

Figure 4.24 A simulated frequency response at the center frequency

$f_0=10.7$ MHz and the quality factor $Q_{HQ1} = 124.4$ of Technique 1 shown in Figure 3.2.

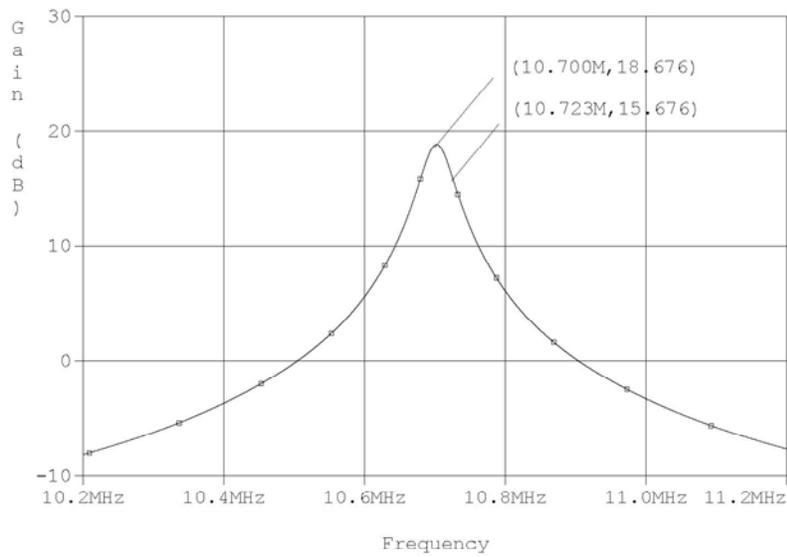


Figure 4.25 A measured frequency response at the center frequency

$f_0=10.7$ MHz and the quality factor $Q_{HQ2} = 232$ of Technique 2 shown in Figure 3.3.

As shown in Figures 3.2 and 3.3, all transistors, capacitor C_1 and $2C_1$, and R_C are modeled by the parasitic extractions of Figure 4.22 and 4.23. All current sinks are LM334

(National Semiconductor Data, 2000). The bias current $I_1 = I_2 = 1$ mA. Figure 4.24 illustrates the simulated frequency response of Technique 1 of a fully balanced high-Q current-tunable Gm-C bandpass filter shown in Figure 3.2 at the center frequencies $f_0 = \omega_{HQ}/(2\pi) = 10.7$ MHz, it can be seen from Figure 4.2 that the bandwidth (BW1) are $2 \times 43 = 86$ kHz and therefore the simulated quality factor Q_{HQ1} ($=f_0/BW1$) is relatively high at approximately 124.4 which is consistent with the value of $\beta = 128$.

Figure 4.25 illustrates the simulated frequency response of Technique 2 of a fully balanced high-Q current-tunable Gm-C bandpass filter shown in Figure 3.3 where the bias current $2I_3 = 1.2$ mA, at the center frequencies $f_0 = \omega_{HQ}/(2\pi) = 10.7$ MHz. It can be seen from Figure 4.4 that the bandwidth (BW2) are $2 \times 23 = 46$ kHz and therefore the measured quality factor Q_{HQ2} ($=f_0/BW2$) is relatively high at approximately 232.

4.11 Comparisons to Other 10.7-MHz Gm-C Bandpass Filters

As mentioned earlier in Chapter 1, 10.7-MHz bandpass filters are typically based on switched capacitors (SC) or Gm-C techniques. Table 4.2 particularly compares various results of the proposed Gm-C Techniques 1 and 2 to those of 10.7 MHz existing Gm-C approaches. In an attempt to enable fair comparisons, all center frequencies are fully homogenous at 10.7 MHz. For purposes of information, irrelevant results of SC techniques as well as relevant results of Gm-C techniques that are not fully homogenous are also included in Table 4.2, although some comparisons may be somewhat unfair. It can be observed from Table 4.2 that the proposed 10.7-MHz Techniques 1 and 2 offer not only the high-Q factors of 121 and 223, compared to others between 10 to 55, but also the wide dynamic ranges at 1% IM_3 of 87.45 dB and 101.02 dB, compared to others between 61 to 68 dB. In addition, the total output noises are $5.303 \mu V_{rms}$ and $2.5589 \mu V_{rms}$ compared to others between 226 to $707 \mu V_{rms}$.

Table 4.2 Comparisons of the proposed Gm-C bandpass filter and existing Gm-C approaches. (SC techniques are also included for information.)

