High input impedance voltage-mode universal filter and its modification as quadrature oscillator using VDDDDAs

Sunti Tuntrakool¹, Montree Kumngern², Roman Sotner³, Norbert Herencsar³, Peerawut Suwanjan⁴ & Winai Jaikla⁴*

¹Department of Telecommunications Engineering, Faculty of Engineering, King Mongkut’s Institute of Technology Ladkrabang, Bangkok 10520, Thailand
²Department of Radio Electronics, Faculty of Electrical Engineering and Communication, Brno University of Technology, Brno 61600, Czech Republic
³Department of Telecommunications, Faculty of Electrical Engineering and Communication, Brno University of Technology, Brno 61600, Czech Republic
⁴Department of Engineering Education, Faculty of Industrial Education and Technology, King Mongkut’s Institute of Technology Ladkrabang, Bangkok 10520, Thailand

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The second order universal voltage-mode filter using voltage differencing differential difference amplifiers (VDDDDAs) has been proposed. It has high input impedance voltage-mode biquad filter with orthogonal tune of natural frequency and quality factor. The proposed filter simultaneously provides five filter responses: low-pass (LP), high-pass (HP), band-reject (BR), all-pass (AP) and band-pass (BP) in the same circuit topology. The natural frequency and quality factor can be tuned electronically and orthogonally dc bias current. The output impedance at output nodes HP, AP and BR has low impedance which can connect to other circuit without the use of voltage buffers. The proposed filter consists of three VDDDDAs, one grounded resistor and two grounded capacitors. This makes the proposed filter suitable for integrated circuit development. With slightly modifying the proposed filter, the voltage-mode quadrature sinusoidal oscillator with low output impedance and independent control of condition of oscillation (CO) and frequency of oscillation (FO) has been achieved. The results shown in this paper are from PSPICE simulation and experiment to validate the proposed circuits.

Keywords: Analog filter, VDDDA, Voltage-mode, Single input-multiple output, Oscillator

1 Introduction

The oscillator circuit and analog active filter are popular and standard topic for circuit design. They are widely used for their important requirements for application in electrical and electronic system and also very popular in using for circuit design of continuous-time analog signal processing. There are many fields that using filters circuit such as communications, measurement, and instrumentation, and control systems¹. Especially, researchers have been very considerably interest in several functions filter which is called universal filter or multifunction filter. The single-input multiple-output (SIMO) is the most popular analog filter where different output filter functions can be simultaneously realized by the same circuit topology².

Using of active building block for circuit design is very popular in use. It gives the flexibility for designer to realize the high performance circuit using minimum number of active element³–⁷. With mentioned features, the principle of active building blocks for both current and voltage mode circuit are introduced by Biolek et al.⁶ Voltage differencing differential difference amplifier (VDDDA)⁸ is one of the interests. It allows interesting utilization and design of more profitable or more exacting application especially the electronic controllability. From literature reviews, it is found that not much research using VDDDA has been published for instance the voltage-mode first order all pass filter⁸, oscillator⁸–¹⁰. The excellent multiple-input multiple-output (MIMO) voltage-mode universal filter using VDDDA was proposed in literature¹⁰–¹⁴. These filters can provide complete standard transfer functions with

*Corresponding author (E-mail: winai.ja@kmitl.ac.th)
high inputs and low outputs impedance. The natural frequency and quality factor can be electronically and orthogonally controlled. However, these filters cannot be considered as universal filter because all five filter responses cannot be simultaneously provided. The multiple-input single-output (MISO) voltage mode filter was introduced by Herencsar et al.15 This filter consists of single active building block, single MOS transistor and two floating capacitors. It can provide five filter responses depending on the appropriate selecting input voltage. The natural frequency and quality factor can be electronically tuned. However, this filter cannot be easy to cascade without the use of voltage buffers. Moreover, the use of floating capacitors is not attractive for integration.

This contribution presents a SIMO voltage-mode filter with high input impedance, emphasizing on use of VDDDAs. The proposed filter composes of three active elements, one grounded resistor and two grounded capacitors which are suitable for fabricating in monolithic chip or off-the-shelf implementation. The proposed filter can provide five standard functions such as low-pass, high-pass, band-reject, all-pass and band-pass. The quality factor and natural frequency can be electronically and orthogonally adjusted. With slight modification of the proposed filter, the voltage-mode quadrature oscillator with low output impedance is achieved.

