中国科学技术大学
University of Science and Technology of China

An Isolated DC-DC Converter with a Cross-Coupled Shoot-Through-Free Class-D Oscillator Meeting the CISPR-32 Class-B EMI Standard

潘东方 中国科学技术大学

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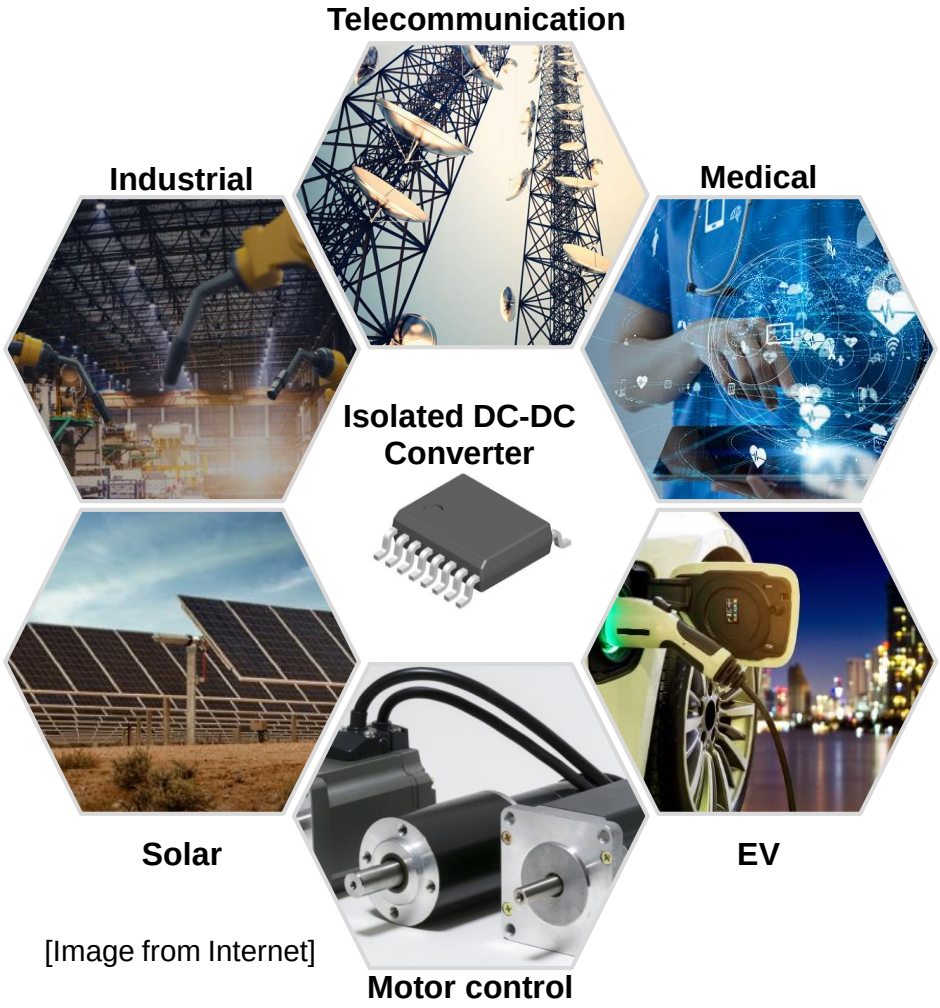
Outline

- **Motivation and Challenges**
- **Proposed Low-EMI Isolated DC-DC converter**
  - EMI Mechanism for Isolated DC-DC Converter
  - Proposed Cross-Coupled Shoot-Through-Free Class-D Oscillator
  - System Architecture and Voltage Series-Combining Transformer in LGA package substrate
- **Measurement Results**
- **Conclusions**

Motivation

- **Isolation Solution** for industrial, solar, motor control, EV, medical and telecommunication applications



[Image from Internet]

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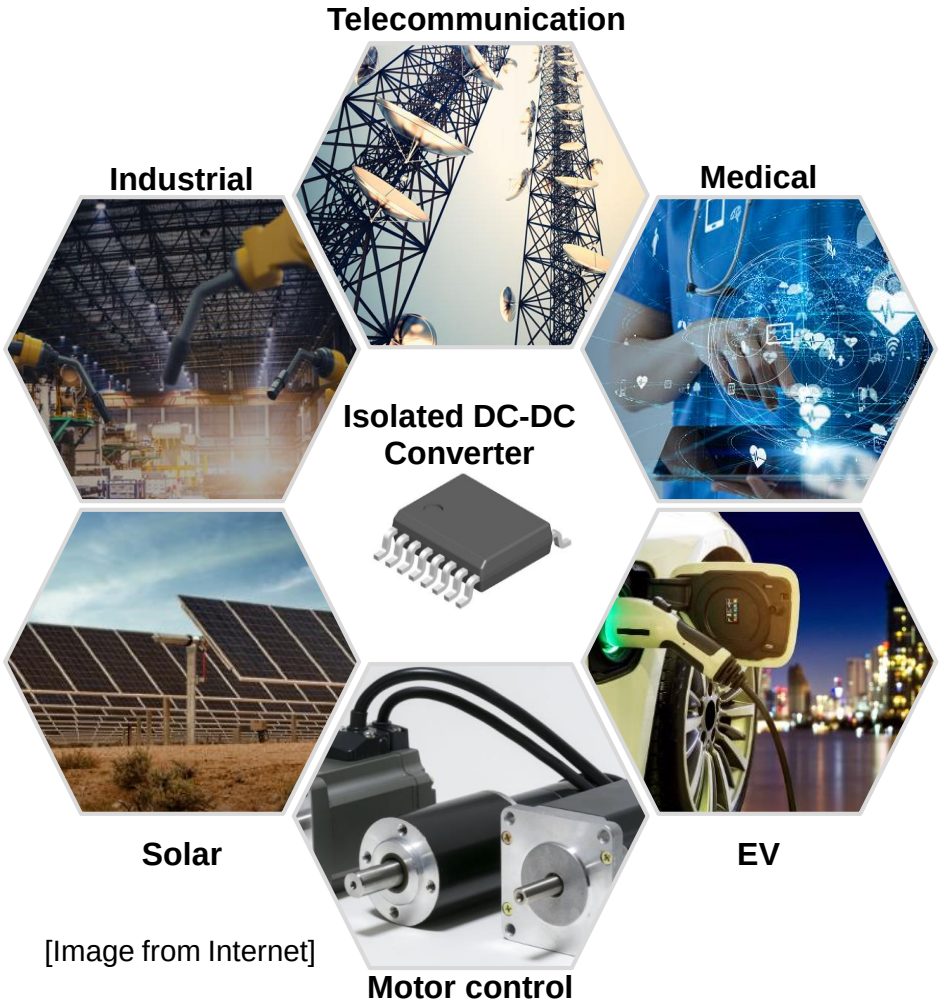
- **Isolation Solution** for industrial, solar, motor control, EV, medical and telecommunication applications



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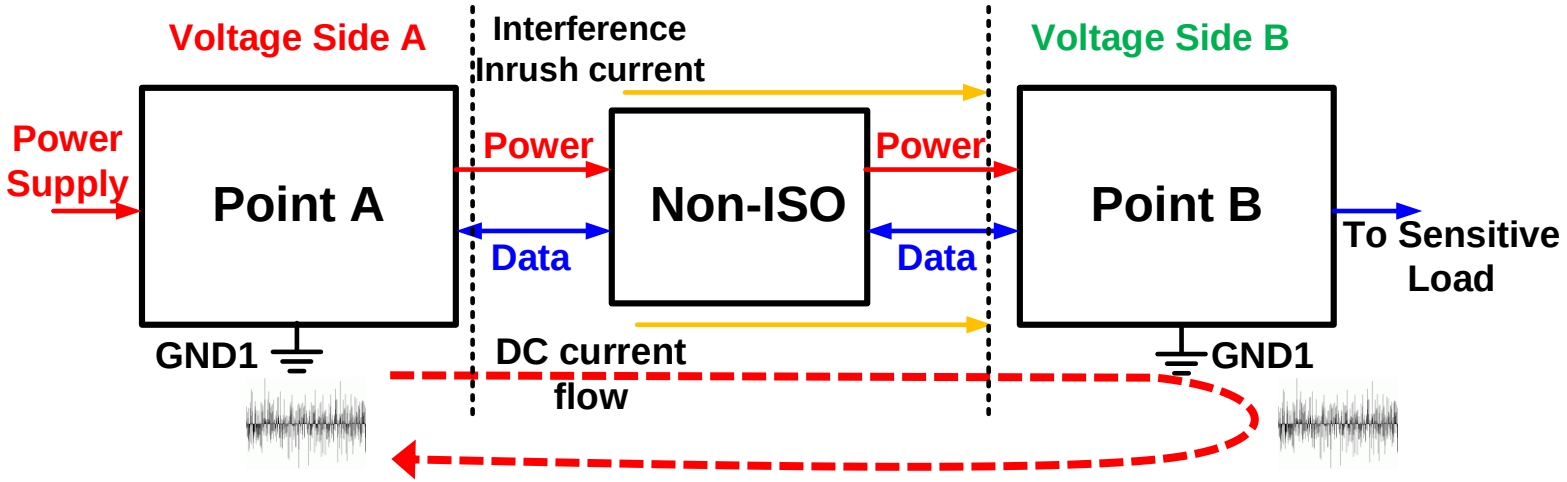
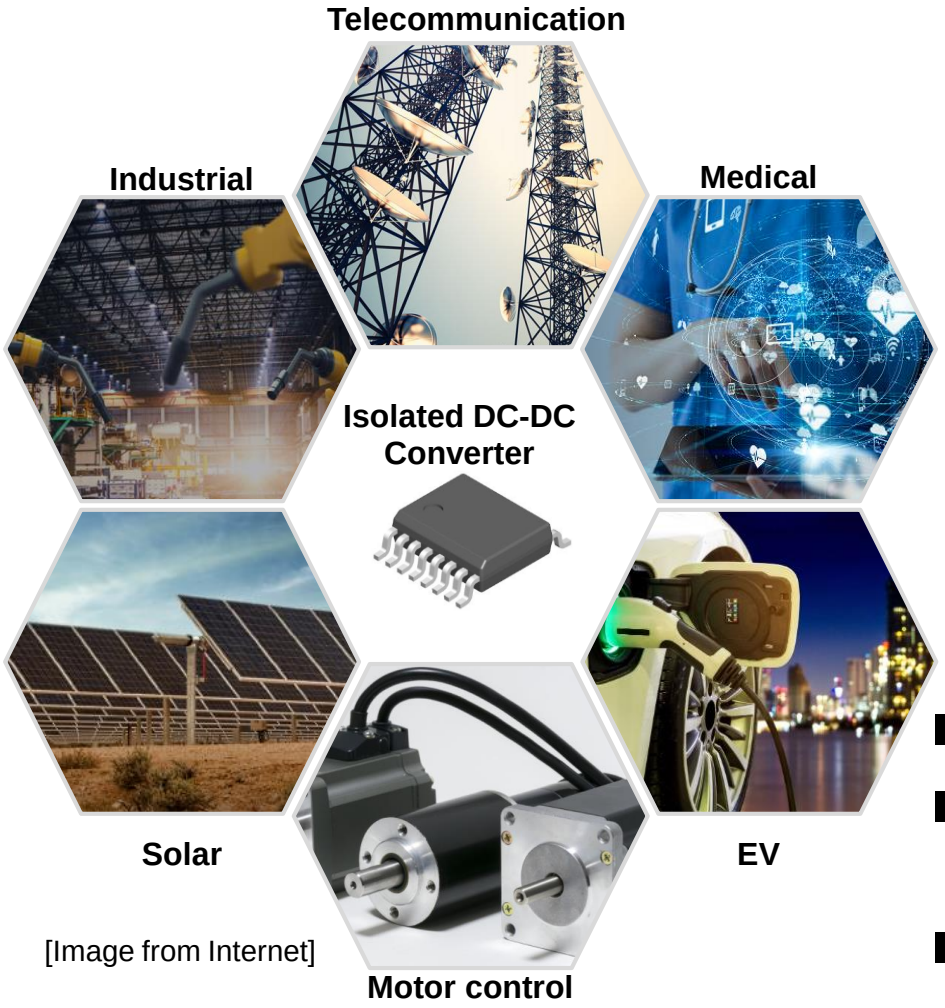


Motivation

- **Isolation Solution** for industrial, solar, motor control, EV, medical and telecommunication applications



