Advanced Power Management Techniques for Portable Applications

---Introduction of power-on-chip development

PMU→SIMO→Embedded→Integrated→Wireless→Eco

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Introduction of the power-on-chip development

1)PMU

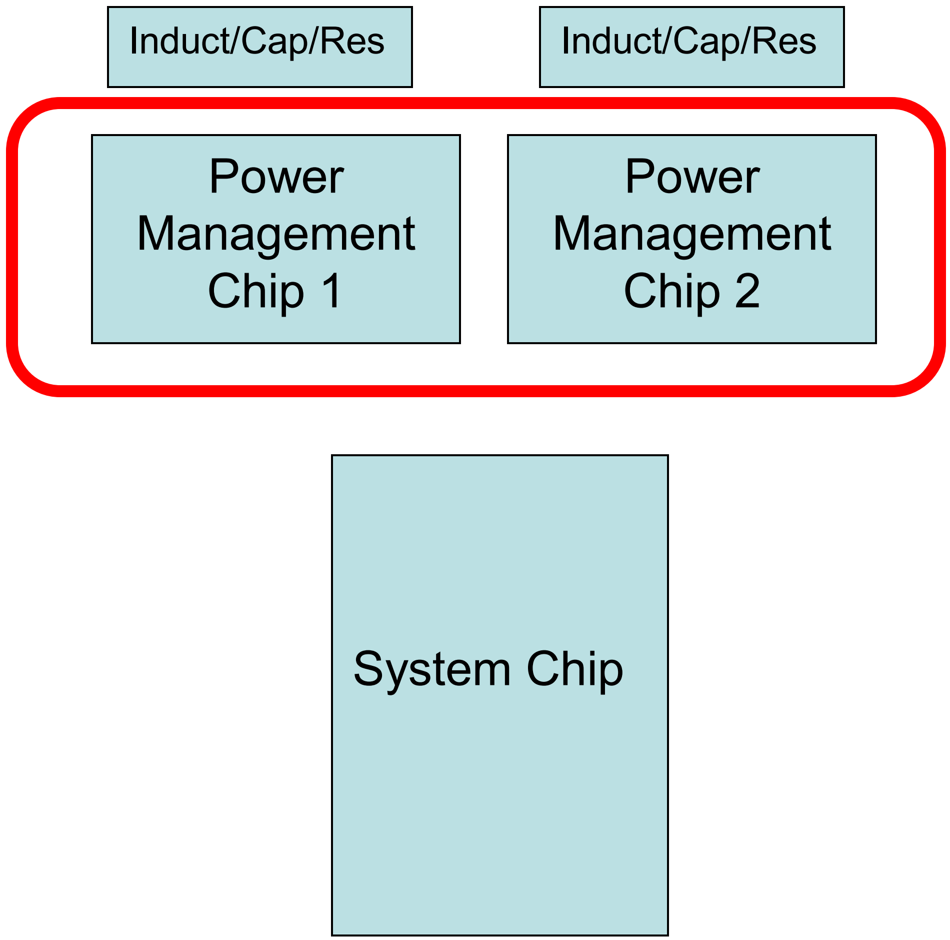
2)SIMO

3)Embedded Power

4)Integrated Power

5)More

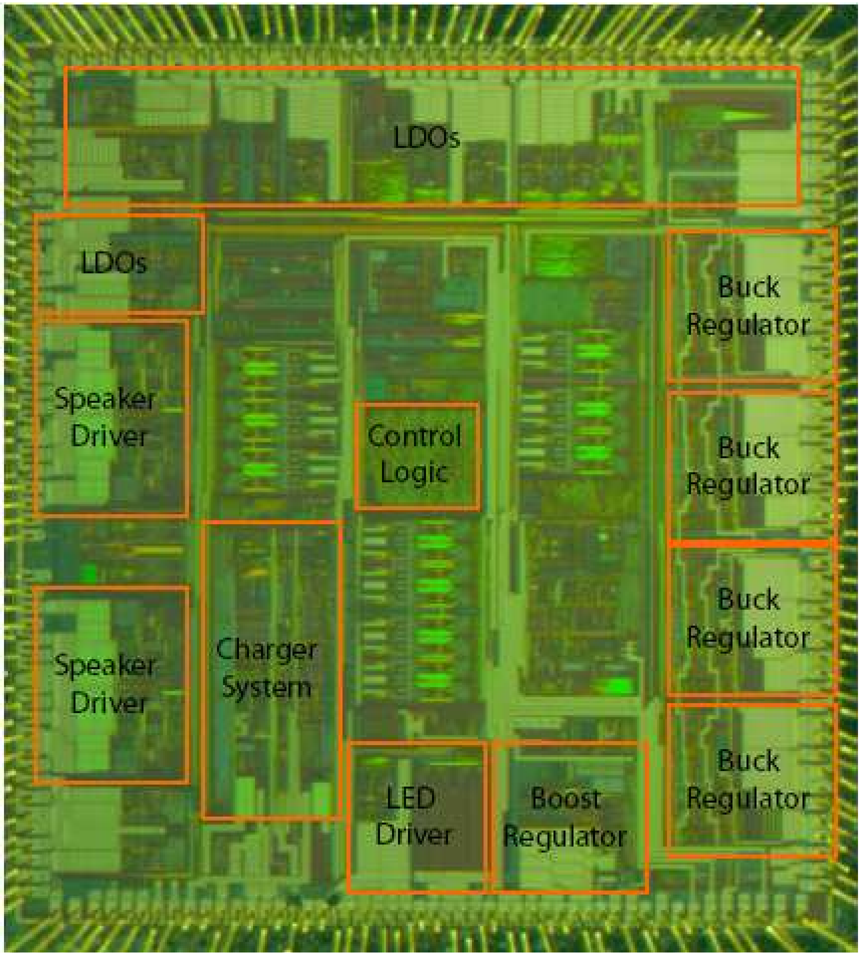
A System Solution in Portable Applications



Power Management Units (PMU)

- Integration to improve system flexibility
- Small package and small form of factor
  - Cost reduction
    - Package cost
    - BOM cost
  - Performance improvement
    - Efficiency
    - Easy sequence control

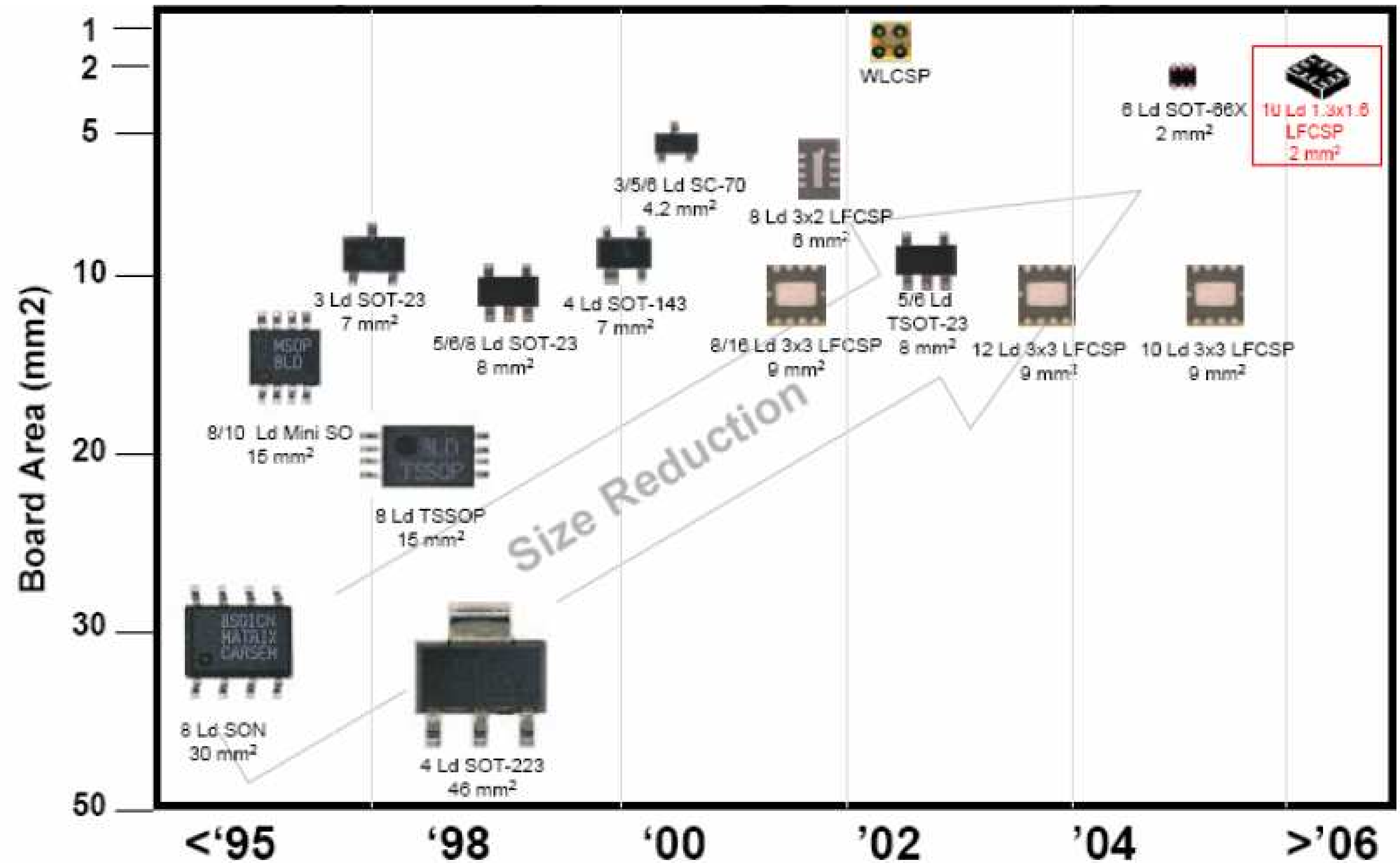
Product Example



Ref: C. Shi, CICC 2006, pp. 85-88

- Charger
- Switching regulators
  - buck
  - boost
  - buck/boost
  - inverter
- LDO
- Backlight driver
- Audio driver
- Ambient light sensor
- Touch panel sensor
- RTC
- Sequence control
- Voltage monitor and supervisory

Package Roadmap



WLCSP Solution

- Package size is as large as die size

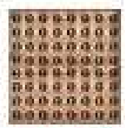
Cost

VS.

Size

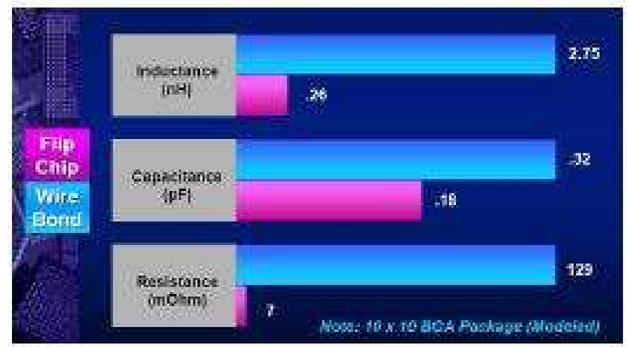
6mm x 6mm

VS.



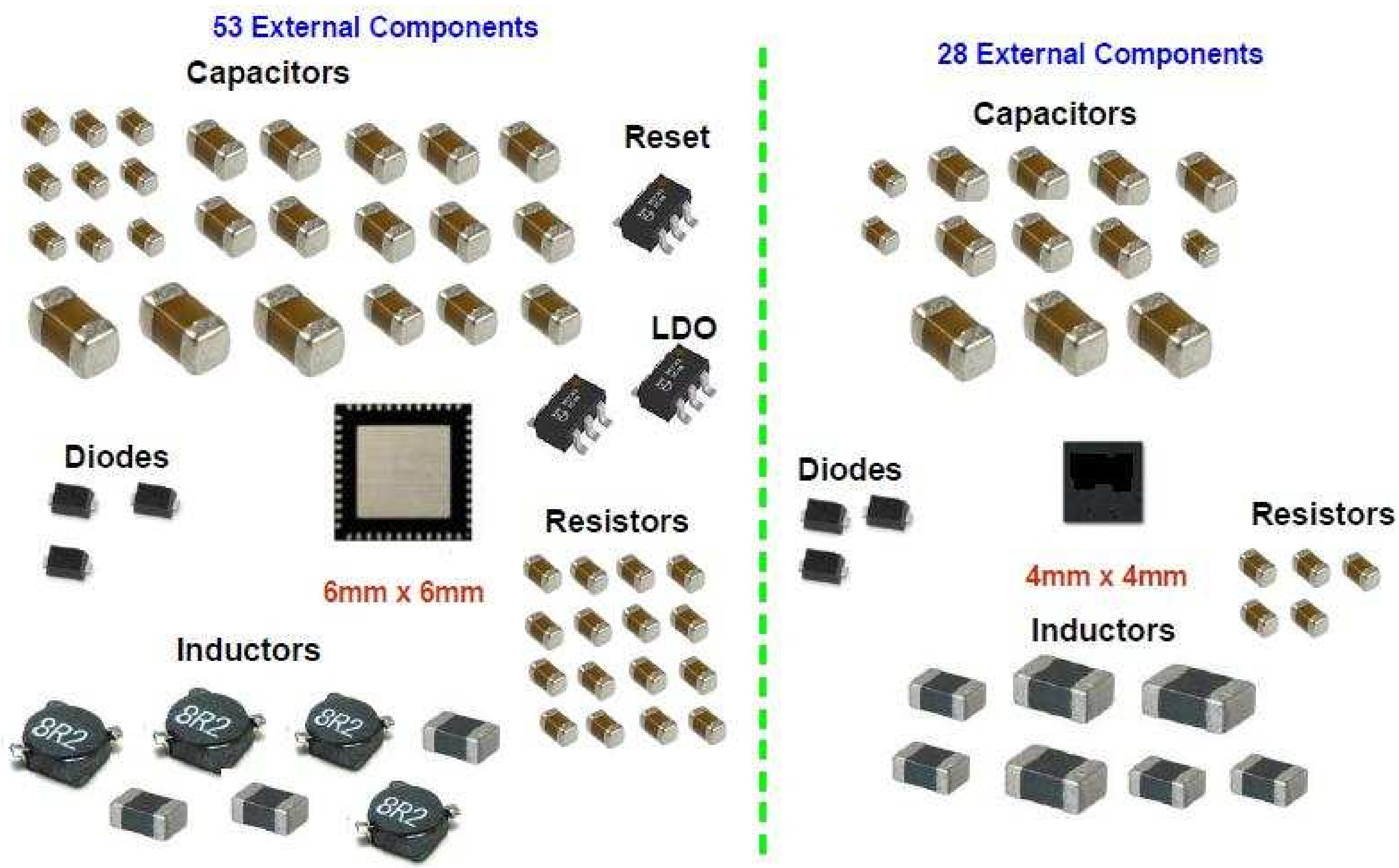
4mm x 4mm

Performance



Lower Rdson = Better Efficiency

BOM Reduction



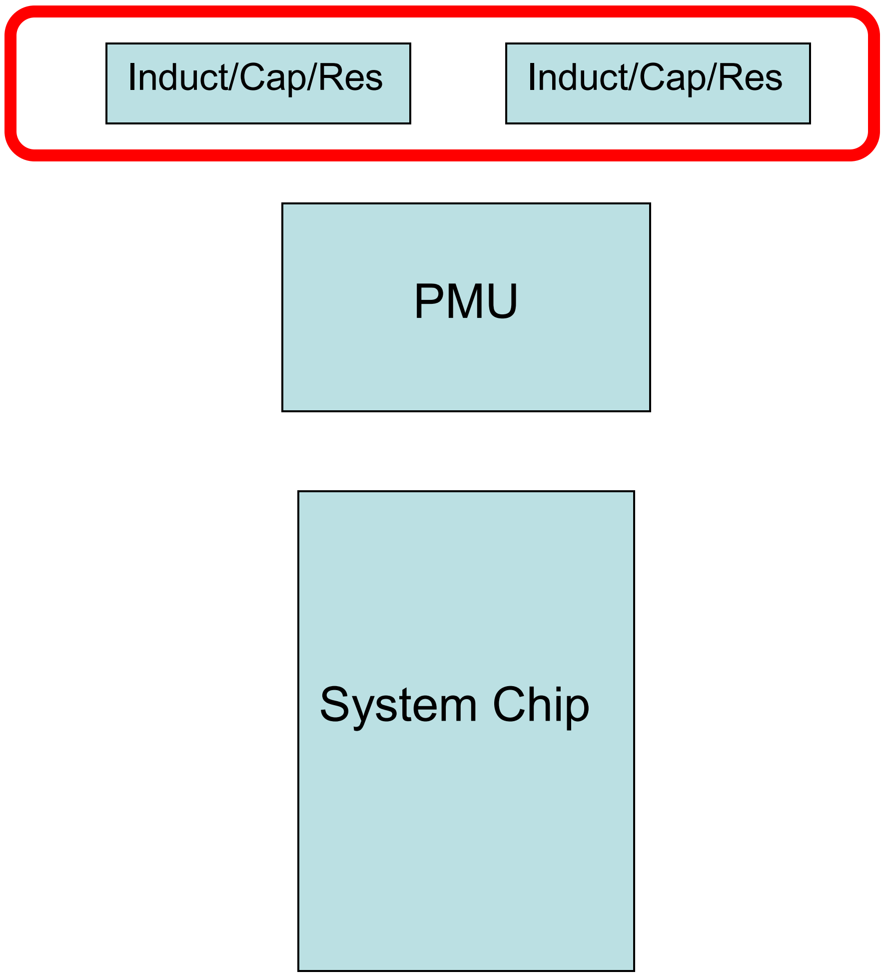
PMU Topics

- Trend
  - More functions/high density
  - Smaller/thinner/cheaper package
  - Higher frequency
- Issue
  - Thermal
  - Noise coupling and crosstalk
  - Design challenge in high switching frequency
    - Current sensing for current mode control

PMU Design Considerations

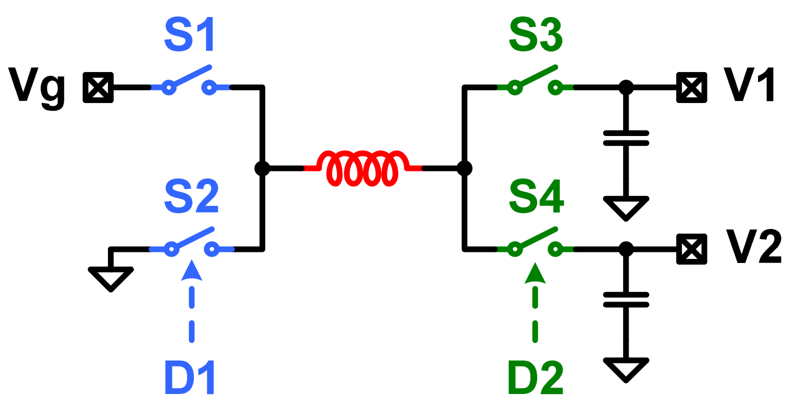
- System optimization, not chip optimization
- Power and analog supply separation
- Layout strategy
  - Power stage position
  - Crosstalk between channels
  - Guardring and sensitive line routing

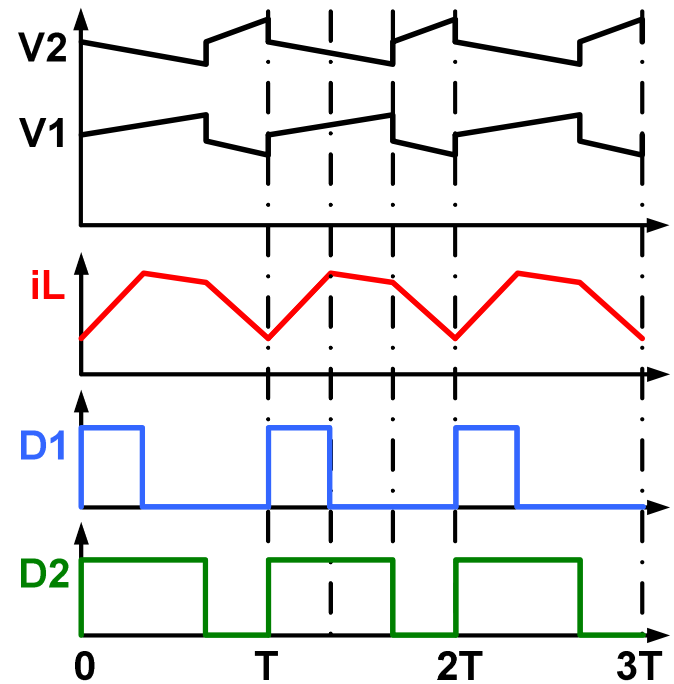
A System Solution in Portable Applications



