Advanced Wireless Power and Data Transmission Techniques for Implantable Medical Devices

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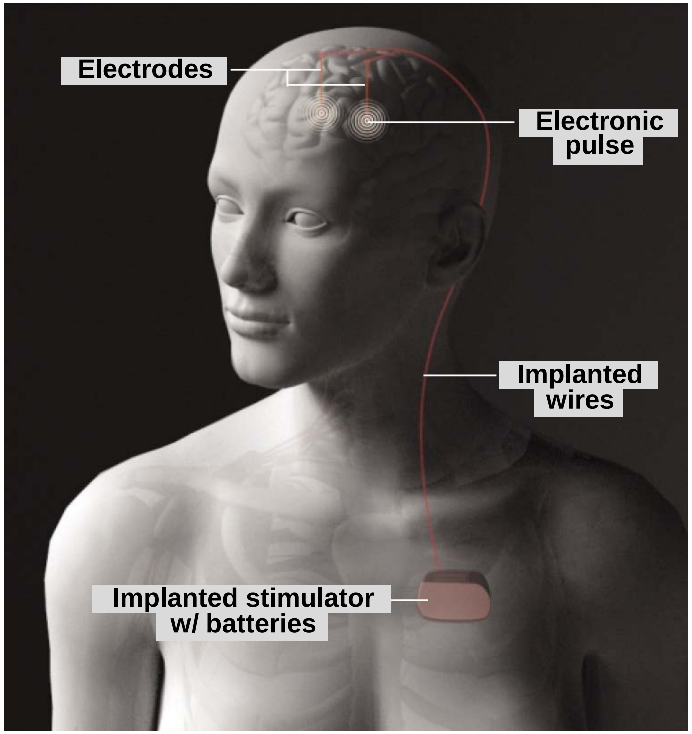
Wireless IMD Applications

Boston Retinal Prosthesis

Nucleus Cochlear Implant

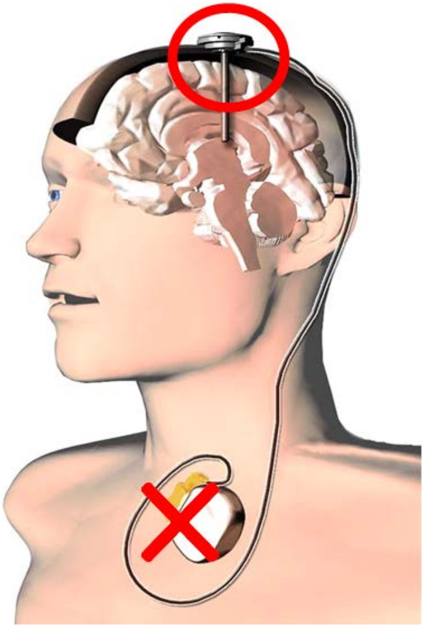


Chest-mounted Deep Brain Stimulation (DBS)

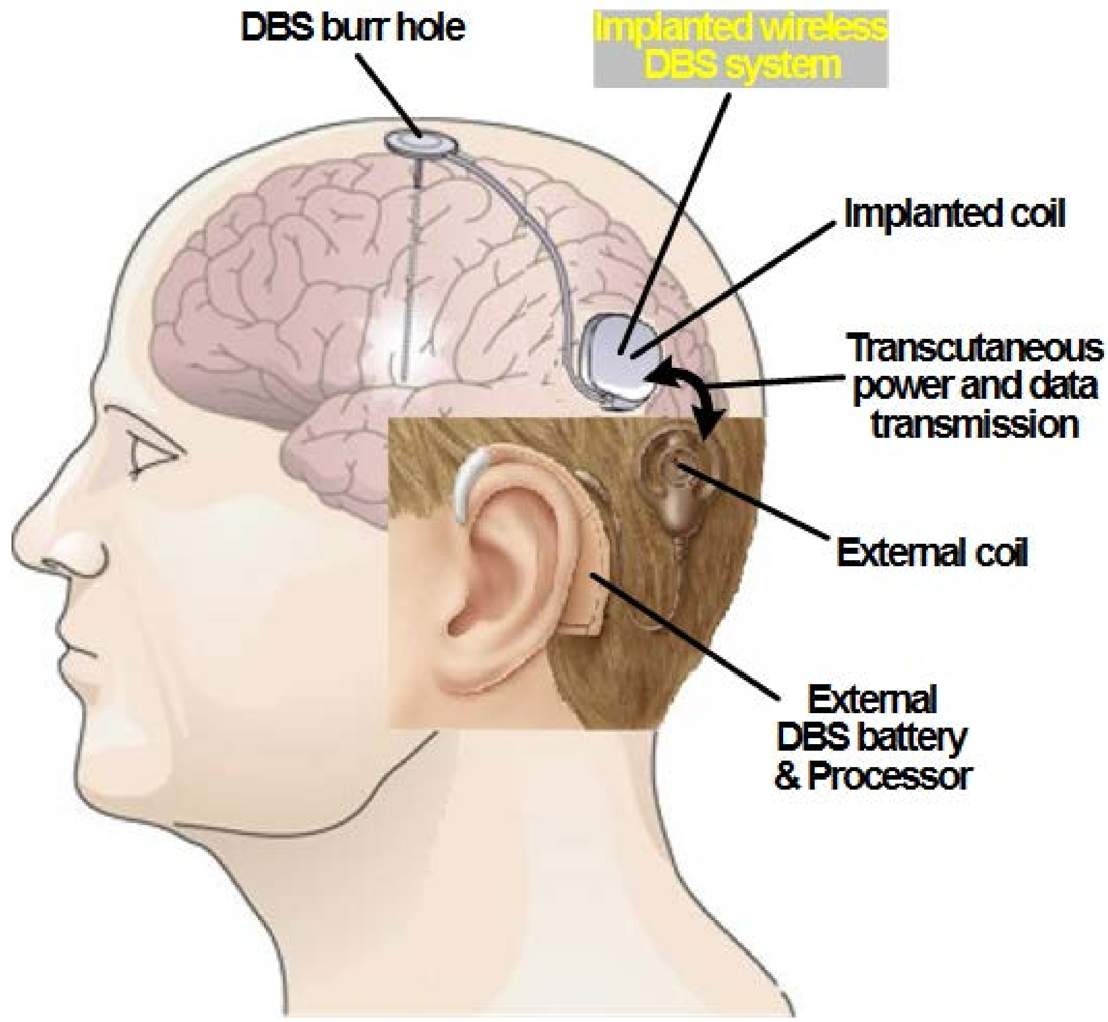
IMD: Implantable Medical Device

- Treat neurological diseases (e.g. DBS) or substitute sensory modalities (retinal/cochlear implant), high power, large volume
- Battery-powered chest-mounted DBS
  → Head-mounted DBS with wireless power transfer

Wireless IMD Applications

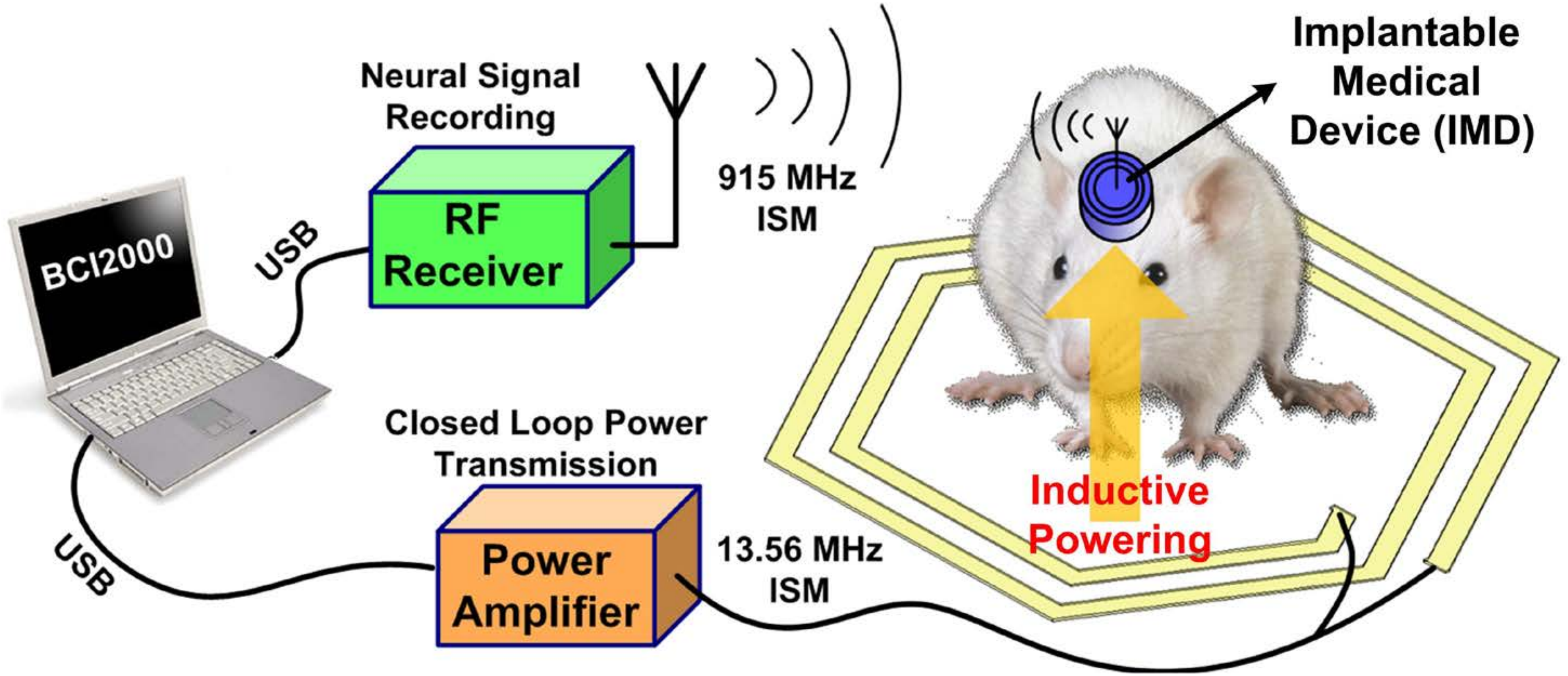


Cochlear Implant



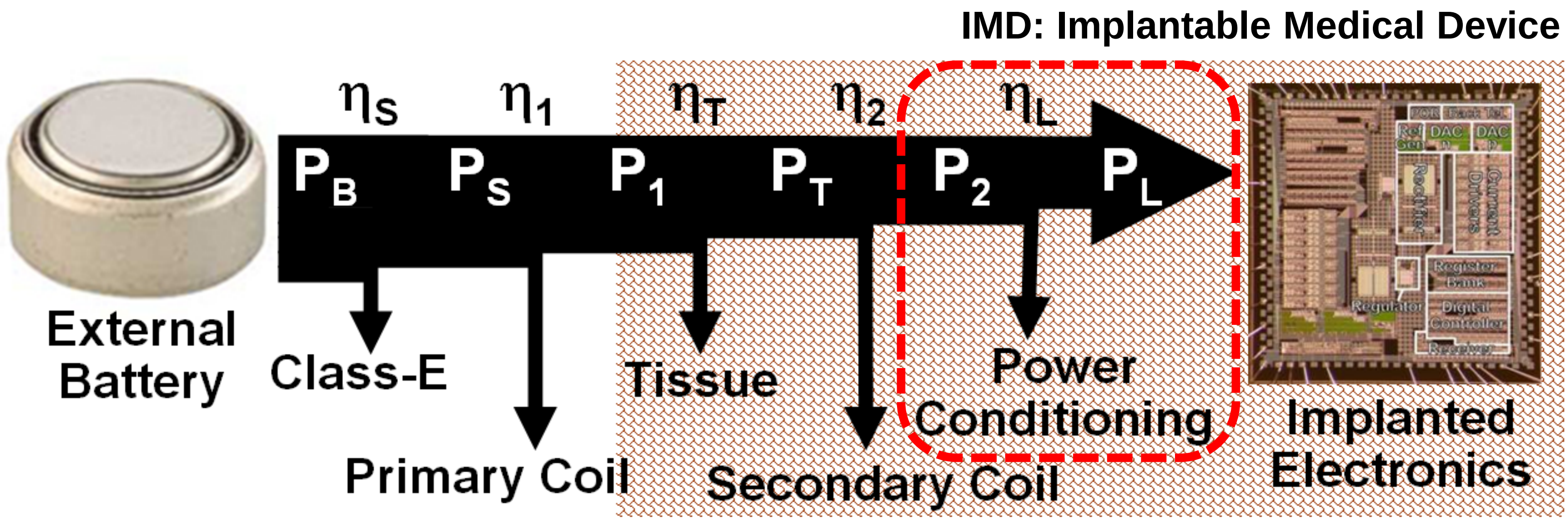
Head-mounted DBS with wireless power transfer

Wireless IMD Applications



- Size/weight of batteries affect animal movements and behavior.
  → Wireless power transmission via inductive links
- Inductively powered IMDs for long-term uninterrupted electrophysiology experiments on small freely moving animal.

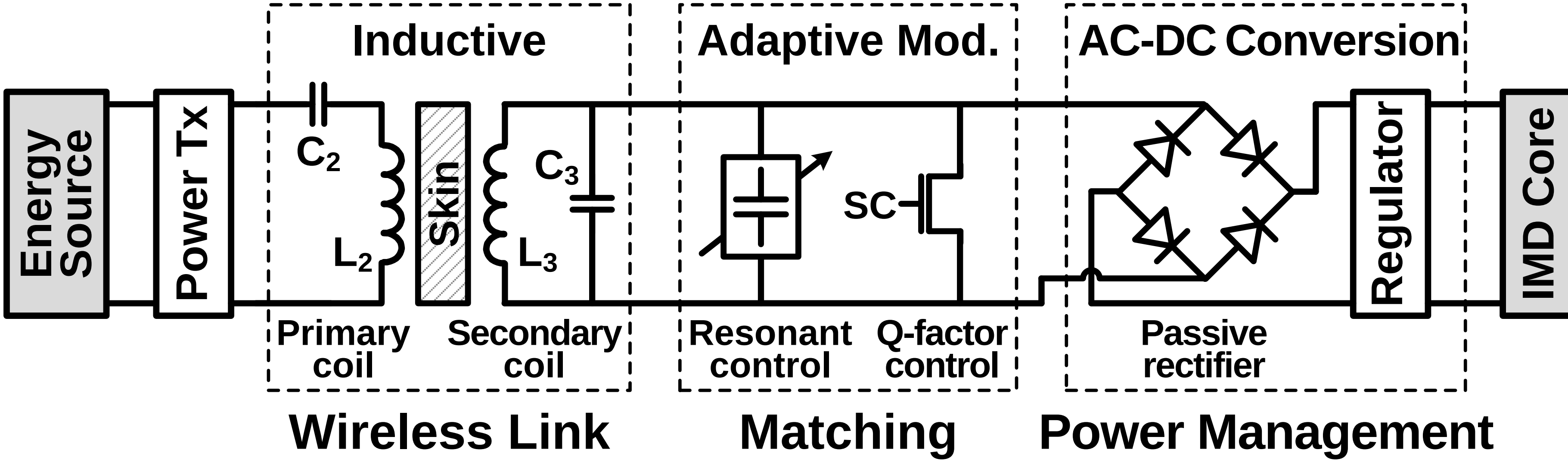
Wireless Power Transmission Efficiency



With higher IMD power efficiency from the secondary coil to the tissue:

- The IMD can operate with lower received power from a further coil distance (small coils implanted deep in the body).
- Small power consumption in IMDs reduces the risk of tissue damage from heating and interference.

Wirelessly-Powered IMD Structure



Various WPT techniques in every stage of power flow:

- Wireless power transmission link (across the skin)
- Matching and adaptive Q-modulation (inside the body)
- Power management units (inside the body)

Outline

- **Optimized Wireless Power Transfer Links**
- **Power Conversion and Management Circuits**
- **Low-Power Wireless Data Telemetry**
- **Conclusions**

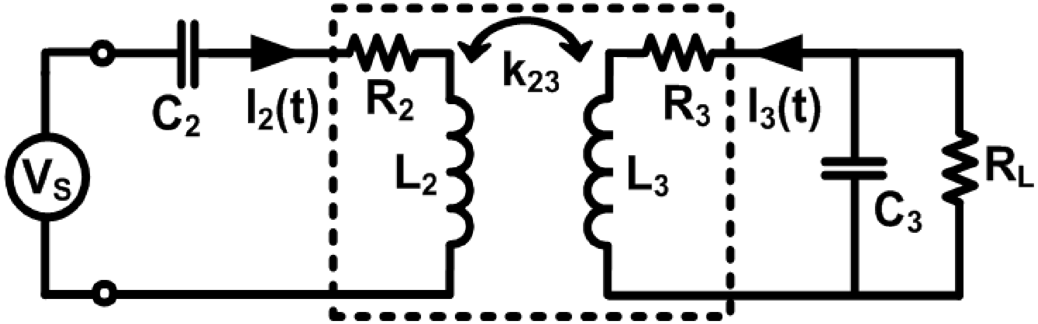
Outline

- **Optimized Wireless Power Transfer Links**
  - **- Conventional 2-Coil Inductive Links**
  - **- Multi-Coil (3-Coil) Inductive Links**
  - **- Q-Modulation Concept**
  - **- Q-Modulation Power Management (QMPM)**
- **Power Conversion and Management Circuits**
- **Low-Power Wireless Data Telemetry**
- **Conclusion**

Power Transfer Efficiency (PTE) in 2-Coil Inductive Links

- **The 2-coil power transfer efficiency (PTE):**

$$\eta_{2-coil} = \frac{k_{23}^2 Q_2 Q_{3L}}{1 + k_{23}^2 Q_2 Q_{3L}} \cdot \frac{Q_{3L}}{Q_L}$$



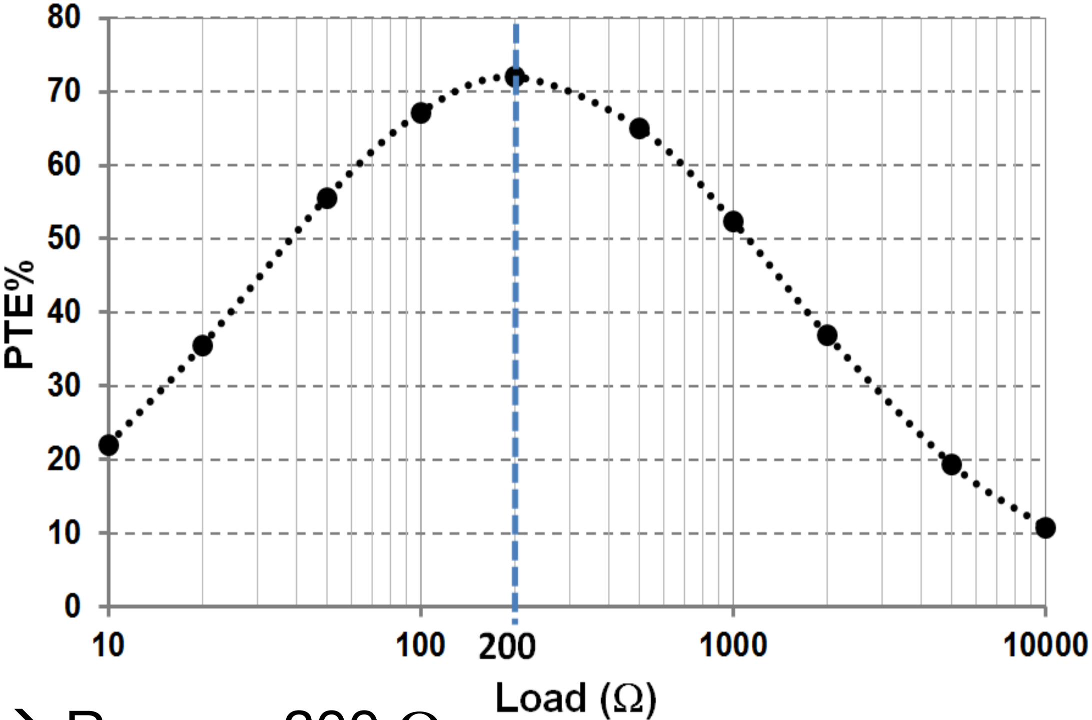
- **PTE is highly dependent on:** k_{23}, Q_2, Q_3, Q_L **(load Q)**