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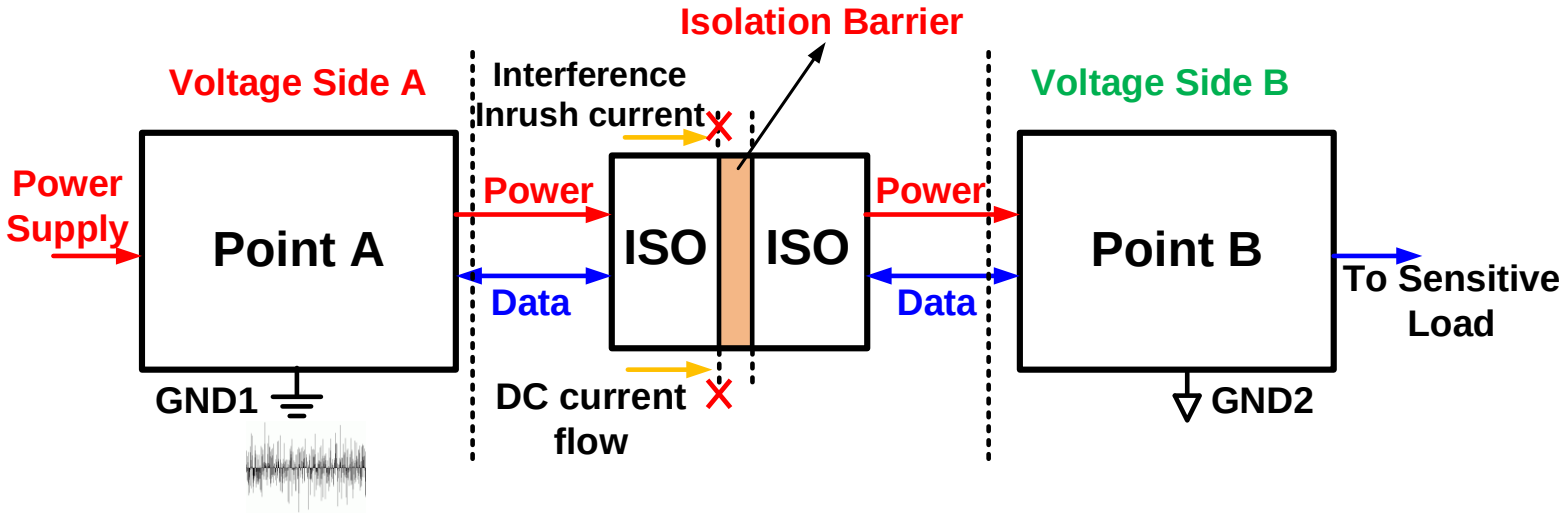
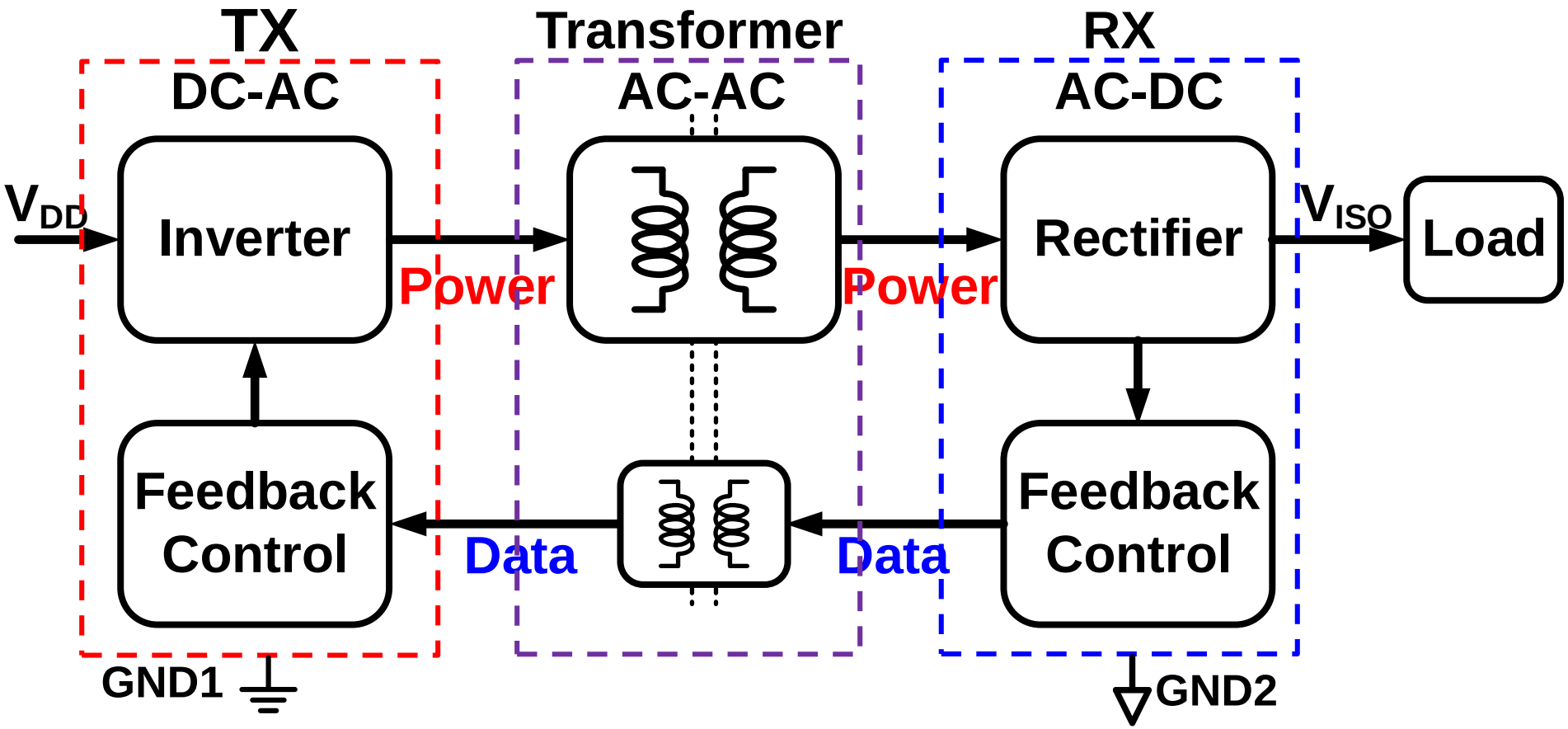


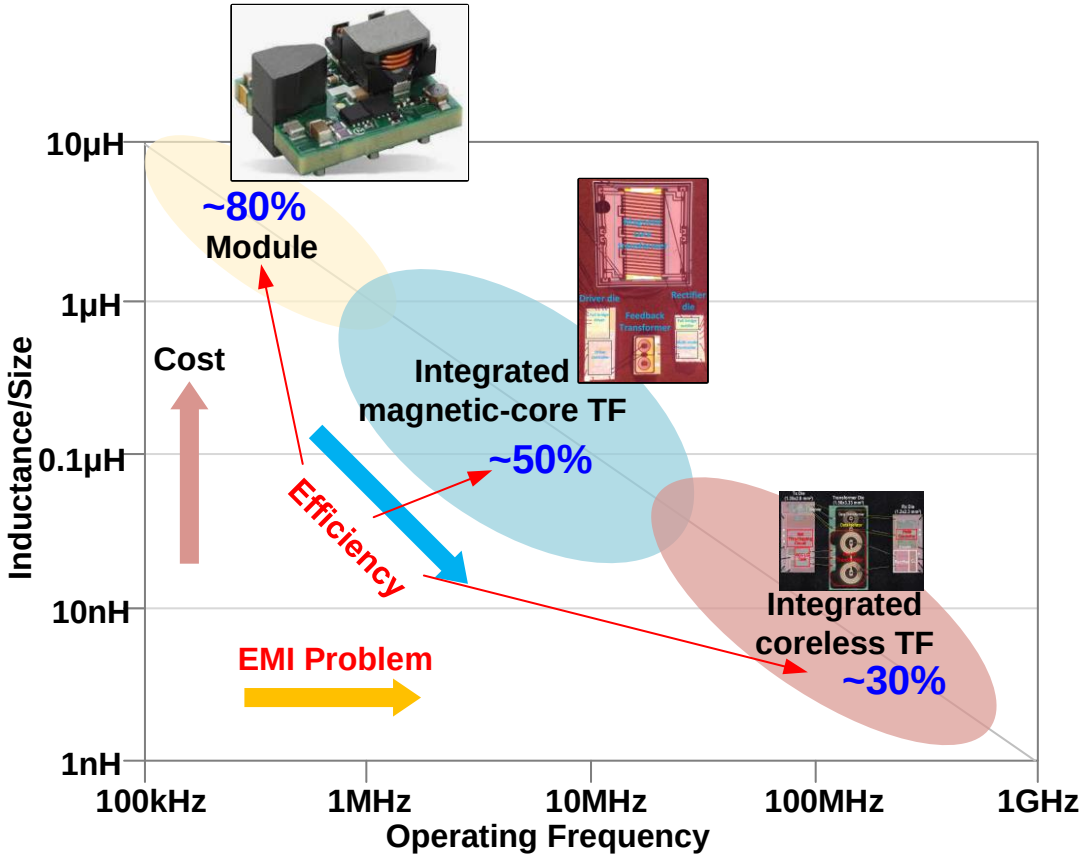
- **Galvanic isolation**: Electrical insulation between point A and B
- **Preventing DC and unwanted AC currents between two points**
- **Ensure reliability and safety of system**

Block Diagram of Transformer Isolation



- Isolated DC-DC converter: **TX chip, RX chip and micro-transformer chip**

Challenges

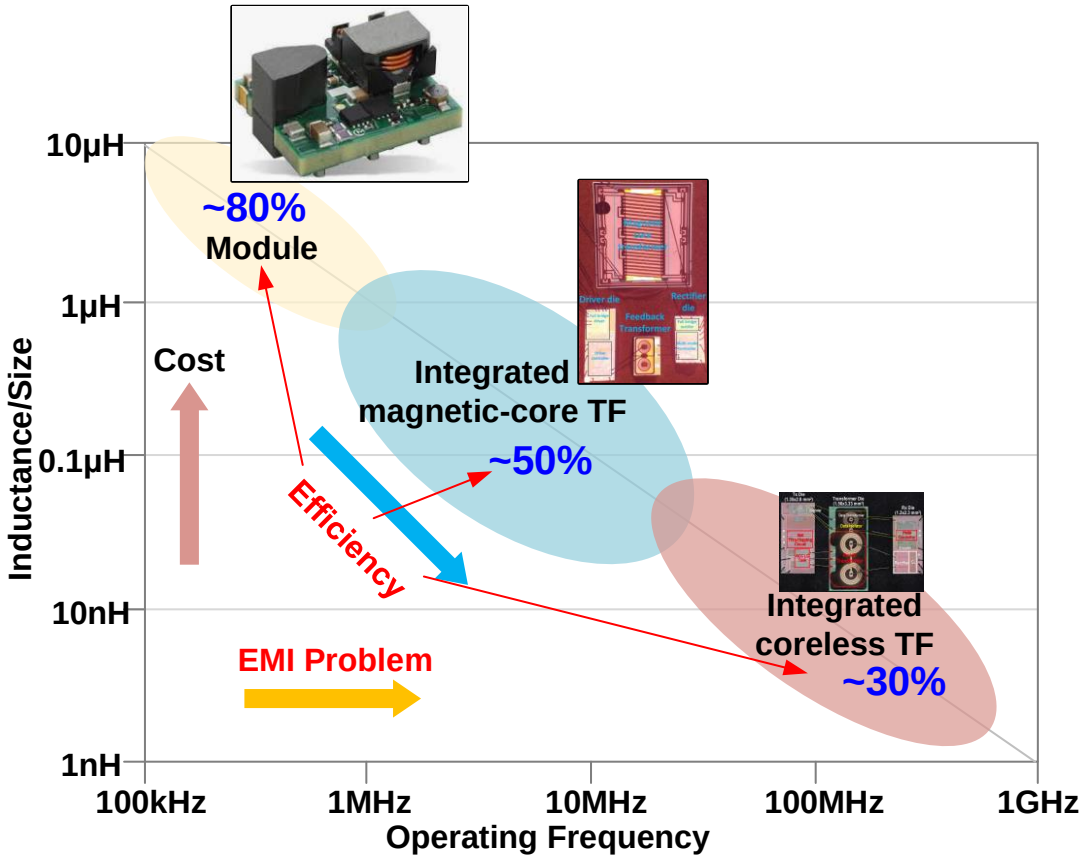


[Image from ADI]

Small Size → High Frequency

- **Challenge 1:** Cost vs. EMI
- Integrated transformer➔ Small Size ➔ high operating frequency
- **Challenge 2:** Cost vs. Efficiency
- Integrated transformer➔ Small Size ➔Limited Q

Challenges



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Small Size → High Frequency → Large EMI & LOSS

- **Challenge 1:** Cost vs. EMI
- Integrated transformer➔ Small Size ➔ high operating frequency➔ **EMI issue**
- **Challenge 2:** Cost vs. Efficiency
- Integrated transformer➔ Small Size ➔Limited Q➔ **Low efficiency**

How to improve the EMI performance and efficiency of isolated DC-DC converters with low-cost?

