A 0.0094mm$^2$/Channel Time-Based Beat Frequency ADC in 65nm CMOS for Intra-Electrode Neural Recording

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Motivation

Conventional

[N-bit [µV~mV]

Proposed

[N-bit [µV~mV]
Motivation

Conventional

[μV–mV]

+       -

PA      LNA      BPF      PGA      BUF      AN MUX      ADC

N-bit

Proposed

[μV–mV]

+       -

TIA      BPF      BF-ADC

Technology Scaling

N-bit

C. Lopez, IEEE TBioCAS, 2017
Clinical Applications

- Alzheimer’s disease is 6\textsuperscript{th} leading cause of death in US
- Neurodegenerative disease that also affects families of the patients
- $200B$ annual cost
- Need new tools to study causes to find cure
• **Neural BFADC Recording system**
• **Fully Integrated on-chip enabling high channel count density**
• **Digital Time-based Beat Frequency ADC**
Analog Front End

Signal

Ref

TIA

BPF

OSC

BFADC

\[ f_{\text{SIG}} \]

\[ f_{\text{REF}} \]

\[ \Delta f = |f_{\text{REF}} - f_{\text{SIG}}| \]

\[ N = f_{\text{REF}} / \Delta f \]

Freq. subtractor

\[ V_{\text{DD}}/2 \]

\[ V_{\text{DD}}/2 \]

\[ V_{\text{in}} \]

\[ V_{\text{out}} \]

Thick Ox
Band-pass Filter

Signal

Ref

TIA

BPF

OSC

BFADC

OSC

DFF

Counter

Freq. subtractor

HPF

Thick Ox

+ NWell Caps

V_{HPF}

V_B

LPF

V_{LPF}

Thick Ox

V_B

Measured SNDR, (dB)

65nmLP, 0.8V, 25C

Spikes

LFPs

65nmLP, 0.8V, 25C

f_{REF}

f_{SIG}

\Delta f = |f_{REF} - f_{SIG}|

N = f_{REF} / \Delta f

f_{SIG}

V

B

V

B

\Delta f

\Delta f = |f_{REF} - f_{SIG}|

N = f_{REF} / \Delta f

Counter

Freq. subtractor

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f_{REF}

f_{SIG}

\Delta f = |f_{REF} - f_{SIG}|

N = f_{REF} / \Delta f

f_{SIG}

V

B

V

B

\Delta f

\Delta f = |f_{REF} - f_{SIG}|

N = f_{REF} / \Delta f

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Freq. subtractor

65nmLP, 0.8V, 25C

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f_{REF}

f_{SIG}

\Delta f = |f_{REF} - f_{SIG}|

N = f_{REF} / \Delta f

f_{SIG}

V

B

V

B

\Delta f

\Delta f = |f_{REF} - f_{SIG}|

N = f_{REF} / \Delta f

Counter

Freq. subtractor

65nmLP, 0.8V, 25C

Spikes

LFPs
Current Controlled Oscillator

Signal

Ref

TIA

BPF

OSC

\[ f_{SIG} = f_{REF} - f_{SIG} \]

\[ N = f_{REF} / \Delta f \]

\[ \Delta f = |f_{REF} - f_{SIG}| \]

BFADC

Freq. subtractor

Counter

\[ V_{DDH} \]

\[ V_{IN} \]

2b

Coarse tuning

Fine tuning

3b

\[ Code = 00100 \]

Frequency, (MHz)

Bias, (V)

Graph:

65nmLP, 1.2V, 25C

Code = 00100

0.2 0.4 0.6 0.8 1 1.2

0 40 80 120 160 200
Beat Frequency ADC

\[ \Delta f = |f_{\text{REF}} - f_{\text{SIG}}| \]

\[ N = f_{\text{REF}} / \Delta f \]
Silicon Odometer Beat Frequency Ckt

\[
\Delta V_T (\text{a.u.})
\]

- **Trapping**
- **Detrapping**

- **Diagram:**
  - Circuit diagram with labeled nodes A, B, C, D, and Q.
  - DFF (Delay-Flop-Flop) block.
  - Trap and Carrier section.

- **Graph:**
  - 
  - Vertical axis: \( \Delta V_T \) in a.u.
  - Horizontal axis: Time

- **Equation:**
  \[
  T \quad A \quad u \quad \Delta \quad V \quad T
  \]

- **Title:** Silicon Odometer Beat Frequency Ckt
Silicon Odometer Beat Frequency Ckt

Trapping Detrapping

D Q
DFF

\[ \Delta V_T (\text{a.u.}) \]

0

0.4

0.8

1.2

A

B

C

S

Carrier

D

Trap
Silicon Odometer Beat Frequency Ckt

\[ \Delta V_T (\text{a.u.}) \]