2 Principle of Operation

2.1 VDDDA overview

The principle of VDDDA was introduced by Biolek et al.6 Later, Herencsar et al.8 proposed the internal construction of VDDDA using CMOS technology. Symbol and equivalent circuit of VDDDA are shown in Fig. 1 (a) and (b), respectively, where $V_+$ and $V_-$ are the voltage input terminals which will be converted to be the current at $z$ terminal by transconductance ($g_m$). It is generally tuned by bias current and the differential voltage at terminal $z$, $n$ and $p$ will be send to $w$ terminal with the unity voltage gain. For ideal VDDDA, it has low output impedance at $w$ terminal and high input impedance at terminals $V_+$ and $V_-$. The characteristics matrix equation of ideal VDDDA is described below:

\[
\begin{pmatrix}
I_{+} \\
I_{-} \\
I_{z} \\
I_{n} \\
I_{p} \\
V_{w}
\end{pmatrix} =
\begin{pmatrix}
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
g_m & -g_m & 0 & 0 & 0 & V_z \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & -1 & 1 & 0
\end{pmatrix}
\begin{pmatrix}
V_{+} \\
V_{-} \\
V_z \\
V_n \\
V_p \\
V_w
\end{pmatrix}
\]

Fig. 1 — VDDDA (a) symbol and (b) equivalent circuit

2.2 High input impedance voltage-mode filter using VDDDAs

Figure 2 is the proposed second order filter consisted of three VDDDAs, one grounded resistor and two grounded capacitors. The proposed filter provides simultaneously five filter responses: HP, LP, BR, AP and BP ($BP_1$ and $BP_2$) with high input impedance. Moreover, the output nodes for HP, AP and BR responses exhibit low output impedance. Considering an ideal VDDDA, routine analysis of the proposed filter provides the following voltage transfer functions:

\[
HP(s) = \frac{V_{HP}}{V_{in}} = \frac{-s^2}{D(s)}
\]

\[
LP(s) = \frac{V_{LP}}{V_{in}} = \frac{g_{m1}g_{m2}}{C_1C_2D(s)}
\]

\[
BR(s) = \frac{V_{BR}}{V_{in}} = \frac{g_{m1}g_{m2}}{C_1C_2D(s)}
\]

\[
V_{+}, V_{-}, z, n \text{ and } p. \text{ The characteristics matrix equation of ideal VDDDA is described below:}
\]

\[
\begin{pmatrix}
I_{+} \\
I_{-} \\
I_{z} \\
I_{n} \\
I_{p} \\
V_{w}
\end{pmatrix} =
\begin{pmatrix}
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
g_m & -g_m & 0 & 0 & 0 & V_z \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & -1 & 1 & 0
\end{pmatrix}
\begin{pmatrix}
V_{+} \\
V_{-} \\
V_z \\
V_n \\
V_p \\
V_w
\end{pmatrix}
\]

Fig. 2 – Presented voltage-mode filter

\[
\begin{pmatrix}
I_{+} \\
I_{-} \\
I_{z} \\
I_{n} \\
I_{p} \\
V_{w}
\end{pmatrix} =
\begin{pmatrix}
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
g_m & -g_m & 0 & 0 & 0 & V_z \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & -1 & 1 & 0
\end{pmatrix}
\begin{pmatrix}
V_{+} \\
V_{-} \\
V_z \\
V_n \\
V_p \\
V_w
\end{pmatrix}
\]

\[
... (1)
\]

VDDDA1

VDDDA2

VDDDA3

Fig. 1 — VDDDA (a) symbol and (b) equivalent circuit

Fig. 2 – Presented voltage-mode filter
\[ AP(s) = \frac{V_{AP}}{V_{in}} = \frac{s^2 - \frac{g_{ml} s^{3}}{C_1} + \frac{g_{ml} g_{m2}}{C_1 C_2}}{D(s)} \quad \ldots (5) \]

\[ BP_1(s) = \frac{V_{BP1}}{V_{in}} = \frac{\frac{g_{ml} s}{C_1}}{D(s)} \quad \ldots (6) \]

\[ BP_2(s) = \frac{V_{BP2}}{V_{in}} = \frac{\frac{g_{ml} g_{m2} R_s}{C_1}}{D(s)} \quad \ldots (7) \]

where

\[ D(s) = s^2 + \frac{g_{ml} g_{m2} R_s}{C_1} + \frac{g_{ml} g_{m2}}{C_1 C_2} \quad \ldots (8) \]