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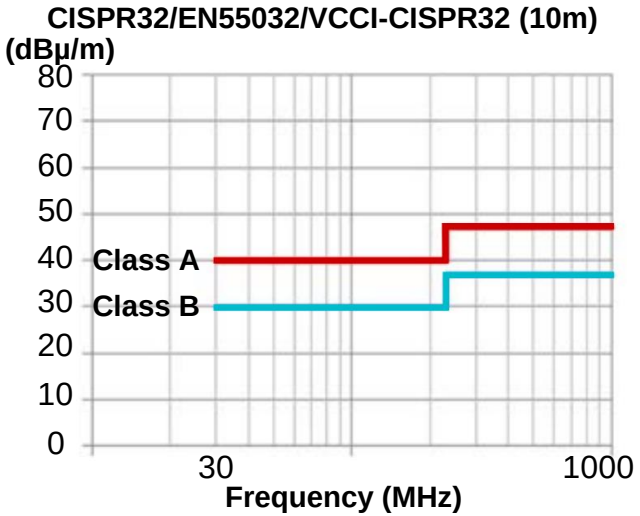
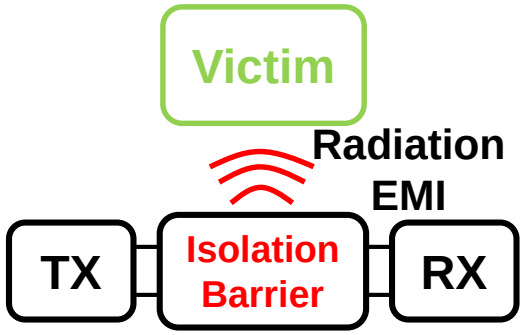
Radiation Source in Isolated DC-DC Converter

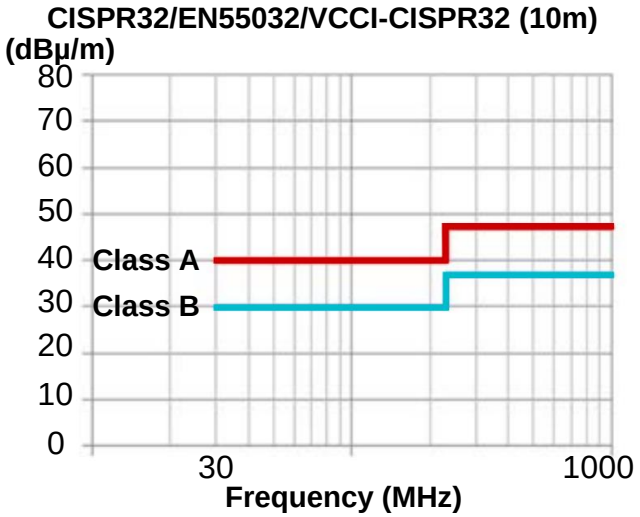




[Image from ADI]

- CISPR 32 radiated emission is an EMC standard for **multimedia equipment**
- Isolated dc-dc converters switch **currents of several hundred mA** at frequencies **more than tens of MHz➔Radiated emission**

Radiation Source in Isolated DC-DC Converter



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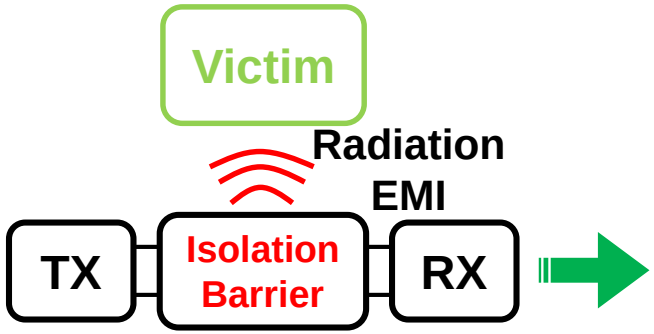
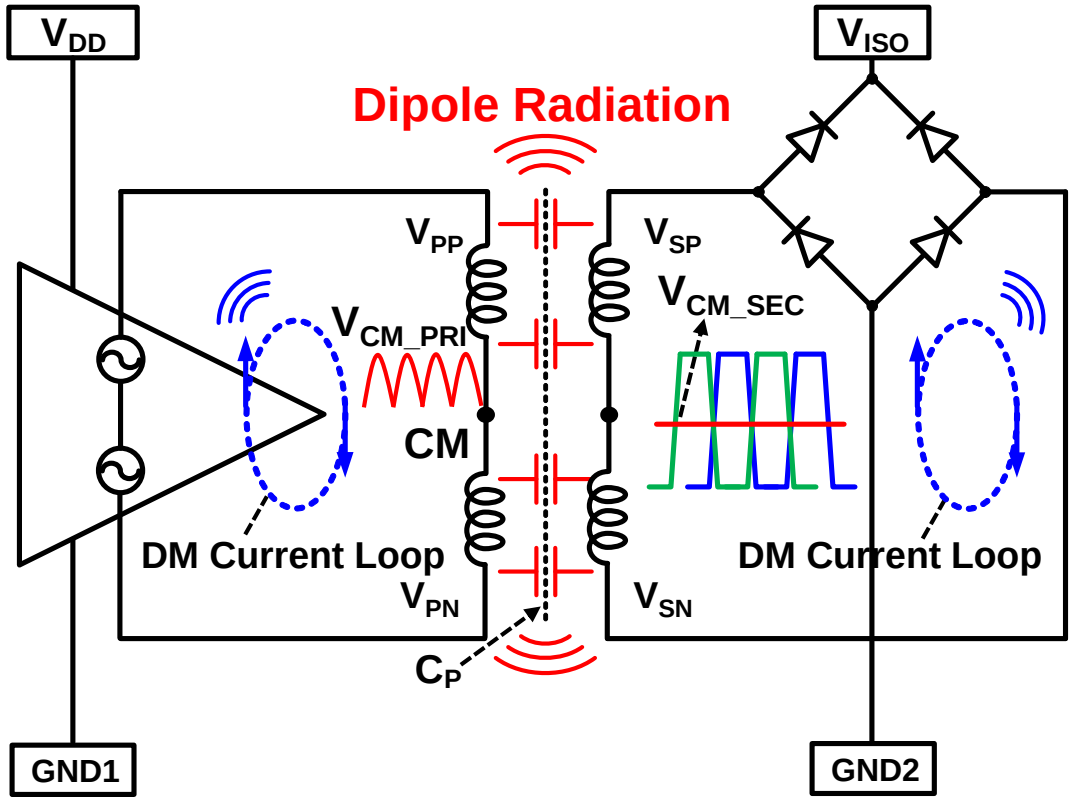
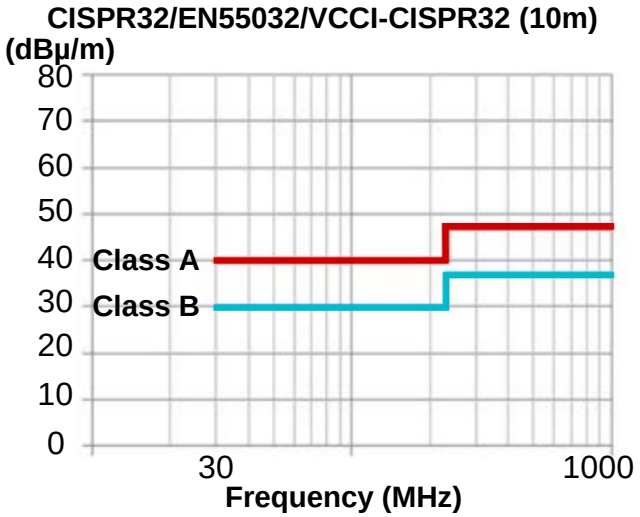


$$P_{rad} \propto (L_{ant} \cdot f_{OSC} \cdot I_{CM})^2$$



- **Dipole radiation** is the dominant radiation EMI source in isolated DC-DC converter
- The **fluctuation of common-mode (CM) voltage** of the transformer ➔ **Large CM Current I_{CM}**
- I_{CM} across the parasitic capacitance C_P of the isolation barrier ➔ Dipole radiation

Radiation Source in Isolated DC-DC Converter



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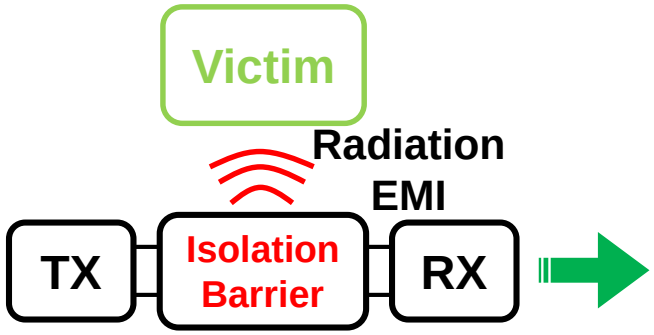

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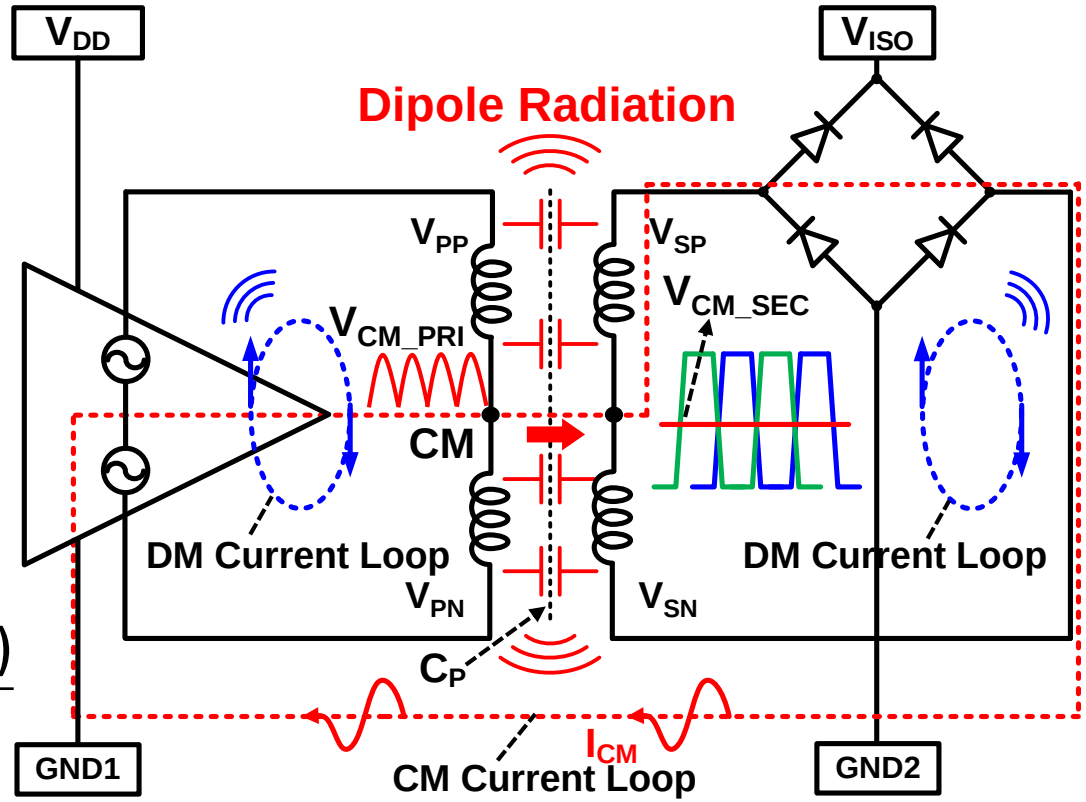
$$I_{CM} = C_P \frac{\partial (V_{CM\_PRI} - V_{CM\_SEC})}{\partial t}$$



