Chapter 2

Reviews of Existing Techniques for Bandpass Filters

2.1 Introduction

Classification of existing techniques for bandpass filters can be based on many aspects. For example, they may be based on one of the basic of the signal processing such as continuous-time (CT) or discrete-time (DT) (Stevenson and Edgar, 1998). Another example is the classification based on the implementation such as off-chip and possible on-chip bandpass filters (Kuhn et al., 2003), as shown in Figure 2.1.

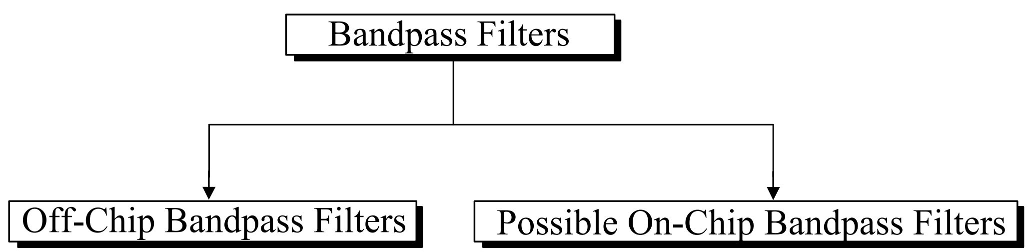

Figure 2.1 An example of classifications of existing techniques for bandpass filters (Kuhn et al., 2003)

Based on types of devices, Figure 2.2 further separates techniques for off-chip bandpass filters into discrete ceramic, surface acoustic wave (SAW), monolithic crystal filters (MCFs) and LC filters (Kuhn et al., 2003).

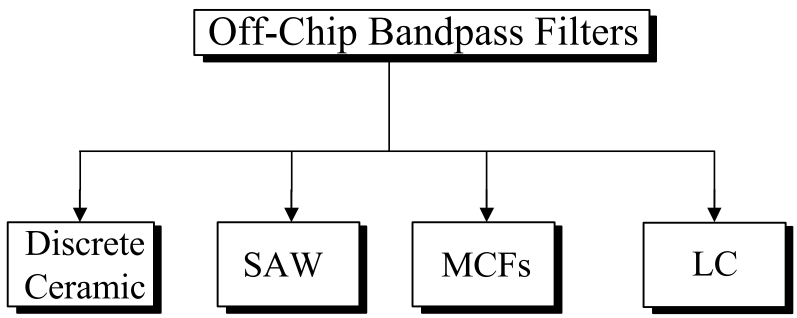

Figure 2.2 Existing techniques for off-chip bandpass filters (Kuhn et al., 2003)

Figure 2.3 separates techniques for possible on-chip bandpass filters into the digital bandpass filters and the analog bandpass filters (Kuhn et al., 2003). Analog bandpass filters can be either analog passive filters or analog active filters. The analog passive filters employ passive devices such as LC and electro-acoustic components. The analog active filters employ techniques such as transconductance-capacitor (Gm-C), switched-capacitor (SC) and Q-enhanced LC (QE-LC) approaches (Kuhn et al., 2003).

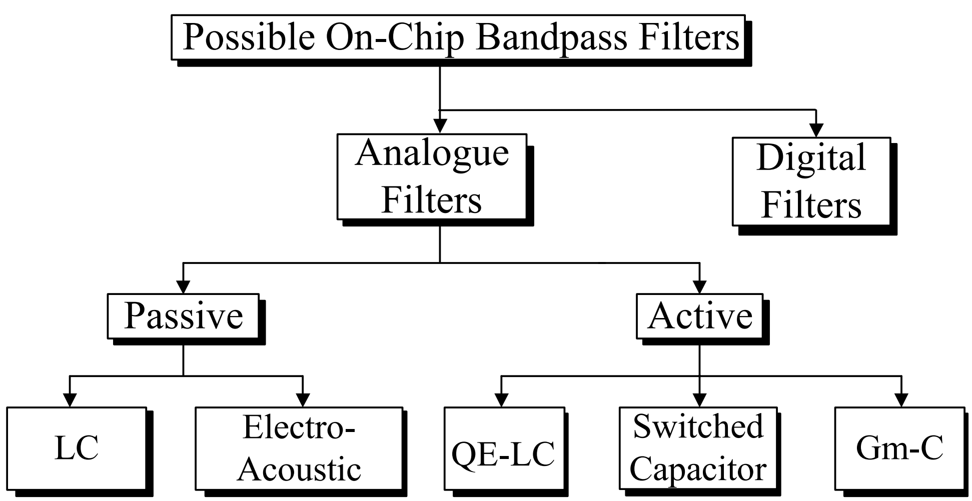

Figure 2.3 Existing techniques for possible on-chip bandpass filters (Kuhn et al., 2003)

Dynamic Ranges (DRs) are important parameters in the design of bandpass filters. For an analog active filter, a dynamic range of the employed filter will upper bound the dynamic range (DR) of the receiver and is therefore of paramount in the design of filters. Section 2.2 describes the dynamic ranges (DRs) of a filter. Section 2.3 briefly reviews existing products for off-chip bandpass filters bases on off-chip components such as discrete ceramic, surface acoustic wave (SAW), monolithic crystal filters (MCFs) and LC filters. Section 2.4 describes existing techniques for possible on-chip bandpass filters in terms of digital filters, analog passive filters based on either LC or electro-acoustic types and analog active filters based on either transconductance-capacitor (Gm-C), switched-capacitor (SC) or Q-enhanced LC (QE-LC) filters. Finally, conclusions can be drawn in Section 2.6.

