Ring Amplifiers for Switched Capacitor Circuits

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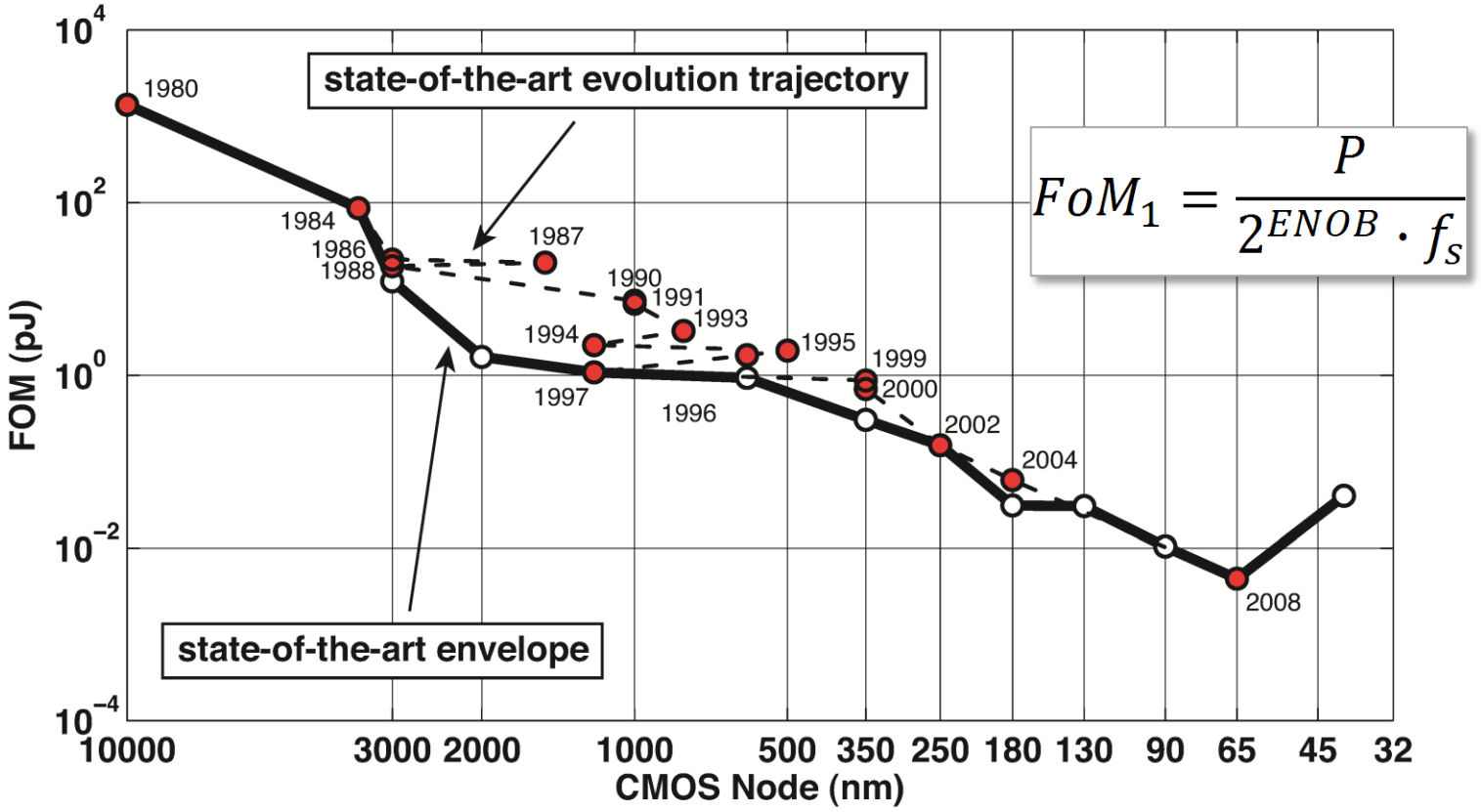
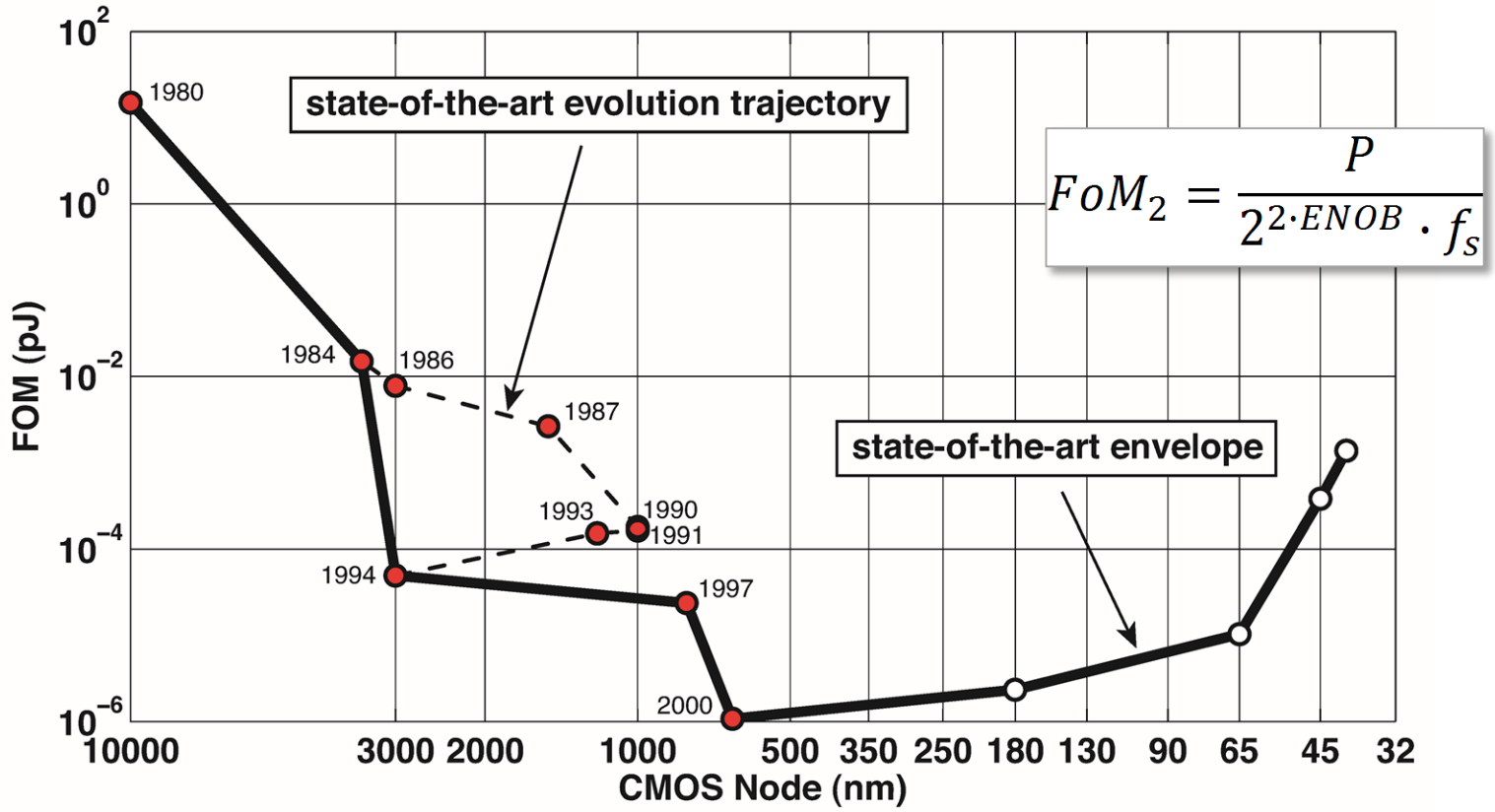
A/D Scaling Trends: FoM_1



- Performance continues to scale well with process
- FoM_1 best describes low/medium-resolution A/D performance

[Jonsson, NORCHIP 2010]

A/D Scaling Trends: FoM_2



- FoM_2 best describes high-resolution A/D performance
- Noise floor degrades faster than power/speed improves.

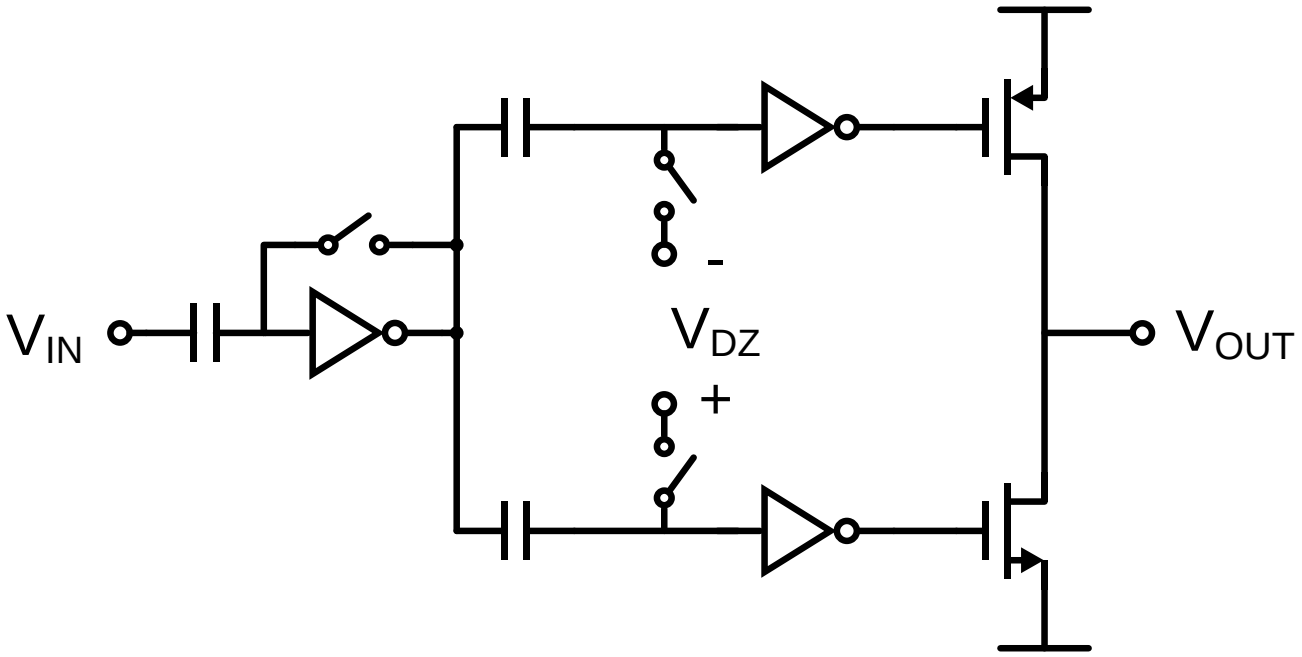
[Jonsson, NORCHIP 2010]

Beating the Trend

We need amplifiers that are:

- Immune to SNR loss from low-voltage, degrading r_o
- Exploit digital scaling benefits
- Avoid conventional RC-based settling

Beating the Trend



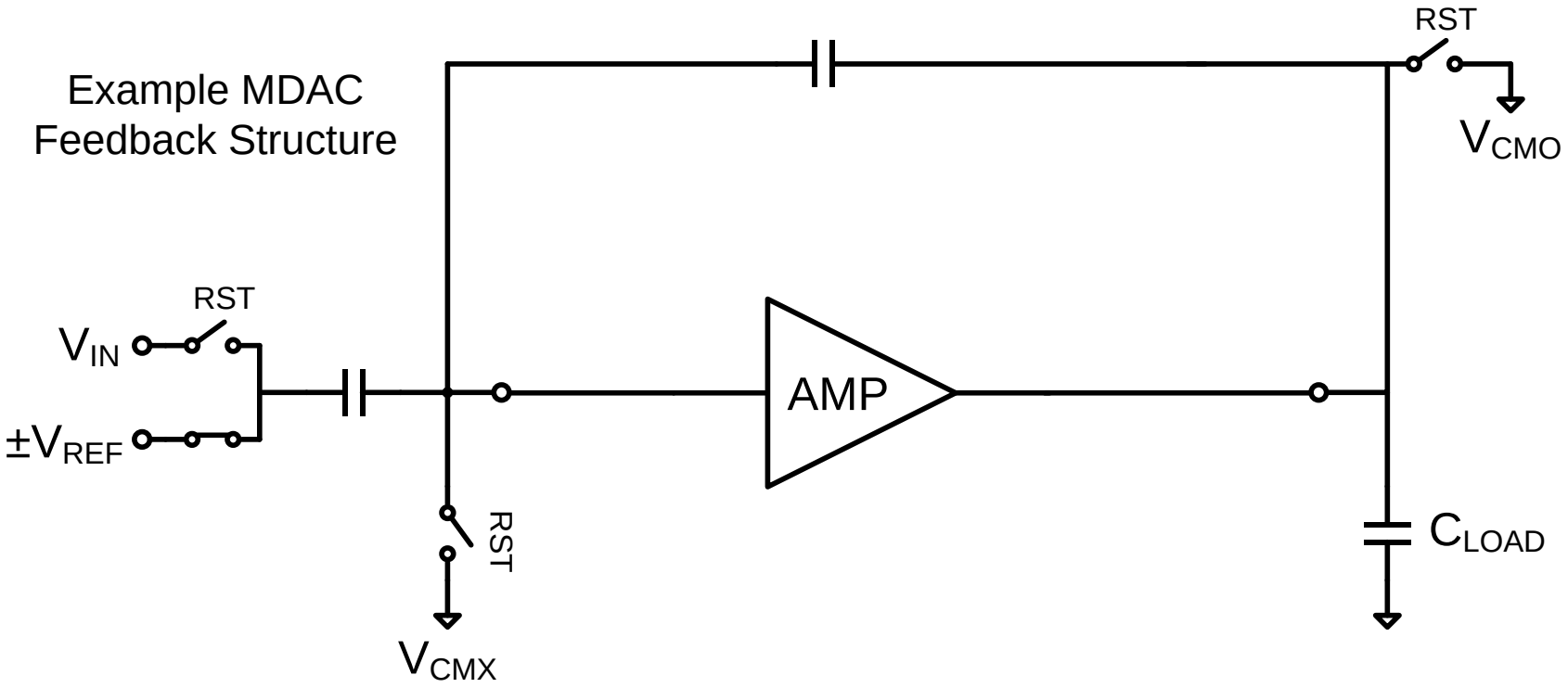
Ring Amplifier

(Ring Amp, RAMP)