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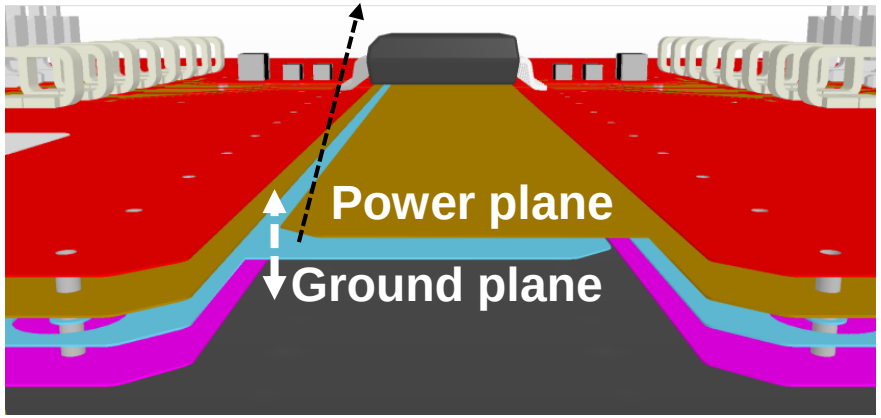
Existing Solution for EMI

Application-level solution

Stitching capacitor on 4-layer PCB



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- Design complex ☹

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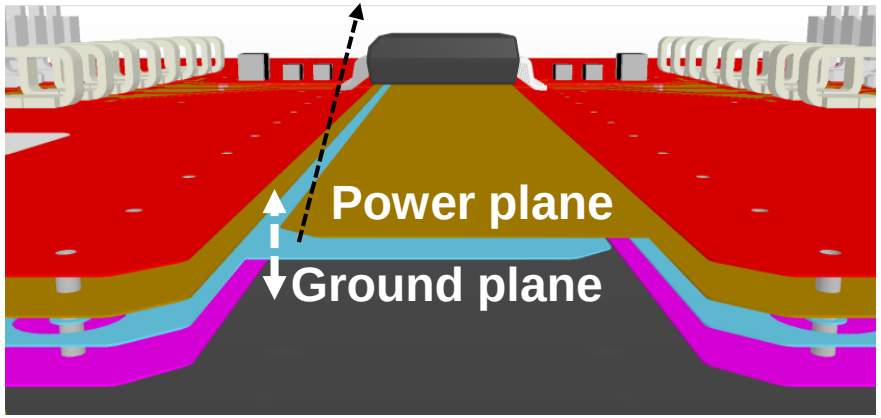

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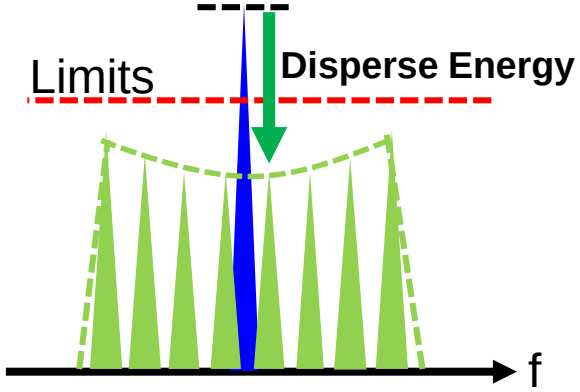
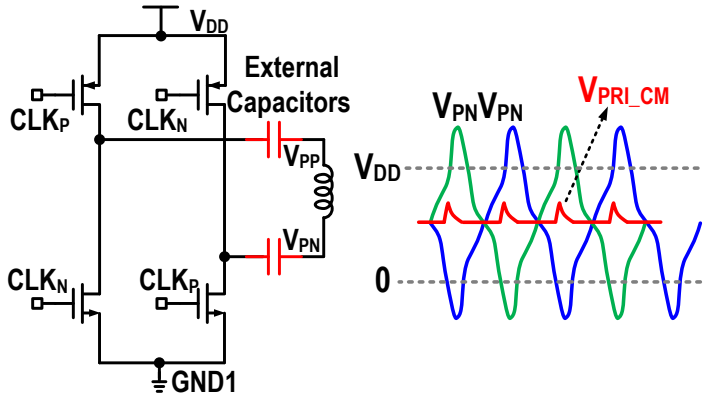
Component-level solution

Spread spectrum technique for TX



- Low cost and effective ☺
- Extra spread spectrum circuit ☹

Symmetric LLCC for TX



[Y. Zhuo ISSCC'19]

- Extra external capacitors ☹
- Low emission ☺

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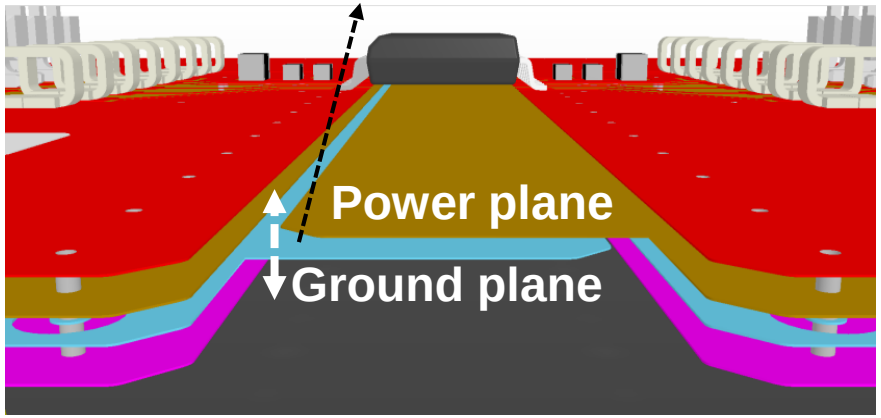

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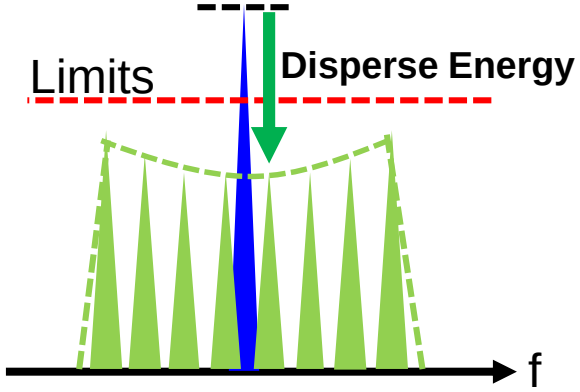

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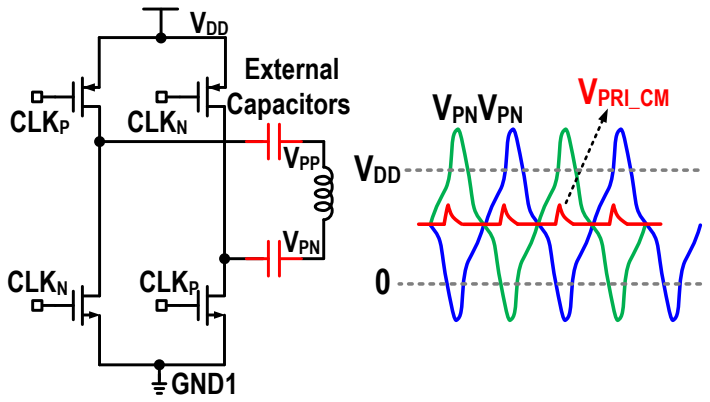

[Y. Zhuo ISSCC'19]

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■ Low-cost circuit techniques in component-level ➔ **Low EMI at the source and cost**

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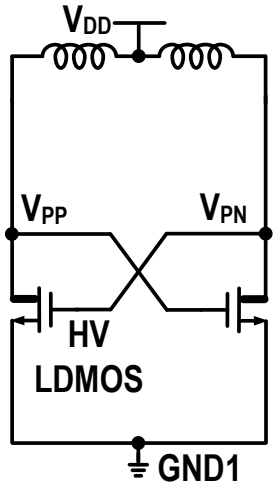
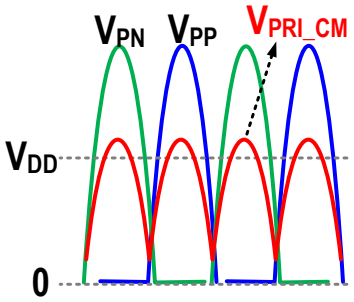
Proposed Class-D Oscillator



[W. Qin ISSCC'19 and D. Pan ISSCC'21]

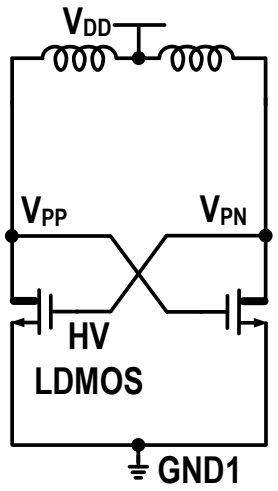


- **Asymmetrical LC Tank**

➔ **Large V_{PRI_CM}**

➔ **High EMI**

Proposed Class-D Oscillator



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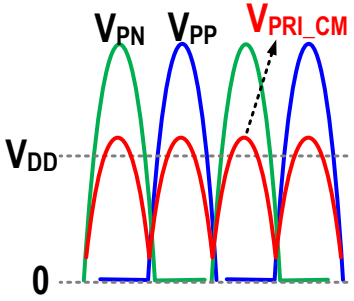
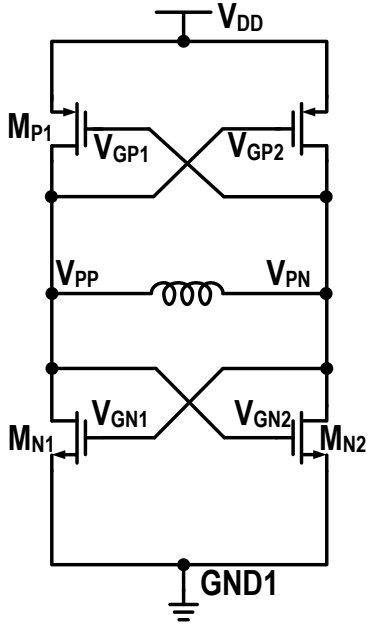
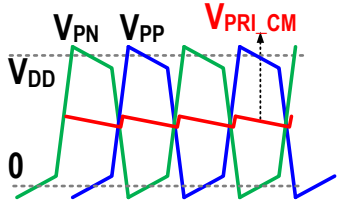
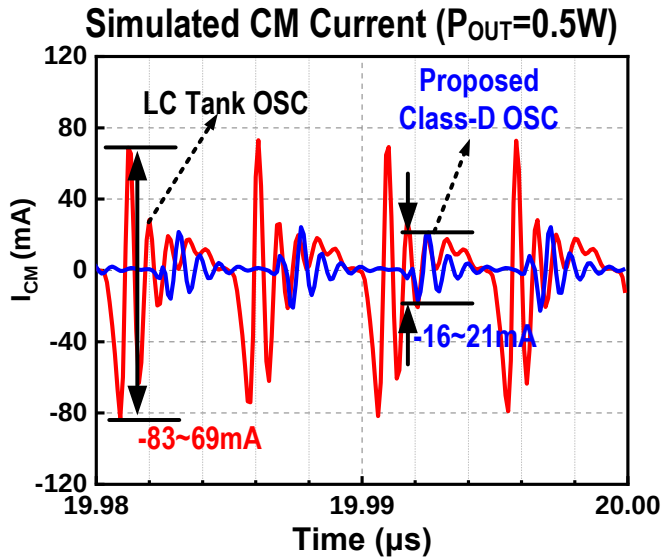
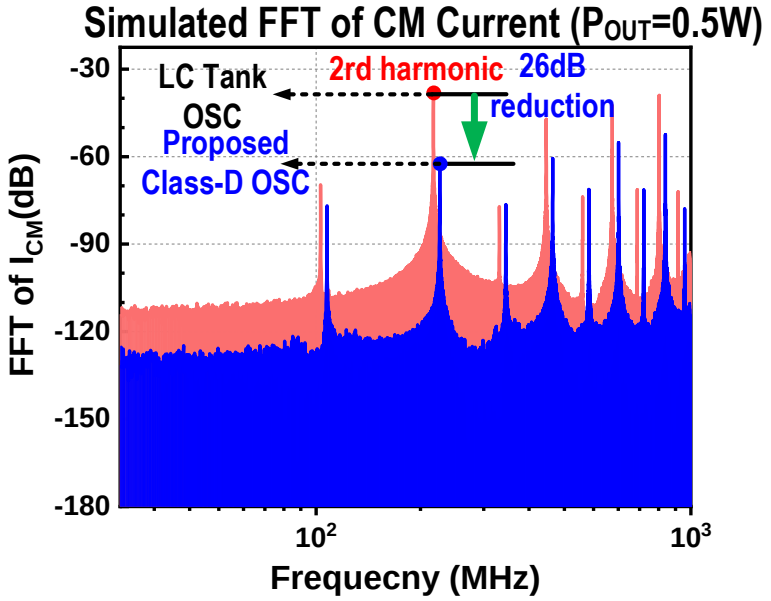