2.2 Dynamic Ranges (DRs)

A dynamic range (DR) of a filter can be defined as a ratio of the maximum power of a signal to the minimum detectable power at the same point. In many cases, the minimum detectable power equals the idle channel noise power of the system (Groenewold, 1992). The maximum power of a signal depends on the type of the signal. In most common cases of a sine wave, the maximum power is equal to the maximum power of the fundamental harmonic.

In other words, a dynamic range (DR) of a filter can be defined as a ratio of the square of the maximum signal amplitude to the square of the minimum detectable signal amplitude. In many cases, the minimum detectable signal equals the idle channel noise of the system (Groenewold, 1992). The maximum amplitude of a signal depends on the type of the signal. In most common cases of a sine wave, the maximum amplitude is equal to the maximum amplitude of the fundamental harmonic.

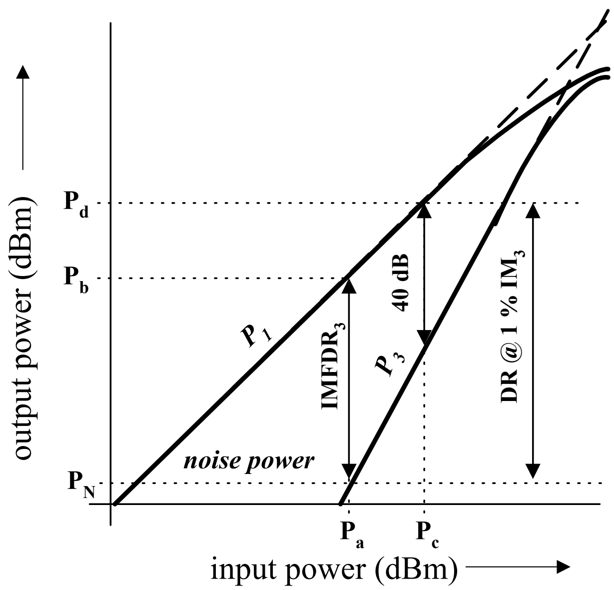

Figure 2.4 Graphical illustration of the third-order intermodulation free dynamic range ($IMFDR_3$) and the dynamic range at 1% IM_3.

Another important specifications in terms of linearity of a system are the intermodulation products (IM) and the intermodulation-free dynamic range (IMFDR). The intermodulation products (IM) are generated from signal components at frequencies, which are the sum or difference of multiples of harmonics of primary signal components. If, for instance, a signal consists of two harmonic components at frequencies f_1 and f_2, then the output signal may contain components at frequencies f_1, f_2, $2f_1$, $2f_2$, $3f_1$, $3f_2$, $f_1 \pm f_2$, $2f_1 \pm f_2$ and $2f_2 \pm f_1$. The components at $2f_1 \pm f_2$ and $2f_2 \pm f_1$ are called the third-order intermodulation products (IM_3). Figure 2.4 depicts examples of the measured output power P_1 (dBm) of a fundamental at frequency f_1 or f_2 and the measured output power P_3 (dBm) of an IM_3 at frequency $|2f_1-f_2|$ or $|2f_2-f_1|$ versus the input power (dBm). Let P_N be the noise power. The intercption of P_1 and P_3 is called third-order intercept point (IIP_3)

Example 2-1: The 3^{rd}-order intermodulation free dynamic range $IMFDR_3$.

It can be seen from Figure 2.4 that the input power P_a results in the output power P_b of a fundamental whilst the output power P_3 of an IM_3 equals to the noise power P_N (or intermodulation free). Therefore the third-order intermodulation-free dynamic range ($IMFDR_3$) = $P_b - P_N$.

Example 2-2: The dynamic range (DR) at 1% IM_3.

It can be seen from Figure 2.4 that the input power P_c results in the output power P_d of a fundamental whilst the output power P_3 of an IM_3 is 40 dB down from the output power P_d (or 1% IM_3). Therefore the dynamic range (at 1% IM_3) = $P_d - P_N$.

2.3 Off-Chip Bandpass Filters

Based on types of devices, Table 2.1 summarizes examples of existing products for off-chip intermediate frequency (IF) and radio frequency (RF) bandpass filters in terms of discrete ceramic, MCFs, SAW, and LC filters (Kuhn et al., 2003).

In Table 2.1, the IF filters are intended for use as channel select filters at standardized IF frequencies from 262 kHz to 110 MHz, whilst the RF filters are RF preselect/image filters intended for use at the front end of cellular and cordless phones where the RF frequencies are from 881 to 914 MHz. The cost is relatively low ($0.30 to $3) when they are purchased in high quantities (e.g. 1,000,000 units). Such a low cost of filters enables widely universal use in consumer products. Therefore on-chip filters have not yet totally replaced such discrete devices.

