Performance Comparison of Capacitive Stacking Techniques for Radio Frequency Mixers

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***Abstract*—This paper presents an analysis of three capacitive stacking techniques in a bottom-plate N-path mixer, which are the Dickson charge pump, Series-Parallel charge pump and Fibonacci charge pump. The three charge pump circuits are compared in a DC-DC application and in a Radio frequency mixer. The performance of the charge pumps is derived based on the voltage gain, taking into account the effects of parasitic capacitances and the on-resistance of the switches in the charge pump. The Dickson and Fibonacci charge pump with passive mixer have shown similar behaviour, both have a decrease in voltage gain around 29% when parasitic capacitance are taken into account. The Series-Parallel charge pump with passive mixer is influenced the most by the effects of the parasitic capacitance with a voltage gain decrease of 70.5%. This decrease in voltage gain is most likely caused by the contribution of the parasitic capacitance in the charge pump to the unwanted low pass filtering in the mixer. A switch on-resistance in the charge pump which is 10 times larger than the switch on-resistance in the mixer is analysed. Due to the increase in switch on-resistance a decrease in voltage gain of 30.8%, 38.3% and 66.4% has been observed for the Dickson, the Fibonacci and the Series-Parallel charge pump, respectively.**

***Index Terms*—Switched Capacitor, Charge Pump, N-Path Mixer/Filter, Mixer-First Receiver.**

I. Introduction

The current state of the art antenna interfaces of radio frequency receivers require resonant structures for impedance matching and to reject out-of-band blockers, but these resonant structures are highly frequency dependent [1]. This frequency dependence limits the frequency range of the receiver.

Passive mixer-first architectures do not need to have these resonant structures in the receiver chain. A passive mixer-first architecture without a radio frequency low-noise amplifier could have the potential to use substantially less power or instead of using less power it could also have the potential to have a greatly increased tuning range and linearity [1]. Passive mixers use a lot of power to drive their switches and to power the clock circuitry that generates the clocks that are needed. These clocks are necessary for the mixer to work and thus cannot be removed to save power.

In [2], a way has been presented to achieve a $6dB$ passive voltage gain with implicit capacitive stacking in a radio frequency front end. However, the potential of using capacitive stacking techniques in passive radio frequency front ends has hardly been examined yet. The objective of this bachelor assignment is to compare various methods of capacitive stacking techniques for use in radio frequency mixers and to identify their limitations.

A lot of research has been done on capacitive stacking techniques, such as DC charge pumps [3]. There are many charge pump topologies and all of them are based on the same principle. They use switches and capacitors to boost/decrease the DC input voltage to the desired DC output voltage [3]. However, the way the switches are configured differs which gives each topology its own characteristics.

The following topologies will be compared in an RF mixer: Dickson charge pump [4], Series-Parallel charge pump [5] and Fibonacci charge pump [6]. These charge pumps will first be examined in a DC-DC application to gain knowledge and insights. Secondly, these insights will then be used to implement the topologies in a radio frequency mixer.

The methods will be compared with the help of analytical derivations, simulations and calculations. The following things will be investigated: the effects of parasitic capacitance in the charge pump on the voltage gain and the influence of the on-resistance of the switches in the charge pump on the voltage gain.

Section II gives an analysis of the charge pump topologies that will be implemented in a radio frequency mixer. Circuit details of the charge pump with passive mixer are presented in Section III and section IV gives the simulations results. Section V presents a comparison and a discussion of these results. A conclusion is given in Section VI.

II. Charge Pump Topologies

A schematic of the Dickson, Series-Parallel and Fibonacci charge pump is shown in Fig. 1. Switch 1 and switch 2 are driven by a non overlapping 50% duty-cycle clock signal. During each clock cycle capacitor $C_1 - C_4$ receive some charge from the preceding capacitor and give some of this charge to the next capacitor. In an ideal situation the output voltage V_{out} of the charge pump increases linearly with the number of stages. However, in reality the output voltage is limited by the parasitic capacitance and the switches in the circuit. Capacitor $C_1 - C_4$ all have a top plate parasitic capacitance αC_{PP} and bottom plate parasitic capacitance βC_{PP} [5] [6]. α and β are determined by the substrate, for simplification it is assumed that $\alpha C_{PP} = \beta C_{PP} = C_{PP}$. These parasitic capacitance decrease the output voltage since a part of the charge that is transferred between the stages is shared with the parasitic capacitor and wasted [7]. The switches decrease the output voltage because they have a non zero on-resistance R_{on} which means that they will act like a resistor when they are on. This on-resistance is ideally as close to zero as possible since then less voltage is dissipated as heat.