Reduce External Inductor

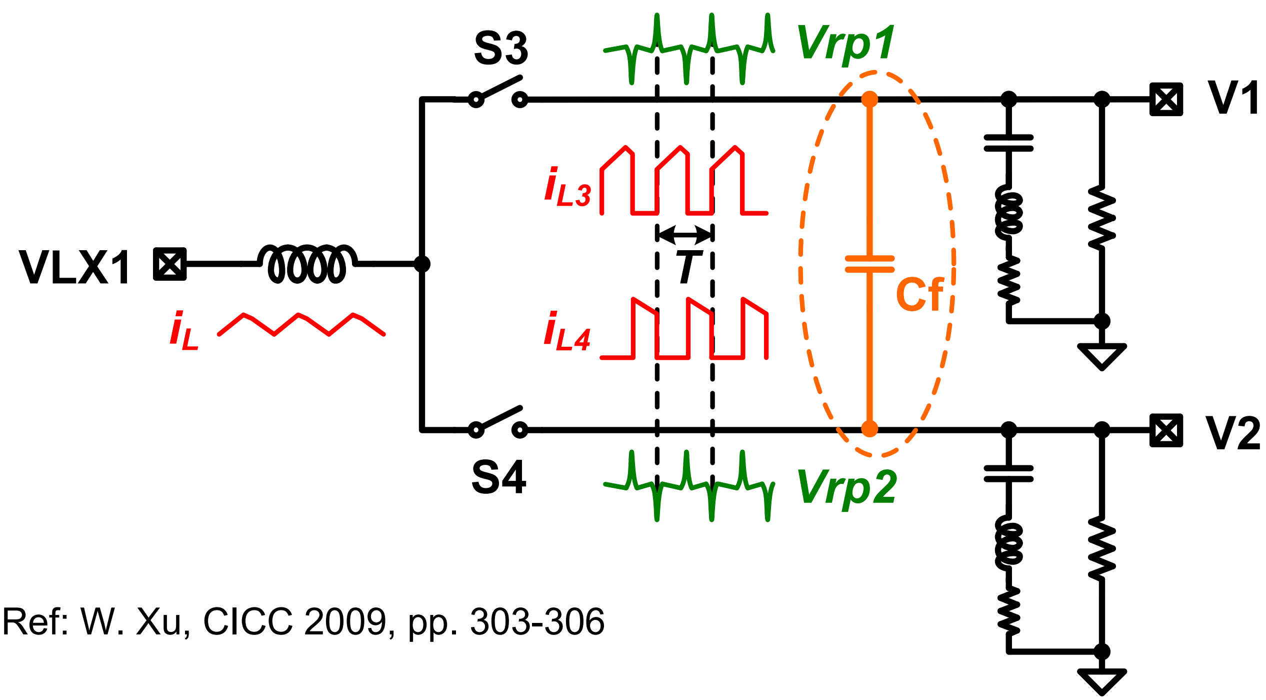
- Single-inductor multiple-output converter
  - Input switches : regulate total energy
  - Output switches: distribute energy
- SIDO buck example





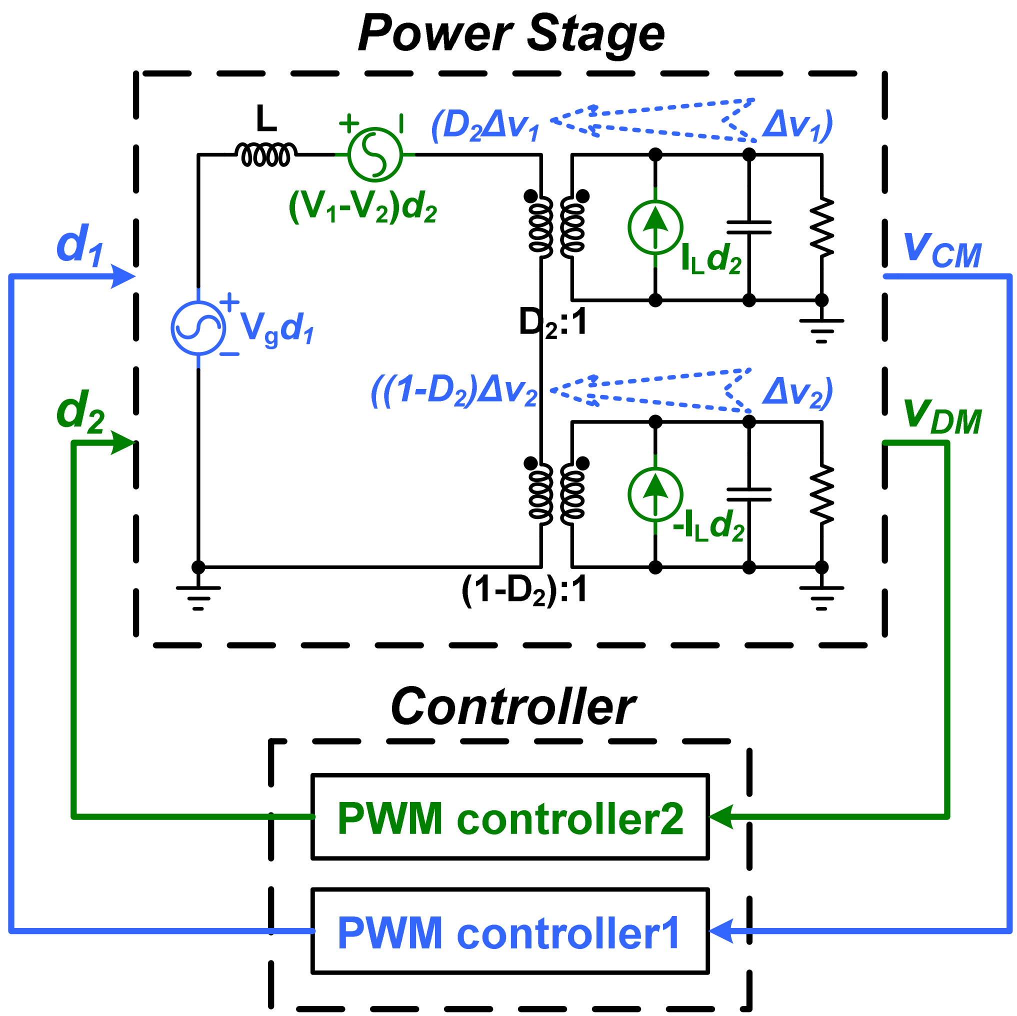
SIMO Ripple: Fly Capacitor

- Ripples and spikes of SIDO buck converter
  - Caused by parasitic ESR and ESL
  - Inverse phase: Vrp1 = -Vrp2
- A fly capacitor across two outputs with a servo common mode control