Table 2.1 Examples of existing products for off-chip IF and RF bandpass filters

Filter	Products	Types	Applications	Frequency	Approximated Price
IF	TOKO HCFM8-262B	Ceramic	AM Broadcast	262 kHz	$1
	TOKO CFMR 455B	Ceramic	AM Broadcast	455 kHz	$1
	MuRata SFP450F	Ceramic	Pager	450 kHz	-
	MuRata SFP4.5MBF	Ceramic	Television Sound	4.5 MHz	-
	MuRata SEE10.7MS2-Z	Ceramic	FM Broadcast	10.7 MHz	$0.30
	ECS ECS-10.7-15B	MCF	Cellular Phone	10.7 MHz	$3
	Siemens B4535	SAW	DECT	110 MHz	$3
RF	MuRata LFC30-01B0881B025	LC	Cellular	881 MHz	-
	TOKO 6DFA-881E-11	Dielectric	Cellular	881 MHz	-
	TOKO 6DFA-914A-14	Dielectric	Cordless Phone	914 MHz	-

Major disadvantages of the off-chip bandpass filters are that off-chip filters are bulky and consume more power to drive external devices (Chung-Yu and Shuo-Yuan, 1997). Consequently, the need for possible on-chip filters for fully viable integrated receivers has increasingly been motivated (Khun et al., 2003 and Chung-Yu and Shuo-Yuan, 1997).

2.4 Possible On-Chip Bandpass Filters

2.4.1 Digital Filters

In theory, digital signal processing (DSP) could ideally be used to implement high precision, wide dynamic range, programmability and high frequency filters (Antoniou, 1993).

In practice, however, DSP solutions are still potentially unsuitable for on-chip bandpass filters because of several reasons including (Kuhn et al., 2003):

(a) The need for analog anti-aliasing filters and external clocks,

(b) The need for more chip areas,

(c) The need for electromagnetic compatibility with low level analog signals,

(d) Requirements for high resolution or high speed analog to digital converters (ADC),

2.4.2 Analog Passive Filters

2.4.2.1 Passive LC Filters

On-chip capacitors can be fabricated in IC processes (Nguyen and Meyer, 1990) whilst on-chip inductors can also be fabricated through the use of planar spiral geometries (Lee et al., 2005). Such inductors are employed routinely in the design of GaAs monolithic microwave circuits (MMICs) operating at several GHz (Negus et al., 1994). More recently, spiral inductors have begun to see commercial applications in silicon processes at low frequencies, where they have been employed in on-chip impedance matching networks (Negus et al., 1994). For the operating frequencies below 2 GHz, the use of spiral inductors have been investigated for lowpass filters (Nguyen and Meyer, 1990) or wide-dynamic-range bandpass filters (Chang et al., 1993; Nguyen and Meyer, 1990; Pipilos and Tsividis, 1994).

Table 2.2 shows the quality (Q) factors and other related parameters of the on-chip LC bandpass filters. As illustrated in Table 2.2, the Q factors of the on-chip LC filters realized to date have been relatively low from 1.3 to 14.4. Another disadvantages are that on-chip LC bandpass filters require additional active circuitry to compensate for coil loss or require substantial process modifications for on-chip, high Q, LC bandpass filters (Duncan et al., 1993).

Table 2.2 Quality (Q) factors and other related parameters of on-chip LC bandpass filters.

Reference	Inductance (nH)	Resonance	Q	Frequency	Turns	Dimension (um)
Gye-An et al. (2005)	12.5	2.7 GHz	12.47	2.495 GHz	1.3	1500
Wu and Chang (2002)	7.76	2.1 GHz	14.4	1.76 GHz	9	490
Chang et al. (1993)	100	800 MHz	1.3	400 MHz	20	440
Chang et al. (1993)	100	3 GHz	3	800 MHz	20	440
Nguyen et al. (1990)	9.7	2.5 GHz	3	900 MHz	9	230
Nguyen et al. (1990)	1.9	9.7 GHz	8	4.1 GHz	4	115

2.4.2.2 Passive Electro-Acoustic Filters

Implementation of on-chip passive electro-acoustic filters may be based on acoustic devices i.e. bulk acoustic wave (BAW) devices or surface acoustic wave (SAW) devices (Kuhn et al., 2003). Bulk acoustic wave (BAW) devices are the resonators of either thin film resonators (TFRs) or film bulk acoustic resonators (FBARs) to emphasize their construction and crystal resonator-like behavior. On-chip SAW devices are the RF active circuitry with a modified bipolar field effect transistor (BIFET) process (Haartsen,1990; Van Zeijl et al., 1989 and Visser et al., 1989). Such on-chip SAW devices are, unlike the off-chip SAW shown in Figure 2.2, not fabricated on the surface of piezoelectric substrate (Shinonaga and Ito, 1992).

Table 2.3 shows the quality (Q) factors and other related parameters of the on-chip electro-acoustic bandpass filters. As illustrated in Table 2.3, several researchers have investigated the possibility of implementing high frequencies and high quality factors of on-chip electro-acoustic filters (Ueda et al., 2005; Loebl et al., 2004; Hikita, 2004; Marksteiner et al., 2003; Ruby et al., 2002). However on-chip electro-acoustic filters with active circuitry in silicon IC processes require process additions or modifications (Kuhn et al., 2003) and require relatively large chip areas (e.g. 80 sq.mm.) at the frequency below 1 GHz (El Oualkadi et al., 2004).

