

## Chapter 5

### Conclusions

Chapter 1 has addressed problems encountered to bandpass filters and an outline of the structure of the dissertation including the quality (Q) factors, the dynamic ranges (DRs) and the sensitivities. In Chapter 2, existing bandpass filters have been reviewed and 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. The 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). The 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.

The analog active filters may be separated into the Q-enhanced LC (QE-LC), the switched-capacitor (SC) and the transconductance-capacitor (Gm-C) filters. A major disadvantage of the QE-LC bandpass filters is that the QE-LC bandpass filters using on-chip spiral inductors require large chip areas in CMOS technology. The switched-capacitor (SC) bandpass filters have been used extensively in baseband or IF band signal processing applications. Primary disadvantages of the SC techniques include the limited dynamic ranges and the need for several requirements such as anti-alias filtering and external

clocks. The transconductance-capacitor (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. At a center frequency of 10.7 MHz, existing SC bandpass filters have suffered from the low Q factors from 10 to 55 and the limited dynamic ranges from 42 to 68 dB whilst existing Gm-C bandpass filters operating at a center frequency of 10.7 MHz have suffered from the low Q factors from 20 to 40 and the limited dynamic ranges from 50 to 68 dB.

Chapter 3 has proposed a new possible system realization of a high-Q bandpass filter. Two new circuit realizations have been proposed through Techniques 1 and 2 of the fully- balanced, high-Q, wide-dynamic-range current-tunable Gm-C bandpass filters. Technique 1 is relatively simple based on two fully balanced components, i.e. a two-input adder and a low-Q-based bandpass filter. The high quality factor  $Q_{HQ1}$  of Technique 1 is approximately equal to a typically high ( $>100$ ) and constant value of the current gain  $\beta$ , and is, for the first time, independent of variables such as a center frequency. Possible solutions for good stability of the quality factor  $Q_{HQ1}$  with temperature have been suggested through the use of Heterojunction Bipolar Transistors (HBTs) where the  $\beta$  is relatively constant. Not only can the need for additional Q-tunable circuits be greatly reduced, the sensitivity of the Q factor can be greatly improved. Technique 2 is also relatively simple based on three fully balanced components, i.e. a two-input adder, a low-Q-based bandpass filter and a differential amplifier. The high quality factors  $Q_{HQ2}$  of Technique 2 is possible through a tunable bias current.

In Technique 1, the sensitivity of  $Q_{HQ1}$  to the variation of  $\beta$  and the sensitivities of  $\omega_{HQ}$  to the variations of  $C_1$ ,  $V_T$ , or  $I_2$  are constant values from  $-1$  to  $1$  and therefore, are

desirably independent of parameters. In Technique 2, for very high-Q realizations, the sensitivities of  $Q_{HQ2}$  to the variation of  $R_C$ ,  $V_T$ , or  $I_3$  are in the same order as other existing approaches whilst the sensitivities of  $\omega_{HQ}$  to the variations of  $C_1$ ,  $V_T$ , or  $I_2$  are constant values from  $-1$  to  $1$ . In Techniques 1 and 2, for a large value of  $\beta$ , the sensitivity of  $\omega_{HQ}$  to the variation of  $\beta$  is not only relatively small but also relatively constant. In addition, dynamic ranges (DRs) of Techniques 1 and 2 are potentially higher than other existing Gm-C approaches due to the use of fully balanced structure and appropriate setting of capacitors.

Chapter 4 has presented simulation and experimental results of the two proposed techniques described in Techniques 1 and 2. For Technique 1, a 10.7-MHz fully balanced, high-Q, 87-dB-dynamic-range current-tunable Gm-C bandpass filter has demonstrated the high-Q factor of 121, the low total noise voltage of  $5.3026 \mu V_{rms}$ , the third-order intermodulation-free dynamic range (IMFDR<sub>3</sub>) of 74.45 dB and the wide dynamic range of 87.45 dB at 1% IM<sub>3</sub>. The center frequency is current tunable over 3 orders of magnitude. The upper limit of the Q factor has been expected at approximately 160 at a maximum common-emitter current gain ( $\beta$ ) of 190. The center frequency is current tunable over 3 orders of magnitude.

Variations of the normalized center frequency  $f_0/(10.7 \text{ MHz})$  of Technique 1 versus the ambient temperature (Celsius) for the temperature uncompensated cases have shown that the normalized center frequency decreases inversely with the ambient temperature. In the temperature compensated case, the effects of the ambient temperature can be compensated and the temperature coefficients are approximately  $-30 \text{ ppm}/^\circ\text{C}$ . Variations of the quality factor of Technique 1 versus the ambient temperature (Celsius) for the

temperature uncompensated cases have shown that the quality factor of Technique 1 increases gradually versus the ambient temperature. The temperature coefficients are approximately 1,010 ppm/°C. In the temperature compensated case, the variations of the quality factor of Technique 1 are reduced and are gradually and slightly in terms of magnitudes versus the ambient temperature. The temperature coefficients are approximately 367 ppm/°C.

The preliminary interpolation of power consumption in Technique 1 has suggested that the higher power consumption of 60 mW at capacitance of 150 pF may be reduced to the lower power consumption of 0.4 mW at capacitance of 1 pF. However, the preliminary interpolation of dynamic range in Technique 1 has suggested that the higher dynamic range of 87.45 dB at capacitance of 150 pF may also be reduced to the lower dynamic range of 65.7 dB at capacitance of 1 pF. High-frequency simulation of Technique 1 has been limited at approximately 600 MHz at the capacitance of 1 pF.

For Technique 2, a 10.7-MHz fully balanced, high-Q, 101-dB-dynamic-range current-tunable Gm-C bandpass filter has demonstrated the high-Q factor of 223, the low total noise voltage of 2.5589  $\mu\text{V}_{\text{rms}}$ , the third-order intermodulation-free dynamic range (IMFDR<sub>3</sub>) of 80.82 dB, and the wide dynamic range of 101.02 dB at 1% IM<sub>3</sub>. The center frequency is current tunable over 3 orders of magnitude.

Variations of the normalized center frequency  $f_0/(10.7 \text{ MHz})$  of Technique 2 versus the ambient temperature (Celsius) for the temperature uncompensated cases have shown that the normalized center frequency also decreases inversely with the ambient temperature. In the temperature compensated case, the effects of the ambient temperature

can be compensated and the temperature coefficients are also approximately  $-30 \text{ ppm}/^\circ\text{C}$ . Variations of the quality factor of Technique 2 versus the ambient temperature (Celsius) for the temperature uncompensated cases have shown that the quality factor of Technique 2 decreases inversely with the ambient temperature. In the temperature compensated case, the effects of the ambient temperature are reduced.

The preliminary interpolation of power consumption in Technique 2 has suggested that the higher power consumption of 70 mW at capacitance of 150 pF may be reduced to the lower power consumption of 0.47 mW at capacitance of 1 pF. However the preliminary interpolation of dynamic range in Technique 2 has suggested that the higher dynamic range of 101.02 dB at capacitance of 150 pF may also be reduced to the lower dynamic range of 80 dB at capacitance of 1 pF. High-frequency simulation of Technique 2 has been limited at approximately 500 MHz at the capacitance of 1 pF. Finally, comparisons of Techniques 1 and 2 to other 10.7-MHz Gm-C approaches have been included. The two proposed 10.7-MHz techniques described in Techniques 1 and 2 offer the high-Q wide-dynamic-range current-tunable Gm-C bandpass filters.