Performance	This work Technique 2	This work Technique 1	Tajalli 2003	Chung-Yu 2001	Munoz 2001	Stevenson 1998	Steyaert 1992	Garduno 2005	Matinez 2003	Hammoud ^a 2002	Quinn 2000	Nagari 1998	Nagari 1997
Design Techniques Technologies Orders	Gm-C BJT 2	Gm-C BJT 2	Gm-C CMOS 2	Gm-C CMOS 2	Gm-C CMOS 2	Gm-C CMOS 2	Gm-C CMOS 4	SC CMOS 2	SC CMOS 6	SC CMOS -	SC CMOS 6	SC CMOS 2	SC Bi CMOS 2
Simulation results	√	√	√	√	√	×	×	×	×	√	×	√	√
Experimental results	√	√	×	×	×	√	√	√	√	×	√	√	√
IC Fabrication	×	×	×	×	×	√	-	√	√	×	√	√	√
Center Freq : fo (MHz)	10.7	10.7	10.7	10.7	10.7	10.7	10.7	10.7	10.7	10.7	10.7	10.7	10.7
Bandwidth (kHz)	48	88	-	500	267.5	535	300	1070	464	305.7	-	1070	368.9
Q factors	223	121	-	21.4	40	20	-	10	-	35	55	10	29
Sampling Freq. (MHz)	-	-	-	-	-	-	-	65	-	-	-	107	22.8
Sensitivity of $\omega\omega$	-1 to 1	-1 to 1	-	-	-	-	-	-	-	-	-	-	-
Sensitivity of Q	2Q	1	-	-	-	-	-	-	-	-	-	-	-
Output noise Density ($\mu\text{Vrms}/\sqrt{\text{Hz}}$)	0.0004	0.016	-	-	-	-	-	-	-	-	-	1	0.38
Total output noise (μVrms)	2.5589	5.303	-	-	-	-	-	-	295	-	226	707	240
IIP ₃ (dBm)	-2	1	-	-	-	-	-	-	-	-	-	-	-
Dynamic Ranges @ 1 % IM ₃ (dB)	101.02	87.45	-	-	-	-	68	-	-	-	61	58.4	-
@ 3 % IM ₃ (dB)	-	-	-	-	-	-	-	-	58	-	-	-	68
IMFDR ₃ (dB)	80.82	74.45	-	-	-	-	-	-	-	-	-	-	-
Power Consumption P _C (mW)	70	60	16	6	-	108	220	-	9	-	16	23	17

4.12 Conclusions

Simulation and experimental results of the two proposed Techniques 1 and 2 have been presented. For Technique 1 shown in Figure 3.2, a 10.7-MHz fully balanced, high-Q, 87-dB-dynamic-range current-tunable Gm-C bandpass filter has been demonstrated. The quality Q factor Q_{HQ1} is approximately equal to a typically high and constant value of a common-emitter current gain (β) and is, for the first time, independent of variables such as a center frequency. Technique 1 has shown the high-Q factor of 121, the low total noise voltage of $5.3026 \mu V_{rms}$, the third-order intermodulation-free dynamic range (IMFDR₃) of 74.45 dB and the wide dynamic range of 87.45 dB at 1% IM₃. The upper limit of the Q factor has been expected at approximately 160 at a maximum common-emitter current gain (β) of 190. The center frequency is current tunable over 3 orders of magnitude.

For Technique 2 shown in Figure 3.3, a 10.7-MHz fully balanced, high-Q, 101-dB-dynamic-range current-tunable Gm-C bandpass filter has been demonstrated. The high-Q factor is possible through a tunable bias current. Technique 2 has shown the high-Q factor of 223, the low total noise voltage of $2.5589 \mu V_{rms}$, the third-order intermodulation-free dynamic range (IMFDR₃) of 80.82 dB, and the wide dynamic range of 101.02 dB at 1% IM₃. The center frequency is current tunable over 3 orders of magnitude.

Measured variations of the normalized center frequency $f_0/(10.7 \text{ MHz})$ of both Techniques 1 and 2 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 to the normalized center frequencies can be compensated and the measured temperature coefficients are approximately $-30 \text{ ppm}/^\circ\text{C}$.

Temperature compensation for the quality factor of Technique 1 has been demonstrated. In the uncompensated case, the quality factor Q_{HQ1} of Technique 1 increases gradually versus the ambient temperature and the measured temperature coefficients are approximately 1,010 ppm/°C. In the compensated case, the variations of Q_{HQ1} are reduced and are gradually and slightly in terms of magnitudes versus the ambient temperature. The measured temperature coefficients are approximately 367 ppm/°C. Temperature compensation for the quality factor of Technique 2 has been described. In the uncompensated case, the quality factor Q_{HQ2} decreases inversely with the ambient temperature. In the compensated case, the effects of the ambient temperature are reduced.

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.

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 simulations in terms of the center frequency and the quality factor versus capacitance have suggested that the quality factors of both Techniques 1 and 2 have been maintained relatively high whilst the upper frequency of Techniques 1 and 2 at the capacitance of 1 pF, have been limited at approximately 600 MHz and 500 MHz, respectively. 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.