Dynamically Biased 1 MHz Low-pass Filter with 61 dB peak SNR and 112 dB Input Range

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**Motivation**

- Dynamically biased current mode filter:
  - 112 dB input range (THD < -40 dB).
  - Quiescent power consumption of 575 $\mu$W.
Outline

- Principle of distortionless dynamic biasing.
- Third-order Butterworth filter.
- Measurement results.
- Comparison.
- Conclusions.
First order log-domain filter

\[ I_{o+}(s) = \frac{I_{g}/I_{tune}}{1 + sC_1V_t/I_{tune}} \]

[Punzenberger & Enz '97]

- Linear from \( i_{i+} \) to \( i_{o+} \)
- Output noise \( \sim I_{bias} + kI_{bias}^2 \); Power diss. \( \sim I_{bias} \).
- \( I_{bias} \downarrow \Rightarrow \) Output noise \( \downarrow \) & Power dissipation \( \downarrow \).
- But, filtered \( I_{bias}(t) \) appears at the output.
Pseudo-differential operation

\[ I_{in} \rightarrow h(t) \rightarrow i_{o+} \quad i_{o-} \rightarrow -i_{in} \]

\[ i_{o+} = (i_{in} + I_{bias}(t)) \cdot h(t) \quad \quad i_{o-} = (-i_{in} + I_{bias}(t)) \cdot h(t) \]

\[ i_{out} = i_{o+} - i_{o-} = 2i_{in} \cdot h(t) \]

- Large signal linearity \( \Rightarrow \) cancellation of \( I_{bias} \).
Dynamic biasing

- Decrease $I_{bias}$ for small input amplitudes.
- SNR improvement for small signals while maintaining linearity and time-invariance.
- Output noise depends on total input signal.
Third-order Butterworth filter

\[
\frac{1}{1 + \frac{s}{\omega_p}} + \frac{1}{1 + \frac{s}{2\omega_p}} + \frac{1}{1 + \frac{s}{\omega_p}}
\]

\[i_{out} = i_{o+} - i_{o-}\]
Minimizing distortion due to Early effect

- Large $g_m$ for $I_{fb}$ to reduce distortion due to Early effect.
- $C_c$: pole-zero compensation.
Feedback paths in the filter

Separate emitter follower for the feedback path ensures frequency response integrity.
Chip photograph

- Capacitor (0.19 mm²)
- Active circuit
- 0.52 mm²
Measurement conditions

- $V_{dd} = 2.5$ V.
- $I_{tune} = 5 \mu$A.
- $I_{bias}$: 3 $\mu$A to 2.5 mA.
- “Dynamic” bias: $I_{bias} = 2 \times$ the single-ended input peak, subject to a minimum of 3 $\mu$A.
- 400 kHz input for THD measurements.
- 1 MHz $\pm$ 20 kHz inputs for $IM_3$ measurements.
Measured results: Frequency response

- Frequency response with $I_{bias}$ from 3 $\mu$A to 2.5 mA
- Signal frequency response
- Bias leakage
- Passband detail

Graph showing dB vs. frequency (f/MHz) with multiple traces for different bias currents.
Measured results: Noise

- Noise floor: $4.4 \, \text{nA}_{\text{rms}}$
- Differential rms noise (0–2MHz)
Measured results: Distortion

Input range = 112 dB

S / N

S / THD

S / IM₃

6.2 nA pk

2.5 mA pk

differential peak input / A

dB
Output with dynamically changing bias

- 20µA single-ended peak input @ 600 kHz.
- $I_{bias}$ switched from 24µA to 114µA.
- Barely perceptible change in the output.
Measured results: Power consumption

- Differential input peak: 575 µW
- Power consumption: 2.5 mW

Current consumption / A

Power consumption / mW

Graph showing the relationship between differential input peak and power consumption.
<table>
<thead>
<tr>
<th>Summary</th>
<th></th>
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<tbody>
<tr>
<td><strong>Technology</strong></td>
<td><strong>0.25µm BiCMOS</strong></td>
</tr>
<tr>
<td><strong>Area (excl. pads)</strong></td>
<td><strong>0.52 mm²</strong></td>
</tr>
<tr>
<td><strong>Supply voltage</strong></td>
<td><strong>2.5 V</strong></td>
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<tr>
<td><strong>-3 dB BW</strong></td>
<td><strong>930 kHz</strong></td>
</tr>
<tr>
<td><strong>$I_{bias}$</strong></td>
<td><strong>$3\mu A$</strong></td>
</tr>
<tr>
<td><strong>Power diss. ($P_d$)</strong></td>
<td><strong>575µW</strong></td>
</tr>
<tr>
<td><strong>Output noise</strong></td>
<td><strong>4.4 nA</strong></td>
</tr>
<tr>
<td><strong>THD (input peak = 0.5$I_{bias}$)</strong></td>
<td><strong>-64.3 dB</strong></td>
</tr>
<tr>
<td><strong>IM₃ (input peak = 0.5$I_{bias}$)</strong></td>
<td><strong>-39.5 dB</strong></td>
</tr>
<tr>
<td><strong>Input range (THD ≤ 40 dB)</strong></td>
<td><strong>112 dB</strong></td>
</tr>
<tr>
<td><strong>Maximum $P_d / \text{Order} \cdot \text{BW}$</strong></td>
<td><strong>9.35 nJ</strong></td>
</tr>
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</table>
Comparison

Previously published filters

This work

Input range [dB]

Normalized power dissipation / J

first-order passive RC low-pass
Conclusions

- A technique for dynamic biasing without disturbing the output.
- Noise and power reduction for small input signals.
- A log-domain filter with 112 dB input range in a 0.25 µm BiCMOS technology.
- Quiescent power: $40 \times$ smaller than maximum.
- Over an order of magnitude improvement in power efficiency of analog filters.