Table 2.3 Quality (Q) factors and other related parameters of on-chip electro-acoustic bandpass filters.

Reference	Type	Frequency	Q	Size (sq.mm.)
Hikita (2004)	SAW	900 MHz	>1000	80
Hikita (2000)	SAW	800 MHz	-	80
Vale et al. (1990)	BAW	1.1 GHz	>1500	58
Ueda et al (2005)	BAW	2 GHz	1200	3.2
Loebl et al. (2004)	BAW	1.2 GHz	>1000	1.3
Marksteiner et al. (2003)	BAW	3.4 GHz	>1200	-
Ruby et al. (2002)	BAW	1.9 GHz	1000	-
Yatsuda et al. (2002)	SAW	3.5 GHz	1300	-
Knauer (1997)	BAW	2.45 GHz	1500	-

2.4.3 Analog Active Filters

A vast majority of research in on-chip filtering has dealt with the design of active filters on which hundreds of papers have been published and numerous textbooks have been written. The analog active filters may be grouped into three main categories as follows (Kuhn et al., 2003):

(a) Q-enhanced LC (QE-LC) filters,

(b) Switched-capacitor (SC) filters and

(c) Transconductance-capacitor (Gm-C) filters.

2.4.3.1 Q-Enhanced LC (QE-LC) Filters

As mentioned earlier in Section 2.4.2.1, the quality factors in the passive LC filters are relatively low from 1.3 to 14.4 due to the loss in inductors (Kuhn et al., 2003). Alternatively, Q-enhanced LC (QE-LC) filters can be implemented with an active circuit to compensate for the loss in inductors (Pipilos and Tsividis, 1994). The compensation can be either in series-mode or in parallel-mode (Kuhn et al., 1994). The series-mode employs an active negative resistor placed in series with the inductor (Duncan et al., 1993 and Kuhn et al., 1994) whilst the parallel-mode employs an active negative conductance placed in parallel with the inductor (Tsividis, 1993; Pipilos and Tsividis, 1994).

Table 2.4 Quality (Q) factors, dynamic ranges (DRs) and other related parameters of the Q-enhanced LC (QE-LC) bandpass filters.

Reference	Frequency (GHz)	Q	Power (mW)	DRs (dB)	Process	Volatge Required (V)
Kuhn (2003)	0.9	45	39	78	-	3.0
Li and Tsividis (2002)	1.88	5-20	48.6	63	0.25 um BiCMOS	2.7
Mohieldin (2003)	1.80	22.5	43.2	42	0.50 um CMOS	2.7
Bantas and Koutsoyamopoulos (2004)	1.04	5-180	11.4-15.5	80	0.35 um CMOS	2.7
Dulger et al. (2003)	2.10	20-170	5.2	34	0.35 um CMOS	1.3
Naderi et al. (2005)	2.00	81	1	50	0.13 um CMOS8RF	1.2

Table 2.4 shows the quality (Q) factors, dynamic ranges (DRs) and other related parameters of existing QE-LC bandpass filters. As illustrated in Table 2.4, the Q factors of QE-LC filters are typically high.

A major disadvantage of QE-LC filters based on on-chip inductors at low frequency (below GHz) is that QE-LC filters suffer from the loss of series resistances in CMOS technology (Naderi et al., 2005). In addition, the high Q factors usually happen at a frequency higher than that desired. Therefore, QE-LC filters are still potentially unsuitable for an IF band from 10 MHz to 100 MHz (Kuhn et al., 2004).

2.4.3.2 Switched-Capacitor (SC) Filters

Switched-capacitor (SC) techniques can provide precision filtering in the face of wide fabrication tolerances (Ausin et al., 2003). By simulating a resistor's current-voltage relationship with charge sharing via capacitors and FET switches, RC time constants become dependent on capacitor ratios and clock rates alone. Since capacitor ratios can be held to tolerances as tight as 0.1% to 0.5% on a chip (Tsividis et al., 1986), very accurate responses can be achieved. The primary disadvantages of SC implementations include the need for fast settling amplifiers, the need for anti-alias filtering at the input and the need for reconstructive smoothing at the output (Kuhn, et al., 2003 and Praveen, et al., 2003).

Table 2.5 shows quality (Q) factors, dynamic ranges (DRs) and other related parameters of existing switched-capacitor (SC) bandpass filters. As shown in Table 2.5, a good example of SC bandpass filters demonstrated the operating frequencies of 4.28 kHz, the dynamic range of 79 dB and the power dissipation of 4 mW (Quinn, 1998). In particular, FM radio receivers require an IF filter set at a center frequency of 10.7 MHz. Existing SC bandpass filters operating at a center frequency of 10.7 MHz have, however, repeatedly suffered from low Q factors from 10 to 55 and limited dynamic ranges from 42 to 68 dB. In addition existing SC bandpass filters operating at center frequencies above 10.7 MHz have suffered from low Q factors from 8 to 73.5 and limited dynamic ranges from 37 to 65 dB.

