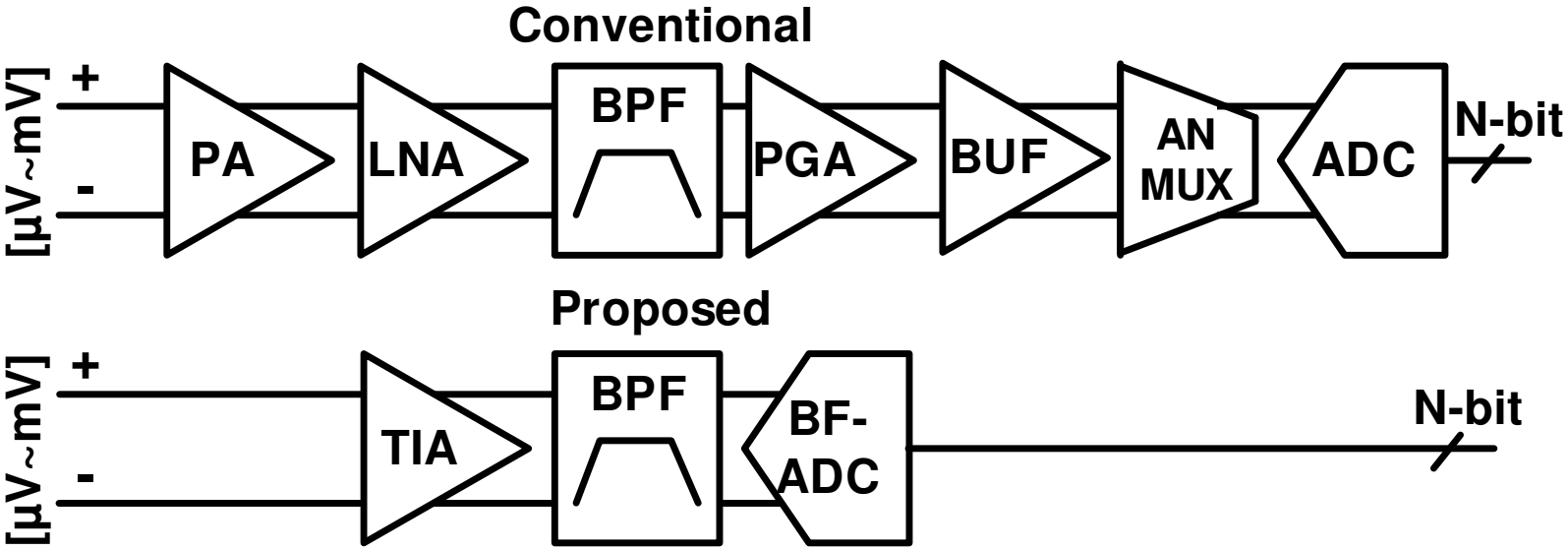
A 0.0094mm^2/Channel Time-Based Beat Frequency ADC in 65nm CMOS for Intra-Electrode Neural Recording

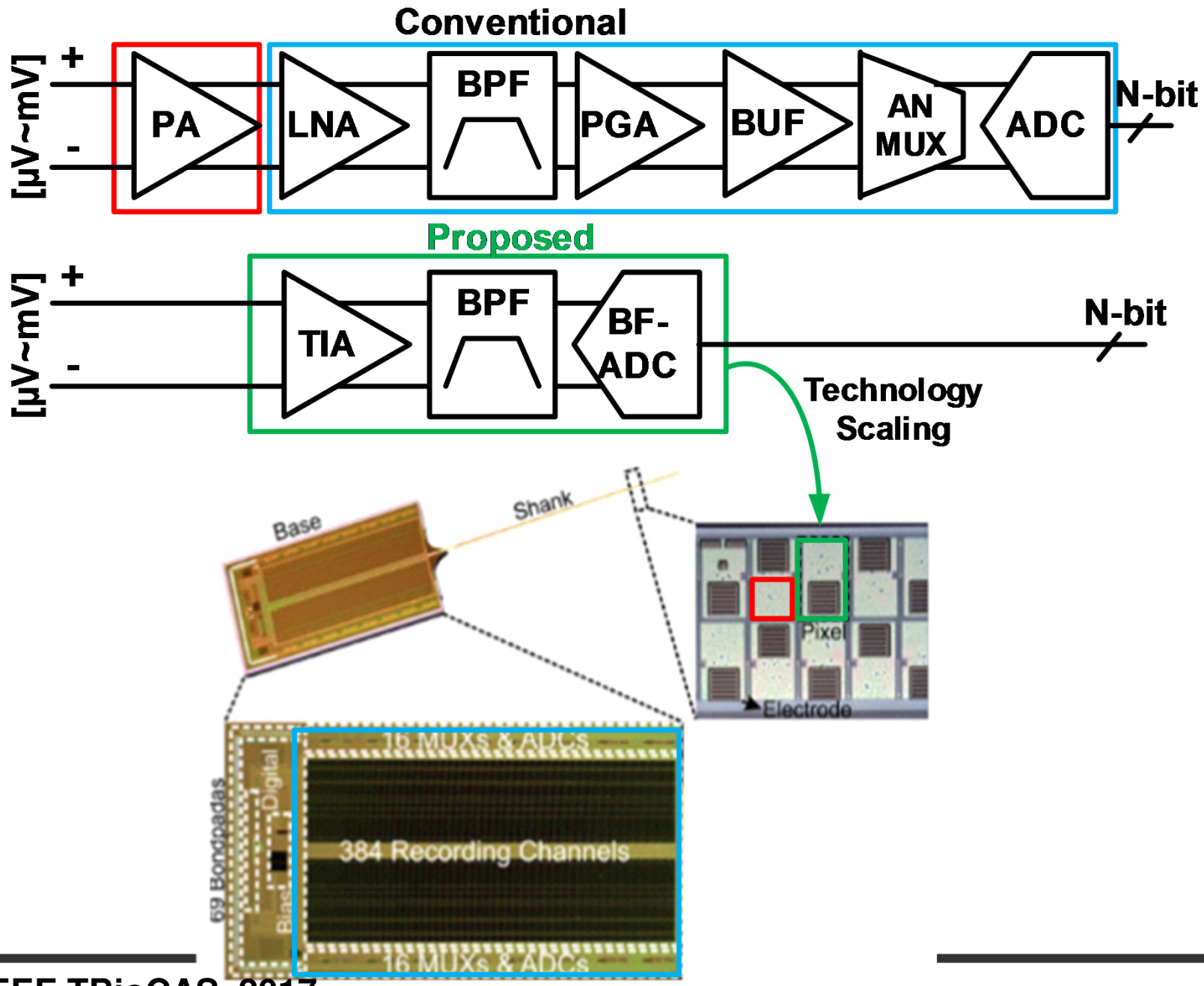
Luke Everson[1], Somnath Kundu[1], Gang Chen[2], Zhi Yang[3], Timothy J. Ebner[2], and Chris H. Kim[1]

[1]Dept of Electrical and Computer Engineering
[2]Dept of Neuroscience
[3]Dept of Biomedical Engineering
University of Minnesota, Minneapolis, MN 55455 USA

Motivation


Conventional
[µV~mV]
+
-
PA
LNA
BPF
PGA
BUF
AN MUX
ADC
N-bit
Proposed
[µV~mV]
+
-
TIA
BPF
BF-ADC
N-bit

