Design Techniques for VHF/UHF High-Q Tunable Bandpass Filters Using Simple CMOS Inverter-Based Transresistance Amplifiers

Ping-Hsing Lu, Chung-Yu Wu, and Ming-Kai Tsai

Abstract—In this paper, CMOS inverter-based wideband transresistance $R_m$ amplifiers are proposed and analyzed. Using the $R_m$ amplifiers, tunable VHF/UHF $R_m$-C bandpass biquadratic filters can be designed. In these filters, the center frequency $f_c$ can be post-tuned by adjusting the control voltages of the $R_m$ amplifiers. The pseudodifferential configuration uses the extra inversely connected and self-shorted inverters for $Q$ enhancement. Experimental results have shown that the center frequency $f_c$ of the single-ended-output $R_m$-C bandpass biquad is 386 MHz (258 MHz) and $Q = 1.195 (Q = 1.012)$ for $\pm 2.5$ V ($\pm 1.5$ V) supply voltage. The power consumption is 24.83 mW (3.42 mW), and the dynamic range is 61 dB (55.5 dB). For pseudodifferential-output high-$Q$ configuration, the measured quality factor $Q$ can be as high as 360 with $f_c = 222.7$ MHz. When $Q = 94$, the power consumption is 56.2 mW and the measured dynamic range is 57.8 dB for $\pm 2.5$ V supply voltage.

I. INTRODUCTION

In recent years, several types of filters can be operated in very high frequency (VHF) ranges [1]-[5]. Most VHF filters [2]-[4] are built with transconductance-C ($G_m$-C) integrators which are formed by an open-loop transconductance element with a capacitive load. Thus, these filters are called the $G_m$-C filters. In contrast to the $G_m$-C integrator, a new design concept using the transresistance-$C$ ($R_m$-C) differentiator as the building block has been developed recently [6], [7]. The proposed filter implementation method can realize a VHF bandpass biquadratic filter with the center frequency above 100 MHz.

In this work, the simple CMOS inverter-based $R_m$ amplifier is used to realize VHF and ultrahigh frequency (UHF) tunable bandpass filters. The proposed simple $R_m$-C bandpass biquad can be operated at frequencies above 300 MHz, and the center frequency $f_c$ can be tuned by adjusting the control voltages of the tunable $R_m$ amplifier. In these inverter-based filters, the signal swing can be effectively enlarged since only two transistors are connected in series between the power supplies. Moreover, the simple structures are suitable for reduced-supply-voltage systems.

To enhance the quality factor $Q$ of the bandpass biquad, the pseudodifferential configuration with extra inversely connected inverters in parallel with extra self-shorted inverters as active loads [4] is developed. The supply voltages of the self-shorted inverters offer a very effective $Q$ enhancement and can be regarded as the $Q$-tuning control voltages.

II. DESIGN OF VHF/UHF BIQUADRATIC FILTERS

Fig. 1(a) shows the basic $R_m$-C differentiator, using the CMOS inverter with shunt–shunt feedback resistance $R_f$ as the wideband $R_m$ amplifier. The $R_f$ is formed by the parallel triode-operated MOSFET transistors MNF/MPF and can be tuned by adjusting the control voltages $V_{CN}$ and $V_{CP}$. Considering the intrinsic capacitances of the MOS transistors as filter elements, the simple $R_m$-C differentiator can be regarded as a VHF/UHF bandpass biquadratic filter [7]. The small-signal equivalent circuit is depicted in Fig. 1(b), where $C_e$ including the external capacitance loading $C_L$. The $g_f$ is the reciprocal of the feedback resistance $R_f$, which is dependent on the control voltages $V_{CN}$ and $V_{CP}$. Neglecting one parasitic zero located in the gigahertz region, the transfer function can be expressed as

$$
\frac{V_o}{V_m} = \frac{sC_f \cdot D}{A \cdot s^2 + B \cdot s + C}
$$

(1)

where

$$
A \equiv (C_d + C_f) \cdot (C_f + C_o) + C_f \cdot C_o
$$

(2)

$$
B \equiv g_m \cdot C_f + g_d \cdot (C_d + C_f + C_L) + g_f \cdot (C_f + C_o)
$$

(3)

$$
C \equiv (g_m + g_d) \cdot g_f
$$

(4)

$$
D \equiv -(g_m - g_f)
$$

(5)

Therefore, both the pole frequency $\omega_p (= \sqrt{C/A})$ and the quality factor $Q (= \sqrt{A \cdot C/B})$ of the biquad can be obtained.