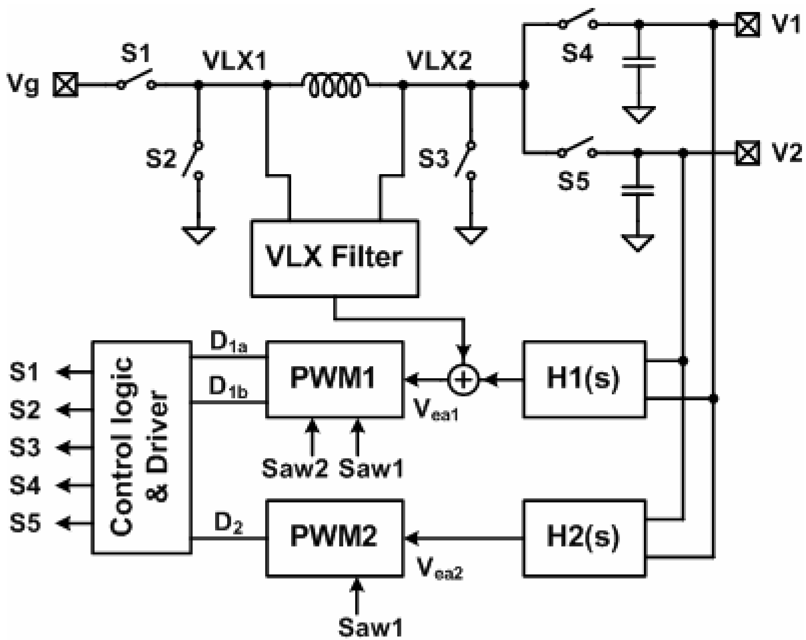


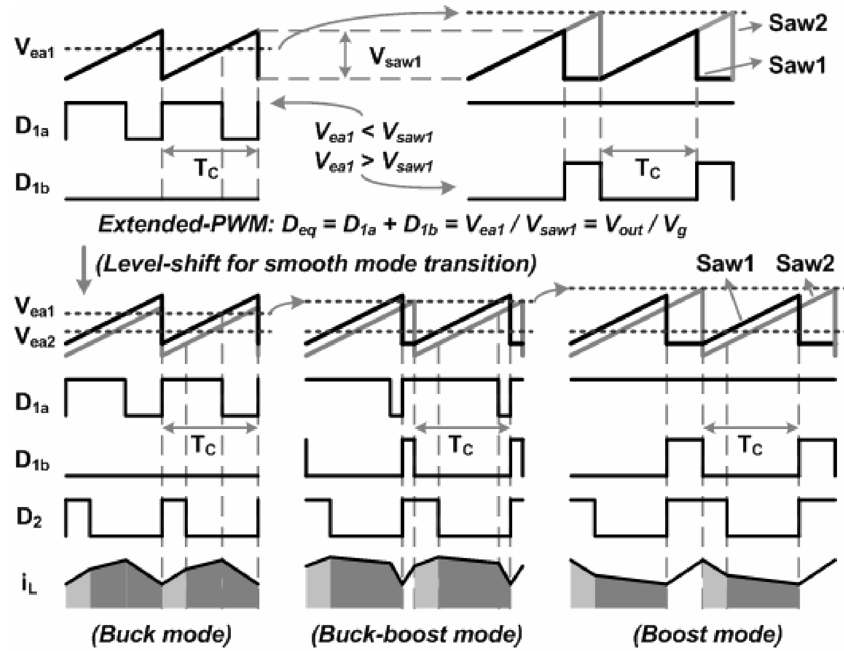
Ref: W. Xu, CICC 2009, pp. 303-306

Multi-Loop Feedback System



Extended-PWM (EPWM) control

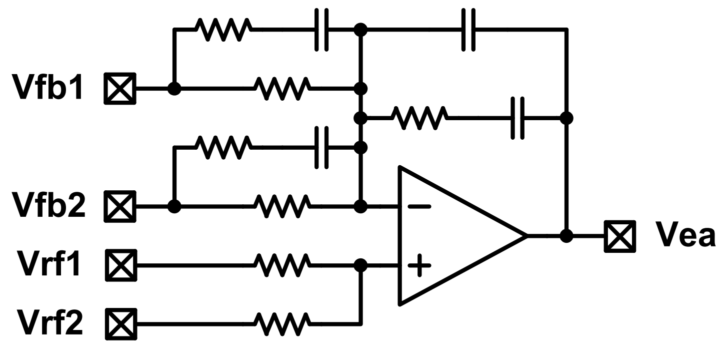


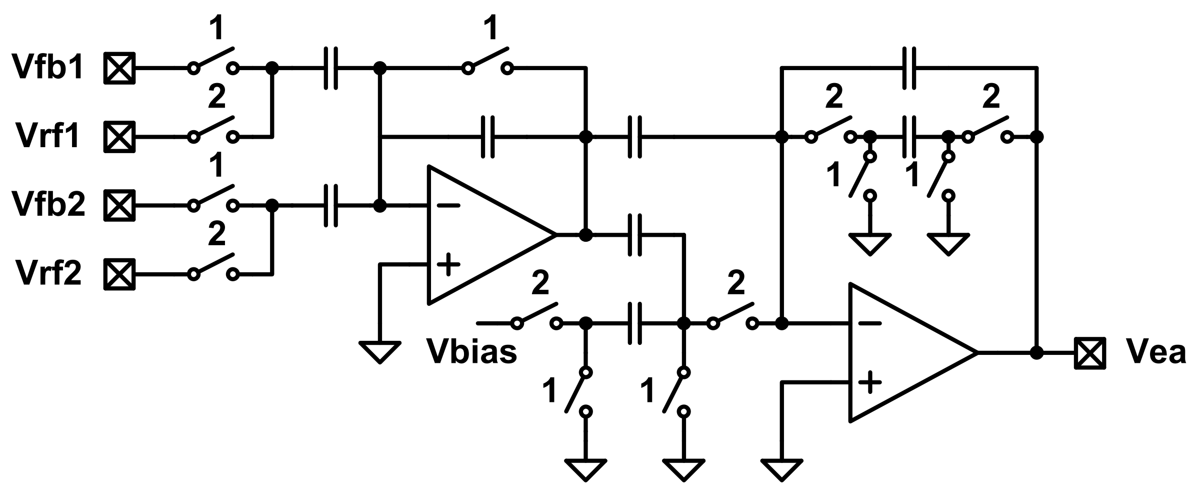


Ref: W. Xu, ISSCC 2011

Loop Compensation

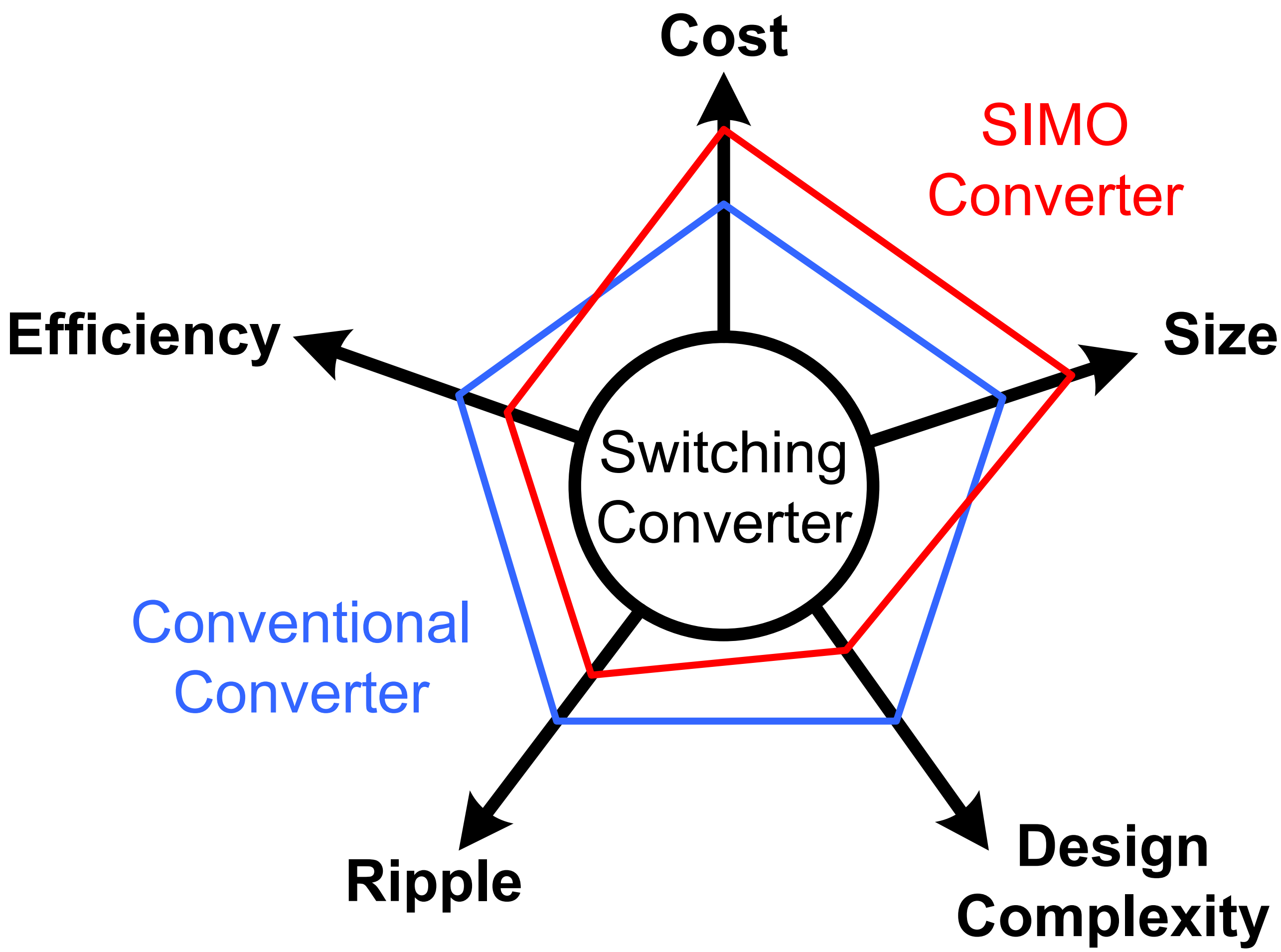
- Continuous vs. Discrete-time



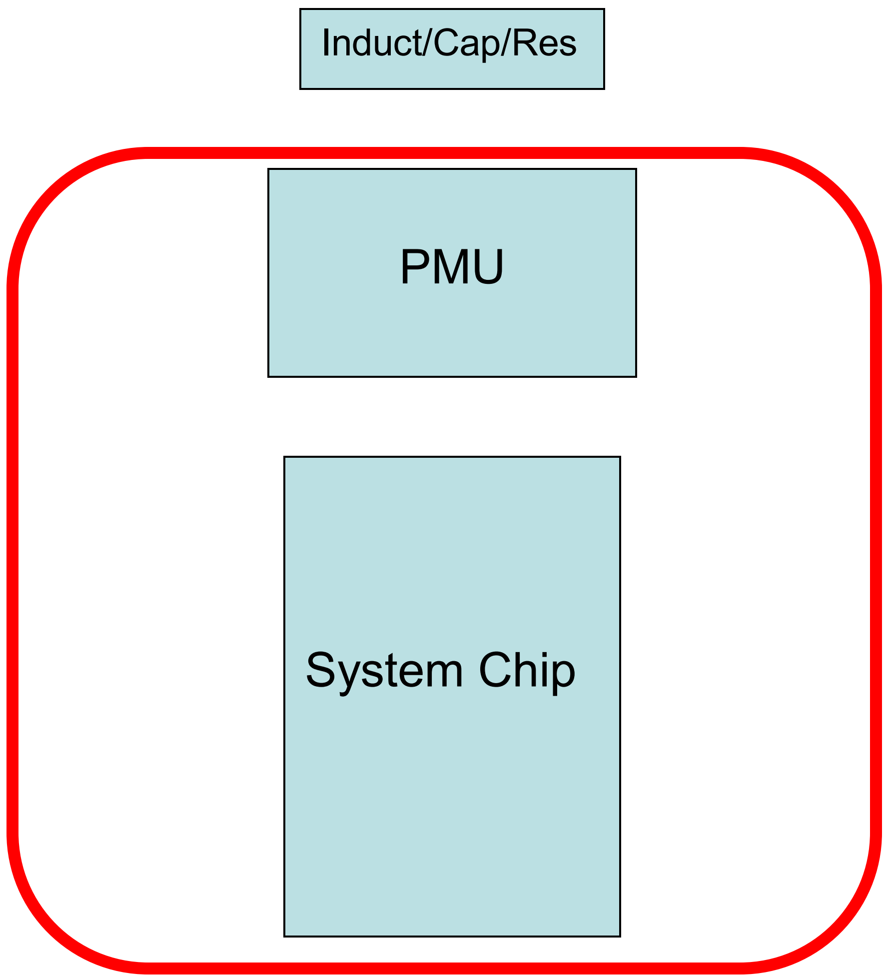


Ref: M. Belloni, ISSCC 2008, pp. 444-445

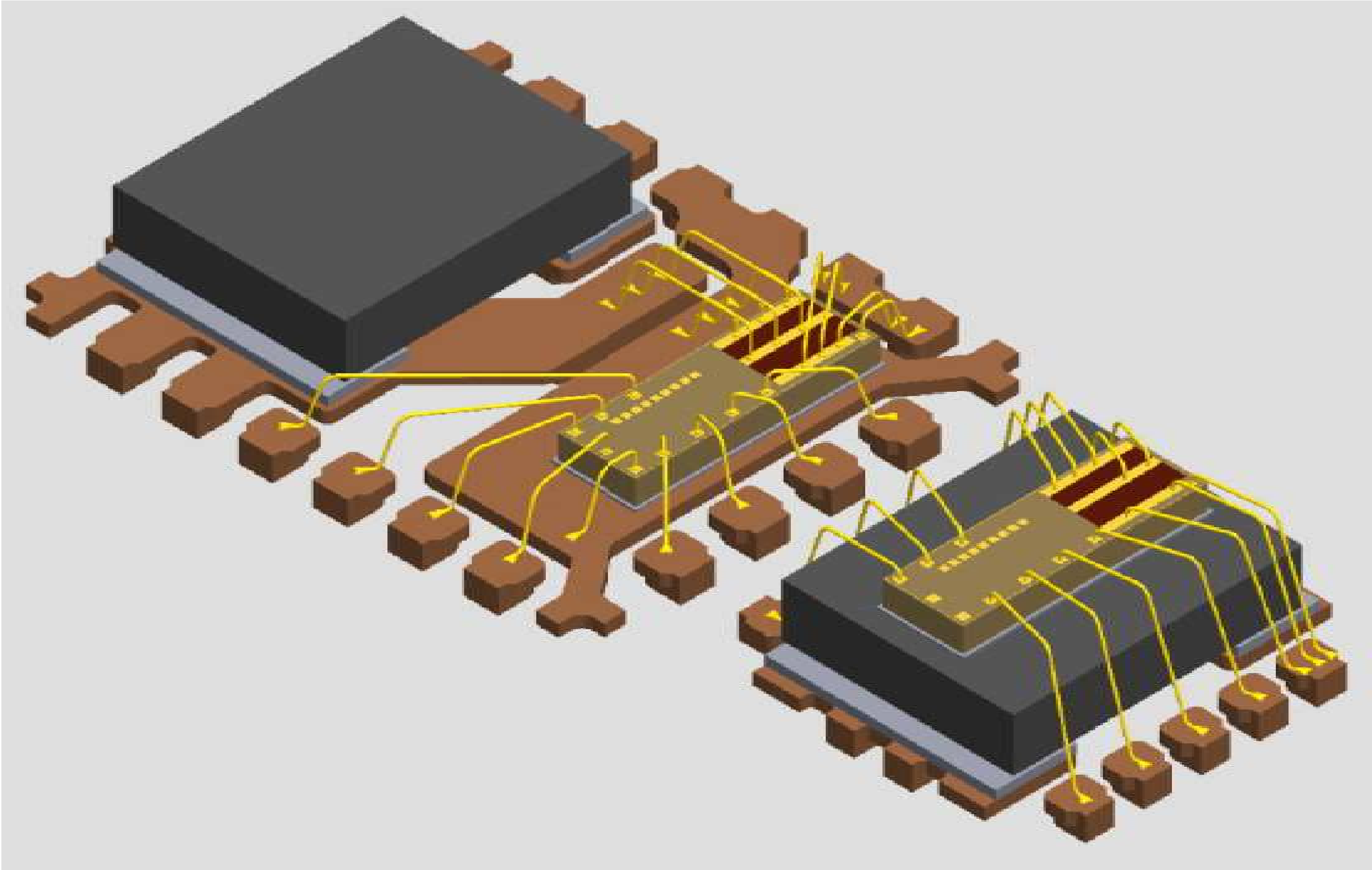
SIMO: Trade-off



A System Solution in Portable Applications

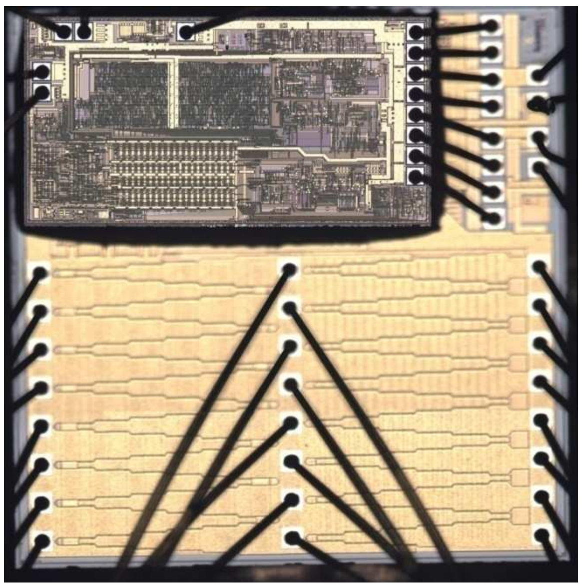


System in Package (SiP)

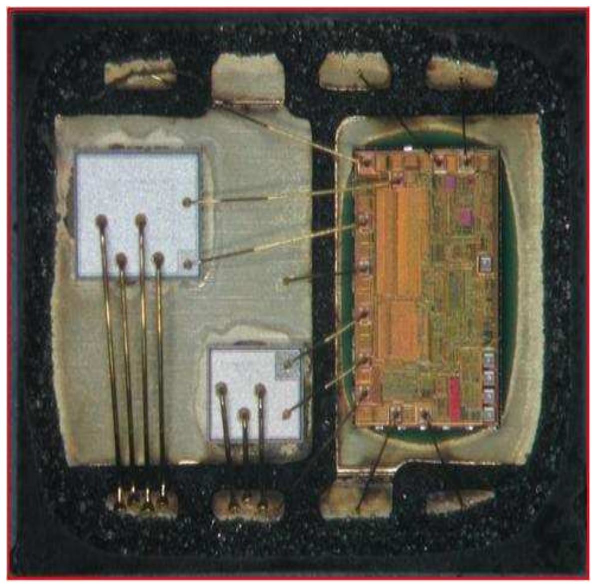


Ref: Lotfi, IEEE APEC 2010

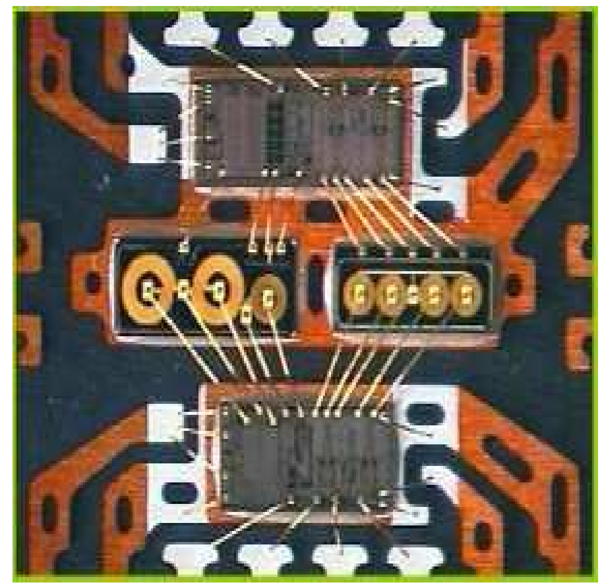
SiP: Stack & Side



Controller + Power transistor



Controller + Power transistor



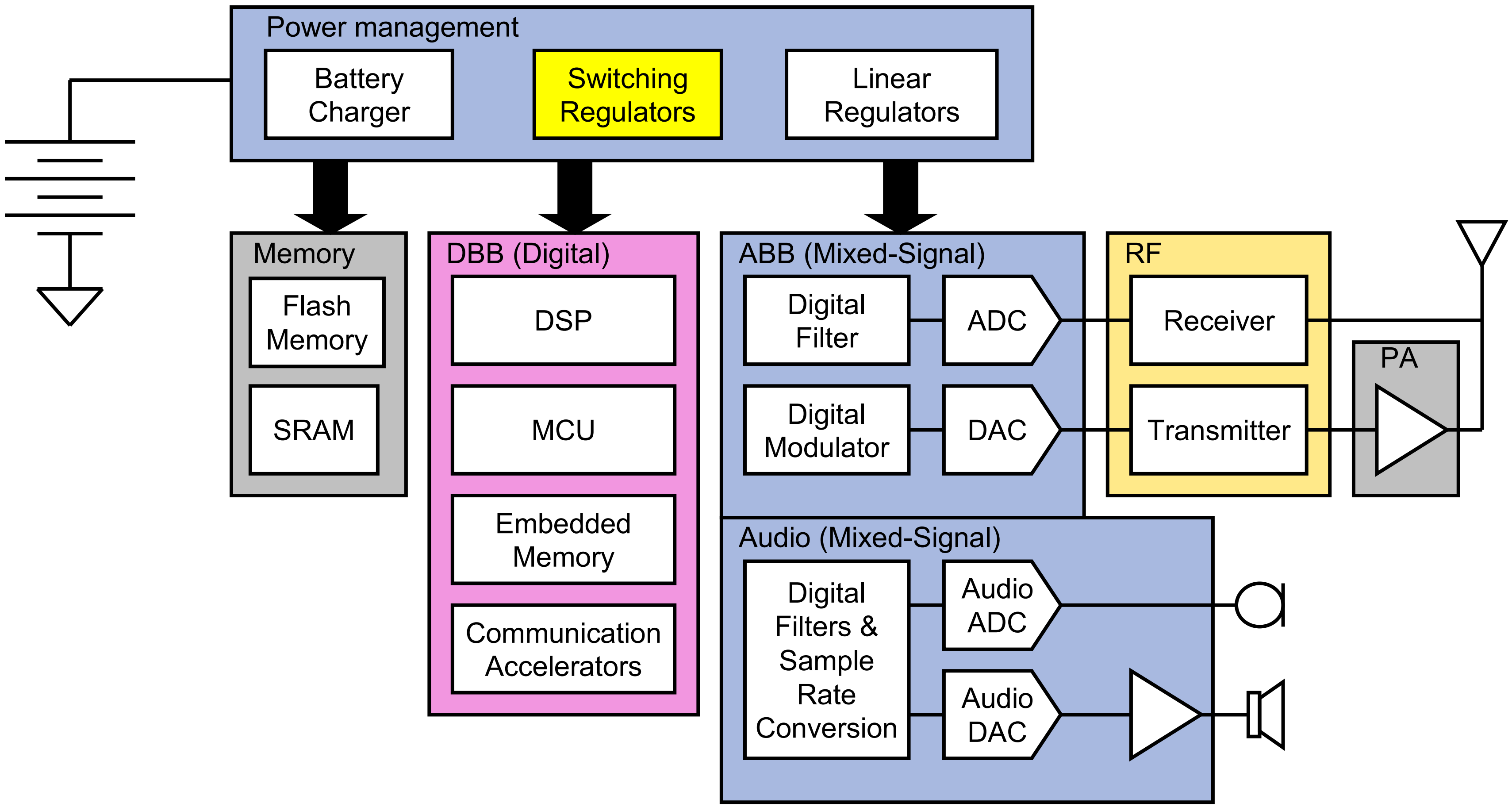
Regulator + Inductor

Ref: B. Chen, IEEE APEC 2010

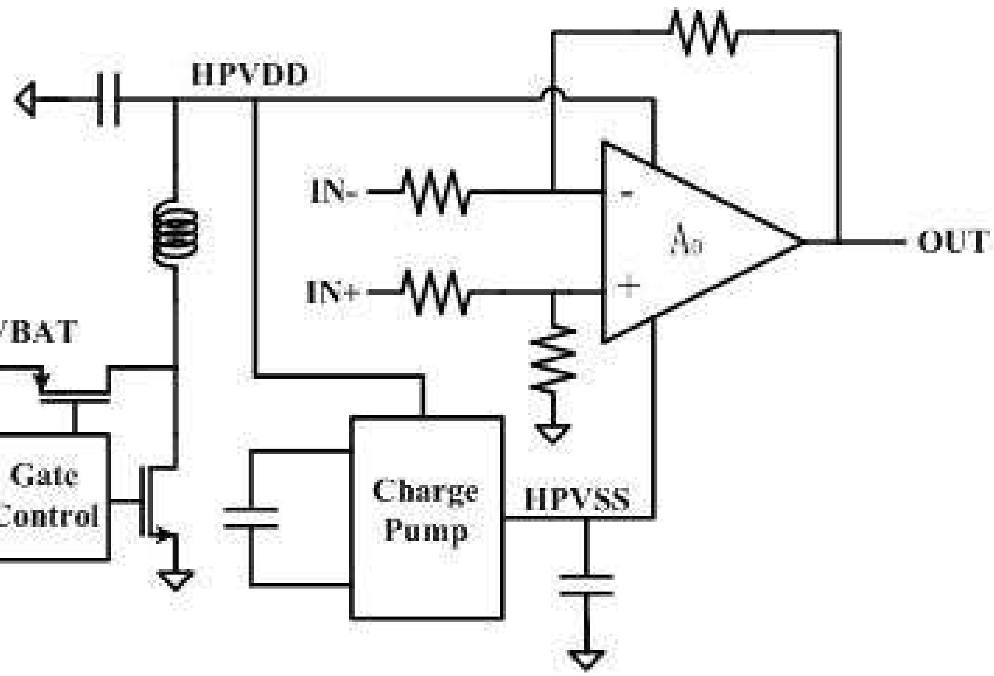
SiP Technique

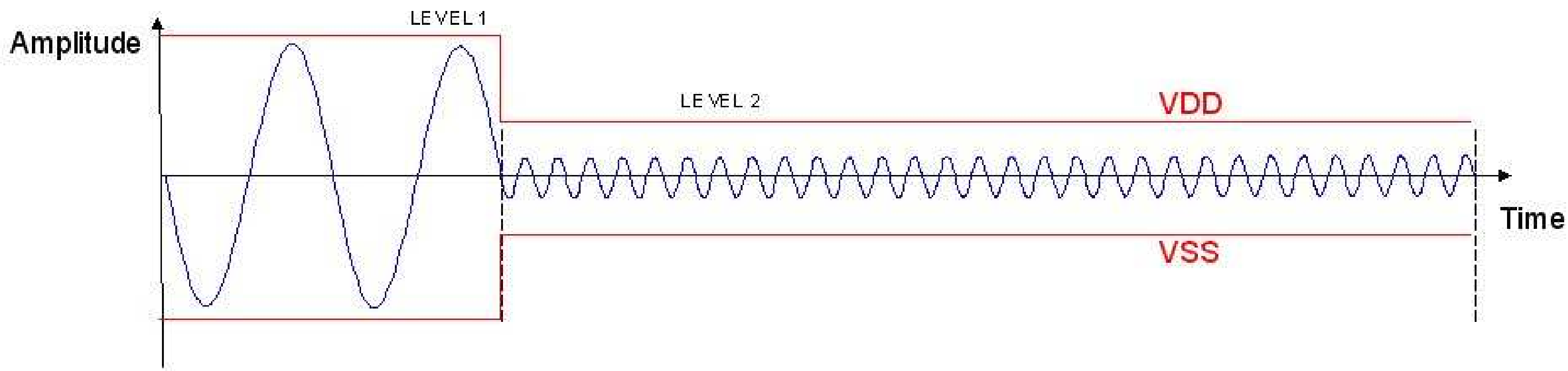
- Now
  - Magnetic materials on silicon
    - Inductance <100nH
    - Switching frequency > 20MHz
  - Regulator with integrated inductor
    - Assembly with standard MCM process
- Future
  - Increase the integration density
  - Multi die to single die

