A FULLY PROGRAMMABLE LOG-DOMAIN BANDPASS FILTER USING MULTIPLE-INPUT TRANSLINEAR ELEMENTS

Ravi Chawla†, Haw-Jing Lo†, Arindam Basu††, Paul Hasler†, and Bradley A. Minch†††

School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA†
School of Electrical Engineering, Indian Institute of Technology, Kharagpur, India††
School of Electrical and Computer Engineering, Cornell University, Ithaca, NY†††

ABSTRACT

In this paper we present a second order log-domain bandpass filter using multiple input translinear elements (MITEs) operating at a 3V supply. We enhance the capabilities of the filter by utilizing programmable MITE structures as well as programmable current sources, which are covered in this paper. The synthesized bandpass filter is implemented and fabricated using these programmable translinear devices (MITEs). Experimental results are shown from circuit fabricated on a 0.5µm nwell CMOS process available through MOSIS.

1. INTRODUCTION

Log-domain filters have recently become an integral part of the family of continuous-time filters. These filters have externally linear transfer function but internally are highly non-linear [1, 2]. All the log-domain filters use translinear elements to do the filtering on logarithmically compressed voltage signals. The internal exponential and logarithmic non-linearities of these translinear elements are used to design filters with the possibility of wide dynamic range. Also, these filters become important in systems with low supply voltages and hence, low voltage signal swings as most of the processing is done in current-mode.

The most important component of a log-domain filter is the translinear element. This paper uses a multiple-input translinear element (MITE), as proposed in [3], which uses floating-gate (FG) transistors operating in subthreshold or weak-inversion. The use of FGs help in making these filters tunable to get the desired frequency response and quality factor, Q, after fabrication. In addition, use of FGs can help in correcting for any mismatches in the current sources. This becomes extremely important in design of log-domain bandpass filters, which require current subtraction to get the bandpass response. The advantage of using MITEs is that they can be easily fabricated and characterized in a standard CMOS process, as compared to using BJTs.

A lowpass filter using these MITEs was presented in [4]. Figure 2 shows the schematic of a second order bandpass filter that was fabricated using MITEs. The second order sections can be used to then design higher order bandpass filters by cascading these second order sections. Also, these higher order filters can be synthesized from the state-space methods as described in [5].

2. MULTIPLE INPUT TRANSLINEAR ELEMENTS

The multiple–input translinear element (MITE) is a device that produces an output current that is exponential in a weighted sum of its input voltages. This structure entails the actual layout of the MITE, illustrating the PFET cascode and T-gates. This allows for the MITE to be isolated in programming mode.

\[
I = I_s e^{(k_1v_1 + k_2v_2 + \ldots + k_nv_n)/U_T}
\]
where \( I_s \) is a pre-exponential scaling current, \( k_n \) is a dimensionless positive weight, \( V_n \) is the \( n \)th input voltage, and \( kT/q \) is the thermal voltage. Individual MITEs can be networked together to construct low-power translinear circuits, called MITE networks. These networks can implement static or dynamic, linear or nonlinear systems [3].

The programmable MITE that we use to implement the second order log-domain filter is shown in Fig. 1. The cascode reduces the effect of the overlap capacitance between the gate and drain of the transistor. This enables the MITE to run at higher frequencies. In addition, the cascode reduces the Early effect, forcing the output current to be almost entirely dependent on the input gate voltages as per (1). We use hot electron injection and tunneling to program our FG MITEs as explained in [6]. This structure is also simpler to program, since during programming we can isolate the MITE by simply setting \( V_{pcascode} \) to \( V_{DD} \) and \( V_{ncascode} \) to ground. Given this architecture we are then able to synthesize a function entirely in the same row or column of an array to maintain control of the gate line for programming.

The bias current sources \( I_{\tau 1} \) and \( I_{\tau 2} \) (see Fig. 2) are produced by a floating-gate transistor, and mirrored through a NFET cascode current mirror (see Fig. 3). Through the use of a PFET floating gate transistor, we are able to accurately fix the output current to any desired level by applying the same programming techniques that are used for the MITEs.

3. SECOND ORDER SECTION BANDPASS FILTER

Figure 2 shows the log-domain bandpass filter using programmable MITEs. The synthesis of lowpass log-domain filters using MITEs is presented in [4]. The transfer function of a second order log-domain bandpass filter is given by:

\[
\frac{I_{\text{out,BPF}}}{I_{\text{in}}} = \frac{sA}{s^2\tau_1\tau_2 + s\tau_1 + 1}
\]

where \( A \) is the mid-band gain and \( \tau_1, \tau_2 \) are time constants set by the dominant capacitances in the circuit similar to the way as in \( G_m - C \) filters.

Using these time constants, the center frequency and the quality factor, \( Q \), for a bandpass filter can be defined as:

\[
\tau = \frac{1}{\omega} = \sqrt{\tau_1\tau_2}
\]

\[
Q = \sqrt{\frac{\tau_2}{\tau_1}}
\]

Equation (2) can be represented as a set of first-order differential equations as:

\[
\tau_1 \frac{dI_1}{dt} = I_{\text{in}} - I_2
\]

\[
\tau_2 \frac{dI_2}{dt} = I_1 - I_2
\]

\[
I_{\text{out,BPF}} = \frac{dI_2}{dt} = \frac{I_1 - I_2}{\tau_2}
\]

where \( I_1 \) is a temporary variable.