It is found from Eqs (2-8) that the proposed filter is the unit gain filter, then, for any practical use, additional voltage amplifiers are needed to achieve gain from the active filter. However, the gain is probably obtained for \( BP_1 \) only if specific quality factor (\( Q \)) is set. The natural frequency (\( \omega_0 \)) and \( Q \) of each filter response can be expressed as following:

\[ \omega_0 = \sqrt{\frac{g_{ml} g_{m2}}{C_1 C_2}} \quad \text{and} \quad Q = \frac{1}{g_{ml} R_s} \sqrt{\frac{C_1 g_{m2}}{C_2 g_{ml}}} \quad \ldots (9) \]

From Eq. (9), it is found that the quality factor can be electronically tuned via \( g_{m2} \) without affecting the natural frequency. Moreover, if \( g_{ml} \) is equal to \( g_{m2} \), the natural frequency can be electronically adjusted without affecting the quality factor. However, it is found that the proposed circuit needs component matching conditions (i.e., \( g_{m2}=1/R \)) for realizing \( AP \) response. The relative sensitivities of the proposed filter can be found in Eq. (10):

\[ S_{e_{s1}} = S_{e_{s2}} = \frac{1}{2}; \quad S_{c_{e1}} = S_{c_{e2}} = -1/2; \]

\[ S_{o_{e1}} = S_{o_{e2}} = -1; \quad S_{c_{e1}} = S_{c_{e2}} = -1/2; \quad S_{o_{e1}} = S_{o_{e2}} = -1/2 \quad \ldots (10) \]

It is found that the active and passive sensitivities are equal or less than unity in magnitude.

3 Non-Ideal Case

Practically, the performances of the proposed filter are affected by the influence of voltage tracking error from the unity-value gain of internal differential voltage buffer and parasitic terminal impedances of VDDDA. In this section, these parameters will be taken into account. For non-ideal case the voltage at \( w \) terminal is rewritten as shown below:

\[ V_w = \beta_3 V_i - \beta_2 V_n + \beta_1 V_p \quad \ldots (11) \]

From Eq. (10), \( \beta_3, \beta_2, \beta_1 \) and \( \beta_p \) are the voltage error gains from \( z, n, p \) terminals to \( w \) terminal, respectively. The influences of parasitic impedances of \( V_{1}, p_{1}, n_{2} \) and \( n_{3} \) terminals will be negligible because of their connection to low-impedance outputs (\( w_{3} \) terminal) and input voltage source. The most importance parasitic impedances are the impedance at \( z_{1} \) (\( R_{zi}/C_{zi} \)), \( n_{1} \) (\( R_{ni}/C_{ni} \)), \( V_{i2} \) (\( R_{vi2}/C_{vi2} \)), \( z_{2} \) (\( R_{zi2}/C_{zi2} \)) and \( p_{3} \) (\( R_{pi3}/C_{pi3} \)) terminals. However, the parasitic impedances at \( z_{3} \) terminal will be negligible but the operation frequency \( f_{op} \) should be more lower than \( 1/(C_{zi}(R_{zi}+R)) \). The voltage transfer functions for the circuit of Fig. 3 are given in Eqs (12-17):

\[ \frac{V_{BP}}{V_{in}} = -\beta_3 \left[ s^2 C_i C_z + s \left( C_i G_z + C_z G_i \right) + G_i G_z \right] \quad \ldots (12) \]

\[ \frac{V_{BP}}{V_{in}} = \frac{\beta_3 g_{ml} g_{m2} R_s}{C_i C_z} \quad \ldots (13) \]

\[ \frac{V_{BP}}{V_{in}} = \frac{\beta_3 g_{ml} g_{m2} R_s}{C_i C_z} \quad \ldots (14) \]

\[ \frac{V_{BP}}{V_{in}} = -\beta_3 \left[ s^2 C_i C_z + s \left( C_i G_z + C_z G_i \right) + G_i G_z \right] \quad \ldots (15) \]

