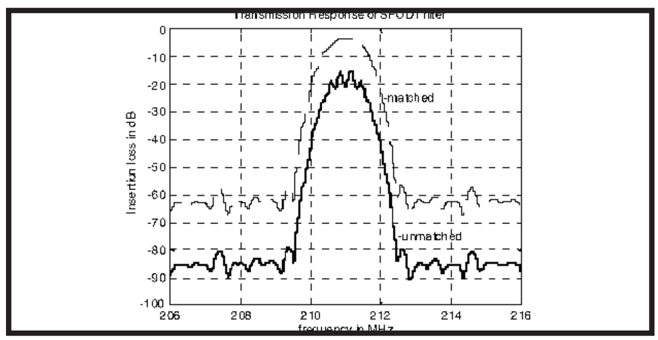
Figure 3. 4-Pole TCRF Design for IF Applications

Low-loss IF SAW filters at around 80 MHz for narrow channel analog systems like AMPS applications employing the 4-pole Transversely-Coupled Resonator Filter design (TCRF, Figure 3) are now widely available. In addition to being low-loss (6 to 10 dB), these filters have excellent rejection in suppressing images after the mixing stage. It was also used as the RF front-end filter between 200 and 300 MHz in earlier narrow band pagers to allow down conversion directly to 455 KHz IF frequency without going through a first IF frequency of 21.4 MHz. Since the bandwidth is very narrow, quartz SAW substrate is exclusively used to minimize frequency drift due to temperature. Standard frequencies at 82.2, 83.16, 85.05, 86.85, and 90 MHz are available. 13.3 x 6.5 x 1.3 mm^3, 15.4 x 6.5 x 1.5 mm^3, and other LCCs are widely used. There are many suppliers of these "standard" filters from Japan and Europe.

2.5 Low-Loss IF SAW Filters for Narrow Band Applications

IF filtering in digital cellular systems usually requires wider bandwidth and stringent delay characteristic. Single-Phase Unidirectional Transversal SAW filter (SPUDT) is one of the few designs used to achieve the bandwidth and delay requirements for the digital systems. The SPUDT design ingeniously directs power transmission from the electrical port to the forward acoustical port by setting a certain phase shift (±45° or ±135°) between the transduction center and the reflection center. When the matching of the electrical port begins, the insertion loss will decrease (Figure 4). The triple transit echo will also decrease (reflection coefficient decreases) as the acoustical reflection and the piezoelectric regeneration begin to cancel out.

Figure 4. SPUDT Design for IF Applications



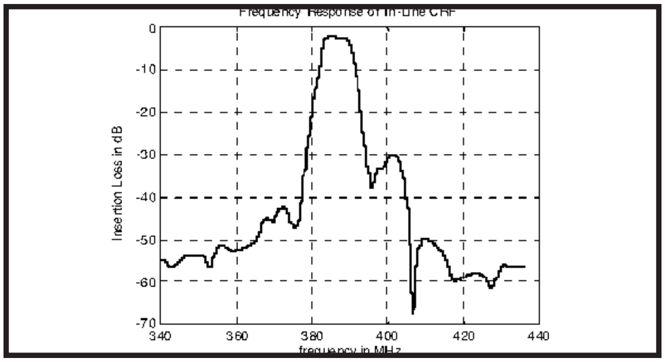
Comparing with the conventional transversal filter design which has only a transduction function to work with, the challenge for the SPUDT design is now one has to properly account for the reflection function also. The In-Line CRF design described in the low-loss RF SAW filters section can also be used to provide even wider bandwidth than the SPUDT design in IF applications (Figure 5). Table 3 compares their applications and performance. Depending on the requirements, devices in LCCs with footprints anywhere from 5 x 5mm^2 to 19 x 6.5mm^2 are available.

Similar to the analog systems like AMPS (or IS-54), we begin to see standardized IF frequencies in some popular digital wireless terminals (e.g. 71 MHz for GSM, 110.592 MHz for DECT, 130 MHz for PDC, 248.45 MHz for PHS et al.). Same as the low-loss RF SAW filters, suppliers of these standard low-loss IF

9. Saw-Based Frequency Control Product Applications

SAW filters are usually more bulky and costly than the low-loss RF SAW filters. Many designers are seeking ways to reduce the size as a means to reduce the cost[18]. In-Line CRF design can usually fit into smaller packages than the SPUDT design and circuit matching is in general not needed.

Most IF filterings in emerging systems though, are implemented differently; very much dependent on the system designers. In the US there are tremendous needs of SAW filters to perform IF filtering for different new wireless equipment (terminals and base stations) based on the newly allocated PCS bands. These new systems will be operating at the 1.8 to 2.0 GHz range.

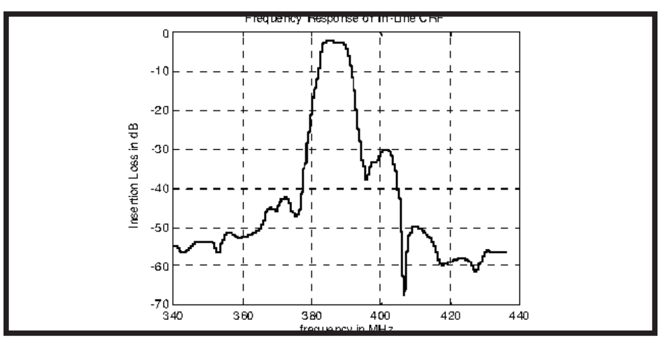


The equipment will very likely need to down convert the radio signals to IF frequency (50 to 500 MHz) for processing.

Figure 5. In-Line CRF Design for IF Applications

2.6 SAW Filters for CDMA Base station Applications

The technique of using direct sequence spread spectrum method in providing multiple access to frequency channels (CDMA) is gaining momentum worldwide. In



the US, IS-95 regulates the usage of this technology for cellular applications in the 900 MHz range. New systems using the CDMA will appear in the PCS band.

Figure 6. Frequency Response of a 131.01 MHz SAW Filter for CDMA Base station Applications

Conventional SAW filters, though high in insertion loss, offer unsurpassed selectivity (low shape factor) and high rejection. They begin to find extensive applications in the terminals and base station of existing and emerging systems[19]. One example is a 131.01 MHz SAW filter for IF filtering in CDMA base station (Figure 6). Quartz substrate is used for such a device in order to meet the 1.25 MHz channel width requirement over temperature. For many emerging CDMA systems (e.g. W-CDMA), SAW filters will probably continue to be the only solution which can provide robust filtering function in the IF segment.

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