To determine the actual voltage gain of the Dickson, Series-Parallel and Fibonacci charge pump an in depth analysis is needed, but since that is not the scope of this paper the three charge pumps will be looked at shortly to get a rough understanding of the difference between the topologies.

A. Dickson Charge Pump

The Dickson charge pump [4] shown in Fig. 1a is a 4-stage charge pump with a voltage gain of 5 [V/V]. It uses two pulse trains that are in anti-phase to charge and pump its capacitors C_1-C_4. The voltage gain of the Dickson charge pump in an ideal situation can be estimated with the following equation, where N is the number of stages:

$$G_D = N + 1 \tag{1}$$

B. Series-Parallel Charge Pump

The Series-Parallel charge pump [5] shown in Fig. 1b is a 4-stage charge pump with a voltage gain of 5 [V/V]. Every capacitor is charged in a parallel configuration with V_{in} and then switched to a series configuration, which is uses to read out all capacitors and V_{in} at once. In an ideal situation the voltage gain is estimated with the following formula, with N being the number of stages:

$$G_{SP} = N + 1 \tag{2}$$

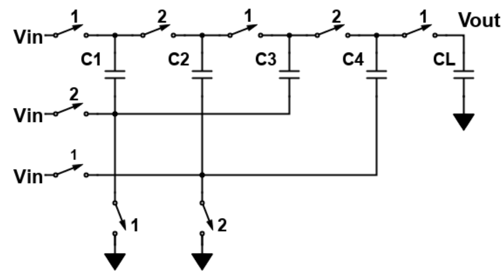
C. Fibonacci Charge Pump

The Fibonacci charge pump [6] shown in Fig. 1c is a 3-stage charge pump with a voltage gain of 5 [V/V]. The Fibonacci charge pump has the highest ideal voltage gain for the least amount of stages needed [7]. In an ideal situation the voltage gain of the Fibonacci charge pump is given by the Nth Fibonacci number, where N is the number of stages [5]:

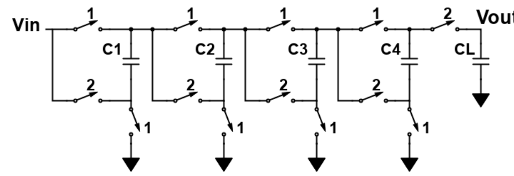
$$G_F = 1.16e^{0.483N} \tag{3}$$

III. Circuit Design

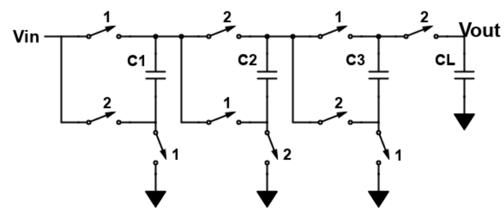
In this section, three charge pump with mixer configurations are described which are build on the bottom-plate mixer proposed in [2], a schematic of the mixer can be seen in Fig. 2a. It's a 4-path bottom plate N-path filter with resistor R_1 of 50Ω and capacitors C_1 to C_4 of $6.4pF$. The voltage is readout from the bottom plate of the capacitors at V_{A1}, V_{VA2}, V_{A3} and V_{A4}, the switches are turned on/off by a 4-phase non-overlapping clock shown in Fig. 2b with a frequency f_{LO} of $1GHz$ and the mixer switches have an on-resistance $R_{on,mixer}$ of 38Ω. After many cycles the voltage over the capacitors V_C is equal to the average input voltage the capacitor has seen, while it



(a) Schematic of 4-Stage Dickson charge pump [7].



(b) Schematic of 4-Stage Series-Parallel charge pump [5].



(c) Schematic of 3-Stage Fibonacci charge pump [7].