The pole frequency $\omega_p$ can reach the VHF (or even UHF) ranges due to the simple structure, but it is sensitive to the parasitic capacitances. Thus, the tuning scheme is needed. In this structure, the tunable $g_f$ offers the post-tuning compensation through the adjustment of the $r_m$. 

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control voltages $V_{CN}$ and $V_{CP}$. Moreover, the simple configuration makes it possible to operate under the reduced supply voltages, such as $\pm 1.5$ V. With low supply voltages, however, the tuning range of the $r_n$-control voltages $V_{CN}$ and $V_{CP}$ will be reduced since they should keep the feedback transistors from operating in the saturation regions.

Fig. 2 shows the pseudodifferential configuration of the VHF $R_{n-C}$ bandpass filter with two inversely connected inverters INV3 and INV4 between the differential output nodes in parallel with two self-shorted inverters INV5 and INV6. These extra inverters are added to obtain a high and tunable $Q$. Fig. 3(a) shows the small-signal equivalent differential-mode half-circuit. Fig. 3(a) can be simplified as shown in Fig. 3(b), where $C'_f$ and $g'_d$ are expressed as

$$C'_f = C_{v1} + C_{d} + 2 \cdot C_{f3} + C_{o4} + 2 \cdot C_{f4} + C_{i5} + C_{o5} \tag{6}$$

and

$$g'_d = g_{d1} + g_{d4} + g_{d5} + g_{m5} - g_{m4} \tag{7}$$

where each $C_{ij}$ ($C_{oj}$) is the equivalent capacitance at the input (output) node of the corresponding inverter INVj and $C_n$ is the corresponding feedback capacitance. $g_{m5}$ ($g_d$) is the sum of the transconductances (drain conductances) of the PMOS and NMOS transistors which form the inverter INVj.

As can be seen from (7), the $g'_d$ can be monotonously reduced by decreasing $g_{o5}$ and $g_{o4}$, which can be achieved by decreasing the supply voltages $V_{DD2} = -V_{SS}$ of INV5. Since Fig. 3(b) is similar to Fig. 1(b), but with $C_n$ and $g_d$ replaced by $C'_f$ and $g'_d$ due to the extra inverters at the output nodes, the reduced $g'_d$ makes the $Q$ value increase. Therefore, $V_{DD2} = -V_{SS}$ can be regarded as the $Q$-tuning control bias. Especially, when $g'_d < 0$, the quality factor $Q$ is heavily enhanced while $f_c$ is decreased slowly. Thus, the high-$Q$ bandpass biquad can be implemented at high enough $f_c$. By using both the $Q$-tuning bias $V_{DD2} = -V_{SS}$ and the $r_n$-control voltages $V_{CN}$ and $V_{CP}$, $Q$ and $f_c$ can be iteratively tuned to the specified values.

However, as the operational frequency of the continuous-time filters is increased, the nonideal effects of parasitic capacitance become more pronounced and unpredictable, which results in the automatic tuning being more difficult. Therefore, the master–slave control systems are not suitable in the VHF range since they have critical matching requirements among integrated elements. However, the adaptive technique seems to be an encouraging solution for tuning in VHF since there is no critical matching requirement as in the master–slave control systems [6]. But, it is still a struggling job now since the tuning of the $f_c$ and $Q$ is interdependent and the $Q$-tuning voltage comes from a source that must deliver current.

### III. Experimental Results

The proposed inverter-based VHF/UHF $R_{n-C}$ biquadratic filters have been fabricated in 0.8 $\mu$m double-poly-double-metal CMOS technology. The photomicrographs of the single-ended-output $R_{n-C}$ bandpass biquadratic filter and the pseudodifferential high-$Q$ bandpass biquad are shown in Fig. 4(a) and (b), respectively.

Fig. 5 shows the measured frequency response of the fabricated single-ended-output $R_{n-C}$ bandpass biquad with $C_d = 1.2$ pF and $C_i = 0.2$ pF, when the $r_n$-control voltages $V_{CN} = -V_{CP} = 1.8$ V. The measured center frequency $f_c$ and quality factor $Q$ are 368.11 MHz and 1.195, respectively. Compared with the simulated values, $f_c$(sim) = 375.8 MHz and $Q$(sim) = 1.1027, the deviations are about 2.7% and 8.4%, respectively. These deviations resulted from the imprecise parasitic capacitance estimation due to the process variations and the extra parasitic capacitances induced by the interconnections.

