A Bulk-controlled Pseudo-Floating Gate Bandpass Filter

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Abstract: In this paper we present a bulk-controlled Pseudo Floating-Gate (BCPFG) Bandpass filter. The filter has a limited Open-Loop gain and linearity for supply voltages down to $600mV$. The filter is based on Pseudo Floating-Gate active load amplifier and in addition to gain, it offers frequency band adjustment. Both the low- and high-frequency cutoffs are controlled electronically using bias voltages through the transistor bulks. The BCPFG BP filter enjoys low component spread and compactness, containing only small size transistors and capacitors suited for integration. The simulations presented in this paper are valid for the $90nm$ CMOS transistor models from STM having a VDD equal to $1.2V$ and threshold voltage of $250mV$.

Key–Words: Analog, Tunable Filter, Bulk-Controll LATEX

1 Introduction

Tunable filters are attractive circuits in many applications such as radio communication. Tuning of the filters must be in a way that the all the various signal bands that are passed through or blocked by the filter are equal regarding gain and linearity. It is also important that the bandwidth is kept constant over the tuning range and that tuning is done in a predictable way to insure good control of the cut-off frequencies. The filter presented in this paper fulfills all these requirements and in addition operates with low supply voltages down to $VDD/2$ suited for low supply voltage applications. The need for low power and low voltage analog circuit design, is driven by two main factors, namely the downscaling of CMOS processes [1, 2] and portable electronic devices. Low voltage and low power are the key aspects of circuits used in portable devices that are powered by batteries. There is also an extensive research on ambient energy harvesters with the aim to replace batteries in various applications [3, 4]. The filter presented in this paper is based on a pseudo-floating gate [5, 6, 7]. The pseudo-floating gate is a kind of floating gate where the floating gate is biased weakly using high resistive resistors. These resistors can be made of active or passive components. Floating gates offer many advantages, such as multiple input and possibility of change of the threshold voltage seen from the input. Another important advantage of floating-gate is that the capacitive input limits the gate-leakage [8] that occurs due thin gate oxides. Leakage in thin oxide is one of main challenges in newer technologies and in further downscaling. The kind of pseudo floating gate presented in this paper uses transistors operating in weak inversion to bias the floating gate. In this approach the bulk of the transistors can be used actively to tune the cutoff frequencies of the amplifier.

2 The bulk-controlled Pseudo Floating-Gate(BCPFG) Amplifier

The bulk controlled Pseudo Floating-Gate Amplifier (BCPFGA) is shown in figure 1. The amplifier is based on an active-load common-source amplifier, made of transistors $M4$ and $M2$. The transistors $M4$ is connected as diode in order to operate as an active load for the amplifing transistor $M2$. The input of this inverter is made floating using an input capacitor, C_{in}. The floating gate is biased by transistors $M1$ and $M3$. These transistors form a non-inverting buffer that operates in weak inversion and are used to initiate the floating gate. The output of the inverter is connected to the input of the non-inverting buffer and the output of the non-inverting buffer is connected to the input of the inverter which forms a loop. This loop will force the floating-gate and the output of the inverter towards a weak and a continuous equilibrium state close to $VDD/2$. This equilibrium state allows the circuit to be used as an auto-zeroing amplifier for analog applications. Active load amplifiers, as the one presented in

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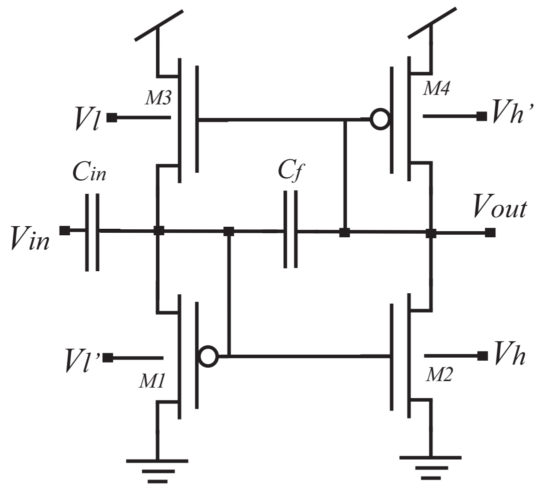