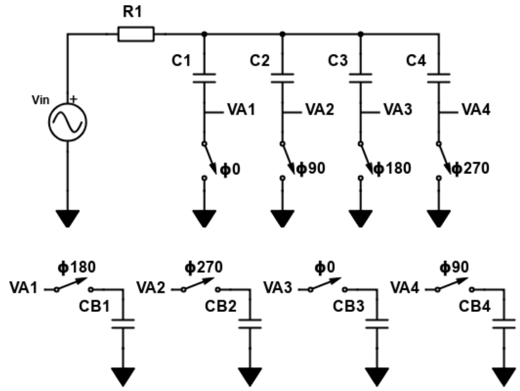
Fig. 1: Schematics of the charge pump topologies with $G = 5$, switch 1 and switch 2 are driven by non-overlapping 50% duty-cycle clock signals.

was connected to ground. This voltage can be seen as a DC voltage which is necessary for the input of the charge pumps.

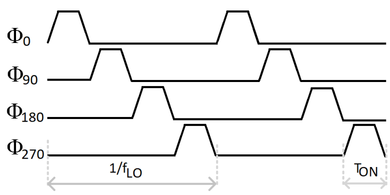
The capacitors in the mixer have a parasitic capacitance between the top plate and the substrate αC_P and a parasitic capacitance βC_P between the bottom plate and the substrate. For simplification reasons it is assumed that $\alpha C_P = \beta C_P = C_P$. The parasitic capacitance C_P is 1.3% of the capacitance of capacitor C_1 to C_4 [2].

The parasitic capacitance in the mixer cause unwanted low pass filtering, which results in signal degradation [8]. Since capacitor C_{B1} to C_{B4} is isolated from capacitor C_1 to C_4 through switches the parasitic capacitance of these capacitors does not contribute to the unwanted low pass filtering. This will not be the case when C_{B1} to C_{B4} is replaced with a charge pump, since the capacitors in the charge pump have to be charged they will not be isolated from capacitor C_1 to C_4. Therefore the parasitic capacitance of the charge pumps C_{PP} will contribute to the unwanted low pass filtering.

This parasitic capacitance and switch resistance will also be used for the parasitic capacitance and switches in the charge pumps, so $C_{PP} = 1.3\%$ and $R_{on} = 38\Omega$. This decision has been made, because the charge pump with mixer



(a) Capacitor C_{Bn} can be seen as the first capacitor in the charge pump.



(b) 4-phase non overlapping clock.

Fig. 2: Schematic of mixer circuit with capacitive stacking [2].

configurations are built on this bottom plate mixer and keeping the mixer circuit and the charge pump circuit as equal as possible makes it more interesting for a comparison between the two.

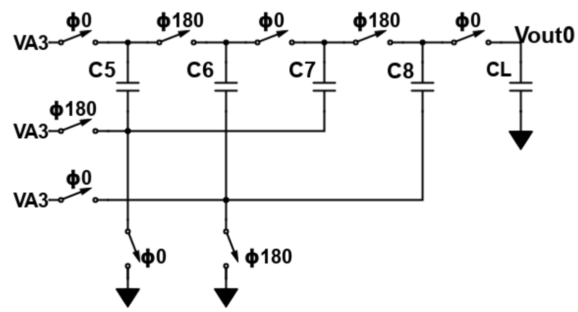
In order to examine the effects of the parasitic capacitance in the charge pump on the voltage gain, a simulation can be done where $C_{PP} = 0$ and a simulation can be done where $C_{PP} = 1.3\%$, while keeping all other variables the same. Since the parasitic capacitance in the charge pump will result in additional signal degradation, the voltage over capacitor C_1 to C_4 will decrease. The comparison of the voltage gain is only relative when this is taken into account and therefore for the results the input voltage should be the voltage over the capacitor without this extra signal degradation. The voltage gain can be calculated by dividing the output voltage with the input voltage:

$$G = \frac{V_{out0}}{V_{C1}} \tag{4}$$

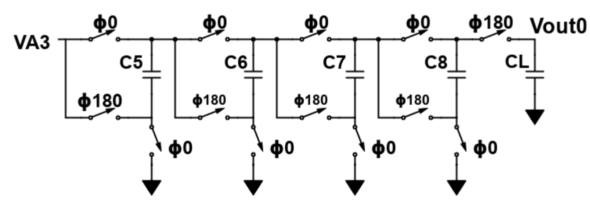
Using the same method, the effect of the on-resistance of the switches in the charge pump on the voltage gain can be investigated. The parasitic capacitance cannot be neglected in this analysis and therefore $C_{PP} = 1.3\%$. The switch on-resistance in the charge pump will be analysed for $R_{on} = 0.1R_{on,mixer}$, $R_{on} = R_{on,mixer}$ and $R_{on} = 10R_{on,mixer}$. These values will give a good approximation of the behaviour the voltage gain will have for smaller or larger on-resistances in the charge pump.