Table 2.5 Quality (Q) factors, dynamic ranges (DRs) and other related parameters of existing switched-capacitor (SC) bandpass filters.

Reference	Frequency	Q	Power (mW)	DRs (dB)	DRs @1% IM_3 (dB)	DRs @3% IM_3 (dB)	Process	Size (mm^2.)
Ng et al. (2002)	44 MHz	73.5	85.5	-	-	-	0.35 um CMOS	-
Ng and Luong (2005)	28 MHz	8	19.6	37	-	-	0.35 um CMOS	1.65
Haigh et al. (1991)	20 MHz	15.87	440	65	-	-	0.5 um GaAs	8.6
Quinn et al. (2000)	10.7 MHz	55	16	-	61	-	0.6 um CMOS	0.69
Hammouda (2002)	10.7 MHz	35	-	-	-	-	0.35 um CMOS	-
Baschirotto et al. (1996)	10.7 MHz	29.4	16	68	-	-	1.2 um BiCMOS	1.6
Nagari et al. (1997)	10.7 MHz	29	17	-	-	68	1.2 um BiCMOS	1.6
Garduno and Silva-Martinez (2005)	10.7 MHz	10	-	59	-	-	0.35 um CMOS	-
Nagari and Nicollini (1998)	10.7 MHz	10	23	-	58.4	-	0.8 um CMOS	0.3
Song (1988)	10.7 MHz	-	500	42	-	-	2.25 um CMOS	2
Silva-Martinez et al. (2003)	10.7 MHz	-	11.5	-	-	58	0.35 um CMOS	0.84
Quinn (1998)	4.28 MHz	-	4	79	-	-	0.8 um CMOS	0.75
Song and Gray -1986	3.1 MHz	-	45	51	-	-	1.75 um CMOS	2
Wang et al. (2001)	833 kHz	8	-	-	-	-	1.2 um CMOS	0.12

Table 2.5 (Cont.) Quality (Q) factors, dynamic ranges (DRs) and other related parameters of existing switched-capacitor (SC) bandpass filters.

Reference	Frequency	Q	Power (mW)	DRs (dB)	DRs @1% IM_3 (dB)	DRs @3% IM_3 (dB)	Process	Size (mm^2.)
Choi et al. (1983)	260 kHz	-	70	70	-	-	4 um CMOS	-
Baschirotto et al. (1998)	99.82 kHz	102	10	54	-	-	0.3 um BiCMOS	7
Inchang and Fox (2003)	50 kHz	10	< 1	40	-	-	0.25 um CMOS	0.12
Ausin et al. (2002)	17.4 kHz	303	-	-	-	-	0.8 um CMOS	-
Chang and Tong (1993)	3.75 kHz	-	-	73	-	-	5 um CMOS	1.8

2.4.3.3 Transconductance-capacitor (Gm-C) Filters

In the design of most modern filters, suitable resistors are often not available, and MOSFETs biased in the resistive region are often used instead. In addition, the desire to operate at high frequencies with smaller chip areas often rules out the use of operational amplifiers. Simpler active filters with fewer internal nodes can be created using operational transconductance (Gm) amplifiers and capacitors (C), implemented with a small number of FETs, bipolar (NPN and VPNP) and/or CMOS transistors (Voorman and Veenstra, 2000). The names given to the resulting filter designs include transconductance-capacitor (Gm-C) filters (Tsividis, 1994 and Quinn et al. 2000) or OTA-C filters (Tsividis, 1994).

The discipline of on-chip Gm-C filter design has been well established through several reviews in articles appeared on the subject in leading journals (Lebel et al., 2005; Praveen et al., 2003; Hassan et al., 2002), as well as books (Kardontchik, 1992; Nauta, 1993; Silva-

Martinez et al., 1993) or collections of reprinted articles (Tsividis, 1994). Nevertheless, commercial products of Gm-C filters have been limited primarily to lowpass filters designed for use in read channels of disk drives such as the ADS96 from Analog Devices, (Kuhn, et al., 2003). The commercial products of Gm-C bandpass filters include the operating frequency of 5.5 MHz with the Q factor of 20 designed at Philips as a part of a television chroma, luminance, and sound separator IC (Kuhn et al., 1994), and the operating frequency of 55 kHz with the Q factor of 10 designed at Sony in an AM receiver (Okanobu et al., 1992). However, it is not clear from the available literature if these filters have made them into marketed products (Kuhn, et al., 2003).

Table 2.6 shows quality (Q) factors, dynamic ranges (DRs) and other related parameters of existing transconductance-capacitor (Gm-C) bandpass filters. As shown in Table 2.6, existing Gm-C bandpass filters demonstrated low quality (Q) factors from 2 to 50 and limited dynamic ranges from 45 to 75 dB. As mentioned earlier in Section 2.4.3.2, FM radio receivers require an IF filter set at a center frequency of 10.7 MHz. Existing Gm-C bandpass filters operating at a center frequency of 10.7 MHz have, however, repeatedly suffered from low Q factors from 20 to 40 and limited dynamic ranges from 50 to 68 dB. In addition existing Gm-C bandpass filters operating at center frequencies above 10.7 MHz have suffered from low Q factors from 2 to 30.3 and limited dynamic ranges from 60 to 66 dB. Another disadvantages of existing Gm-C bandpass filters are that the Q factors have generally been a function of variables such as a center frequency (Comer et al., 1997 and Ali et al., 2000) or have particularly been inversely proportional to the center frequency (Liu and Karsilayan, 2003 and Voghell and Sawan, 2000).