- **Asymmetrical LC Tank**
  - ➔ **Large V_{PRI_CM}**
  - ➔ **High EMI**
- **Symmetrical Structure**
  - ➔ **Small V_{PRI_CM}**
  - ➔ **Low EMI**





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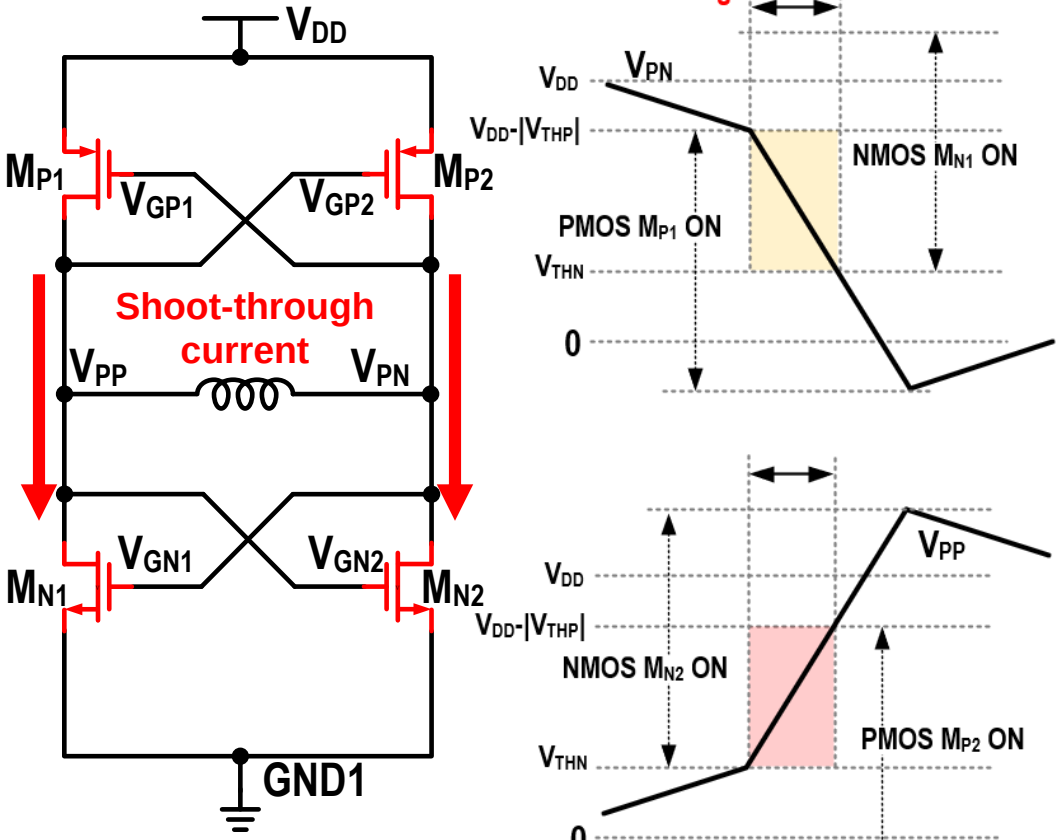
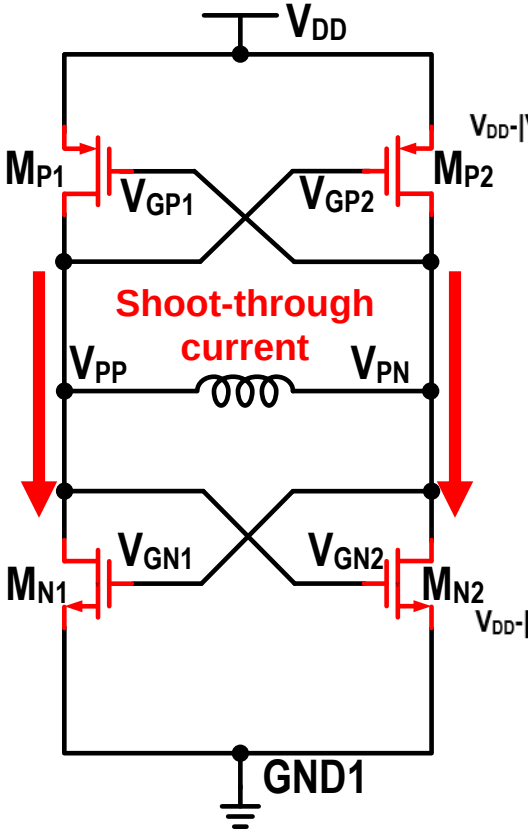
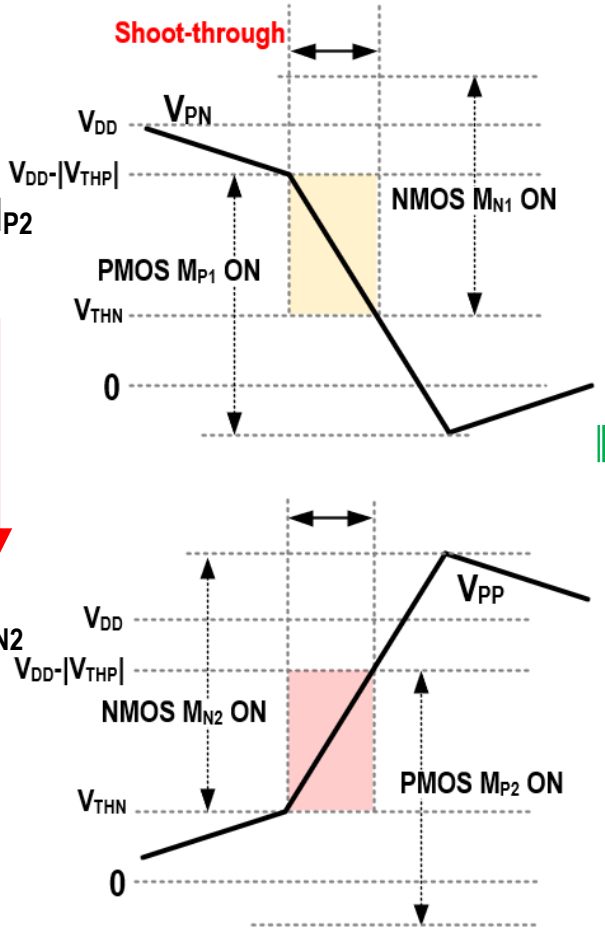
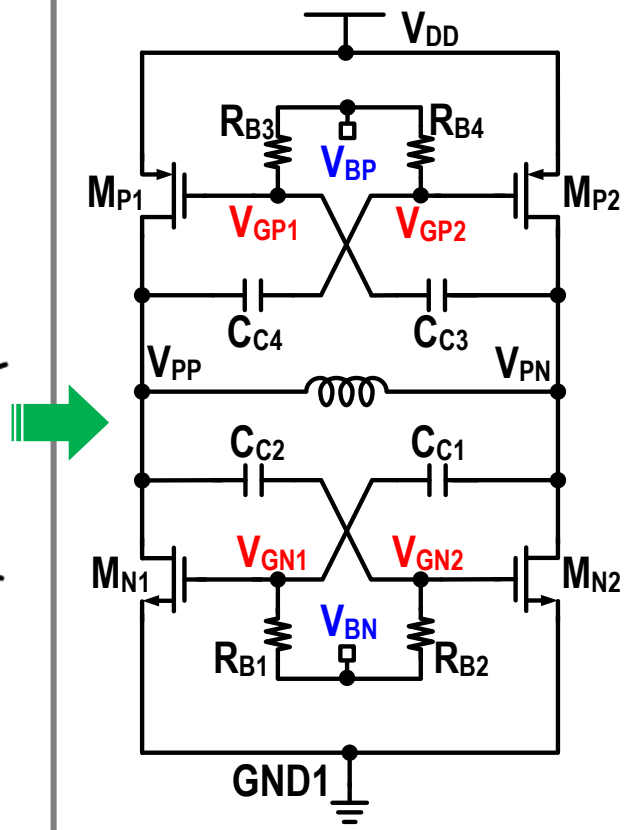


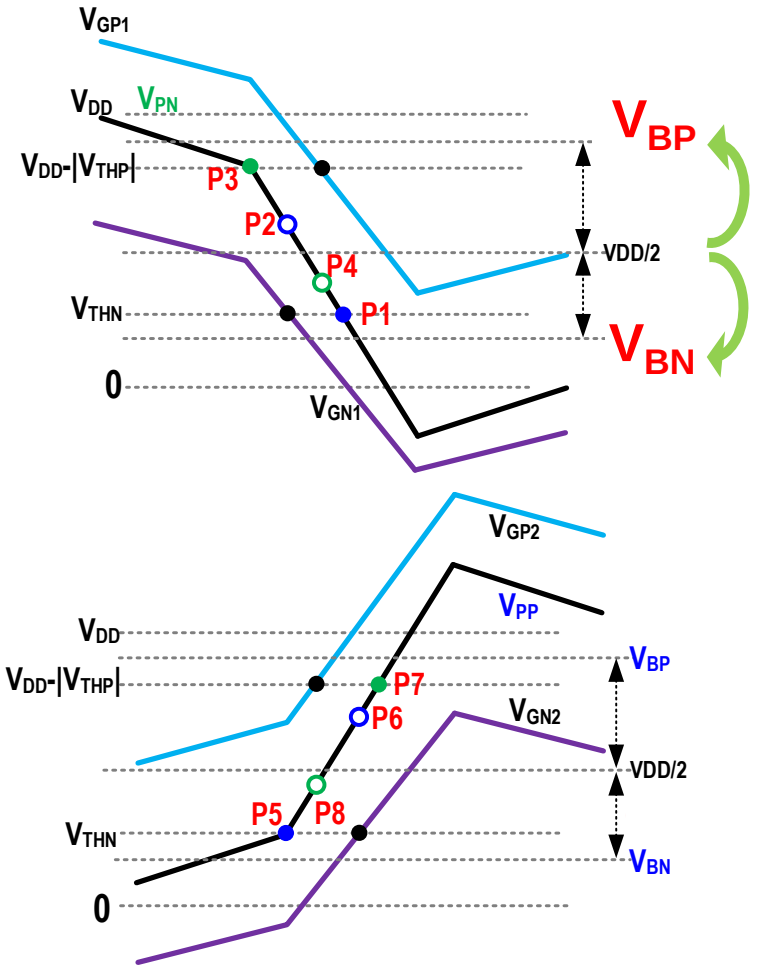
- M_{N1} and M_{P1} are both turned on when $V_{THN}<V_{PN}<V_{DD}-|V_{THP}|$ ➔ **Large shoot-through current**

