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_o 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_o of the single-ended-output R_m-C bandpass biquad is 386 MHz (258 MHz) and $Q = 1.195$ ($Q = 1.012$) for ± 2.5 V (± 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 $f_o = 222.7$ MHz. When $Q = 94$, the power consumption is 56.2 mW and the measured dynamic range is 57.8 dB for ± 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_o 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_o 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

$$\frac{V_o}{V_{\text{in}}} \cong \frac{sC_d \cdot D}{[A \cdot s^2 + B \cdot s + C]} \tag{1}$$

where

$$A \cong (C_d + C_i) \cdot (C_f + C_o) + C_f \cdot C_o \tag{2}$$

$$B \cong g_m \cdot C_f + g_d \cdot (C_d + C_i + C_f) + g_f \cdot (C_f + C_o) \tag{3}$$

$$C \cong (g_m + g_d) \cdot g_f \tag{4}$$

$$D \cong -(g_m - g_f). \tag{5}$$

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

The pole frequency ω_o 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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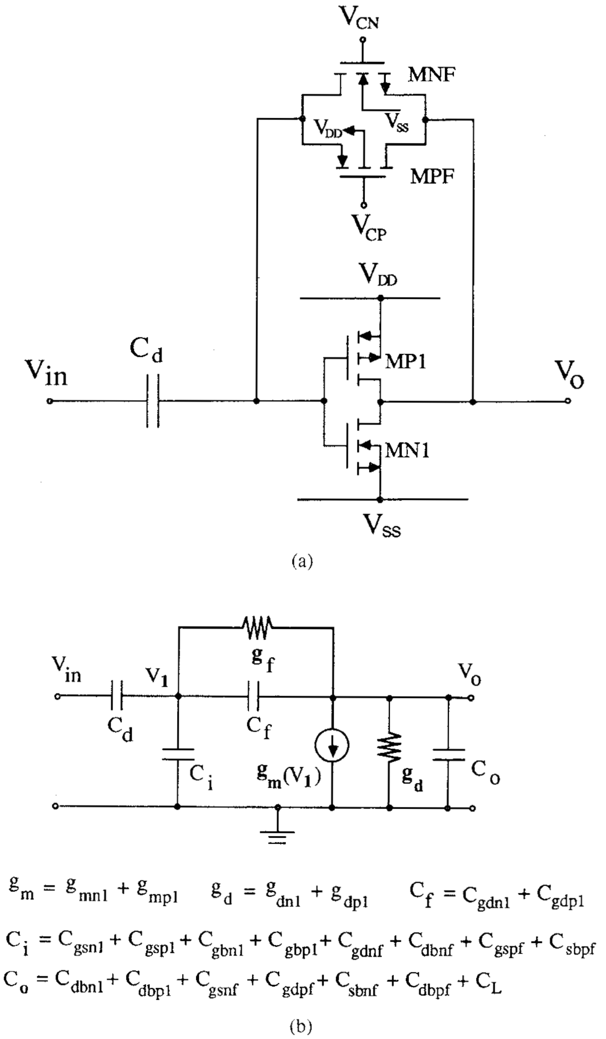


Fig. 1. (a) The inverter-based VHF R_m-C bandpass biquad and (b) the small-signal equivalent circuit.

control voltages V_{CN} and V_{CP}. Moreover, the simple configuration makes it possible to operate under the reduced supply voltages, such as ± 1.5 V. With low supply voltages, however, the tuning range of the r_m-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_m-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_o' and g_d' are expressed as

$$C_o' = C_{o1} + C_{i3} + 2 \cdot C_{f3} + C_{o4} + 2 \cdot C_{f4} + C_{i5} + C_{o5} \tag{6}$$