Over five measured chips, the mean value of the measured center frequency $f_c$ is 358.01 MHz with a standard deviation of 2.58%. Because the $R_{n-C}$ VHF bandpass filter with its characteristics depend critically on parasitic
effects, the parameter deviations are mainly due to the process variations. For comparison, the statistical Monte-Carlo analysis has been performed according to the technological worst cases and the matching properties. Two crucial SPICE parameters of MOS transistors, zero-bias threshold voltage (VTO) and carrier mobility (UO), are specified by using the 3-sigma Gaussian distribution with ±10% variations. The simulated mean value of the center frequency is 351.4 MHz whereas the standard deviation is 2.51%.

Fig. 6 shows the comparison of the simulated and measured results of the single-ended-output $R_m$-C bandpass biquad versus the $r_m$-control voltage $V_{CN} = -V_{CP}$. When $V_{CN} = -V_{CP}$ changes from 2.0 V to 1.4 V, the measured $f_c$ (Q) of the fabricated bandpass filter changes from 388 MHz (1.0752) to 173 MHz (1.4805). The available tuning range of $f_c$ is as high as 215 MHz. Although there exists the center-frequency shifts from the simulated results, the tuning trend can be confirmed by the experimental results.

When the supply voltages are reduced to ±2.0 V and ±1.5 V, the available tuning ranges and center frequencies are reduced. However, the filter center frequencies are still higher than 100 MHz. This shows the feasibility of the proposed filter in the low-supply-voltage operation. The measured characteristics of the $R_m$-C bandpass biquad for different supply voltages are summarized in Table I.

Fig. 7 shows experimentally the Q-enhancement effect of the fabricated pseudodifferential high-Q $R_m$-C bandpass biquad with $C_d = 1 \text{ pF}$ and $C_f = 0.4 \text{ pF}$, when $V_{CN} = -V_{CP} = 2.0 \text{ V}$ and the Q-tuning control voltage $V_{DD2} = -V_{SS2}$ changes from 1.80 to 1.252 V. The measured characteristics of the pseudodifferential high-Q bandpass biquad configuration of Fig. 2 versus the adjustable Q-tuning control voltage $V_{DD2} = -V_{SS2}$ are shown in Fig. 8. For different $r_m$-tuning control voltage $V_{CN} = -V_{CP}$, the Q value increases sharply with the decreasing $V_{DD2} = -V_{SS2}$ and reaches a high value above 300 whereas the center frequencies are linearly decreased.

The measured characteristics of the pseudodifferential
Fig. 3. (a) The small-signal equivalent differential half-circuit of the pseudodifferential \( R_{\text{c}}C \) bandpass biquad and (b) the simplified circuit of (a).

\[
\begin{align*}
\frac{1}{g_d'} &= \frac{1}{g_{d1}} + \frac{1}{g_{d4}} + \frac{1}{g_{d5}} + \frac{1}{g_{m5}} - \frac{1}{g_{m4}} \\
C_0' &= C_{o1} + C_{i3} + C_{o4} + C_{i5} + 2C_{f3} + 2C_{f4}
\end{align*}
\]

Fig. 4. The photomicrographs of (a) the single-ended-output \( R_{\text{c}}C \) bandpass biquad with the output buffer and another output buffer as reference path and (b) the pseudodifferential high-\( Q \) \( R_{\text{c}}C \) bandpass biquad with the output buffer.
Table I
Comparison of the Measured Characteristics of the Single-Ended-Output VHF/UHF $R_c$-C Bandpass Biquad for Different Supply Voltages

<table>
<thead>
<tr>
<th>Power Supply Voltages</th>
<th>Power Supply Voltages</th>
<th>Power Supply Voltages</th>
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<tbody>
<tr>
<td>$V_{DD} = V_{SS} = 2.5$ V</td>
<td>$V_{DD} = V_{SS} = 2.0$ V</td>
<td>$V_{DD} = V_{SS} = 1.5$ V</td>
</tr>
</tbody>
</table>

