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Direct-Charge-Transfer Pseudo-N-Path SC Circuit Insensitive to the Element Mismatch and Opamp Nonidealities

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Abstract. A novel pseudo-N-path switched-capacitor circuit is described. Its center frequency is insensitive to element mismatch as well as to the finite gain and bandwidth of the opamps used. In this new architecture, the charges from the input source to the output are not transferred by an opamp; rather the opamp is used only as a buffer. The performance of the circuit is superior to that of a regular pseudo-N-path structure.

Key Words: switched capacitor resonator, opamp nonidealities, direct-charge transfer, pseudo-N-path circuit, element mismatch

1. Introduction

N-path filters have passbands centered at frequencies determined by the clock rate and the circuit structure rather than by the component values. This allows the realization of narrow-band filters with very low sensitivity to the component values. Unfortunately, clock feedthrough and path mismatch in these circuits will cause spectral tones located at the center of the passband. To eliminate this effect, pseudo-N-path (PNP) SC filters have been proposed [1]. In some PNP filters, each path charge follows exactly the same route through the circuit, and hence there cannot exist any path asymmetry. On the other hand, there are error sources in the PNP circuit due to the finite gain and bandwidth of the opamps used. The deviation from ideal response caused by the finite gain can be reduced using circuit techniques such as correlated-double-sampling (CDS) [2]. Finite bandwidth limitations, however, were not considered in previous work; instead, wideband opamps were used [3–5]. Another error source in the PNP is path mismatch, which causes a mixing of the input signal with the f_{clock}/N clock where $f_{clock} = 1/T$ is the sampling rate of the overall filter and N is the number of paths. In this paper, a novel PNP resonator using direct charge transfer is described, and it is shown to be more robust to all these effects than structures disclosed earlier.

2. Pseudo-N-Path Resonator using Opamp Charge Transfers

The ideal transfer function of the resonator considered is

$$H(z) = \frac{z^{-1/2}}{1+z^{-2}} \tag{1}$$

This translates into the discrete-time input-output relation $v_o(n) = v_{in}(n-1/2) - v_o(n-2)$. Hence, in the earlier PNP resonator shown in Fig. 1(a) [3] the new output contains the delayed input as well as the output inverted and delayed by two clock cycles ($2T$). In this structure, the differential output voltage is provided by two feedback capacitors, say $C1p$ and $C1n$ during clock phase 'a'. This output voltage remains stored on the same capacitors for two clock periods ($2T$). Then $C1p$ and $C1n$ are interchanged, and they transfer their charges to the new feedback capacitors, $C3p$ and $C3n$ during clock phase 'c'. Unfortunately, due to imperfect charge transfer, it also integrates some error signal charges with a delay T. Hence there is a z^{-1} term generated in the denominator of $H(z)$. Additionally, the first-order and the second-order terms in the denominator are also affected by the finite opamp gain and bandwidth, causing non-ideal integration These effects will be analyzed in the following subsections.