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

where each C_{ij} (C_{oj}) is the equivalent capacitance at the input (output) node of the corresponding inverter INVj and C_{fj} is the corresponding feedback capacitance. g_{mj} (g_{dj}) 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_{m5} and g_{d5}, which can be achieved by decreasing the supply voltages $V_{DD2} = -V_{SS2}$ of INV5. Since Fig. 3(b) is similar to Fig. 1(b), but with C_o and g_d replaced by C_o' and g_d' due to the extra inverters at the output nodes, the reduced g_d' makes the Q value increase. Therefore, $V_{DD2} = -V_{SS2}$ can be regarded as the Q-tuning control bias. Especially, when $g_d' < 0$, the quality factor Q is heavily enhanced while f_o is decreased slowly. Thus, the high-Q bandpass biquad can be implemented at high enough f_o. By using both the Q-tuning bias $V_{DD2} = -V_{SS2}$ and the r_m-control voltages V_{CN} and V_{CP}, Q and f_o 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_o 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_m-C biquadratic filters have been fabricated in 0.8 μm double-poly-double-metal CMOS technology. The photomicrographs of the single-ended-output R_m-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_m-C bandpass biquad with $C_d = 1.2$ pF and $C_L = 0.2$ pF, when the r_m-control voltages $V_{CN} = -V_{CP} = 1.8$ V. The measured center frequency f_o and quality factor Q are 368.11 MHz and 1.195, respectively. Compared with the simulated values, $f_{o\,(\mathrm{sim})} = 375.8$ MHz and $Q_{(\mathrm{sim})} = 1.1027$, the deviations are about 2.7% and 8.4%, respectively. These deviations resulted from the imprecise parasitic capacitances 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_o is 358.01 MHz with a standard deviation of 2.58%. Because the R_m-C VHF bandpass filter with its characteristics depend critically on parasitic

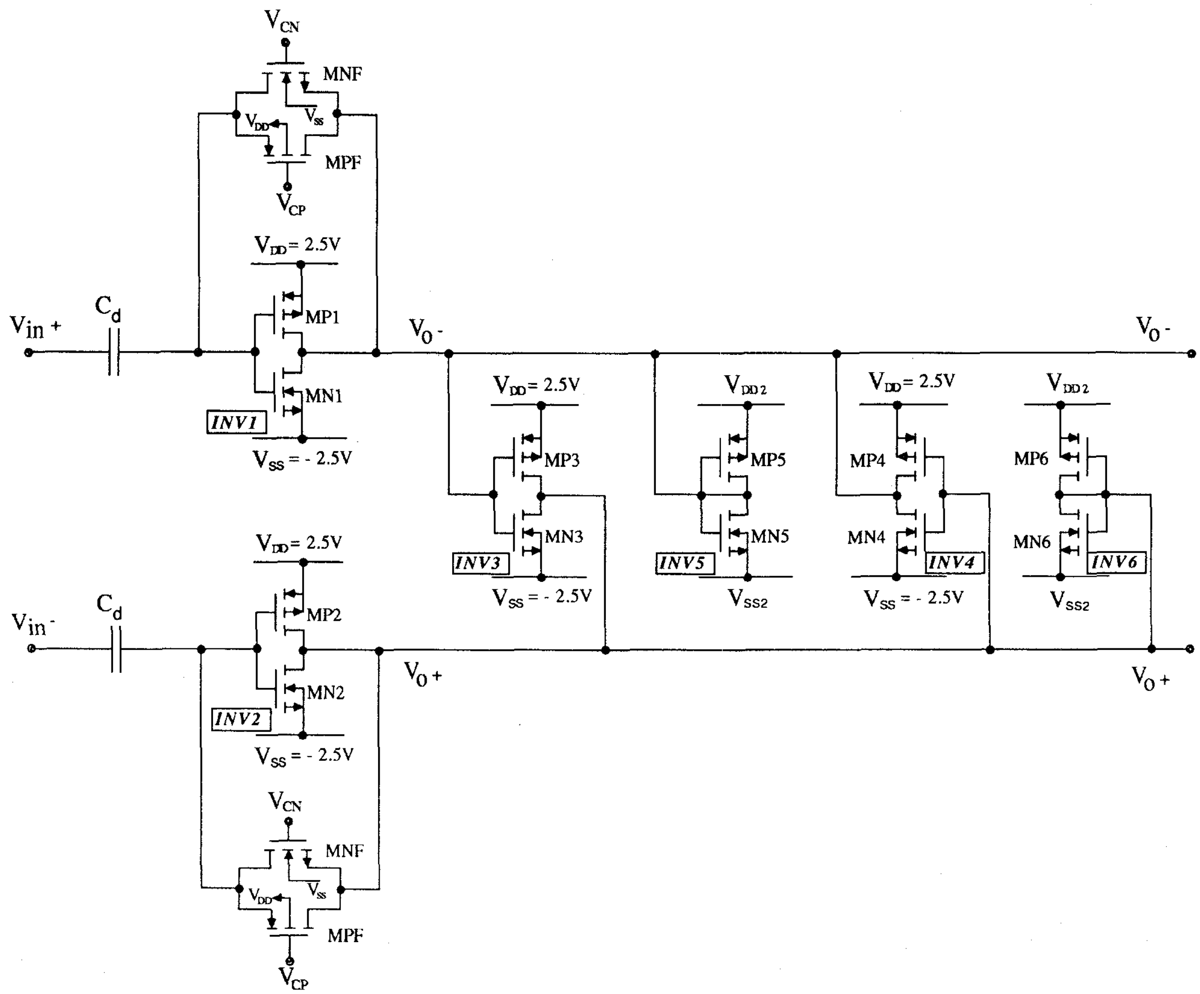


Fig. 2. The pseudodifferential configuration of the R_m-C bandpass biquad with two extra inversely connected inverters INV3 and INV4 between the differential output nodes in parallel with two extra self-shorted inverters INV5 and INV6.