As mentioned in the introduction $6dB$ voltage gain in a 4-path bottom plate mixer can be achieved with an implicit capacitive stacking technique, the reader is referred to [2] for the analysis. The $6dB$ voltage gain is achieved by reading out the voltage over the bottom plate of C_1-C_4 when they are in anti-phase. So C_1 is connected to ground during ϕ_0 which means that it should be read out during ϕ_{180}. This can be done by connecting a switch to the bottom plate of the capacitor as shown in Fig. 2a.

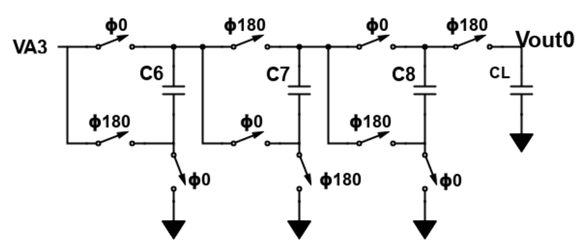
When C_1 is read out during ϕ_{180} then V_{A1} is equal to $2V_{C3}$, when C_2 is read out during ϕ_{270} then V_{A2} is equal to $2V_{C4}$, when C_3 is read out during ϕ_0 then V_{A3} is equal to $2V_{C1}$ and when C_4 is read out during ϕ_{90} then V_{A1} is equal to $2V_{C2}$. These capacitor voltage relations will be used for the configuration of the charge pumps to maximize the achievable voltage gain by starting with an input voltage that is twice as big as the normal input V_C.



(a) Configuration of charge pump P_0 for the Dickson mixer.



(b) Configuration of charge pump P_0 for the Series-Parallel mixer.



(c) Configuration of charge pump P_0 for the Fibonacci mixer.

Fig. 3: Schematic of charge pump P_0.

TABLE I: Charge Pump Configurations.

Charge Pump	V_{in}	Switch 1	Switch 2	V_{out}
P_0	V_{A3}	$\phi0$	$\phi180$	V_{out0}
P_{90}	V_{A4}	$\phi90$	$\phi270$	V_{out90}
P_{180}	V_{A1}	$\phi180$	$\phi0$	V_{out180}
P_{270}	V_{A2}	$\phi270$	$\phi90$	V_{out270}

There are 4-paths in the mixer and therefore 4 charge pumps P_0, P_{90}, P_{180} and P_{270} are needed. Charge pump P_0 is used for V_{C1}, P_{90} is used for V_{C2}, P_{180} is used for V_{C3} and P_{270} is used for V_{C4}. Since all charge pumps have the same behaviour it is not necessary to analyse all 4 charge pumps and therefore for each topology only charge pump P_0 will be considered. The configurations of the charge pumps can be derived with the schematic of the charge pumps shown in Fig. 1 and Table I. The configuration of Charge pump P_0 for all three topologies can be seen in Fig. III.

IV. Simulation Results

The simulations are performed in LTspiceXVII.

A. Simulations Dickson Charge Pump With Passive Mixer

The Dickson charge pump with passive mixer circuit in Fig. 3a has been simulated. The output and input voltage of charge pump P_0 with $R_{on} = 38\Omega$ for $C_{PP} = 0$ and for $C_{PP} = 1.3\%$ is shown in Fig. 4a and Fig. 4b. Using these graphs and equation 4 a voltage gain can be calculated for when $C_{PP} = 0$ and for when $C_{PP} = 1.3\%$. Respectively G_{DI} and G_{DR}.

$$G_{DI,38\Omega} = \frac{0.309V}{0.052V} = 5.94\ [V/V] \tag{5}$$

$$G_{DR,38\Omega} = \frac{0.221V}{0.052V} = 4.25\ [V/V] \tag{6}$$

Fig. 4a shows that the voltage gain has been reduced with 28.5% when parasitic capacitance are taken into account. Fig. 4b shows that the voltage over capacitor C_1 has been reduced with 23.4%.