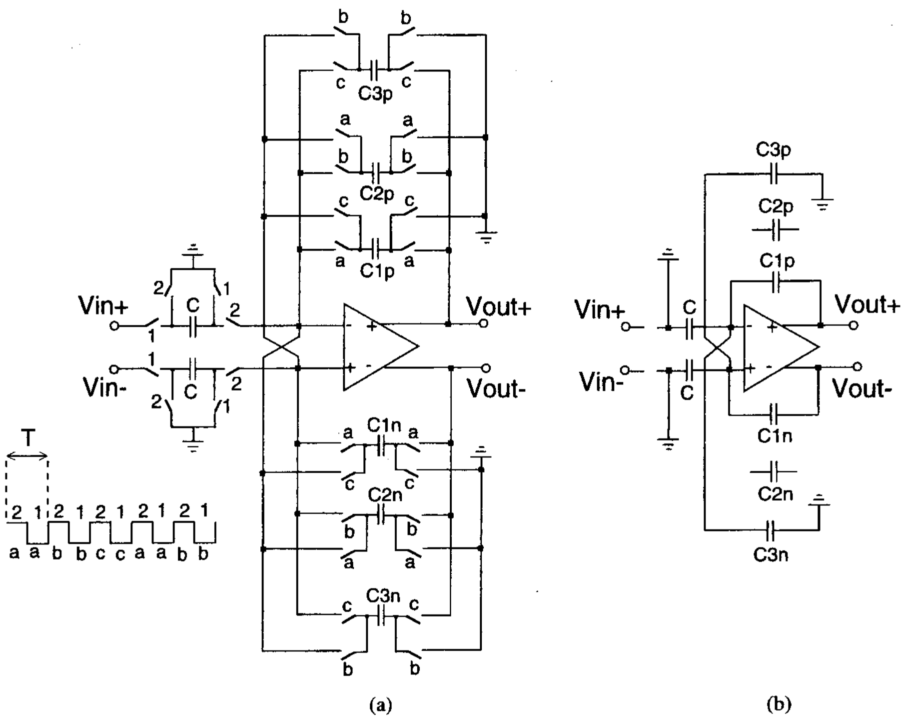

Fig. 1. Pseudo-N-path SC resonator with opamp-aided charge transfer: (a) circuit diagram; (b) circuit during clock phases 'a' and '2'.

2.1. *Finite Opamp Gain Effects in PNP Circuit with Opamp-Aided Charge Transfer*

The analysis is first performed in the time domain. Figure 1(b) shows the circuit during clock phases 'a' and '2'. For a finite opamp gain A_{dc}, charge conservation gives

$$
\begin{aligned}
&C1\left(V_o(n)+\frac{V_o(n)}{A_{dc}}\right)\\
&\quad=-C1\frac{V_o(n-1)}{A_{dc}}+C3\left(-V_o(n-2)-\frac{V_o(n-2)}{A_{dc}}\right)\\
&\quad\quad-C3\frac{V_o(n)}{A_{dc}}+C\left(V_{in}(n-1/2)-\frac{V_o(n)}{A_{dc}}\right) \qquad (2)
\end{aligned}
$$

Ideally, $C1$ is equal to $C2$ and $C3$. For simplicity, they will be denoted by C_i. The transfer function becomes

$$
\begin{aligned}
H(z)&=\frac{V_o(z)}{V_{in}(z)}\\
&=\frac{n_1\cdot z^{-1/2}}{1+d_1\cdot z^{-1}+d_2\cdot z^{-2}} \qquad (3)
\end{aligned}
$$

where

$$
d_1=\frac{1}{2+A_{dc}+C/C_i},\qquad n_1=C/C_i\cdot A_{dc}\cdot d_1
$$
$$
\text{and}\quad d_2=(1+A_{dc})\cdot d_1. \qquad (4)
$$

Ideally, n_1, d_1 and d_2 are equal to 1, 0 and 1, respectively. As can be seen from equation (3), both center frequency shift and resonant gain loss occur in the opamp-aided charge-transfer PNP resonator.

2.2. *Finite Opamp Bandwidth Effects in Opamp-Aided Charge-Transfer PNP Circuit*

Incomplete linear settling can be modelled by multiplying the input charges by $(1-g)$. Also, there is some charge kept by the $C1$ capacitors from the clock cycle before, due to incomplete settling. The time-domain equation is

$$
\begin{aligned}
C1\cdot V_o(n)&=(1-g)(C\cdot V_{in}(n-1/2)-C3\cdot V_o(n-2))\\
&\quad+g\cdot C1\cdot V_o(n-1). \qquad (5)
\end{aligned}
$$

When $C3$ and $C1$ are replaced by C_i,

$$H(z) = \frac{C}{C_i} \frac{(1-g)\cdot z^{-1/2}}{1 - g\cdot z^{-1} + (C/C_i)\cdot(1-g)\cdot z^{-2}} \quad (6)$$

results. Hence, both gain loss and center frequency shift occur in the PNP resonator, when the opamp used has finite bandwith.

3. PNP Resonator with Direct Charge Transfer

The proposed new PNP circuit is shown in Fig. 2(a). It uses direct charge transfer (DCT) [4,6].