\[ \frac{V_{BP}}{V_{in}} = \frac{\beta_3 g_{ml} g_{m2} R_s}{C_i C_z} \quad \ldots (16) \]

\[ \frac{V_{BP}}{V_{in}} = -\beta_3 \left[ s^2 C_i C_z + s \left( C_i G_z + C_z G_i \right) + G_i G_z \right] \quad \ldots (17) \]

where

\[ D'(s) = \left[ s^2 + \frac{G_i G_z + \beta_3 g_{ml} g_{m2} R_s C_i}{C_z C_i} + \frac{\beta_3 g_{ml} g_{m2} R_s}{C_i} \right] \quad \ldots (18) \]
\[ C'_1 = C_1 + C_{22} + C_{1+2} + C_{1+3}, \quad C'_2 = C_2 + C_{24} + C_{n1} + C_{p3}, \quad G'_1 = G_{11} + G_{22} + G_{1+3} \text{ and } G'_2 = G_{12} + G_{l1} + G_{p3}. \] Also non-ideal values of \( \omega_0 \) and \( Q \) are found in Eqs (19) and (20), respectively:

\[ \omega'_0 = \sqrt{G'_2 \frac{G'_1 + \beta_3 g_m g_m RG'_1 + \beta_3 g_m g_m}{C'_1 C'_2}} \quad \ldots (19) \]

\[ Q' = \frac{1}{\sqrt{\frac{C'_2 G'_2 + G'_1}{\beta_3 g_m g_m R}}} \left( G'_2 G'_1 + \frac{\beta_3 g_m g_m}{C'_1 C'_2} \right) \quad \ldots (20) \]

### 4 Simulations Results

PSPICE simulations of the proposed filter in Fig. 2 were performed. The implementation of the CMOS VDDDA was same as described elsewhere. Parameters of a 0.18 µm TSMC CMO technology (level 7) with ±0.9 V voltage supply and \( V_{IH} = -0.35 \) V was used for simulation of PMOS and NMOS transistors. From Table 1, aspect ratios of PMOS and NMOS transistors are listed. It is seen that the parasitic resistances at terminals \( V_+ \), \( V_- \), \( n \), and \( p \) (\( R_v, R_n, R_p, \) and \( R_s \)) exhibit high because they are gate resistance. Other simulated parasitic element values for each terminal (\( I_B = 50 \) µA) are \( C_{v+} = 55.5 \) fF, \( C_{v-} = 53.2 \) fF, \( R_v = 570.54 \) kΩ, \( C_z = 15.4 \) fF, \( R_z = 424 \) fF and \( C_p = 4.25 \) fF. The simulated voltage error gains, \( \beta_1 \), \( \beta_2 \), and \( \beta_p \) are equal to 0.997. The filter was designed with the parameters of its components as follows: \( C_1 = C_2 = 47 \) pF, \( R = 3.3 \) kΩ, \( I_{B1} = I_{B2} = I_{B3} = 50 \) µA. It yields the natural frequency of 1.047 MHz and quality factor of 1. The theoretical pole frequency is about 1.058 MHz. From the results, the gains responses for \( LP, BP_1, BP_2 \) and \( HP \) of the proposed filter obtained from Fig. 2 are shown in Figs 3-5 which are the gain response and phase response of \( BR \) and \( AP \) responses, respectively. It is obviously that the proposed filter can simultaneously provide low-pass, high-pass, band-pass, band-reject and all-pass functions without modifying circuit topology. The gain response of \( BP_2 \) difference \( I_{B3} \) is shown in Fig. 6, where \( I_{B3} \) was set to 20 µA, 50 µA and 200 µA. The quality factor evaluated based on the simulation results was 1.49, 1, and 0.65, respectively. This is confirmed by Eq. (9) that the quality factor can be electronically tuned by \( I_{B3} \) without affecting the natural frequency. High \( Q \) value can be achieved by setting \( I_{B3} \) as low as possible. The highest simulated \( Q \) is 26.66 (\( I_{B3} = 1 \) µA) and the lowest simulated \( Q \) is 0.384 (\( I_{B3} = 400 \) µA).

Figure 7 shows the dependence of the THD of \( LP \) filter on input voltage level. The THD is not over 1% when the input signal is lower 650 mV. In this test, sinusoidal signal with 100 kHz in-band frequency was fed into the proposed filter.