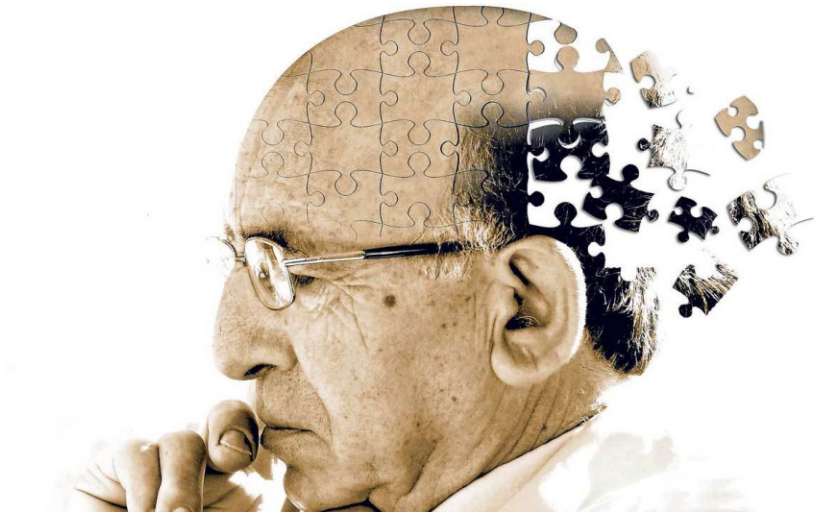
Motivation

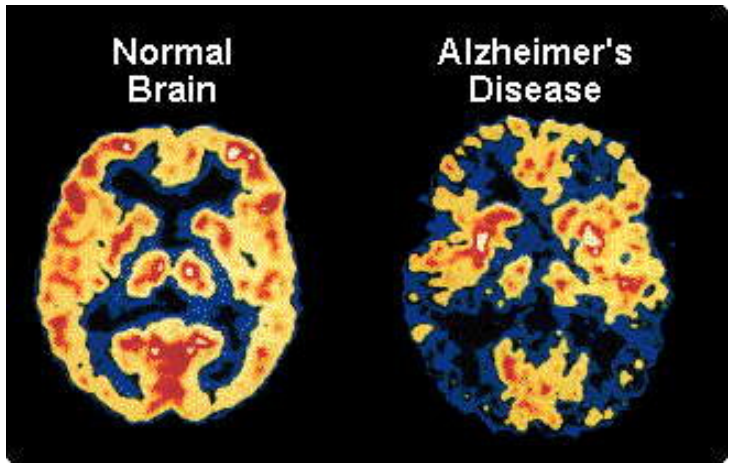


C. Lopez, IEEE TBioCAS, 2017

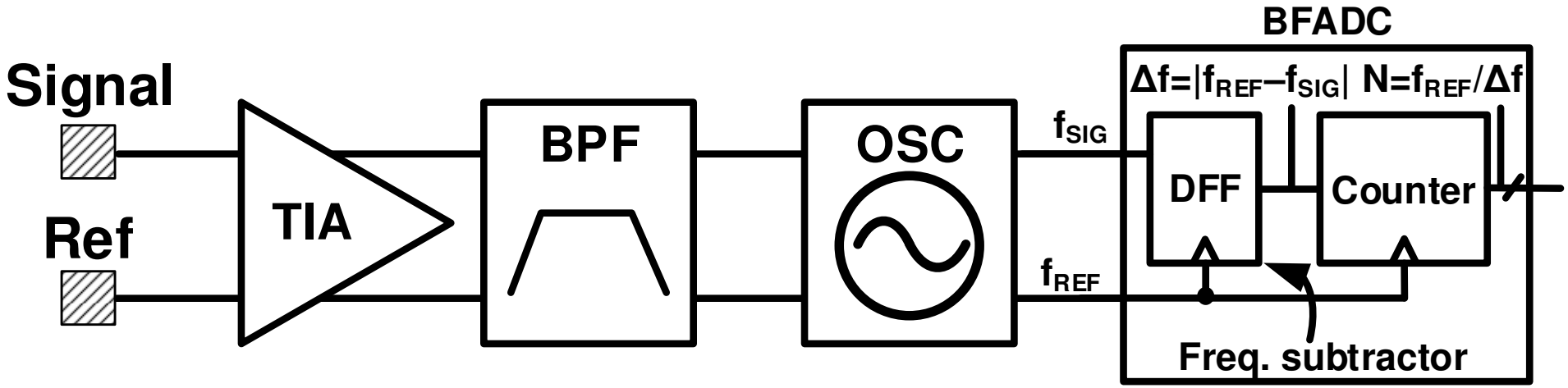
Clinical Applications

- **Alzheimer's disease is 6th leading cause of death in US**
- **Neurodegenerative disease that also effects families of the patients**
- **$200B annual cost**
- **<u>Need new tools to study causes to find cure</u>**



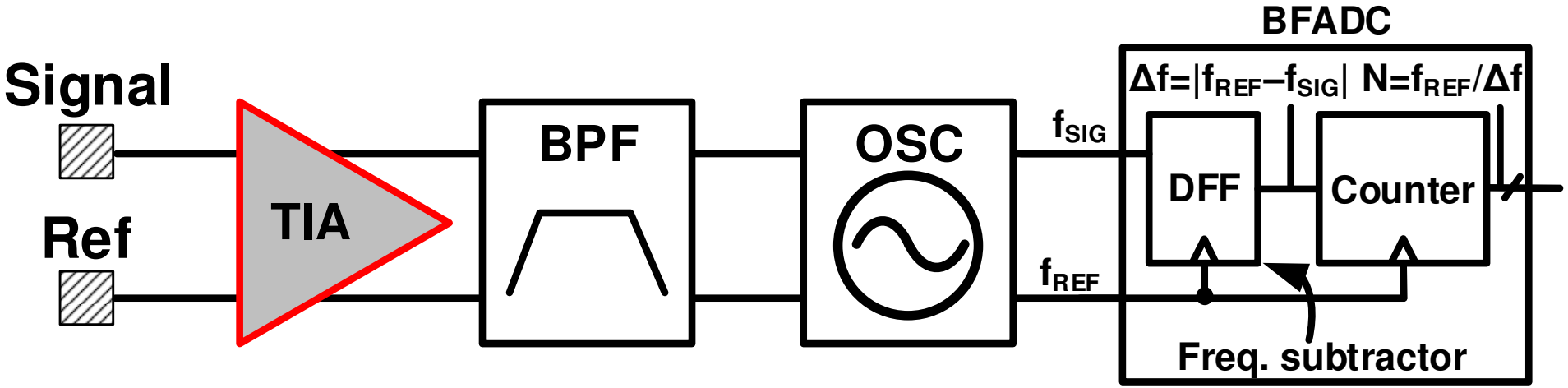


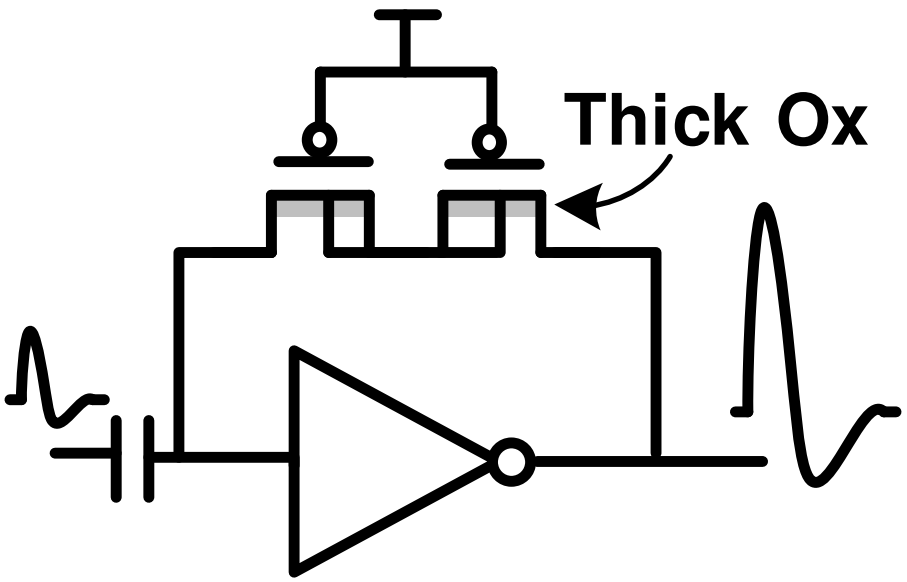
Schematic

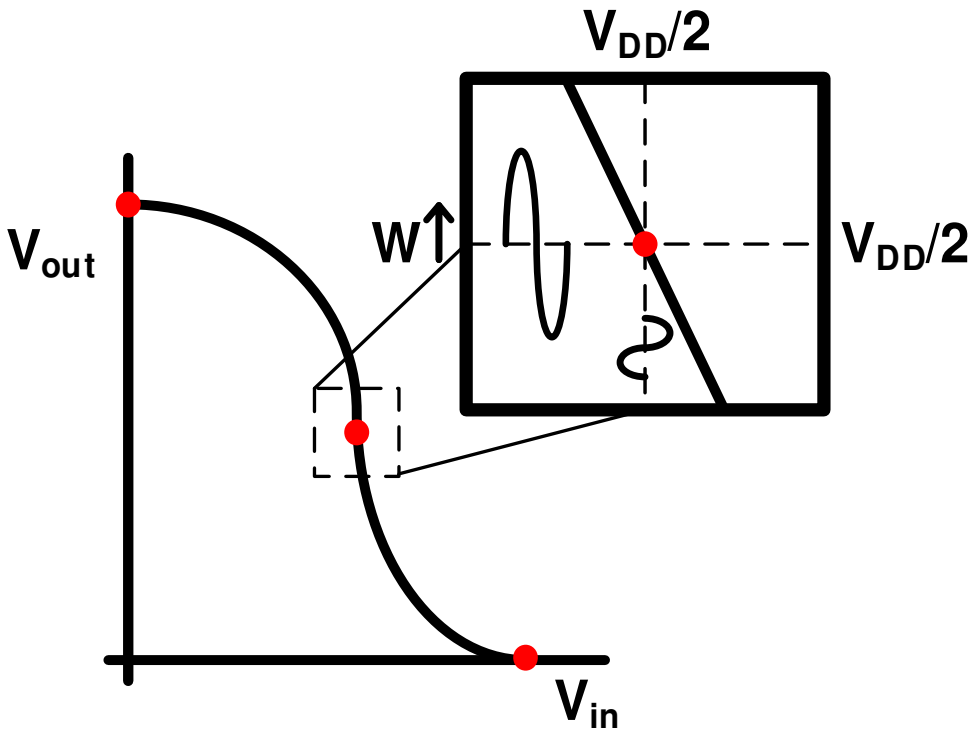


- Neural BFADC Recording system
- Fully Integrated on-chip enabling high channel count density
- Digital Time-based Beat Frequency ADC