Proposed Class-D Oscillator



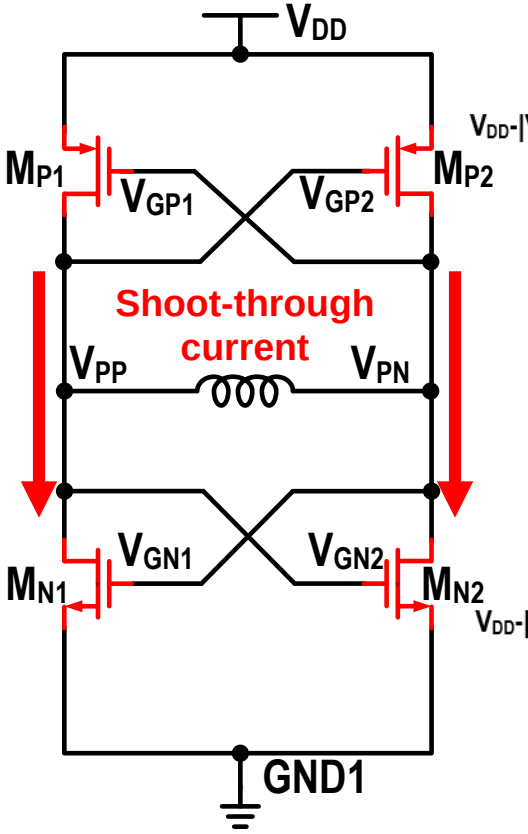


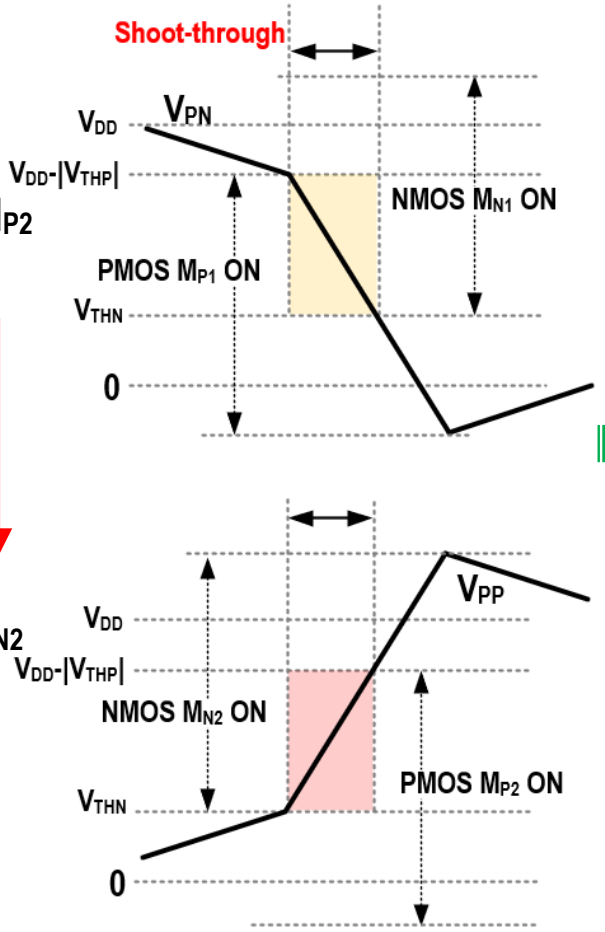


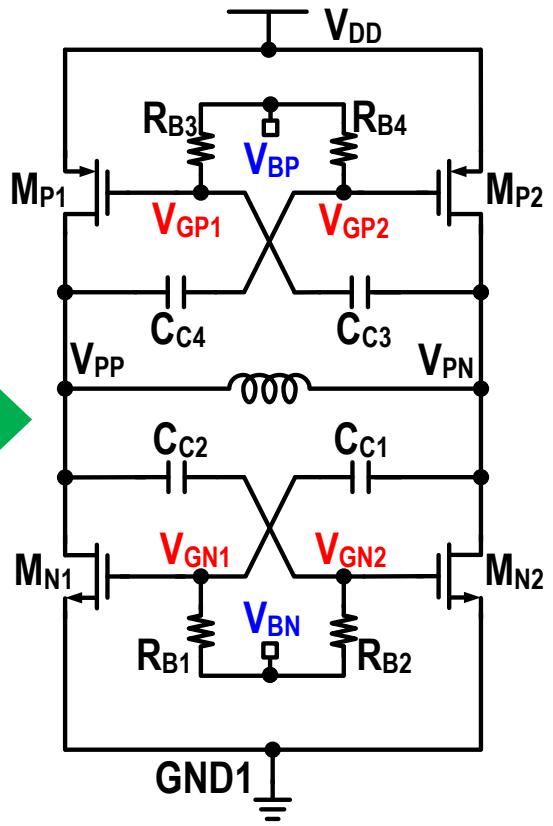


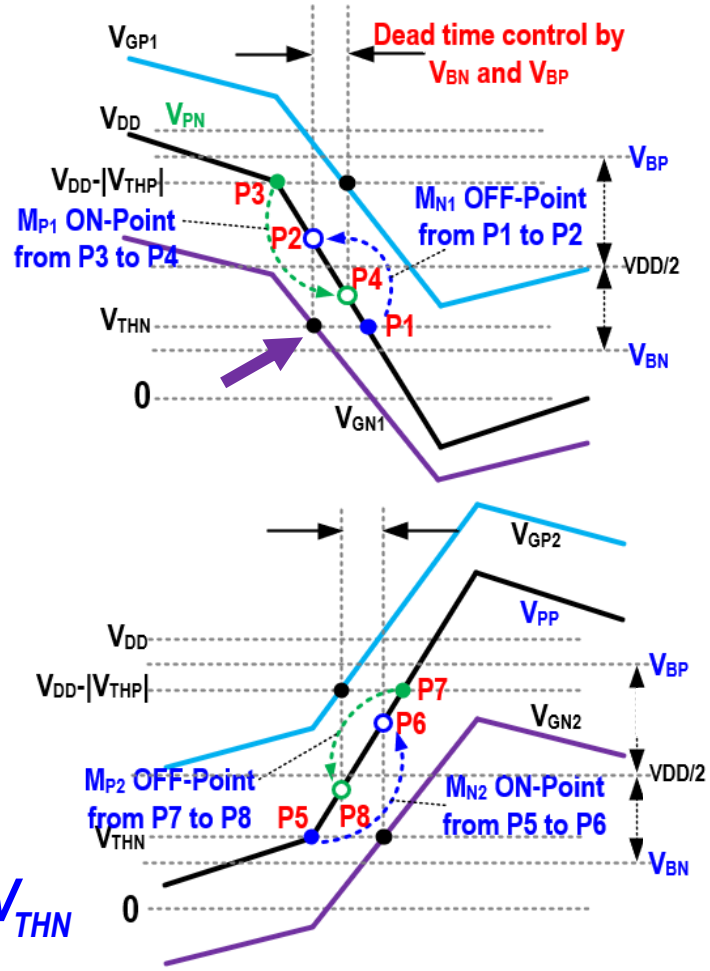
- Gate CM voltages for NMOS and PMOS controlled separately (V_{GP1}&V_{GN1} **shifted up/down**)

Proposed Class-D Oscillator





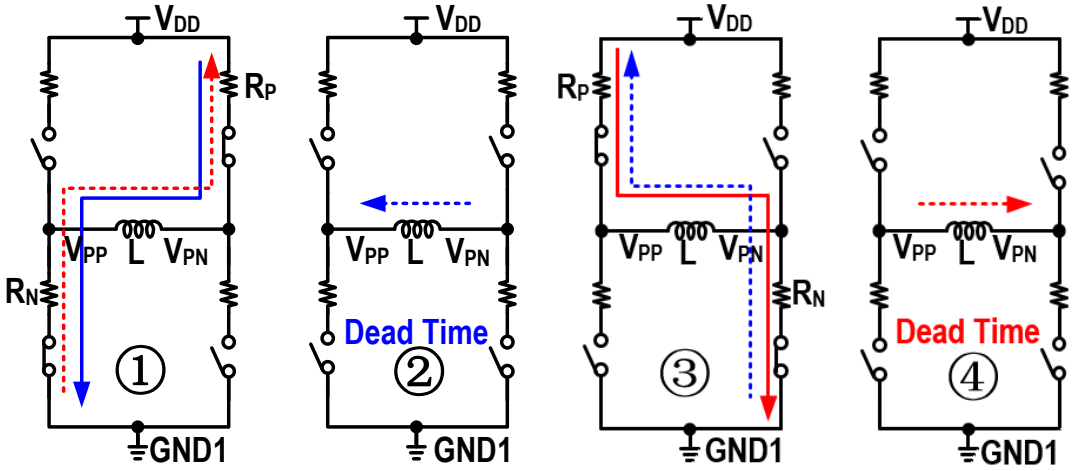


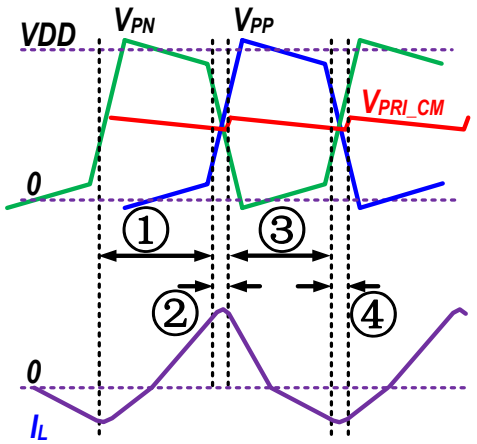


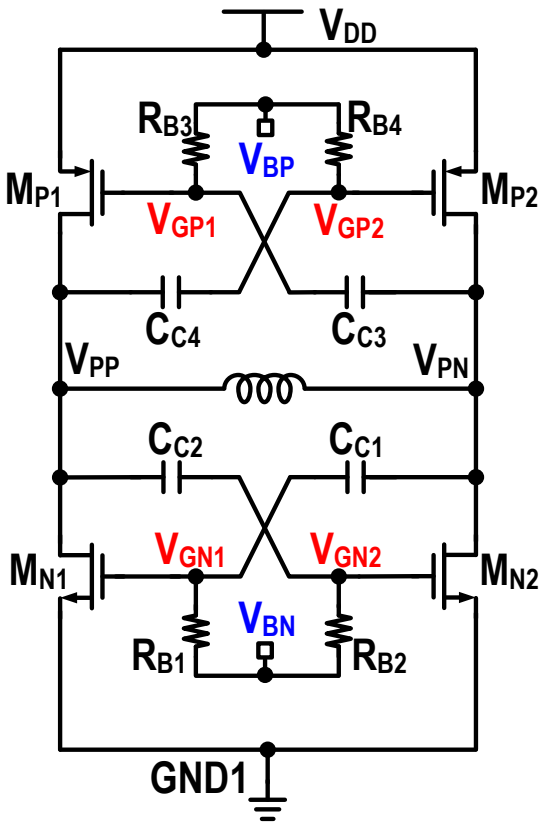
$$V_{BP} - V_{BN} > V_{DD} - |V_{THP}| - V_{THN}$$

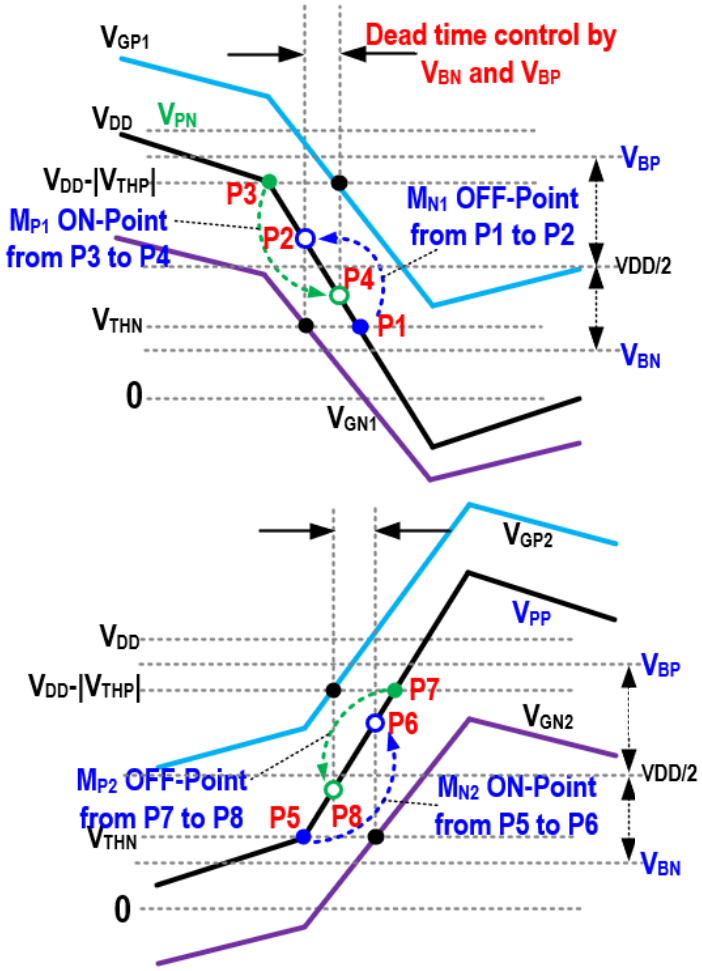
- As long as P_2 is ahead of P_4 that results in the condition of V_{BP}-V_{BN}>V_{DD}−|V_{THP}|−V_{THN}, M_{N1} will be turned off before M_{P1} is turned on ➔ The shoot-through current can be avoided

Proposed Class-D Oscillator









- State 1 and 3: Main operation states to alternately charge the primary coil to transfer power
- State 2 and 4: Dead-time