### 5 Comparison with Existing SIMO Voltage-Mode Filters

The proposed SIMO voltage-mode filter in Fig. 2 is compared with several SIMO voltage-mode filters from. It is found from Table 2 that there are VM
MISO structures having even some low-output impedance outputs. However, their other drawbacks are in missing possibility for electronic control, requirements for floating passive elements and higher number of active elements (4 or 5).

All these problems are solved in solution presented in this paper.

6 Modification of Proposed Filter as Quadrature Oscillator

By connecting node $V_{BP1}$ to $V_{in}$ and interconnecting terminal $V_+$ and $V_-$ of VDDDA1 and VDDDA2 of the circuit in Fig. 2 according to the principle reported in earlier study as illustrated in Fig. 8, the voltage-mode quadrature oscillator with low output impedance can be achieved. The characteristic equation of the oscillator in Fig. 8 is obtained as:

$$s^2 + (1 - g_{m1}R) \frac{g_{m1}}{C_1} s + \frac{g_{m1}g_{m2}}{C_1C_2} = 0 \quad \ldots (21)$$

According to Eq. (21), the frequency of oscillator (FO) and condition of oscillation (CO) is written as:

$$\omega_0 = \sqrt{\frac{g_{m1}g_{m2}}{C_1C_2}} \quad \ldots (22)$$

Fig. 7 – Dependence of output harmonic distortion of LP filter on the input voltage

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<td>1+2</td>
<td>yes yes yes yes yes</td>
<td>yes yes yes</td>
<td>CMOS &amp; commercial IC</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2 – Comparison of various SIMO voltage-mode filters
It is found from Eq. (22) that the FO and CO are independently and electronically controlled. The relationship of \( V_{O2} \) and \( V_{O1} \) is follows:

\[
\frac{V_{O2}}{V_{O1}} = \frac{s C_1}{g_{m1} g_{m3}} \quad \text{… (23)}
\]

At oscillation frequency \((\omega_0)\), the magnitude of \( V_{O2}/V_{O1} \) is written as:

\[
\left| \frac{V_{O2}}{V_{O1}} \right| = \frac{1}{g_{m3}} \sqrt{\frac{C_1 g_{m2}}{C_2 g_{m1}}} \quad \text{… (24)}
\]

It is found from Eq. (24) that the changing of \( g_{m1} \) or \( g_{m2} \) for controlling the FO causes change of amplitude \( V_{O2} \) and \( V_{O1} \) during tuning process. This phenomenon will increase the THD if amplitude reaches high levels due to the limits of dynamical range of VDDDA. However, this can be alleviated by simultaneously changing \( g_{m1} \) and \( g_{m2} \) (\( I_{B1} = I_{B2} \)). As stated above, the amplitude of quadrature output voltage \( V_{O1} \) and \( V_{O2} \) is equal for all frequency. However, to unify unbalance of produced amplitudes \( V_{O1} \) and \( V_{O2} \) as well as to reduce the THD, the simple AGC circuit for amplitude stabilization can be easily applied to terminal \( z \) of VDDDA3.

The proposed oscillator in Fig. 8 was simulated with the parameters of its components; \( C_1 = C_2 = 47 \) pF, \( R = 3.3 \) k\( \Omega \), \( R_p = 330 \) k\( \Omega \), \( I_{B1} = I_{B2} = 50 \) \( \mu A \) and \( I_{B3} = 51.5 \) \( \mu A \). The W/L of NMOS in AGC is \( 9 \) \( \mu \)m /1.08 \( \mu m \). It yields the FO of 1.014 MHz. The theoretical FO is about 1.058 MHz. The results of this simulation are, respectively, shown in Figs 9 and 10. The total harmonic distortion for \( V_{O1} \) and \( V_{O2} \) are 0.68 \% and 76 \%, respectively. Tuning of simulated and theoretical FO is shown in Fig. 11, where \( I_{B1} \) and \( I_{B2} \) are equal and were adjusted from 10 \( \mu A \) – 300 \( \mu A \). The range of FO controlled from 0.31 MHz – 2.42 MHz was obtained. It is found that there is some deviation between theoretical and simulated value due to the parasitic element as analyzed in Eq. (19).