- Trapping
- Detrapping

Diagram of Silicon Odometer Beat Frequency Ckt

- DFF
- S, Carrier, D
- Trap

Graph showing Trapping and Detrapping

[Diagram and graph details]
Silicon Odometer Beat Frequency Ckt

- Sub-ps resolution + sub-μs measurement time
Beat Frequency ADC

Signal

Ref

TIA

BPF

OSC

f_{SIG}

f_{REF}

\Delta f = |f_{REF} - f_{SIG}|

N = f_{REF}/\Delta f

Conventional

freq = f_{SIG}

df = f_{REF}/N_0

freq = f_{REF}/N_0

250MHz

225MHz

245MHz

225MHz

250MHz

5MHz

25MHz

N_{OUT} = 50

N_{OUT} = 45

freq = f_{SIG}/N

freq = f_{REF}/N_0

BFADC

DFF

Counter

Freq. subtractor
Linear vs BFADC Transfer Function

![Transfer Function Diagram](image)

<table>
<thead>
<tr>
<th>$N_0$</th>
<th>Linear Quantizer</th>
<th>BF Quantizer (This work)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>50</td>
<td>$49^2 = 2401$</td>
</tr>
<tr>
<td>100</td>
<td>100</td>
<td>$99^2 = 9801$</td>
</tr>
<tr>
<td>200</td>
<td>200</td>
<td>$199^2 = 39601$</td>
</tr>
</tbody>
</table>

(Table shows quantizer gain normalized to $f_{REF}$)
Bench-top Performance

- $F_{\text{in}} = 416\text{Hz}$
- $N = 34.5$ gain is $\sim 1100$
- $0\text{dBFS} = 1.2\text{V}$
In-vivo Results

- Purkinje fibers in anesthetized WT/FVB mouse
- Tungsten stimulation electrode
- Glass micropipette recording electrode
- Flavoprotein Autofluorescence to locate fibers
## Comparison Table

<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>ADC Type</td>
<td>Beat Freq.</td>
<td>VCO</td>
<td>CT-$\Delta\Sigma$</td>
<td>VCO-$\Delta\Sigma$</td>
<td>1-Step BF</td>
<td>Incr.-$\Delta\Sigma$</td>
</tr>
<tr>
<td>Process/Supply</td>
<td>65nm/0.8V</td>
<td>40nm/1.2V</td>
<td>130nm/1.2V</td>
<td>130nm/1.2V</td>
<td>65nm/1.2V</td>
<td>180nm/1.2V</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>4.5kHz</td>
<td>200Hz</td>
<td>15MHz</td>
<td>1.7MHz</td>
<td>1.2KHz</td>
<td>4kHz</td>
</tr>
<tr>
<td>Sampling Rate</td>
<td>50kHz</td>
<td>3kHz</td>
<td>500MHz</td>
<td>250MHz</td>
<td>50kHz</td>
<td>8kHz</td>
</tr>
<tr>
<td>$\text{In}_{0\text{db}}$ [dBFS]*</td>
<td>-84</td>
<td>-75</td>
<td>-80</td>
<td>-75</td>
<td>-86</td>
<td>-85</td>
</tr>
<tr>
<td>$\text{SNDR}_{1\text{mVpp}}$ [dB]**</td>
<td>20.9</td>
<td>35</td>
<td>20</td>
<td>14</td>
<td>22</td>
<td>22</td>
</tr>
<tr>
<td>$\text{ENOB}_{1\text{mVpp}}$ [b]**</td>
<td>3.17</td>
<td>5.52</td>
<td>3.03</td>
<td>2.03</td>
<td>3.36</td>
<td>3.36</td>
</tr>
<tr>
<td>Power</td>
<td>52uW</td>
<td>7uW</td>
<td>20mW</td>
<td>910uW</td>
<td>34uW</td>
<td>34.8uW</td>
</tr>
<tr>
<td>FoM @ $F_{\text{in}}$ [pJ/Conv]***</td>
<td>683 @ 900Hz</td>
<td>380 @ 3Hz</td>
<td>81.4 @ 4.15MHz</td>
<td>66.6 @ 500kHz</td>
<td>1252 @ 300Hz</td>
<td>424 @ 175Hz</td>
</tr>
<tr>
<td>Chip Area [mm$^2$]</td>
<td>0.046</td>
<td>2.16</td>
<td>1.3</td>
<td>0.04</td>
<td>0.096</td>
<td>0.0564</td>
</tr>
<tr>
<td>Area/Ch [mm$^2$] (Relative)</td>
<td>0.0094 (1x)</td>
<td>0.135 (14.5x)</td>
<td>1.3 (138x)</td>
<td>0.04 (4.3x)</td>
<td>0.078 (8.3x)</td>
<td>0.0564 (5.9x)</td>
</tr>
<tr>
<td>Experiment</td>
<td>In-vivo</td>
<td>In-vitro</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

*Input Amplitude at SNDR=0dB, 0dBFS=1.2V  **Reported at $V_{\text{in}}=1\text{mV}_{pp}$  ***FoM =Power/(2*BW*2$^{\text{ENOB}}$)


Die Photo

- All passives on-chip
- 0.0094mm$^2$/channel
- 0.046mm$^2$ Total area
Conclusions

- Beat Frequency ADC for Intra Electrode Neural Recording proposed
- Fully integrated- no off-chip passives
- Low channel area 0.0094mm$^2$
- 20.9dB SNDR @ 1mV$_{pp}$ input
- *In-vivo* experiment supports efficacy

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