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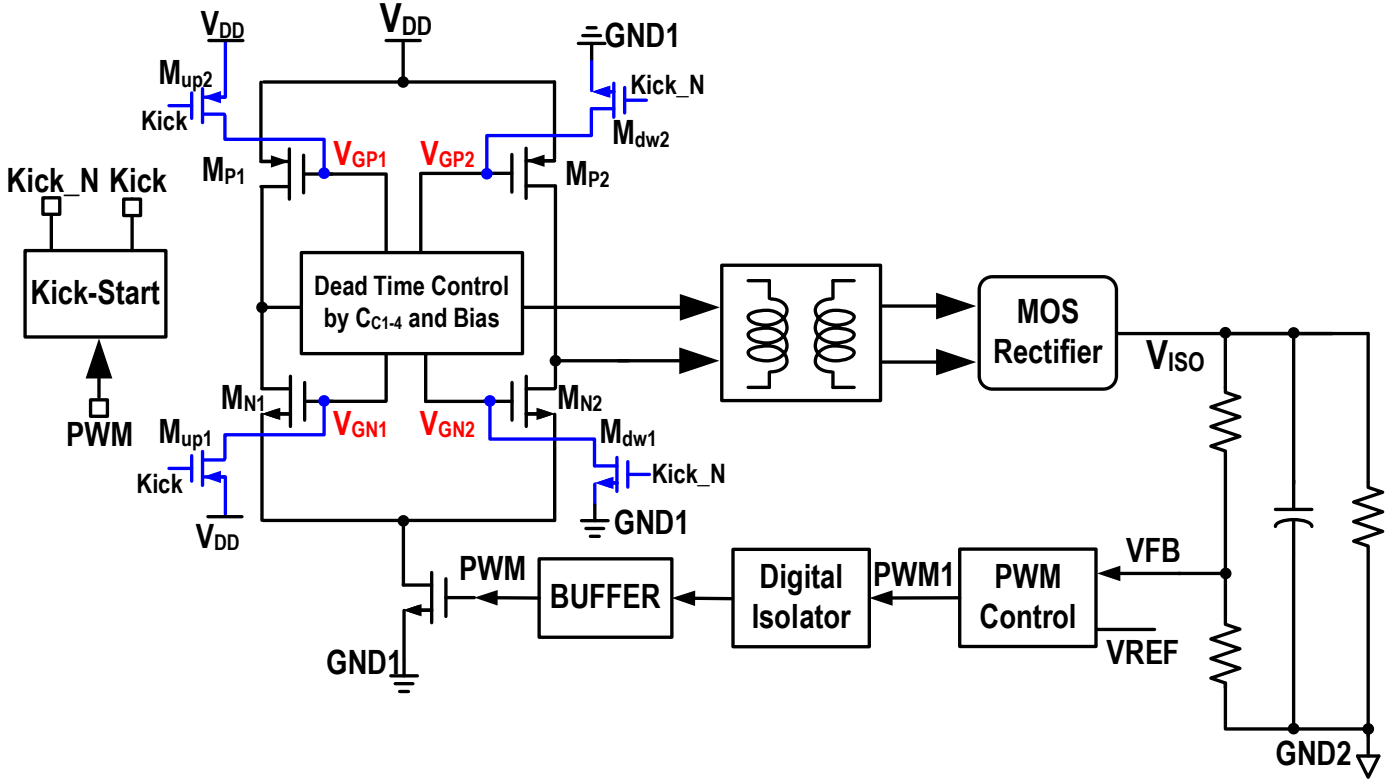
System Architecture



- A full-bridge MOS rectifier with PWM control is implemented in the RX
- PWM signal is transmitted from TX to RX via a data isolator

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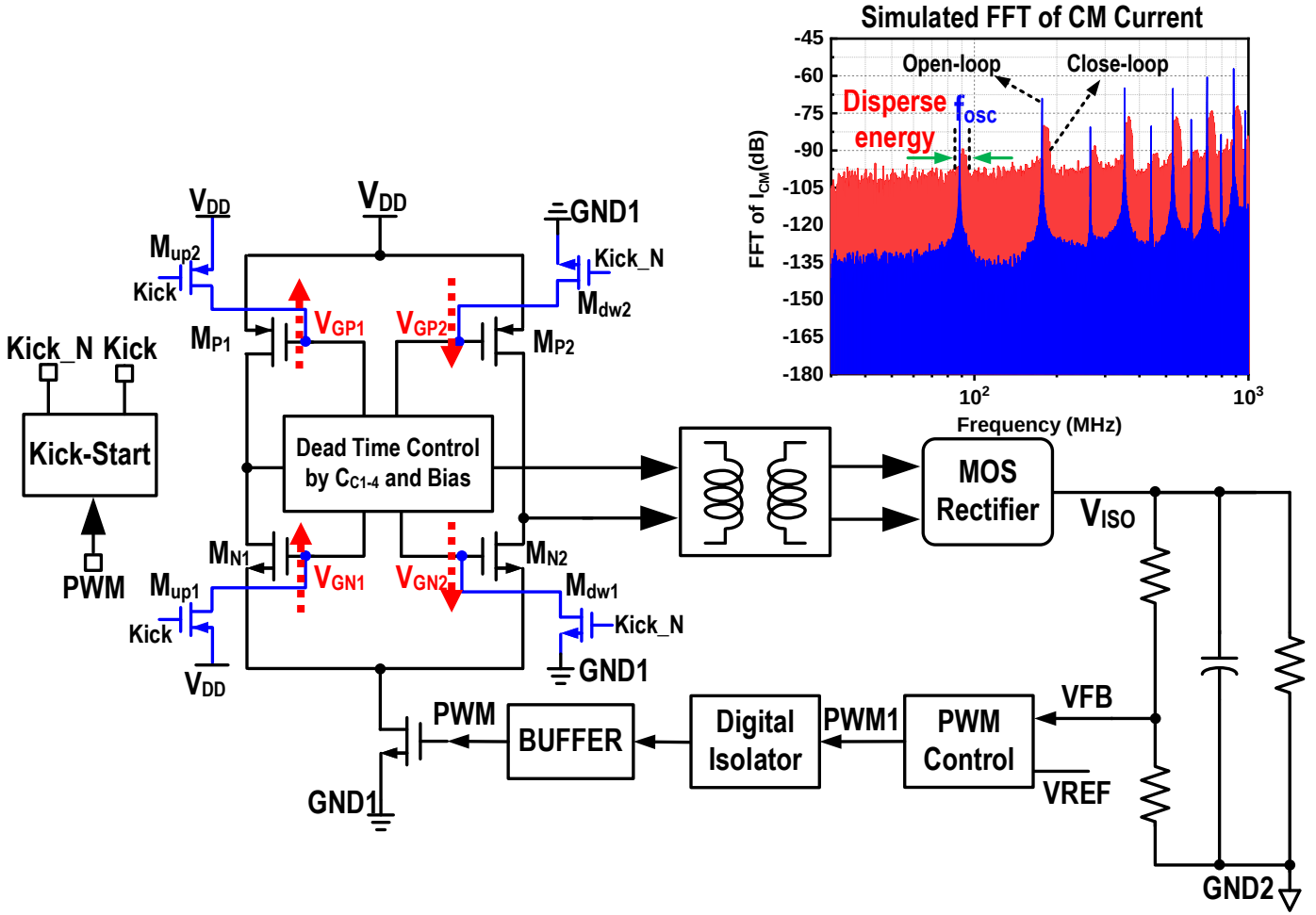
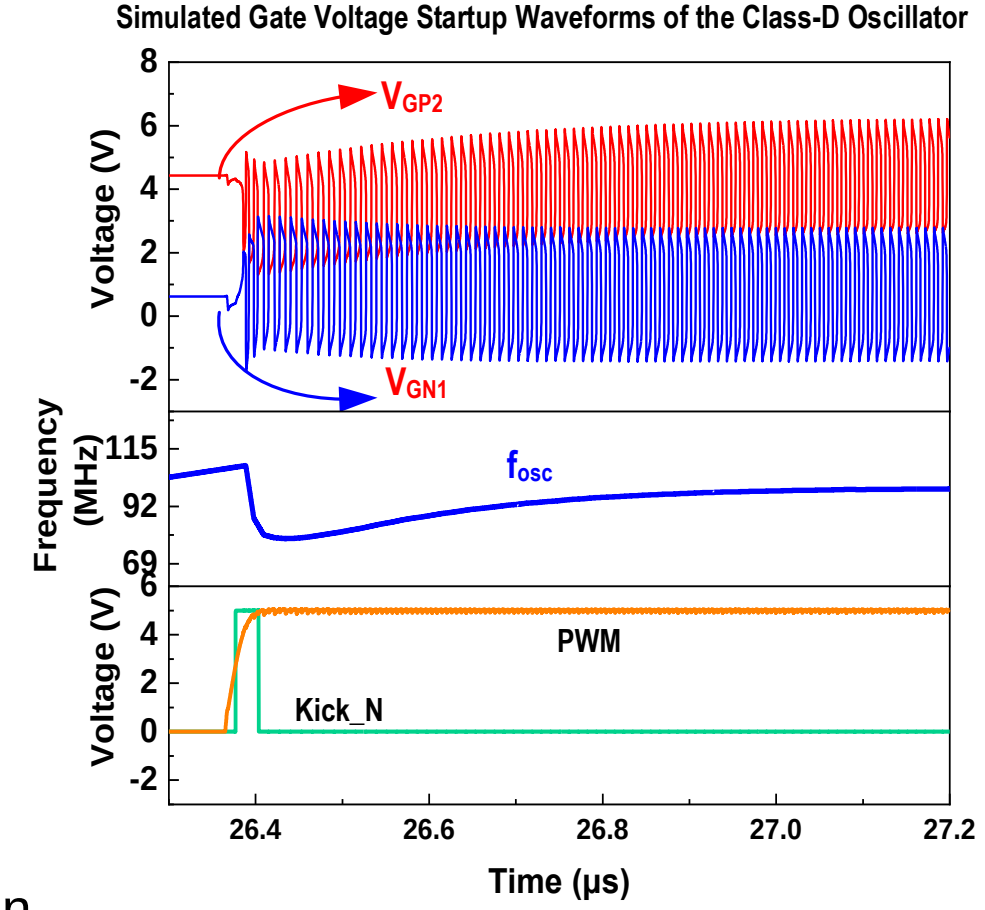
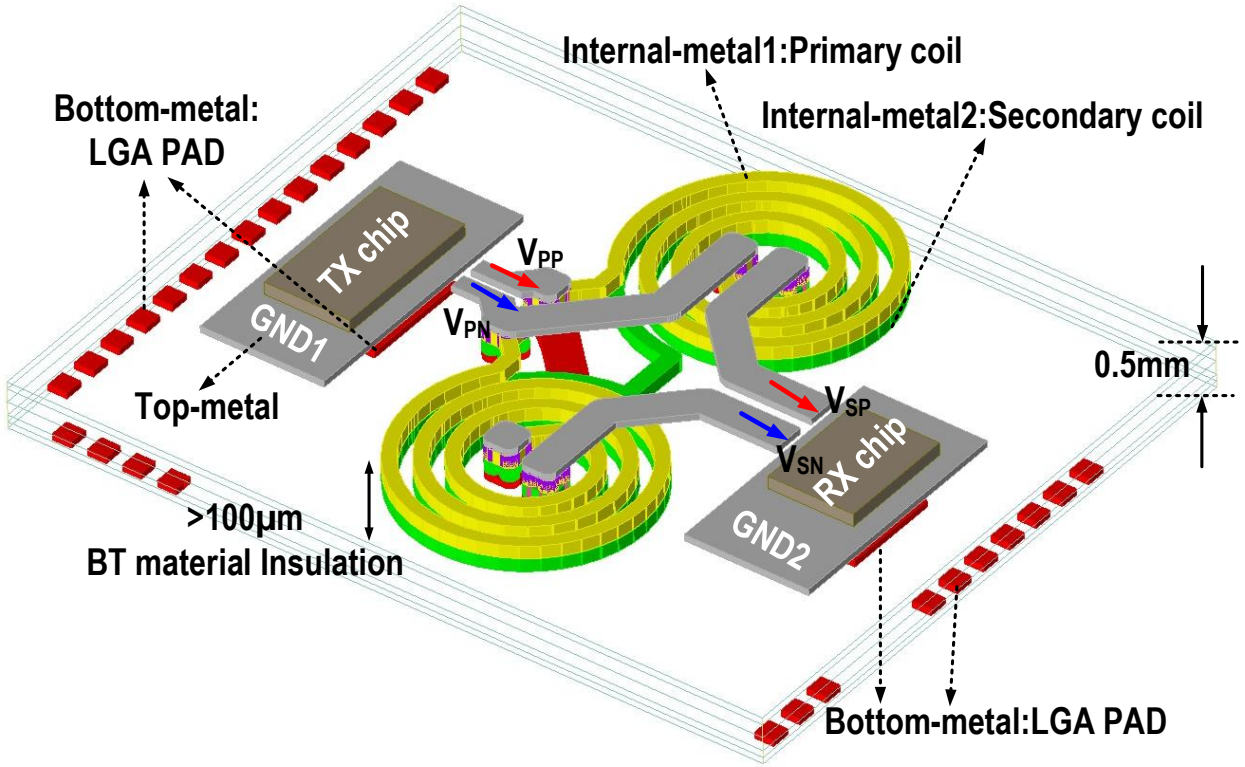