The tuning of \( g_m \) by adjusting \( I_B \) will change the value of parasitic elements.

### 7 Experimental Results

The performances of the proposed filter and oscillator were also experimentally investigated. The
VDDDA was constructed from the available commercial ICs, AD830 and LM13700 as illustrated in Fig. 12. The transconductance of LM13700 is 
\[ g_m = \frac{I_B}{2V_T} \]
where \( V_T \) is thermal voltage (\( V_T \approx 26 \text{ mV} \) at room temperature). The proposed filter was firstly tested with following conditions; the supply voltage \( \pm 5 \text{ V} \), \( C_1 = C_2 = 5.6 \text{ nF} \), \( I_{B1} = I_{B2} = I_{B3} = 115 \text{ mA} \)

\( (g_{m1} = g_{m2} = g_{m3} = 2.211 \text{ mA/V}) \) and \( R = 0.45 \text{ k}\Omega \). With these conditions, the natural frequency and quality factor are 62.853 kHz and 1, respectively. The experimental gain response of \( BP_2 \), \( BP_1 \), \( LP \), \( HP \), \( BR \)

\( \) and \( AP \) is shown in Fig. 13. The experimental natural frequency is about 61 kHz which was about 2.948% deviated from theoretical value. The tuning of \( Q \) without affecting natural frequency is confirmed by the experimental result of \( BP_2 \) filter in Fig. 14 where the value of \( I_{B3} \) was changed to 57.5 \( \mu \text{A} \), 115 \( \mu \text{A} \) and 230 \( \mu \text{A} \). The measurements of output voltage \( V_{BP2} \) is also shown in Fig. 15 where the 50 mV sinusoidal voltage with 63 kHz of frequency was applied as input signal.

The proposed oscillator in Fig. 8 was tested with following conditions; the supply voltage \( \pm 5 \text{ V} \), \( C_1 = C_2 = 5.6 \text{ nF} \), \( I_{B1} = I_{B2} = I_{B3} = 115 \text{ mA} \)

\( (g_{m1} = g_{m2} = g_{m3} = 2.211 \text{ mA/V}) \) and \( R = 0.54 \text{ k}\Omega \).
With these conditions, the FO is 62.9 kHz. Figure 16 shows the measured output voltage where the experimental FO was about 61.86 kHz which was about 1.579 % deviated from theoretical value. It is also found that the output voltages $V_{o1}$ and $V_{o2}$ are quadrature sinusoidal signal.

8 Conclusions

Voltage-mode bi-quad filter has been proposed in this study. The advantages of the proposed filter are as follows. Firstly, it can perform variety of filters, i.e., low-pass, high-pass, band-pass, band-reject and all-pass functions. Secondly, the quality factor and the natural frequency can be electronically and orthogonally controlled. Finally, the filter has high input impedance. Moreover, the output voltage terminals for functions high-pass, band-reject and all-pass are low output impedance. The proposed filter consists of three VDDDDAs, one grounded resistor and two grounded capacitors, which are attractive for either IC implementation. With slightly modifying the proposed filter, the voltage-mode quadrature oscillator low output impedances is achieved. The CO and FO can be independently and electronically tuned. Moreover, the ratio of amplitudes $V_{o1}$ and $V_{o2}$ is constant on the tuning of FO if $I_{B1}$ and $I_{B2}$ are simultaneously tuned. Simulation results confirmed theoretical anticipation and validity of the synthesis. The power consumption for proposed filter is 0.343 mW and for proposed oscillator (with AGC circuit) is 0.346 mW. Moreover, the experimental results using available commercial ICs (AD830 and LM13700) are included and they meet very well with theoretical presumptions.

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References

9 Chaichana A, Jaikla W, Suwanjan, P & Tuntrakool S, A new quadrature sinusoidal oscillator for telecommunication system using VDDDDAs, International Conference on Intelligent Informatics and Biomedical Sciences (ICIIBMS), 2015.
16 http://ljgjohn.eecn.ceat.okstate.edu/5263/processparam/t4bk_lo_epi-params.html
45 Bajer J, Vavra J, Biolek D & Hajek K, Low-distortion current-mode quadrature oscillator for low-voltage low-power applications with non-linear noninertial automatic gain control, (Linkoping, Sweden), 2011