Ring Amplification

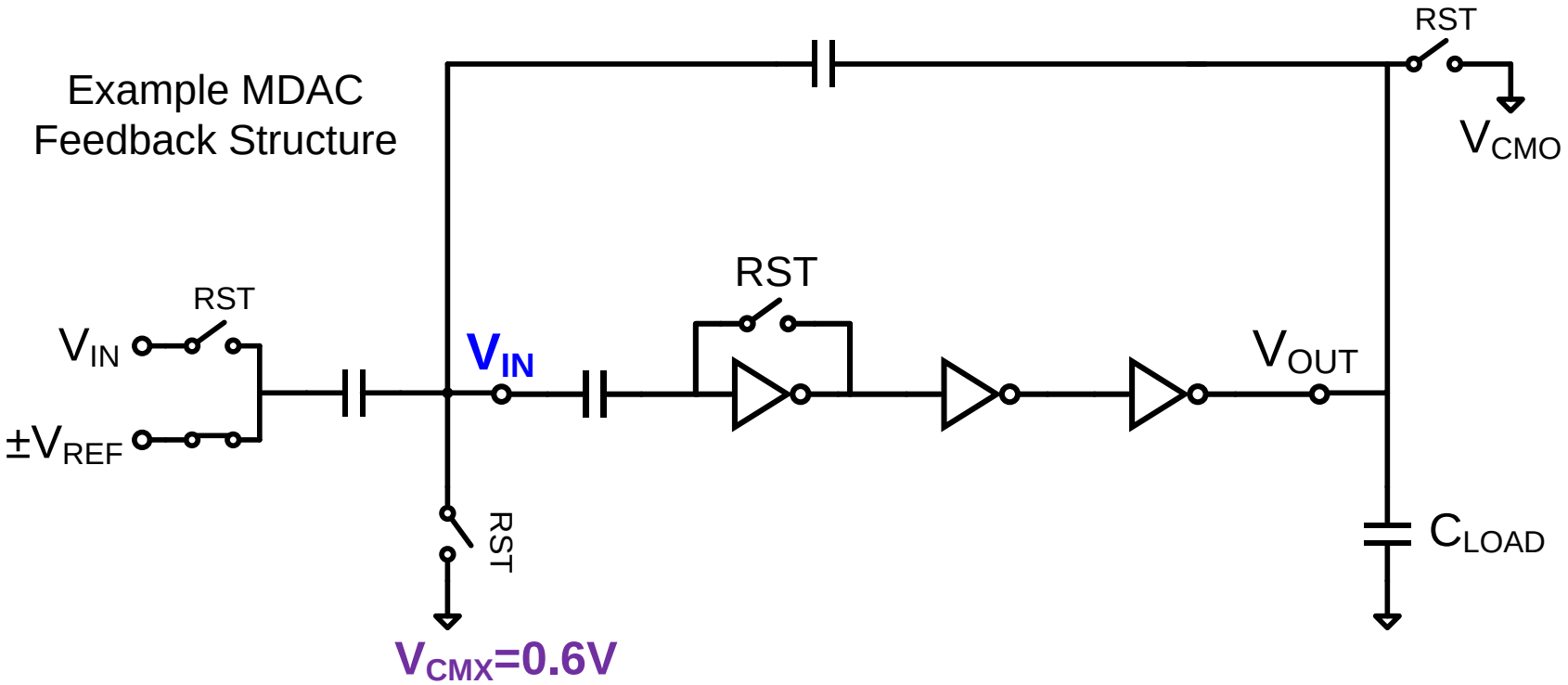
Basic Theory

Ring Amplifier: Basic Theory



- Basic MDAC test structure

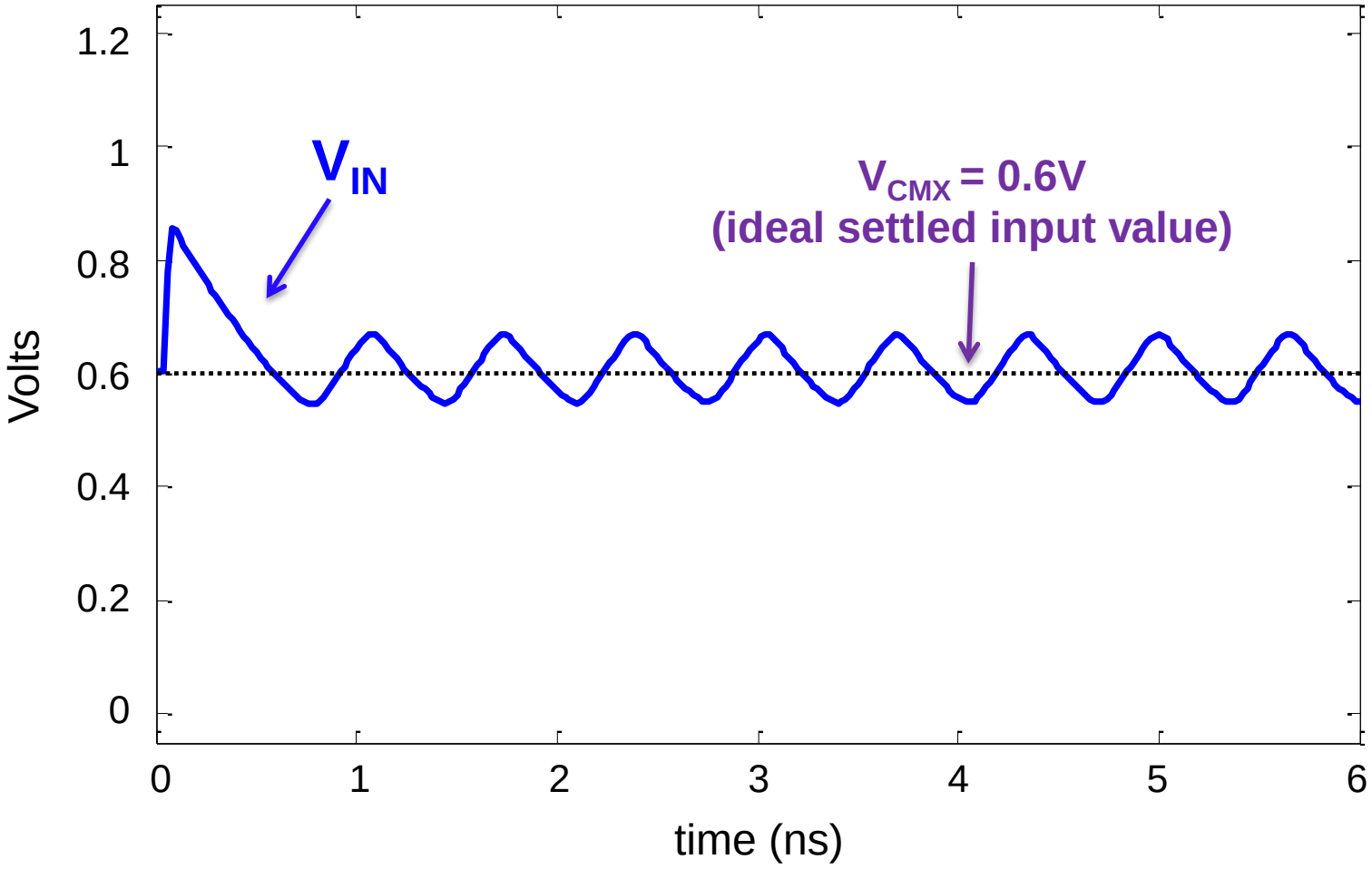
Ring Amplifier: Basic Theory



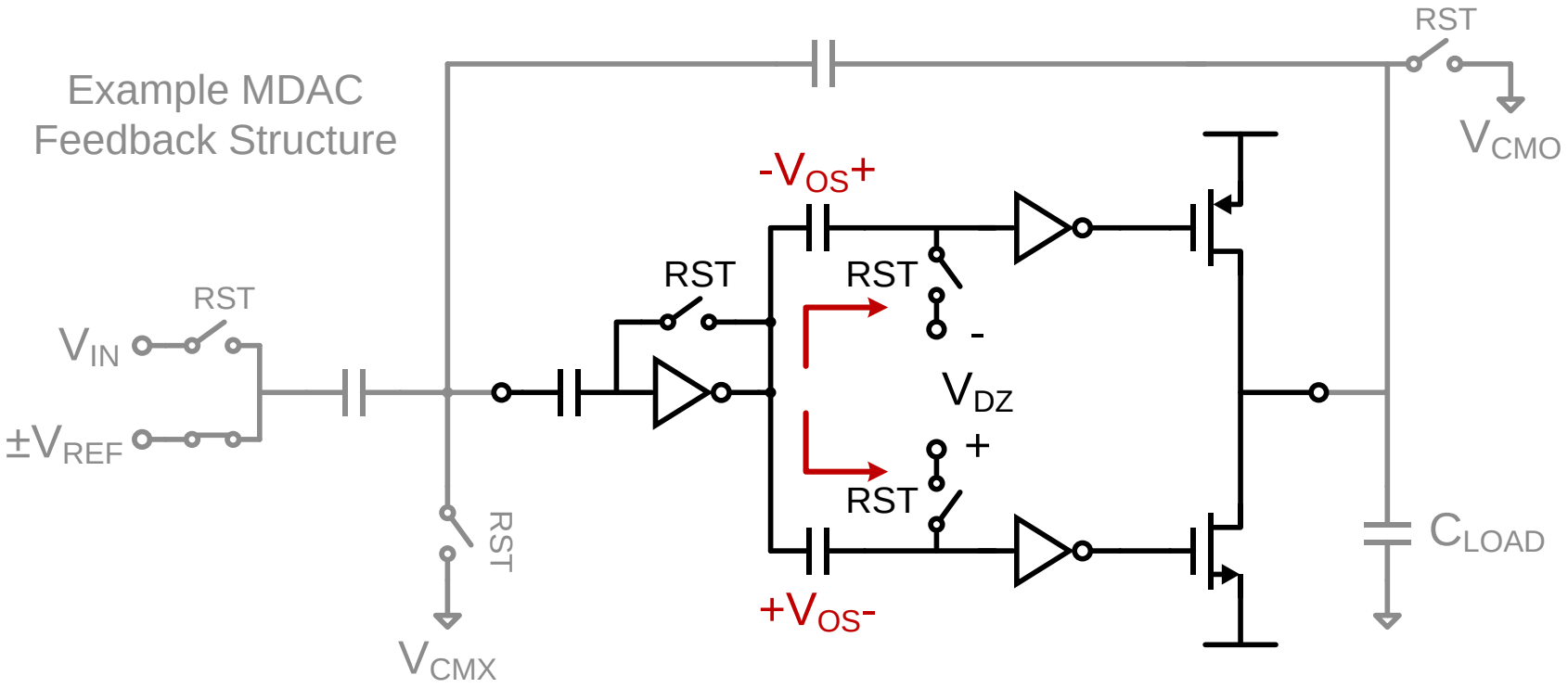
- Ring Oscillator
- Unstable…

  …but will oscillate around the correct settled value

Ring Oscillator Sample Waveform

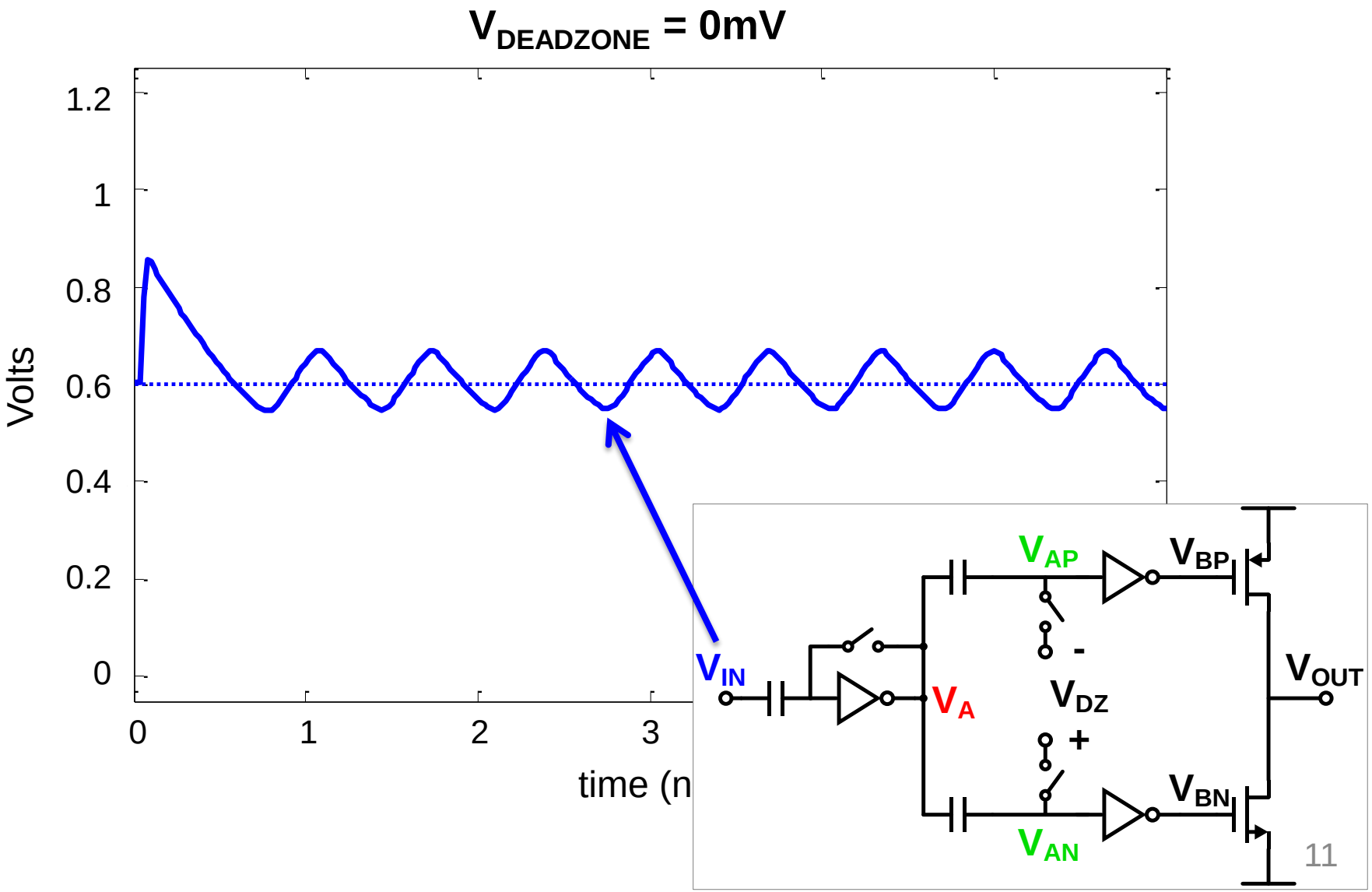


Ring Amplifier: Basic Theory

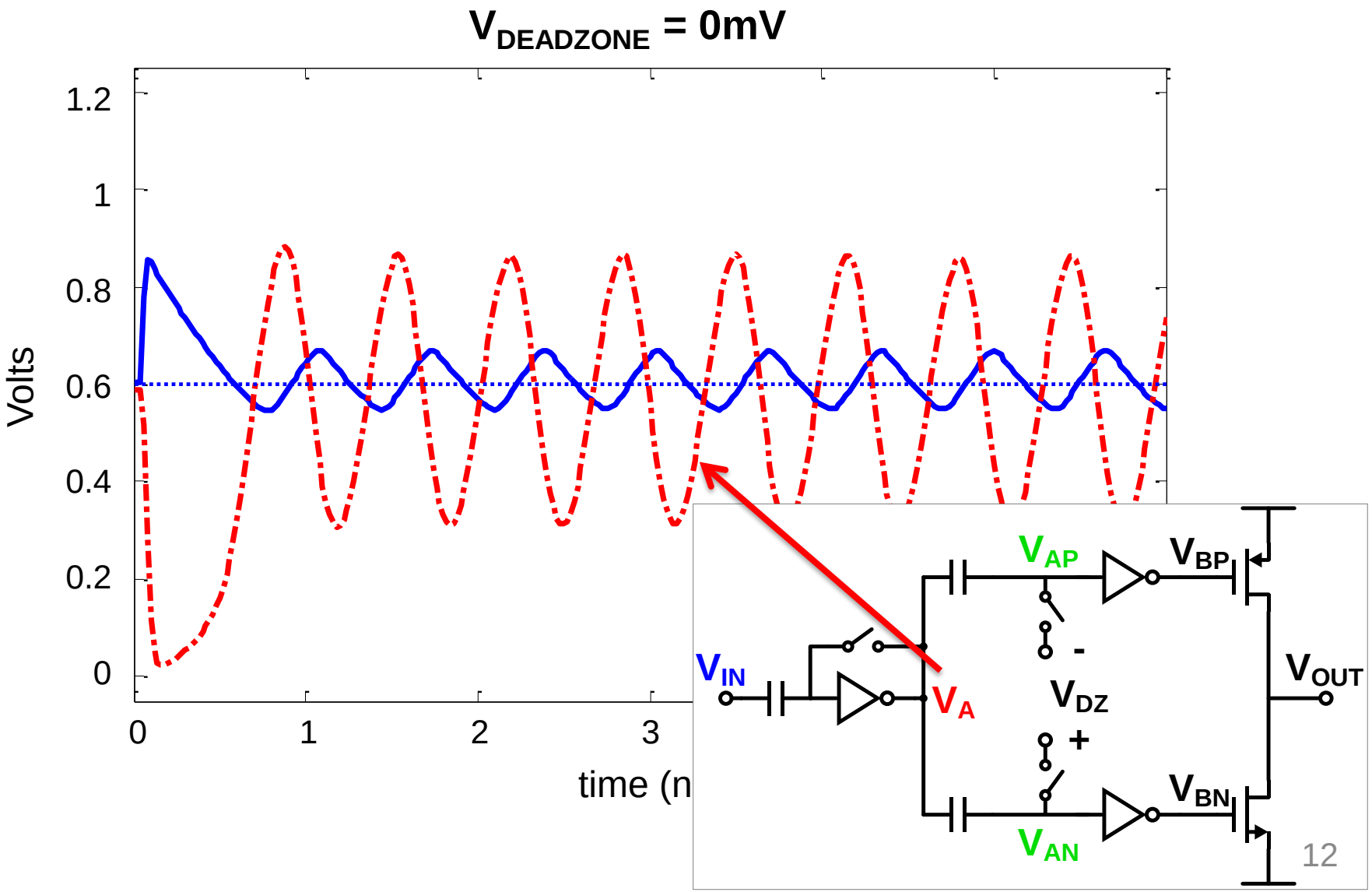


- Split signal into two separate paths
- Embed offset in each path

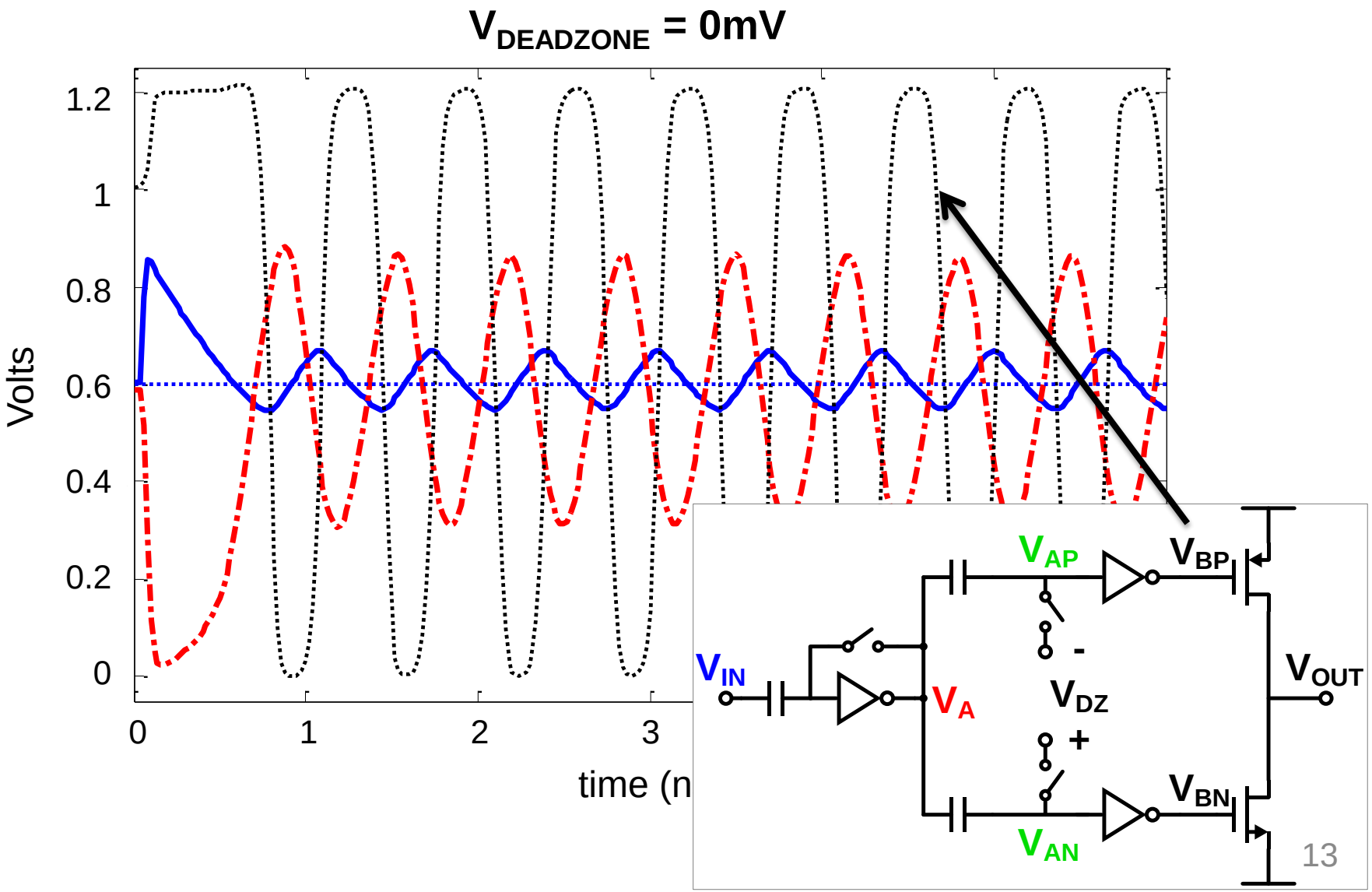
Ring Amplifier Sample Waveform



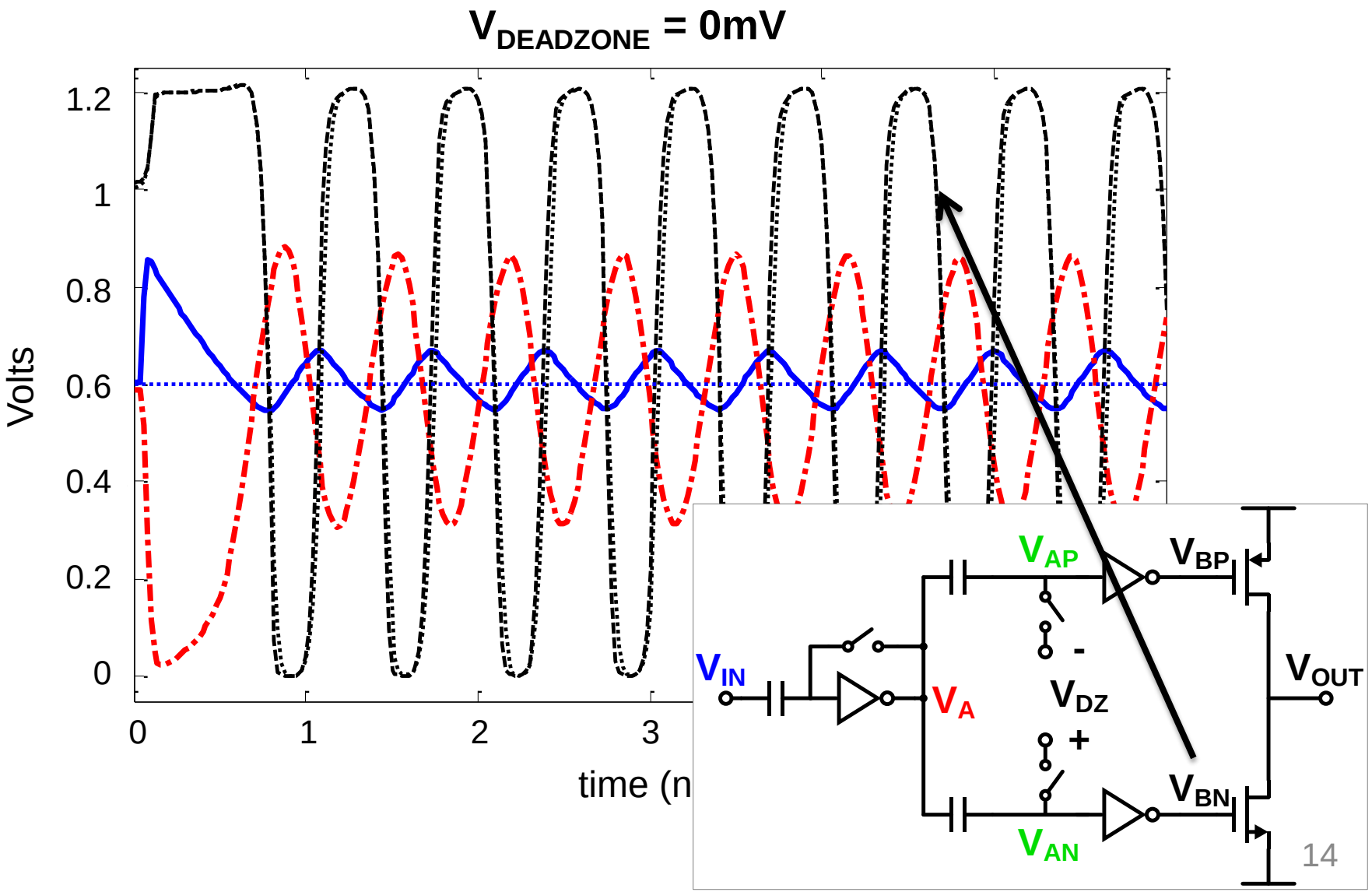
Ring Amplifier Sample Waveform



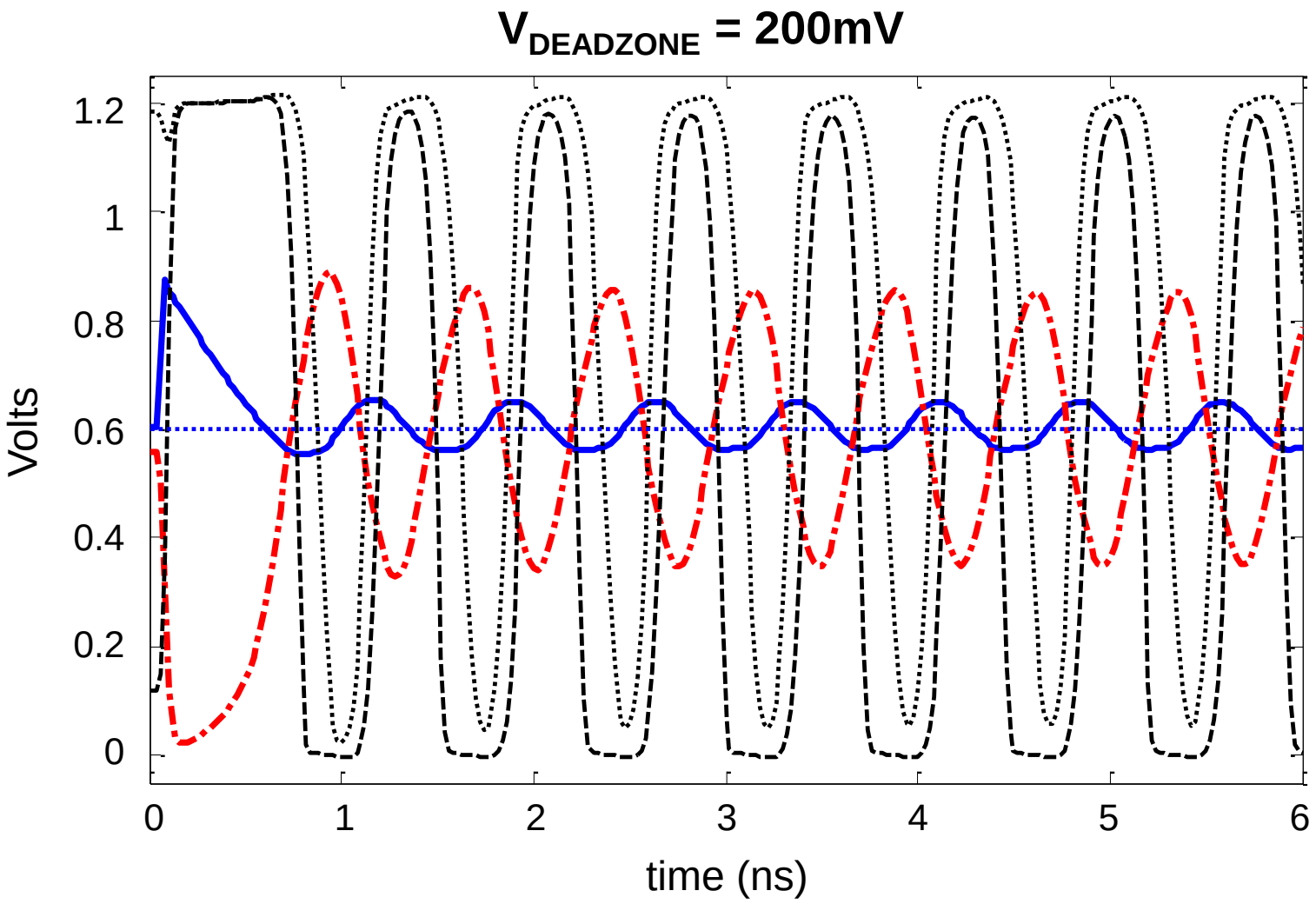
Ring Amplifier Sample Waveform



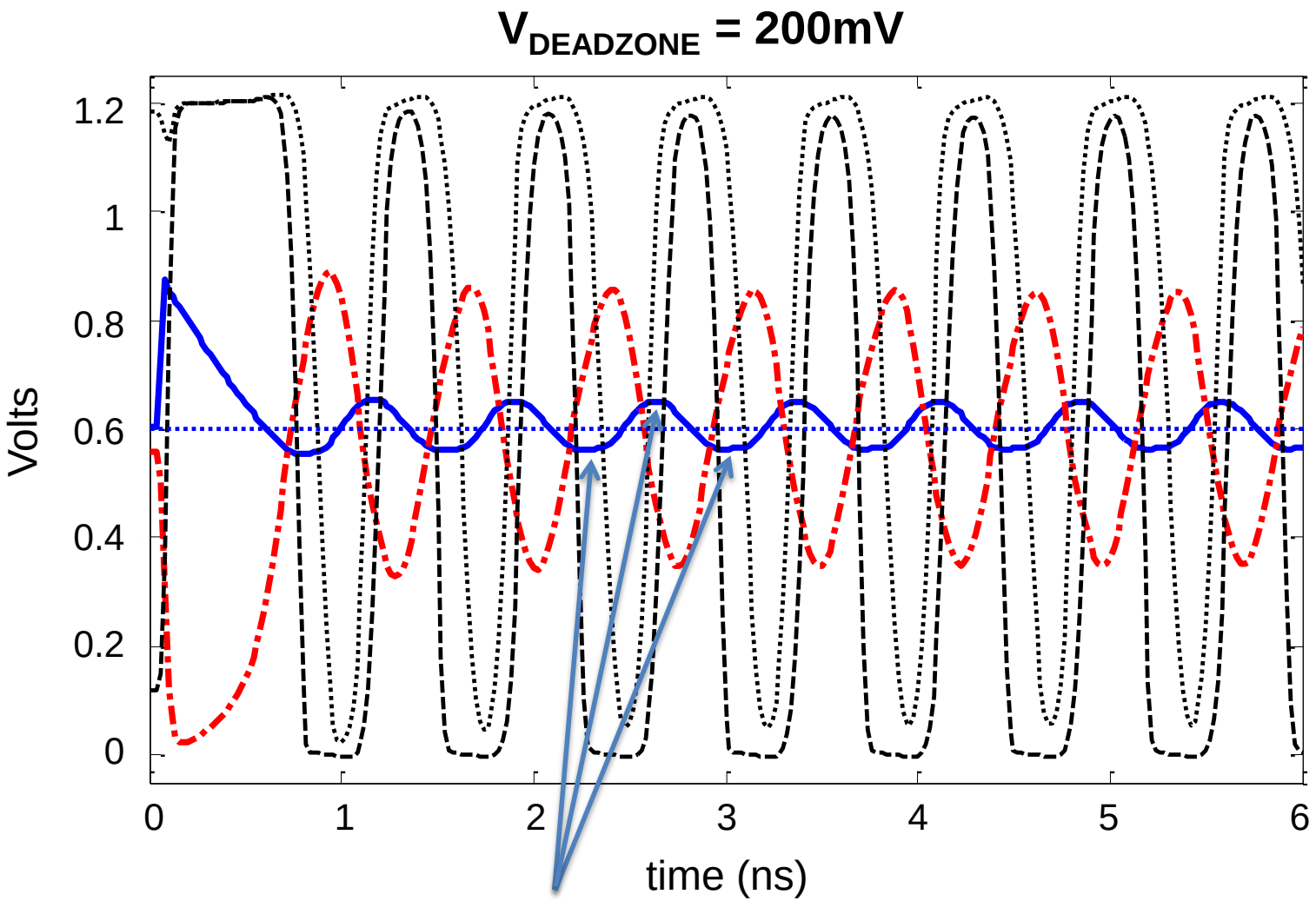
Ring Amplifier Sample Waveform



Ring Amplifier Sample Waveform

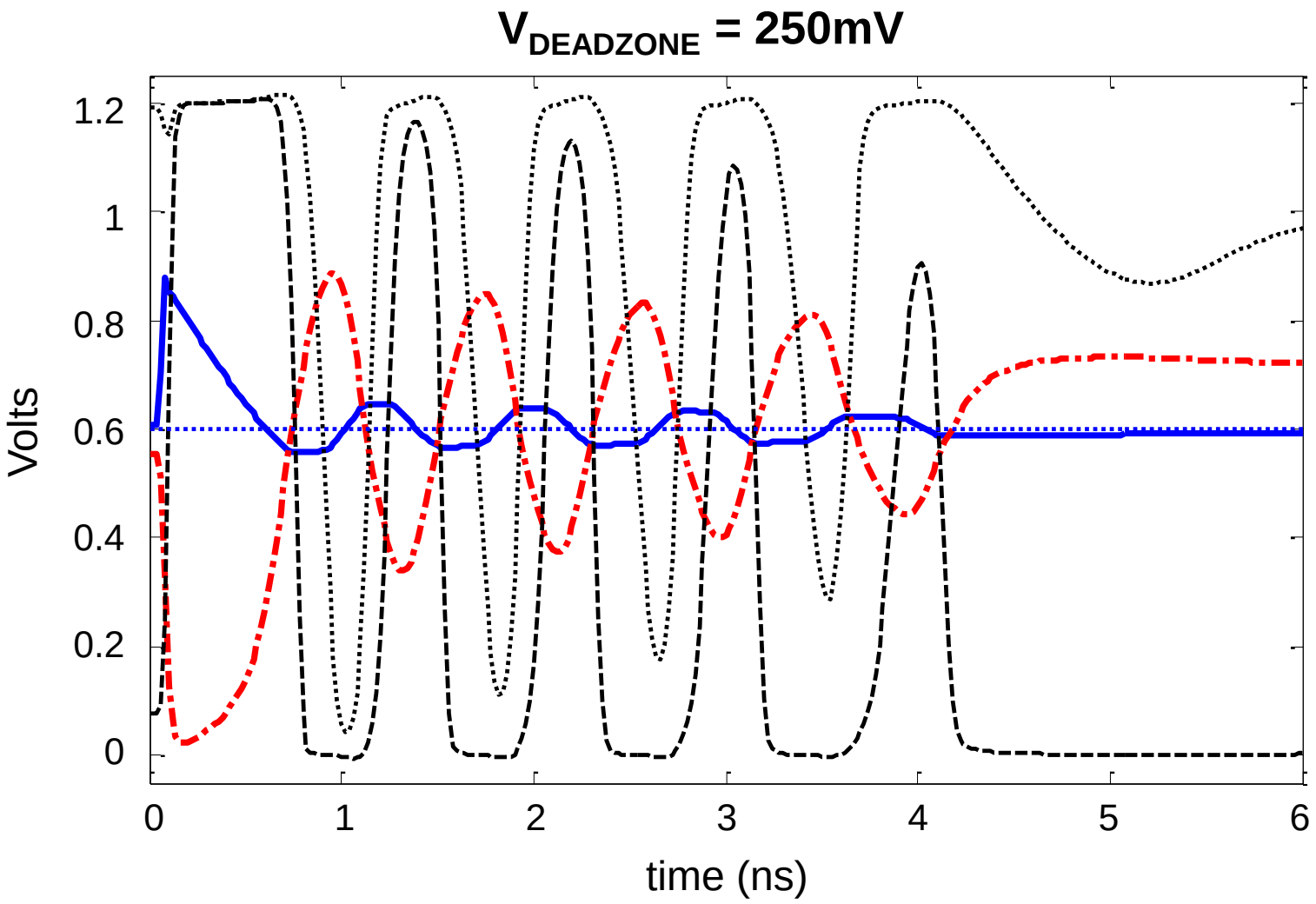


Ring Amplifier Sample Waveform

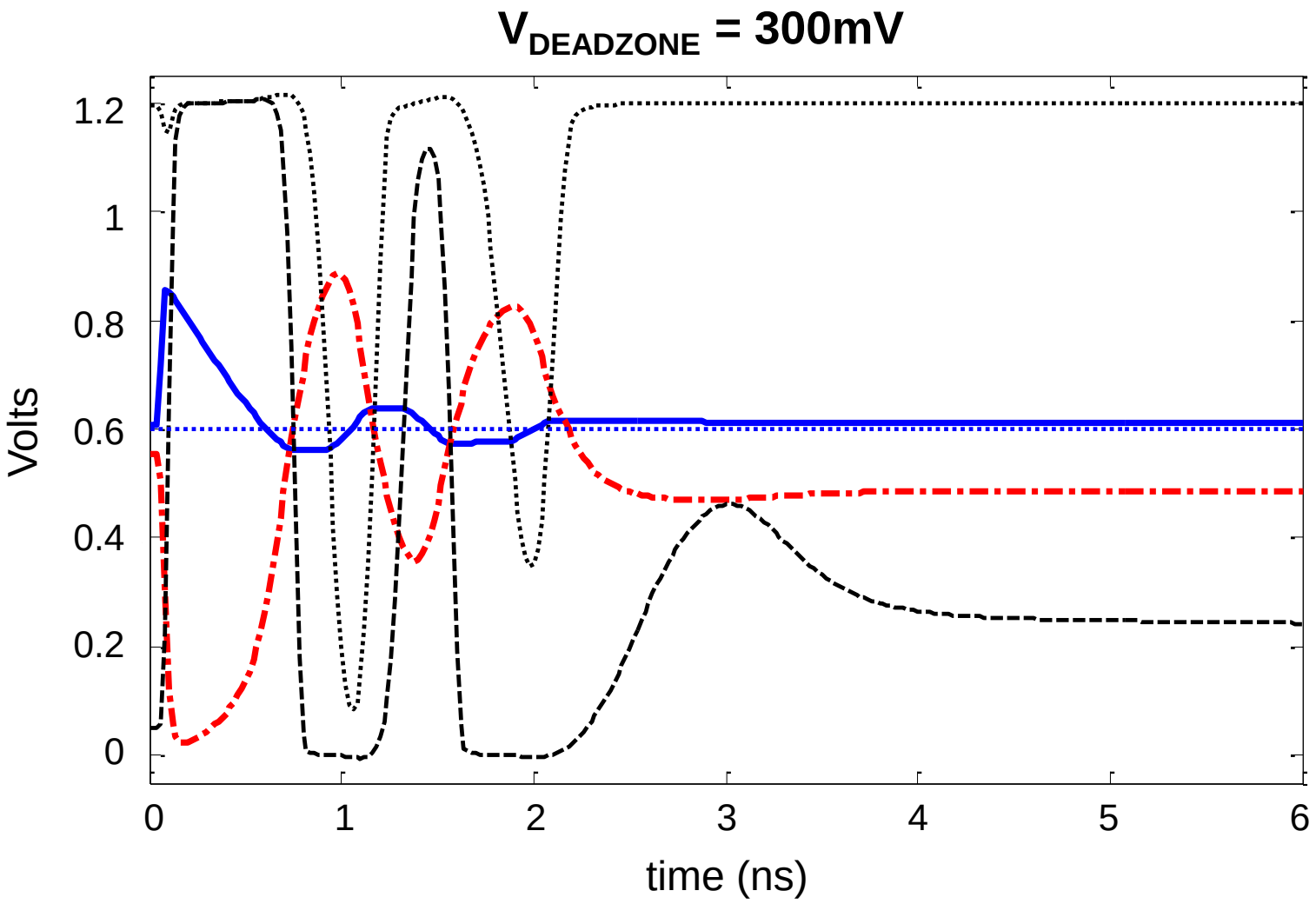


Plateaus form at dead-zone crossings

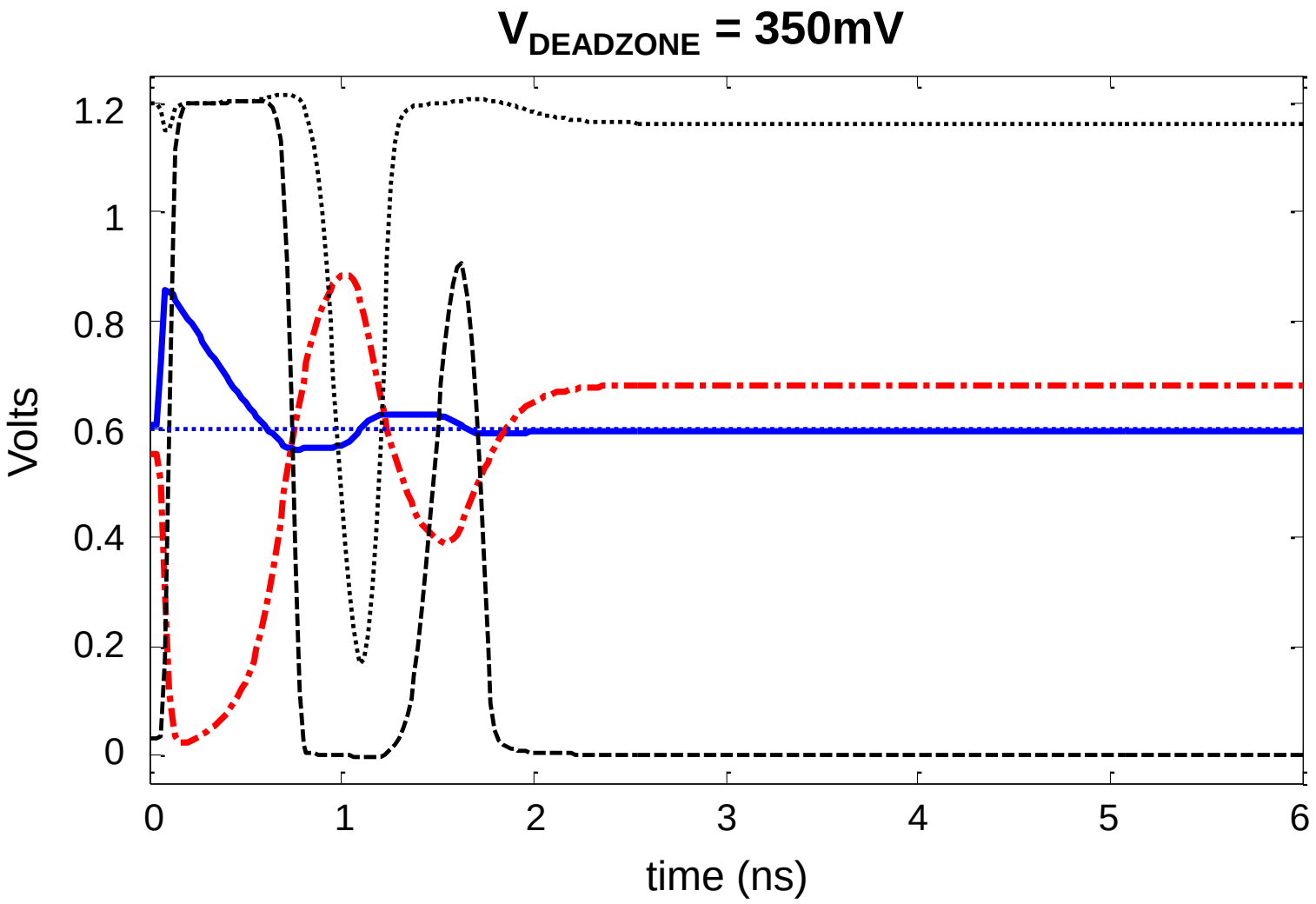
Ring Amplifier Sample Waveform



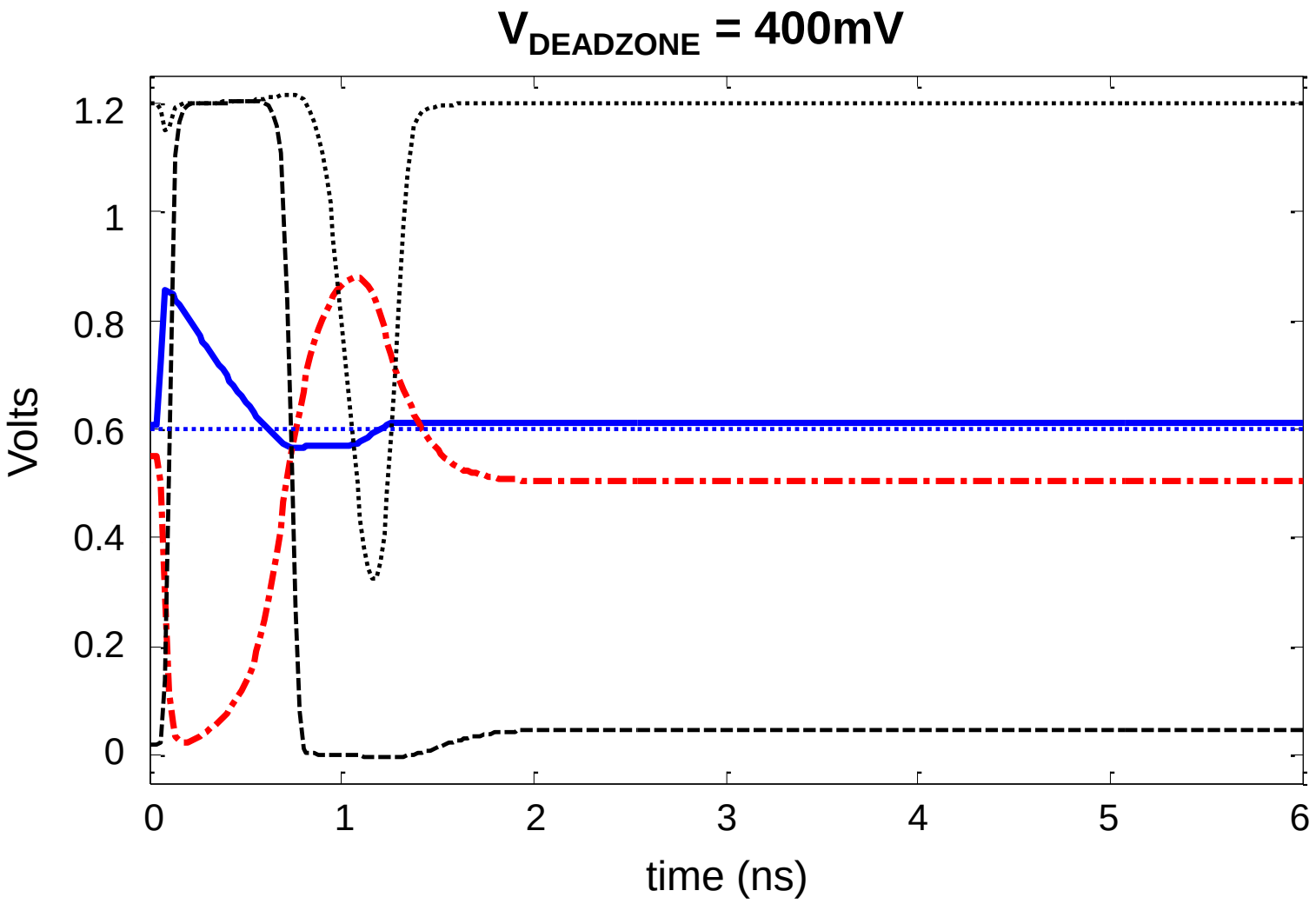
Ring Amplifier Sample Waveform



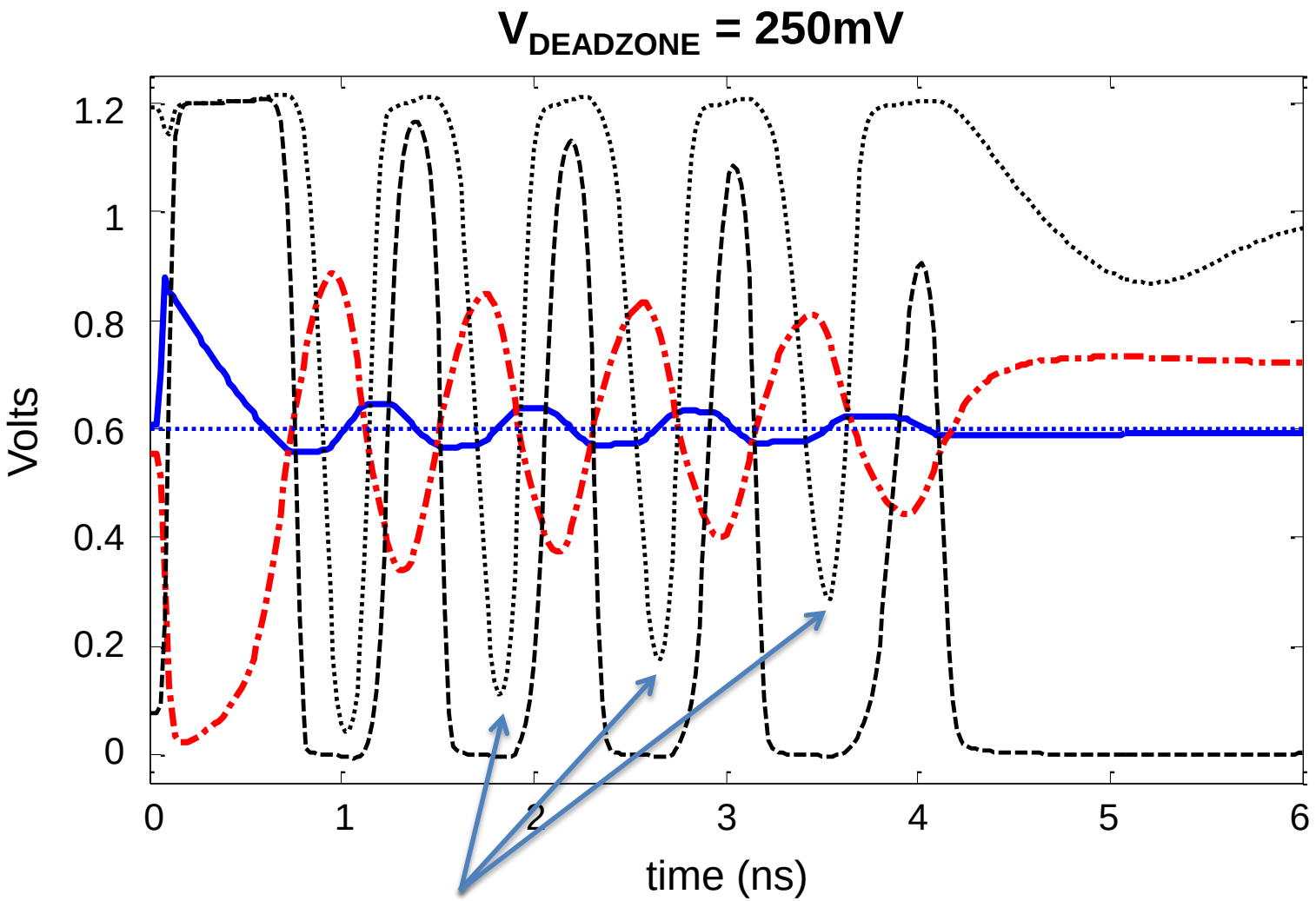