Embedded Power

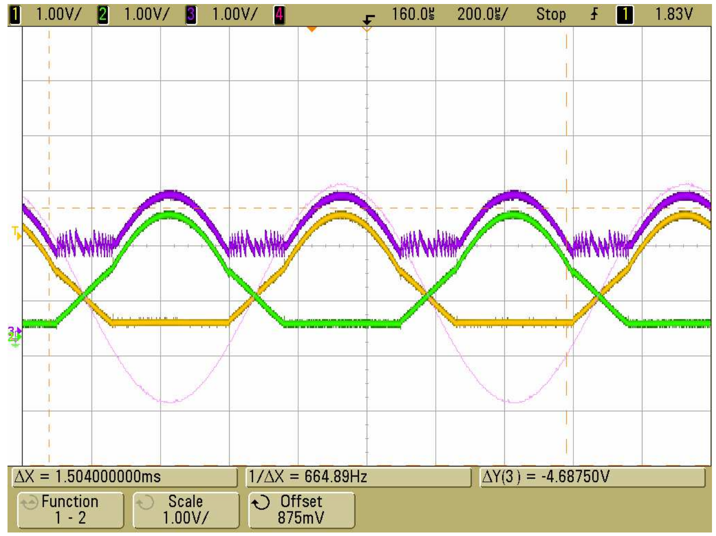


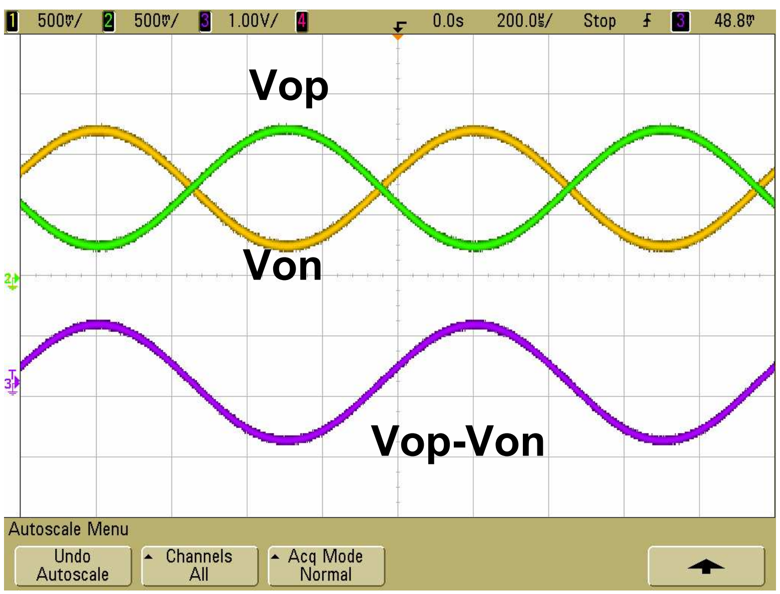
Class G / Class I

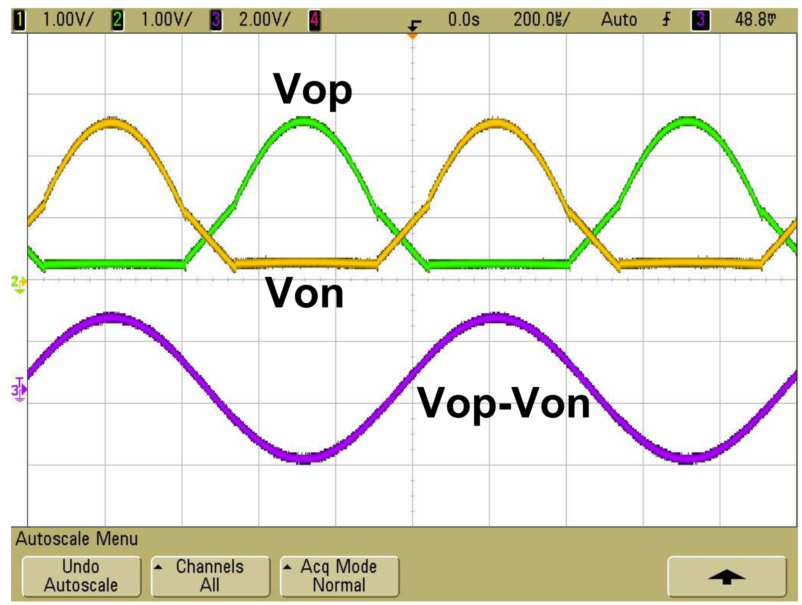




Output Waveforms of class G



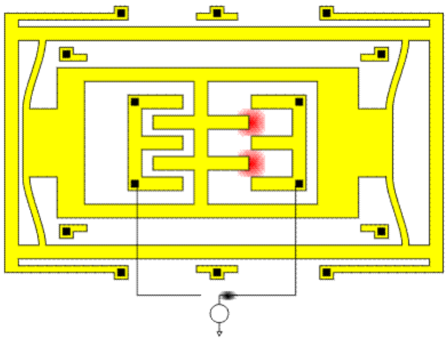




(a) Vout,pp=2V

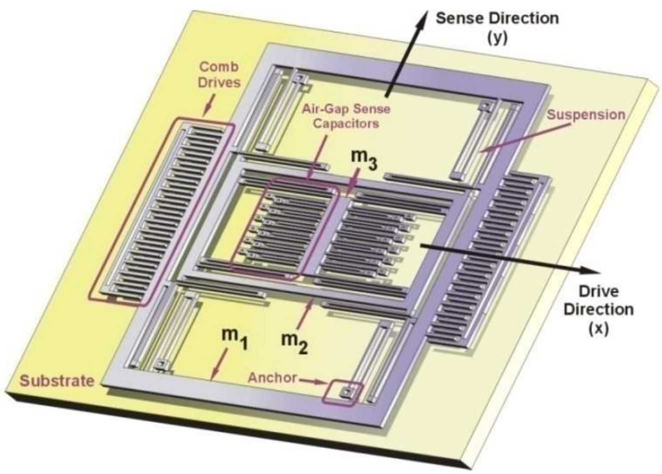
(b) Vout,pp=4.8V

HV in MEMS



- Low Insertion Loss
- High Linearity
- High Isolation

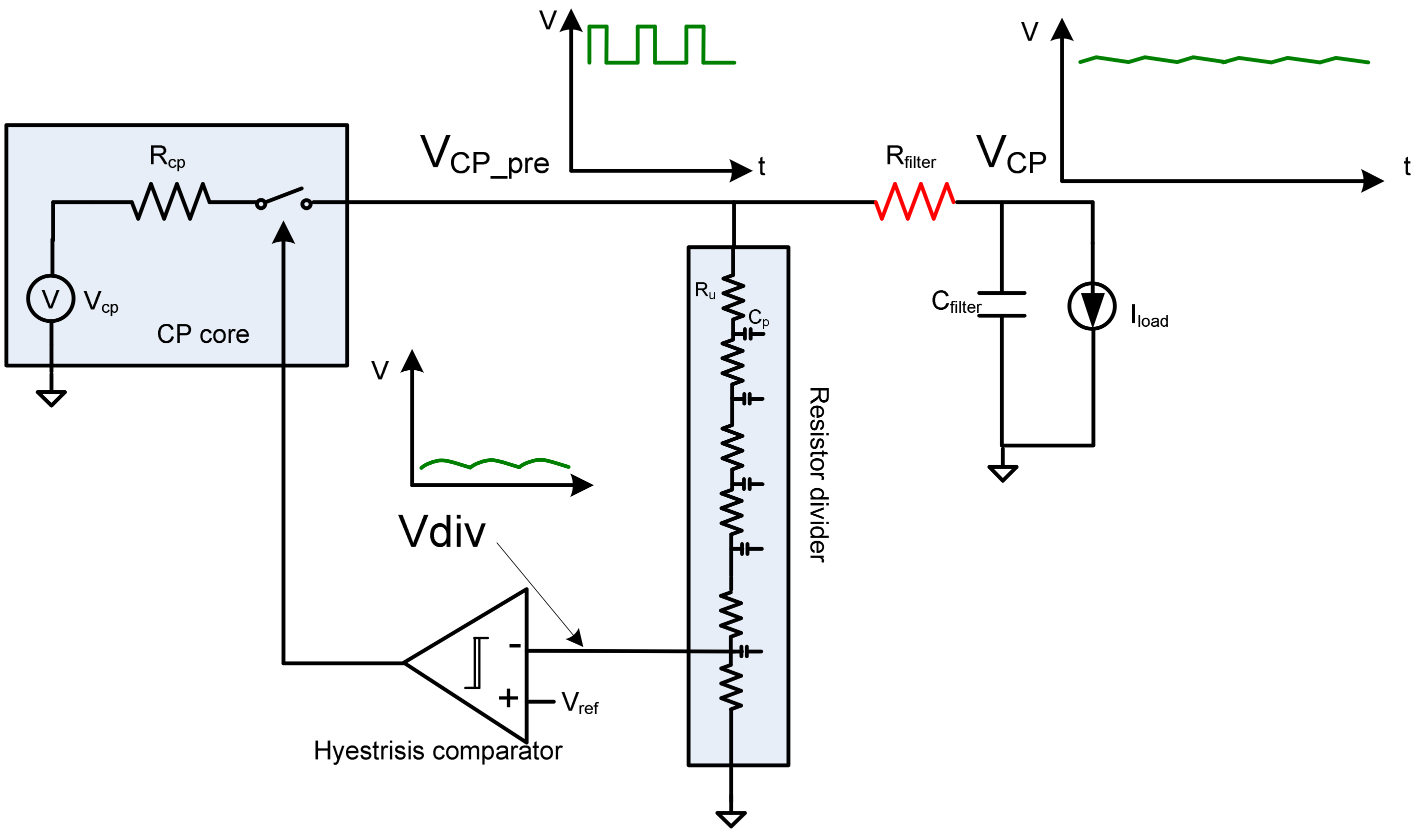
- MEMS Gyroscope
  - Mechanical Structure of gyro needs to be driven by HV electrostaticsly.
  - Coriolis signal $\propto$ Force $\propto$ V^2
  - Increased SNR



How to Generate the HV

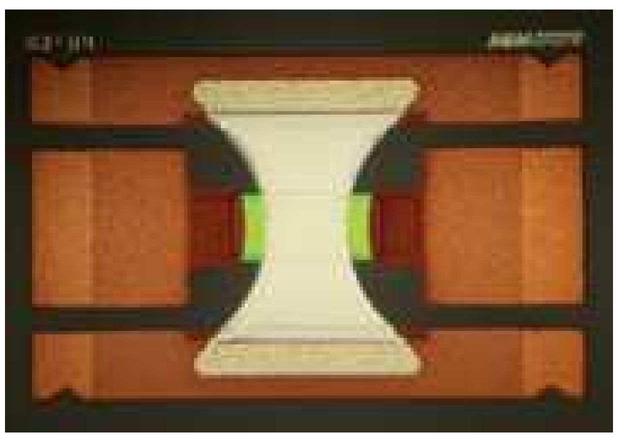
- Inductor based
  - Expensive
  - Two pinouts
- Capacitor based
  - One pinout
  - Integrated capacitor can be used as the MEMS capacitance drops while its process improves
  - ~100uA

Integrated HV Charge Pump

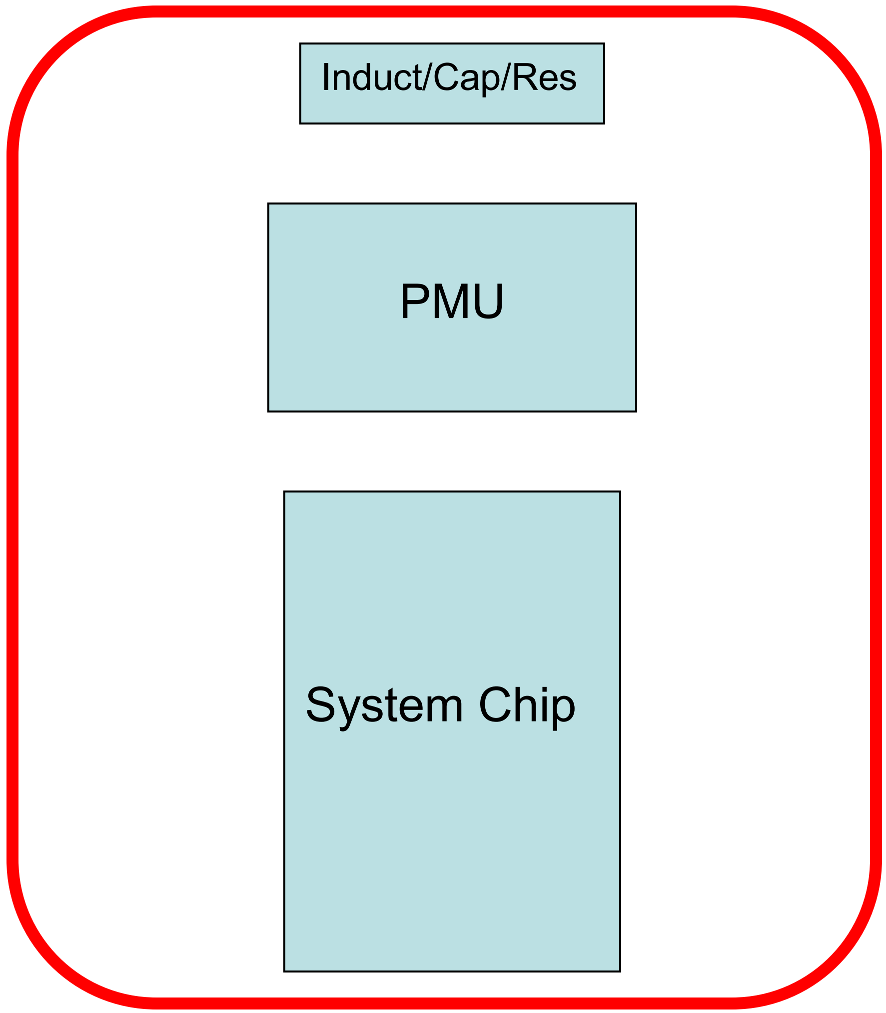


Other Applications of HVCP

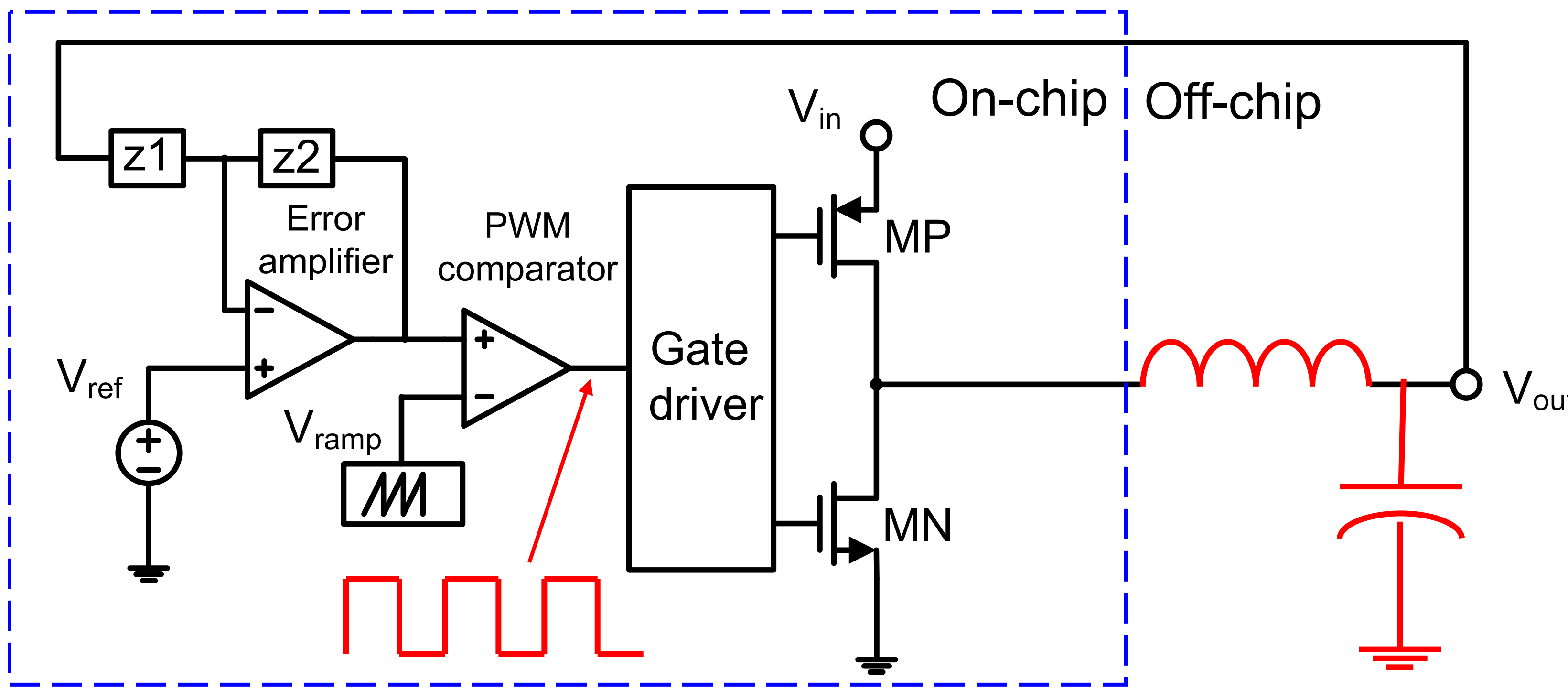
- E^2PROM
- Flash Memory
- MEMS Switches
- Liquid Crystal Lens Driver
- More...



A System Solution in Portable Applications

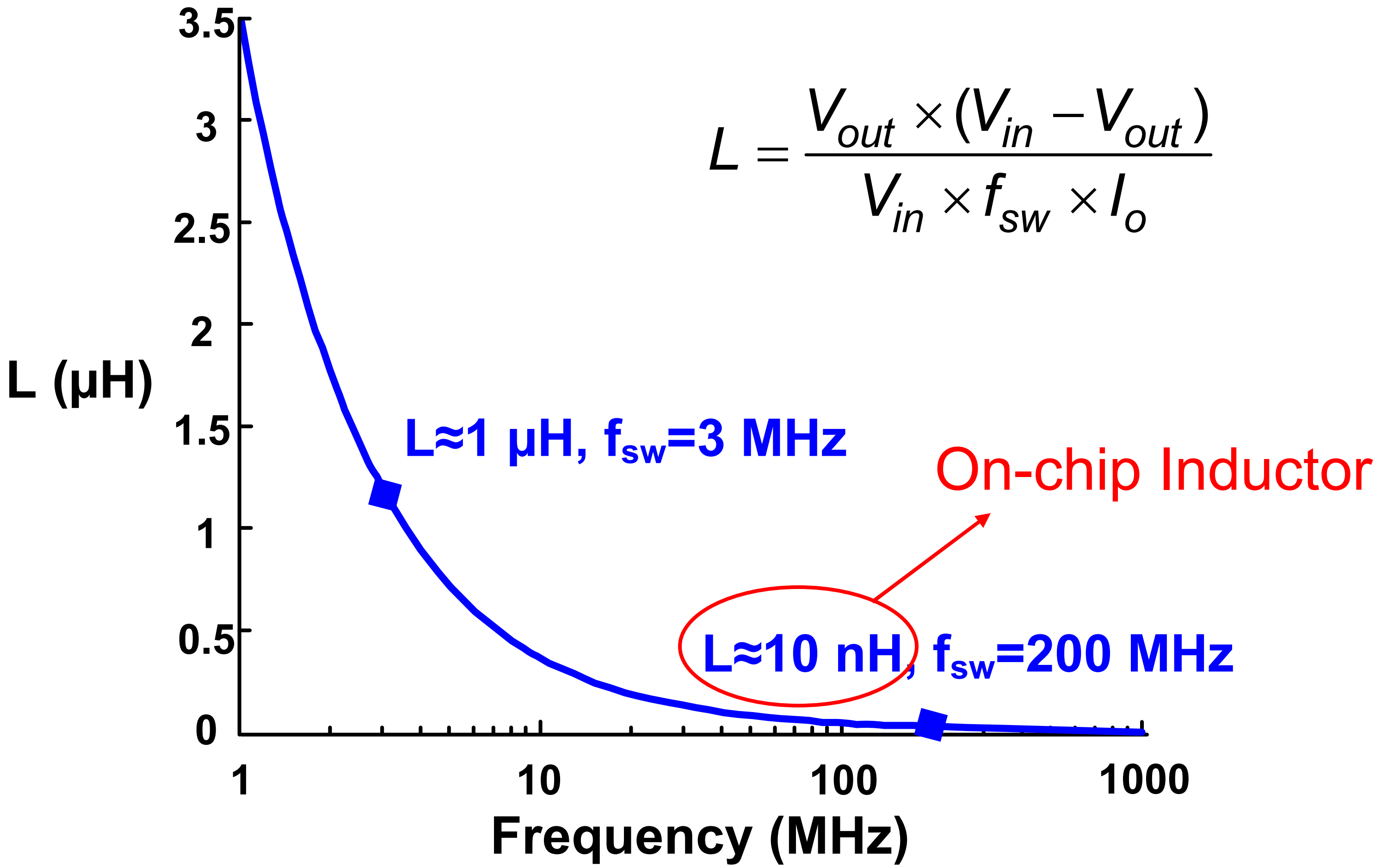


Motivation



- Integrated DC-DC converters are needed with SOC and on-chip power scaling

Inductance *vs* Frequency

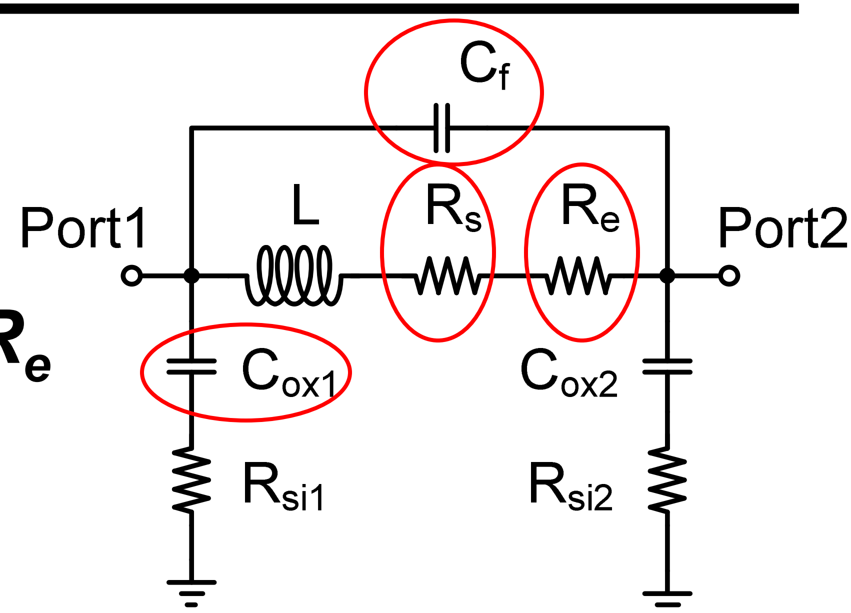


Challenge: low Quality factor results in low power efficiency

Q-factor *vs* Power Efficiency

- Parasitic resistances
  - Metal resistance: $\boldsymbol{R_s}$
  - Substrate resistance: $\boldsymbol{R_e}$

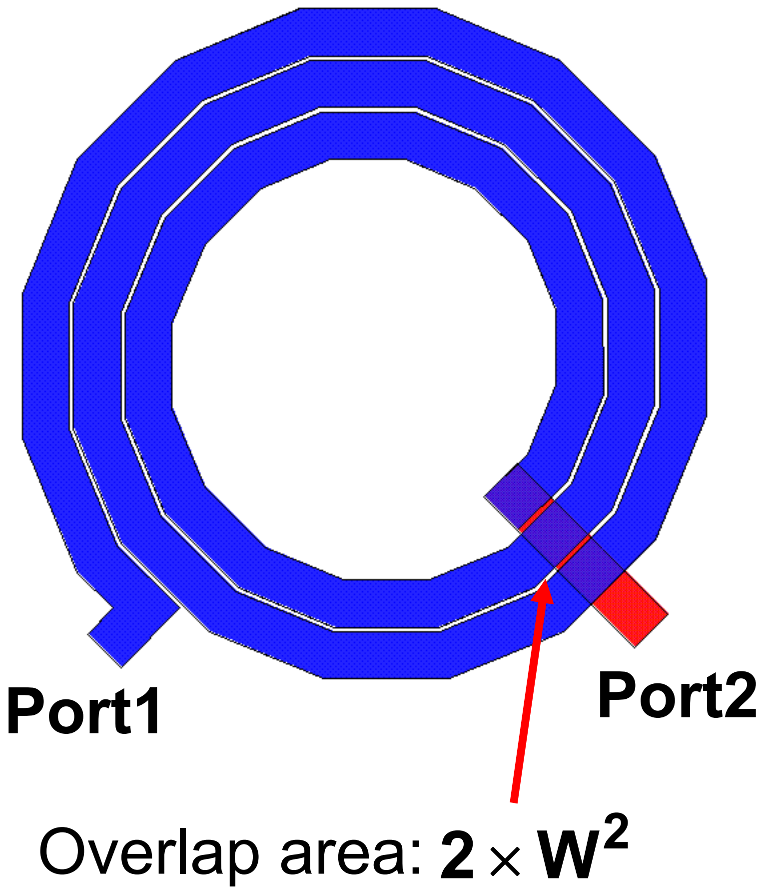
$$P_{con} = I_{rms}^{2} \times R$$



- Parasitic capacitances
  - Spiral-to-substrate capacitance: $\boldsymbol{C_{ox}}$
  - Spiral-to-underpass overlap capacitance: $\boldsymbol{C_f}$