Table 2.6 Quality (Q) factors, dynamic ranges (DRs) and other related parameters of existing transconductance-capacitor (Gm-C) bandpass filters.

Reference	Frequency	Q	Power (mW)	DRs (dB)	DRs @ 1% IM3 (dB)	Process	Size (mm^2.)
Lebel et al. (2005)	40 MHz	10.64	< 1	-	-	0.18 um CMOS	-
Zhiqiang et al. (2005)	2.4 GHz	-	4.5	-	-	0.25 um CMOS	-
Praveen et al. (2003)	100 MHz	20	92.4	-	-	0.5 um CMOS	0.91
Salthouse and Sarpeshkar (2003)	2.4 GHz	-	4.5	-	-	0.25 um CMOS	-
Tajalli and Atarodi (2003)	10.7 MHz	-	16	-	-	Bipolar	16
Hassan et al. (2002)	30 MHz	-	1	61	-	0.6 um CMOS	-
Raisanen-Ruotsalainen et al. (2002)	5.4 kHz	-	< 1	-	-	0.6 um CMOS	1.07
Choi and Luong, (2001)	70.0 MHz	-	120	66	-	0.5 um CMOS	0.96
Chung-Yu and Chung-Yun (2001)	10.7 MHz	21.4	6	-	-	0.25 um CMOS	-
Munoz et al. (2000)	10.7 MHz	40	-	-	-	CMOS	-
Choi and Luong (2000)	50.5 MHz	-	120	66	-	0.5 um CMOS	0.96
Voghell and Sawan (2000)	60 MHz	2	2.33	-	-	0.35 um CMOS	-
Yamazaki et al. (1999)	450 kHz	21.46	12.4	-	-	0.35 um CMOS	2.5
Minot and Degrugillier (1998)	84.6 MHz	30.30	-	-	-	BiCMOS	-
Stevenson and Edgar (1998)	10.7 MHz	20	108	-	-	1.2 um	3.24

Table 2.6 (Cont.) Quality (Q) factors, dynamic ranges (DRs) and other related parameters of existing transconductance-capacitor (Gm-C) bandpass filters.

Reference	Frequency	Q	Power (mW)	DRs (dB)	DRs @ 1% IM3 (dB)	Process	Size (mm^2.)
Chang et al. (1996)	700 kHz	-	70	75	-	0.7 um CMOS	4.8
Adachi et al. (1994)	455 kHz	-	33	64	-	1.5 um CMOS	
Kuhn et al. (1994)	5.5 MHz	20	-	-	-	-	-
Okanobu et al.(1992)	55 kHz	10	-	-	-	-	-
Silva-Martinez et al. (1992)	10.7 MHz	-	220	-	68	1.5 um CMOS	6
Steyaert and Silva-Martinnez (1992)	10.7 MHz	-	220	-	68	CMOS	-
Krummenacher and Ruymbeke (1990)	200 kHz	-	1.2	54	-	3 um CMOS	2.5
Pu and Tsividis (1990)	10 MHz	-	25	45	-	1.75 um CMOS	4
Koyama et al. (1989)	10.7 MHz	-	80	50	-	Bipolar	4
Koyama et al. (1989)	40 kHz	-	80	49	-	Bipolar	2
Krummenacher (1989)	95 MHz	12.5	-	-	-	3 um CMOS	-
Wang et al. (1989)	12.5 MHz	-	360	60	-	3 um CMOS	7.8
Park and Schaumann (1988)	4.0 MHz	-	900	75	-	3 um CMOS	23
Chiou and Schaumann (1986)	10.7 MHz	-	650	60	-	Bipolar	16
Rigby and Lampard (1986)	650 kHz	50	100	65	-	Bipolar	-
Khorramabadi and Gray (1984)	500 kHz	-	55	60	-	6 um CMOS	4
Moulding et al. (1980)	5.5 MHz	20	-	-	-	Bipolar	<< 11

2.5 The State of the Art Techniques for 10.7-MHz Gm-C Bandpass Filters

As mentioned earlier in Section 2.4.3.3, the 10.7-MHz Gm-C bandpass filter with the highest Q factor is presented by Monoz et al. (2000), whilst 10.7-MHz Gm-C bandpass filter with the widest dynamic range is presented by Silva-Matinez et al. (1992).

2.5.1 A 10.7 MHz a High-Q Gm-C Bandpass Filter (Monoz et al., 2000)

The technique presents a new CMOS low-voltage linear transconductor for Very High Frequency (VHF). It uses multiple-input floating-gate transistors (MIFGTs). The proposed transconductor operates under constant low-voltage supply as low as 1.2 V and its transconductance and output resistance are independently tunable. It is suitable to be used in HF continuous time filters with programmable center frequency and quality factor.