$Q_{3L} = Q_3 Q_L / (Q_3 + Q_L)$ $\qquad\qquad$ $Q_L = R_L / \omega_0 L$

- **Large R_L (Q_L): Low efficiency in the secondary loop**
- **Small R_L (Q_L): Low efficiency in the primary loop**

Maximizing PTE and PDL in 2-Coil Link

Parameter		Sym	Sim
L_1	Inductance (μH)	L_1	1.2
	Outer diameter (cm)	D_{o1}	27
	Fill factor	Φ_1	0.28
	Num. of turns	n_1	2
	Line width (mm)	w_1	12
	Line spacing (mm)	s_1	35
	Quality factor	Q_1	196
L_2	Inductance (μH)	L_2	0.058
	Coil diameter (cm)	D_{o2}	4
	Wire diameter (mm)	w_2	5.68
	Num. of turns	n_2	1
	Line spacing (μm)	s_2	100
	Quality factor	Q_2	151.5
coupling distance (mm)		d_{12}	50
coupling coefficient		k_{12}	0.032
Power transfer efficiency (%)		PTE	72.0
Power delivered to load (mW)		PDL	215.3



→ $R_{L,PTE} = 200\ \Omega$

- PTE and PDL are highly dependent on R_L
- R_L is often predefined

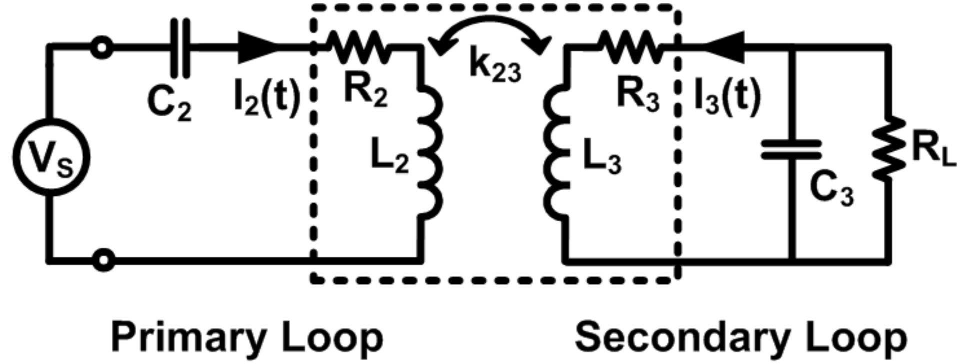
Impedance Transformation

1) Matching circuits 2) Multiple coils

Kiani, Jow, and Ghovanloo, TBioCAS 2011

Maximizing PTE in 2-Coil Inductive Links

$$\eta_{2-coil} = \frac{k_{23}^2 Q_2 Q_{3L}}{1 + k_{23}^2 Q_2 Q_{3L}} \cdot \frac{Q_{3L}}{Q_L}$$



- **An optimal load, *$R_{L,PTE}$*, to maximize the PTE**

$$Q_{L,PTE} = \frac{R_{L,PTE}}{\omega_0 L_3} = \frac{Q_3}{(1 + k_{23}^2 Q_2 Q_3)^{1/2}}$$

- **R_L is often defined by the application** → **Impedance Transformation**

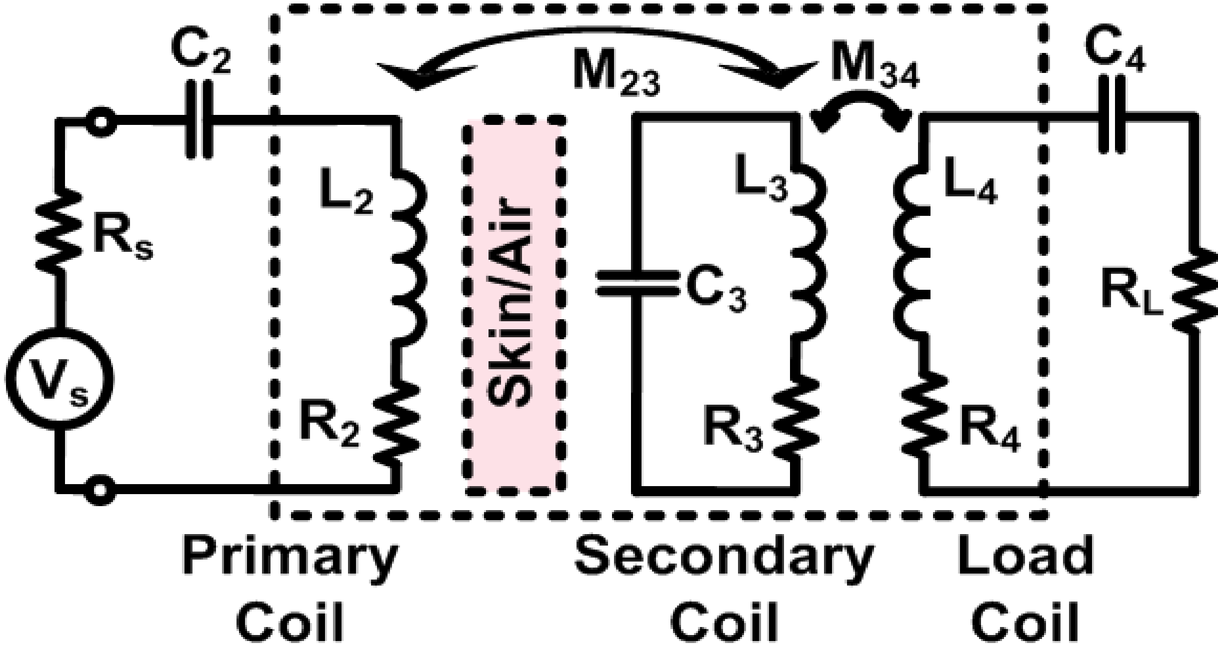
1) Matching circuits

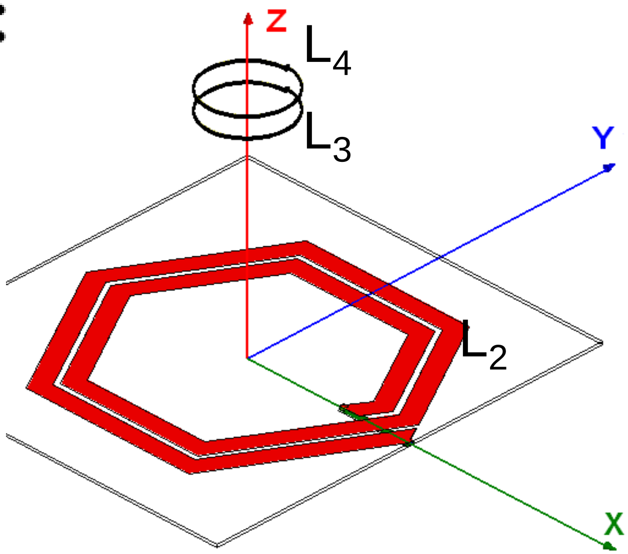
- **More lossy (multiple L & C with Q < 100)**
- **Smaller size and tunable**

2) Multiple coils

- **More efficient (Q > 200)**
- **Easy to match the load**
- **Larger size & not tunable**

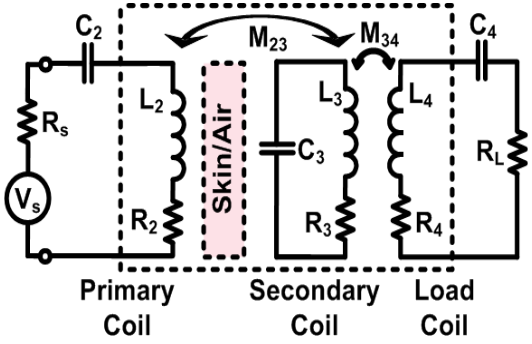
3-Coil Inductive Links for Load Matching



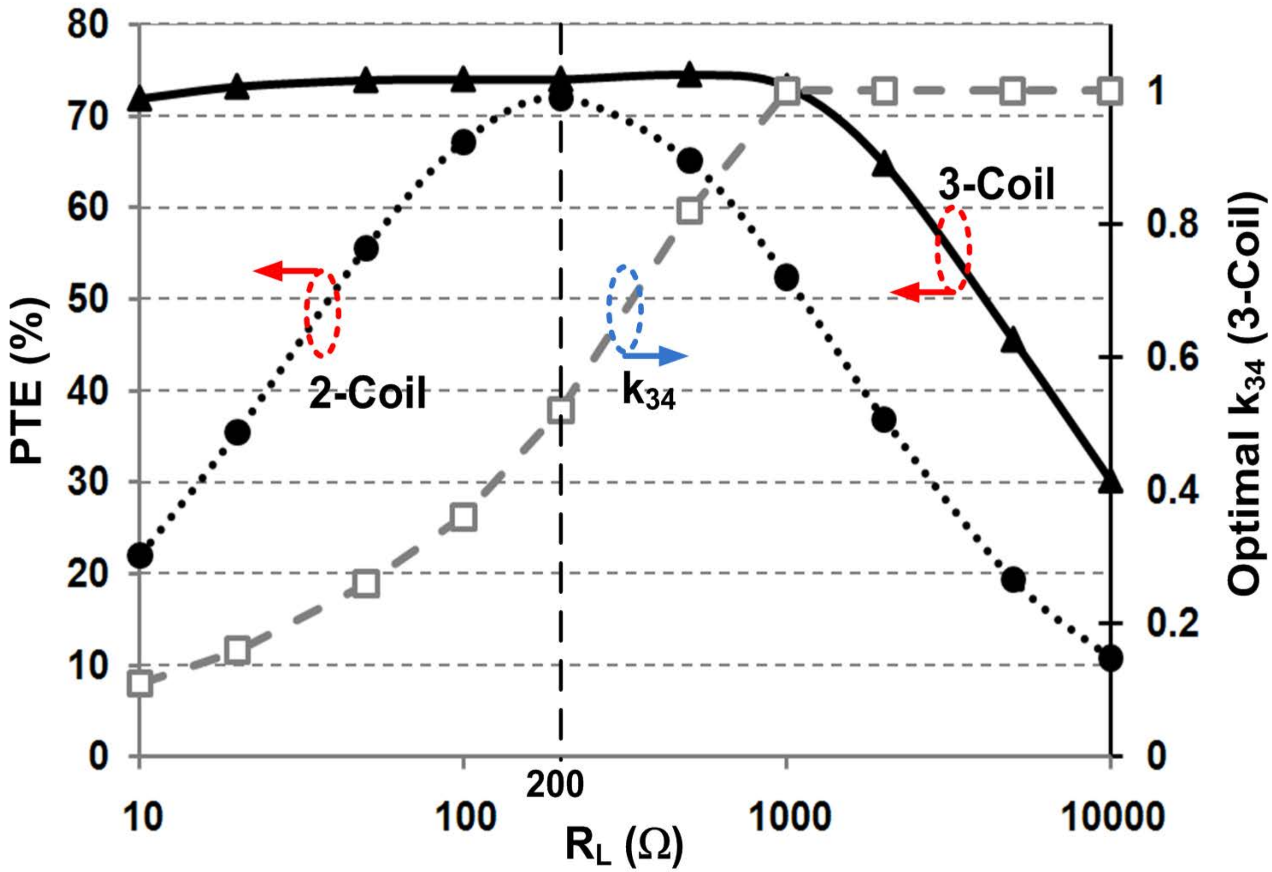


$$\eta_{3-coil} = \eta_{23}\eta_{34} = \frac{(k_{23}^2 Q_2 Q_3)(k_{34}^2 Q_3 Q_{4L})}{[(1+k_{23}^2 Q_2 Q_3 + k_{34}^2 Q_3 Q_{4L})(1+k_{34}^2 Q_3 Q_{4L})]} \cdot \frac{Q_{4L}}{Q_L}$$

Maximizing PTE in 3-Coil Link

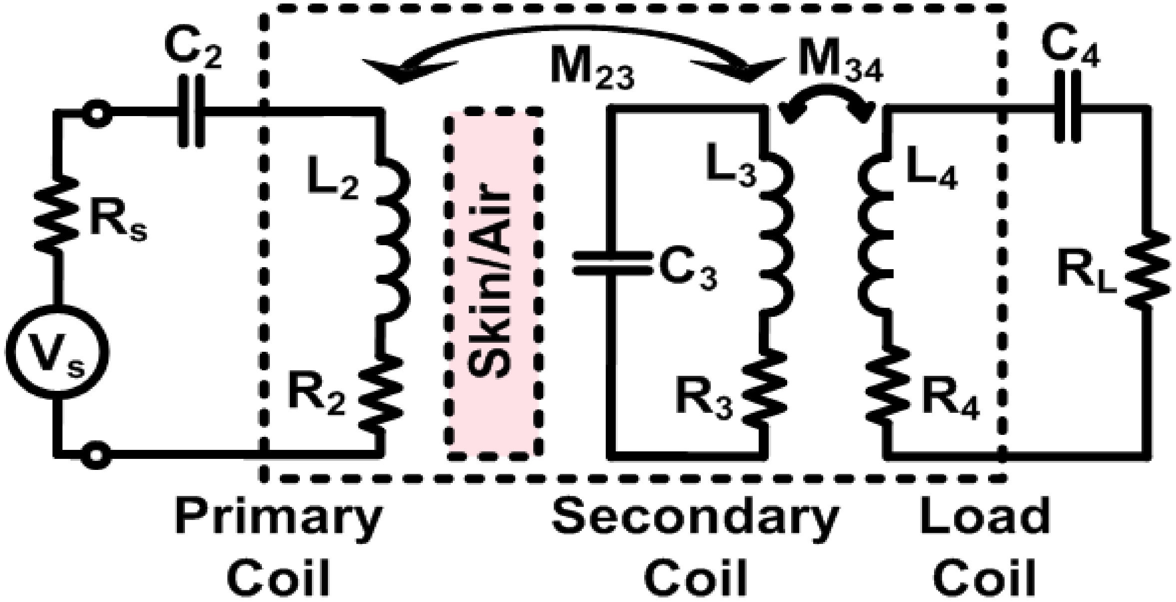


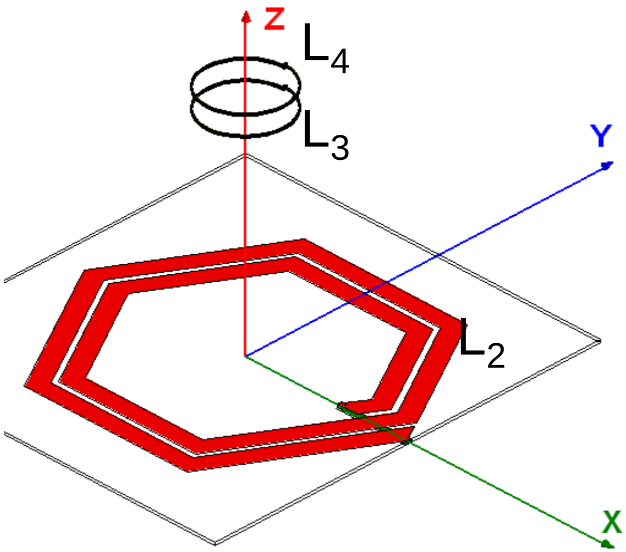
By changing k_{34} (and $R_{ref,3}$), the 3-coil PTE can be kept at maximum for a wide range of R_L.



A 2-coil link does not provide this flexibility, and PTE maximizes only for a specific R_L value.