Ring Amplifier Sample Waveform



Ring Amplifier Sample Waveform

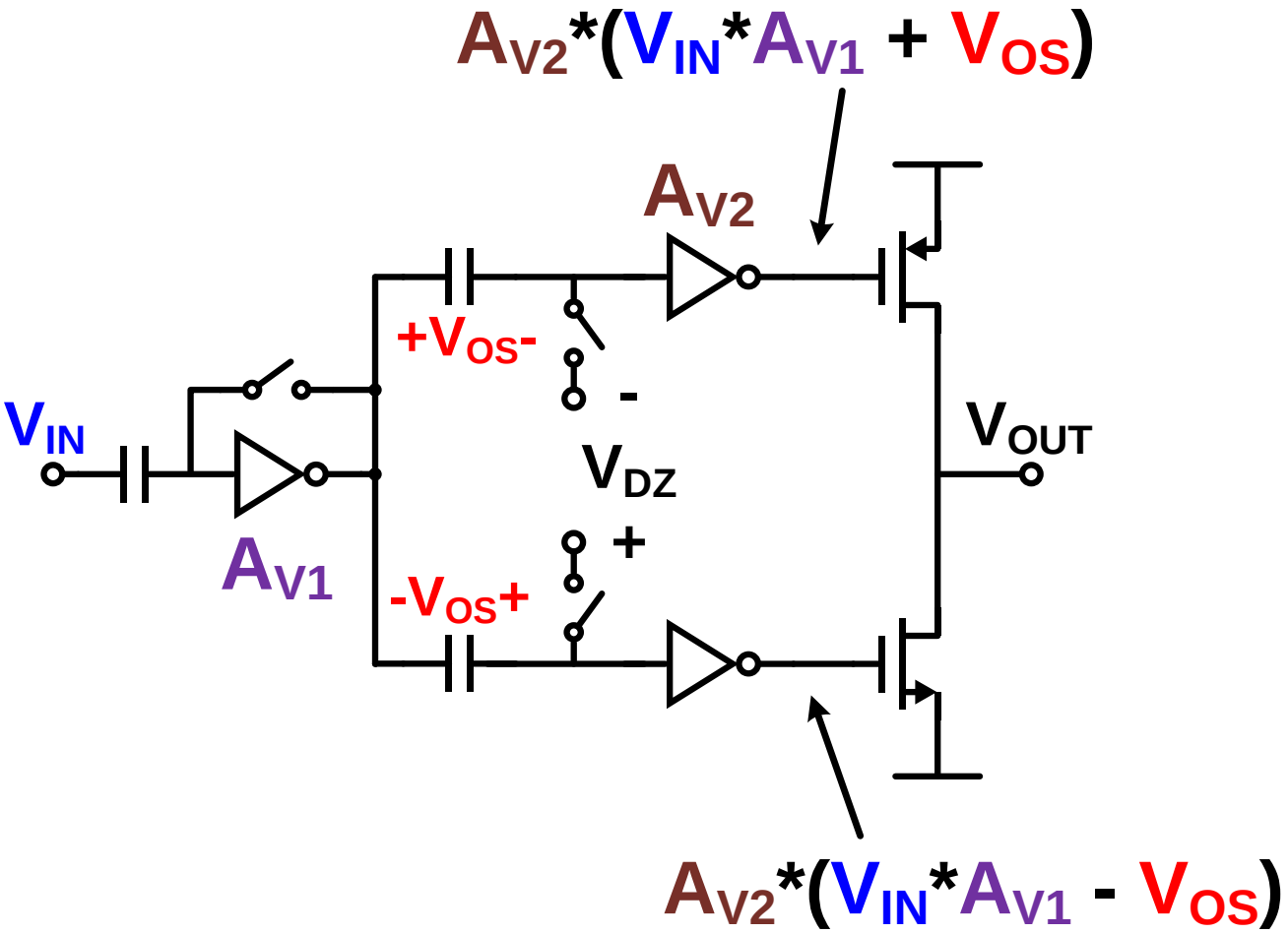


Ring Amplifier Sample Waveform

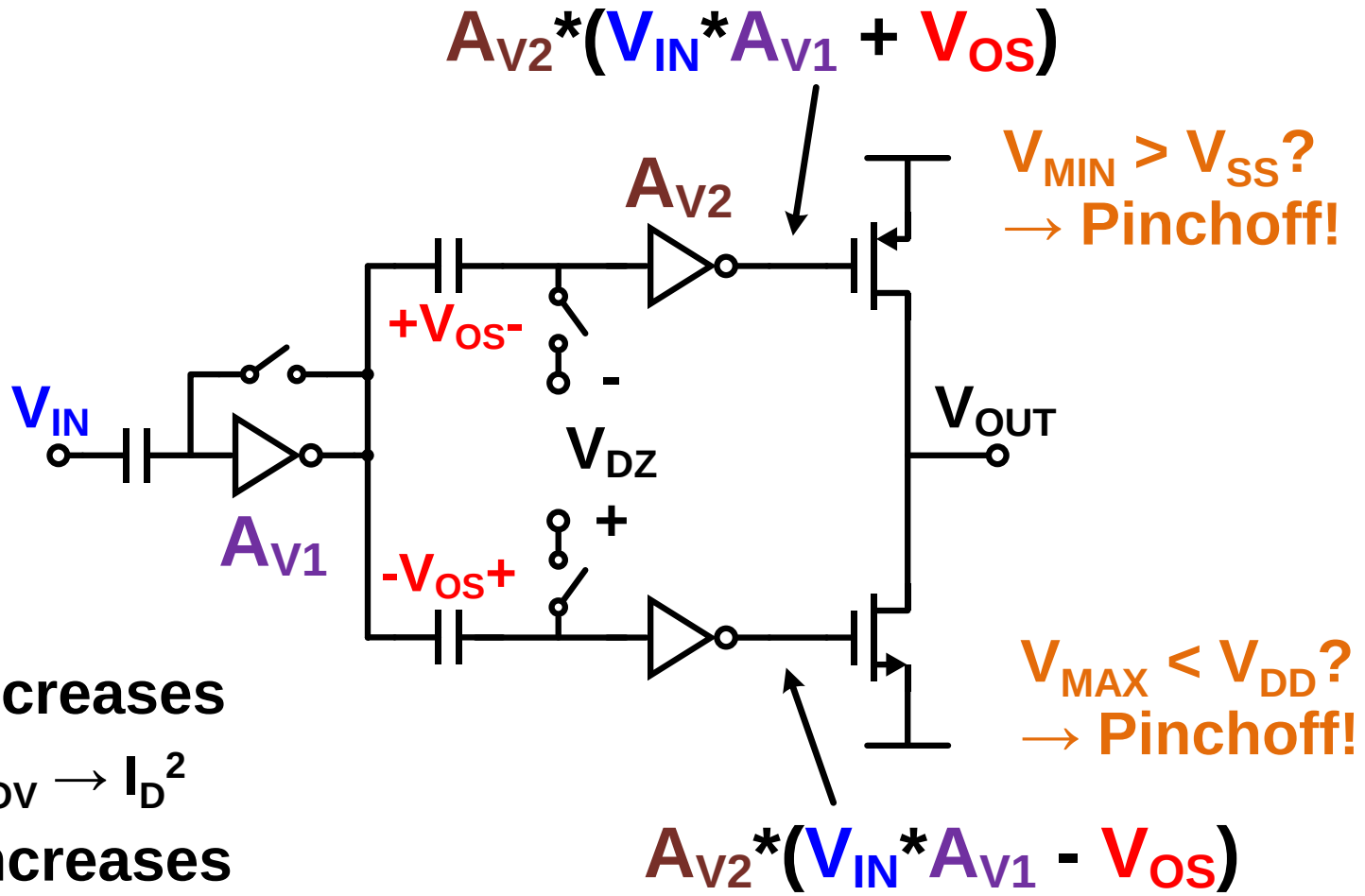


Decreasing V_{OV} reduces slew-rate

V_{OV} Dynamic Pinch-off



V_{OV} Dynamic Pinch-off



- I_D decreases
  - $V_{OV} \rightarrow I_D^2$
- R_o increases
  - Dominant pole → DC

Ring Amplifier Core Benefits

Slew-based charging

- Charges with maximally biased, digitally-switched current sources
  - $V_{OV} = V_{DD}$
  - Can be very small, even for large C_{LOAD}
  - Decouples internal speed vs. output load requirements

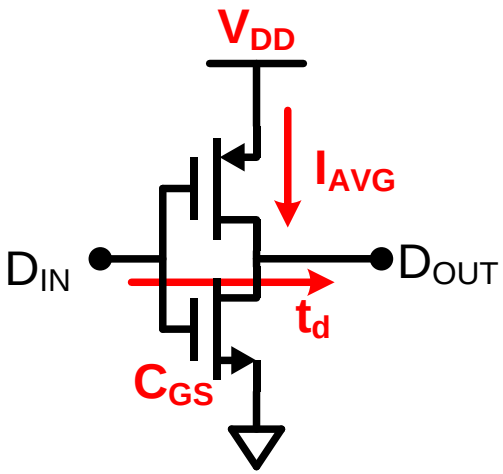
Exponential dynamic stabilization

- Very fast
- Well defined tradeoffs

Ring Amplifier Core Benefits

Scalability (Speed/Power)

- Internal speed/power (mostly) independent of C_{LOAD}
  - Inverter t_d, crowbar current, parasitic C's
  - Digital power-delay product scaling benefits apply
- Power/speed product scales with digital process trends

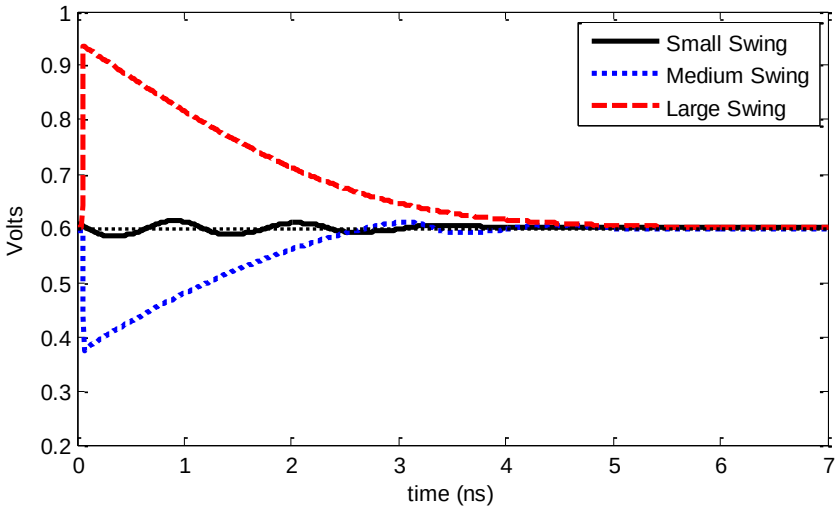


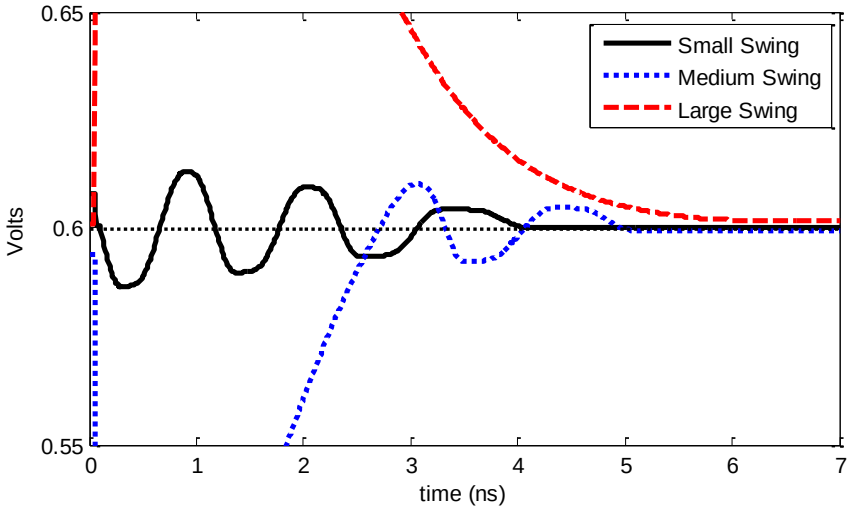
$PDP = V_{DD} \cdot I_{AVG} \cdot t_d = E_{tot}$

Ring Amplifier Core Benefits

Scalability (Output Swing / SNR)

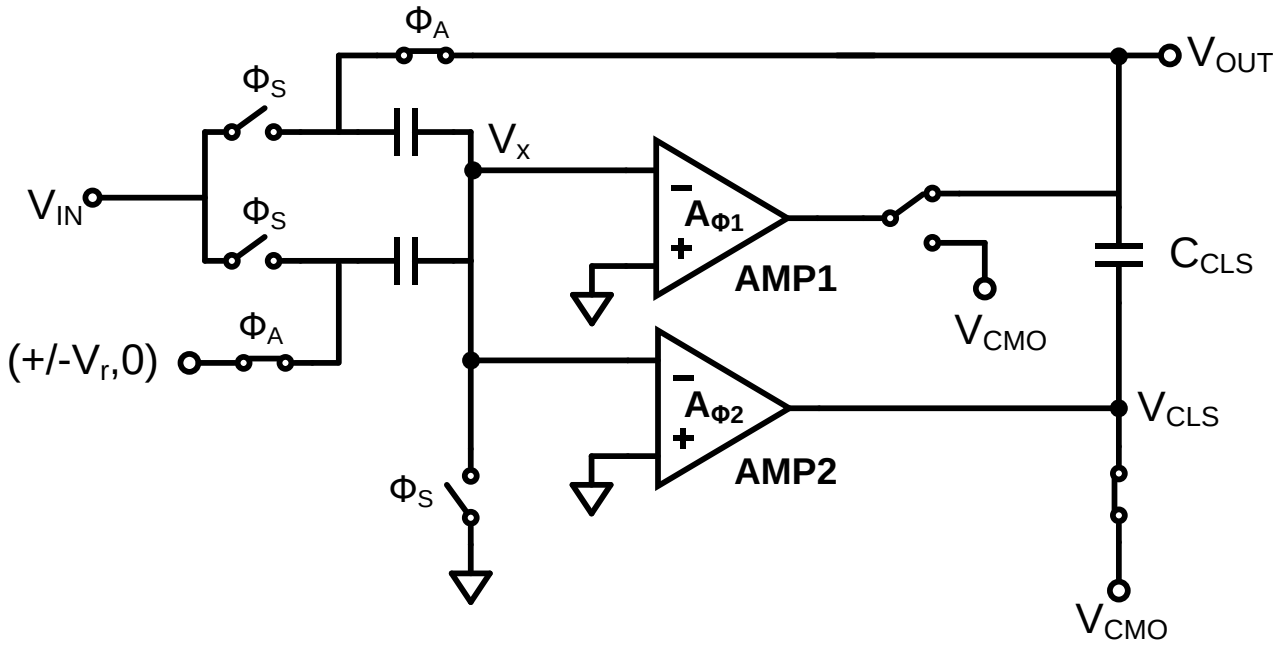