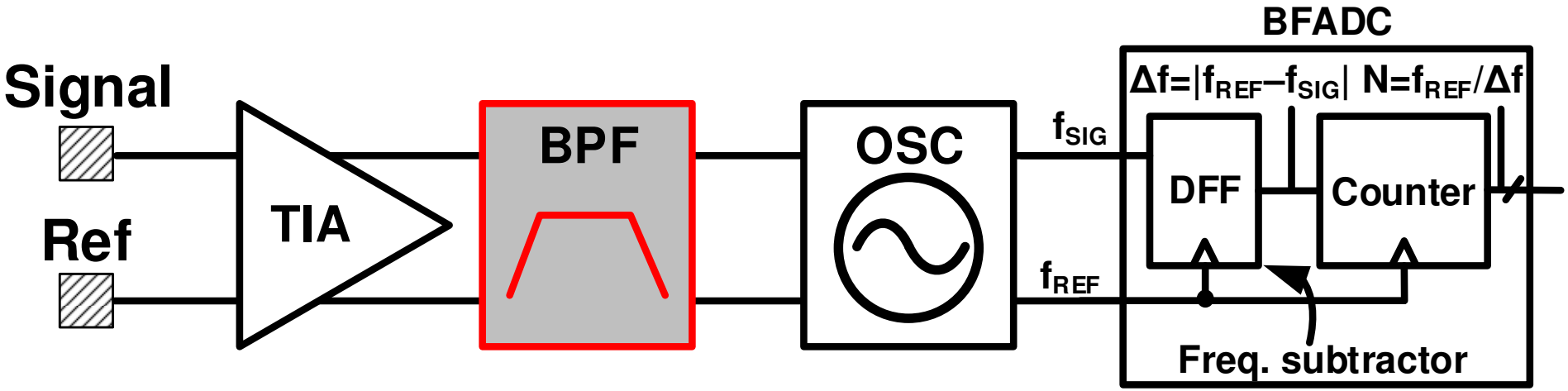
Analog Front End

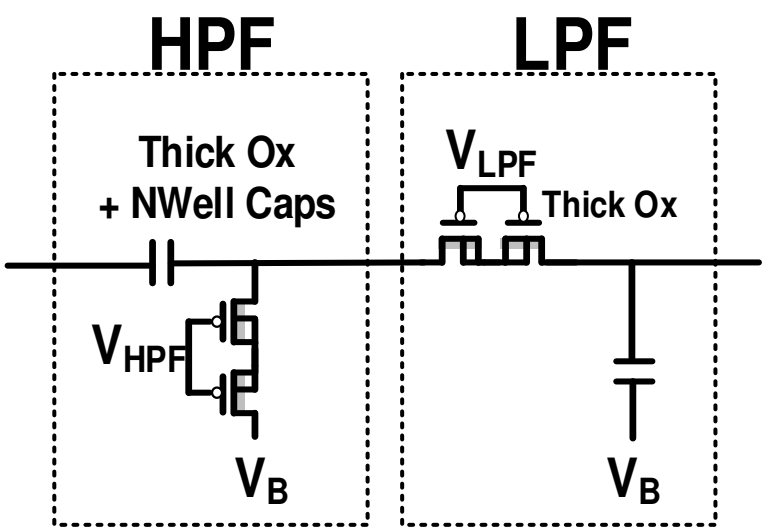


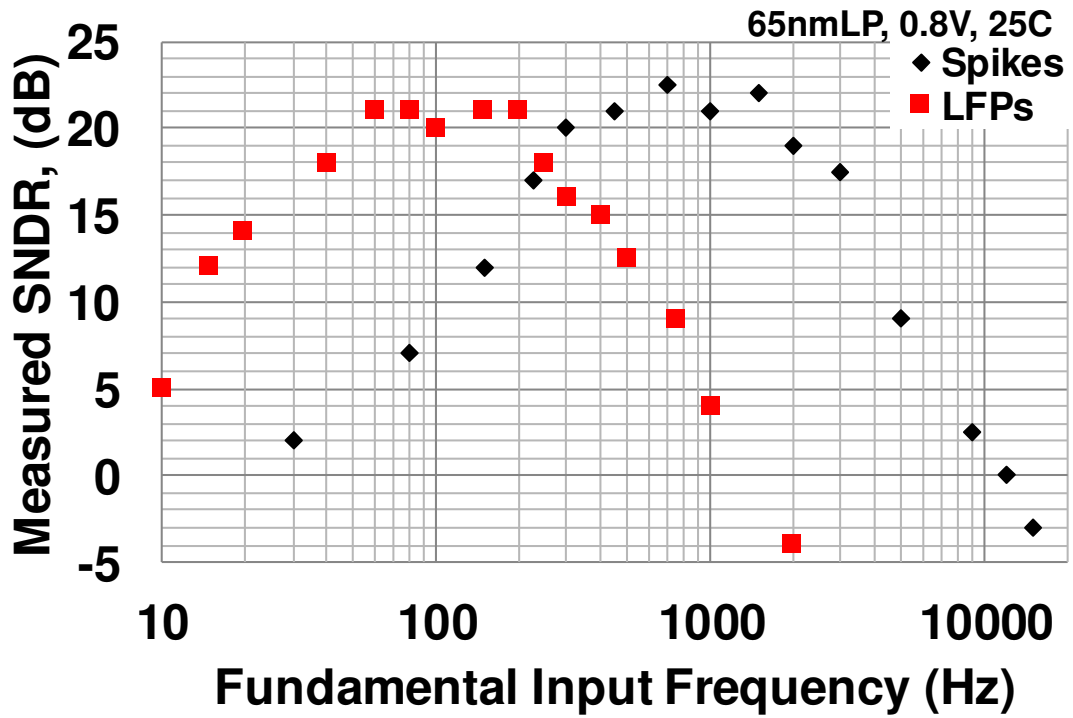




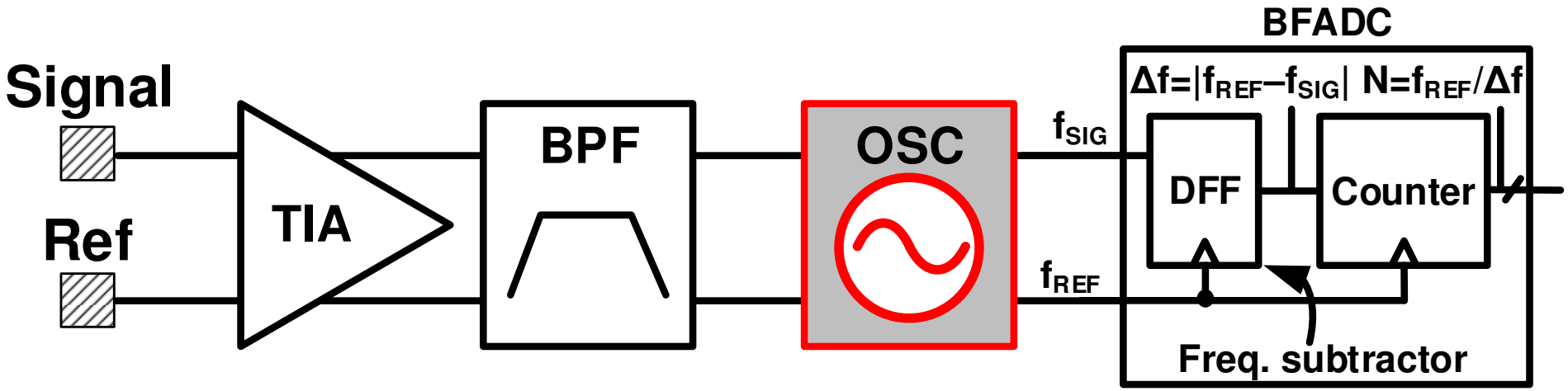
Band-pass Filter

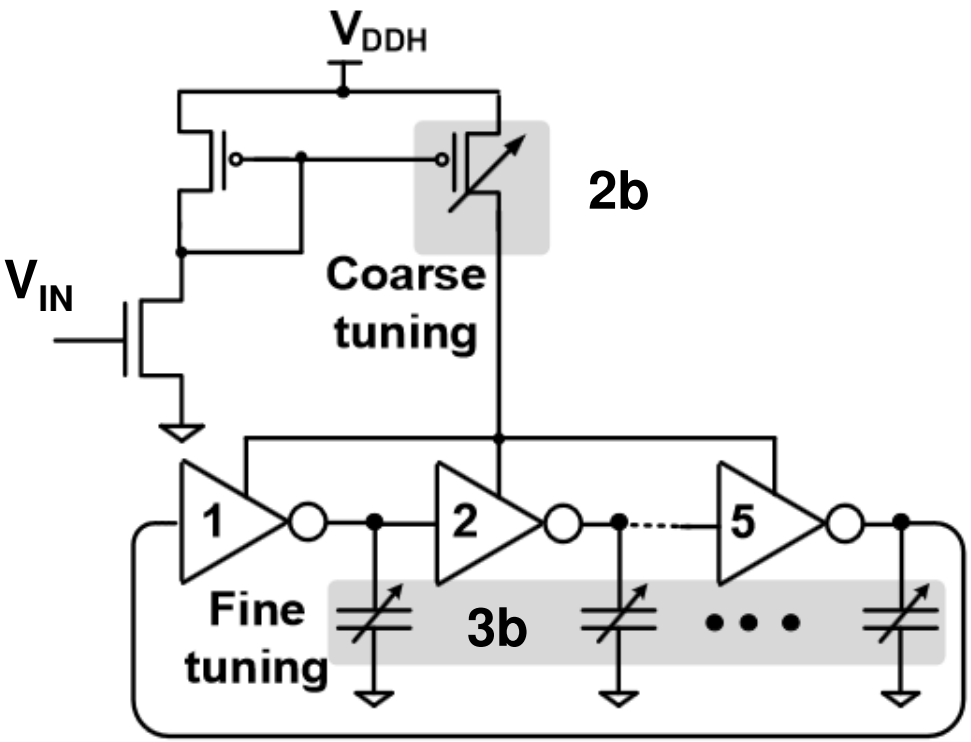


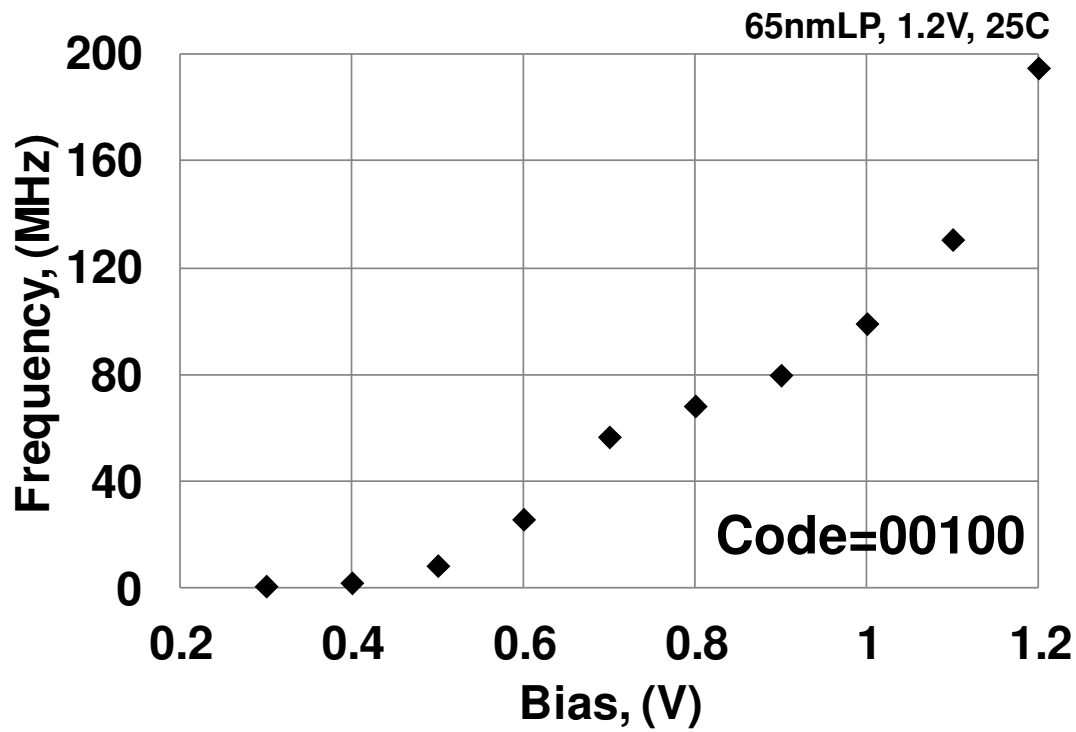