3-Coil Inductive Links for Load Matching

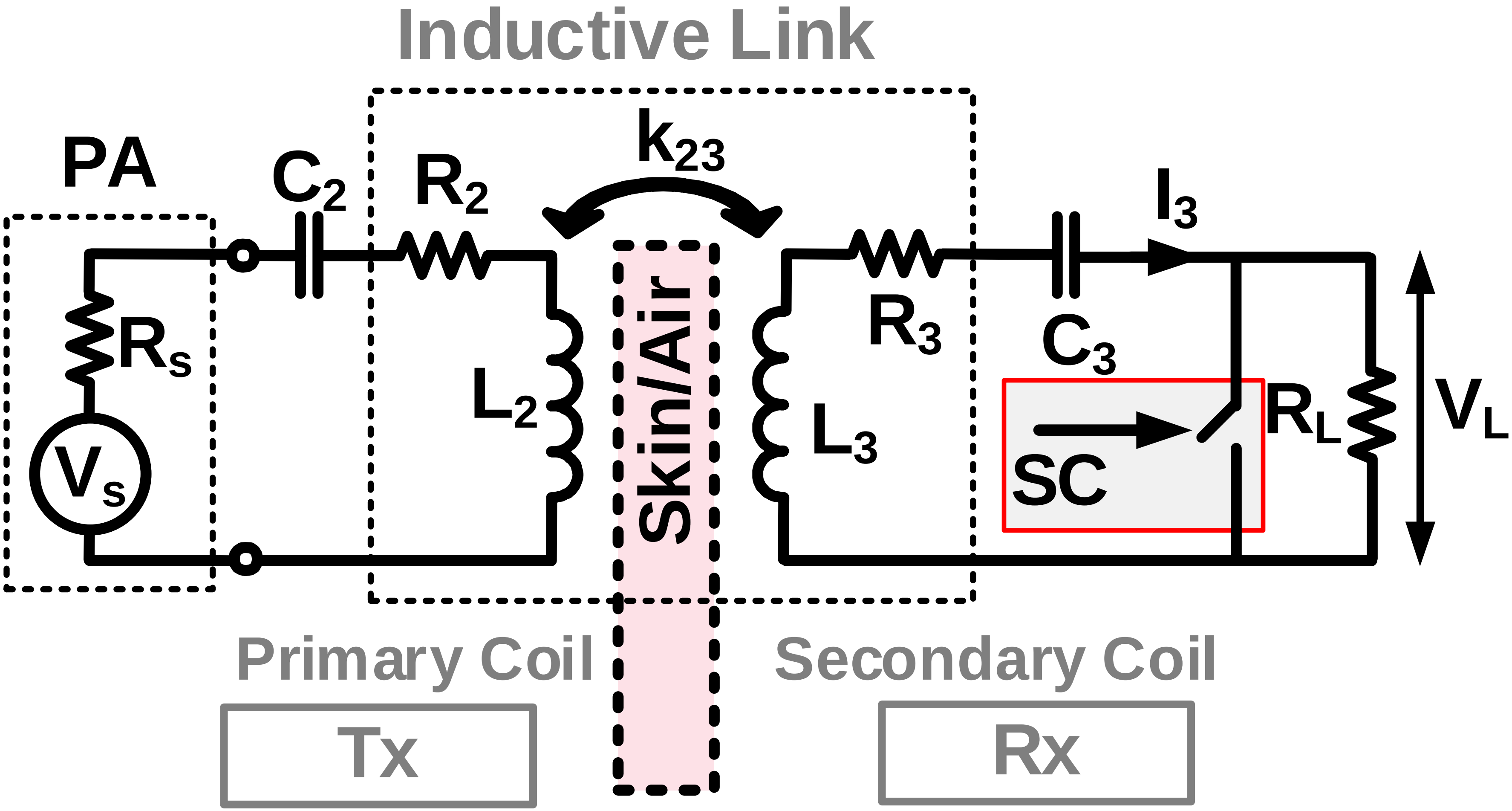




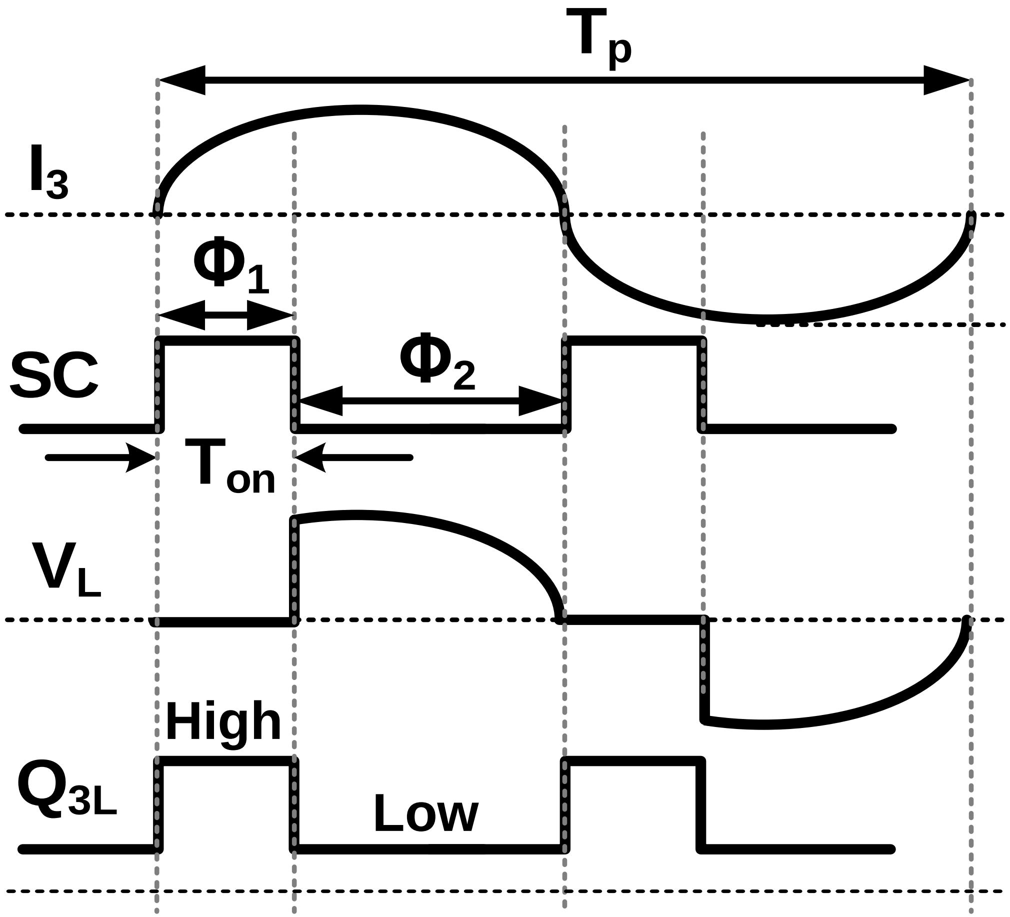
$$\eta_{3-coil} = \eta_{23}\eta_{34} = \frac{(k_{23}^2 Q_2 Q_3)(k_{34}^2 Q_3 Q_{4L})}{[(1+k_{23}^2 Q_2 Q_3 + k_{34}^2 Q_3 Q_{4L})(1+k_{34}^2 Q_3 Q_{4L})]} \cdot \frac{Q_{4L}}{Q_L}$$

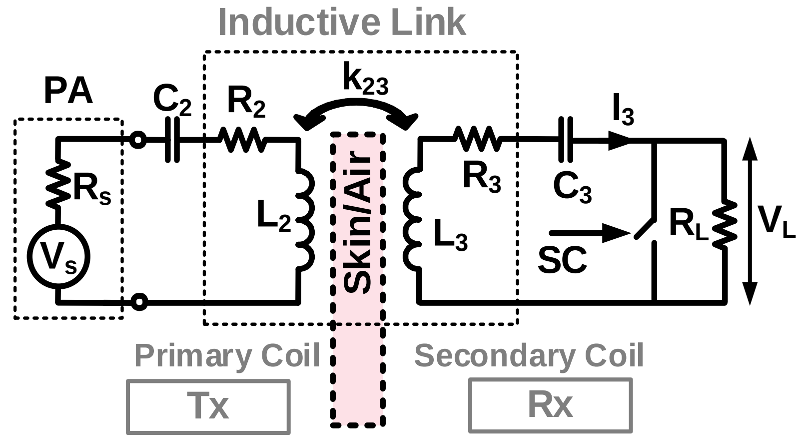
Problem: *k23* and *R_L* change but *k_{34}* is not adjustable during operation!

A Q-Modulation Based Inductive Power Transmission Link



Q-Modulation Inductive Link



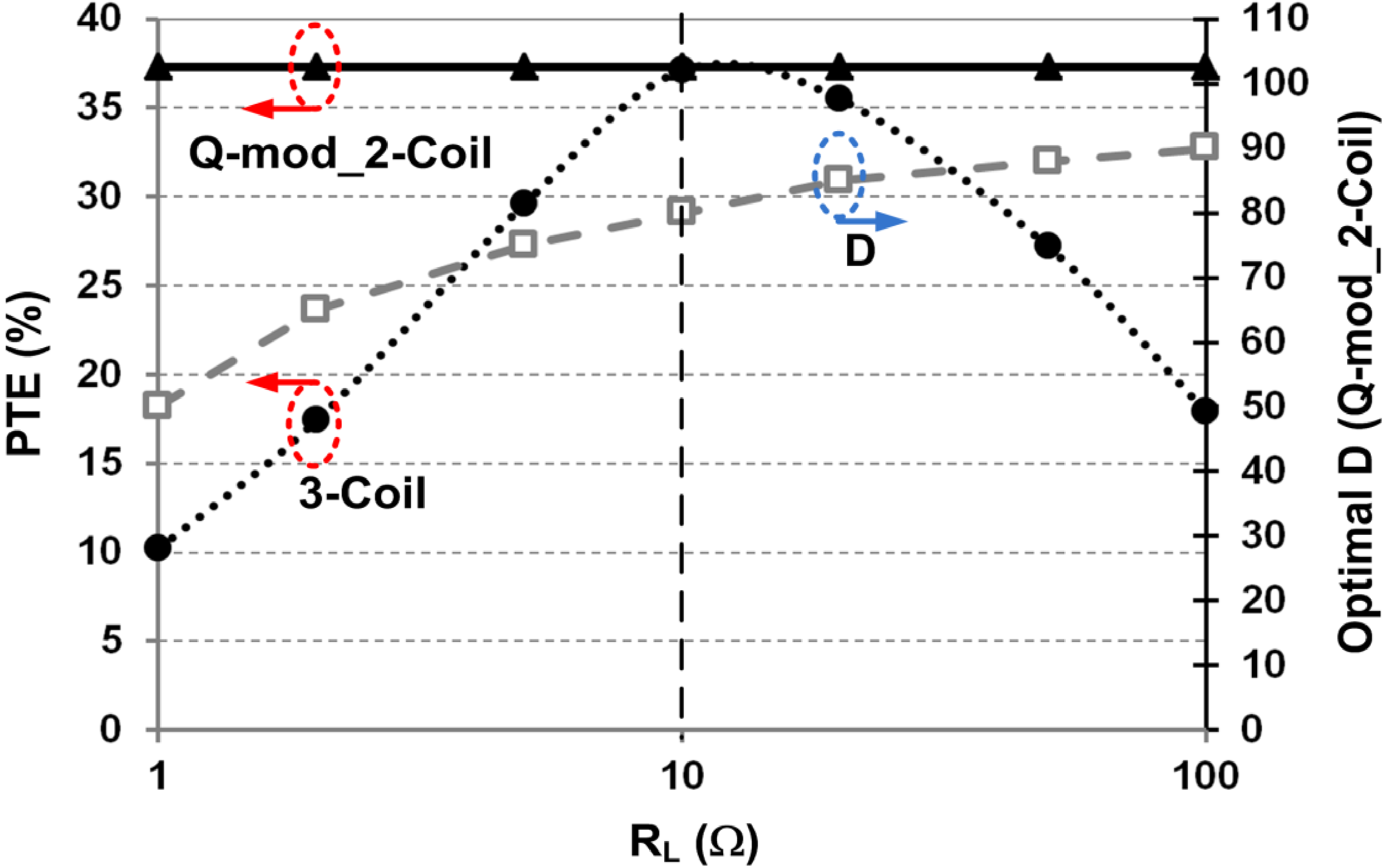


Q-Modulation Parameters

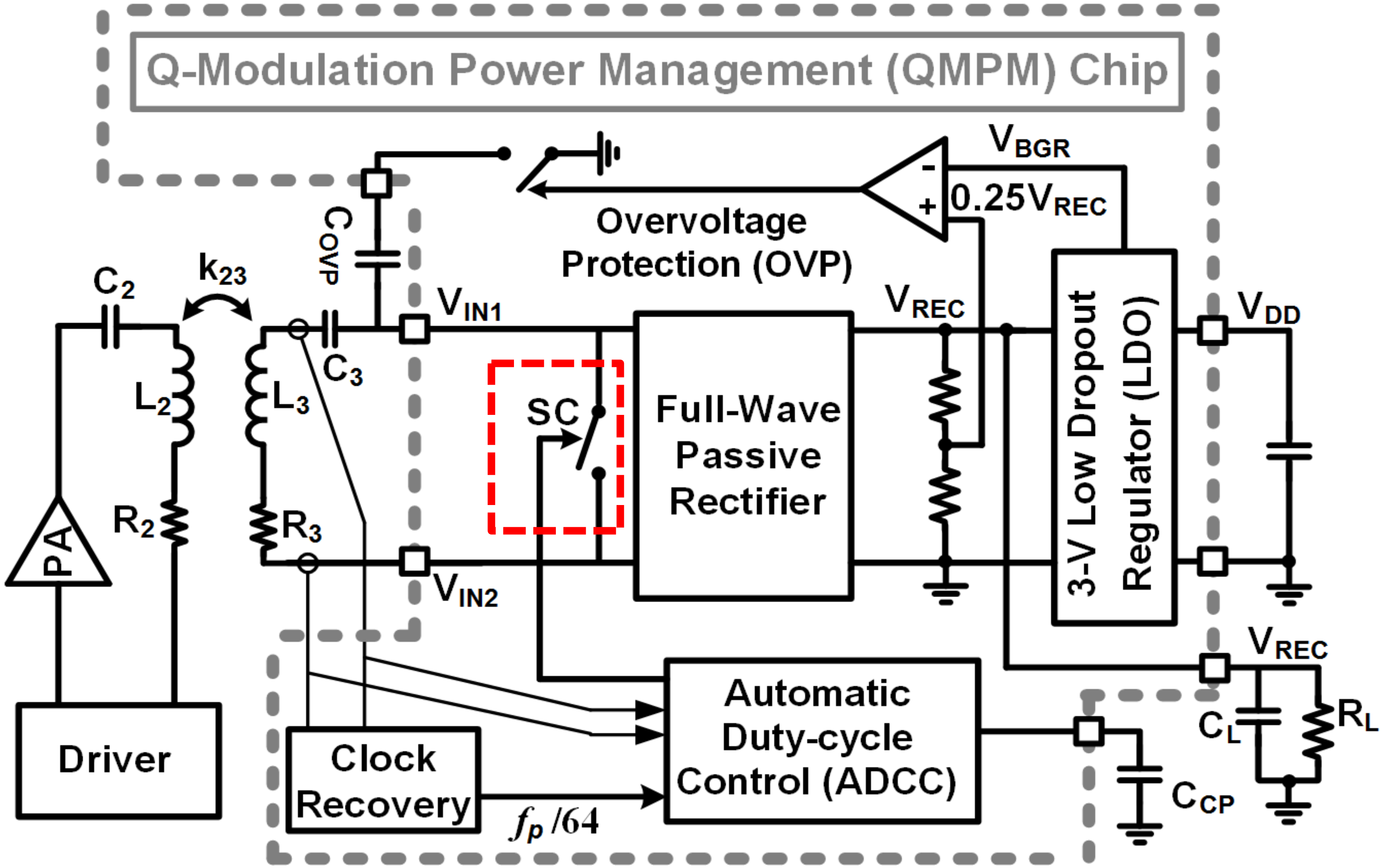
- $T_p/2$ and T_{on}
- Duty cycle: $D=2T_{on}/T_p$
- Switching at time zero crossing of I_3
- Switch resistance: R_{sw}

$$Q_{3L,eq} = \omega_p \frac{0.5 L_3 |I_m|^2}{P_{Rsw} + P_{R3} + P_{RL}} = \frac{\omega_p L_3}{R_3 + R_{sw}(D - \frac{1}{2\pi}\sin(2\pi D)) + R_L(1 - D + \frac{1}{2\pi}\sin(2\pi D))}$$

PTE Comparison between 3-Coil and Q-Modulation Inductive WPT Links

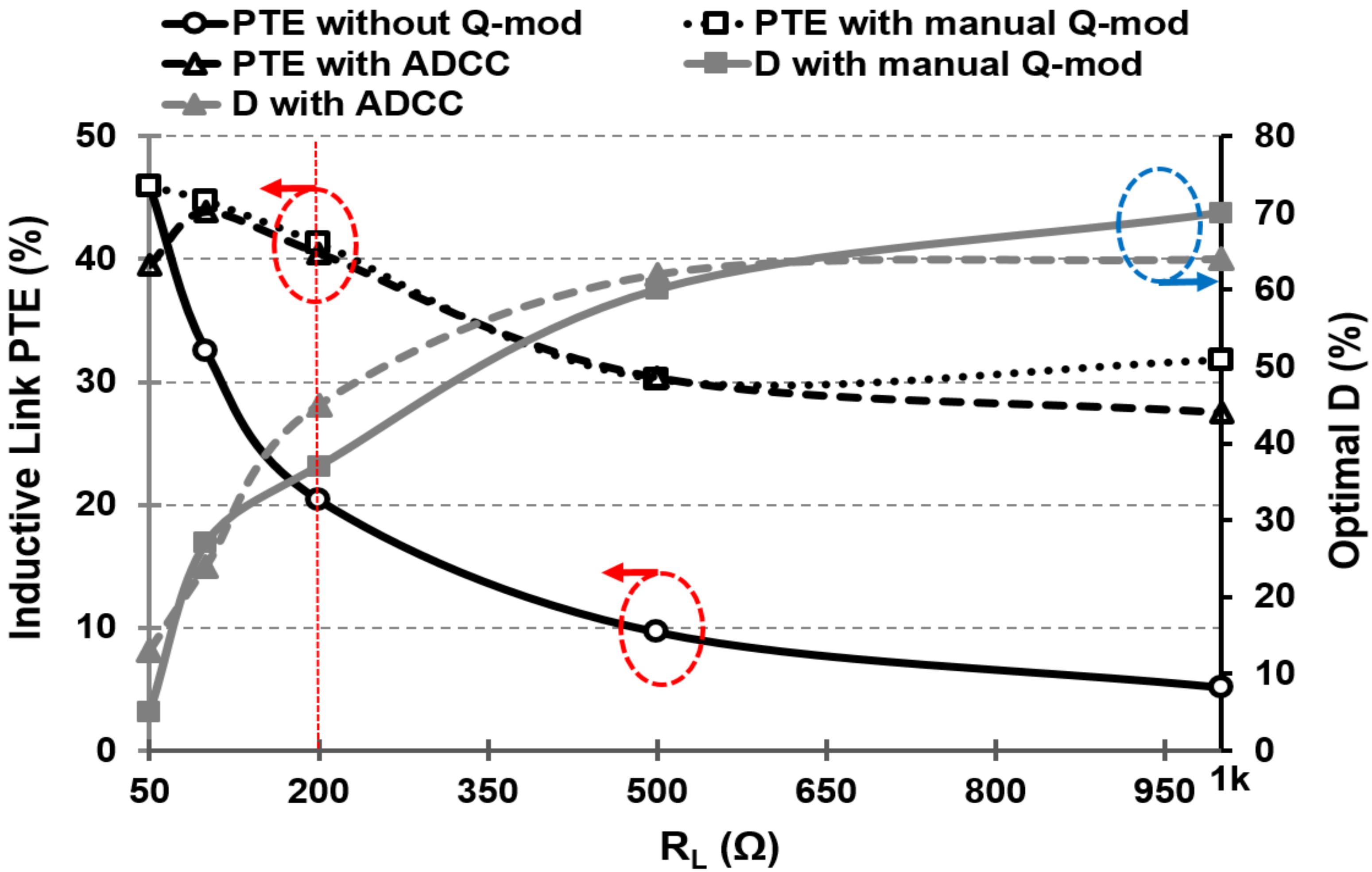


Q-Modulation Power Management (QMPM)



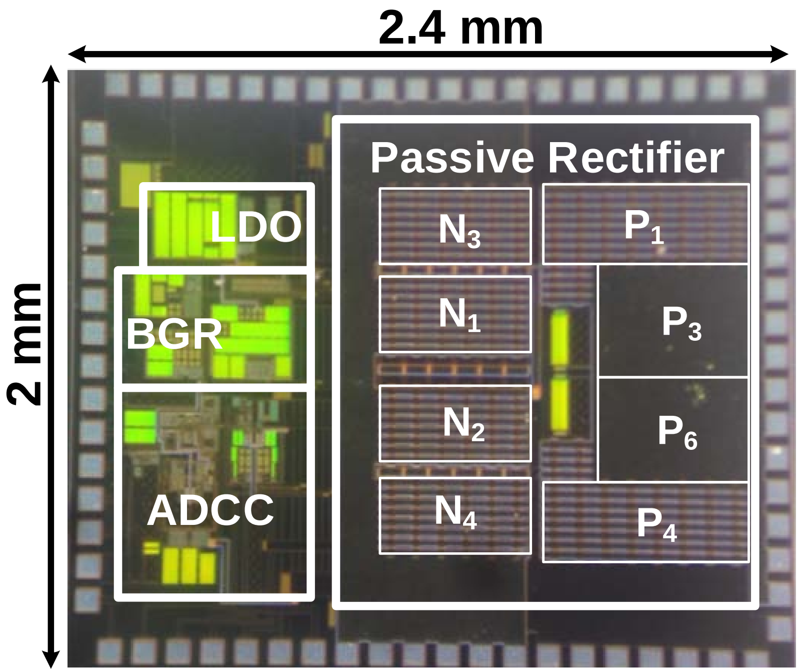
M. Kiani, et al., *ISSCC/JSSC* 2015

Q-Modulation Measurement Results: Load Variation



With Q-modulation, PTE increases by 2x at R_L = 200 Ω!