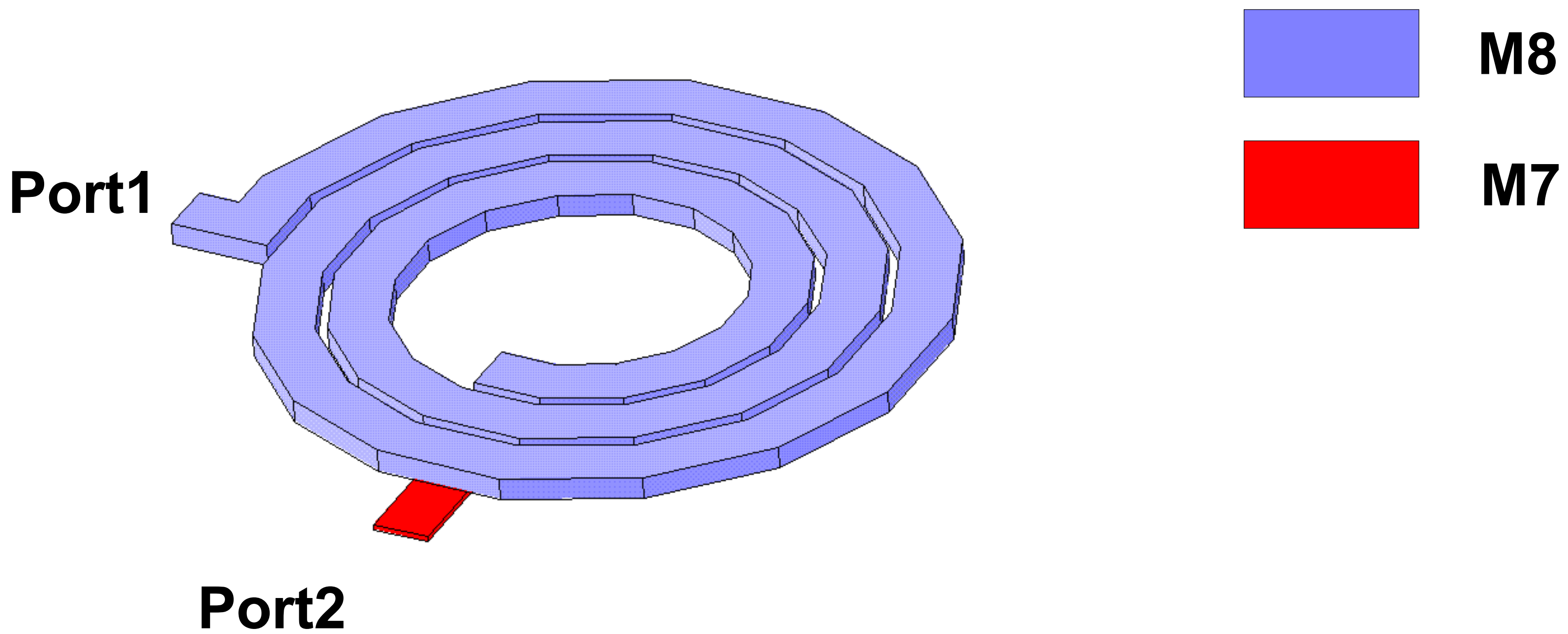
$$P_{sw} = C \times V^2 \times f_{sw}$$

Top View of the Inductor



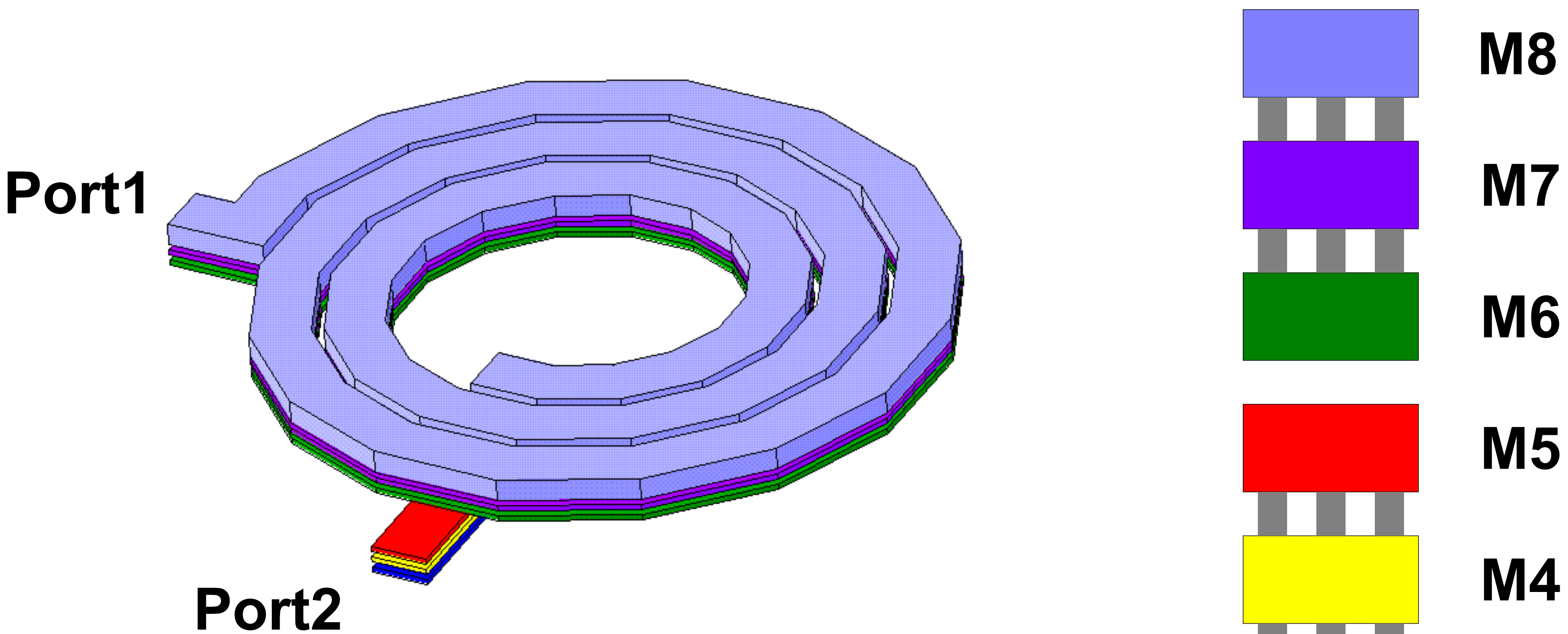
- Number of sides=16
- Number of turns=2.75
- Metal width=100 μm
- Inner diameter=800 μm

Cross-section View



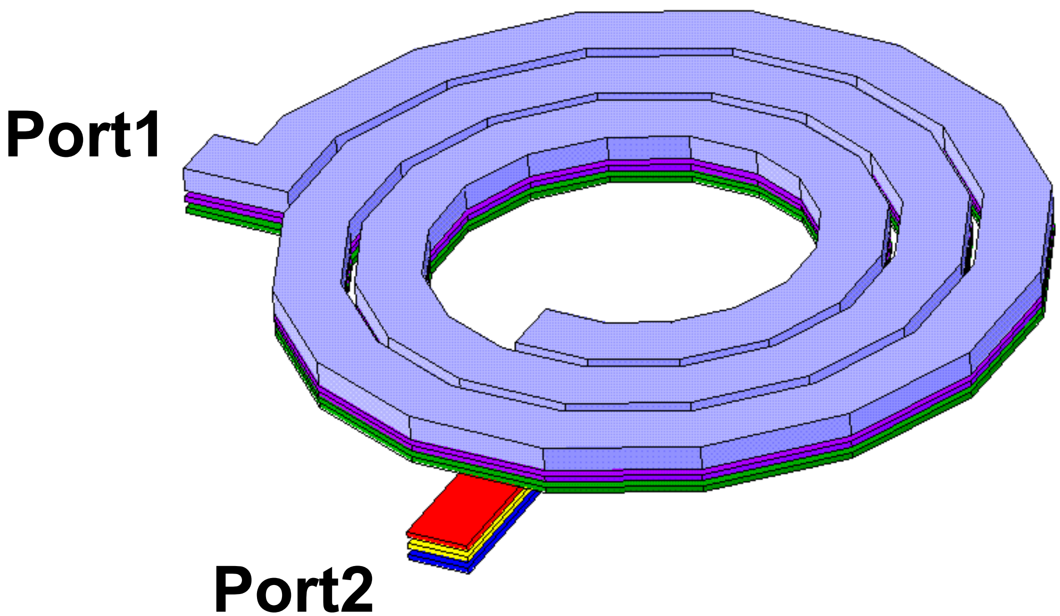
- Basic structure, low quality factor
- We should take advantage of the eight copper layers available in the process!

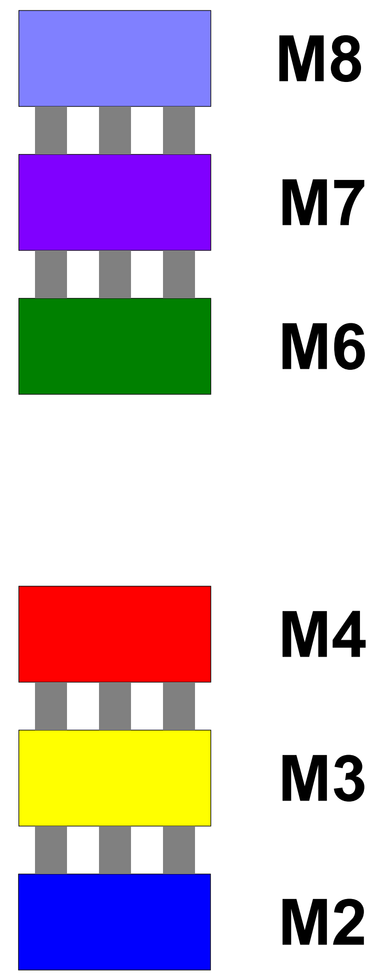
Multi-layer Winding



– Multi-layer winding can reduce the series resistance R_s

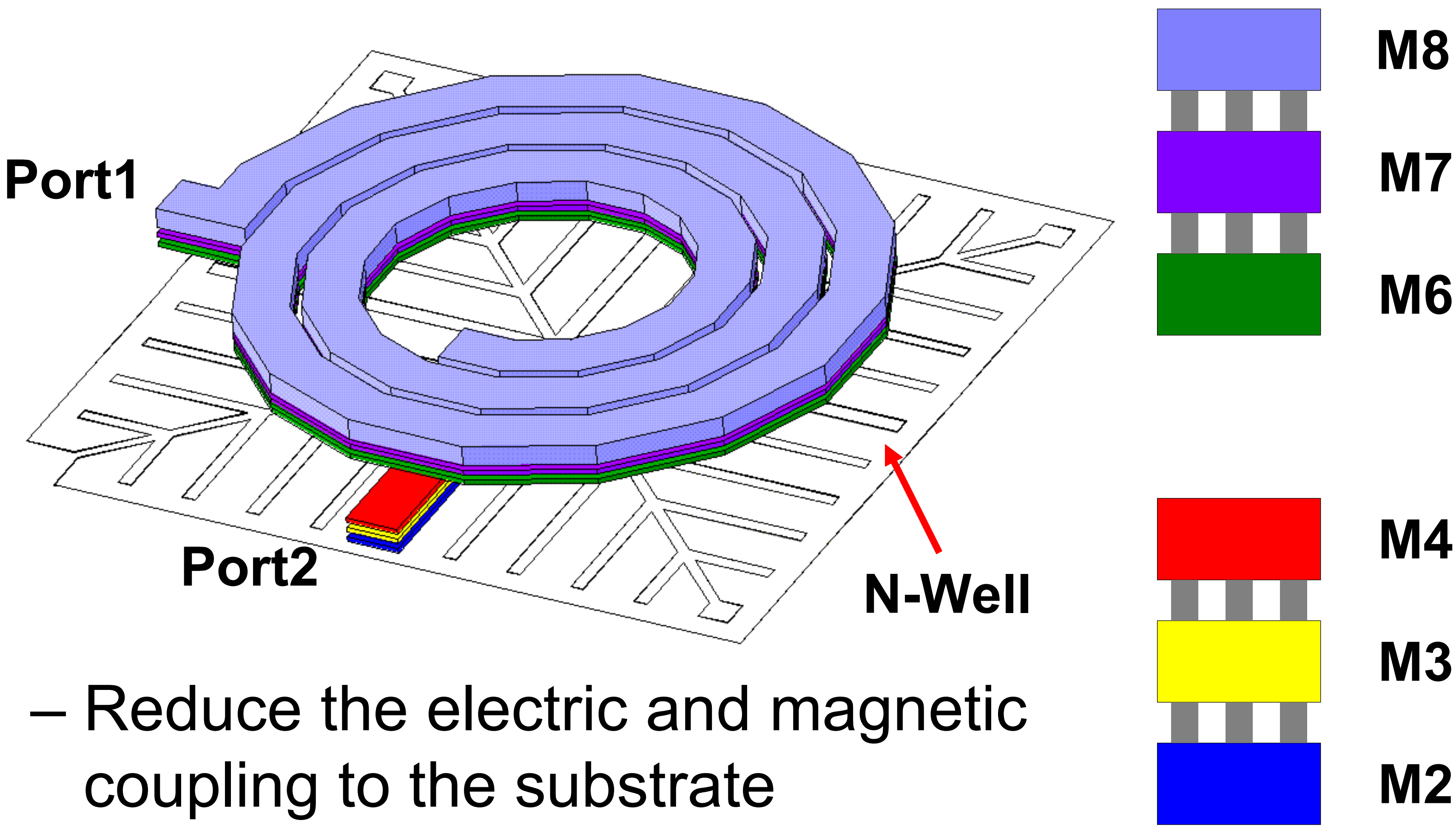
M6-to-M4 Spacing





– M6-to-M4 spacing can reduce the overlap capacitance C_f

Patterned N-Well

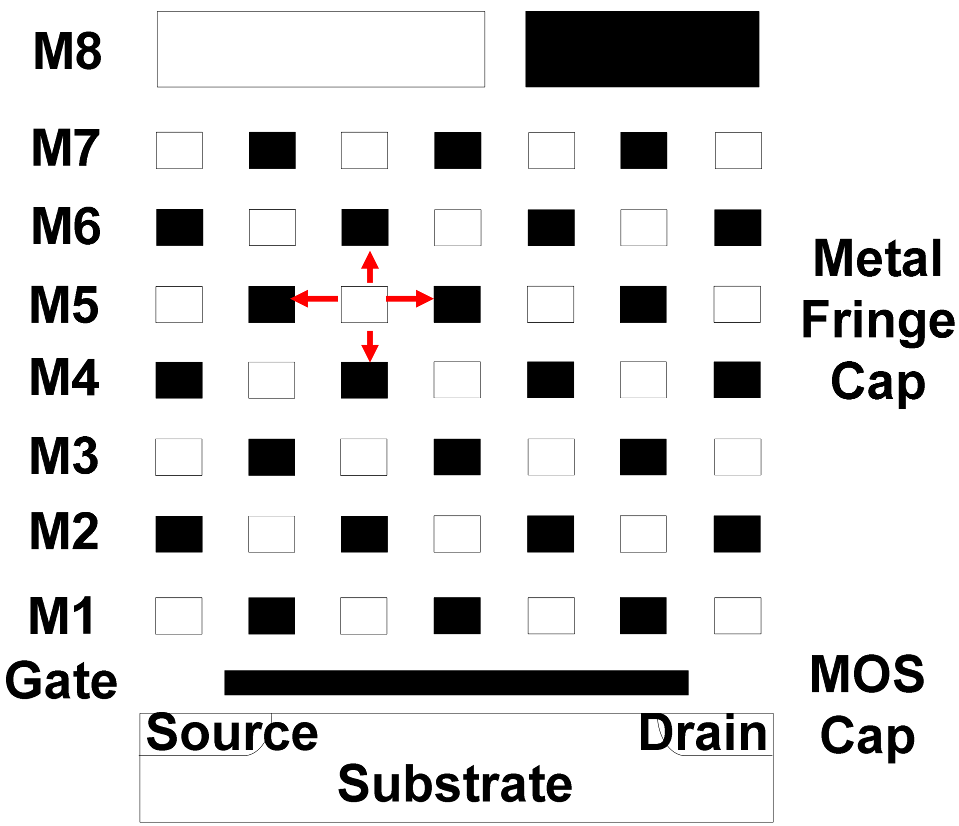


– Reduce the electric and magnetic coupling to the substrate

Performance of the Inductor

	Process	Material	L	R_{series}	$C_{parasitic}$
JSSC07 [1]	0.35μm	0.02 Ω/square Aluminum	22nH	2.5 Ω	25 pF
ESSCIRC08[5]	0.13μm	2 μm Copper+ 1.2 μm Aluminum	9.8nH	1.6 Ω	—
CICC08[3]	0.18μm	Golden bond wire	18nH	1 Ω	—
This work	0.13 μm	3+0.385+0.385 μm Copper	10.5nH	1.2 Ω	3 pF

Improve Area Efficiency

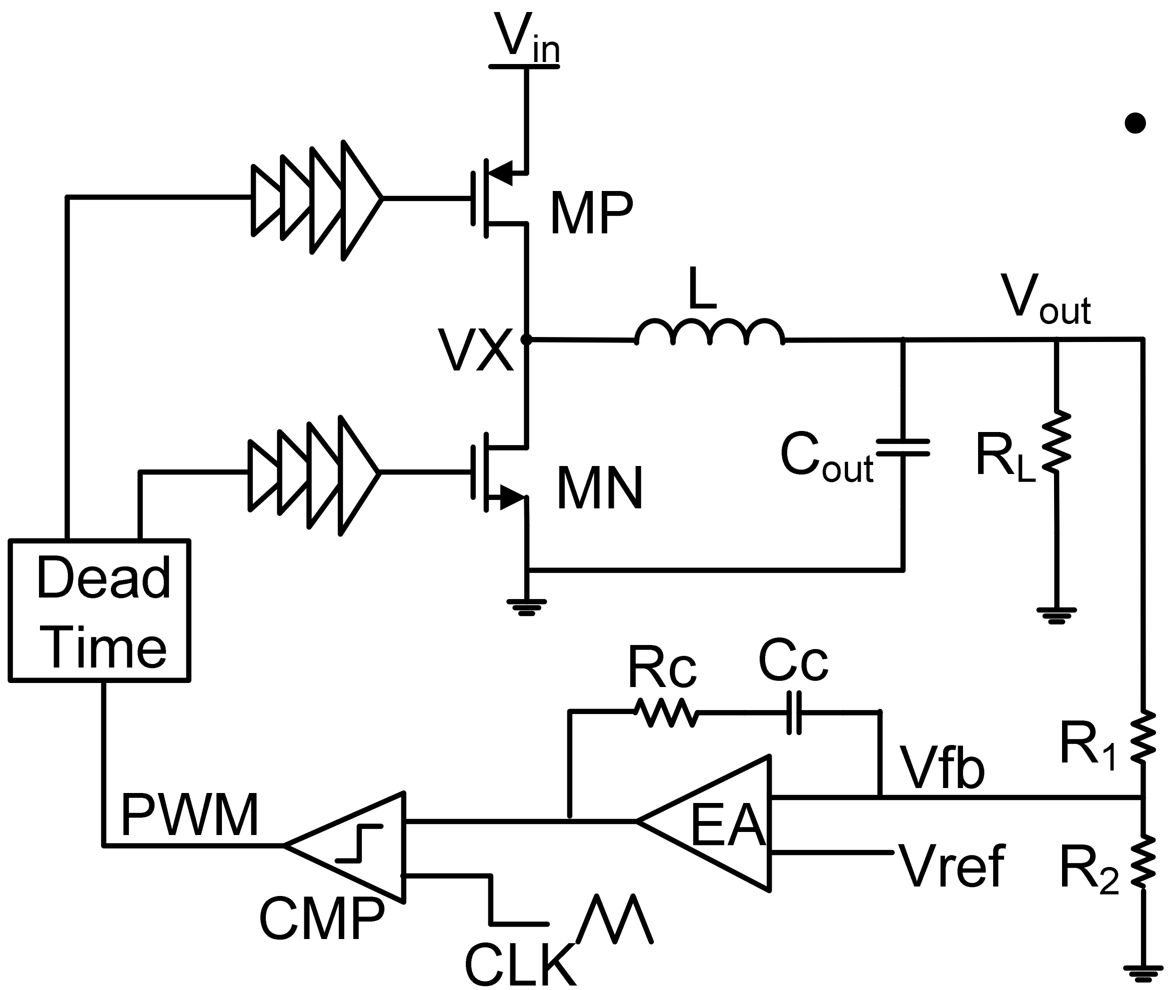


"■" denotes the top plate

"□" denotes the bottom plate

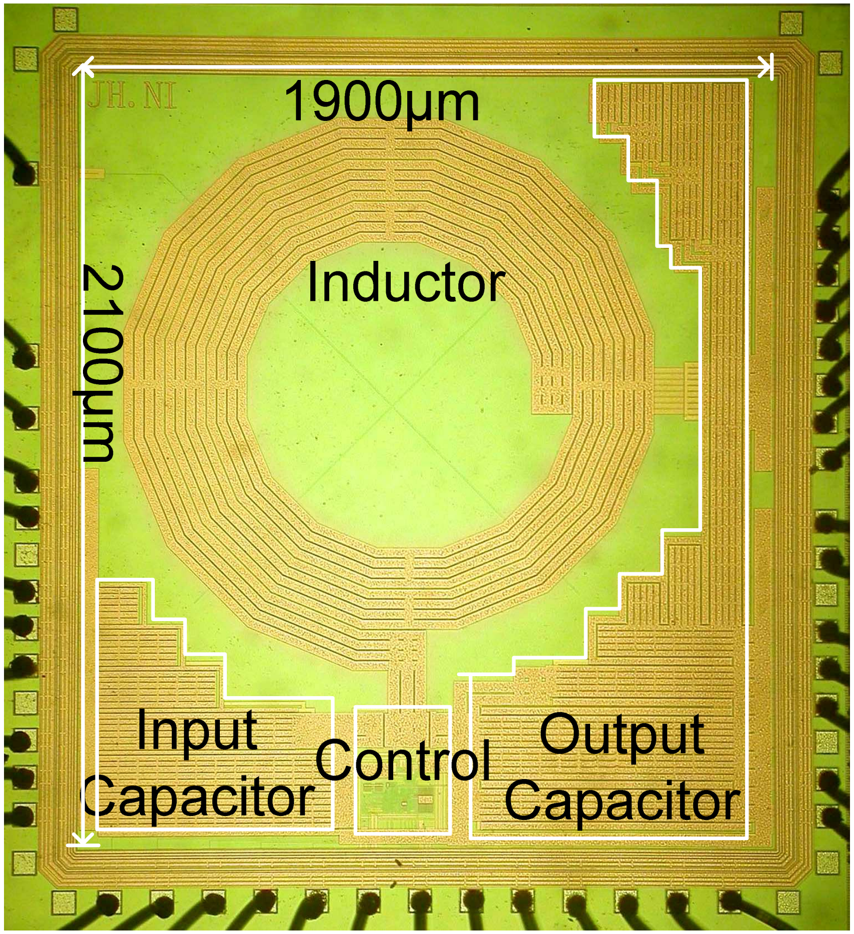
- MOS cap
- Metal fringe cap
  - Vertical
  - Lateral
- ≈3.6 nF/0.62 mm^2
- 44% improvement