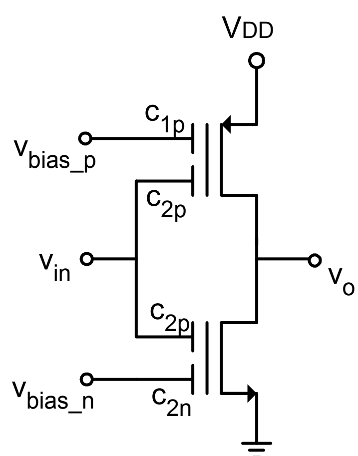

Figure 2.5 The transconductance element using MIFGTs (Monoz et al., 2000).

Figure 2.5 shows the hardware implementation of the transconductor using MIFGTs.The idea is to bias the MIFGT to a voltage higher than the transistors' treshold voltages by means of one of its multiple inputs. Biasing voltages near the supply rails are enough to maintain the transistors in saturation for any input voltage within the suply rails. In the transconductor presented here the biasing voltages V_{bias_p} and V_{btas_n} are also used for tuning purposes.

To evaluate the performance of the transconductor a differential integrator scheme has been implemented with V_{dd} = 1.4 V and V_{dd} = 1.2V. The measured parasitic input capacitance was C_{in} = 0.25pF while the parasitic output capacitance was C_{out} = 0.74pF. Nominal transconductances were g_m = 411 μA/V (with V_{dd} = 1.4 V) and g_m = 117 μA/V (with V_{dd} = 1.2V). These values lead to a maximum filter frequency of $f_{max} = g_m/(C_{in}+C_{out})$ = 66MHz (with V_{dd} = 1.4 V) and f_{max} = 18.8MHz (with V_{dd} = 1.2V). As the output resistance can be tuned by means of the biasing voltages of the common-mode network, the integrator has a tunable dc gain resulting in a controlable quality factor.

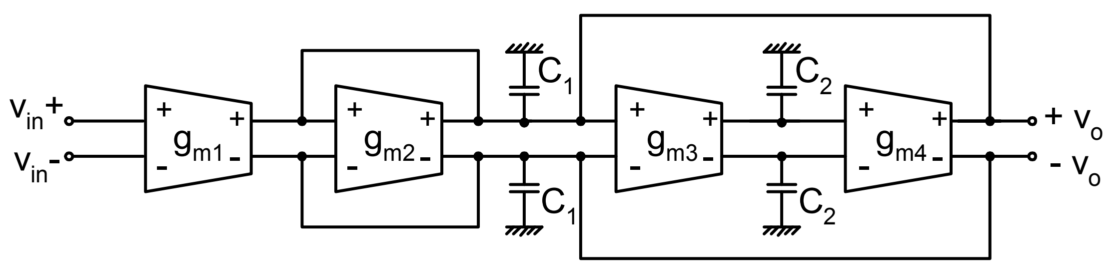

Figure 2.6 The banpass filter scheme implementation (Monoz et al., 2000).

A band-pass biquad filter has been implemented with this integrator. The scheme, shown in Figure 2.6, has a center frequency that can be tuned between 7 MHz and 12 MHz and a quality factor that can be tuned between 6 and 70. For nominal f_o = 10.7MHz, Q = 40 and 700 mV_{pp} post-layout simulations showed a THD = 0.26%.

2.5.2 A 10.7 MHz Wide-Dynamic-Range Gm-C Bandpass Filter

(Silva-Matinez et al., 1992).

The technique uses the low-distortion voltage-to-current transconductors OTA_1 and OTA_2. The example filter architecture is based on 2 biquadratic sections in cascade, as shown in Figure 2.7.

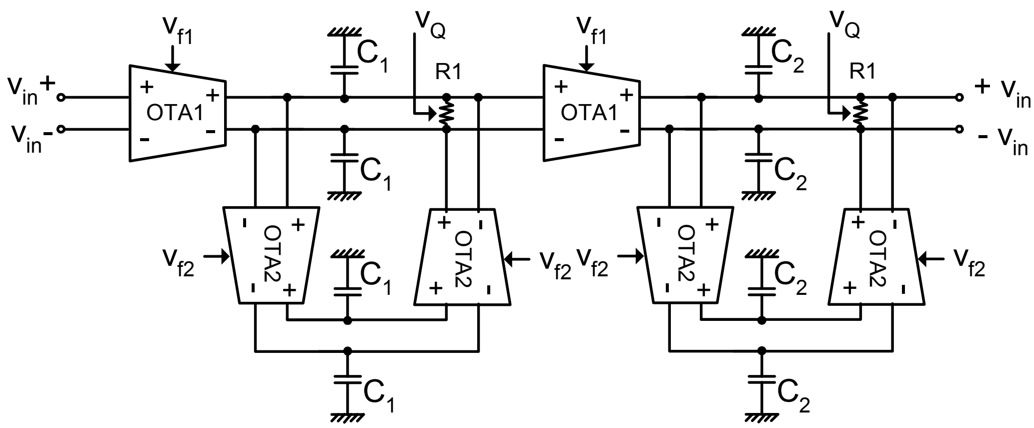

Figure 2.7 An existing wide-dynamic-range Gm-C bandpass filter

(Silva-Matinez et al., 1992).