QMPM Die Micrograph & Benchmarking



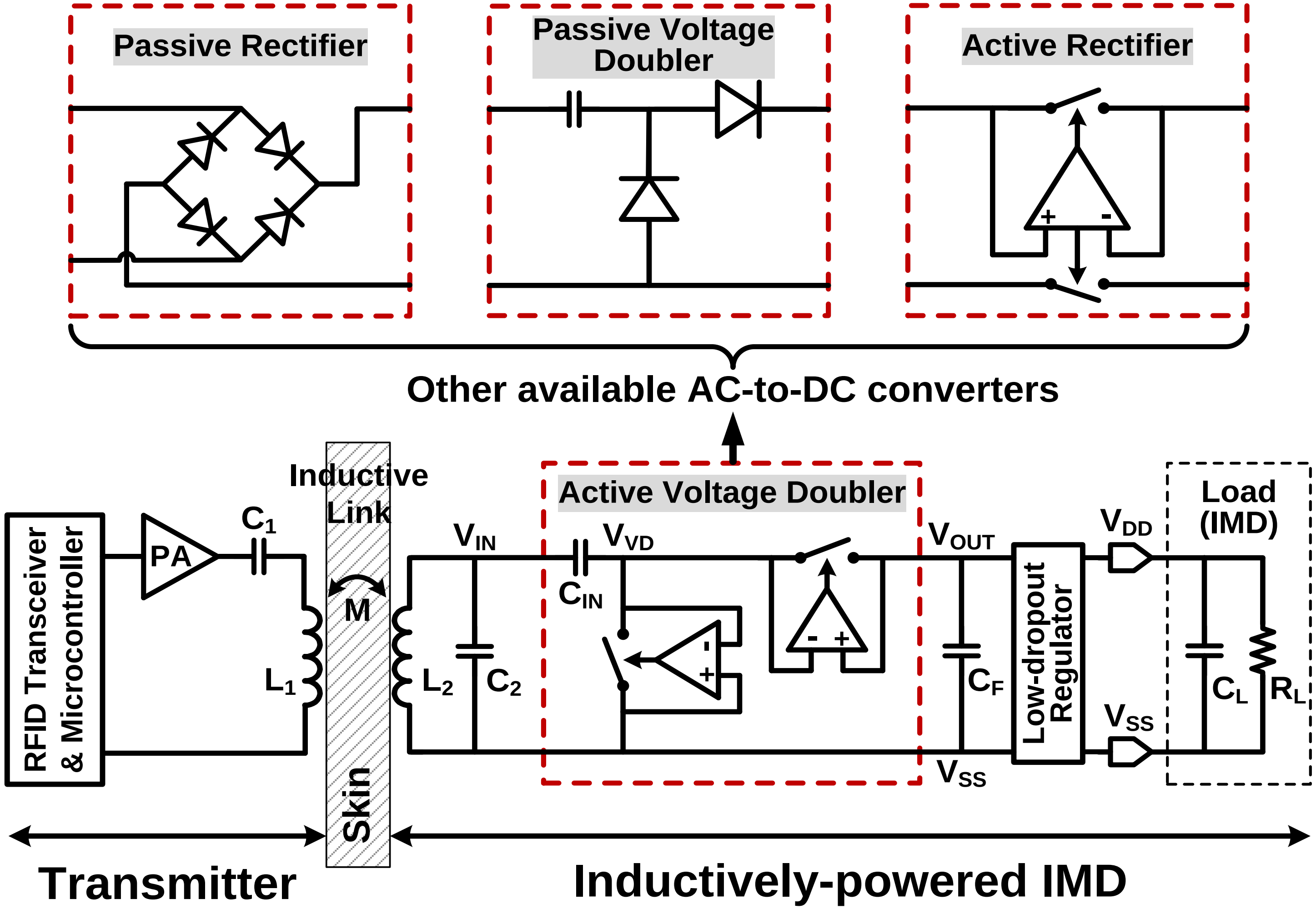
CMOS Technology		0.35µm 4M2P
Nominal Load		15 Ω
Rectifier Cap (C_L)		50 µF
Die Area		4.8 mm^2
Tx/Rx Coils	Diameter	9 / 4 cm
	# of Turns	5 / 14
	Inductance	4.1 / 17.1µH

Publication	Choi, ISSCC13	Lee, ISSCC12	Lu, ISSCC13	This Work
Freq (MHz)	6.78	13.56	13.56	2
V_{REC} (V)	5	3.1	4	4.5
Max Power (W)	6	0.037	0.032	1.45
Meas. PCE (%)	86	77	84	75
Load Matching	NO	NO	NO	YES

Outline

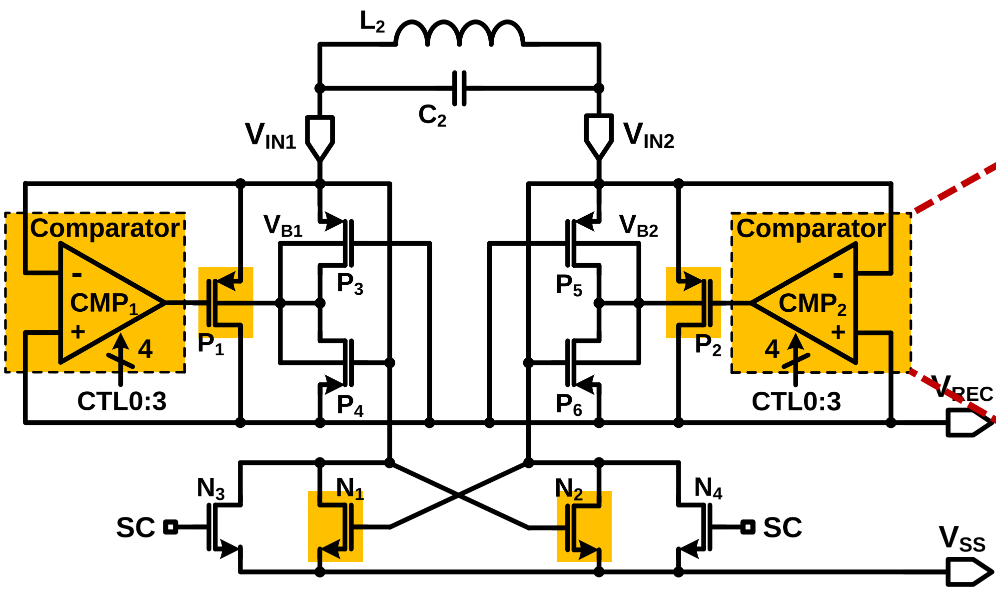
- Optimized Wireless Power Transfer Links
- **Power Conversion and Management Circuits**
  - **- Active AC-DC Converter**
  - **- Reconfigurable AC-DC converter**
  - **- Adaptive Regulating Rectifier**
  - **- Wireless Capacitor Charger**
- Low-Power Wireless Data Telemetry
- Conclusion

Inductively-Powered IMD Structure

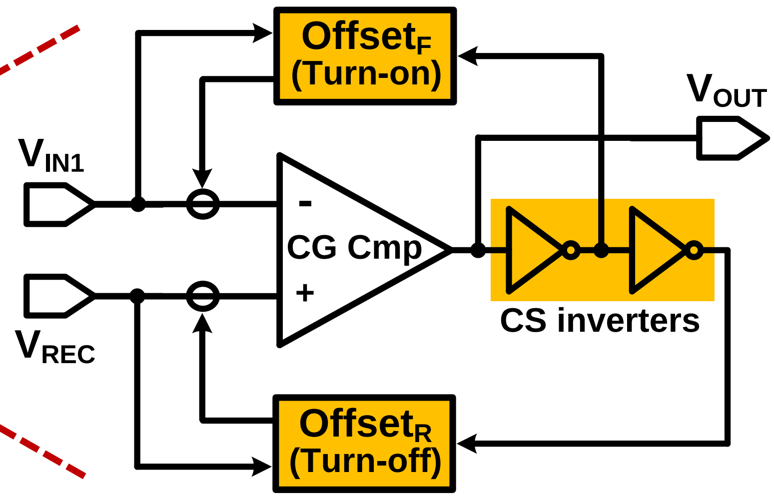


- Comparator-based Active AC-DC converters enable high power conversion efficiency (PCE) and low dropout voltage.

Full-Wave Active Rectifier



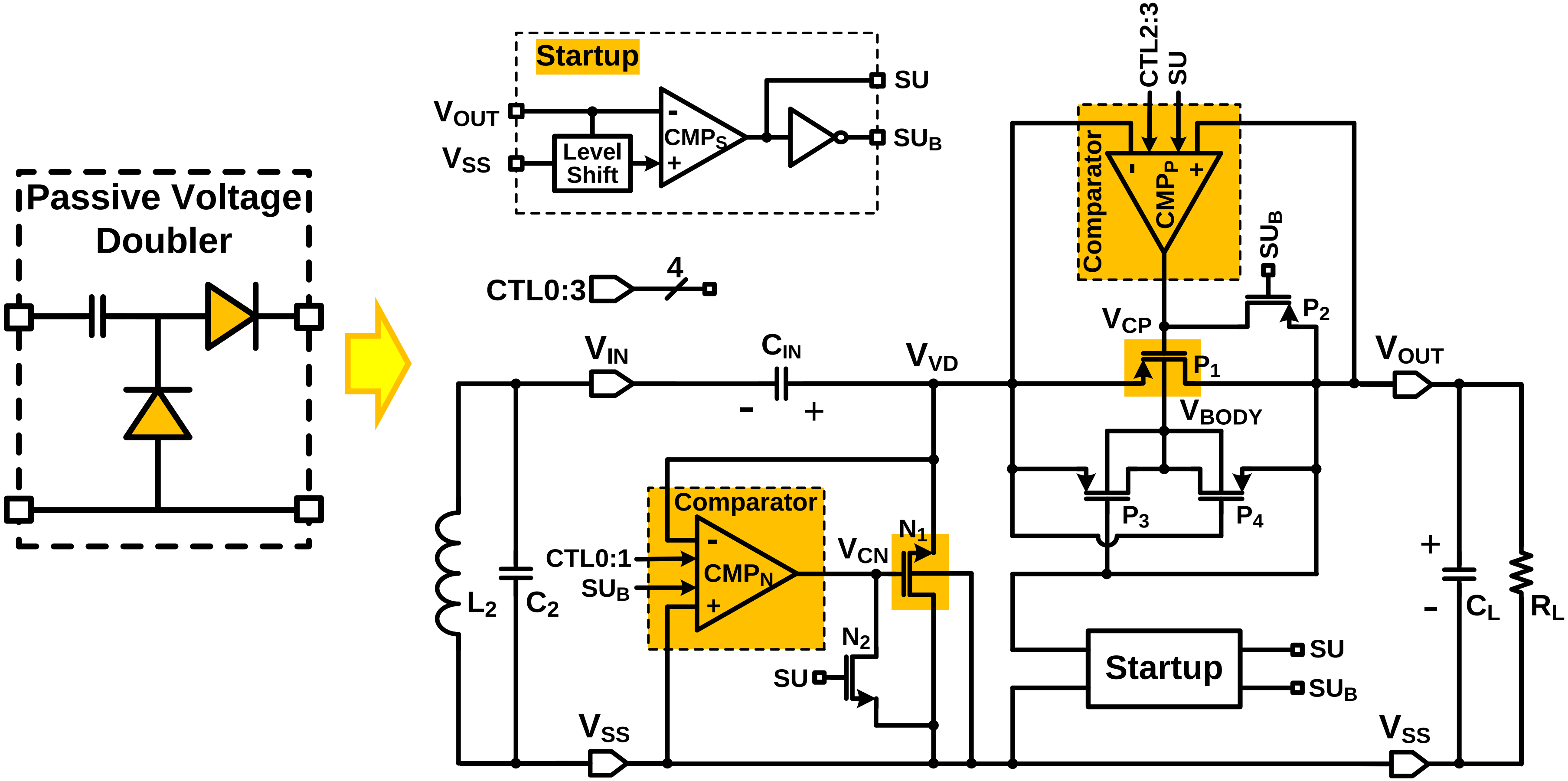
[Full-wave active rectifier]



[Offset-controlled comparator]

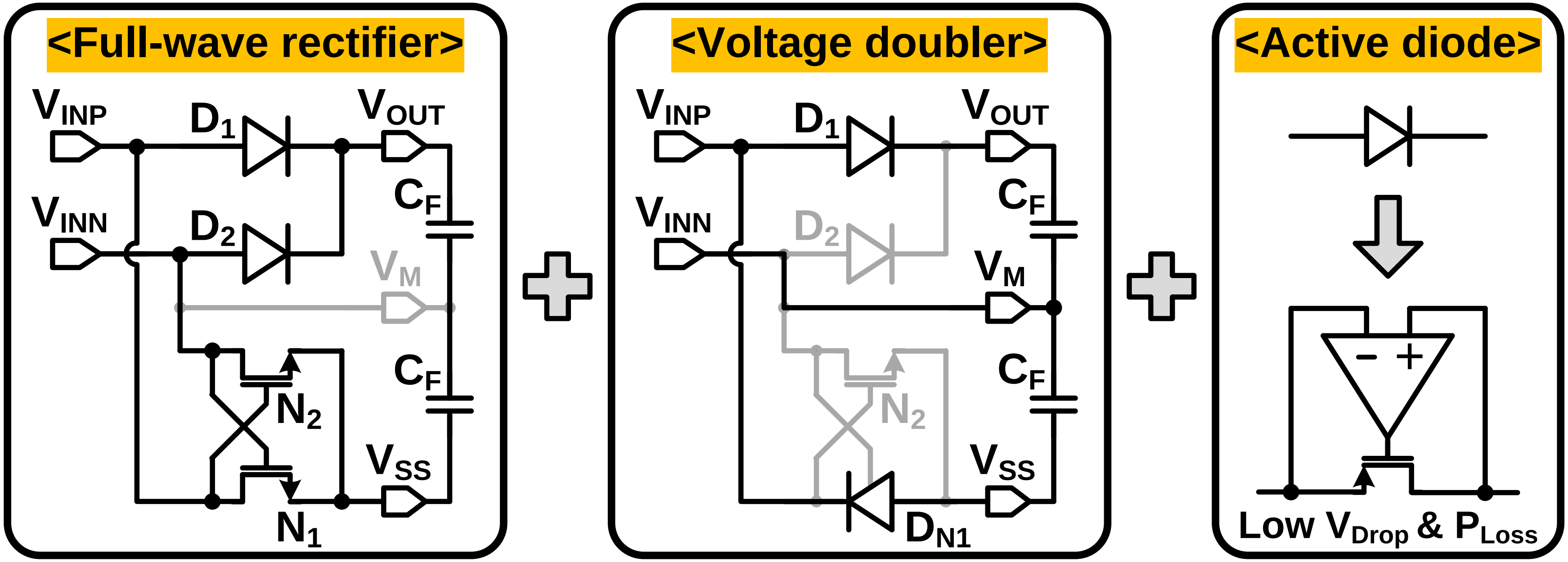
- Rectifying switches are driven by offset-controlled high-speed comparators at 13.56MHz ISM band.
- Offset-control blocks inject offset currents to compensate for both turn-on and turn-off delays.
- High measured PCE of 80.2% with 3.12V DC for 0.5kΩ load.

High-Speed Active Voltage Doubler



- Comparator-based active voltage doubler for high output voltage and high PCE @13.56MHz.
- PCE = 79% with 2.4V DC for 1kΩ load from 1.46V AC input.

Reconfigurable AC-DC Converter

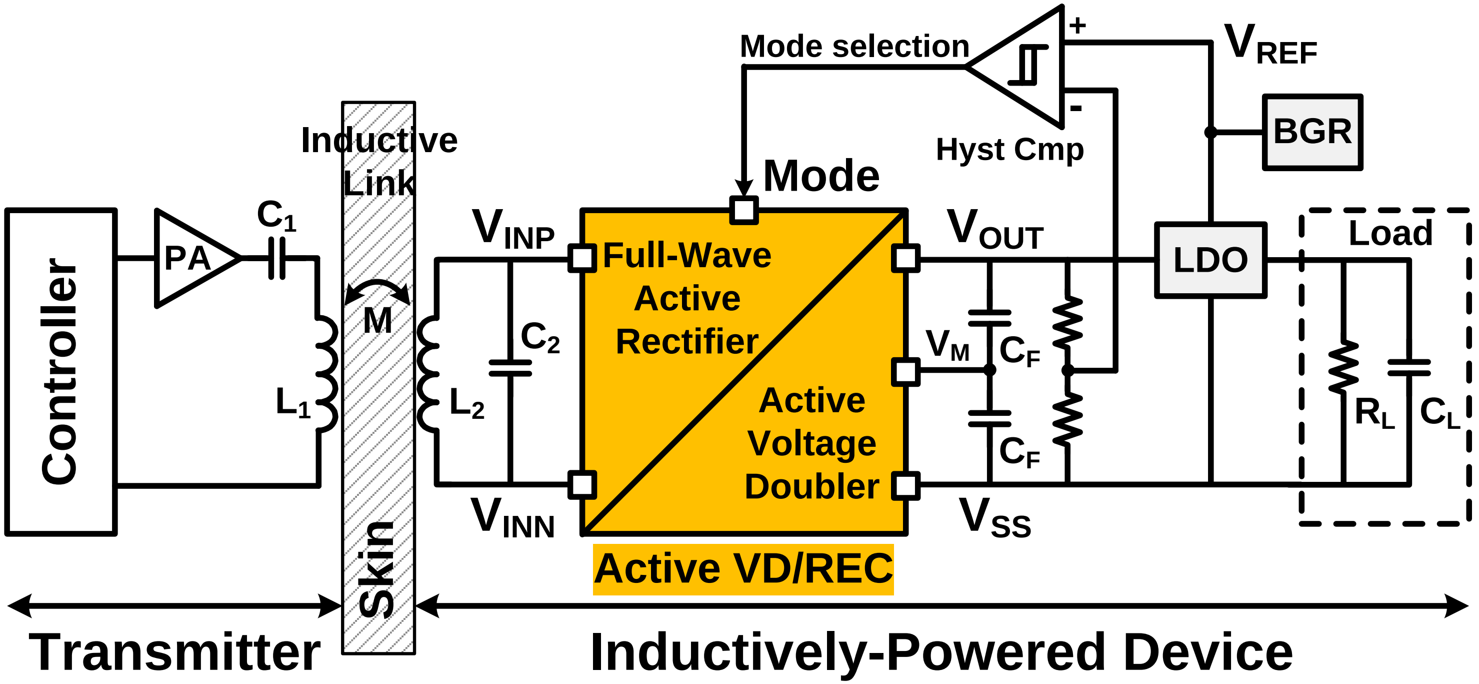


Combining two AC-DC mechanisms into a single circuit:

- VD/REC combines two AC-to-DC converters, i.e. a full-wave rectifier and a voltage doubler, into a single circuit.
- Active diodes driven by high-speed comparators lead to low dropout and high PCE in both VD and REC.