Figure 1: *Schematic of the BCPFG amplifier. The bias voltages Vl and Vh control the current through their respective branches.*

this paper, have low gain and low dynamic range due to the special arrangement of transistos. These drawbacks of the amplifer are more evident for new low supply voltage technologies. On the other hand, they have highly predictable large and small signal characteristics [9]. As the amplifier presented in this paper is to be used as a filter building block, we will allow the low gain, larger than unity and oprate the amplifers for their tunability. In this way the amplifiers can be used as filter building blocks. As we will show in this paper the power supply can be decreased to around $VDD/2$ and the amplifier can still be used as a filter building block. The ratio between the input capacitor C_{in} and the feedback capacitor C_f sets the gain of the amplifier and is given by:

$$A \approx -\frac{C_{in}}{C_f} \tag{1}$$

The cut-off frequency of the amplifier in figur 1 as a function of the currents in the circuit can be given by:

$$f_{cut-off} \approx \frac{I_{DS}}{2C_l VDD} \tag{2}$$

Where the nominator is the current through the transistor $M2$ and C_l is the load capacitor. Bias voltages Vh and Vl are the bulk of the transistors, see figure 1. These bias voltages are used to control the current through each transistor, a principle that reminds of the bulk driven circuits [10, 11]. In bulk driven circuits, the bulk is used as the input of the circuit instead of or together with the gate. Bulk driven circuits, offer higher linearity, but less transconductance, that can again result in higher noise figure. In the circuit presented in this paper we use the bulks just as a way to control the circuit's behavior and not as the input. Changes in the bulk voltage results in changes in the threshold voltage wich can be given by:

$$V_{th} = V_{t0} + \gamma(\sqrt{2\Phi_f - V_{BS}} - \sqrt{2\Phi_f}) \tag{3}$$

where V_{t0} is the threshold voltage when $V_{BS} = 0$, γ is bulk threshold potential, a process constant and Φ_f is the surface potential of the MOS transistor. If we rearrange (3) to separate the constant and bulk voltage dependent terms, it can be rewritten as:

$$V_{th} = V_{t0} - \gamma\sqrt{2\Phi_f} + \gamma\sqrt{2\Phi_f - V_{BS}} \tag{4}$$

In eq. (4) the two first terms are constant and only the third term is dependent on the bulk voltage. At equilibrium, when no ac input signal is applied, the input and output will be $VDD/2$, i.e. the gate-source voltage of all the transistors are $VDD/2$. If we substitute the constant terms in eq(4) with [12] K and V_{gs} with $VDD/2$ and use this in eq. (2) and assume that the transistor $M2$ operates in linear region, the highest cut-off frequency as a function of the effective threshold voltage can be given by:

$$f_h \approx \frac{\beta_{M2} V_{hf_{effective}}^2}{2C_l VDD} \tag{5}$$

where $V_{hf_{effective}} = V_{gs} - V_{th}$ and as a function of the Bulk-Source voltage:

$$f_h \approx \frac{\beta_{M2} VDD - K + \gamma\sqrt{2\Phi_f - V_{BS}}^2}{2C_l VDD} \tag{6}$$

The lowest cut-off is controlled by the non-inverting feedback made of transistors $M3$ and $M4$ that operate in weak inversion region:

$$f_l \approx \frac{2n\beta_{M2} V_T^2 e^{\frac{V_{gs}-V_{th}}{nVT}}}{2C_l VDD} \tag{7}$$

and as a function of the Bulk-Source voltage:

$$f_l \approx \frac{2n\beta_{M2} V_T^2 e^{\frac{VDD-K+\gamma\sqrt{2\Phi_f - V_{BS}}}{2nVT}}}{2C_l VDD} \tag{8}$$

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Where $V_T$is the thermal voltage, n is a slope factor. Equation (5) is an approximation and is valid for small input values. Large ac input voltages can affect the circuits behavior as it directly changes the gate-source voltage of the inverting transistor. Using the bulk as a control node and not the input, makes the devices more flexible regarding control at the same time it offers higher gain since it is gate driven. The main drawback of using the bulk actively is that each transistor needs an extra well, that again will require special and costly processes that offer dual well. Other drawbacks of using the bulk actively are the need for bigger chip area and bad matching.

$transistor$	$M1$	$M2$	$M3$	$M4$
$width$	$500nm$	$120nm$	$120nm$	$500nm$

Table 1: The width of the transistors used in the simulations of the amplifier shown in figure 1.

2.1 Simulations

By changing the supply voltage of the amplifier we are able to control the cut-off frequencies of the amplifier. Figure 2 shows the frequency response of BCPFG amplifier for various power supply voltages from $600mV$ to $1.2V$. Variations in VDD results in variations in the current through the amplifier and non-inverting buffer that again controls the lowest and highest cut-off frequencies of the amplifier. The variations in VDD doesn't effect the gain of the amplifier noticeably down to $600mV$, but voltages below $600mV$ results in attenuation of gain. In the following simulation we added a load capacitor to the circuit. The values of the capacitors in the simulations are as follows: $C_{in} = 20fF$, $C_f = 6fF$ and $C_L = 1fF$.