- Compression immune: rail-to-rail output swing
  - 50dB: Input-referred dead-zone size will limit accuracy
  - 90dB: dynamic pinch-off effects maintain high accuracy
  - V_{OV} pinchoff: decreases V_{DSAT}, decreses I_D, increases r_o





ADC Implementation Details

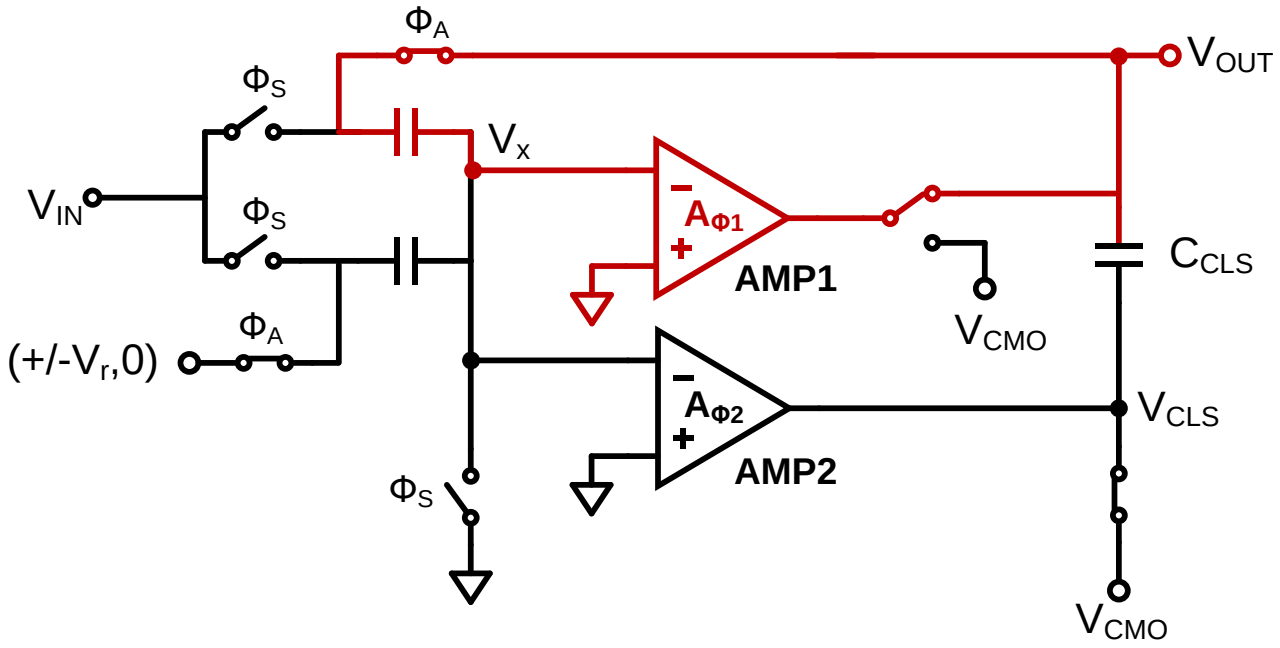
Split-CLS (Correlated Level Shifting)



- Split-CLS
  - Generalized form of Correlated Level Shifting (CLS)

[Hershberg, ISSCC 2010]

Split-CLS (Correlated Level Shifting)



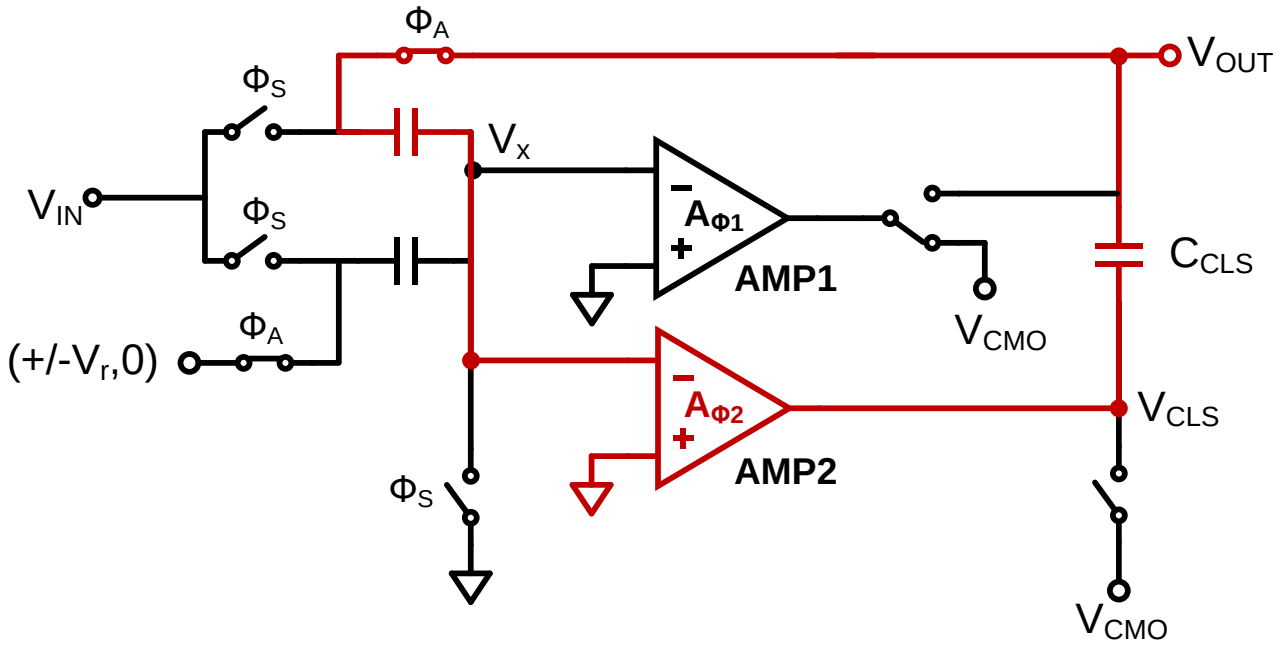
Φ_1:

- amp charges output directly
- processes full signal

Amplifier Design Requirements

	Φ_1	Φ_2
Output Swing	**Large**	**Small**
Slew Rate	**Large**	**Small**

Split-CLS (Correlated Level Shifting)



Φ_2:

- opamp is level-shifted to mid-rail
- processes error only

Amplifier Design Requirements

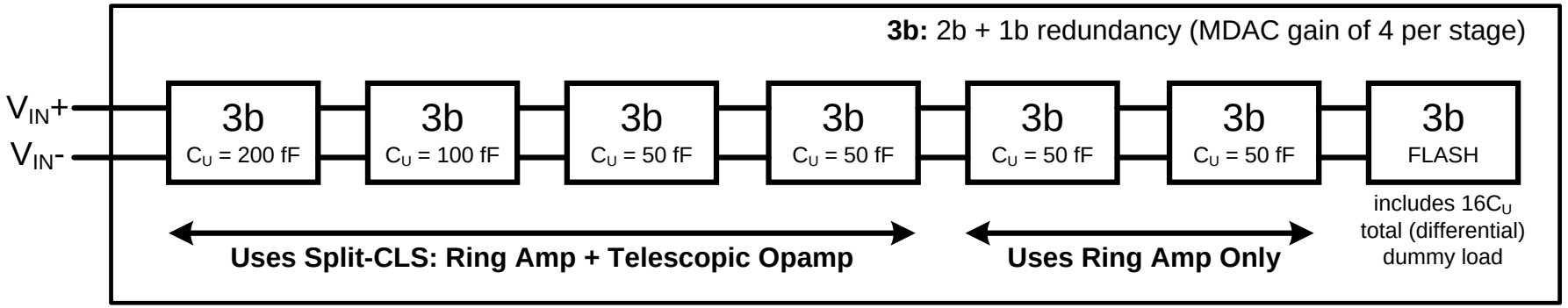
	Φ_1	Φ_2
Output Swing	**Large**	**Small**
Slew Rate	**Large**	**Small**

Split-CLS (Correlated Level Shifting)

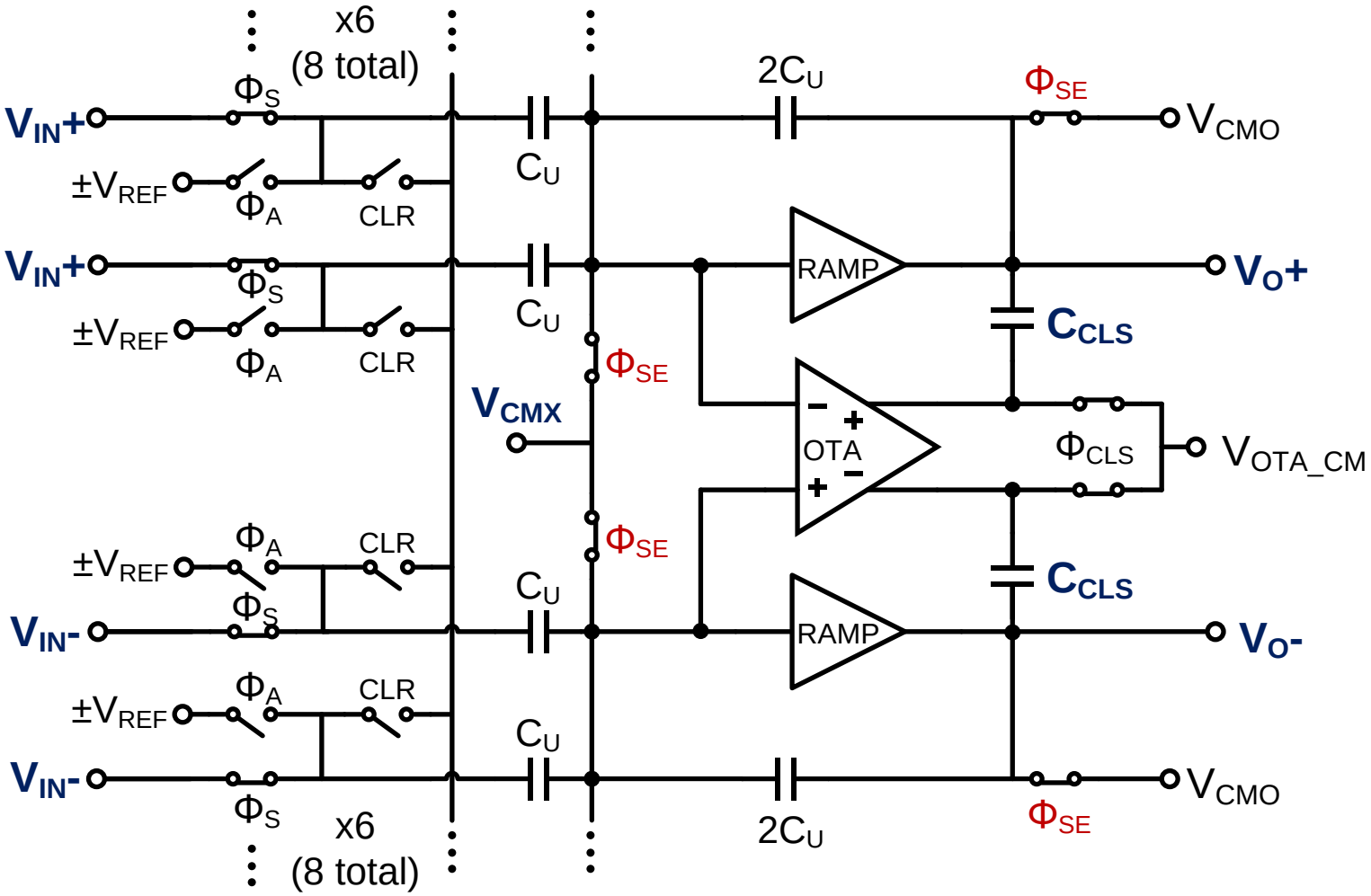
- Optimized design for each phase
  - Increase overall accuracy & efficiency
- This design:
  - Φ_1: Ring Amp
  - Φ_2: Telescopic opamp
- Finite opamp gain error becomes approx. $1 / (A_1 * A_2)$