Lee and Ghovanloo, *ISSCC* 2012

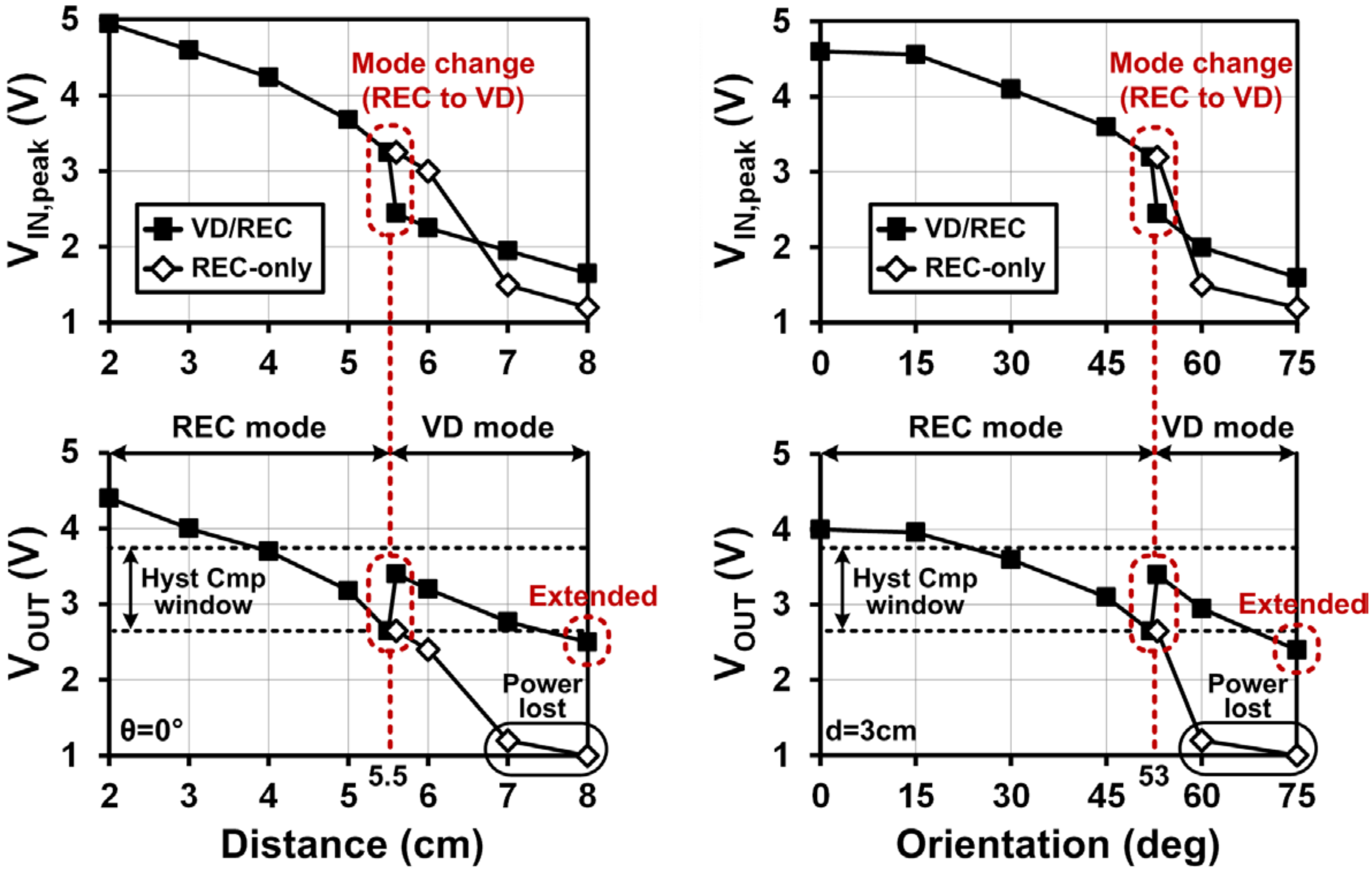
Adaptive Reconfigurable VD/REC



Condition	Mode	Operation	Key Feature
$V_{OUT} > V_{REF(Hyst)}$	0	Full-wave rectifier	High power efficiency (PCE)
$V_{OUT} < V_{REF(Hyst)}$	1	Voltage doubler	High output voltage (V_{OUT})

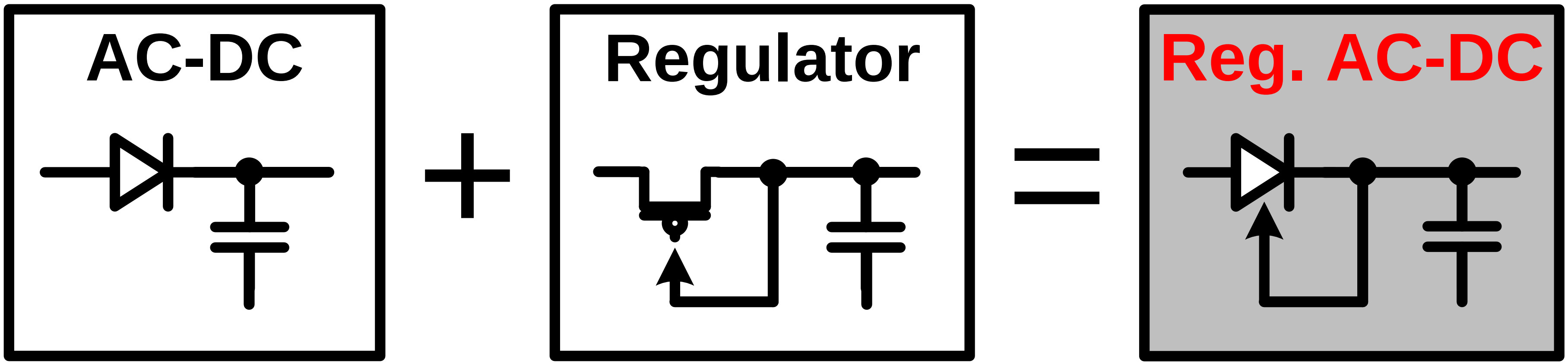
- Adaptive mode control for rectification or voltage doubling
- Extended-range inductive power transmission
- High PCE (70% VD / 77% REC) with active diodes

Power Transmission Range



- VD/REC extends power transmission range by 33% (6cm to 8cm) in coil distance and 41.5% (53° to 75°) in coil orientation, compared to using the rectifier only.

Adaptive Regulating Rectifier

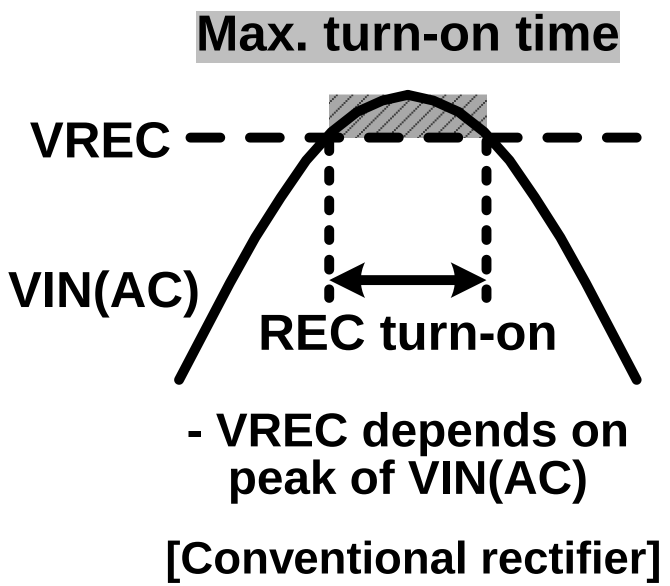


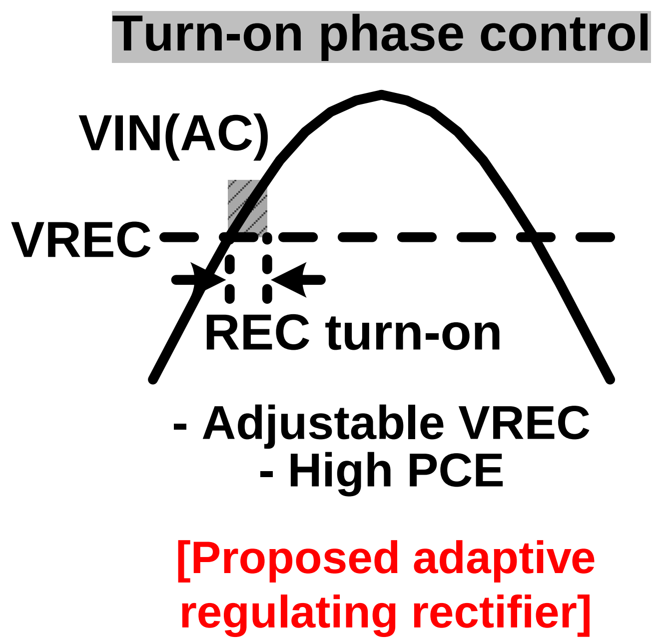
Combining AC-DC conversion and DC regulation into a single structure:

- Adaptive regulating rectifier combines an AC-DC converter and a regulator into a single structure
- Area & power-efficiency one-step power conversion/regulation
- Overall PCE up to 87% at 2MHz without using regulators

H. Lee *et al*. *JSSC* 2013

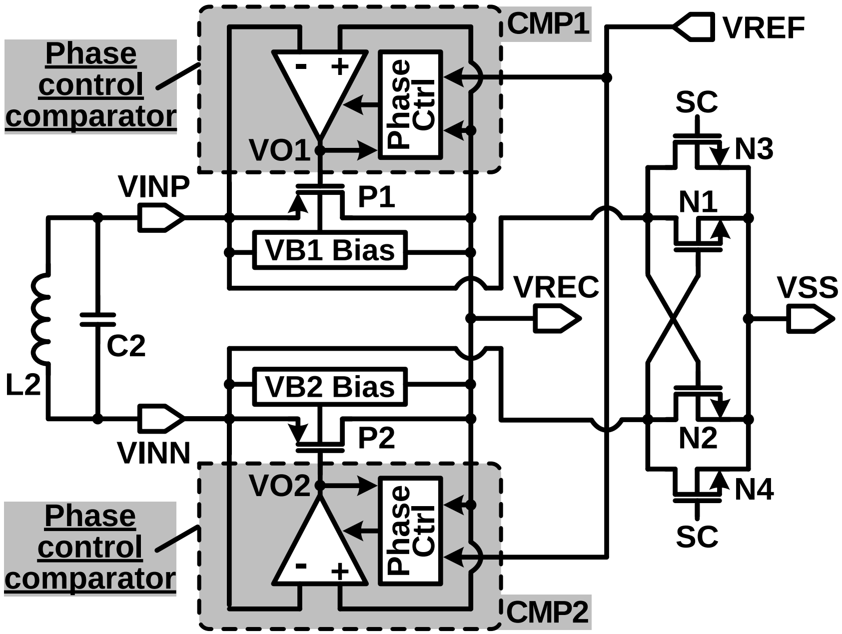
Adaptive Regulating Rectifier Concept



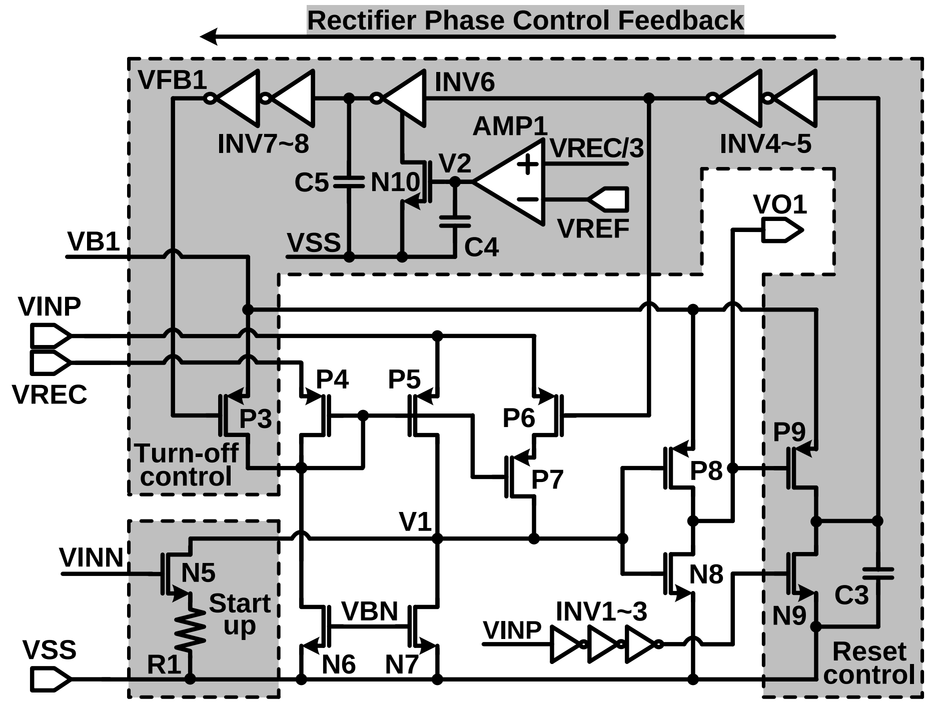


- **Conventional rectifier:**
  - V_{REC} depends on peak of $V_{IN(AC)}$ → V_{REC} is not adjustable.
- **Proposed adaptive regulating rectifier:**
  - Turn-off timing control → V_{REC} is adjustable.
  - High PCE with small voltage drop between V_{REC} and $V_{IN(AC)}$.

Rectifier Phase Control Feedback



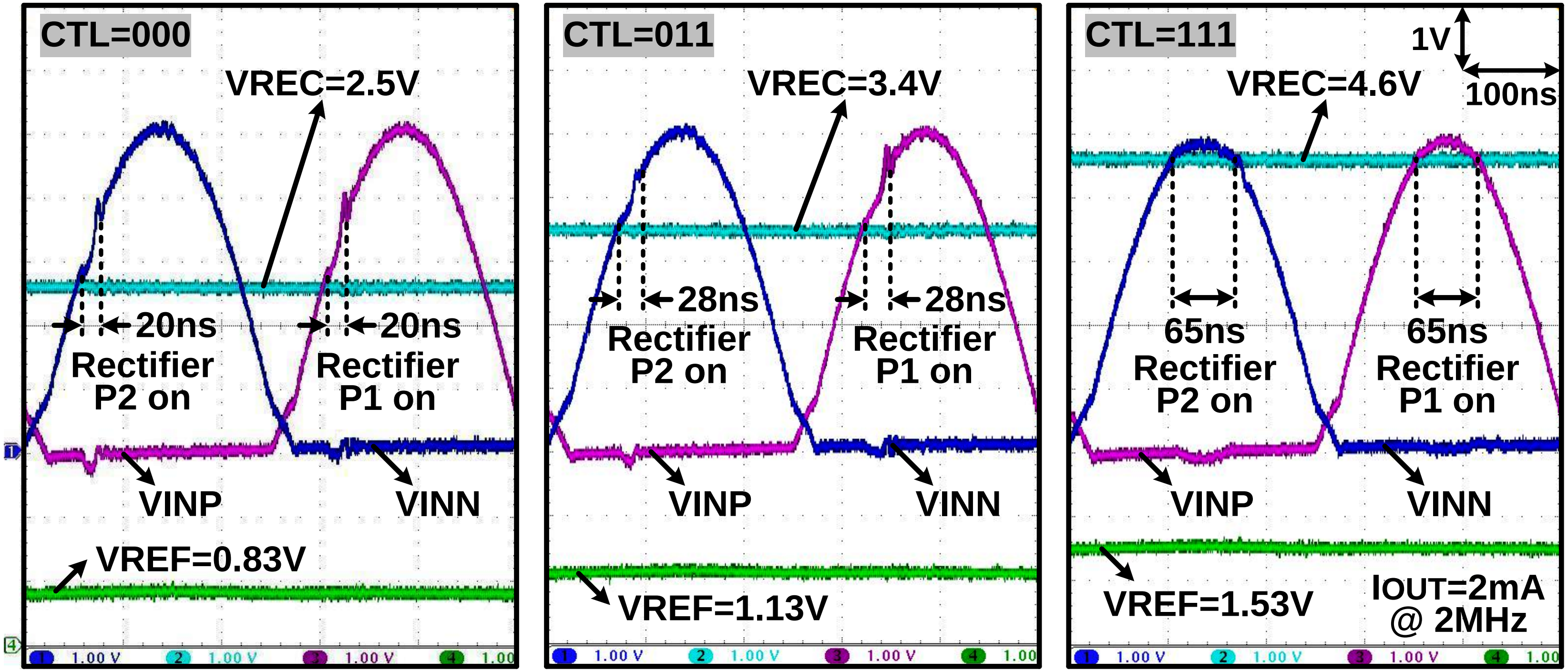
[Adaptive regulating rectifier]



[Phase control comparator]

- Phase control feedback can be added to the conventional comparator to control the rectifier turn-off time.
- Phase control feedback turns off the rectifier after a variable time delay to adjust V_{REC} for a target output voltage.