Based on the above equations and the synthesis method, explained in [4], to implement first order systems, a second order system schematic that was synthesized is shown in Figure 2. For the circuit schematic shown, the time constants are given by (using the same notation as in [4])

\[
\tau_1 = \frac{C_1}{g_{\tau 1}}
\]

\[
\tau_2 = \frac{C_2}{g_{\tau 2}}
\]

Fig. 2. Circuit schematic of the second order log-domain bandpass filter using programmable MITEs. The circuit uses two-input MITEs. The current sources \( I_{\tau 1} \) and \( I_{\tau 2} \) are generated by floating-gate current sources.
where $g_{\tau_1}, g_{\tau_2}$ are transconductances of the MITEs with currents $I_{\tau_1}$ and $I_{\tau_2}$, respectively. The same circuit can also be used to give the lowpass output, $I_2$, by using an extra current mirror for the output.

As can be seen from the equations (3) and (4), the center frequency and the $Q$ of the bandpass filter depend on $\tau_1$ and $\tau_2$, which in turn depend on the transconductances of the MITEs. Also, the response is sensitive to the current subtraction done at the output. Thus, any mismatch in the current sources or in the MITEs currents due to fabrication gradients will have a detrimental effect on the response. The weak inversion operation of MOS further aggravates the problem of current mismatch. The ability to program these FG elements takes care of any such mismatches. This along with the already mentioned features of MITEs in [4] makes this structure a suitable candidate for log-domain bandpass implementation. Using cascodes further makes MITEs more robust to process parameters along with the additional benefits in the programming logic, as mentioned in the above section. Thus, by programming the current sinks $I_{\tau_1}$ and $I_{\tau_2}$, the desired frequency response and $Q$ for the bandpass filter can be obtained.

To obtain high frequency responses, the MITE elements have to be programmed to higher currents to have higher bandwidth of operation. The output current source, $I_3$, is programmed to give a desired DC output current to facilitate the current measurements.

The synthesis procedure used to generate the second order bandpass filter can be generalized to obtain a circuit schematic for a higher-order bandpass filter by decomposing the $n^{th}$ order system into $n$ first order differential equations. Also, higher order bandpass filter can be made by cascading the second order sections discussed above. The advantage of cascading is ease of design and tunability of the response of these higher-order filters.

4. EXPERIMENTAL RESULTS

A simulation plot showing that the designed filter can be tuned over a wide range of frequencies is shown in Fig. 4(a). Figure 4(b) shows the experimental result showing the response at 20 KHz and 200 KHz, which matches with the corresponding simulations. The measurements were limited due to the setup as will be explained in the next section.

Figure 5 shows the simulation and measured bandpass response for the programmed log-domain filter over a range of bias currents (1 to 10nA) to give different corner frequencies. The frequency responses agreed well with the simulation results.

Figure 6 shows the results of programming current sinks to get different values of $Q$ at the same corner frequencies. In this experiment, $I_{\tau_1}$ and $I_{\tau_2}$ were programmed such that the corner frequency was kept constant while changing the $Q$-peak only. This was done by programming the currents to have a constant product while increasing the ratio of $I_{\tau_1}/I_{\tau_2}$. The experiment shows that a $Q$-peak of up to 20 can be obtained from the designed filter.

Fig. 3. Programmable current source. The input bias currents are generated using this NFET cascoded current mirror in conjunction with a PFET floating-gate transistor. The programming ability of the floating-gate transistor allows for precise current levels.

Fig. 4. Frequency corner tuning. (a) Simulated corner frequency tuning illustrating the wide range of possible frequencies. (b) Measured corner frequencies. The corner frequencies are tuned to 20kHz and 200kHz.
5. MEASUREMENT ISSUES

Since log-domain filters have currents as input and output, care must be taken while testing them. The measurements depend heavily on the dynamic range and frequency response of the voltage-to-current conversion block at the input and vice versa at the output. In the initial setup, to perform the measurements presented here, a protoboard was used that had a large capacitance and a poor noise performance. This limited the measurements as the performance of the discrete op-amps used to build the input and output blocks deteriorated due to the board.

The voltage to current conversion block at the input was implemented using a discrete op-amp in negative feedback to generate input currents. The input amplitude was limited to keep the input current as linear and distortion free as possible. These measurements will become easier and less noisy by building a printed-circuit board (PCB) to test the filters. A PCB was designed and sent for fabrication to test the frequency, linearity and noise performance of the second- and higher-order log-domain bandpass filters.

6. CONCLUSION

This paper describes a programmable second order log-domain bandpass filter implementation using MITEs. Experimental results showing frequency- and $Q$-tuning are presented for the circuit fabricated in $0.5\mu m$ double-poly CMOS process. The experimental results agreed with the simulation plots shown in the paper. The second order sections gave $Q$ values of up to 20. These second order sections can be used to build programmable higher order log-domain filters for a variety of applications [1, 2].

7. REFERENCES