The output voltage for charge pump P_0 with $C_{PP} = 1.3\%$ for $R_{on} = 3.8\Omega$, $R_{on} = 38\Omega$ and $R_{on} = 380\Omega$ is shown in Fig. 5. These output voltages are used to calculate the voltage gain for the respective switch on-resistance.

$$G_{DR,3.8\Omega} = \frac{0.2363V}{0.052V} = 4.54\ [V/V] \tag{7}$$

$$G_{DR,380\Omega} = \frac{0.153V}{0.052V} = 2.94\ [V/V] \tag{8}$$

The on-resistance of 3.8Ω results in an increase of the voltage gain of 6.8% in comparison to the voltage gain with an on-resistance of 38Ω. The on-resistance of 380Ω results in a decrease of the voltage gain of 30.8% in comparison to the voltage gain with an on-resistance of 38Ω

B. Simulations Series-Parallel Charge Pump With Passive Mixer

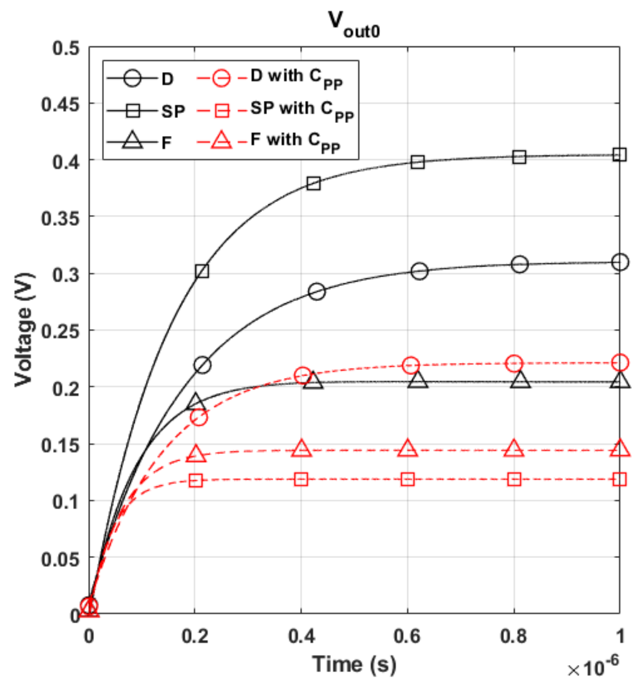
The Series-Parallel charge pump with passive mixer circuit in Fig. 3b has been simulated. The output and input voltage of charge pump P_0 with $R_{on} = 38\Omega$ for $C_{PP} = 0$ and for $C_{PP} = 1.3\%$ is shown in Fig. 4a and Fig. 4b. The gain for when no parasitic capacitance are present is G_{SI} and the gain for when parasitic are taken into account is G_{SR}.

$$G_{SI} = \frac{0.404V}{0.052V} = 7.77\ [V/V] \tag{9}$$

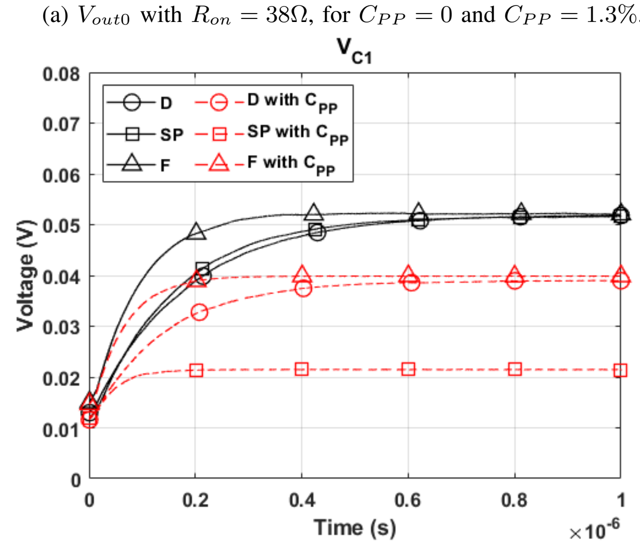
$$G_{SR} = \frac{0.119V}{0.052V} = 2.29\ [V/V] \tag{10}$$

The voltage gain has decreased with 70.5% due to the influence of the parasitic capacitance and the voltage over capacitor C_1 has decreased with 58.7%.

The output voltage for charge pump P_0 with $C_{PP} = 1.3\%$ for $R_{on} = 3.8\Omega$, $R_{on} = 38\Omega$ and $R_{on} = 380\Omega$ is shown in Fig. 5. These output voltages are used to calculate the voltage gain for the respective switch on-resistance.



(a) V_{out0} with $R_{on} = 38\Omega$, for $C_{PP} = 0$ and $C_{PP} = 1.3\%$.