55dB ring amp
\+ 65dB opamp
120dB effective gain

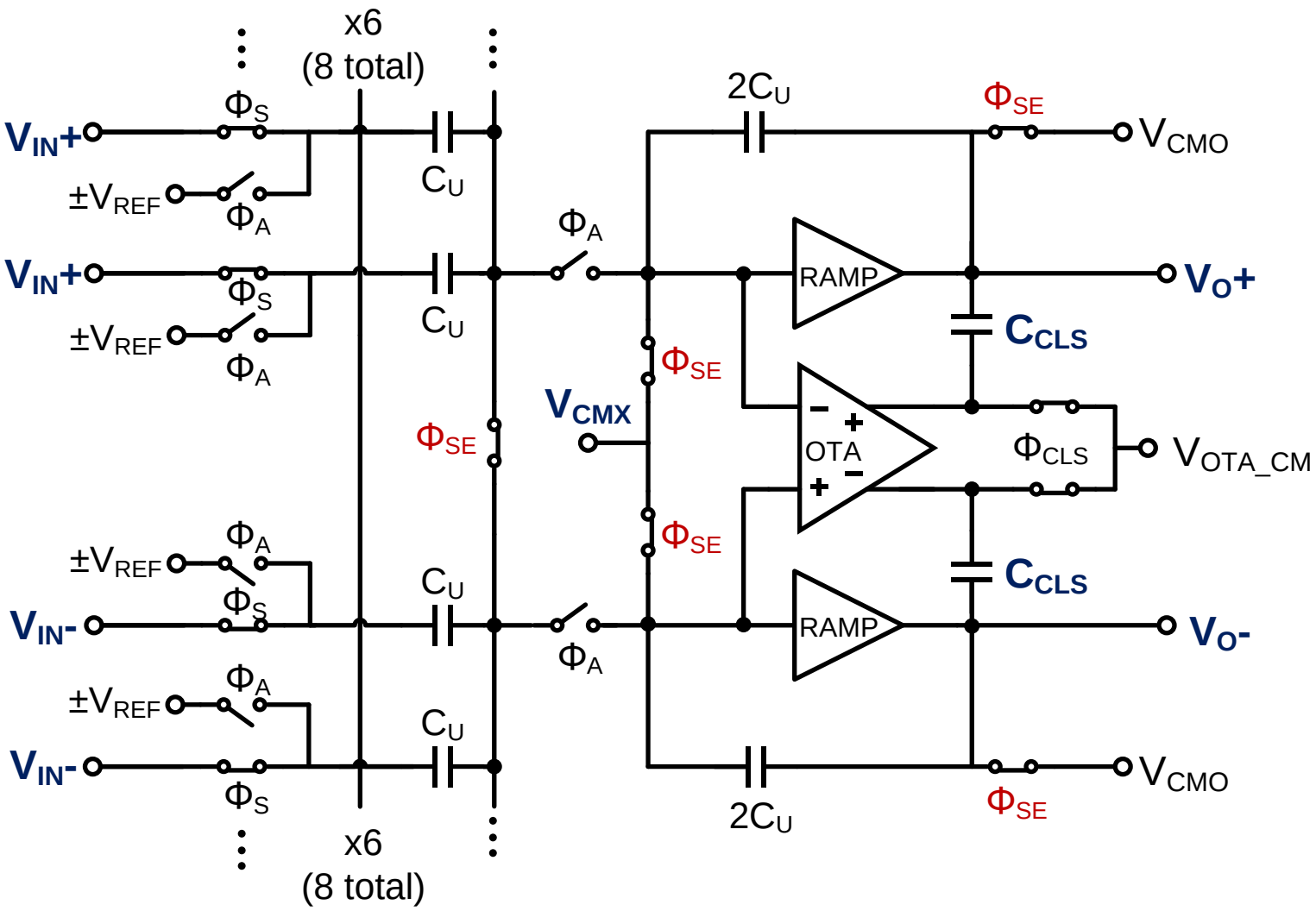
Pipelined ADC Overview



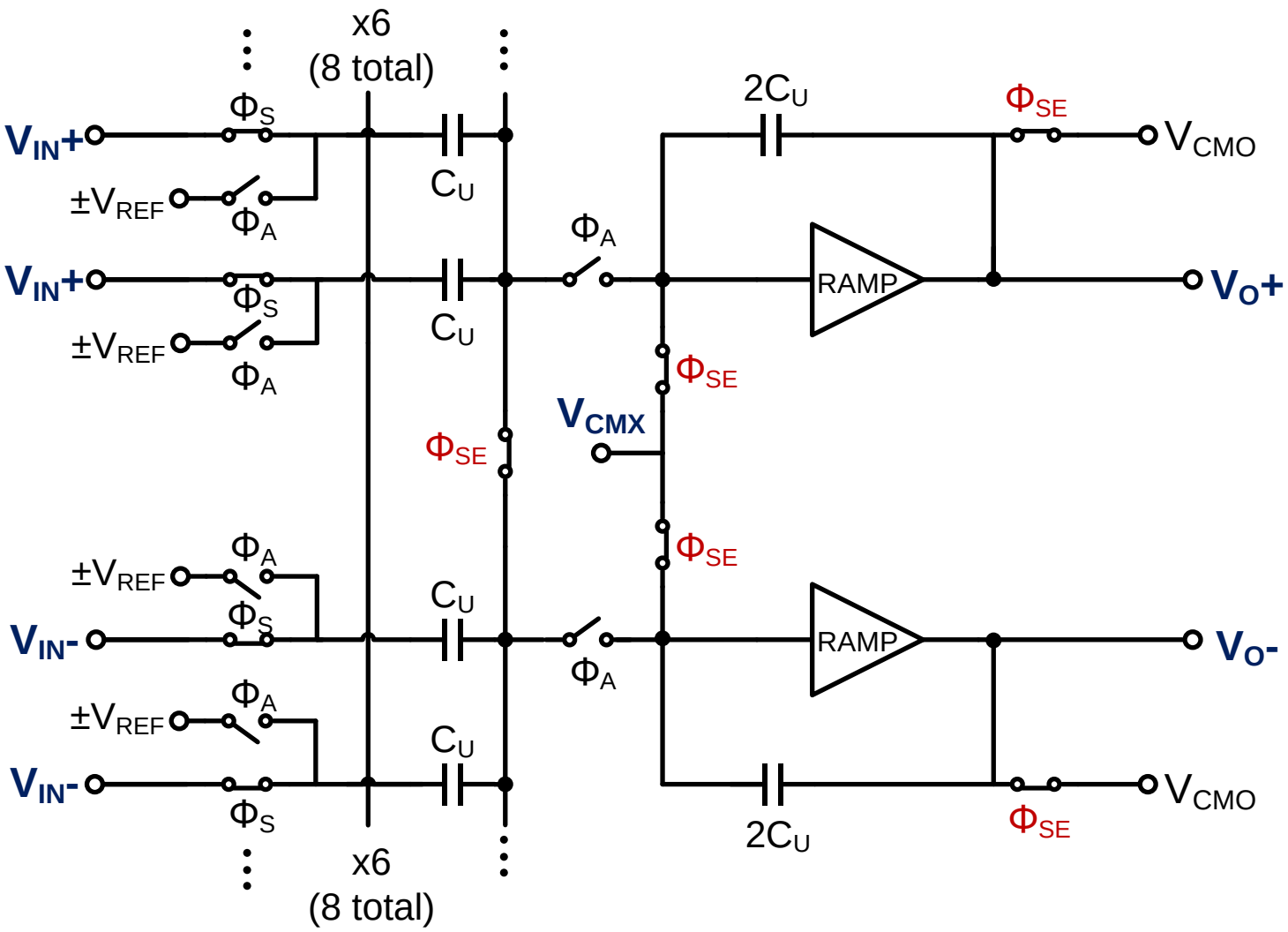
Pipelined ADC Stage 1 MDAC



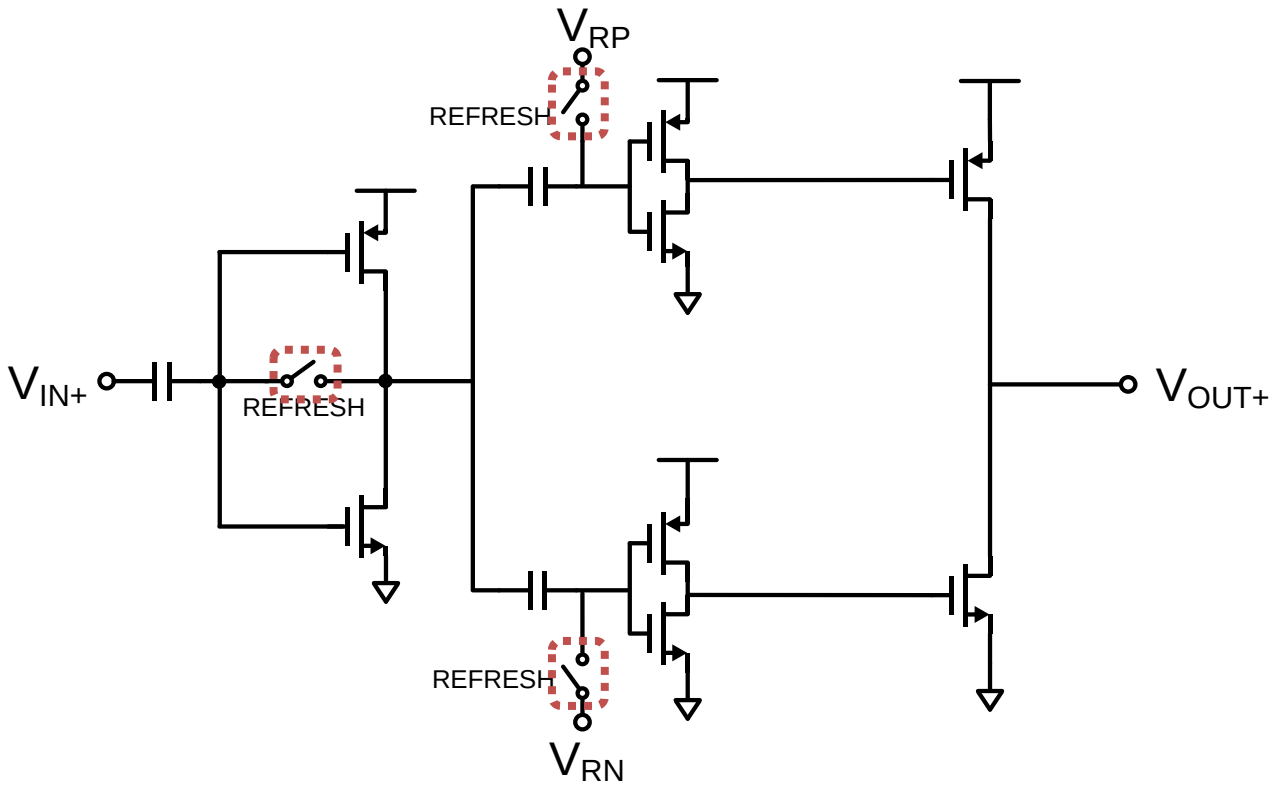
Pipelined ADC Stage 2-4 MDAC



Pipelined ADC Stage 5-6 MDAC

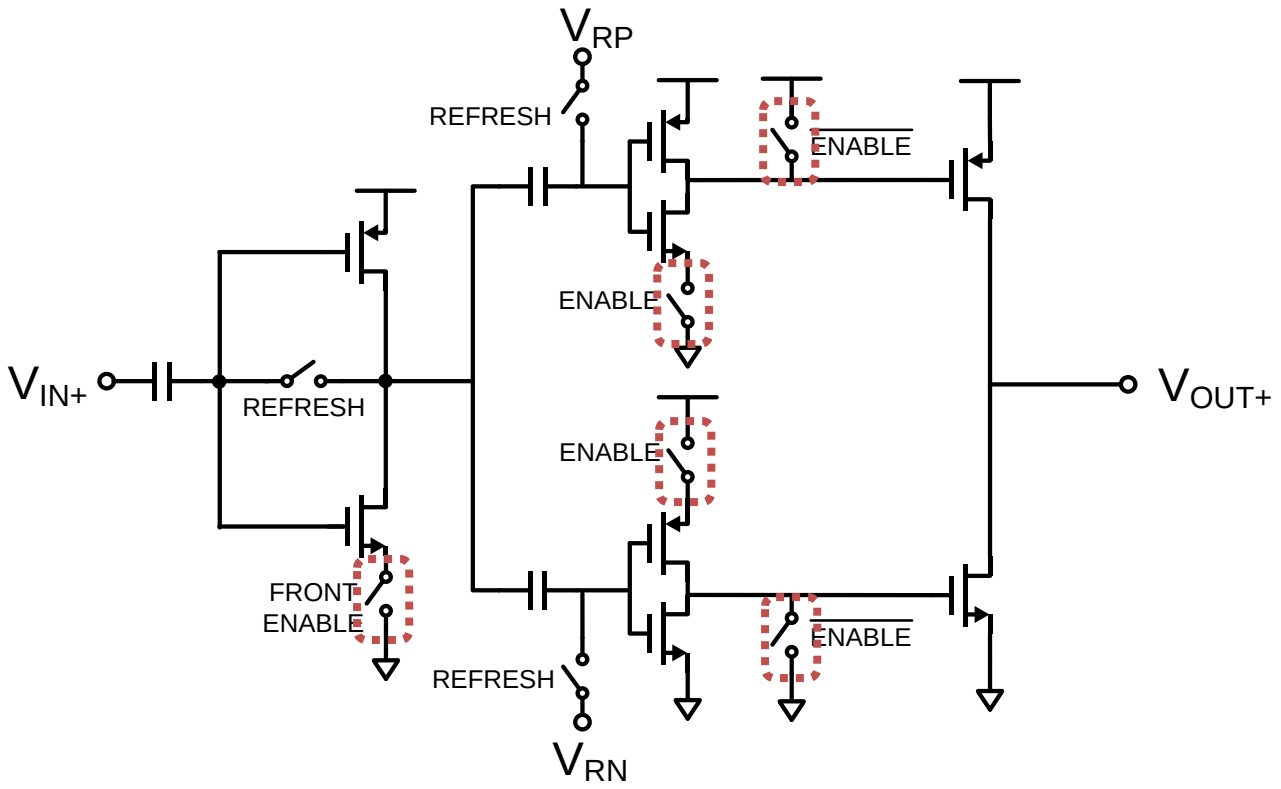


Ring Amplifier Core Structure



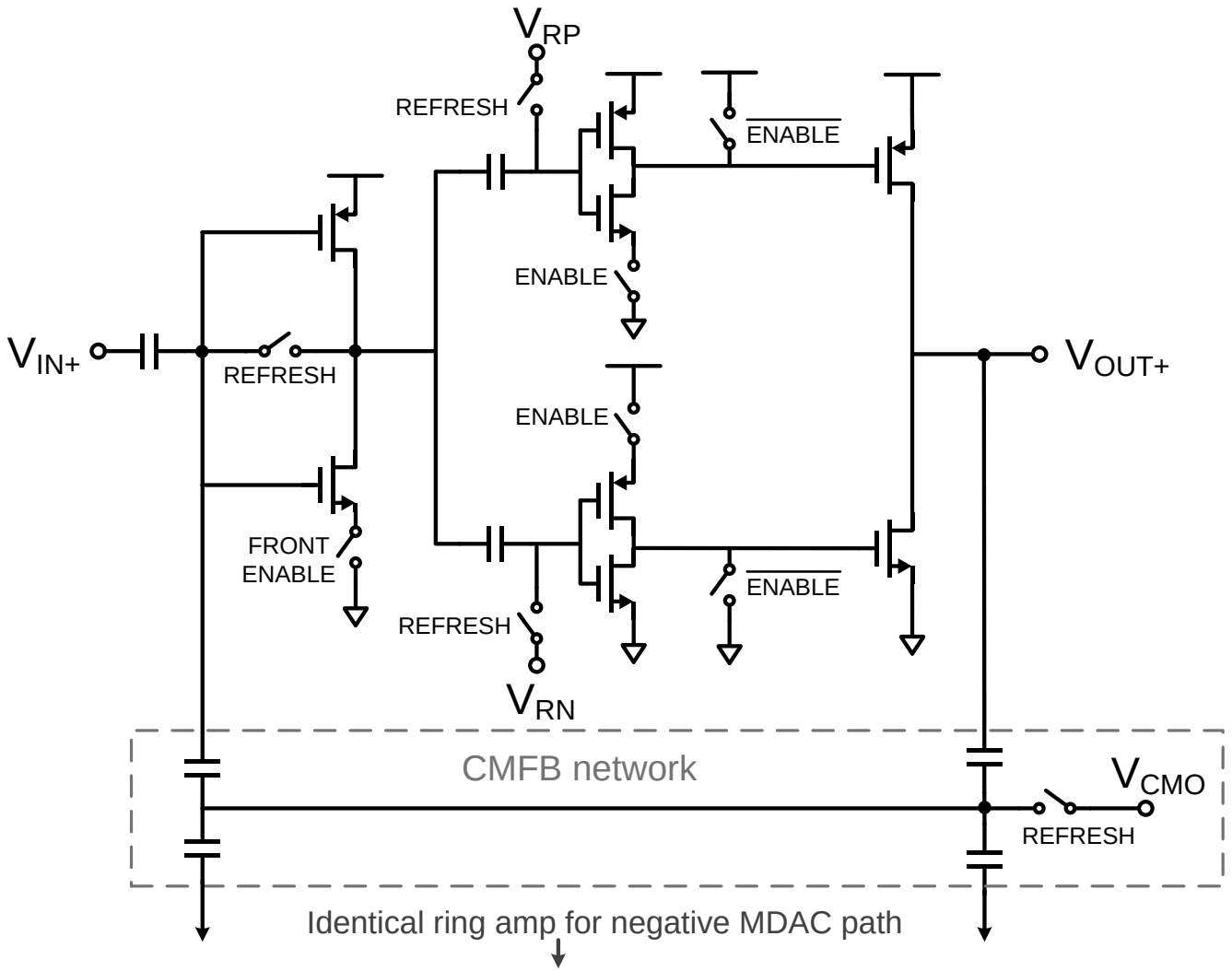
- No need to refresh every cycle.
- Can disable ring amp when not in use

Ring Amplifier Power Save Feature

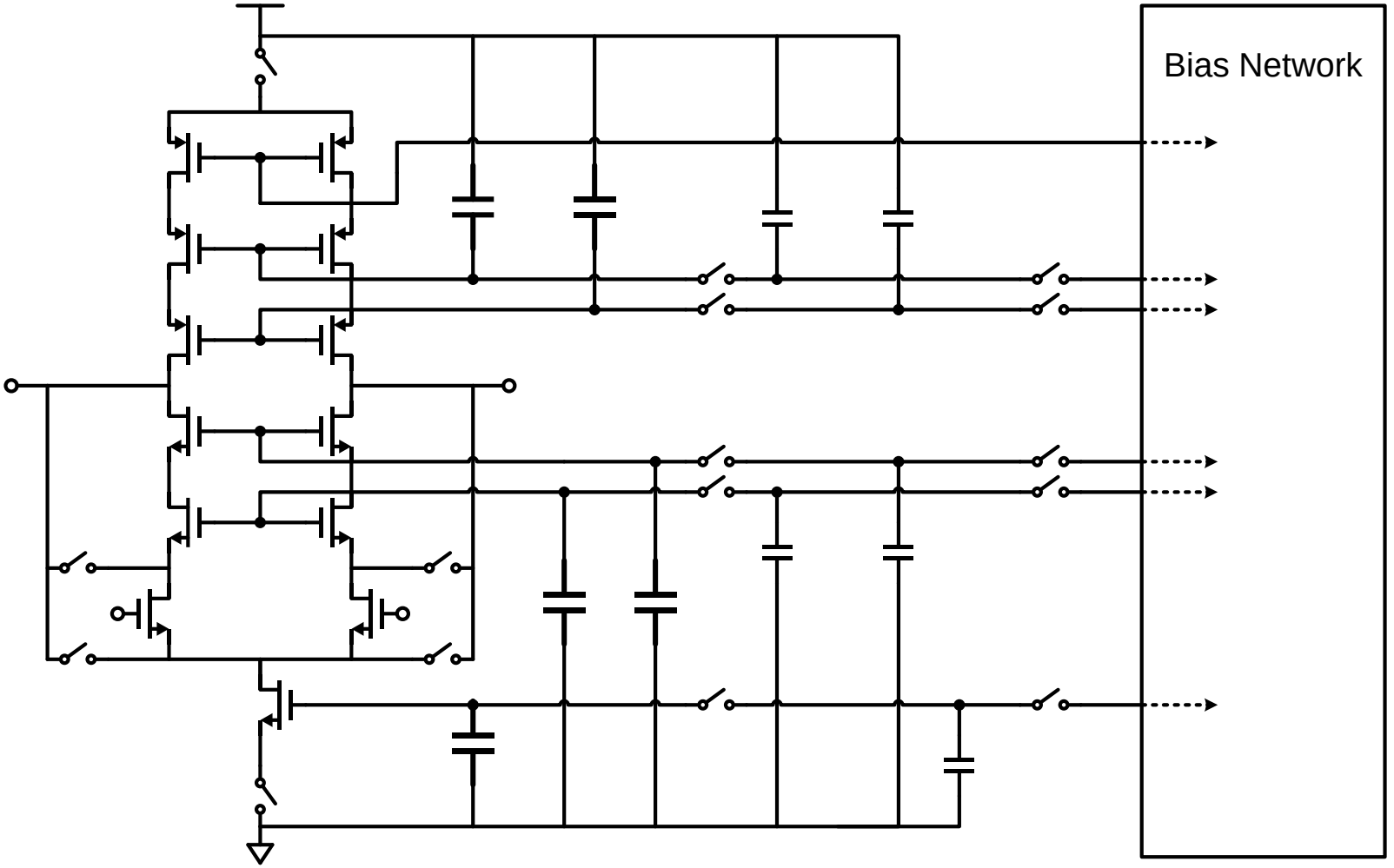


- Only enable when amplifying or refreshing
- Refresh only once every N cycles (during Φ_S)