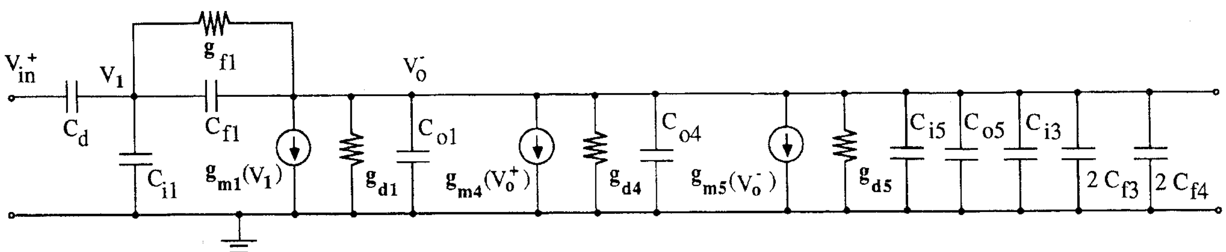
effects, the parameter deviations are mainly due to the process variations. For comparison, the statistical Monte-Carlo analysis has been performed according to the technological worst cases and the matching properties. Two crucial SPICE parameters of MOS transistors, zero-bias threshold voltage (VTO) and carrier mobility (UO), are specified by using the 3-sigma Gaussian distribution with $\pm 10\%$ 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_o (Q) of the fabricated bandpass filter changes from 388 MHz (1.0752) to 173 MHz (1.4805). The available tuning range of f_o 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.

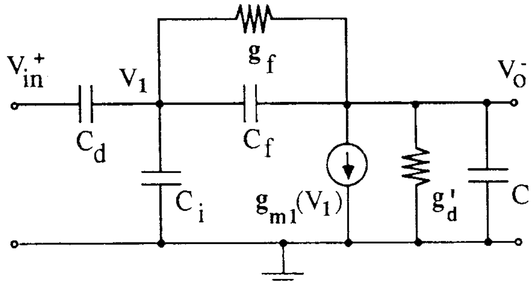
When the supply voltages are reduced to ± 2.0 V and ± 1.5 V, the available tuning ranges and center frequencies are reduced. However, the filter center frequencies are still higher than 100 MHz. This shows the feasibility of the proposed filter in the low-supply-voltage operation. The measured characteristics 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 $C_d = 1$ pF and $C_L = 0.4$ pF, when $V_{CN} = -V_{CP} = 2.0$ 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



(a)