In the rest of this paper simulation presented are with $VDD = 600mV$ and we use the bias voltages Vh and Vl to control the cut-offs of the amplifier.

Figure 3 shows the frequency response of the BCPFG when the bulk of the transistors in the circuit, Vh and Vl is swept from $0V$ to $600mV$ with a step of $50mV$. In this figure we see that the highest cut-off and lowest cutoff can be tuned.

3 Gain and linearity

The BCPFG amplifier reminds of an active load amplifier. The main drawback of these amplifiers are the fact that low dynamic range anf low linearity. According to [9] the maximum voltage swing of such invrter is:

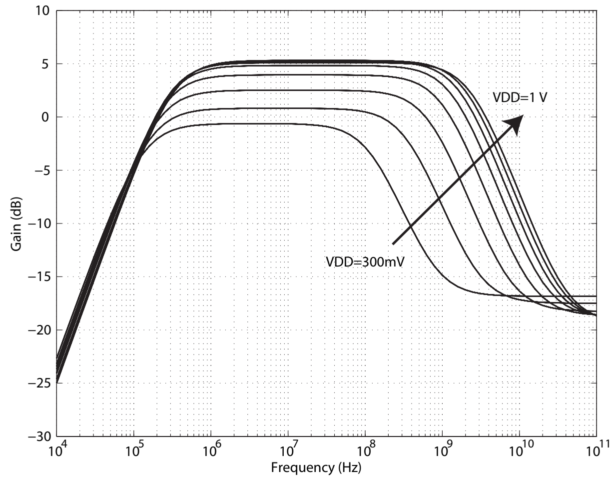

Figure 2: *Figure above shows that the frequency response can be controlled using the bias voltage VDD. VDD values below 400mV gives attenuation*

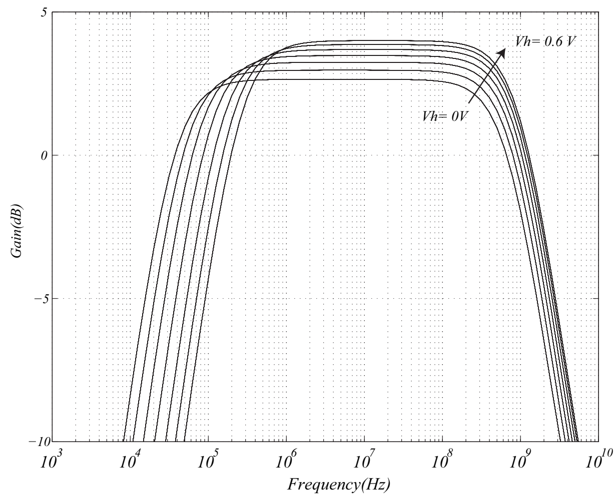

Figure 3: *The frequency response of the BCPFG shown in figure 1 when various bias voltages Vh and VL from 0V to 600 mV is applied.*

$$V_{out}(swing) \approx V_{DD} - |2V_{th}| \quad (9)$$

In our case the threshold voltage is 250mV and thus the maximum voltage swing is 100mV at VDD = 600mV. On the other hand the amplifier is very simple in its design. Figure 5 shows the sine response of the BCPFG amplifier as a function of different bias voltages Vh. From the figure we can see that the circuit experiences small delay as the bias voltage Vh decreases. In this simulation the bias voltage Vl is $0V$. The input signal is marked and has an amplitude of $50mV$ and a frequency of $1MHz$.

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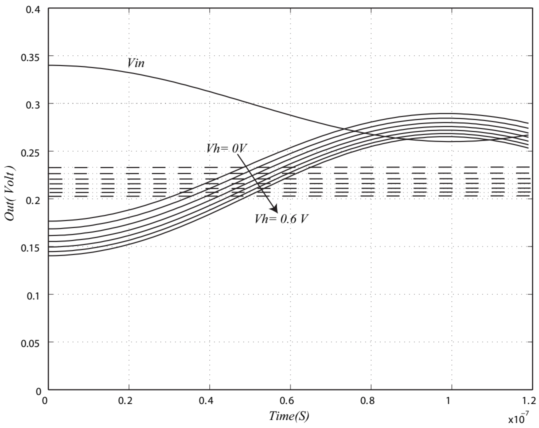

Figure 4: *The sine response of the amplifier shown in figure 1 as a function of different bias voltages Vh when Vl = 0V. The dashed lines are the DC value of the output for different bias voltages on Vh*

Figure 5 is the gain of the BCPFG amplifier. The linearity within 3% deviation is marked with circles on the figure. This area allows a peak-to-peak input voltage of 140mV. From this figure we can see that the circuit has good linearity and this is not effected by bias voltage Vh. These simulations are done with minimum length transistors and an increase in transistor lengths results in increased linearity and gain. An increase in length also effect the frequency response and decreasing the pass band.