Circuit Architecture



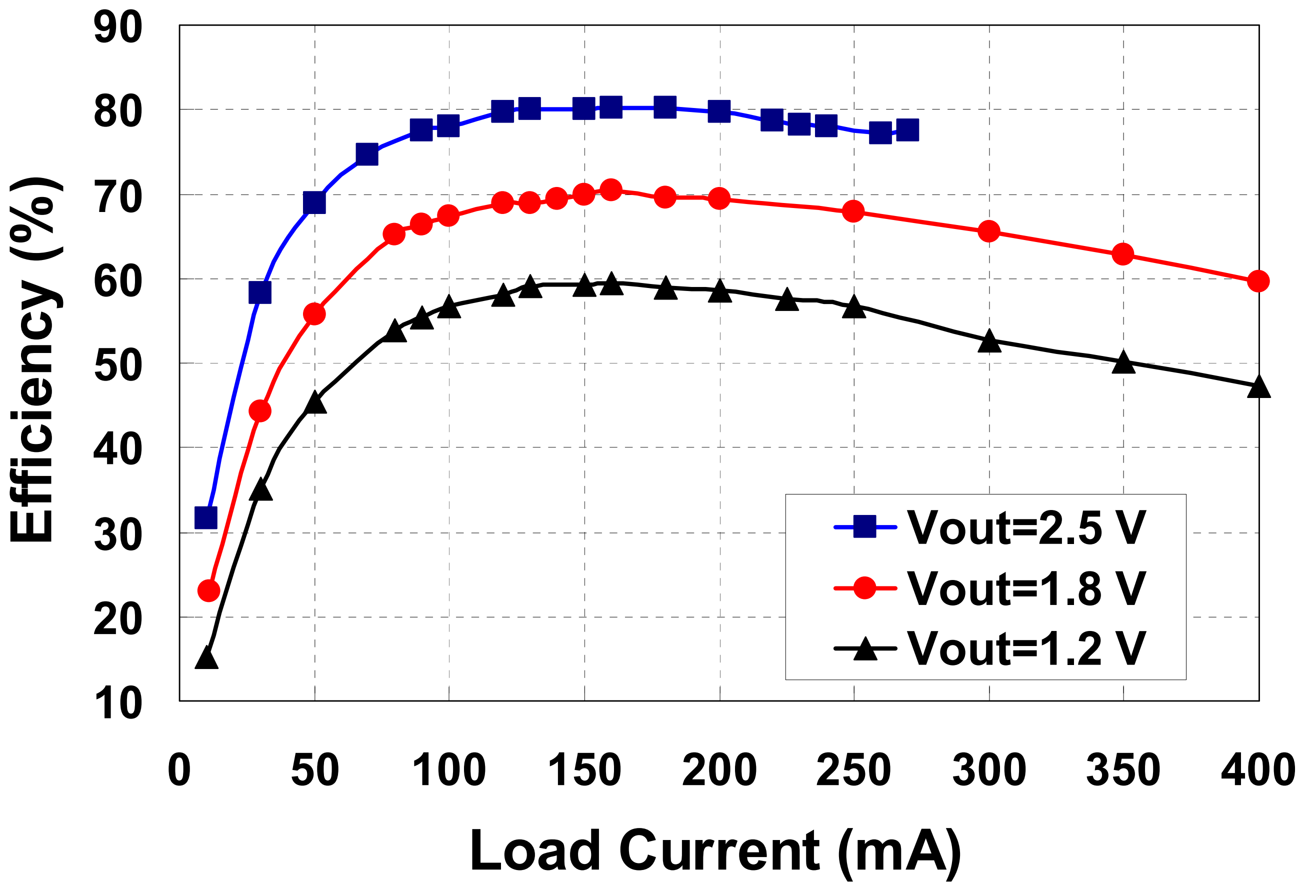
- Features
  - V_{in}=3.3 V
  - fs~250 MHz
  - On-chip *L*
  - On-chip C_{out}
  - Buck converter

Chip Micro-photograph



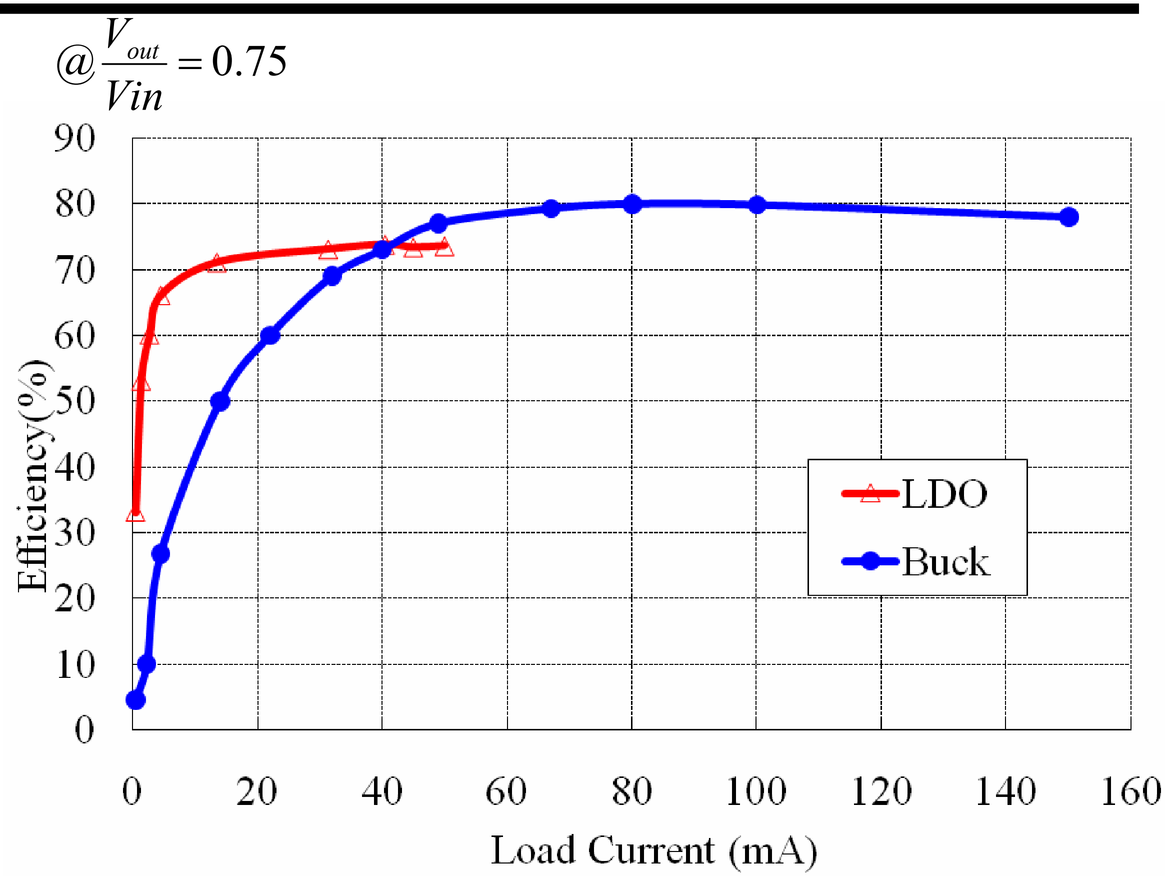
Measured Power Efficiency

The input voltage is 3.3 V for all measurements



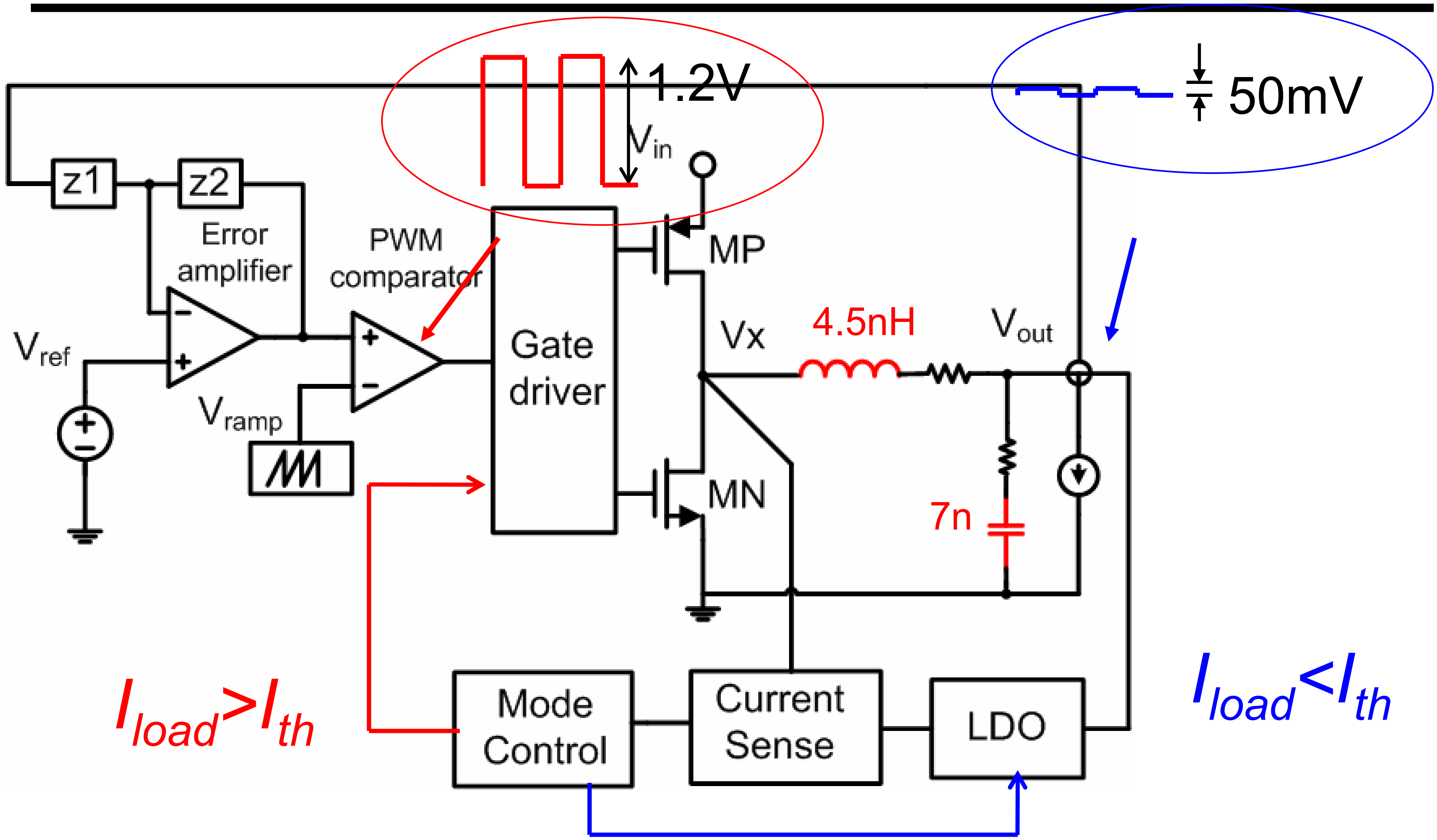
Compare LDO With Buck

Especially, when the load current is zero, the Buck consumes more than 10mW, While the LDO consumes less than 1mW.



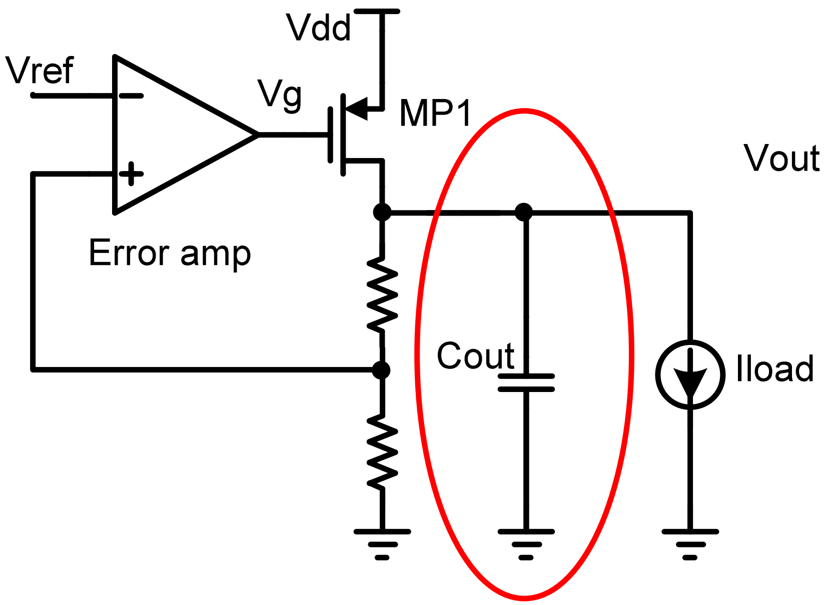
The efficiency of LDO is prior to Buck at light loads, vice versa.

Proposed Structure



LDO Consideration

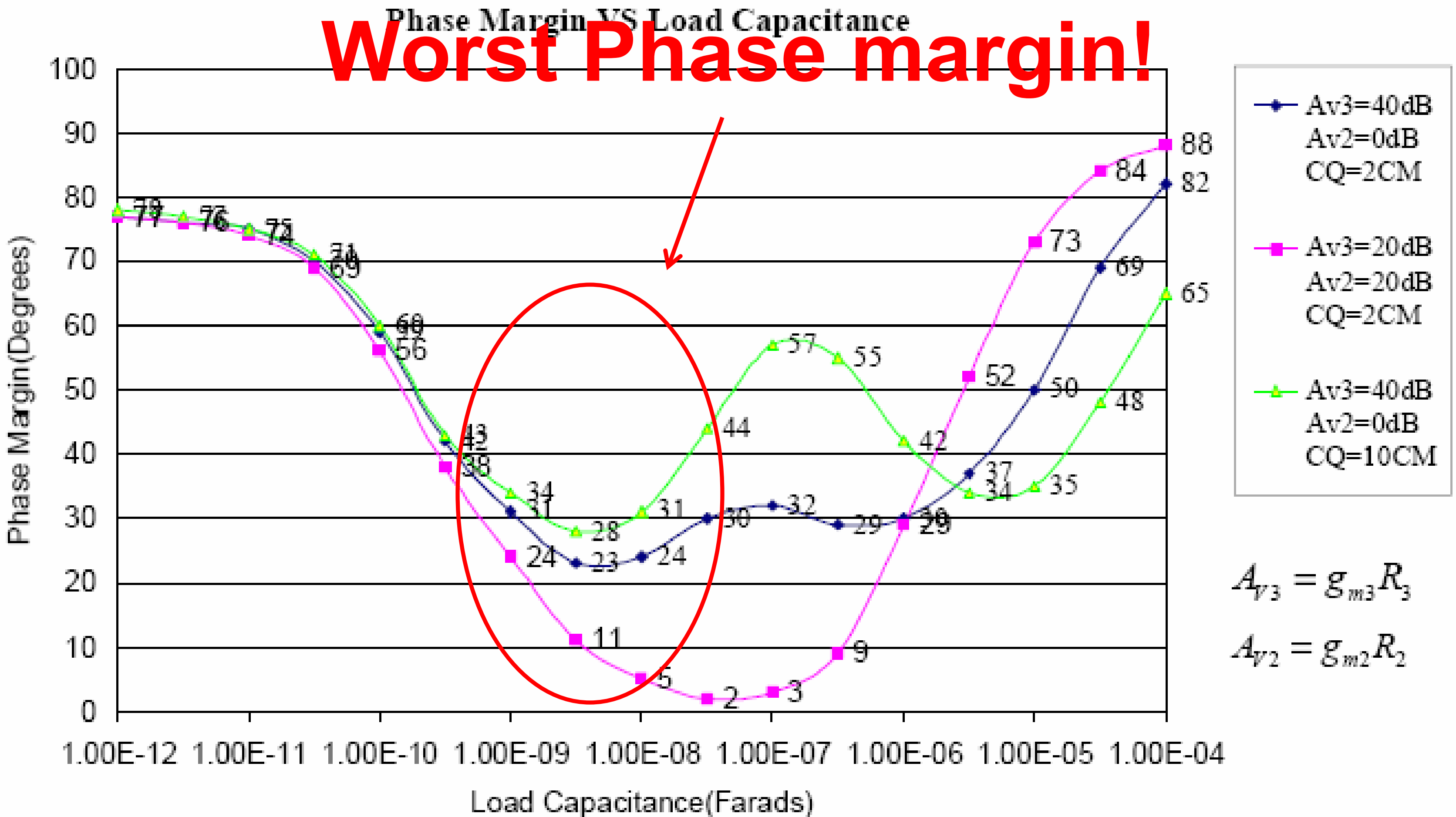
Dominant pole
Non-dominant pole



$$C_{out} = 7nF$$

Stability is difficult to design!