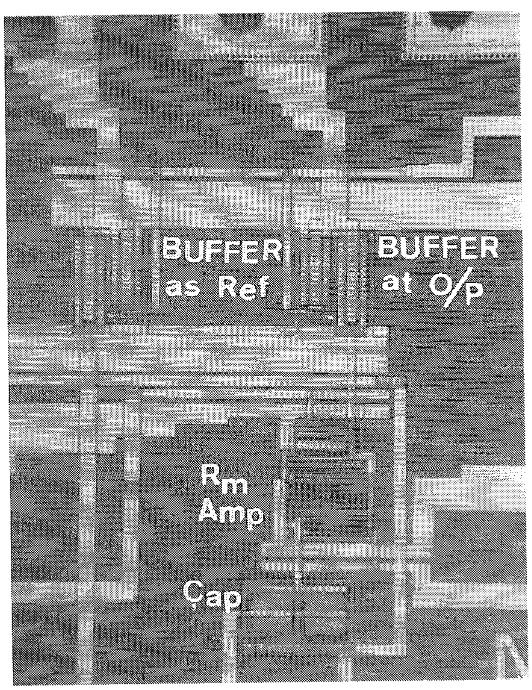


$$g_d' = g_{d1} + g_{d4} + g_{d5} + g_{m5} - g_{m4}$$

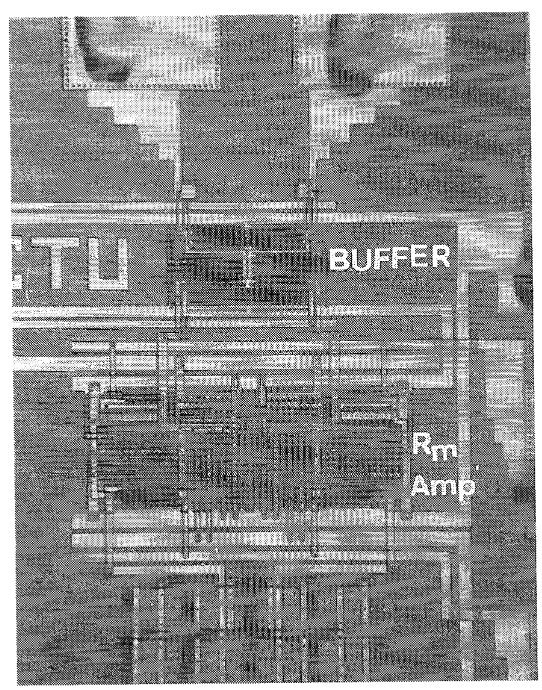
$$C_o' = C_{o1} + C_{i3} + C_{o4} + C_{i5} + C_{o5} + 2\,C_{f3} + 2\,C_{f4}$$

(b)

Fig. 3. (a) The small-signal equivalent differential half-circuit of the pseudodifferential R_m-C bandpass biquad and (b) the simplified circuit of (a).



(a)



(b)

Fig. 4. The photomicrographs of (a) the single-ended-output R_m-C bandpass biquad with the output buffer and another output buffer as reference path and (b) the pseudodifferential high-Q R_m-C bandpass biquad with the output buffer.

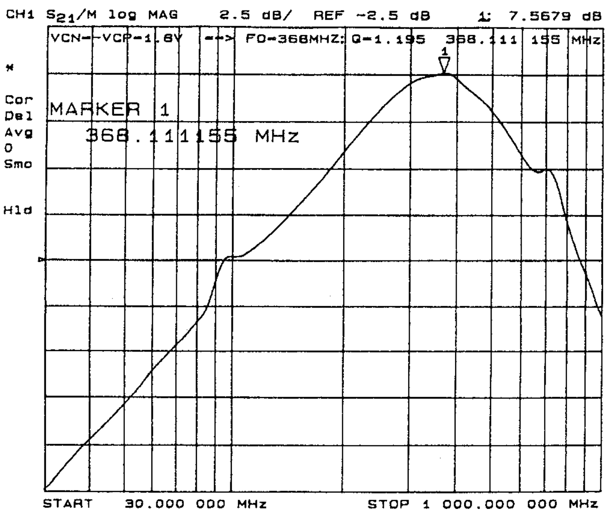


Fig. 5. The measured frequency response of the fabricated single-ended-output R_m-C bandpass biquad with C_d = 1.2 pF and C_L = 0.2 pF, when $V_{CN} = -V_{CP}$ = 1.8 V.

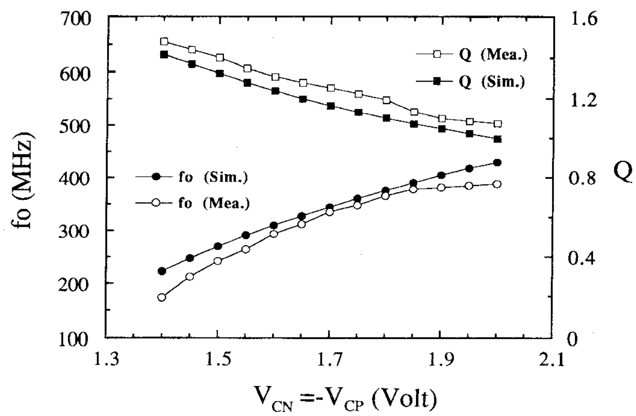


Fig. 6. Comparison of the simulated and measured results of the single-ended-output R_m-C bandpass biquad with C_d = 1.2 pF and C_L = 0.2 pF versus different $V_{CN} = -V_{CP}$.