- Differentiating Cap. $C_d$: 1.2 pF, 1.2 pF, 1.2 pF
- Control Voltages ($V_{CN} = V_{CP}$): 1.8 V, 1.8 V, 1.5 V
- Center Frequency $f_0$: 368.1 MHz, 353.3 MHz, 258.2 MHz
- Quality Factor $Q$: 1.195, 1.082, 1.0116
- Max. Output Swing for 1% IM3: 165 mV$_{rms}$, 154.7 mV$_{rms}$, 75.8 mV$_{rms}$
- Total In-Band Noise (-3 dB BW): 148.6 $\mu$V$_{rms}$, 155.1 $\mu$V$_{rms}$, 127.5 $\mu$V$_{rms}$
- Dynamic Range: 61 dB, 60 dB, 55.5 dB
- Power Dissipation: 24.83 mW, 11.45 mW, 3.42 mW
Control Voltages

\( V_{DD2} = -V_{SS2} \) changes from 1.80 V to 1.252 V, when \( V_{CN} = -V_{CP} = 2.0 \) V.

Fig. 7. The measured frequency responses of the fabricated pseudodifferential high-\( Q R_{51C} \) bandpass with \( C_d = 1.0 \) pF and \( C_i = 0.4 \) pF versus the decreasing \( Q \)-tuning control voltage \( V_{DD2} = -V_{SS2} \) changes from 1.80 V to 1.252 V, when \( V_{CN} = -V_{CP} = 2.0 \) V.

Fig. 8. The measured characteristics of the pseudodifferential high-\( Q \) bandpass biquad of Fig. 2 versus the adjusting \( Q \)-tuning control voltages \( V_{DD2} = -V_{SS2} \) for different \( V_{CN} = -V_{CP} \).

### TABLE II

<table>
<thead>
<tr>
<th>Quality Factor</th>
<th>Quality Factor</th>
<th>Quality Factor</th>
<th>Quality Factor</th>
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<tbody>
<tr>
<td>( Q = 94.05 )</td>
<td>( Q = 29.35 )</td>
<td>( Q = 5.02 )</td>
<td>( Q = 0.98 )</td>
</tr>
<tr>
<td>Control Voltages ( (V_{CN} = -V_{CP}) )</td>
<td>2.0V</td>
<td>2.0V</td>
<td>2.0V</td>
</tr>
<tr>
<td>Control Voltages ( (V_{DD2} = -V_{SS2}) )</td>
<td>1.2564 V</td>
<td>1.30 V</td>
<td>1.41 V</td>
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<tr>
<td>Center Frequency ( f_o )</td>
<td>223.6 MHz</td>
<td>224.4 MHz</td>
<td>234.0 MHz</td>
</tr>
<tr>
<td>Gain at ( f_o )</td>
<td>39.97 dB</td>
<td>30.21 dB</td>
<td>14.22 dB</td>
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<tr>
<td>Max. Output Swing for 1% IM3</td>
<td>199.0 ( mV_{rms} )</td>
<td>288.7 ( mV_{rms} )</td>
<td>306.5 ( mV_{rms} )</td>
</tr>
<tr>
<td>Total In-Band Noise ( (3 \text{ dB BW}) )</td>
<td>255.0 ( \mu V_{rms} )</td>
<td>155.7 ( \mu V_{rms} )</td>
<td>87.35 ( \mu V_{rms} )</td>
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<tr>
<td>Dynamic Range</td>
<td>57.83 dB</td>
<td>65.34 dB</td>
<td>70.85 dB</td>
</tr>
<tr>
<td>Power Dissipation</td>
<td>56.2 mW</td>
<td>56.4 mW</td>
<td>56.7 mW</td>
</tr>
</tbody>
</table>
$R_m$-C bandpass biquad for different $Q$ values, when $V_{DD} = -V_{SS} = 2.5$ V and $V_{CN} = -V_{CP} = 2.0$ V, are summarized in Table II.

IV. CONCLUSIONS

In this work, the simple CMOS inverter-based $R_m$ amplifier is proposed and applied to the design of the VHF/UHF bandpass biquadratic filters. The experimental results have shown that the measured center frequency $f_c$ can be as high as 368 MHz with $Q = 1.195$ for the single-ended-output $R_m$-C bandpass biquad. Also, the post-tuning capability of the center frequency $f_c$ by adjusting the control voltages $V_{CN}$ and $V_{CP}$ has been confirmed. Moreover, the proposed biquads are suitable for the low power and low voltage applications. On the other hand, the $Q$-enhancement and tuning circuit is used in the pseudodifferential configuration of the $R_m$-C biquad to implement high-$Q$ tunable bandpass filters. The experimental results have shown that the maximum $Q$ is 360 with $f_c$ around 223 MHz. In the future, the automatic tuning scheme will be developed.

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