(b) V_{C1} with $R_{on} = 38\Omega$, for $C_{PP} = 0$ and $C_{PP} = 1.3\%$.

Fig. 4: Plot of the input (V_{C1}) and the output (V_{out0}) for Dickson (D), Series-Parallel (SP) and Fibonacci (F).

$$G_{SR,3.8\Omega} = \frac{0.141V}{0.052V} = 2.71\ [V/V] \tag{11}$$

$$G_{SR,380\Omega} = \frac{0.040V}{0.052V} = 0.77\ [V/V] \tag{12}$$

The on-resistance of 3.8Ω results in an increase of the voltage gain of 18.3% in comparison to the gain with an on-resistance of 38Ω. The on-resistance of 380Ω results in a decrease of the gain of 66.4% in comparison to the voltage gain with an on-resistance of 38Ω

C. Simulations Fibonacci Charge Pump With Passive Mixer

The Fibonacci charge pump with passive mixer circuit in Fig. 3c has been simulated. The output and input voltage of charge pump P_0 with $R_{on} = 38\Omega$ for $C_{PP} = 0$ and for $C_{PP} = 1.3\%$ is shown in Fig. 4a and Fig. 4b. The voltage gain for when no parasitic capacitance are present is G_{FI} and the gain for when parasitic are taken into account is G_{FR}.

$$G_{FI} = \frac{0.204V}{0.052V} = 3.92\ [V/V] \tag{13}$$

$$G_{FR} = \frac{0.144V}{0.052V} = 2.77\ [V/V] \tag{14}$$

The voltage gain has decreased with 29.3% due to the influence of the parasitic capacitance and the voltage over capacitor C_1 has decreased with 23.4%.

The output voltage for charge pump P_0 with $C_{PP} = 1.3\%$ for $R_{on} = 3.8\Omega$, $R_{on} = 38\Omega$ and $R_{on} = 380\Omega$ is shown in Fig. 5. These output voltages are used to calculate the voltage gain for the respective switch on-resistance.

$$G_{FR,3.8\Omega} = \frac{0.156V}{0.052V} = 3.00\ [V/V] \tag{15}$$

$$G_{FR,380\Omega} = \frac{0.089V}{0.052V} = 1.71\ [V/V] \tag{16}$$

The on-resistance of 3.8Ω results in an increase of the voltage gain of 8.3% in comparison to the gain with an on-resistance of 38Ω. The on-resistance of 380Ω results in a decrease of the voltage gain of 38.3% in comparison to the gain with an on-resistance of 38Ω.

V. Performance Comparison & Discussion

This Section will compare and discuss the results presented in Section IV.

The voltage gain that is achieved by performing simulations show that the equations for the voltage gain of the charge pumps in the analysis do not hold for the charge pumps with passive mixer. In the analysis the amount of charge pump stages have been selected so that the charge pumps all have a voltage gain of 5 [V/V]. With an input voltage that is $2V_C$ the voltage gain would be expected to be 10 [V/V]. A possible reason that these equations do not hold could be that this approximation is just not complex enough and therefore is not relevant for this circuit.

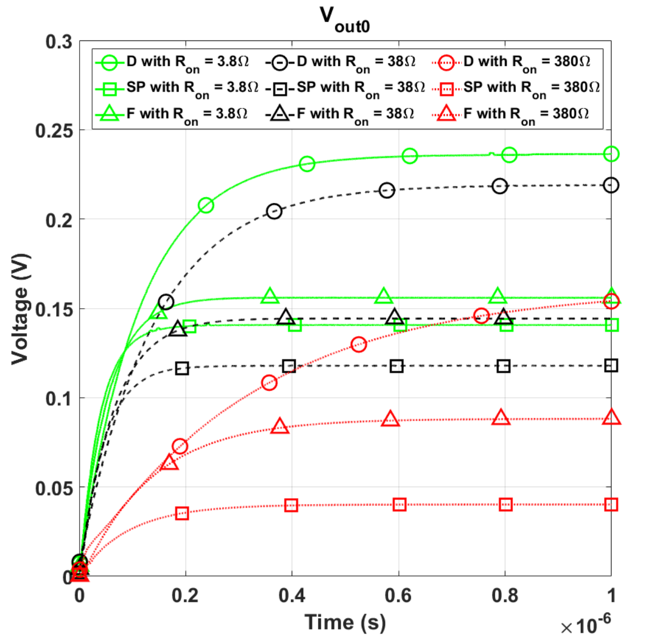


Fig. 5: V_{out0} with $C_{PP} = 1.3\%$, for $R_{on} = 3.8\Omega$, $R_{on} = 38\Omega$ and $R_{on} = 380\Omega$ for Dickson (D), Series-Parallel (SP) and Fibonacci (F).