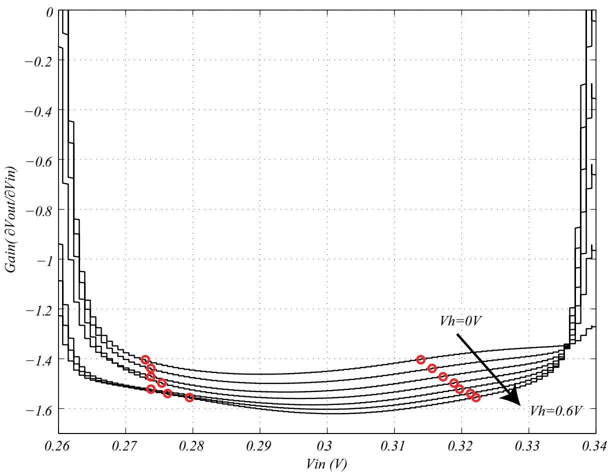

Figure 5: *The gain of the Amplifier shown in figure 1 as a function of different bias voltages Vh when Vl = 0 V. The area with linearity within 3% is marked with circles*

4 The tunable Band Pass filter

Figure 6 shows the band a pass filter realized using 3 BCPFG amplifiers. Amplifier A1 is used for tuning the filter and A2 and A3 form a non-inverting feedback.

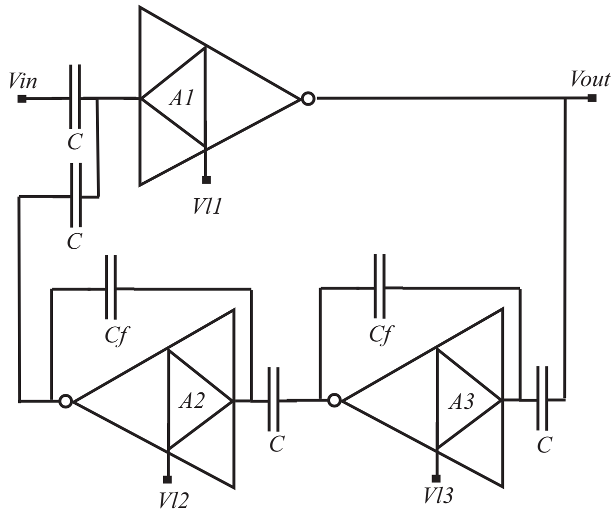

Figure 6: *The Band Pass filter realized using 3 BCPFGAs.*

The frequency response of the Band pass filter in figure 6 is shown in figure 7 where $Vl1$ is varied from $0V$ to $600mV$.

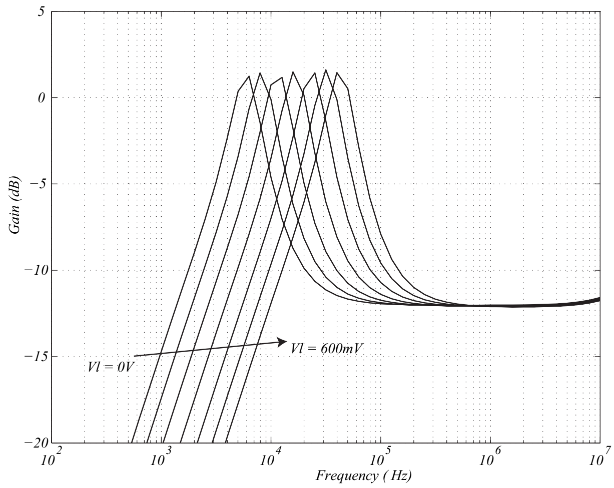

Figure 7: *THe frequency response of the BPF can vary from 6KHz to 40KHz usinfg the bias voltage Vl*

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5 Conclusion

The BCPFF BP filter presented in this paper has good properties regarding linearity and frequency band adjustment for supply voltages down to $600mV$. In this amplifier all the nodes of the transistors, including the bulk are used actively in the design and signal processing. The circuit enjoys low component spread and is very compact. The BCPFGA can be used for designing filters at the same time as it offers a limited voltage gain. We have also presented a tunable bandpass filter designed using the BCPFG amplifier presented in this paper.

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