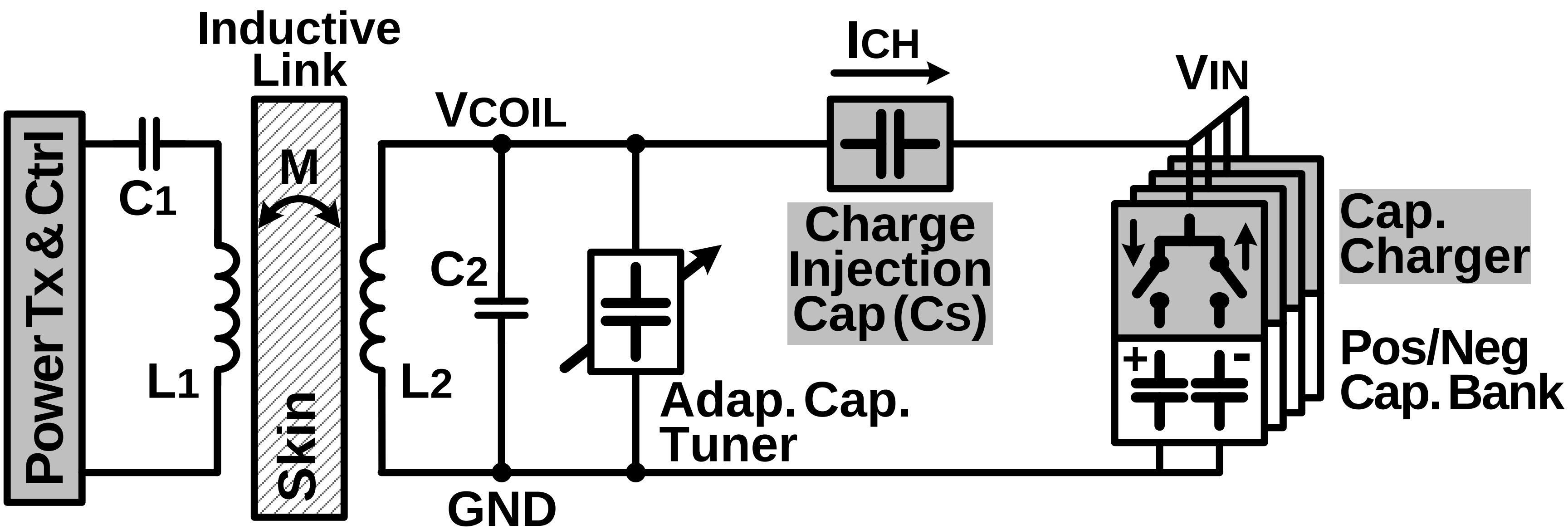
Regulating Rectifier Waveforms & PCE



<u>When the peak input voltage is constant at 5V</u>:

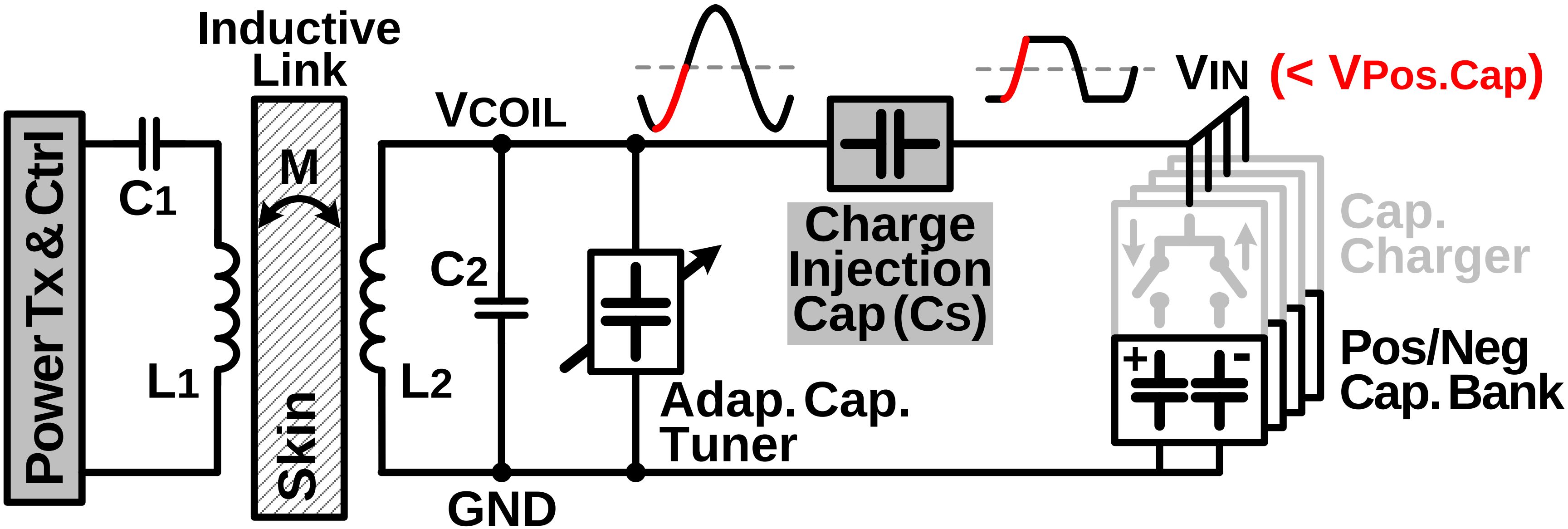
- The regulating rectifier generates adjustable V_{REC} from 2.5V to 4.6V (3-bit) by adjusting the rectifier turn-on phase.
- The regulating rectifier still achieves high PCE of 72~87% at 2MHz when V_{REC} = 2.5~4.6V and I_{OUT} = 2.8mA.

Efficient Wireless Capacitor Charger



- Direct pos/neg capacitor charging from AC coil voltage (V_{COIL})
- A charge injection capacitor (C_S) & a capacitor charger switch generate a fixed amount of charging current (I_{CH}).
- Fixed I_{CH} reduces switching loss, while C_S does not dissipate power, maximizing capacitor charging efficiency (82% @ ±2V).

Wireless Capacitor Charger Operation



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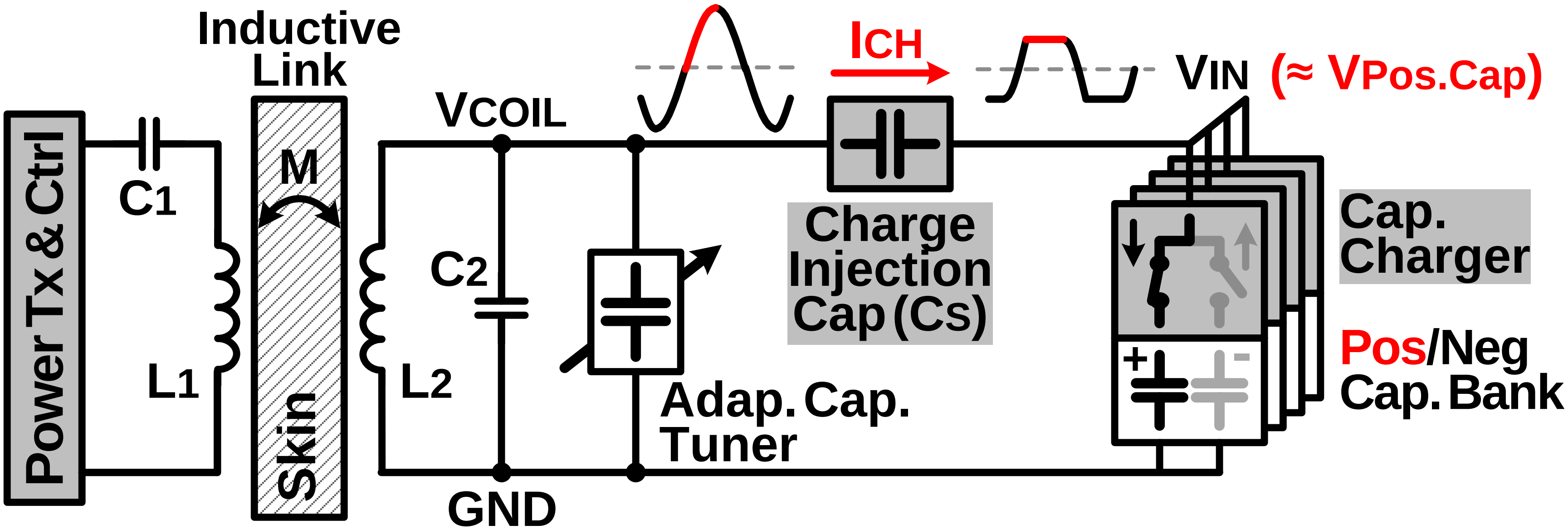

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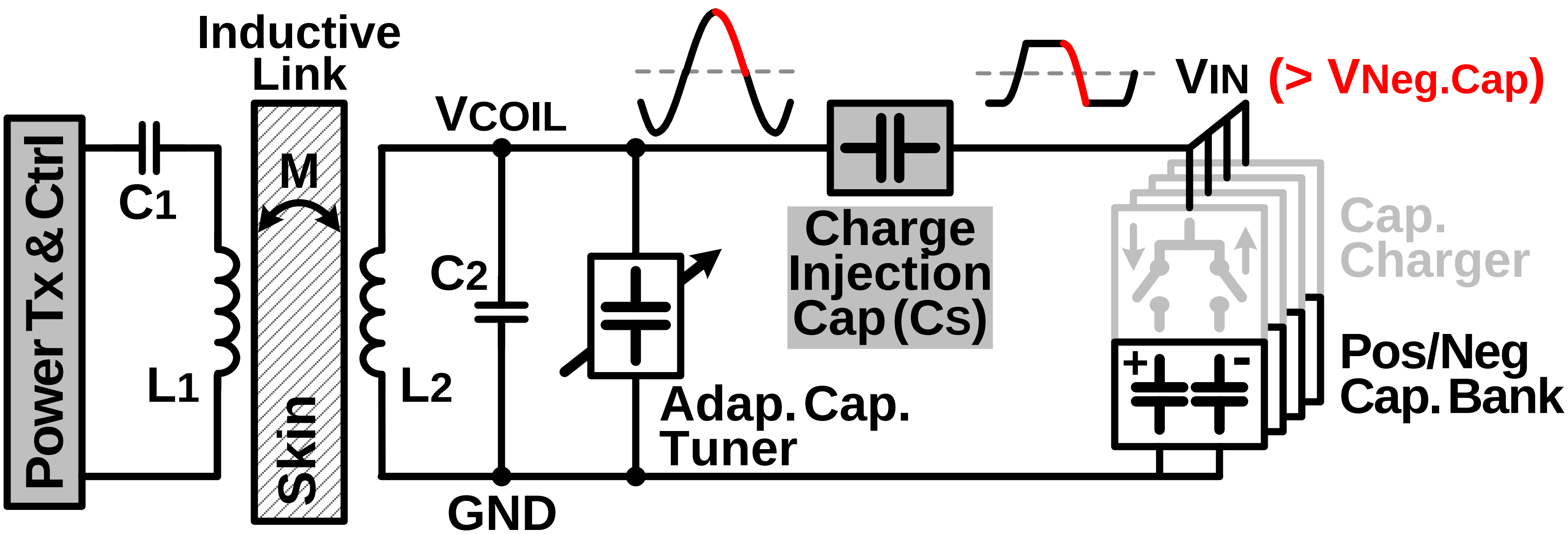

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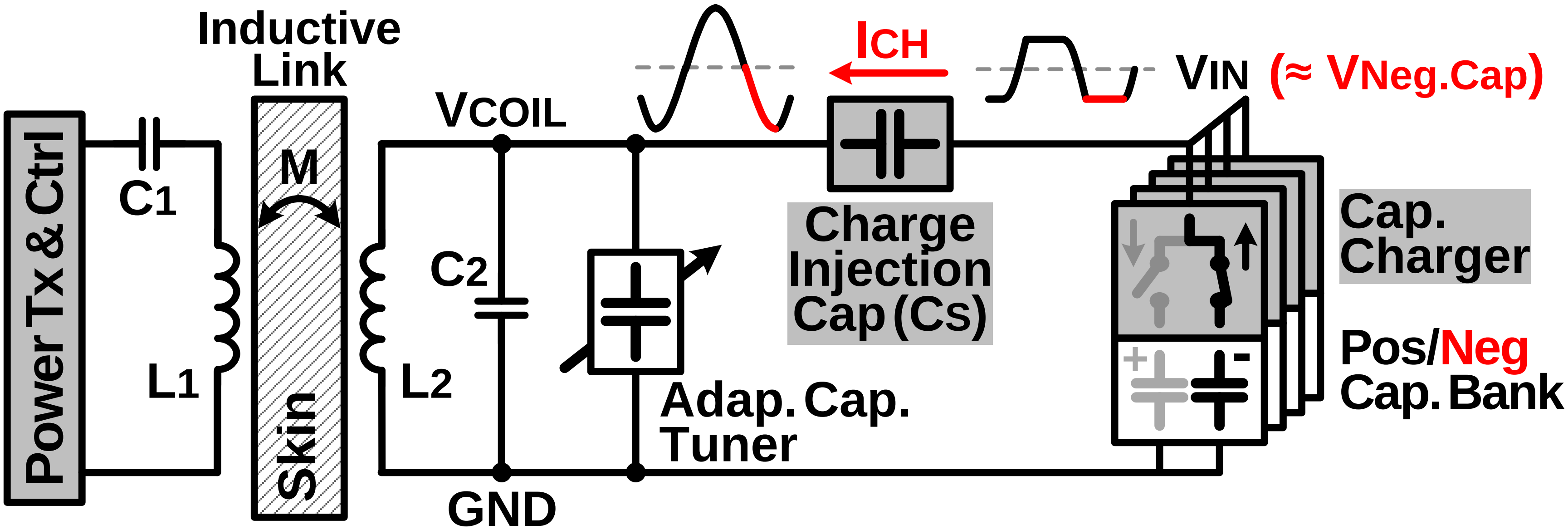

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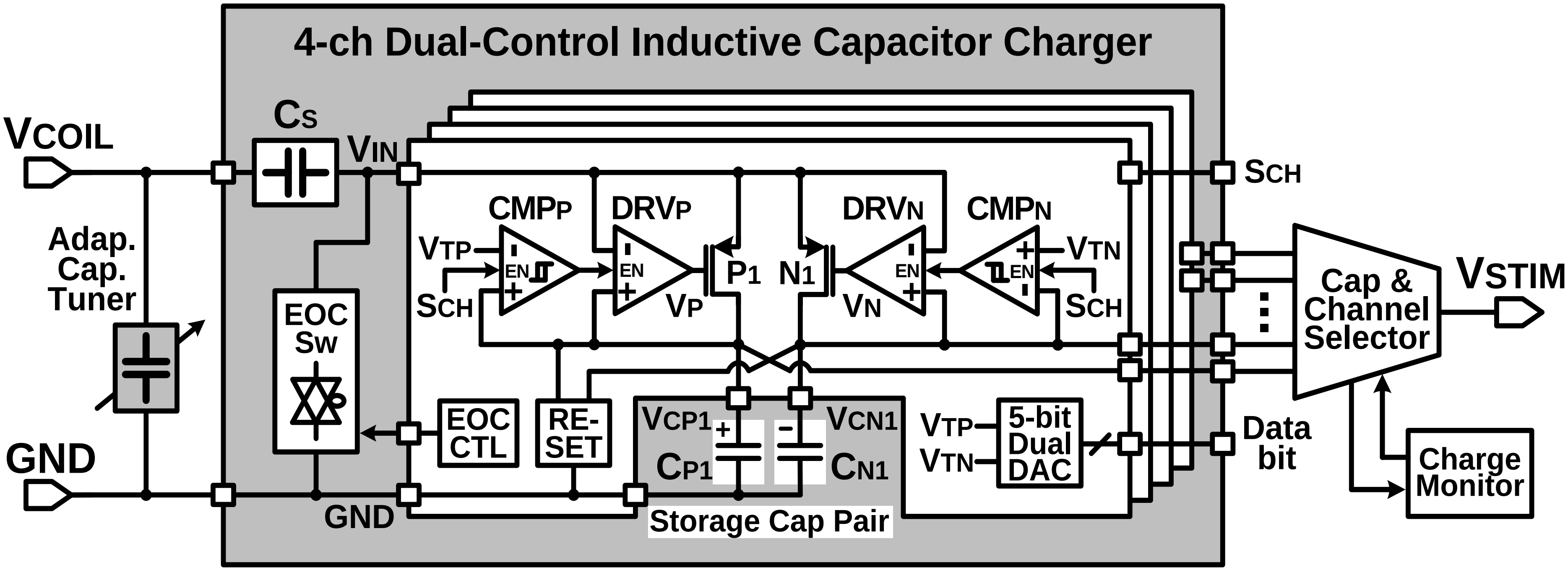
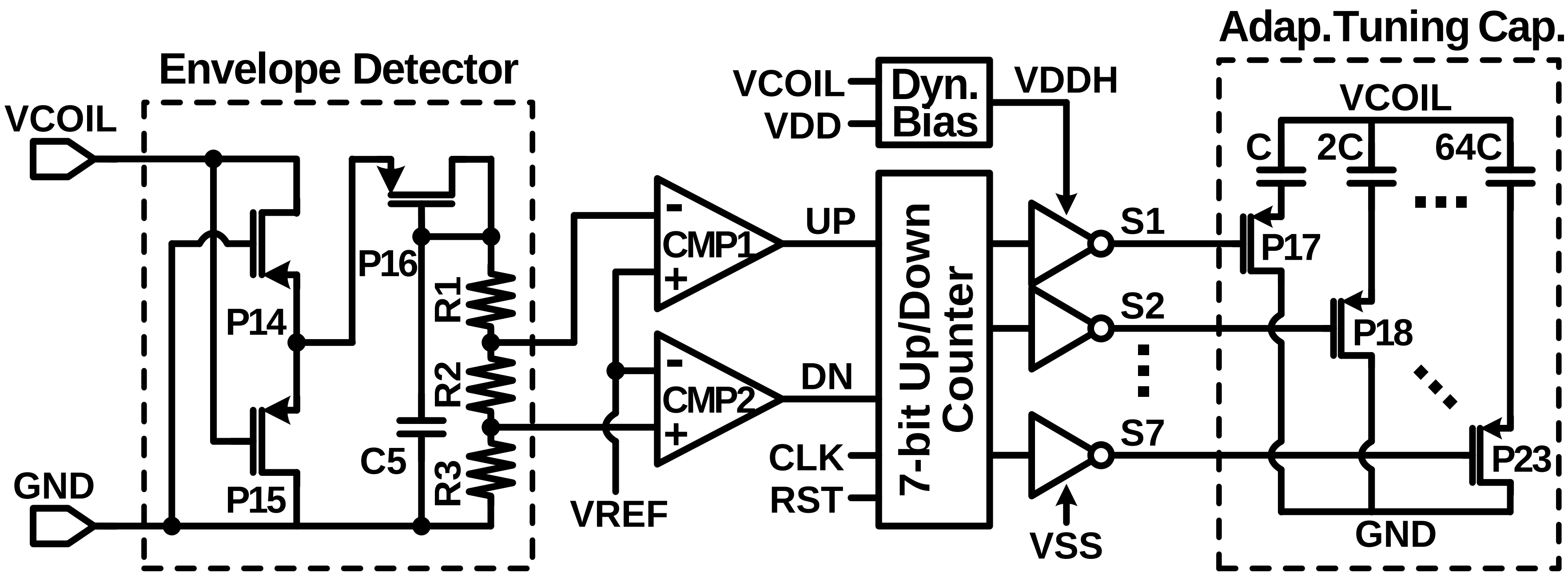
Dual-Control Wireless Capacitor Charger



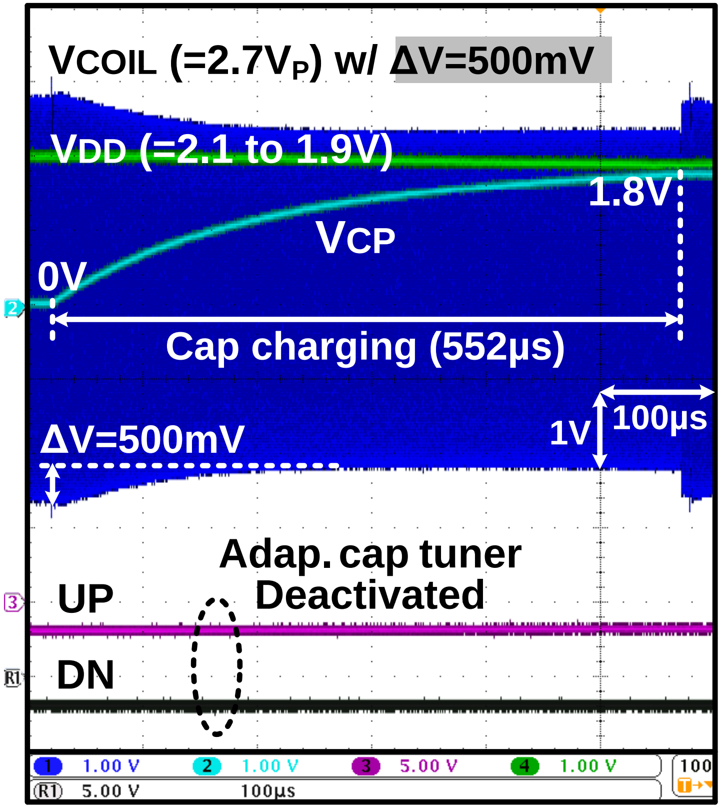
- Dual-voltage control capability for separately charging pos/neg capacitors to their designated target voltages
- Capacitor reset function
- Adaptive capacitor tuning