LDO Consideration

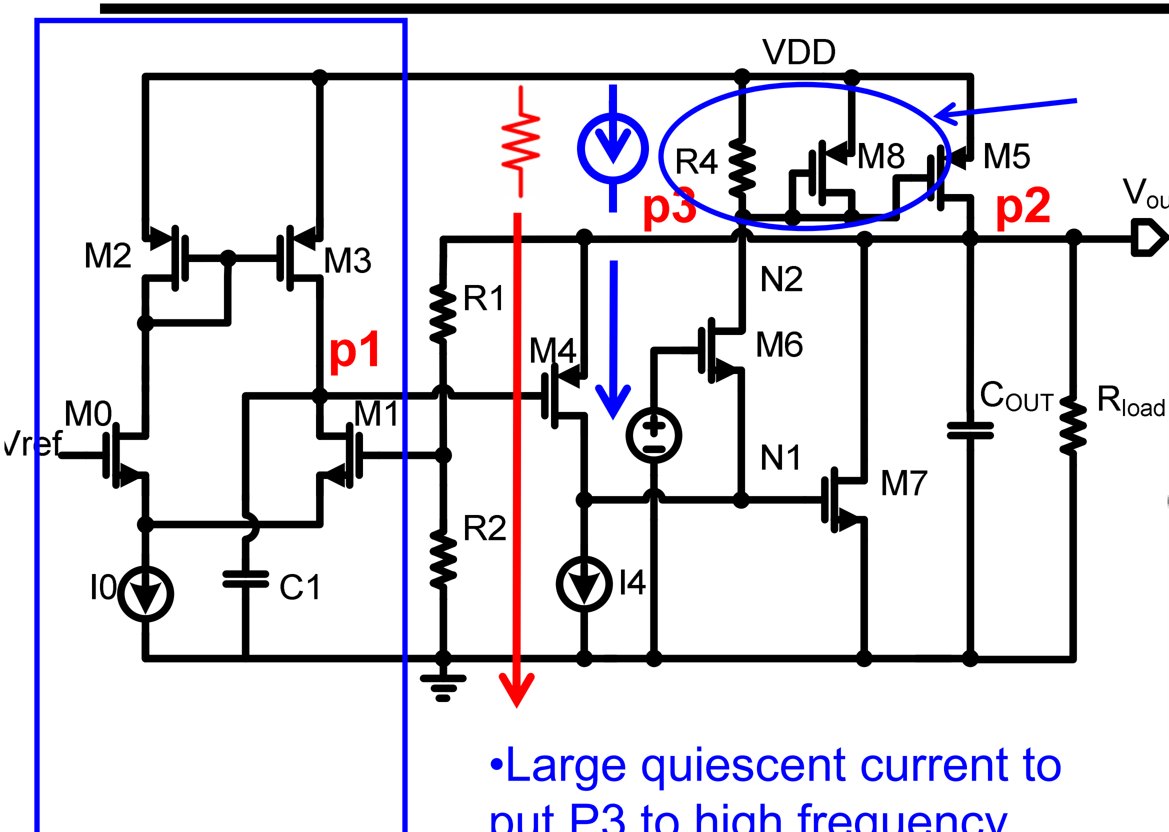


$A_{V3} = g_{m3} R_3$

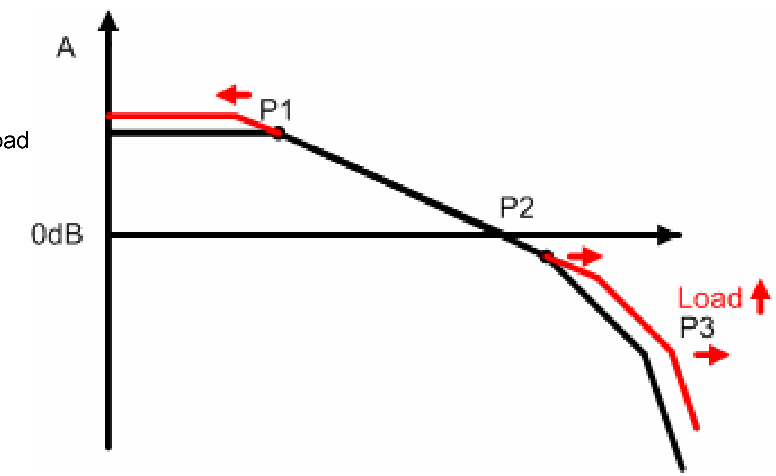
$A_{V2} = g_{m2} R_2$

[2]

Analysis of LDO



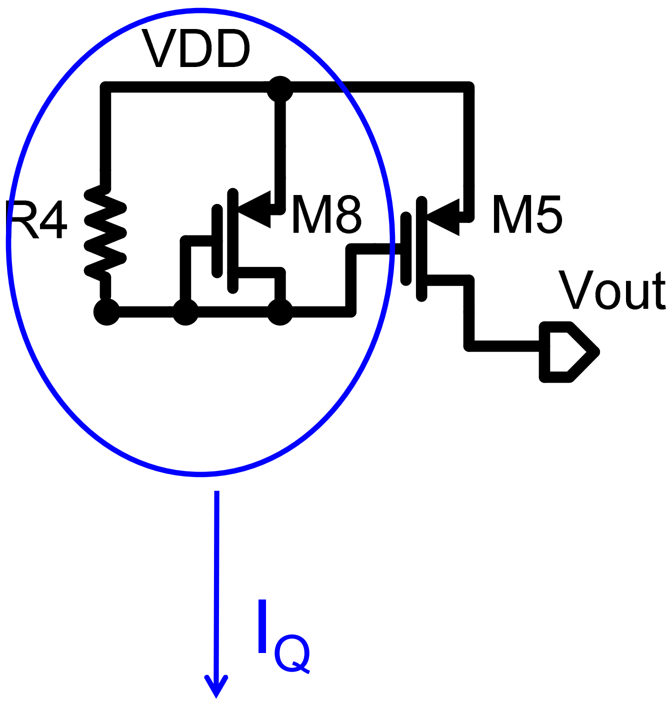
Adaptively Adjust P3

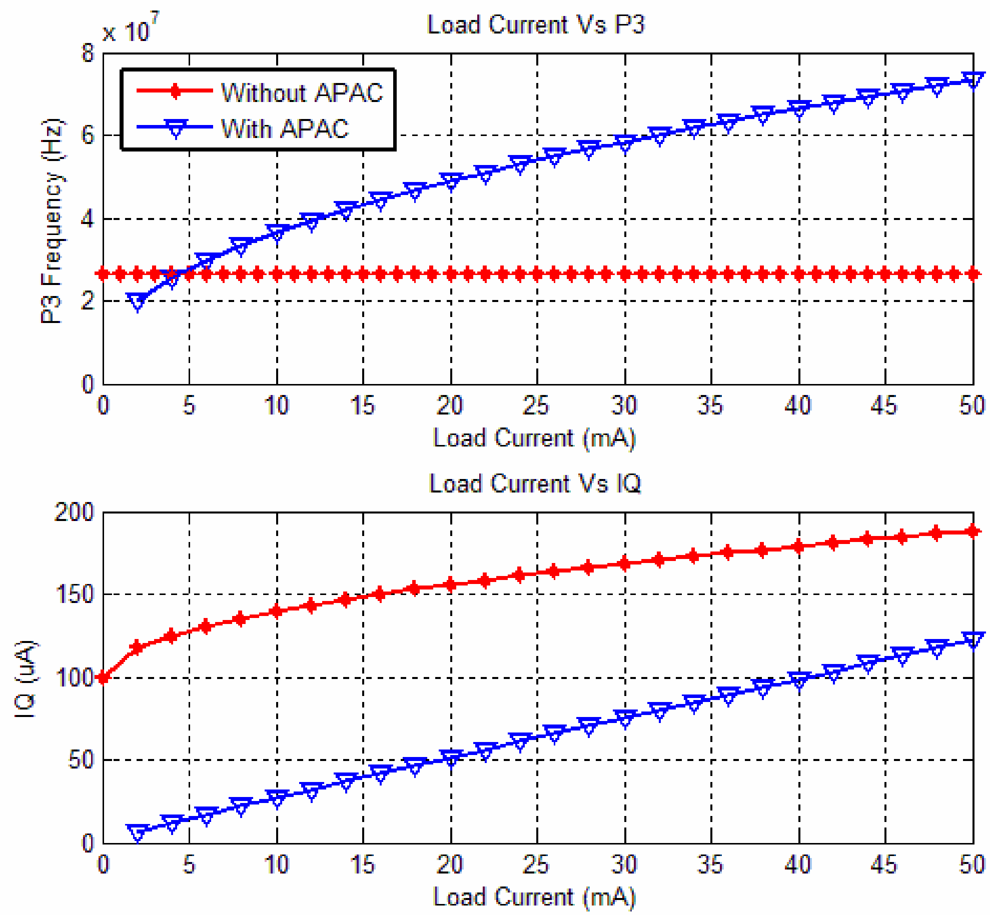


First stage

- Large quiescent current to put P3 to high frequency
- Static condition is hard to control---Vth5↑ , R4↓ , I6↑

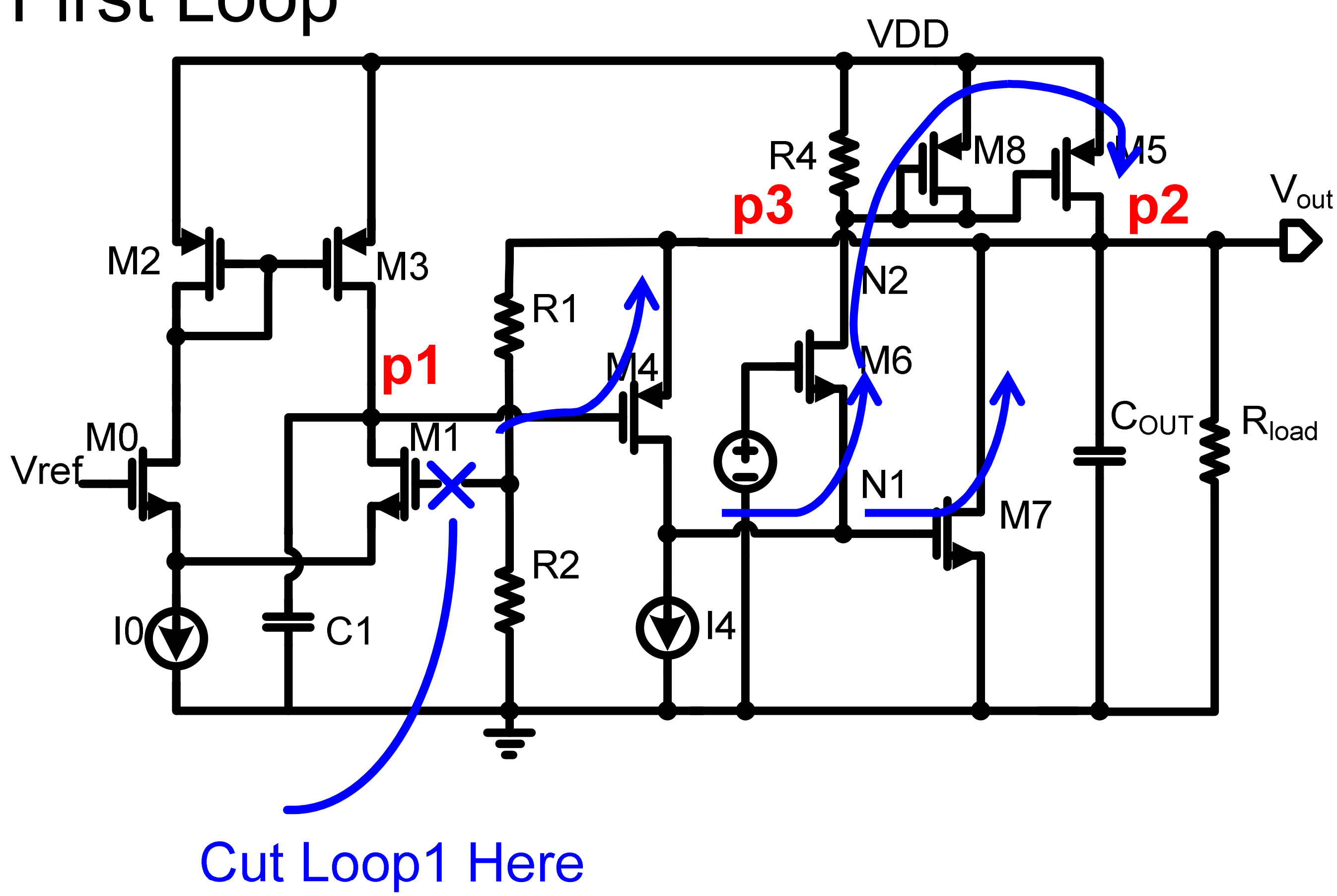
Adaptive P_3 Adjust Circuit



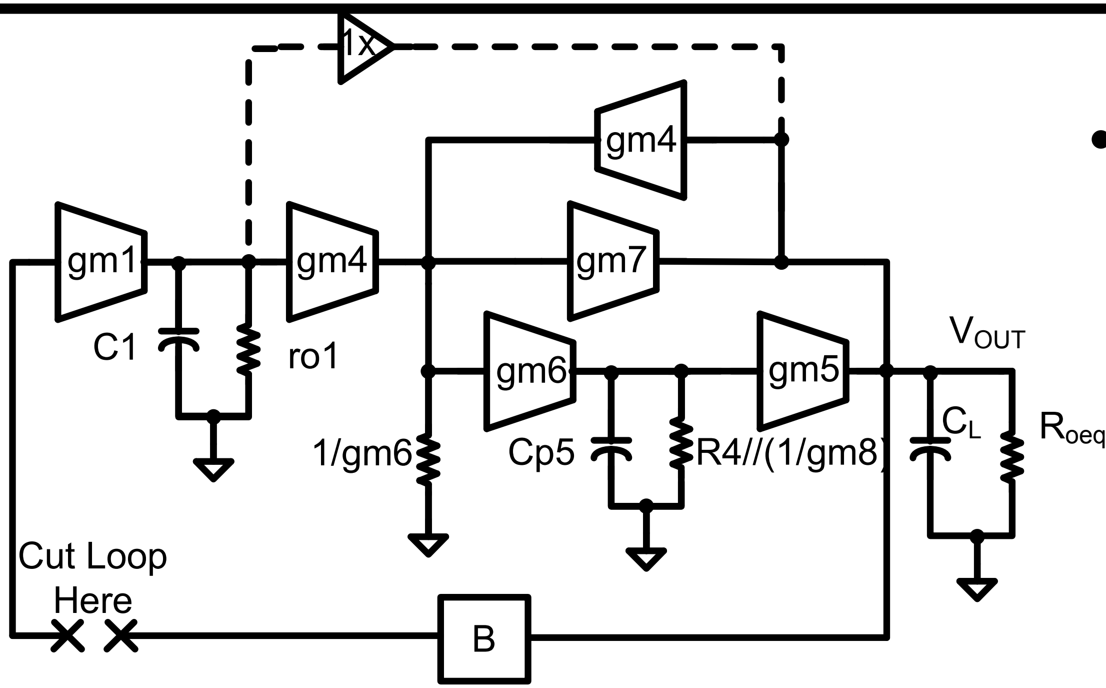


Analysis of Loop1

- The First Loop



Transfer Function of Loop1



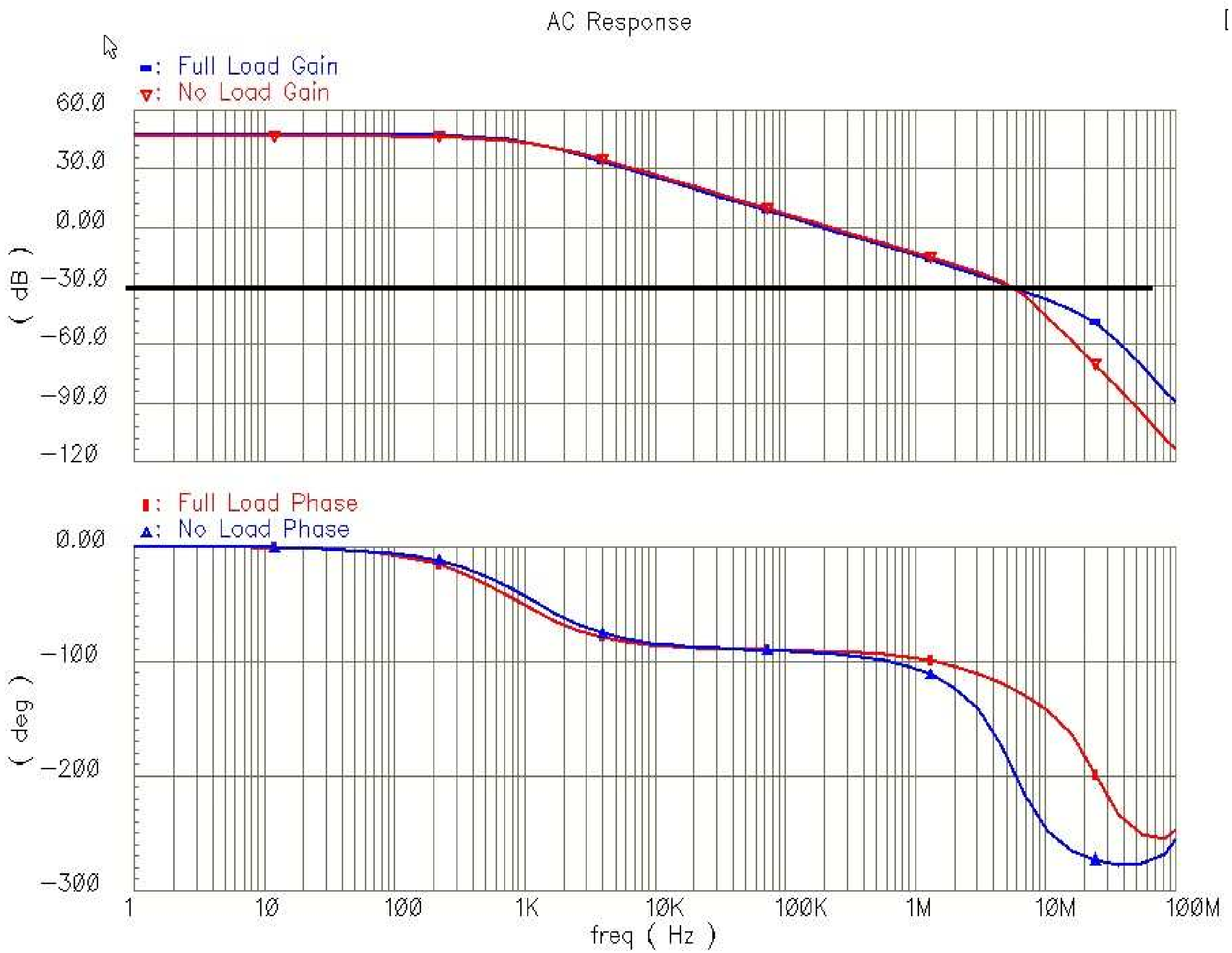
- $C_L >> C1 > Cp5$

$$T(s) \approx \frac{Bg_{m1}r_{o1} \bullet ((C_{p5}Z_4 g_{m4}R_{oeq}(1+g_{m7}/g_{m6}))s + g_{m4}Z_4 g_{m5}R_{oeq})}{(sC_{p1}r_{o1}+1)(s^2 C_{out}C_{p5}R_{oeq}Z_4 + s(C_{p5}Z_4 g_{m4}R_{oeq}g_{m7}/g_{m6} + C_{out}R_{oeq}) + g_{m4}Z_4 g_{m5}R_{oeq})}$$

$$\approx \frac{Bg_{m1}r_{o1} \bullet (\frac{(C_{p5}(1+g_{m7}/g_{m6}))}{g_{m5}}s+1)}{(sC_{p1}r_{o1}+1)(sC_{p5}Z_4+1)(\frac{sC_{out}}{g_{m4}Z_4 g_{m5}}+1)}$$