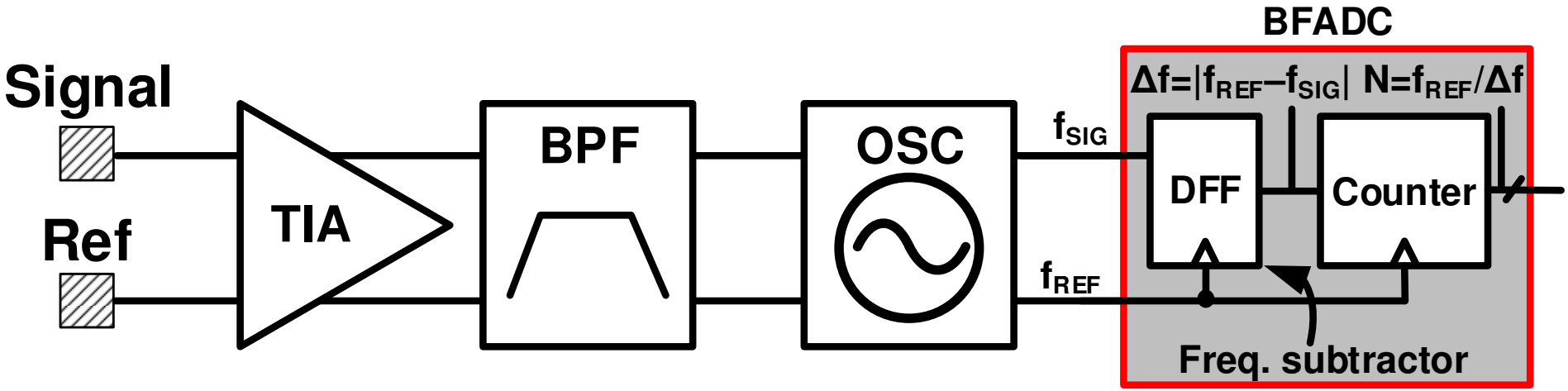
Current Controlled Oscillator



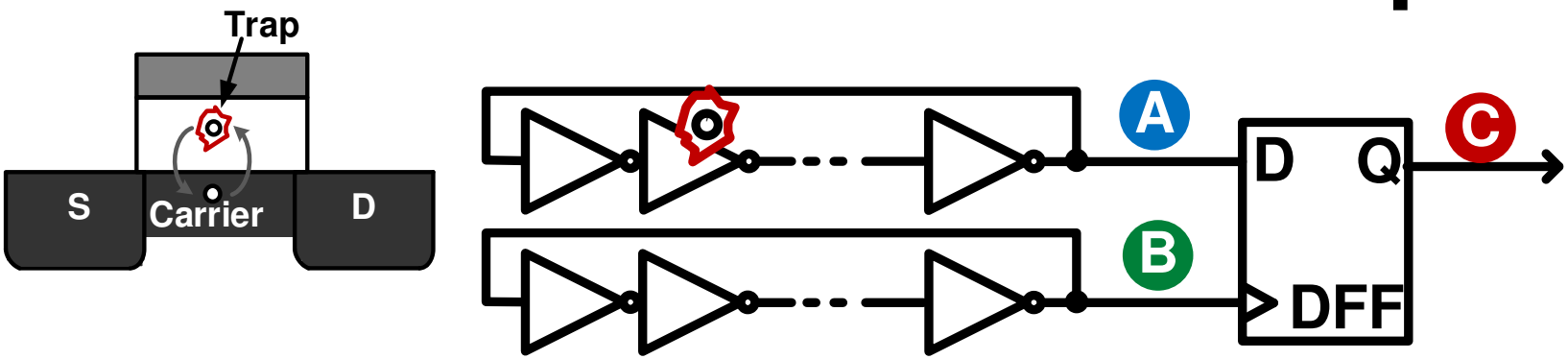


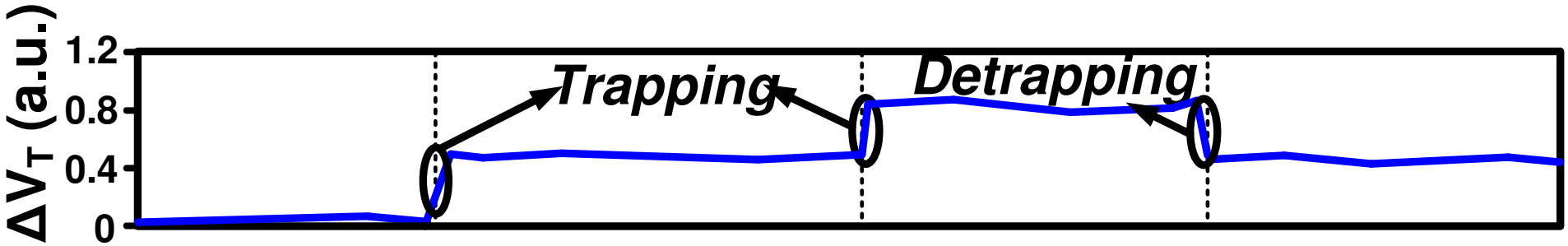


Beat Frequency ADC

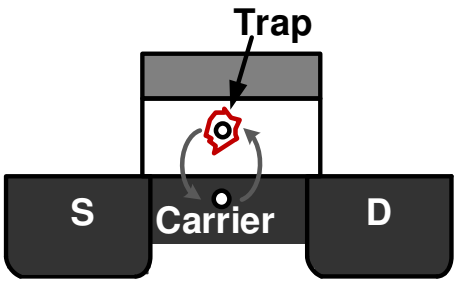


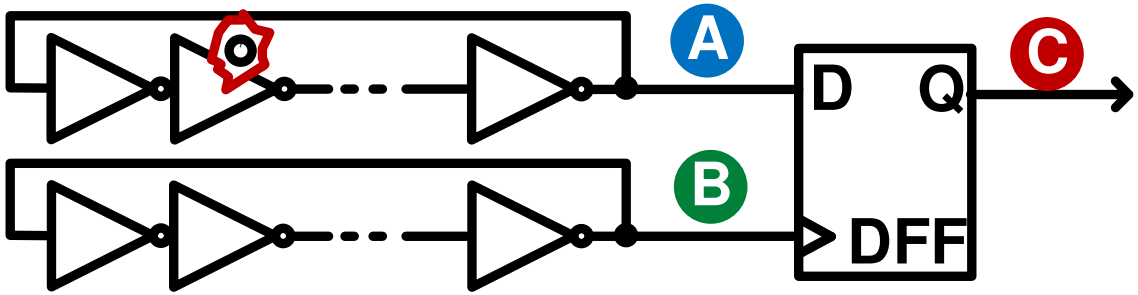
Silicon Odometer Beat Frequency Ckt