In this structure, $C1p$ and $C1n$ hold the differential output voltage $v_{out}(n)$ during clock phase 'c' as shown in Fig. 2(b). At the same time, $C3p$ and $C3n$ are connected between the output and the input of the resonator, and hence they are charged to $-v_{out}(n) + v_{in}(n)$ and $v_{out}(n) - v_{in}(n)$, respectively. Two clock phases ($2T$) later, the $C3$ capacitors are connected as feedback capacitors during clock phase 'b', thus providing $v_{out}(n+2)$.

The finite bandwidth of the opamp does not affect the resonator transfer function since there is no charge transfer through the virtual ground. The finite gain of the opamp, however, introduces an error to the output voltage provided by the feedback capacitors. The time domain equation is then $v_{out}(n+2) = -v_{out}(n)\cdot(1 - 1/A_{dc}) + v_{in}(n)$. The transfer function becomes

$$H(z) = \frac{z^{-2}}{1 + (1-d)\cdot z^{-2}} \quad (7)$$

where $d = 1/A_{dc}$ is the resonant gain error. The non-critical error term d merely reduces the quality factor Q of the resonance. If a higher Q is needed, correlated double sampling (CDS) can be used [2]. Another advantage of the DCT-PNP circuit is that it is not affected by capacitor mismatches, since the same capacitor samples the input and subtracts it from the previous output (in *voltage mode*) to provide the delayed output. Note that the circuit is not fully stray-insensitive; the mismatch of top-plate parasitic capacitances cause second-order effects. The relative mismatches of the top-plate parasitic capacitances introduce additional input signal charges with different amounts at every clock phases.

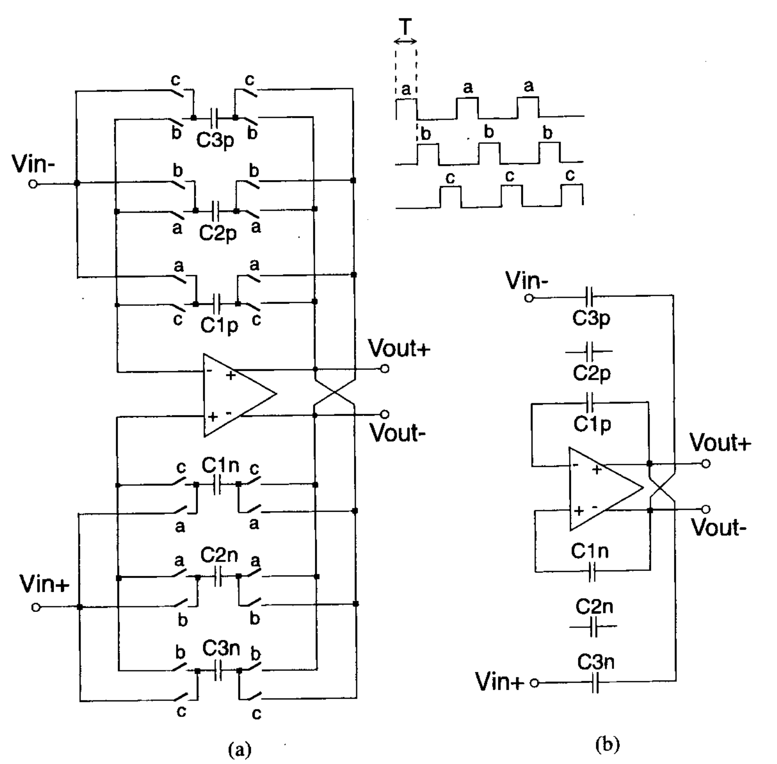

Fig. 2. The direct-charge-transfer pseudo-N-path SC resonator: (a) circuit diagram; (b) circuit during clock phase 'c'.