Adaptive Resonant Capacitor Tuner

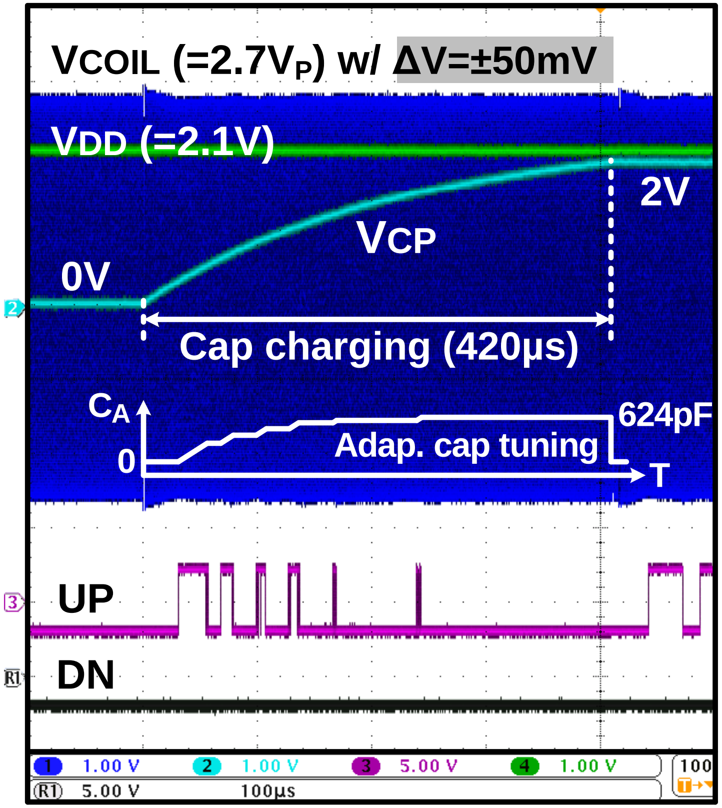


- Effective resonance capacitance varies during charging.
- Coil amplitude detection & comparison
- Adaptive 7-bit tuning capacitors

Adaptive Capacitor Tuner Waveforms



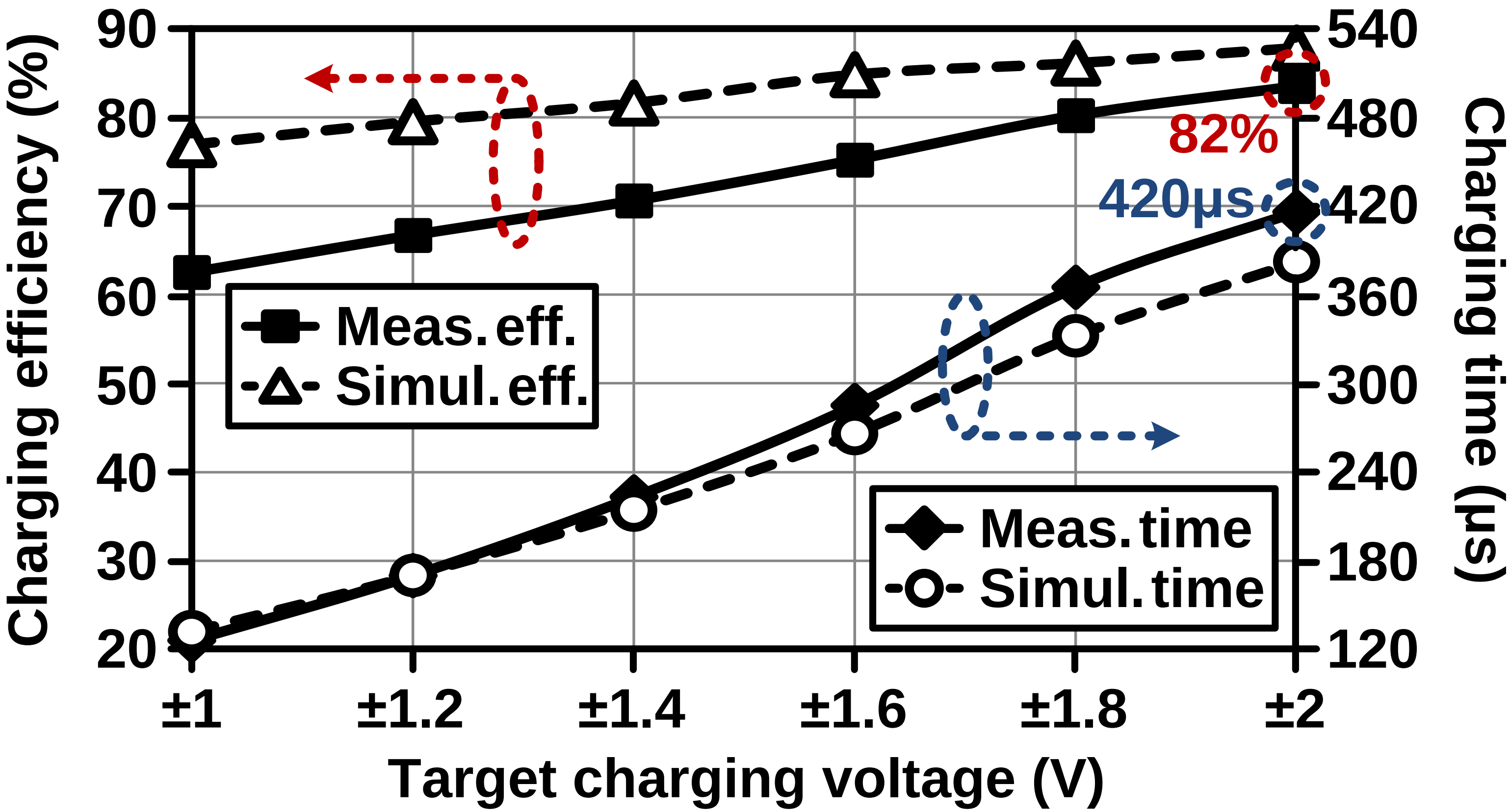
[Adaptive cap. tuner deactivated]



[Adaptive cap. tuner activated]

- During charging, resonant capacitance variation decreases the V_{COIL} amplitude, limiting the proper charging operation.
- An adaptive capacitor tuner keeps V_{COIL} amplitude constant.

Capacitor Charging Efficiency & Time

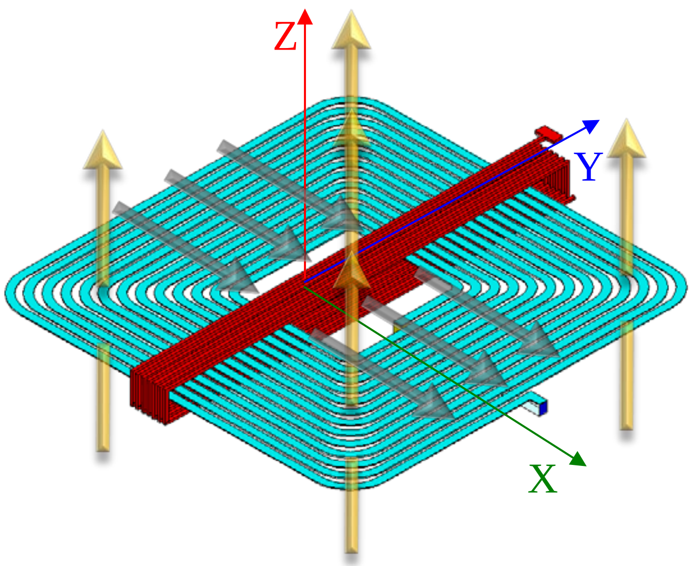


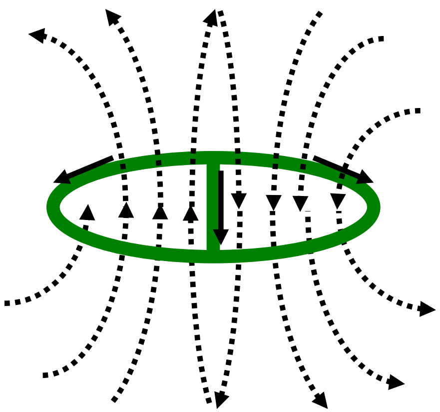
- With 2.7V peak AC input at 2MHz, a pair of 1μF capacitor can be charged up to ±2V in 420μs, achieving high measured charging efficiency of 82%.

Outline

- Optimized Wireless Power Transfer Links
- Power Conversion and Management Circuits
- **Low-Power Wireless Data Telemetry**
  - **- Pulse Delay Modulation (PDM)**
  - **- PDM Transceiver**
  - **- PDM Measurement Results**
- Conclusion

Dual-Band Data/Power Transmission Using Two Pairs of Coils





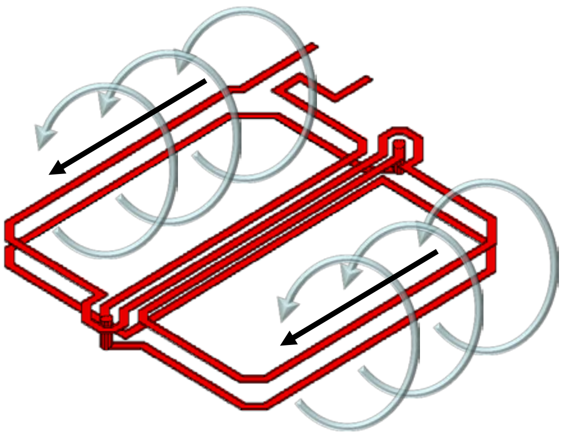
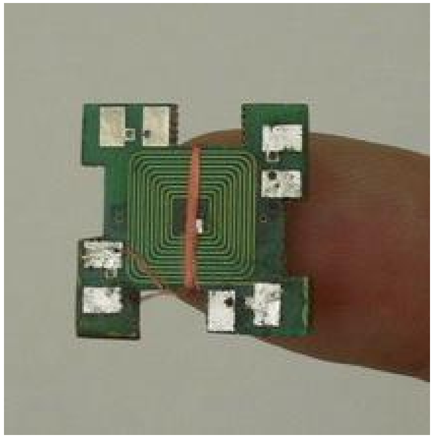
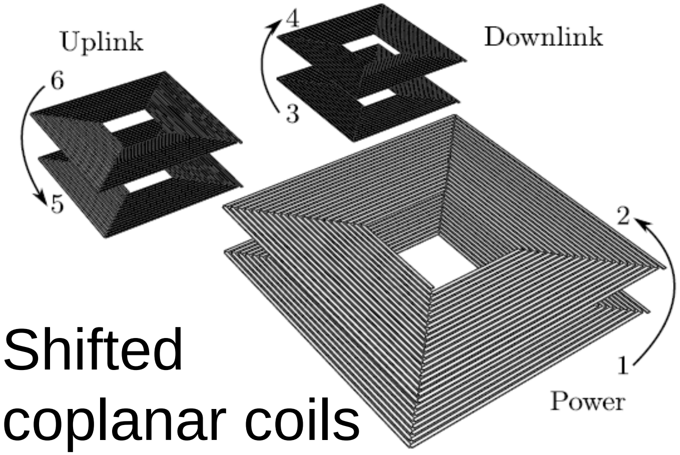


Figure-8 coils

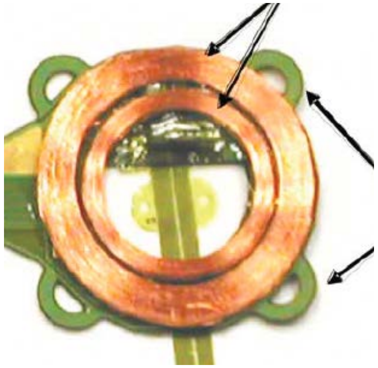
Vertical coils





Shifted coplanar coils

Simard and Sawan

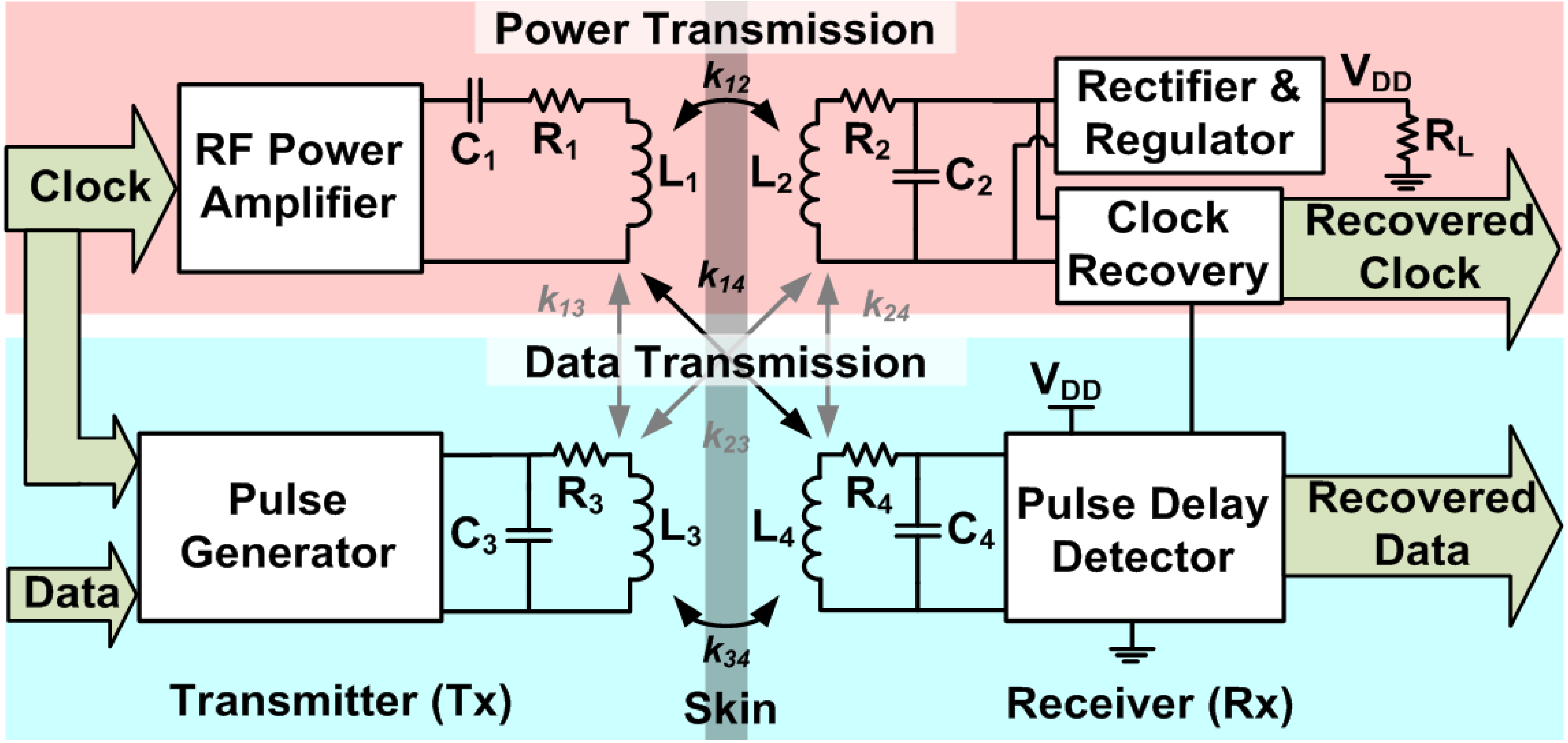


Coaxial coils

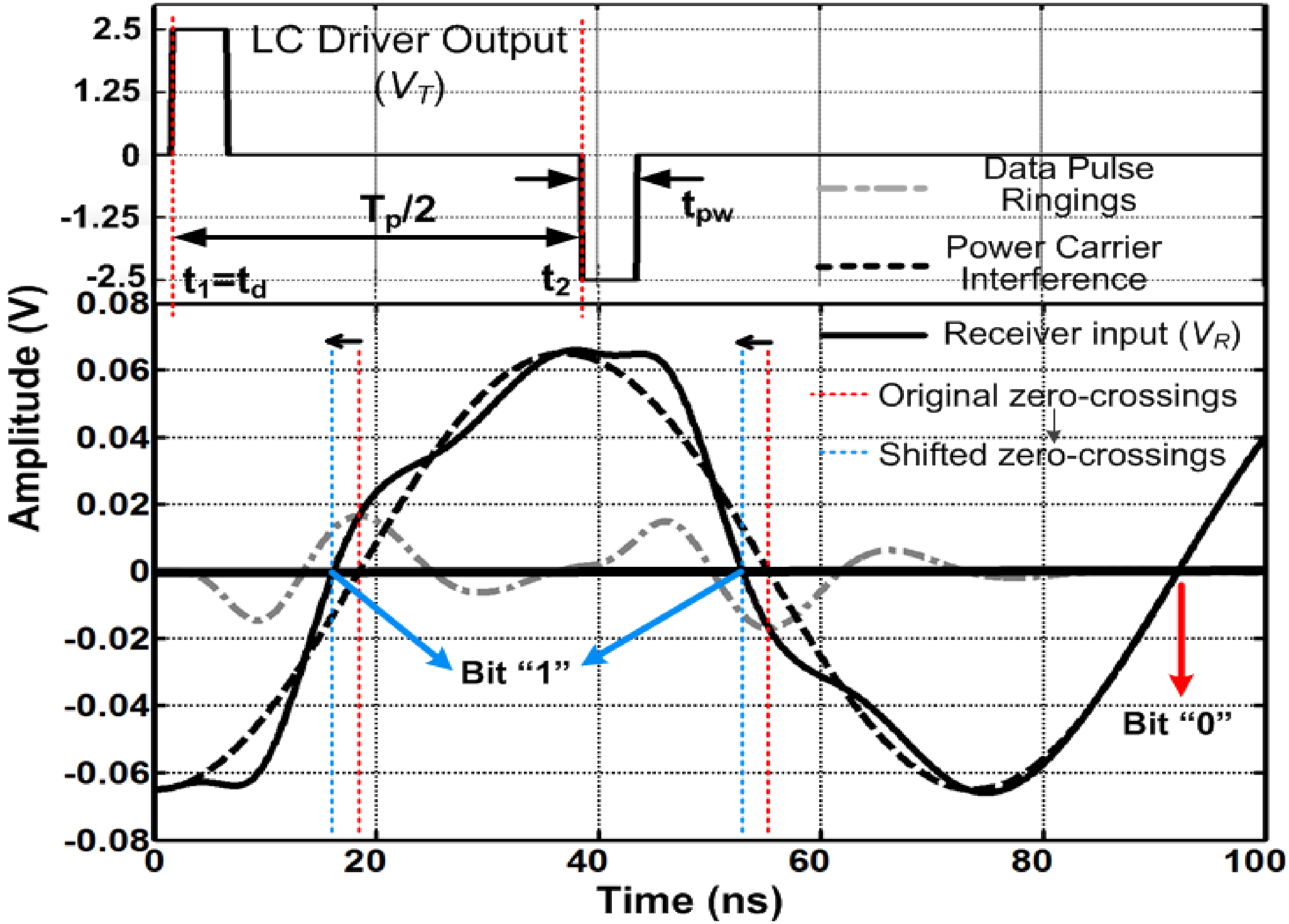
S. Kelly et al. and W. Liu et al.