In an ideal situation the Series-Parallel charge pump mixer has the highest voltage gain $G_{SI,38\Omega} = 7.7\ [V/V]$ of all three configurations. However, when parasitic capacitance are taken into account, the Series-Parallel charge pump mixer also has the highest decrease in voltage gain of 70.5%. The voltage gain of the Dickson charge pump has been reduced with 28.5% when parasitic capacitance are taken into account. This difference is interesting, because the Dickson charge pump mixer has the same amount of capacitors in its charge pump but is not influenced as much by the parasitic capacitance.

The decrease in input voltage of the Series-Parallel charge pump is 58.7% while the input voltage of the Dickson charge pump has been reduced with 23.4%. This is most likely the reason that the Series-Parallel charge pump voltage gain has been reduced with a higher factor than the Dickson charge pump voltage gain. The Series-Parallel charge pump thus results in more signal degradation than the Dickson charge pump. This can be explained by looking at the amount of capacitors that are contributing to the unwanted low pass filtering described in Section III. In the Series-Parallel charge pump all capacitors are connected to capacitor C_1 while it is connected to ground and therefore all parasitic capacitance are contributing to the unwanted low pass filtering. In the Dickson charge pump only halve of all capacitor are connected to capacitor C_1 while it is connected to ground so only halve of them will contribute to the unwanted low pass filtering. The Fibonacci charge pump has the same amount of capacitors simultaneously connected to C_1 and therefore behaves similar to the Dickson charge pump, which can be seen in Fig. 4.

The charge pump mixer that is most affected by the 10 times increase in switch resistance of the charge pump is the Series-Parallel charge pump mixer, with a decrease in voltage gain of 66.4%. A possible reason could be that the Series-Parallel charge pump mixer is highly influenced by the effect of the parasitic capacitance and that an increase in switch resistance creates an unwanted RC filter that has a big influence on the output voltage. The voltage gain of the Dickson charge pump has decreased with 30.8% and the voltage gain of the Fibonacci charge pump has decreased with 38.3%. The decrease is very similar for these charge pumps, which was expected since the influenced of the parasitic capacitance is also very similar for these charge pumps.

The Dickson charge pump has the highest output voltage for all switch on-resistances that have been simulated while taking the parasitic capacitance into account. Therefore for these configurations the Dickson charge pump performs best in comparison to the other charge pumps. However, since the Fibonacci charge pump has the highest ideal voltage gain for the least amount of stages needed, which is described in Section II-C, and behaves similar to the Dickson charge pump. The output voltage of the Fibonacci charge pump will most likely exceed the output voltage of the Dickson charge pump when more stages are added.

VI. Conclusion

In this paper, a comparison has been made between three capacitive stacking technique's in a bottom-plate N-Path mixer. They are compared based on their voltage gain, taking into account the parasitic capacitance and the switch on-resistance. Three charge pump with passive mixer configurations have been described which have been used for this comparison. The simulation results showed that the output voltage of the Dickson and the Fibonacci charge pump have similar behaviour while taking parasitic capacitance into account. The Series-Parallel charge pump did not follow this behaviour. The presence of the parasitic capacitance resulted in a decrease in the voltage gain for the Dickson, Fibonacci and Series-Parallel charge pump respectively of 28.5%, 29.3% and 70.5%. A possible reason for the decrease in voltage gain could be that the parasitic capacitance in the charge pump contributes to the unwanted low pass filtering in the mixer, which results in signal degradation. The Series-Parallel charge pump showed a significant lower voltage gain than the other two charge pumps, because all parasitic capacitance are contributing to the mixer parasitic capacitance. Whereas the Dickson and Fibonacci charge pump only have halve of the parasitic capacitance contributing to the parasitic capacitance in the mixer. A switch on-resistance which is $0.1R_{on,mixer}$ results in a small increase in the voltage gain. While a switch on-resistance which is $10R_{on,mixer}$ results in a voltage gain decrease of 30.8%, 38.3% and 66.4% for the Dickson, Fibonacci and the Series-Parallel respectively.

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