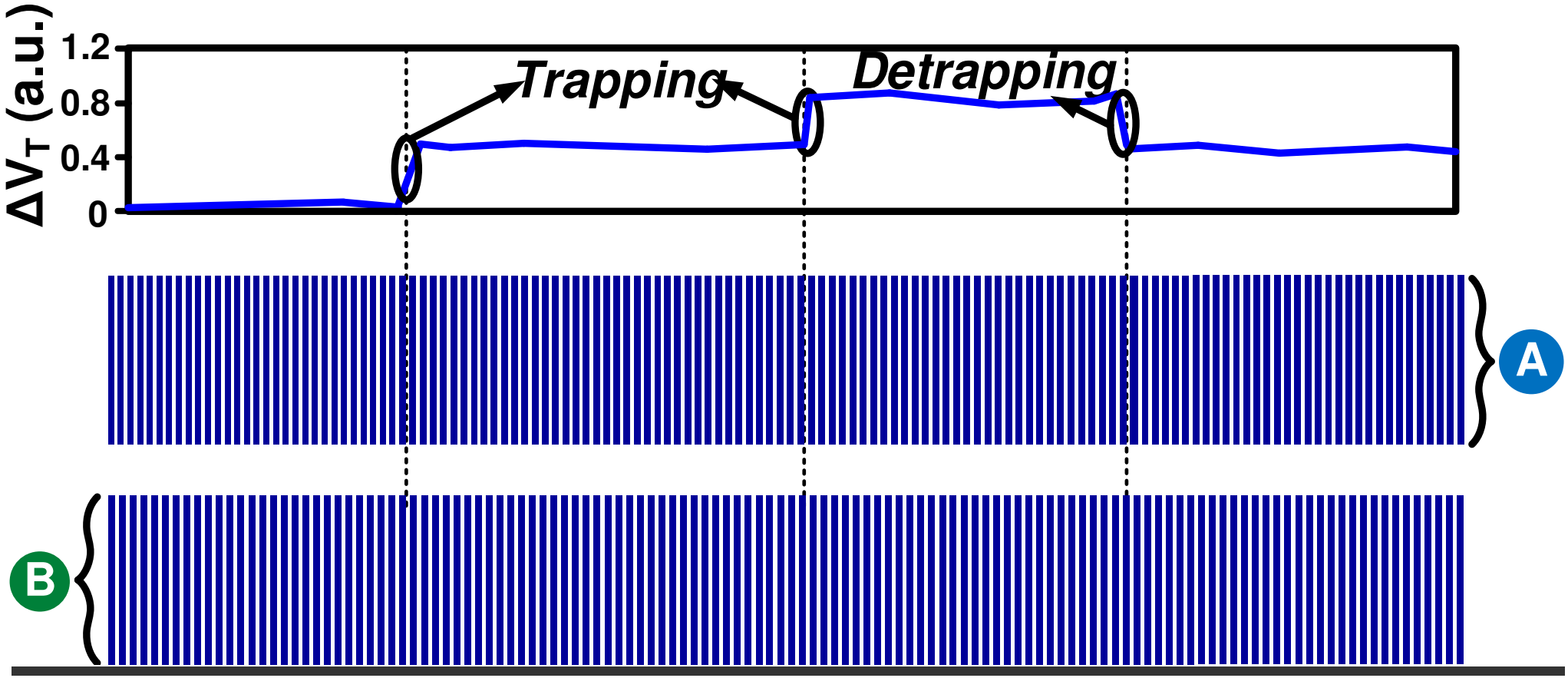




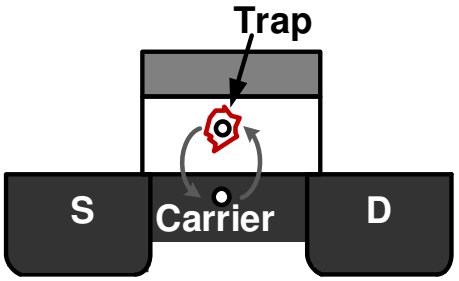
Silicon Odometer Beat Frequency Ckt

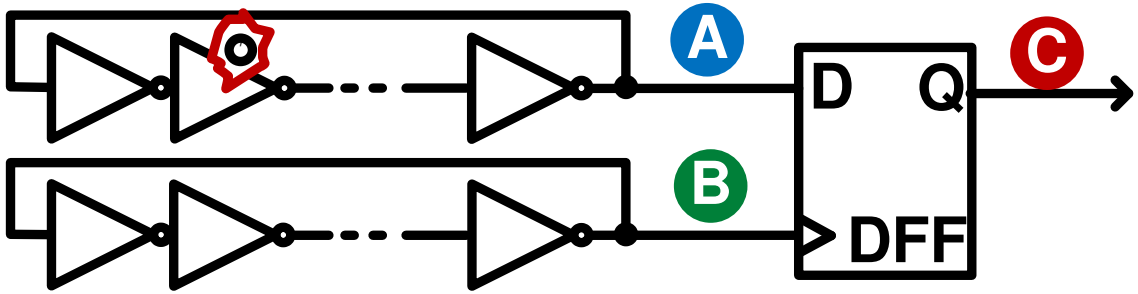


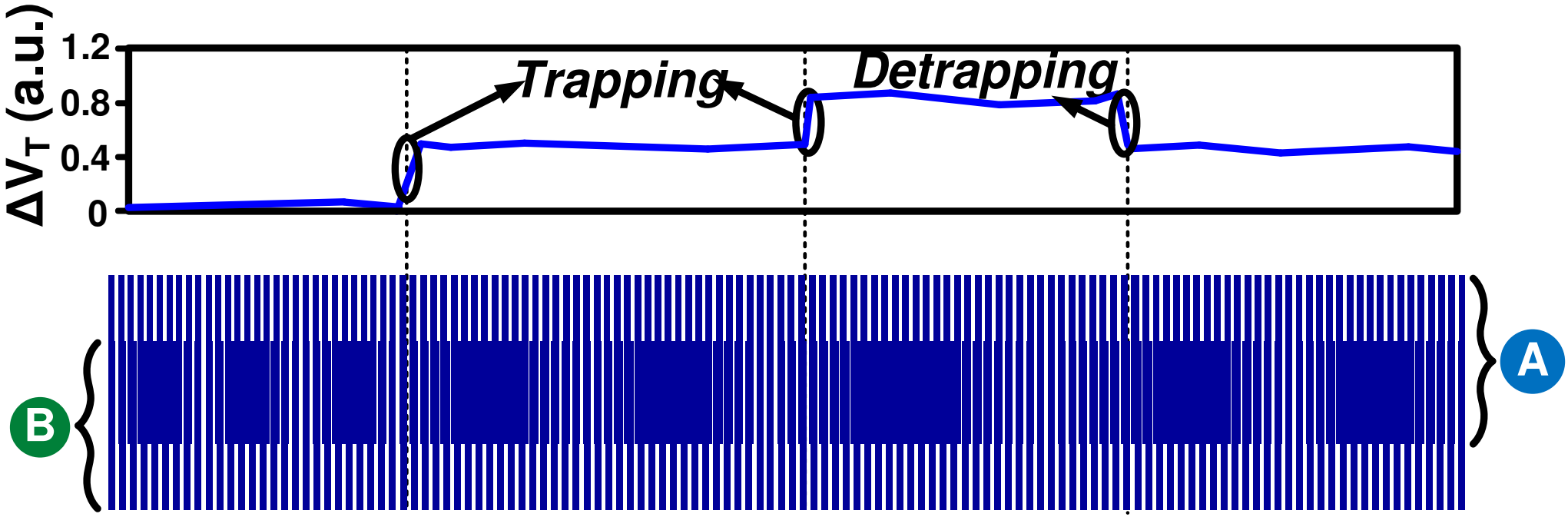




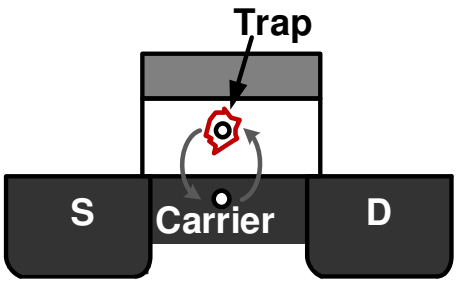
Silicon Odometer Beat Frequency Ckt