Pulse Delay Modulation (PDM) using a Dual-Band Power/Data Link

- Pulse-Based data transmission using a separate data link by modulating the zero-crossings of the undesired power carrier interference across L_4C_4-tank with short decaying ringing.

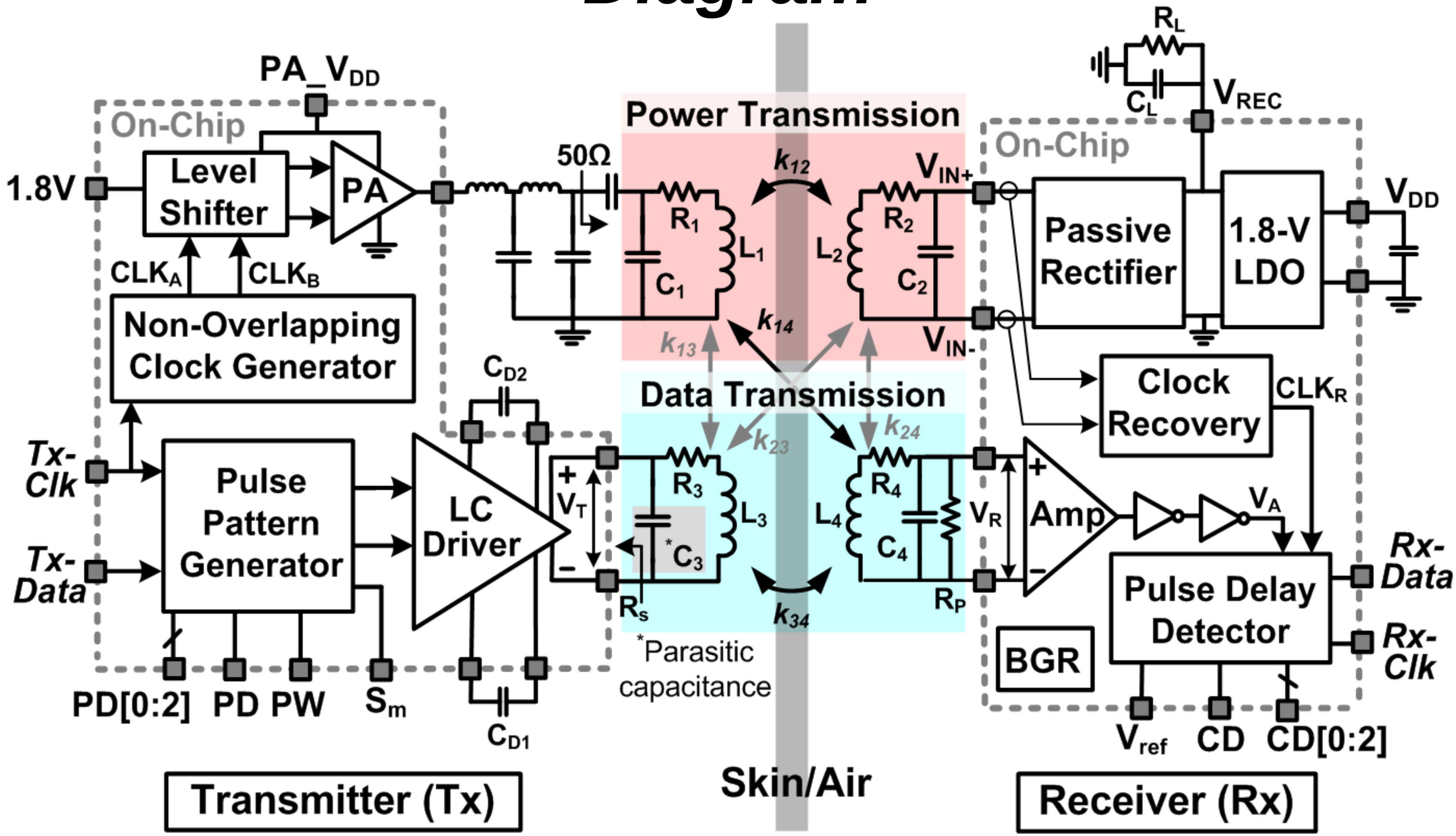


PDM Simulation in MATLAB

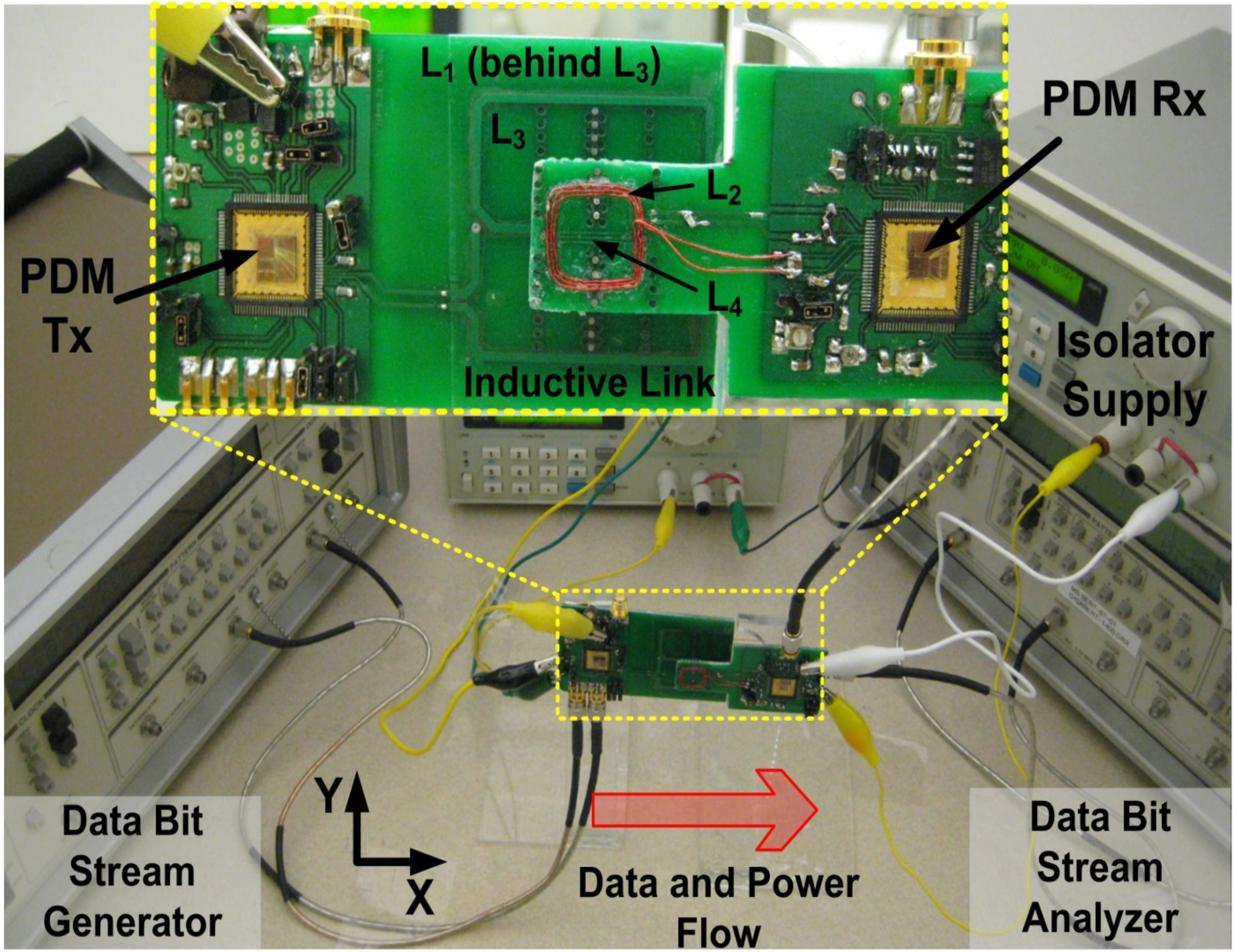


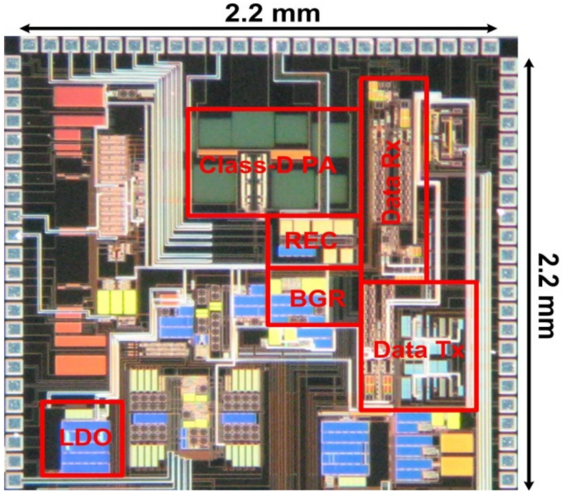
- Zero-crossing timing shift = 2.5 ns
- Signal-to-Interference Ratio (SIR) = -18.5 dB

Fully-integrated PDM-based Transceiver Diagram



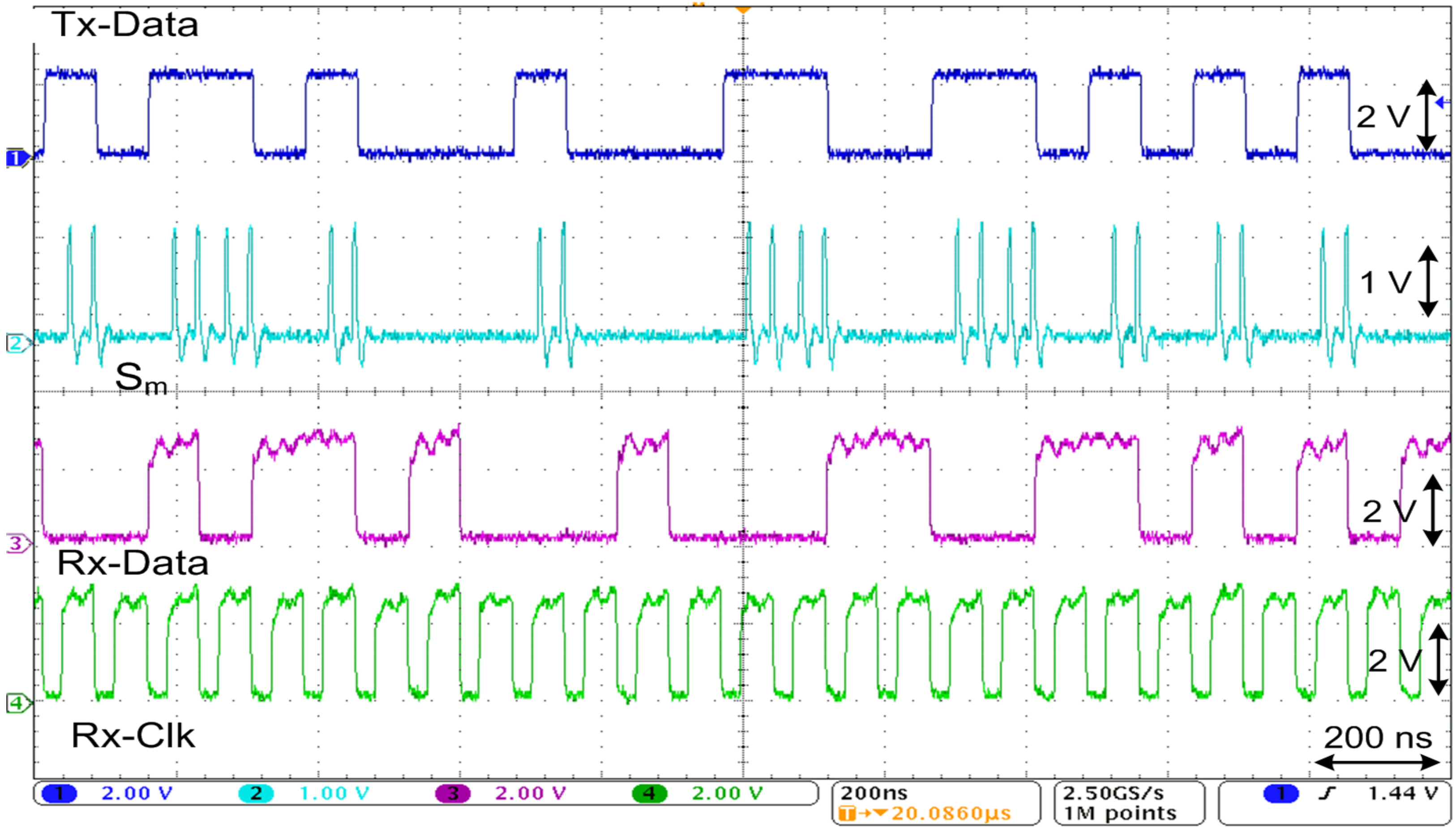
PDM Implementation and Test Setup





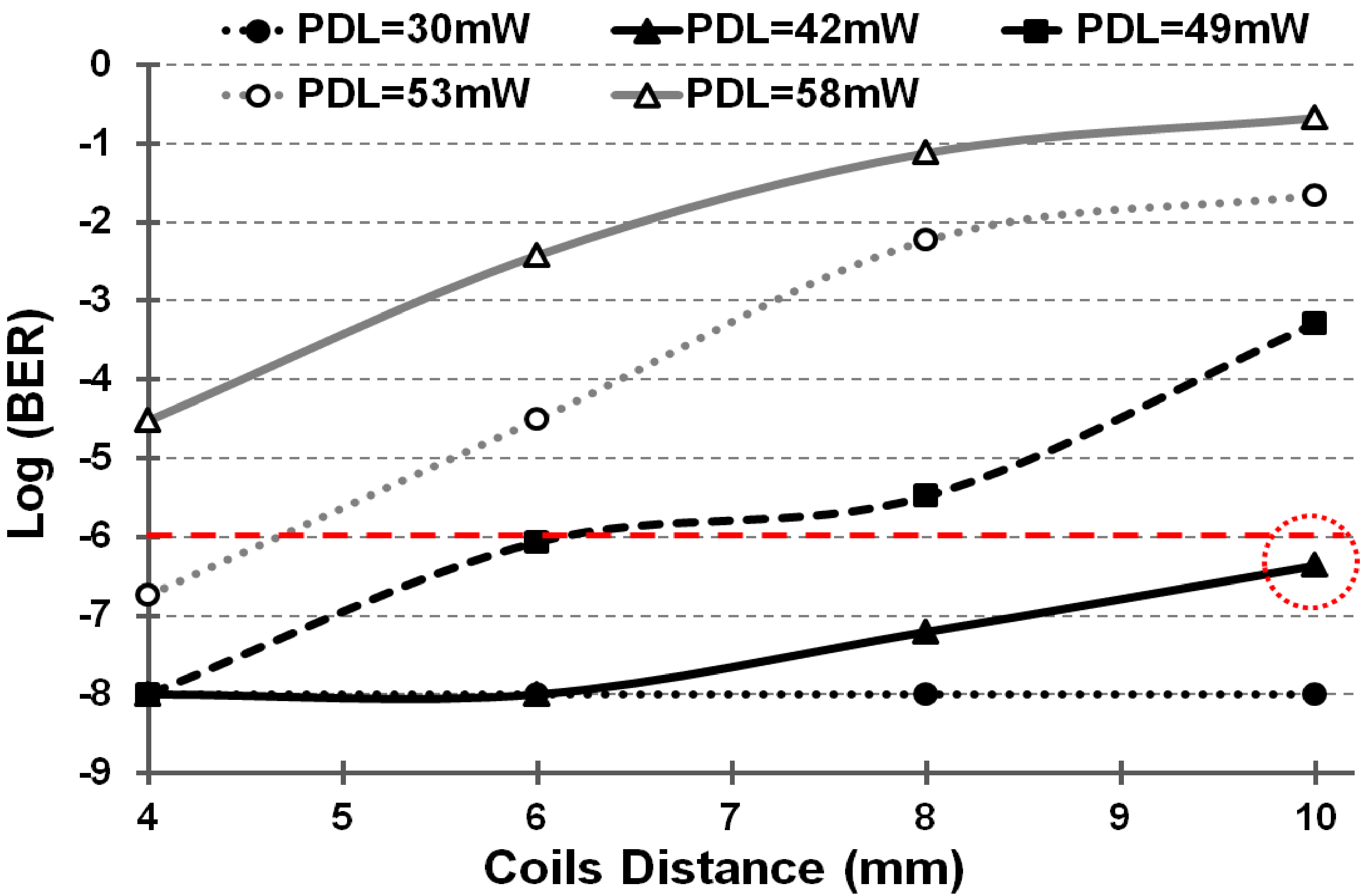
- Std. CMOS TSMC 0.35-µm
- Supply volt. = 1.8 V
- Operating freq. = 13.56 MHz

PDM Measurement Results



- **Data rate = 13.56 Mbps**
- Distance = 10 mm
- Power carrier = 13.56 MHz
- SIR = -18.5 dB
- Delivered power = 42 mW
- Bit error rate (BER) = 4.3×10^{-7}

PDM Measurement Results



PDM Benchmarking

- **PDM advantages:**
  - Low-power consumption of data transceiver
  - Robustness against power carrier interference
  - First inductively-powered pulse-based transceiver

Reference	Mod.	d (mm)	Data Carrier (MHz)	Power Carrier (MHz)	Data Rate (Mbps)	Tx/Rx Power (pJ/bit)	CMOS Tech. (µm)	SIR (dB)	Die Area (mm^2) (Data Tx/Rx)	V_{DD} (V)	BER
Ghovanloo, 2004	pcFSK	5	5/10	5/10	2.5	-/152	1.5	-	-/0.29	5	10^{-5}
Hu, 2005	BPSK	15	10	10	1.12	-/625	0.18	-	-/0.2	1.8	10^{-5}
Mandal, 2008	LSK++	20	25	25	2.8	35.7/1250	0.5	-	2.2/2.2**	2.8	10^{-6}
Rush, 2012	FSK	20	-/5	5	1.25	-	0.8	-	-	2.7	-
Rush, 2012	BPSK	20	48	5	3	1962/-	0.8	-	2.3**	2.7	2×10^{-4}
Simard, 2010	QPSK	5	13.56	1	4.16	-	-	-	-	-	2×10^{-6}
Zhou, 2008	BPSK	15	20	2	2	-/3100	0.35	-12*	-/4.4	4.5	10^{-7}
Chen, 2013+	DPSK	-	20	2	2	-	0.18	-	-	1.8	10^{-7}
This Work	**PDM**	**10**	**50**	**13.56**	**13.56**	**960/162**	**0.35**	**-18.5**	**0.34/0.37**	**1.8**	**4.3×10^{-7}**

* A 1st-order off-chip filter was used to improve SIR to -6 dB. ** Including pads.
+ Second-order filter was used to improve SIR. ++ LSK is only used for uplink.

Conclusions

- Various wireless power and data transfer techniques can be utilized to power up and communicate with IMDs.
- The wireless power transfer consists of several stages, such as the power Tx, inductive link, matching circuit, power conversion and management units.
- Every stage offers the designer with several degrees of freedom and design parameters, which need to be optimally combined by considering designated specifications.
- Low-power wireless data telemetry with simultaneous power interference are important in information-heavy IMDs, in which high performance is desired despite limited received power.

GT- Bionics Lab Members

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