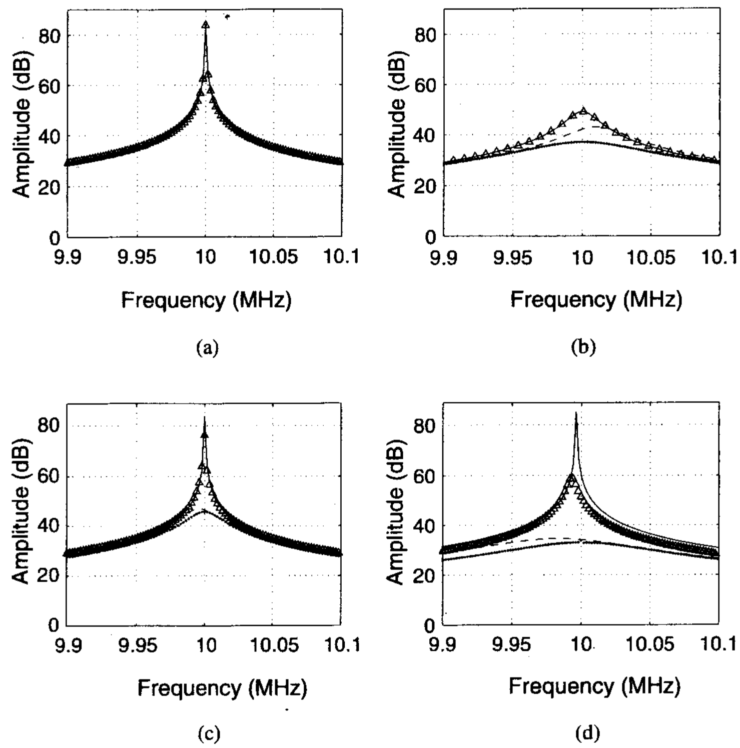

Fig. 3. SWITCAP2 simulation results of resonators using DCT-PNP (continuous line), PNP (dashes), I2P (triangles) and TDL (dots) with $f_{clock} = 20$ MHz: (a) $f_u = \infty$ and $A_{dc} = 120$ dB; (b) $f_u = \infty$ and $A_{dc} = 50$ dB; (c) $f_u = 100$ MHz and $A_{dc} = 120$ dB; (d) $f_u = 80$ MHz and $A_{dc} = 120$ dB.

Hence, these mismatches create tones, which appear outside of the desired band since they are modulated by $1/(3T)$ where number of paths is 3. These mismatch issues are beyond the scope of this paper and discussed in detail in Ref. [7].

4. Simulation Results

SWITCAP2 simulations were used to compare the performances of conventional PNP, DCT-PNP, integrating-two-path (I2P) [8], and two-delay-loop (TDL) [4] structures with nonideal opamps. The results are shown in Fig. 3 for $f_{clock} = 20$ MHz, using double sampling. In Fig. 3(a), the resonant peaks of all resonators occur at $f_{clock}/2$ for the (nearly) ideal case, where the unity-gain-bandwidth ($f_u = \infty$) and the dc gain ($A_{dc} = 120$ dB) of the opamp used do not limit the performance. In Fig. 3(b), the effects of the finite gain limitation of the opamp are shown, for $f_u = \infty$ and $A_{dc} = 50$ dB. The DCT-PNP and I2P circuits show some gain loss, but less than the others. The PNP circuit has both gain loss and frequency shift. The TDL has severe gain loss.

In Fig. 3(c), the effects of the finite bandwidth limitation of the opamp are shown, for $f_u = 100$ MHz and $A_{dc} = 120$ dB. The DCT-PNP circuit has no gain loss or shift in the center frequency, while the PNP and the TDL ones exhibit almost 40 dB gain loss. The I2P has an 8 dB gain loss. In Fig. 3(d), f_u was reduced to $4 \cdot f_{clock} = 80$ MHz. The DCT-PNP circuit remains unaffected, while the PNP and the TDL structures show almost 50 dB gain loss, and the I2P circuit has 26 dB gain loss. In addition, the PNP and I2P circuits have almost 20 kHz and 4 kHz shift in their center frequency locations, respectively. Clearly, the DCT structure is superior to all others in terms of robustness to opamp imperfections.

5. Conclusions

A novel PNP resonator circuit was proposed and compared with other well-known resonator structures. The new architecture eliminates the finite bandwidth effect of the opamp used. In addition, this resonator is not susceptible to capacitor mismatch effects (except those of top-plate parasitics), because the same capacitors are used to sample the input and provide the output. The DCT-PNP circuit is hence especially suitable for high-frequency communication applications.

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