The pole frequencies are controlled by the low-distortion transconductance g_{m2} of the OTA2 and its associated capacitor C_1 as g_{m2}/C_1 . The quality factor Q of each biquad is determined by the product $g_{m2}R_1$ with R_1 being a fully-CMOS-implemented resistor. The dc gain of the biquads is controlled by the low-distortion transconductance g_{m1} of OTA1, and the resistor R_1, and is given by the product $g_{m1}R_1$. The transconductance g_{m1} is equal to $1/R_1$ and the ratio between g_{m1} and g_{m2} is equal to 1/Q. This leads to a bandpass filter with unity peak gain. This results in a nearly-optimum dynamic range around the filter passband frequency.

2.6 Conclusions

Existing bandpass filters may be separated into off-chip and on-chip bandpass filters. As off-chip filters are bulky and consume more power to drive external devices, the need for possible on-chip filters for fully viable integrated receivers has increasingly been motivated. Techniques for possible on-chip bandpass filters may be implemented using digital filters or analog filters. Table 2.7 summarizes advantages and disadvantages of existing on-chip bandpass filters.

As summarized in Table 2.7, digital filters are potentially unsuitable for on-chip bandpass filters because of the need for several requirements such as anti-aliasing filters, external clocks and high-speed analog to digital converters (ADCs). Analog filters can be either analog passive filters or analog active filters. The analog passive filters employ passive devices such as LC or electro-acoustic components. The quality factors in the passive LC bandpass filters are relatively low due to the loss in inductors. Although the quality factors in the electro-acoustic bandpass filters are relatively high, they require process modifications and large chip areas.

As shown in Table 2.7, the analog active filters may be separated into Q-enhanced LC (QE-LC), switched-capacitor (SC) and transconductance-capacitor (Gm-C) filters. The QE-LC filters can be implemented with the active circuit to compensate for the loss in inductors. The high Q factors in QE-LC bandpass filters usually happen at a frequency higher than that desired. Therefore, QE-LC filters are still potentially unsuitable for high Q bandpass filters operating at an IF band from 10 MHz to 100 MHz. Another disadvantage is that QE-LC bandpass filters using on-chip spiral inductors require large chip areas in CMOS technology.

Table 2.7 Advantages and disadvantages of existing on-chip bandpass filters.

Filter Techniques			Advantages	Disadvantages
Digital Filters			High precision, Wide dynamic ranges, Programmability High frequencies	Electromagnetic compatibility, Large chip areas, Requirements for external clocks, Requirements for anti-aliasing filters, Requirements for high speed ADCs
Analog Filters	Passive	LC	Wide dynamic ranges, High frequencies	Low Q factors (3-14.4) Large chip areas
Analog Filters	Passive	Electro-acoustic	Wide dynamic ranges, High frequencies (0.9-3.4 GHz) High Q factors (>1000)	Requirements for process modifications, Large chip areas
Analog Filters	Active	QE-LC	High frequencies (0.9-2.1 GHz)	Large chip areas, Requirements for tuning circuits Limited dynamic ranges (34-80 dB)
Analog Filters	Active	SC	High precision	Limited dynamic ranges (37-79 dB) Low Q factors (10-55) at 10.7 MHz Requirements for anti-aliasing filters, Requirements for external clocks
Analog Filters	Active	Gm-C	High frequencies (5.4 kHz -2.4 GHz)	Limited dynamic ranges (45-68 dB), Requirements for tuning circuits Low Q factors (2-50) Q is a function of frequency.

Switched-capacitor (SC) bandpass filters have been used extensively in baseband or IF band signal processing applications. As illustrated in Table 2.7, primary disadvantages of SC techniques include the limited dynamic ranges and the need for several requirements such as anti-alias filtering and external clocks. In particular, FM radio receivers require an IF filter set at a center frequency of 10.7 MHz. Existing SC bandpass filters operating at a center frequency of 10.7 MHz have suffered from low Q factors from 10 to 55 and limited dynamic ranges from 42 to 68 dB. In addition existing SC bandpass filters operating at center frequencies above 10.7 MHz have suffered from low Q factors from 8 to 73.5 and limited dynamic ranges from 37 to 65 dB.

Finally, Gm-C bandpass filters can be implemented with a small number of FETs, bipolar and/or CMOS transistors, resulting in a fewer internal nodes and a smaller chip areas compared to the use of operational amplifiers. In particular, FM radio receivers require an IF filter set at a center frequency of 10.7 MHz. Existing Gm-C bandpass filters operating at a center frequency of 10.7 MHz have suffered from low Q factors from 20 to 40 and limited dynamic ranges from 50 to 68 dB. In addition existing Gm-C bandpass filters operating at center frequencies above 10.7 MHz have suffered from low Q factors from 2 to 30.3 and limited dynamic ranges from 60 to 66 dB. Another disadvantages of existing Gm-C bandpass filters are that the Q factors have generally been a function of variables such as a center frequency or have particularly been inversely proportional to the center frequency.