Ring Amplifier CMFB

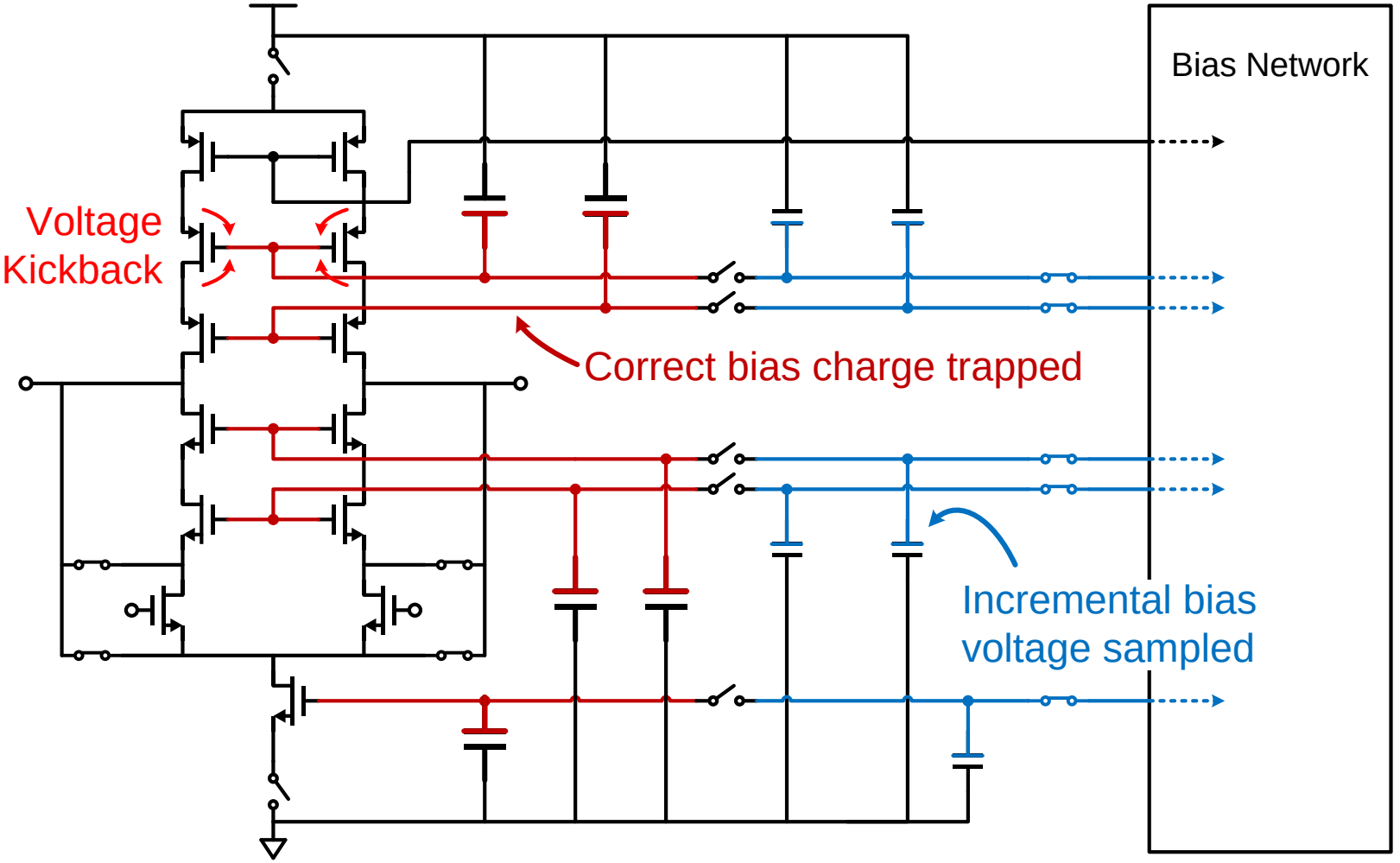


Float-Biased Switched Opamp

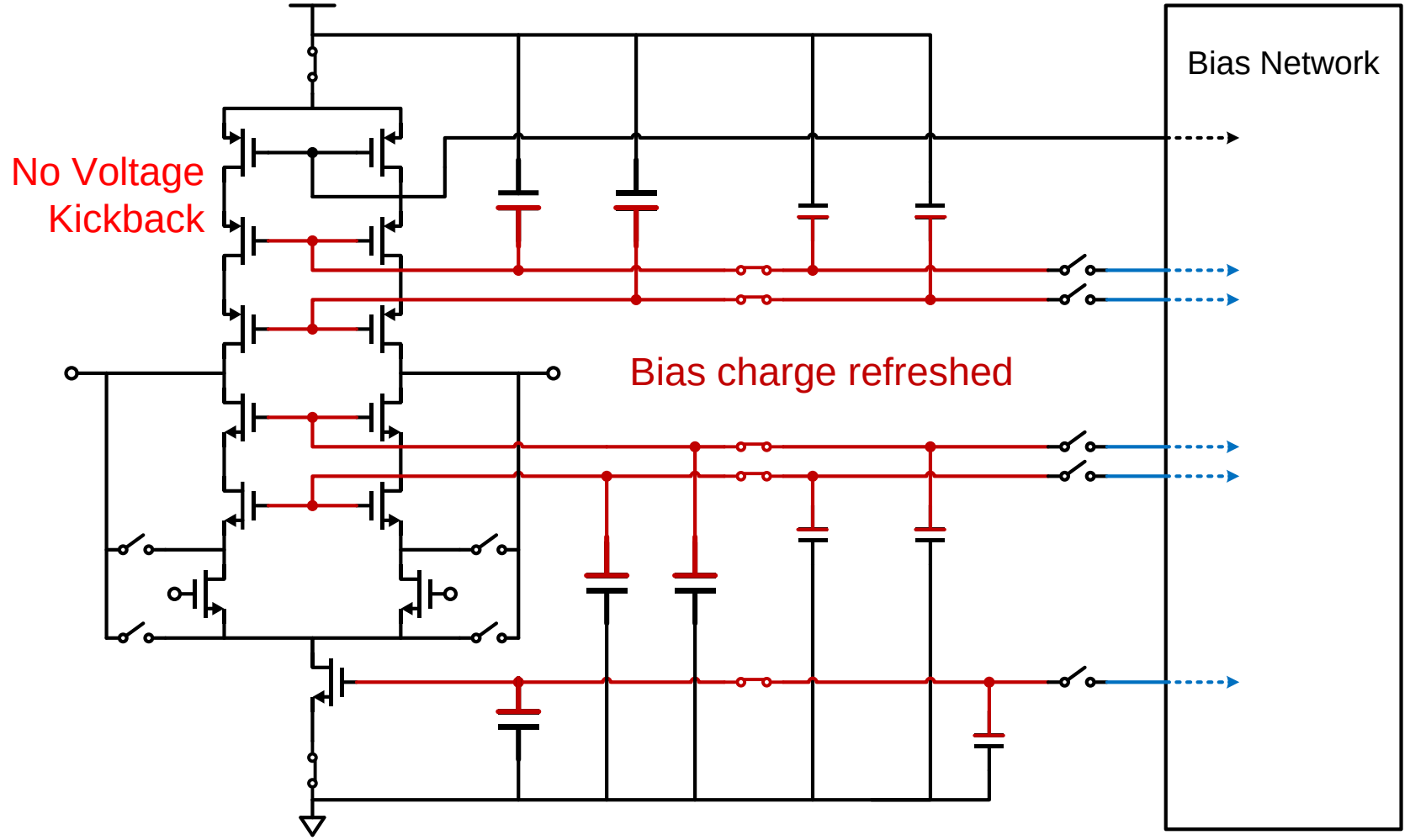


- **Bias network isolation**
- **Fast startup**

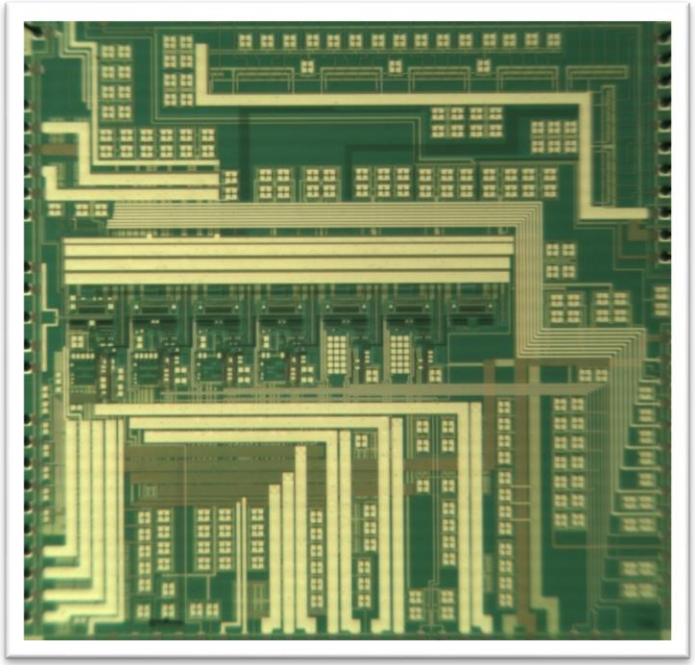
Float-Biased Switched Opamp



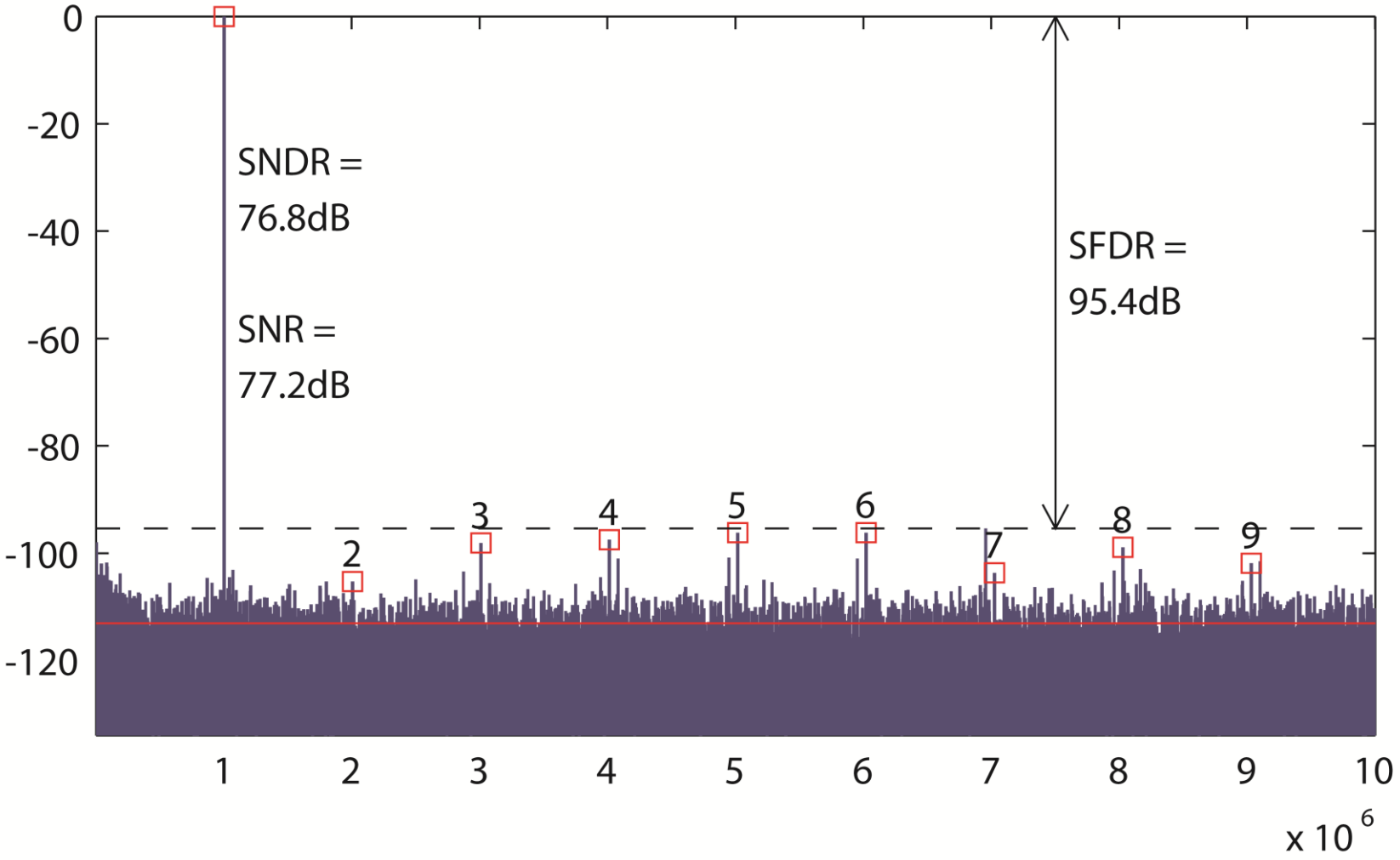
Float-Biased Switched Opamp



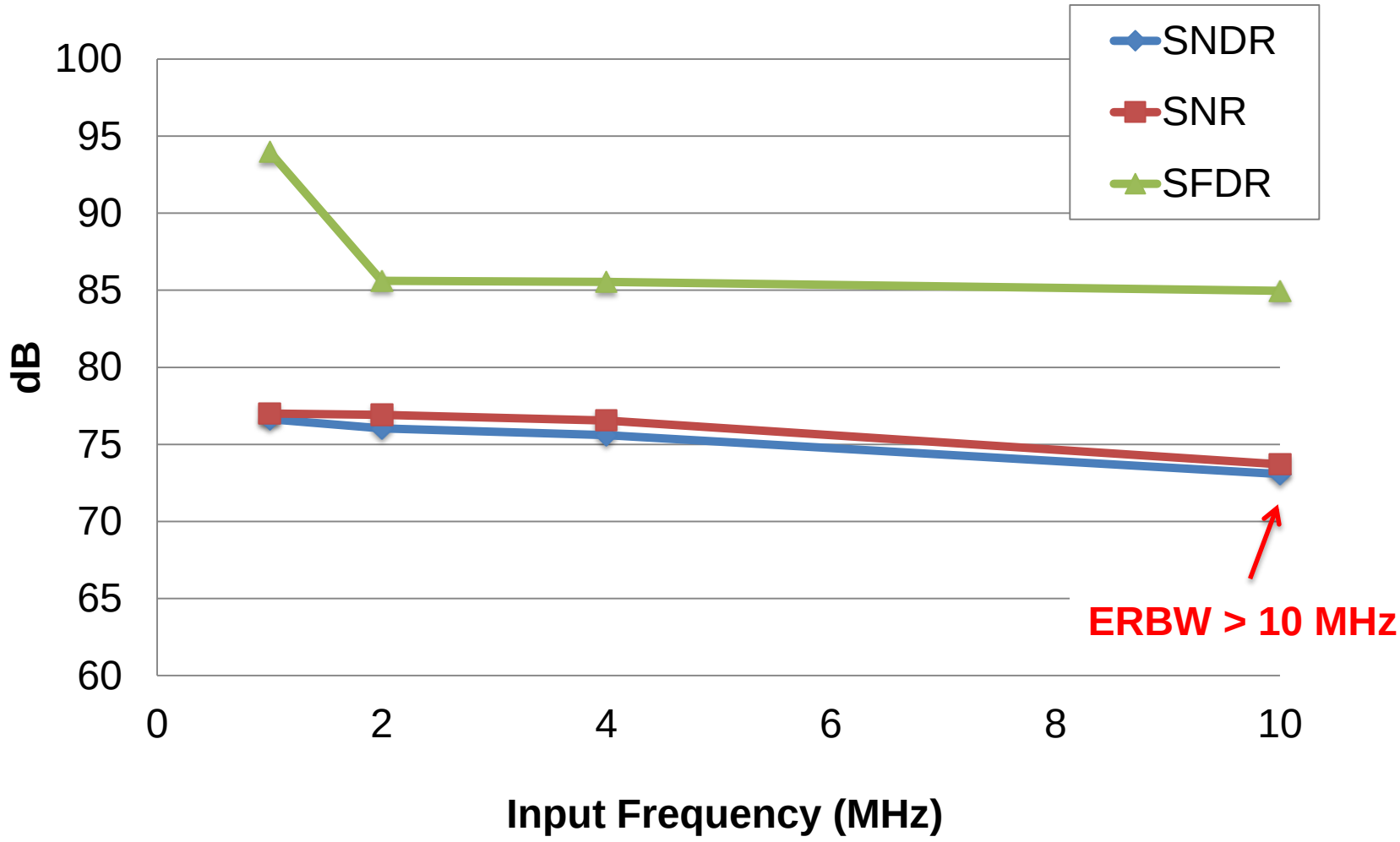
Measurement Results



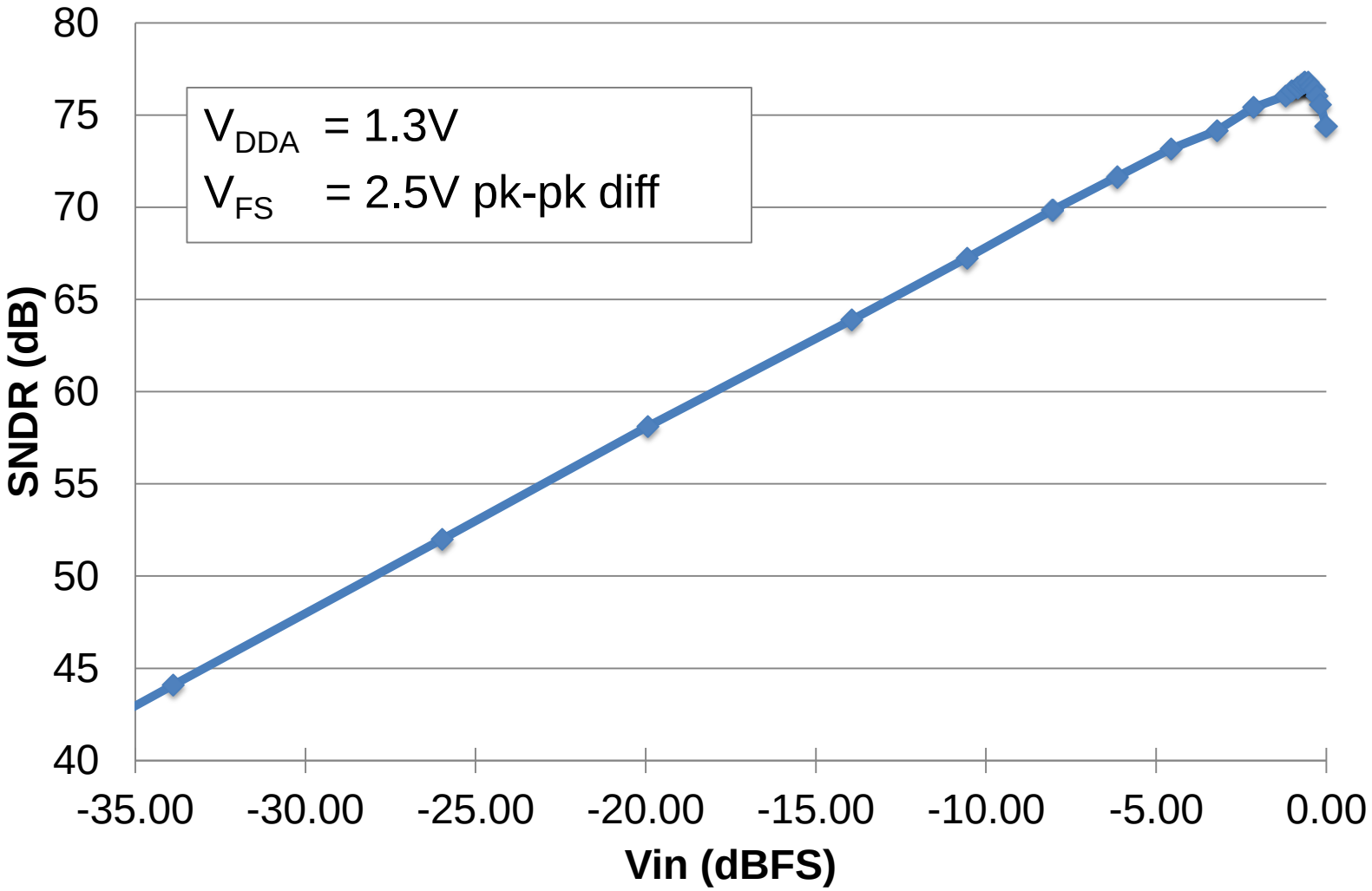
Input Spectrum



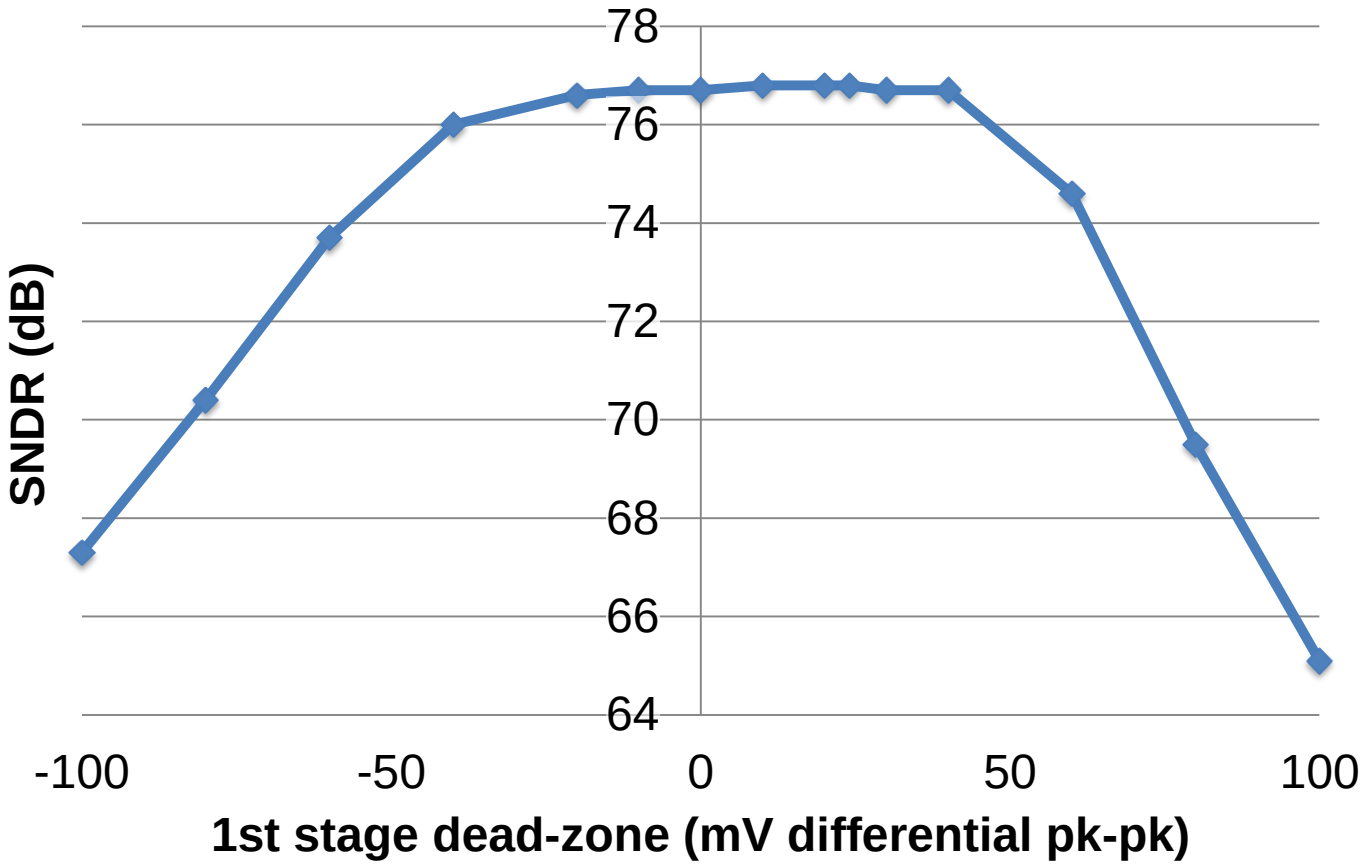
Performance vs. Input Frequency



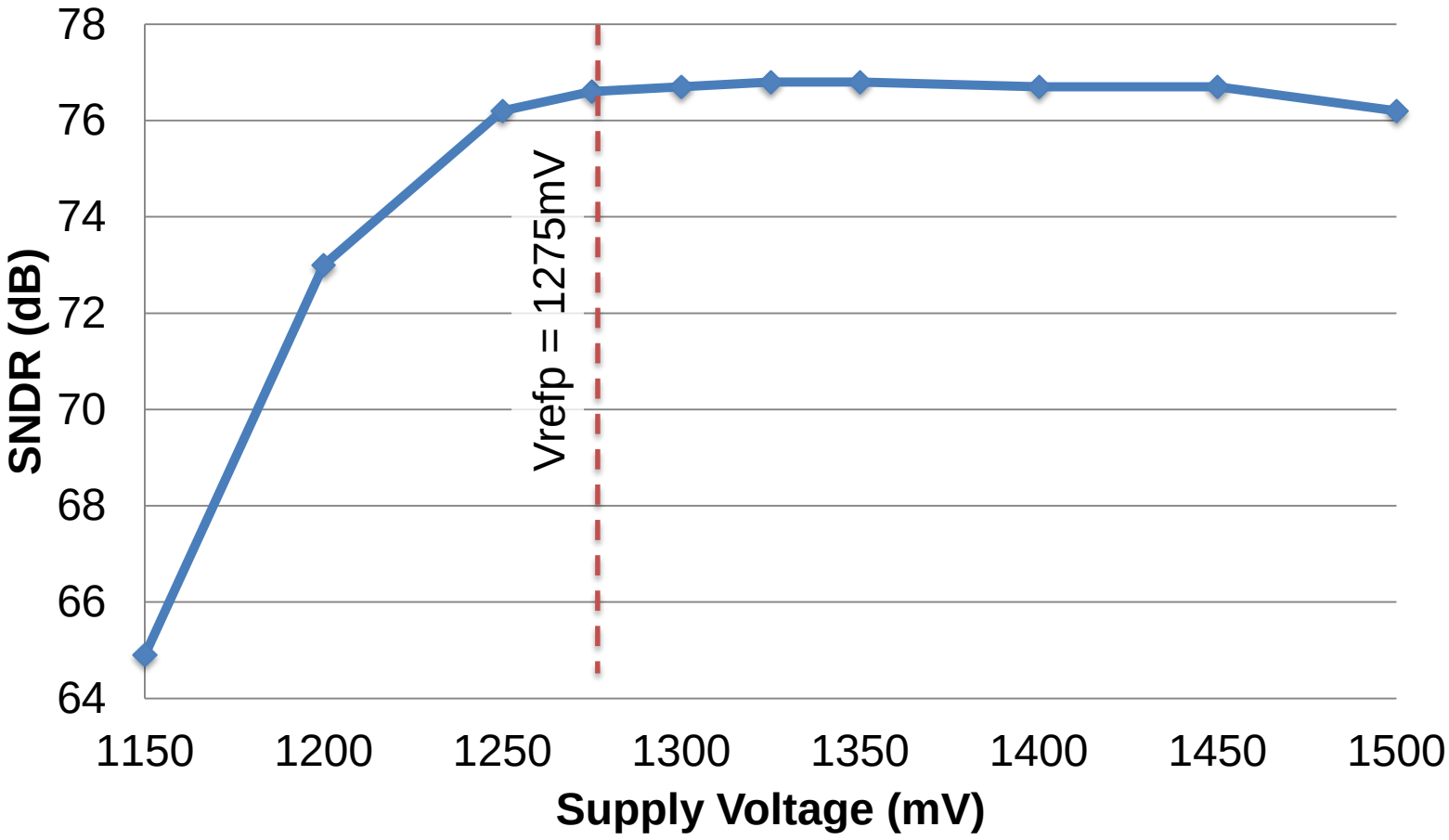
SNDR vs. Input Amplitude



Ring Amp Dead-Zone Sensitivity



Ring Amp Supply Sensitivity



Opamp Float-Bias Switching

- Reduces total opamp power by 35%:

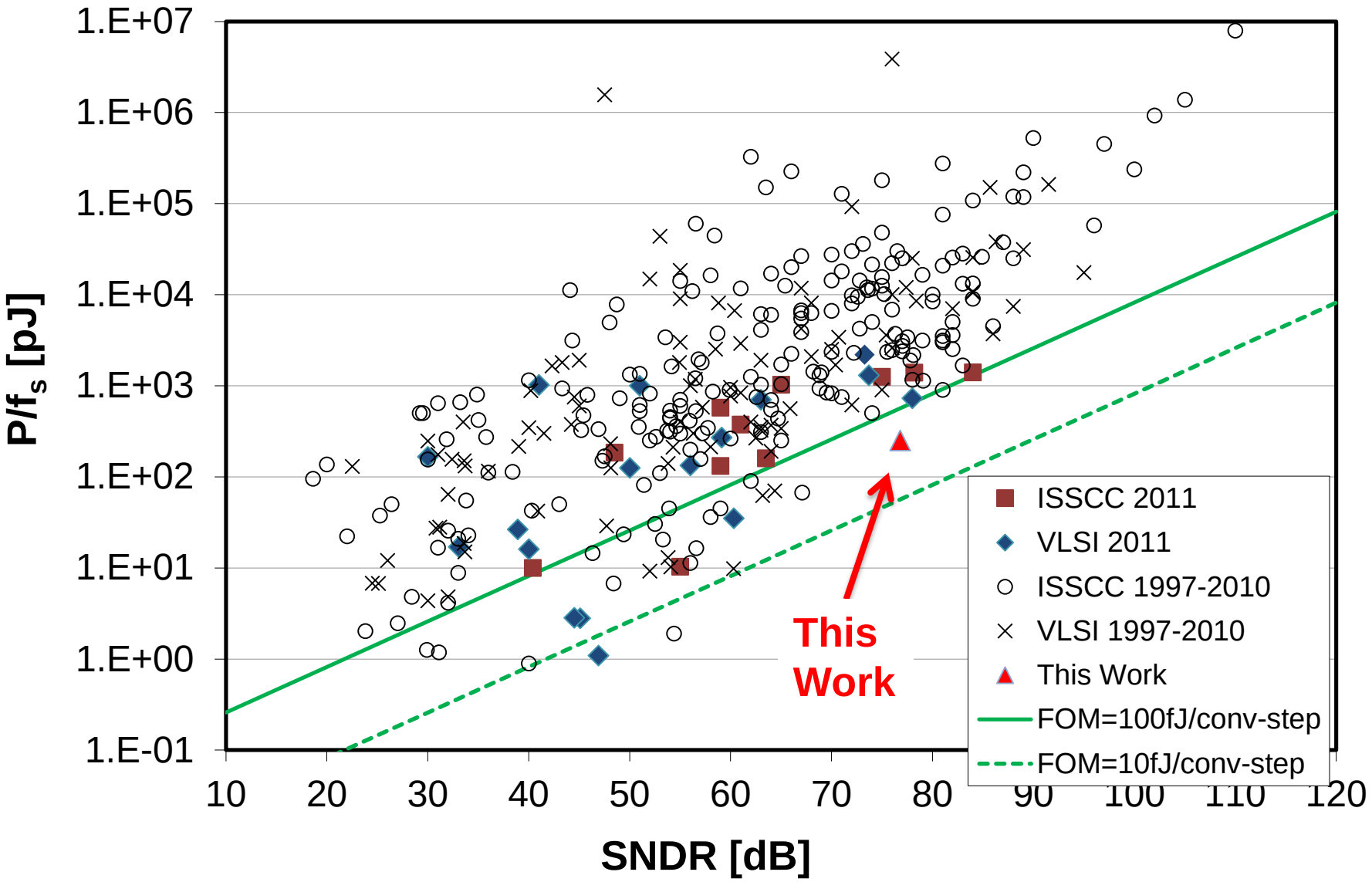
1769uA → 1151uA

- Bias network isolation improves accuracy by 0.6dB:

76.2dB → 76.8dB

Performance Summary

Technology	0.18µm 1P4M CMOS
Resolution	15 bits
Analog Supply	1.3 V
Sampling rate	20 Msps
ERBW	10 MHz
Input Range	2.5 V pk-pk diff.
SNDR	76.8 dB
SNR	77.2 dB
SFDR	95.4 dB
ENOB	12.5 bits
Total Power	5.1 mW
FoM	45 fJ/c-step



Best power efficiency of any high-resolution ADC ever reported (nyquist or oversampling)

[B. Murmann, 2011]

Conclusion

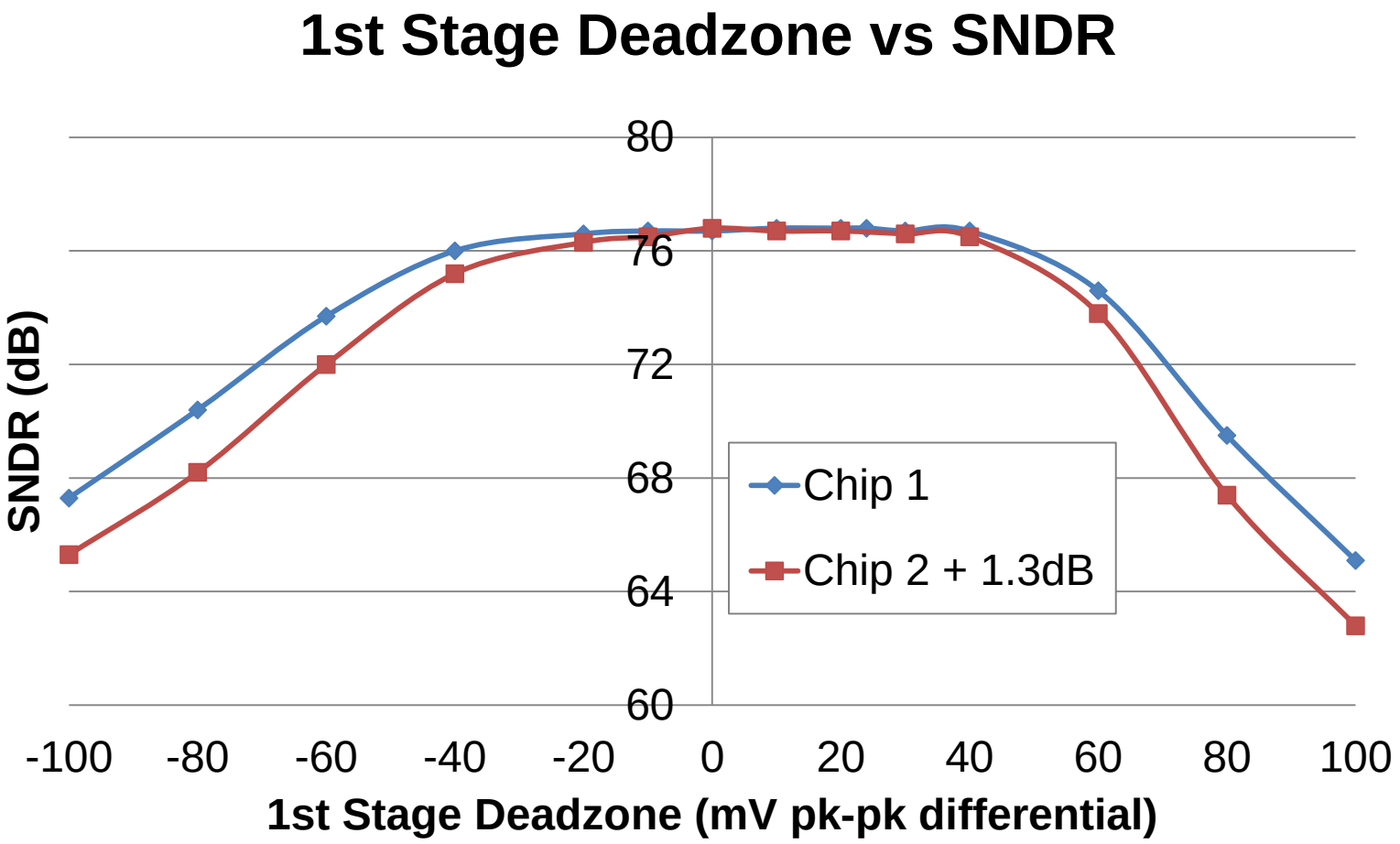
- Ring Amplification
  - High efficiency slew-based charging
  - Rail-to-rail output swing
  - Performance scales with digital process
- Split-CLS
  - Efficient coarse charging
  - Very accurate fine settling
  - High-efficiency, high accuracy amplification

Thank you for your attention

Additional Slides

Possibly useful in Q&A afterwards

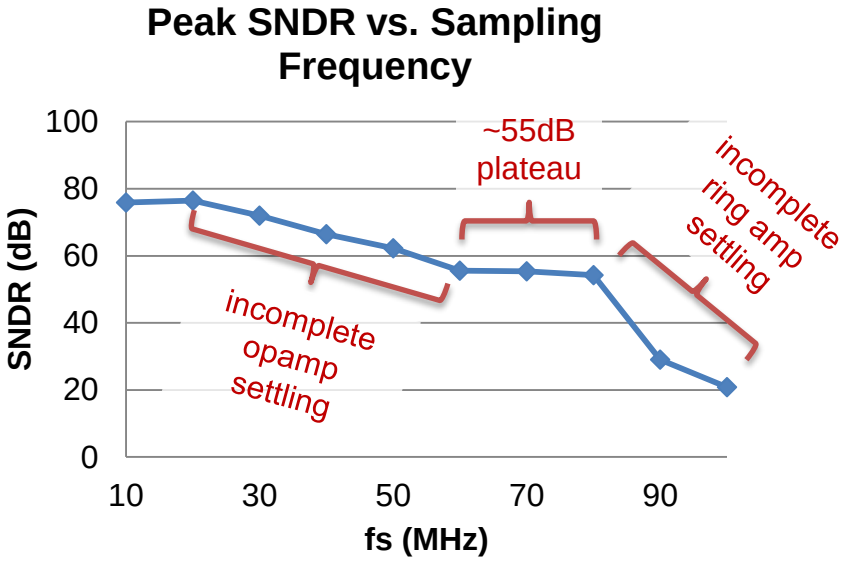
Systematic dead-zone offset



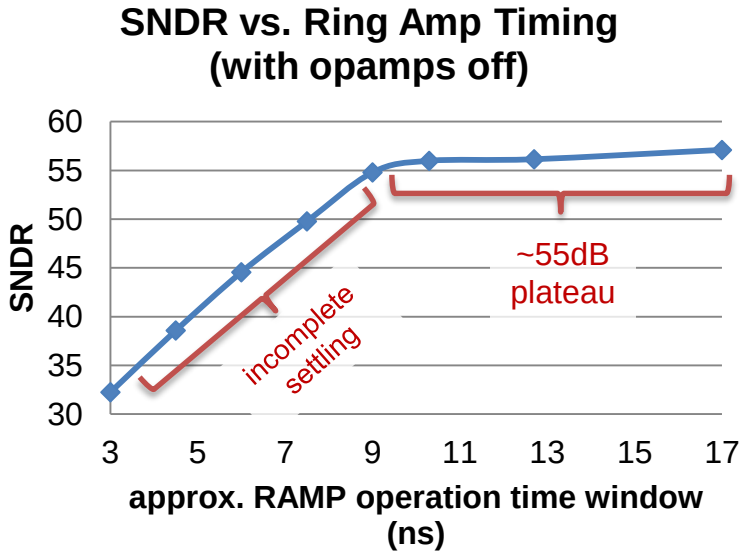
Ring Amp Accuracy

- **Determined using 2 independent test approaches**
- **Ring Amps contribute ~55dB to overall accuracy**

Test method 1:
Increase f_s until opamps don't have enough time to turn on.

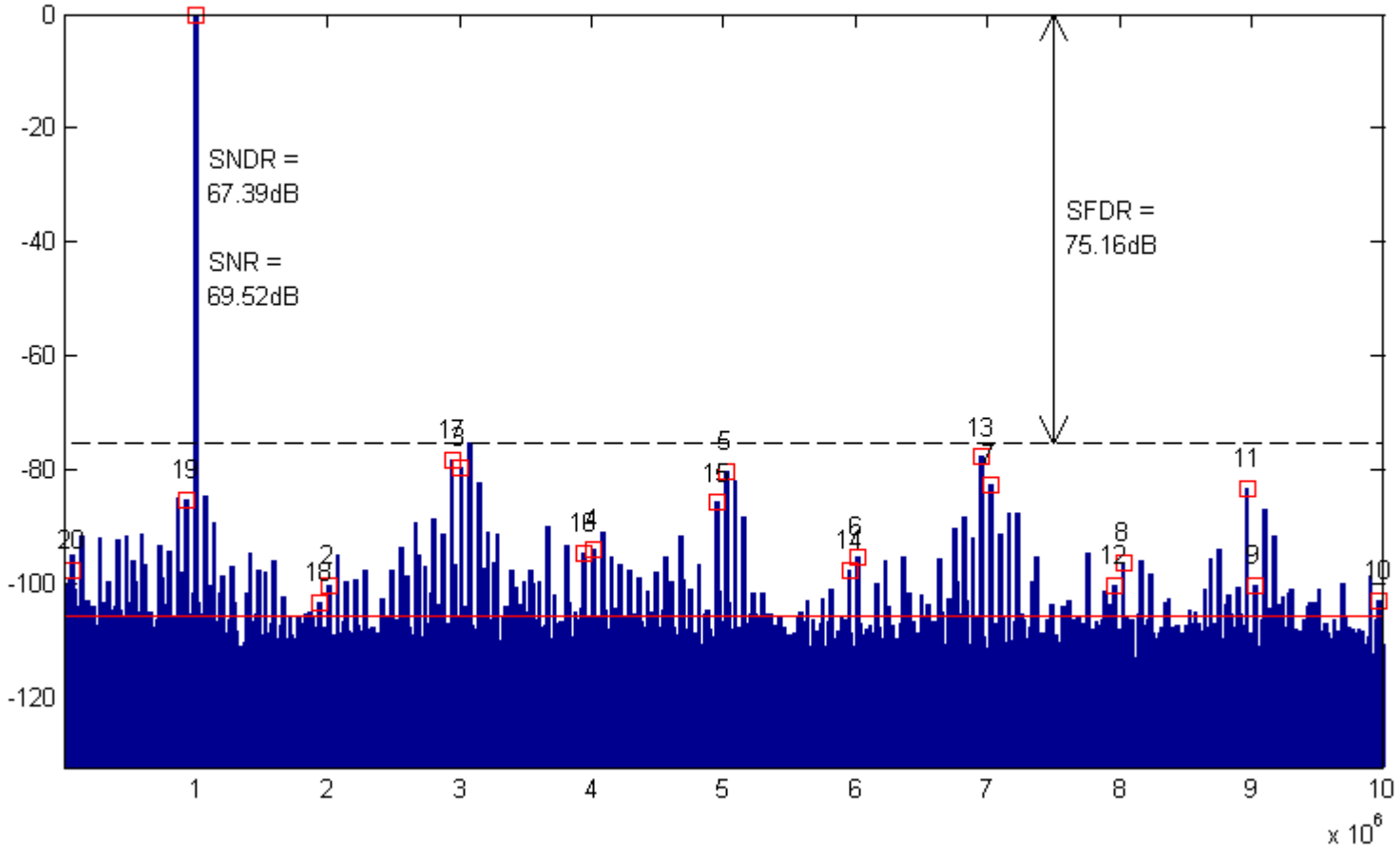


Test method 2:
Power down opamps, and adjust the time the ring amps are allowed to settle.



Input-cap clearing

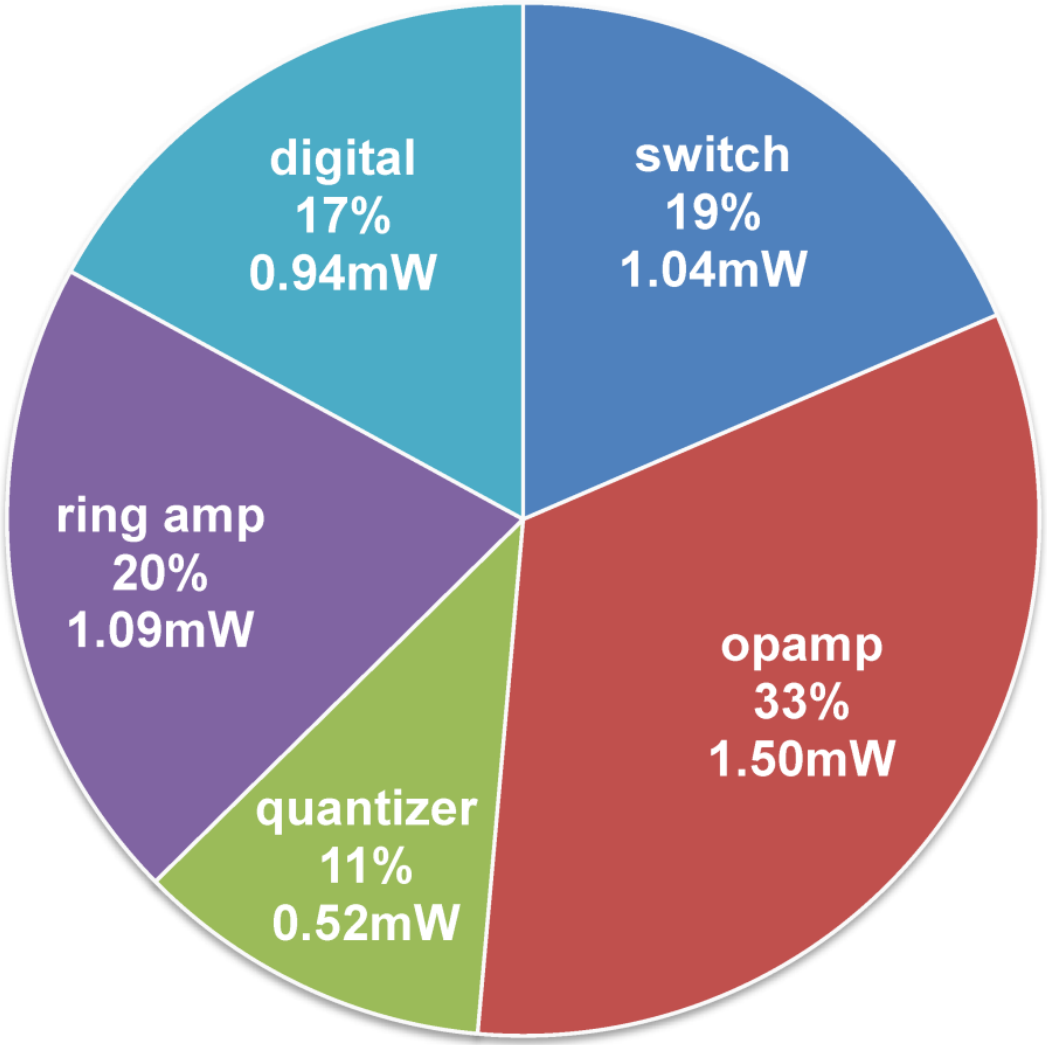
- FFT spectrum when the input capacitors aren't cleared before being re-connected to the chip signal input:



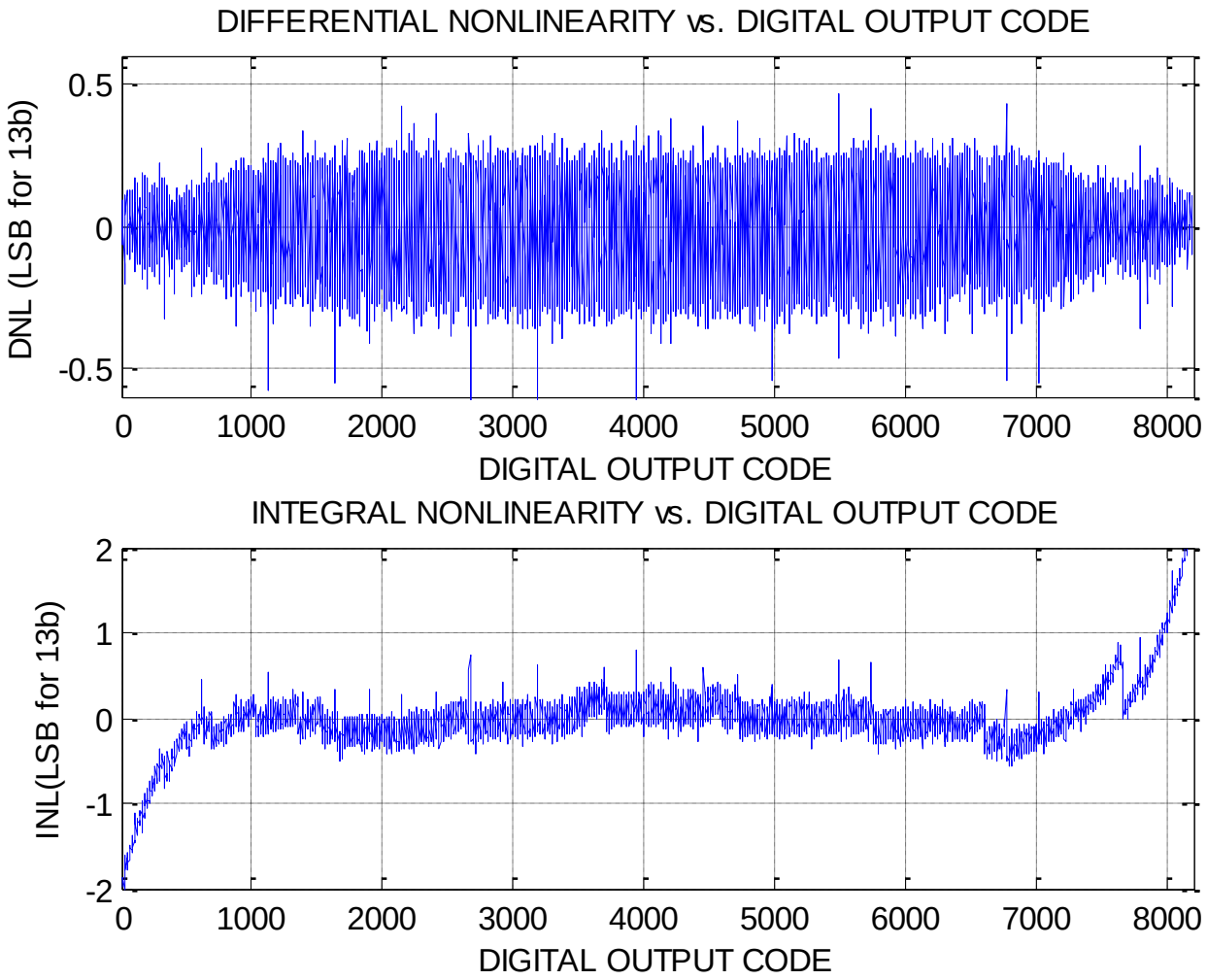
More about Compression Immunity

- Isn't this just a 90dB amplifier that's been limited by the dead-zone size to look like a 60dB amplifier?
  - Answer: No!
- With a well chosen dead-zone value:
  - Current pinches off, increasing r_o
  - V_{OV} shrinks, decreasing V_{DSAT}
  - High gain preserved, even when V_{DS} is very small
- Depends on dead-zone value?
  - Yes, but doesn't actually matter…
  - Small dead-zone: compression immune
  - Large dead-zone: some compression (lower accuracy anyway)

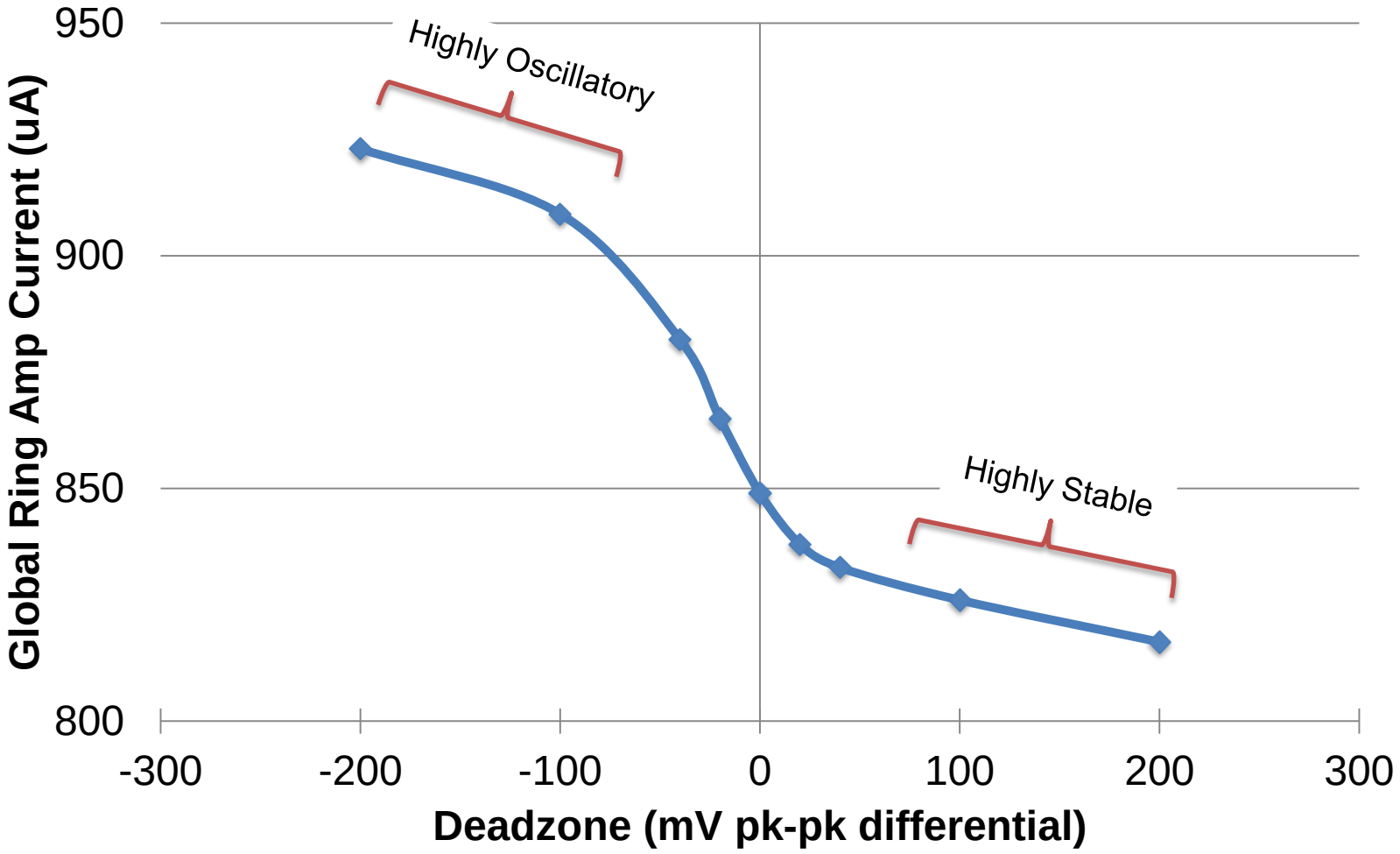
Power Breakdown



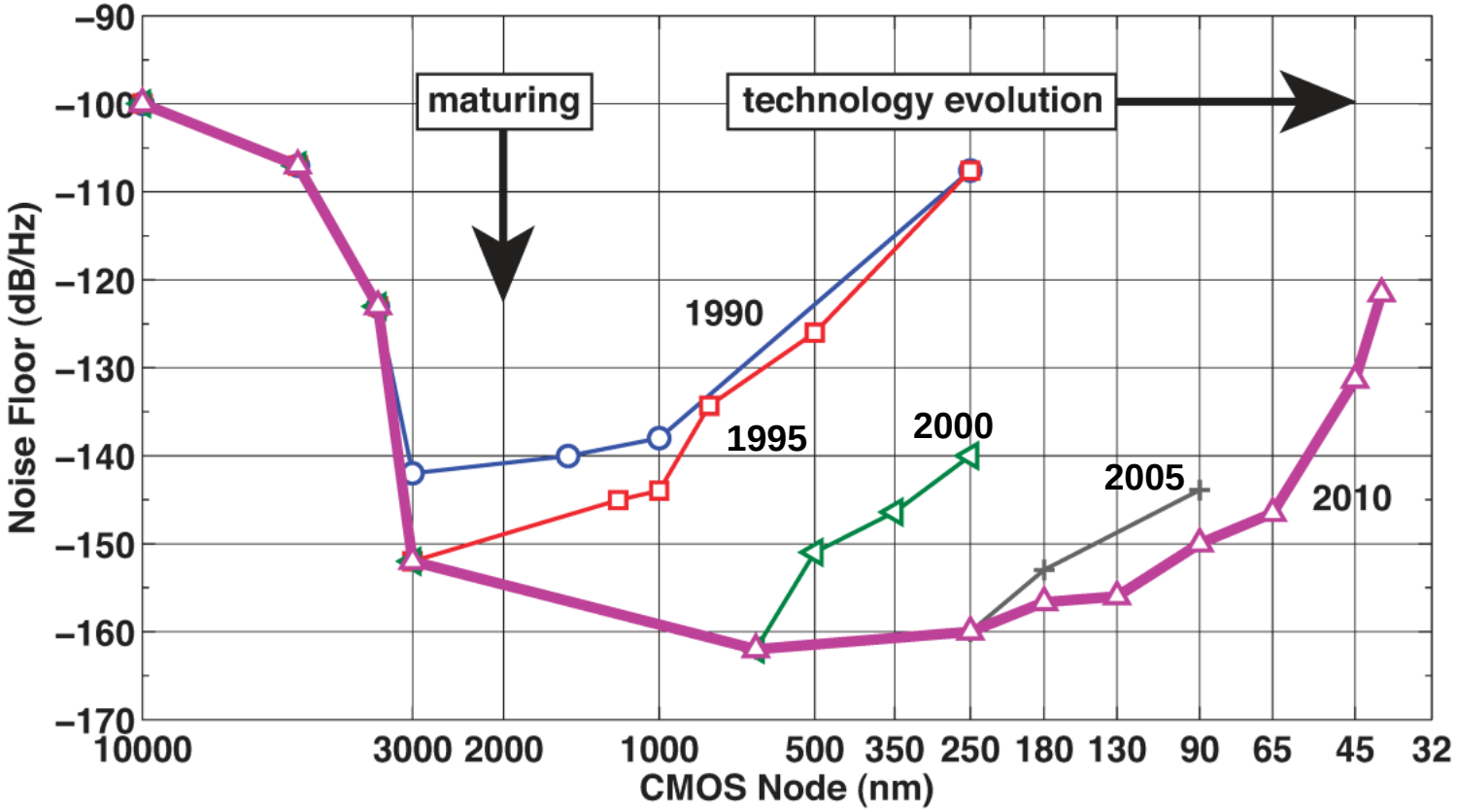
DNL - INL


DIFFERENTIAL NONLINEARITY vs. DIGITAL OUTPUT CODE
DNL (LSB for 13b)
0.5
0
-0.5
0
1000
2000
3000
4000
5000
6000
7000
8000
DIGITAL OUTPUT CODE
INTEGRAL NONLINEARITY vs. DIGITAL OUTPUT CODE
INL(LSB for 13b)
2
1
0
-1
-2
0
1000
2000
3000
4000
5000
6000
7000
8000
DIGITAL OUTPUT CODE

Supply current vs. Stage 1 DZ



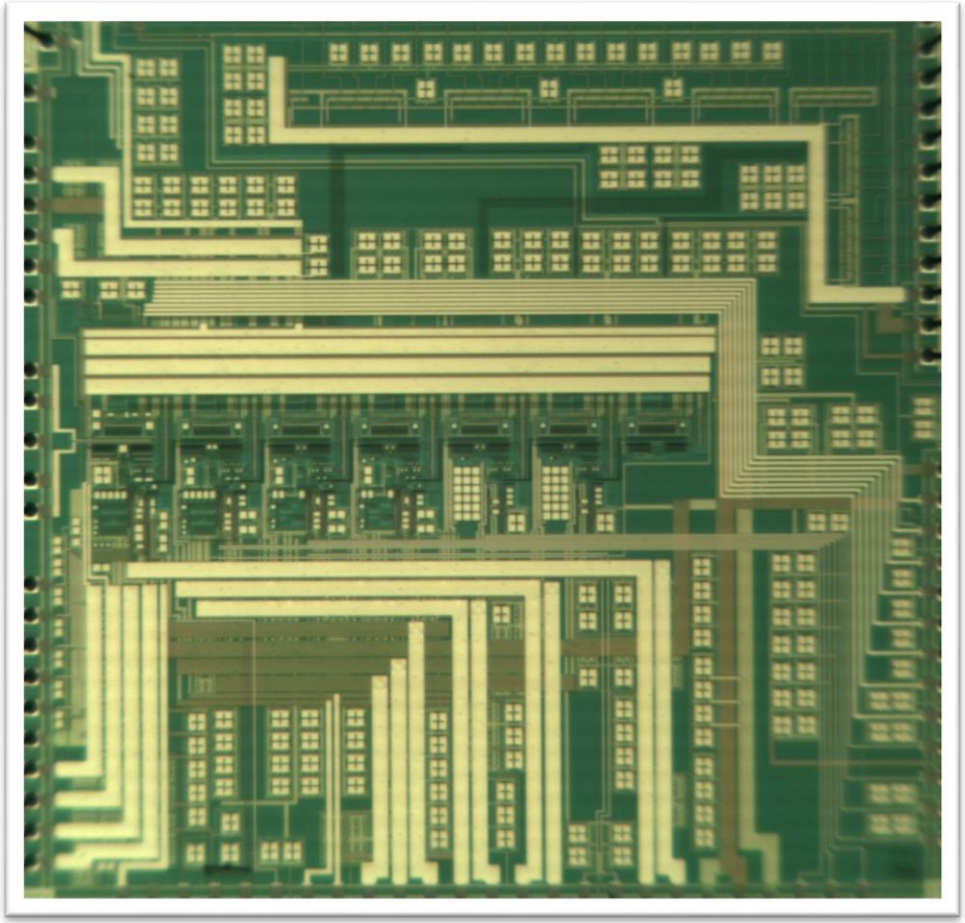
A/D Scaling Trends: FoM_2



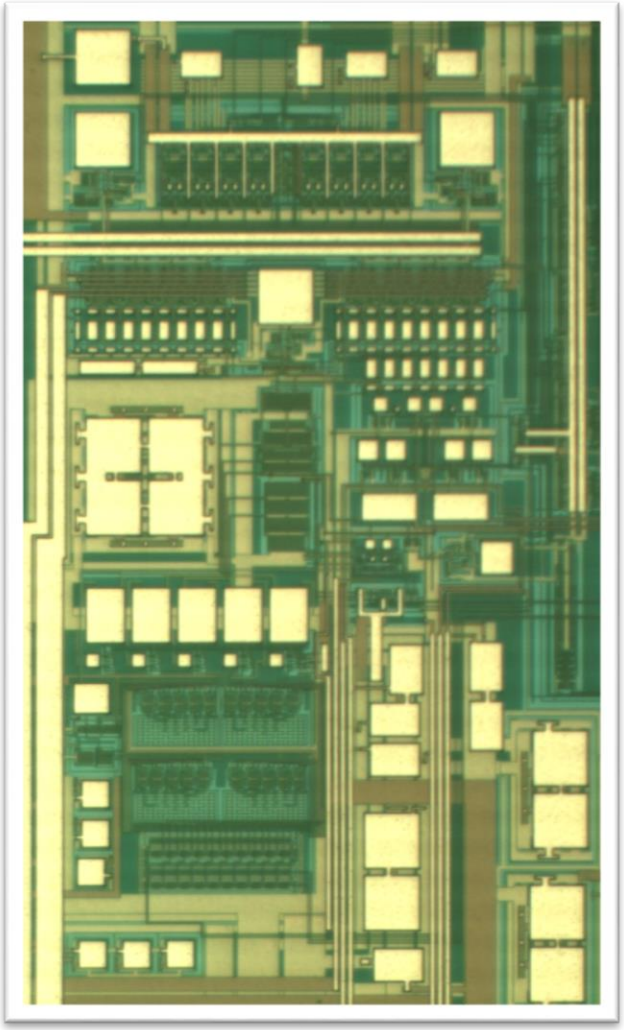
- FoM_2 best describes high-resolution A/D performance
- Noise floor degrades faster than power/speed improves.

[Jonsson, NORCHIP 2010]

Chip Micrograph

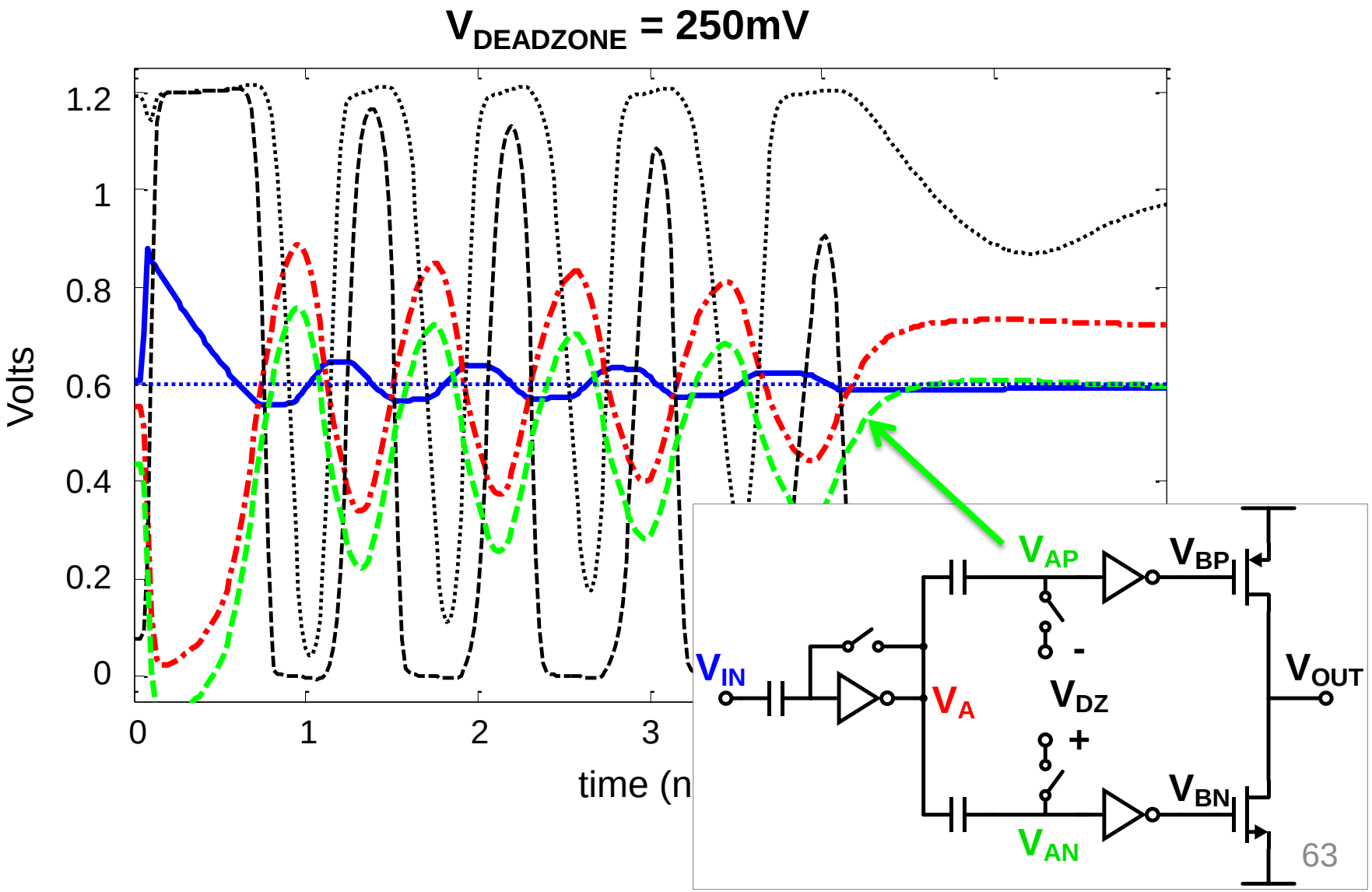


Full die micrograph

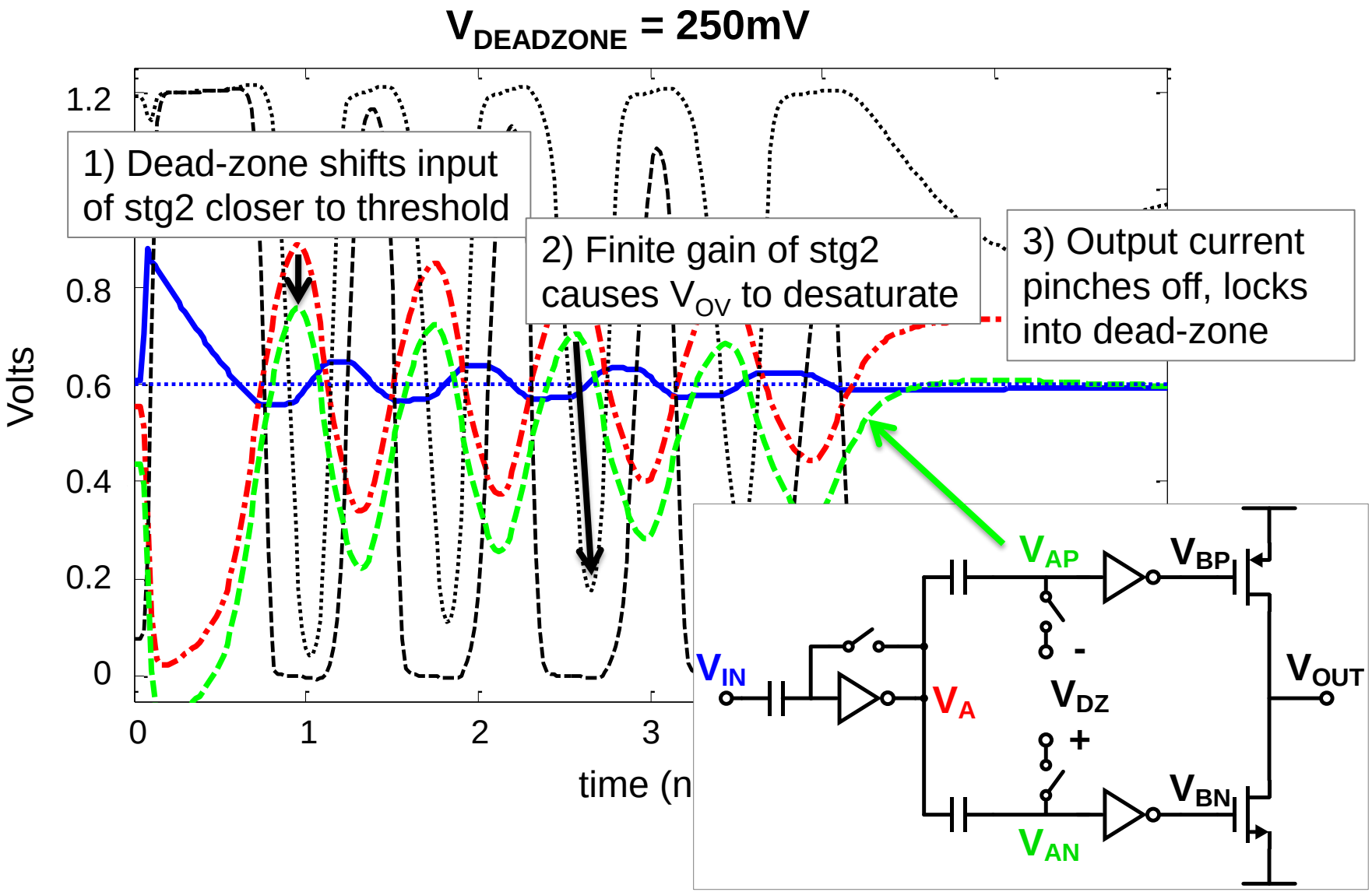


Stage 1 MDAC

Ring Amplifier Sample Waveform



Ring Amplifier Sample Waveform



Ring Amp Power-Save Feature