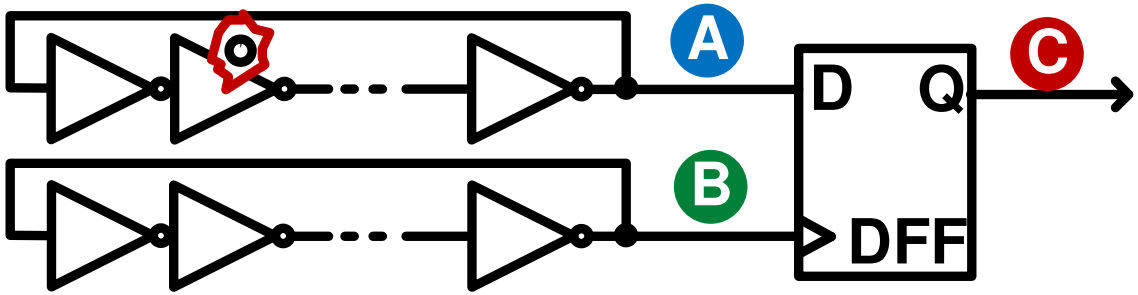


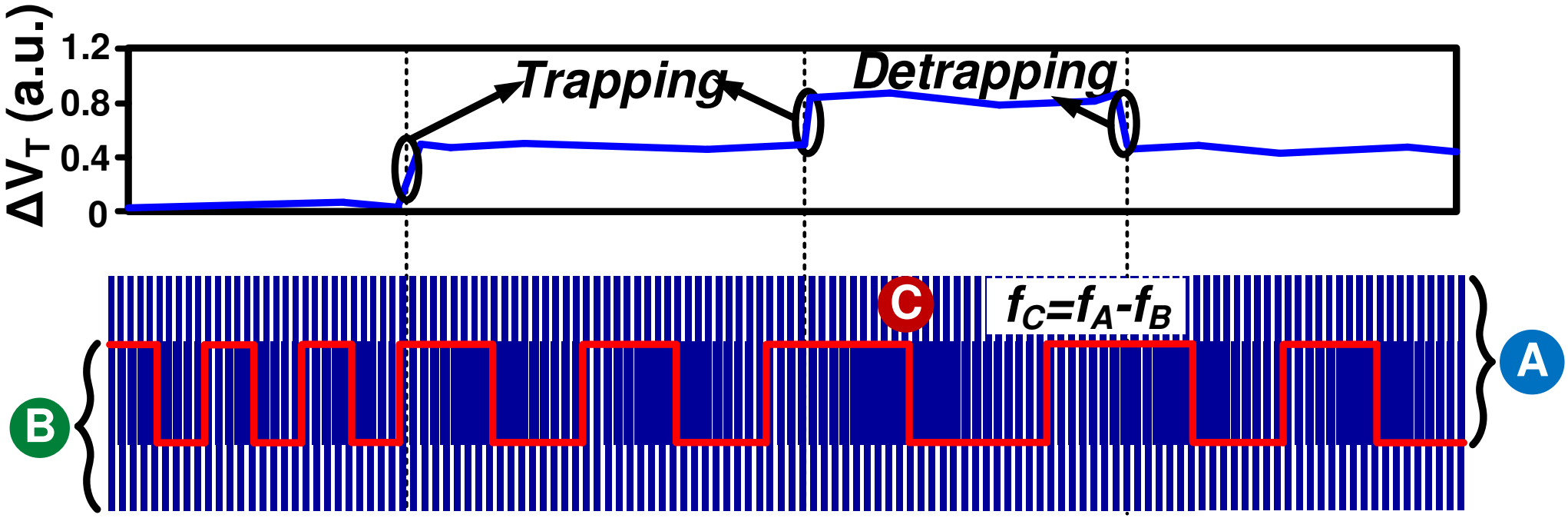




Silicon Odometer Beat Frequency Ckt

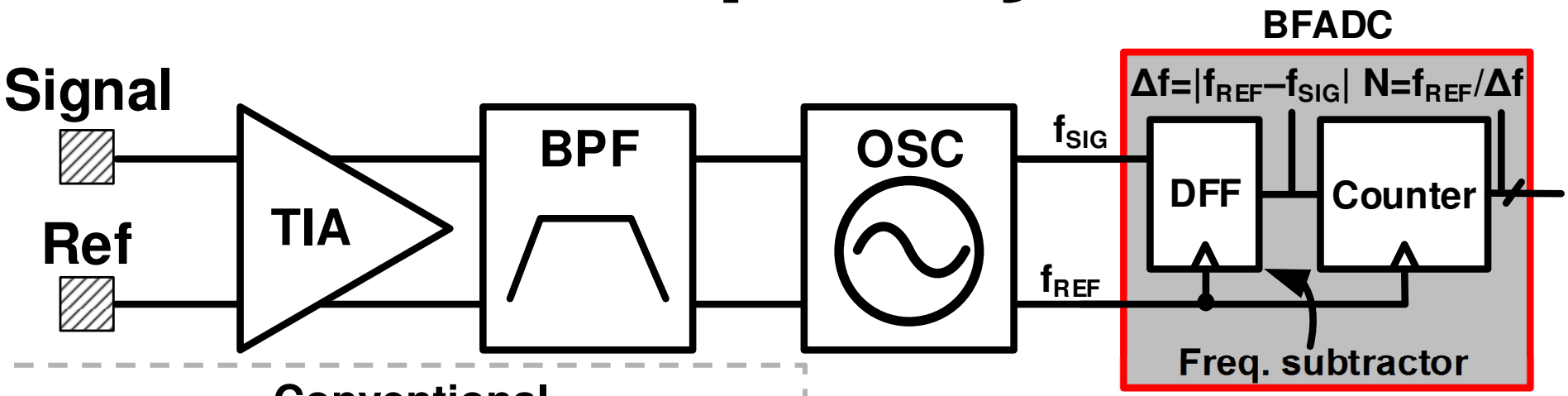


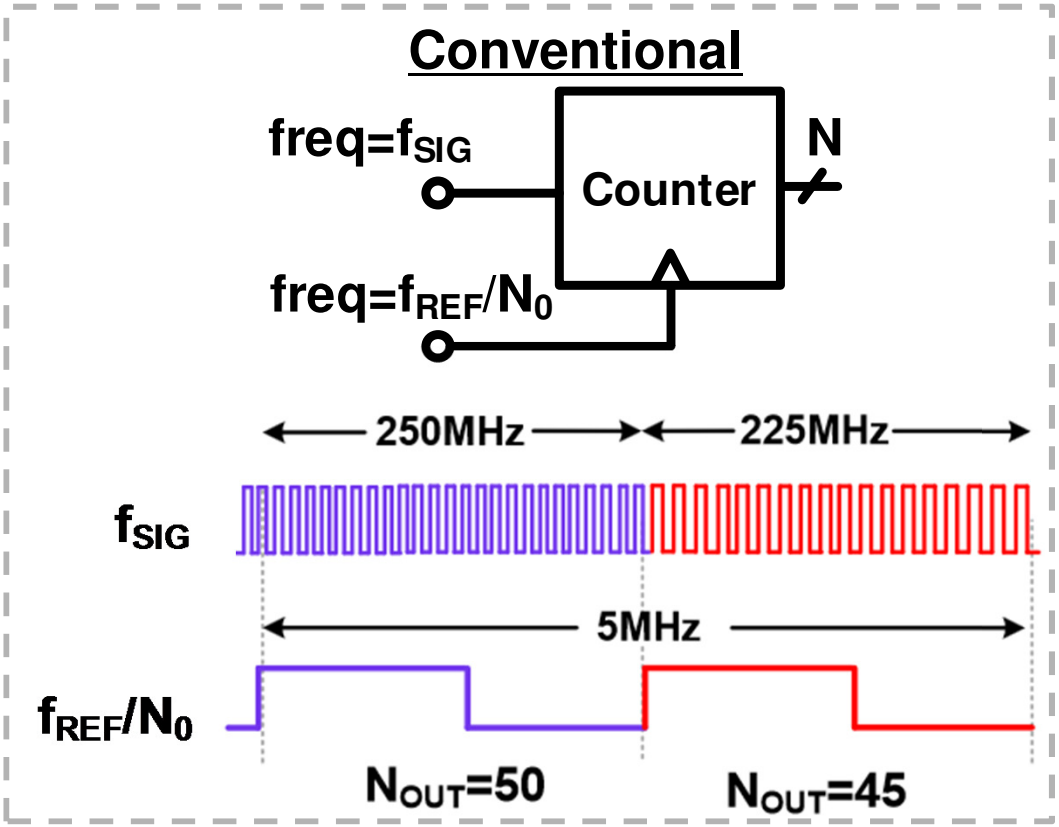


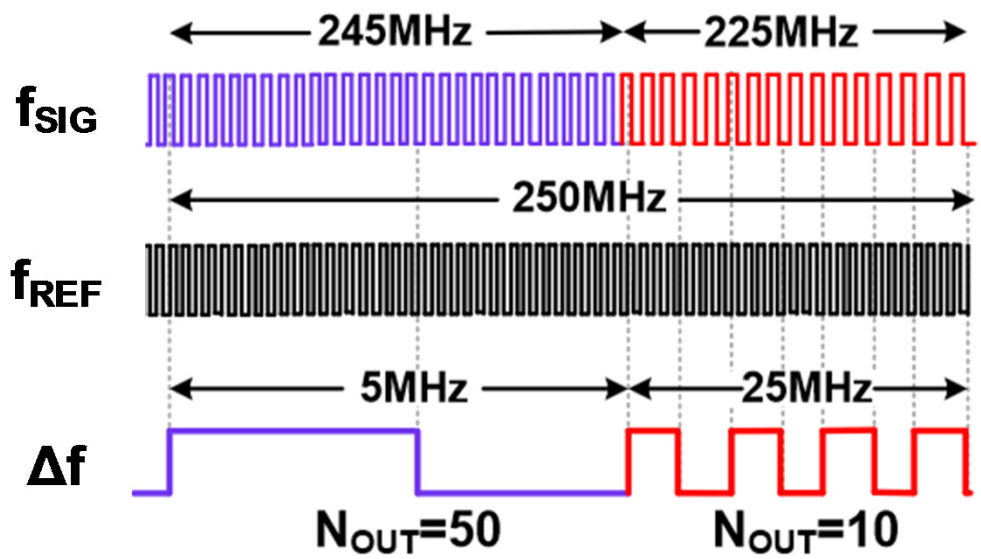


- **Sub-ps resolution + sub-µs measurement time**