TABLE I
COMPARISON OF THE MEASURED CHARACTERISTICS OF THE SINGLE-ENDED-OUTPUT VHF/UHF R_m-C BANDPASS BIQUAD FOR DIFFERENT SUPPLY VOLTAGES

	Power Supply Voltages V_{DD}= -V_{SS} = 2.5V	Power Supply Voltages V_{DD}= -V_{SS} = 2.0V	Power Supply Voltages V_{DD}= -V_{SS} = 1.5V
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_o	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}	154.7mV_{rms}	75.8 mV_{rms}
Total In-Band Noise (- 3 dB BW)	148.6 μV_{rms}	155.1 μV_{rms}	127.5 μV_{rms}
Dynamic Range	61 dB	60 dB	55.5 dB
Power Dissipation	24.83 mW	11.45 mW	3.42 mW

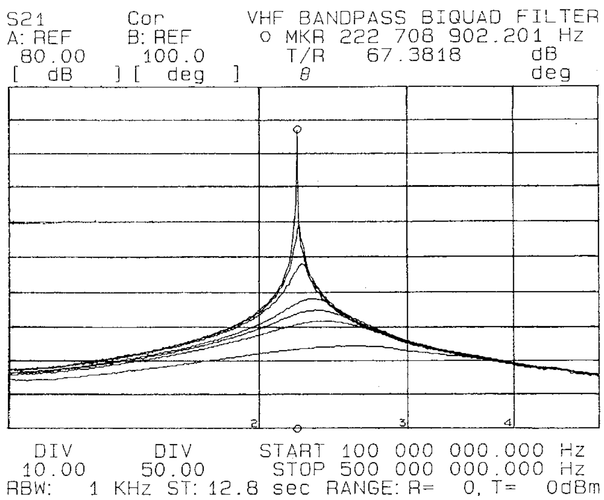


Fig. 7. The measured frequency responses of the fabricated pseudodifferential high-Q R_m-C bandpass with C_d = 1.0 pF and C_L = 0.4 pF versus the decreasing Q-tuning control voltage $V_{DD2} = -V_{SS2}$ changes from 1.80 V to 1.252 V, when $V_{CN} = -V_{CP} = 2.0$ V.

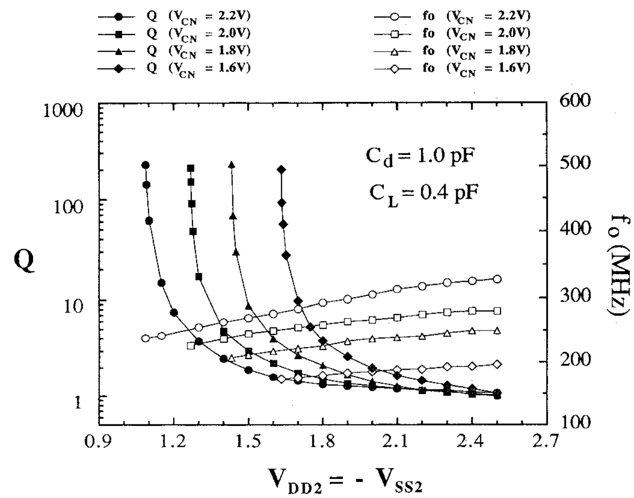


Fig. 8. The measured characteristics of the pseudodifferential high-Q bandpass biquad of Fig. 2 versus the adjusting Q-tuning control voltages $V_{DD2} = -V_{SS2}$ for differnt $V_{CN} = -V_{CP}$.

TABLE II
COMPARISON OF THE MEASURED CHARACTERISTICS OF THE PSEUDODIFFERENTIAL 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

	Quality Factor Q = 94.05	Quality Factor Q = 29.35	Quality Factor Q = 5.02	Quality Factor Q = 0.98
Control Voltages ($V_{CN} = -V_{CP}$)	2.0V	2.0V	2.0V	2.0V
Control Voltages ($V_{DD2} = -V_{SS2}$)	1.2564 V	1.30 V	1.41 V	2.50 V
Center Frequency f_o	223.6 MHz	224.4 MHz	234.0 MHz	276.7 MHz
Gain at f_o	39.97 dB	30.21 dB	14.22 dB	-1.44 dB
Max. Output Swing for 1% IM3	199.0 mV_{rms}	288.7 mV_{rms}	306.5 mV_{rms}	338.2 mV_{rms}
Total In-Band Noise (- 3 dB BW)	255.0 μV_{rms}	155.7μV_{rms}	87.35μV_{rms}	180.5 μV_{rms}
Dynamic Range	57.83 dB	65.34 dB	70.85 dB	65.43 dB
Power Dissipation	56.2 mW	56.4 mW	56.7 mW	79.0 mW

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_o 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_o 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 pseudo-differential 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_o around 223 MHz. In the future, the automatic tuning scheme will be developed.

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