$$Z_4 = R_4 // \frac{1}{g_{m8}}$$

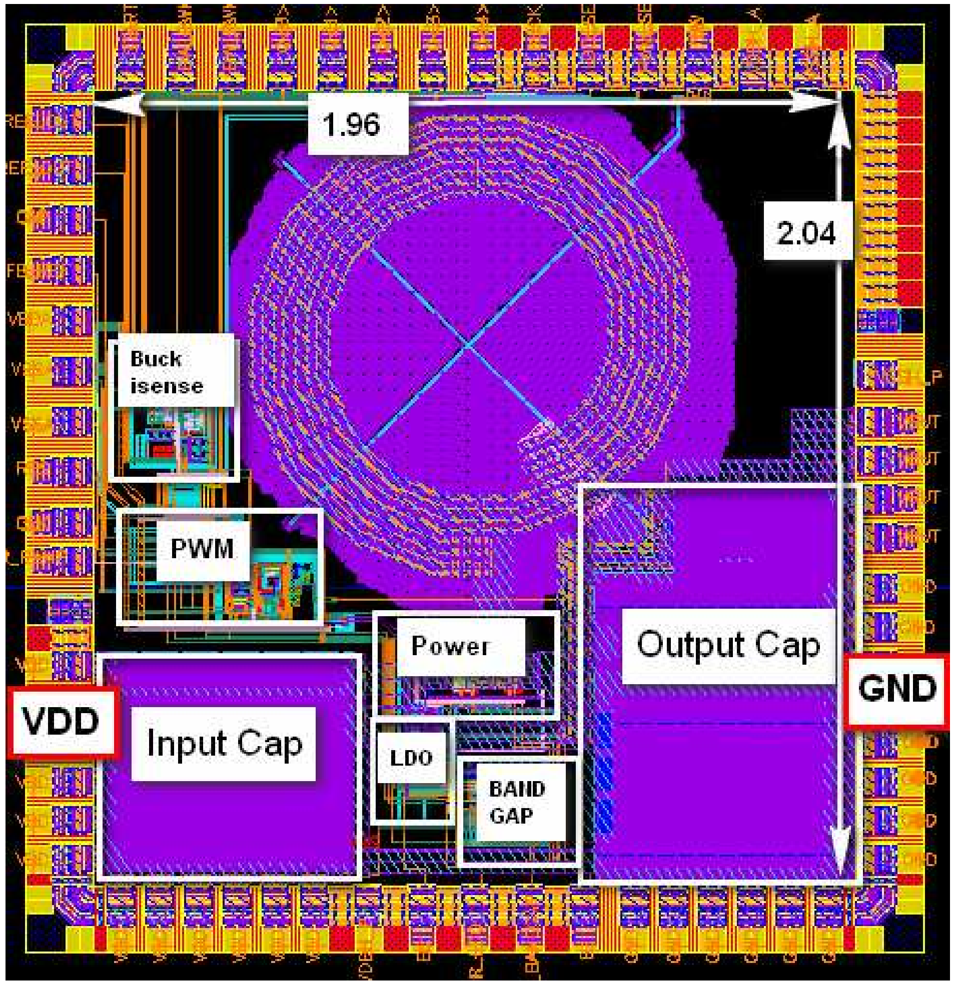
Bode Plot of Loop1



Full Load Condition
GBW=100K
PM=82 degree

No Load Condition
GBW=100K
PM=86 degree

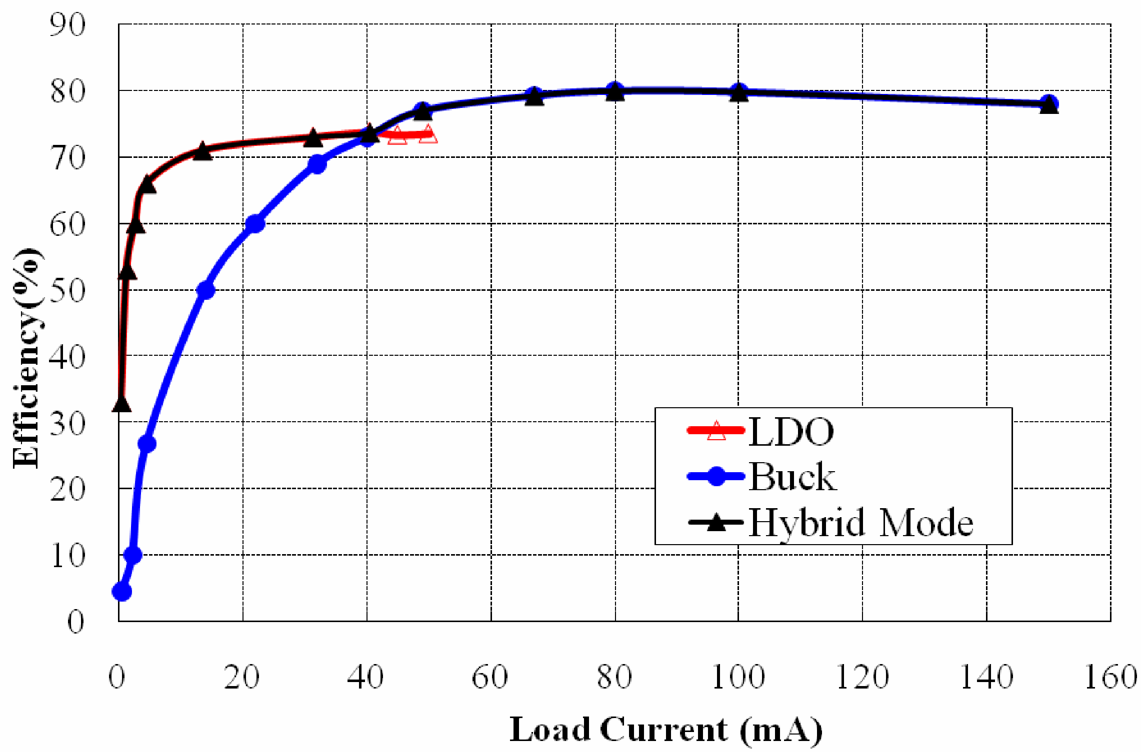
Layout of the Chip



Process: SMIC 0.13 µm 1.2/3.3 V 1P9M RF CMOS

Simulated Power Efficiency

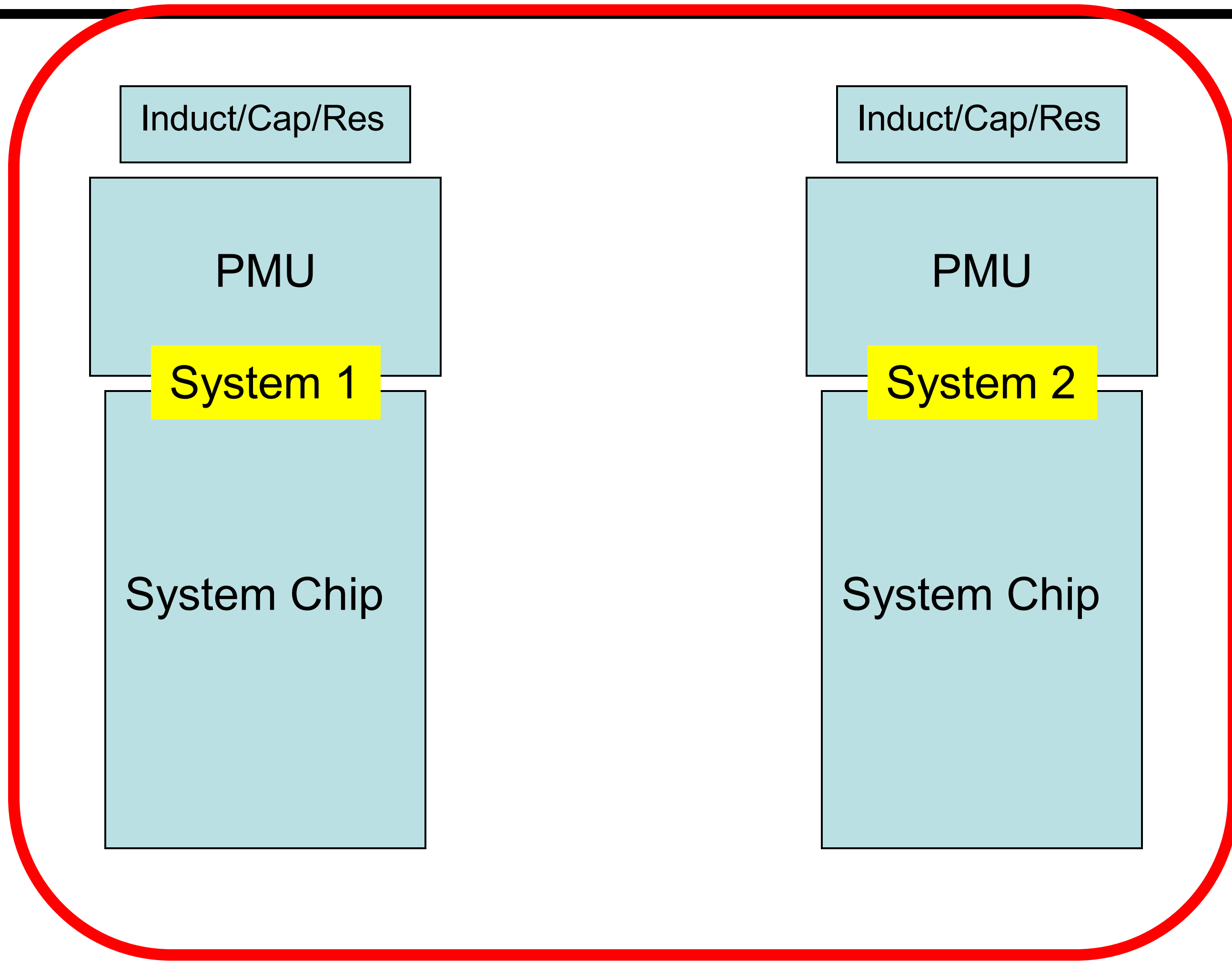
Vin= 1.2 V, Vout=0.9V



More…

To be really invisible

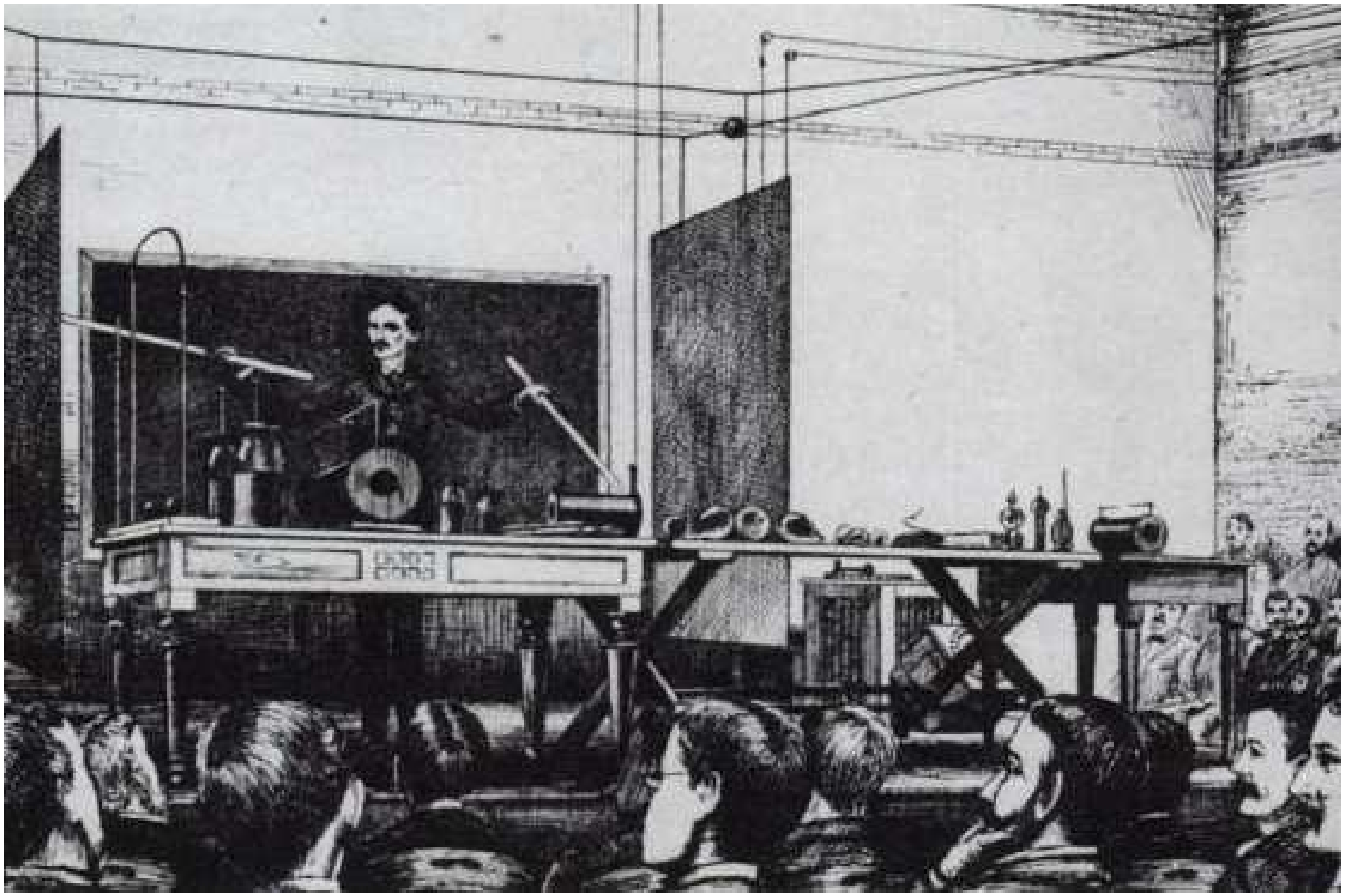
A System Solution in Portable Applications



Wireless Power

- Wireless signal → Wireless power

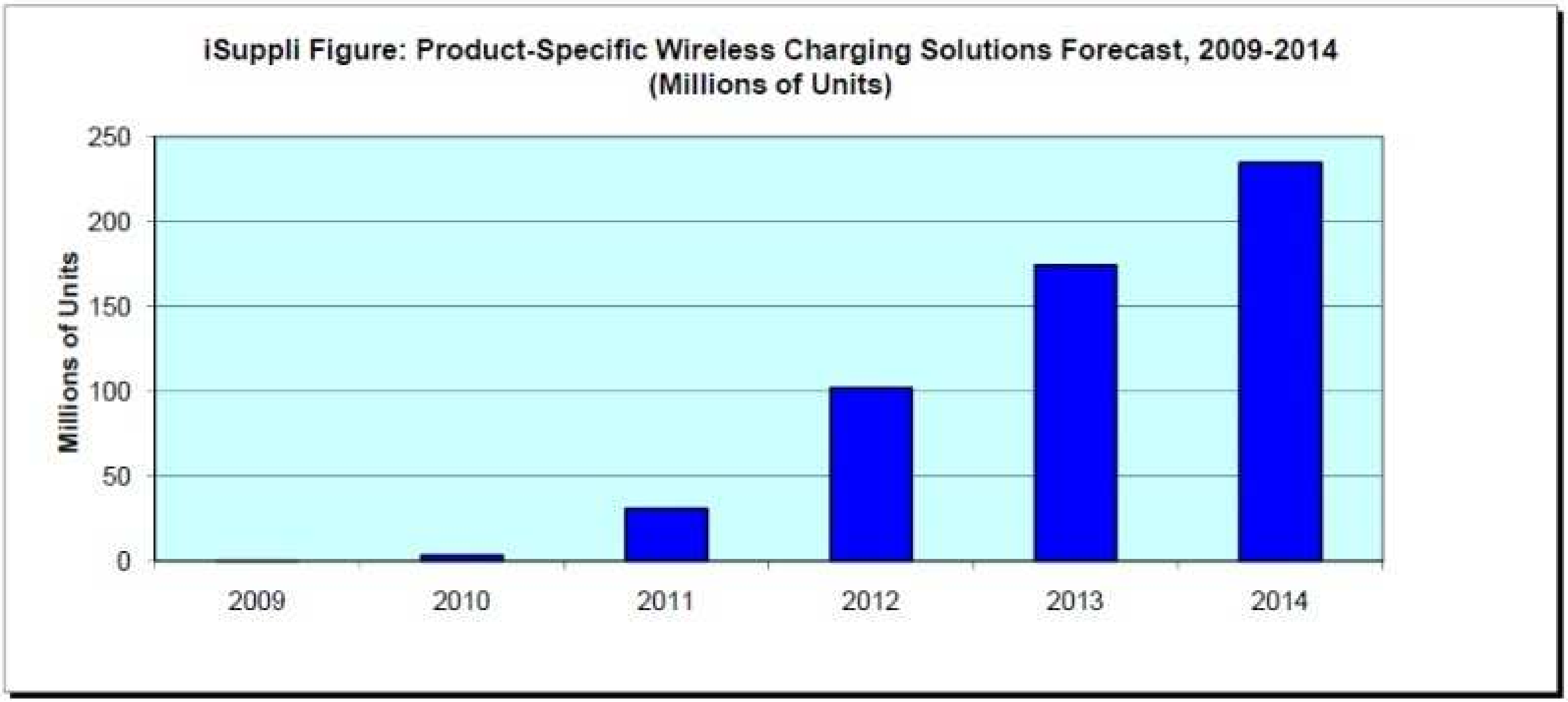
Not a New Topic



Tesla’s high frequency and potential lecture of 1891

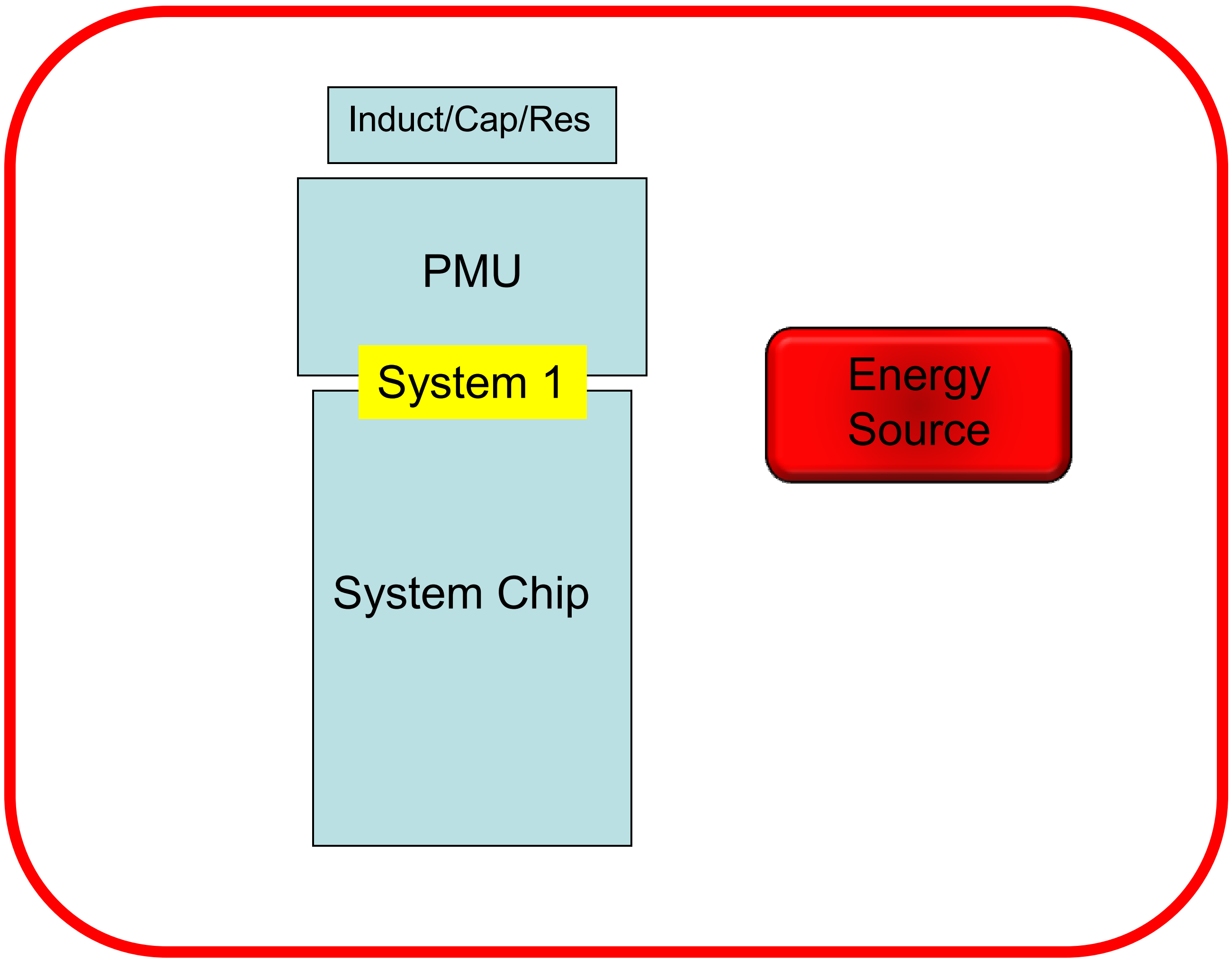
But an Emerging Market

- Mobile phone market drives the growth



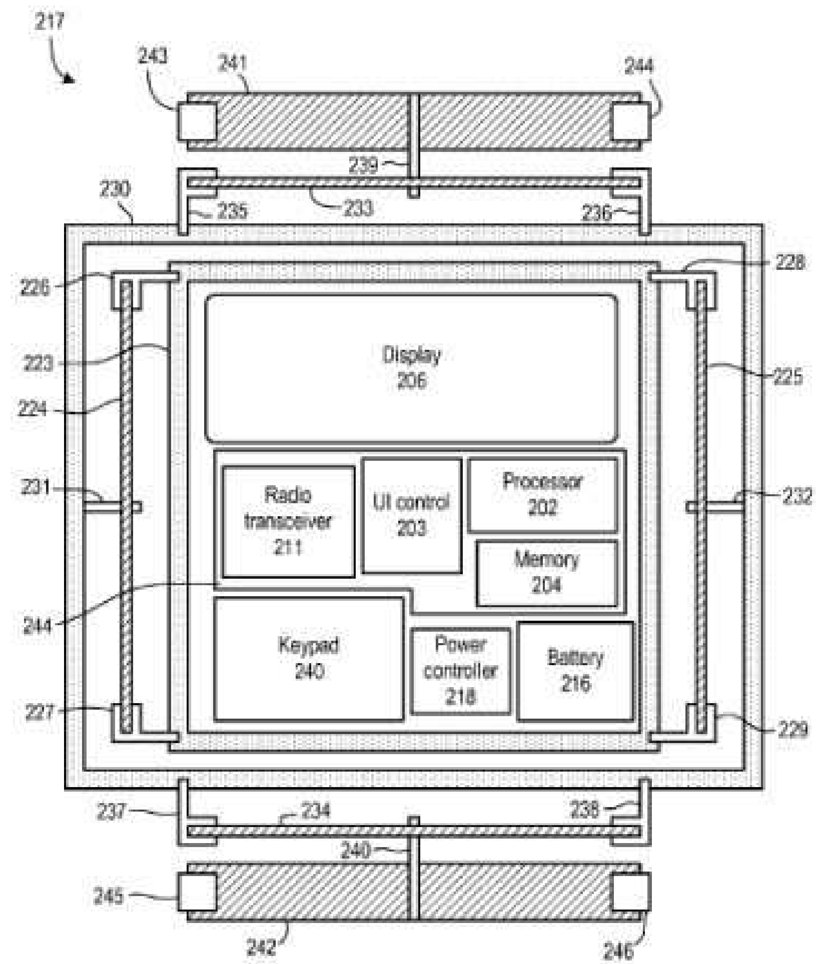
Source: iSuppli Corp. 2010

A System Solution in Portable Applications



Self-Power

- Generate energy
  - From solar
  - From heat
  - From vibration
  - From RF energy
  - From anything…
- E.g. nokia patent
  - Piezoelectric kinetic energy harvester



Source: US patent 2010/0045241 A1

EE: Energy Engineering

- Energy generation
  - Solar energy
  - Piezoelectric energy
- Energy transmission
  - Non-isolated power stage
  - Wireless power
- Energy conversion
  - Linear vs. Switching
  - Inductor based vs. Charge pump

Advanced Power Management Techniques for Portable Applications