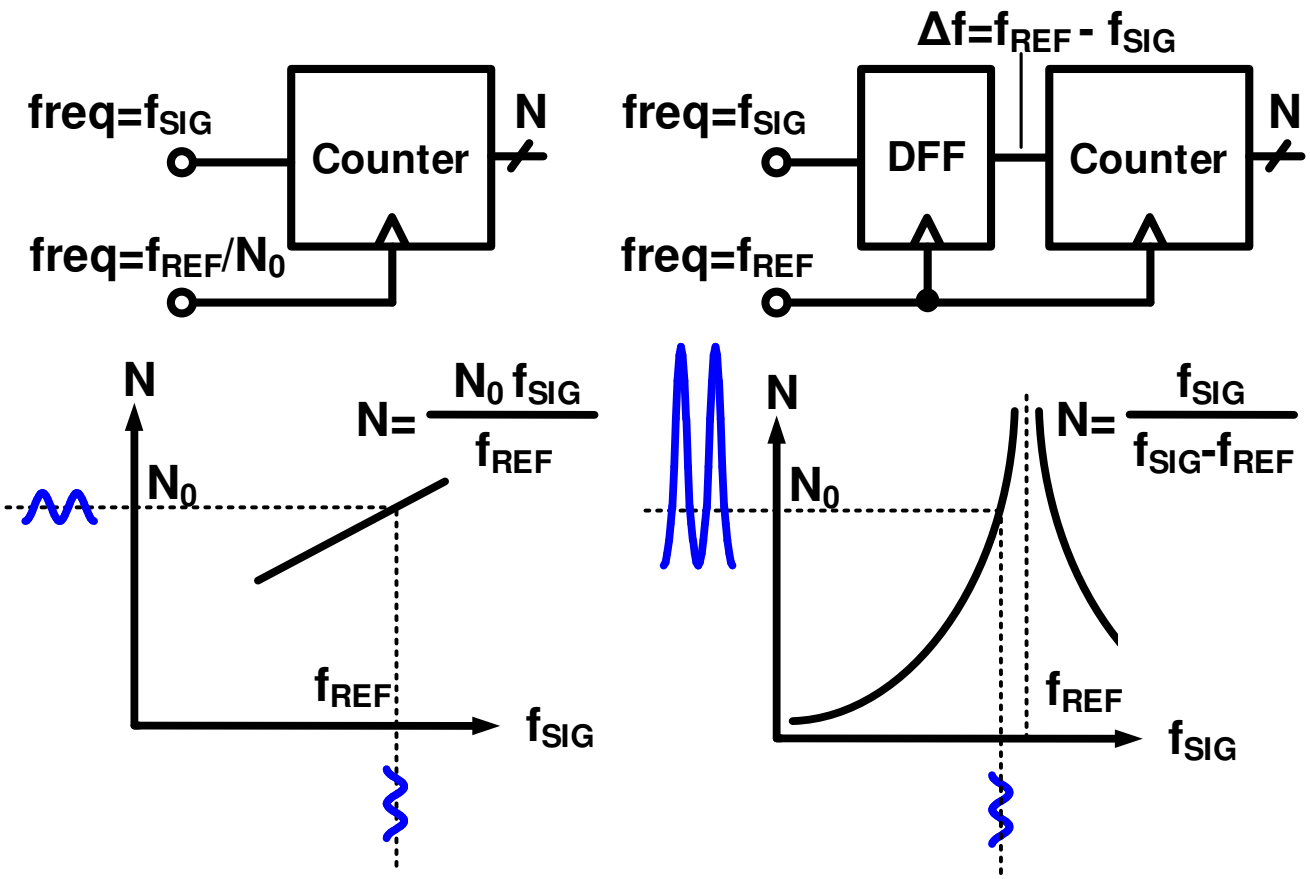
Beat Frequency ADC







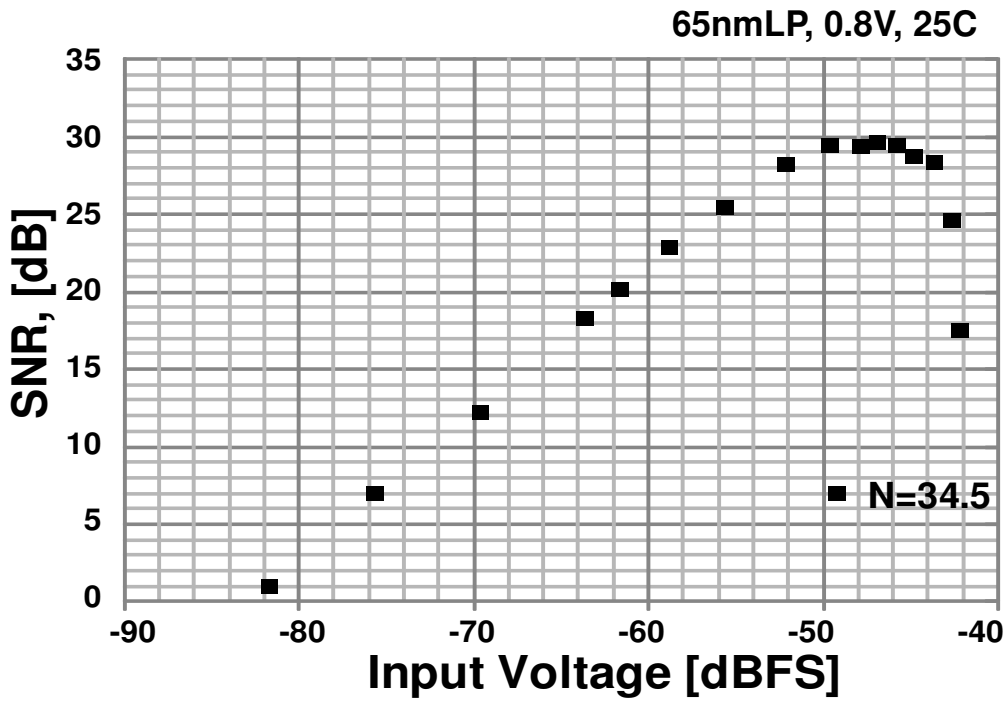
Linear vs BFADC Transfer Function

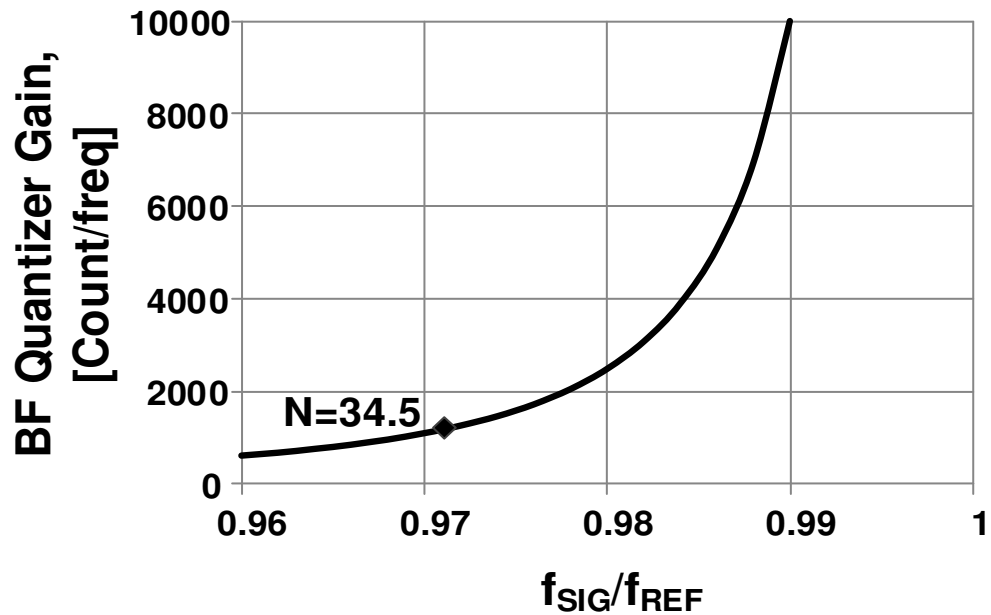


N_0	Linear Quantizer	BF Quantizer (This work)
50	50	$49^2 = 2401$
100	100	$99^2 = 9801$
200	200	$199^2 = 39601$

(Table shows quantizer gain normalized to f_{REF})

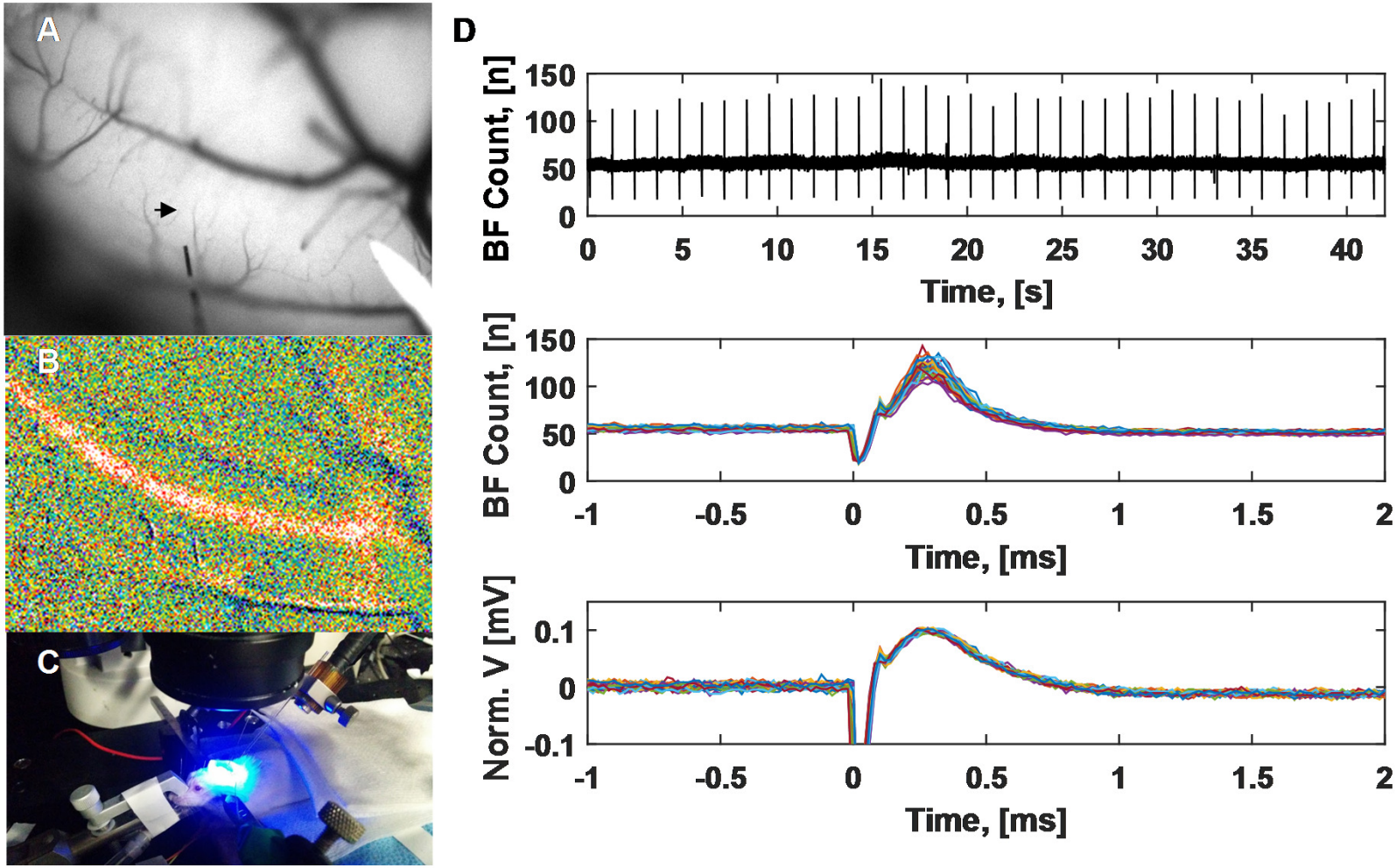
Bench-top Performance





- F_{in} = 416Hz
- N = 34.5 gain is ~1100
- 0dBFS = 1.2V

In-vivo Results



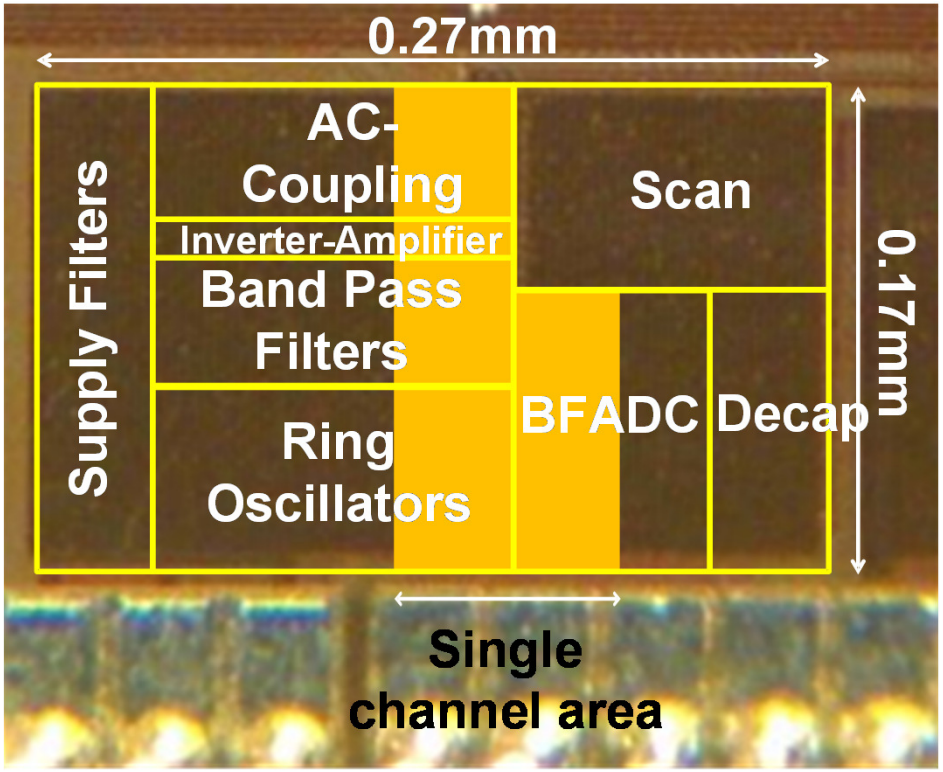
- **Purkinje fibers in anesthetized WT/FVB mouse**
- **Tungsten stimulation electrode**
- **Glass micropipette recording electrode**
- **Flavoprotien Autofluorescence to locate fibers**

Comparison Table

Parameters	This Work	[11]JSSC'17	[12]JSSC'16	[13]CICC'15	[5]CICC'15	[14]TCAS-I'15
ADC Type	Beat Freq.	VCO	CT-$\Delta\sum$	VCO-$\Delta\sum$	1-Step BF	Incr.-$\Delta\sum$
Process/Supply	65nm/0.8V	40nm/1.2V	130nm/1.2V	130nm/1.2v	65nm/1.2V	180nm/1.2V
Bandwidth	4.5kHz	200Hz	15MHz	1.7MHz	1.2KHz	4kHz
Sampling Rate	50kHz	3kHz	500MHz	250MHz	50kHz	8kHz
In_{0db} [dBFS]*	-84	-75	-80	-75	-86	-85
$SNDR_{1mVpp}$ [dB]**	20.9	35	20	14	22	22
$ENOB_{1mVpp}$ [b]**	3.17	5.52	3.03	2.03	3.36	3.36
Power	52uW	7uW	20mW	910uW	34uW	34.8uW
FoM @ F_{in} [pJ/Conv]***	683 @ 900Hz	380 @ 3Hz	81.4 @ 4.15MHz	66.6 @ 500kHz	1252 @ 300Hz	424 @ 175Hz
Chip Area [mm^2]	0.046	2.16	1.3	0.04	0.096	0.0564
Area/Ch [mm^2] (Relative)	0.0094 (1x)	0.135 (14.5x)	1.3 (138x)	0.04 (4.3x)	0.078 (8.3x)	0.0564 (5.9x)
Experiment	*In-vivo*	*In-vitro*	-	-	-	-

**Input Amplitude at SNDR=0dB, 0dBFS=1.2V* ***Reported at V_{in}=1mV_{pp}* ***FoM =Power/(2*BW*2^{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**

This research was supported in part by NSF IGERT grant DGE-1069104 and NIH grant NS 18338.