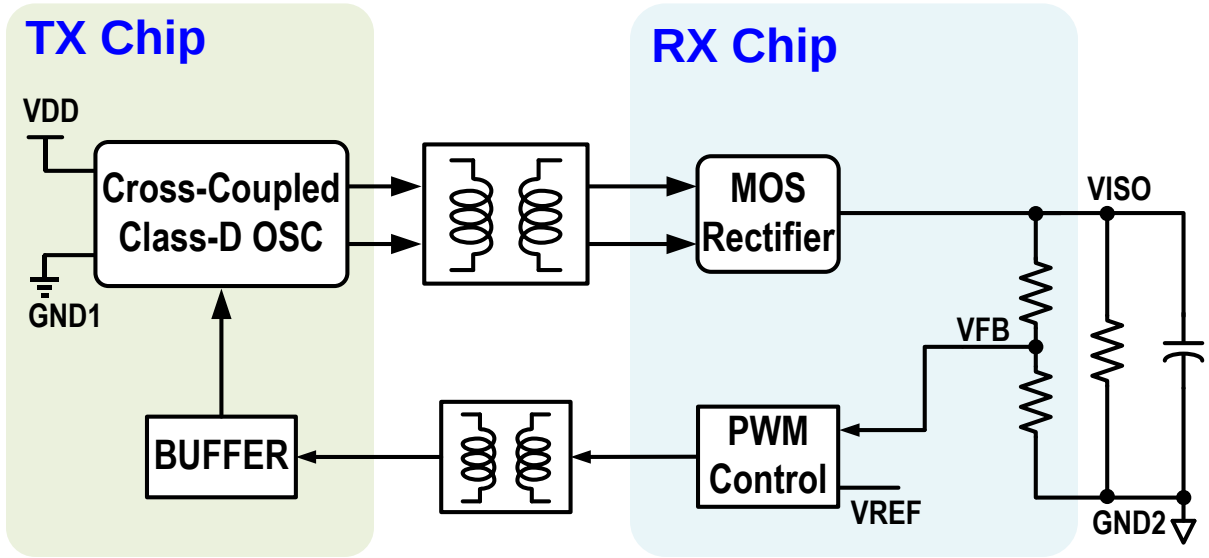


- Kick start circuit kicks the Class-D oscillator to start oscillation
- $V_{GN1/2}$ & $V_{GP1/2}$ pulled up (down)➔Variation of V_{GS} of power transistors➔f_{osc} variation➔Disperse energy

System Architecture

3D View of the proposed isolated DC-DC

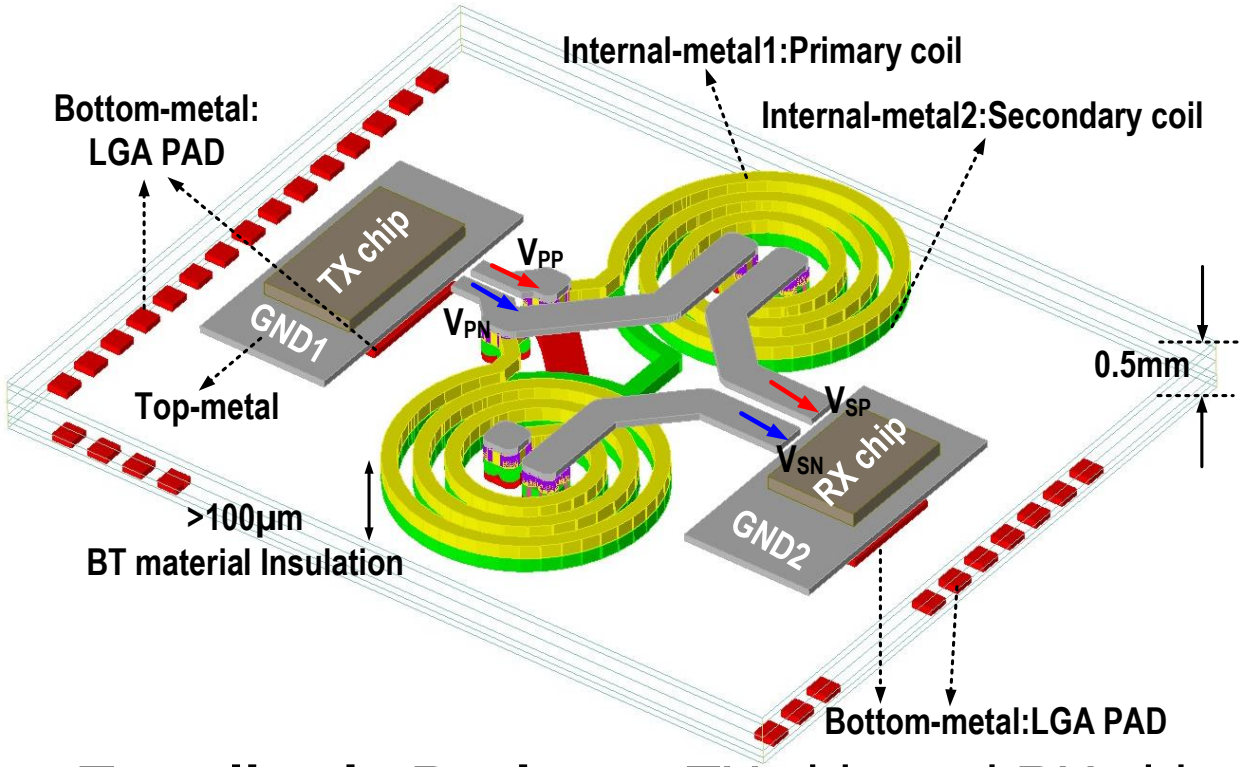


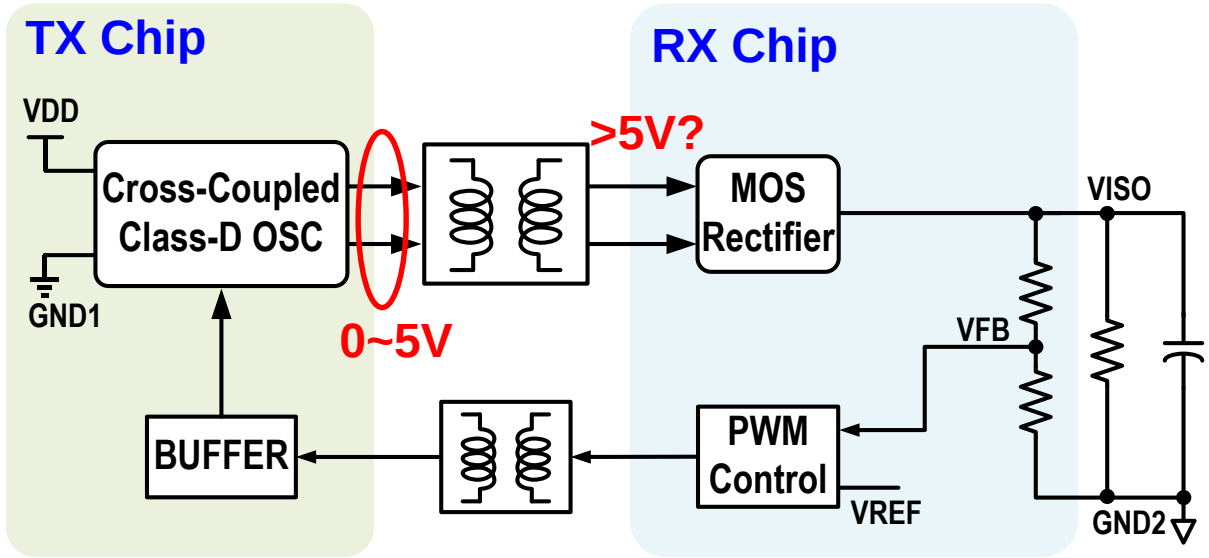


- **Two dies in Package:** TX chip and RX chip
- Core-less **high-Q** transformer in an LGA package substrate for **high efficiency and low-cost**

System Architecture

3D View of the proposed isolated DC-DC

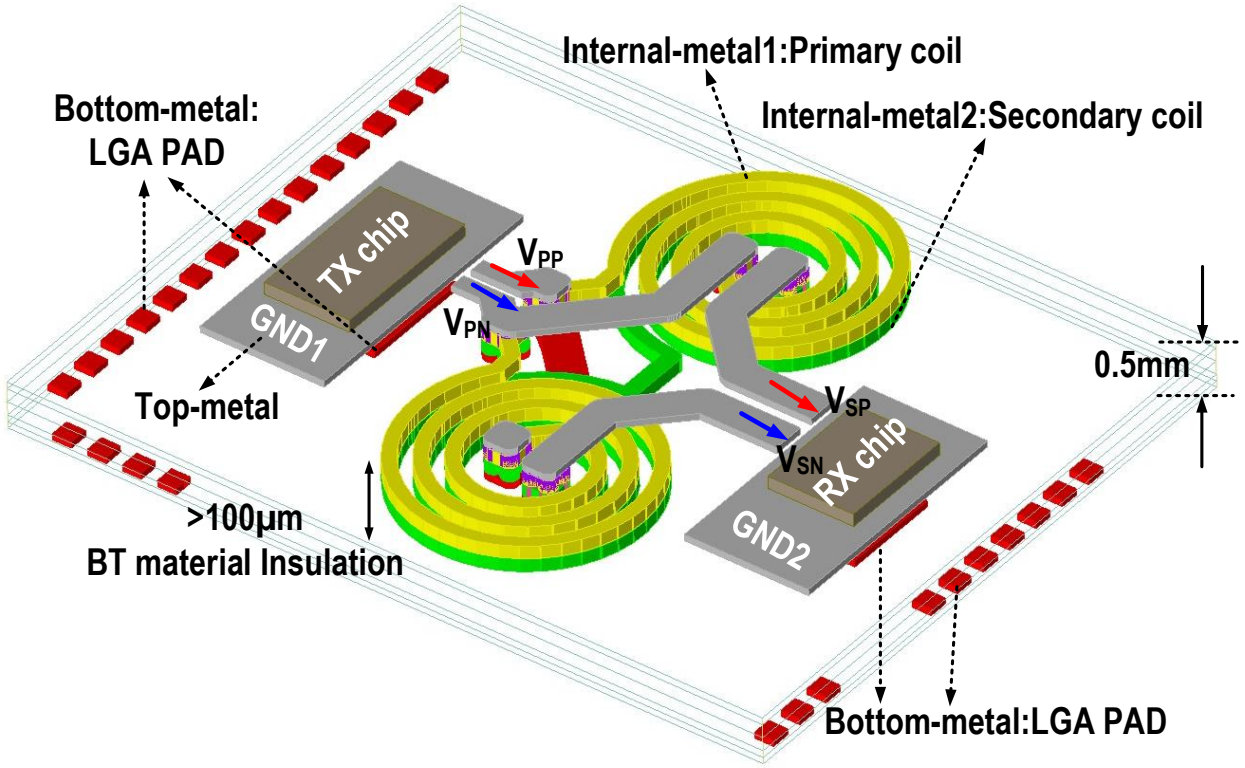


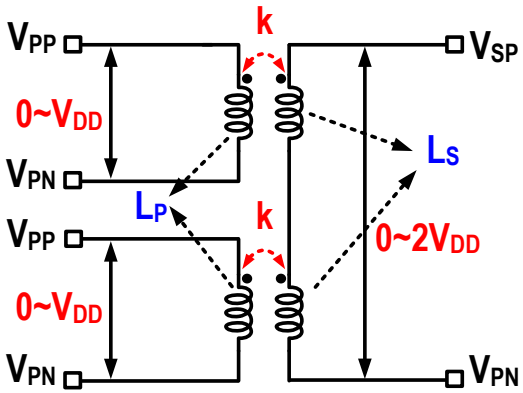


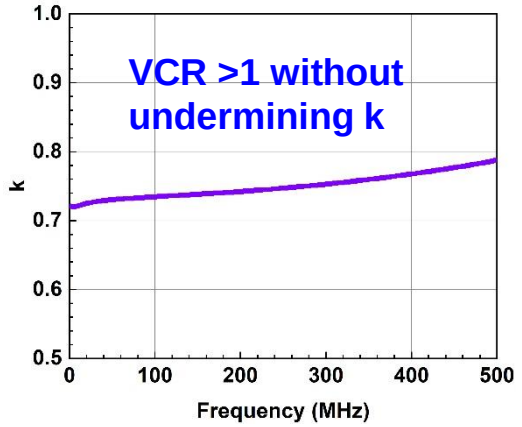
- **Two dies in Package:** TX chip and RX chip
- **Core-less high-Q transformer in an LGA package substrate**
- Output voltage swings of TX are limited to V_{DD} (5V)➔voltage conversion ratio (VCR) of the converter <1

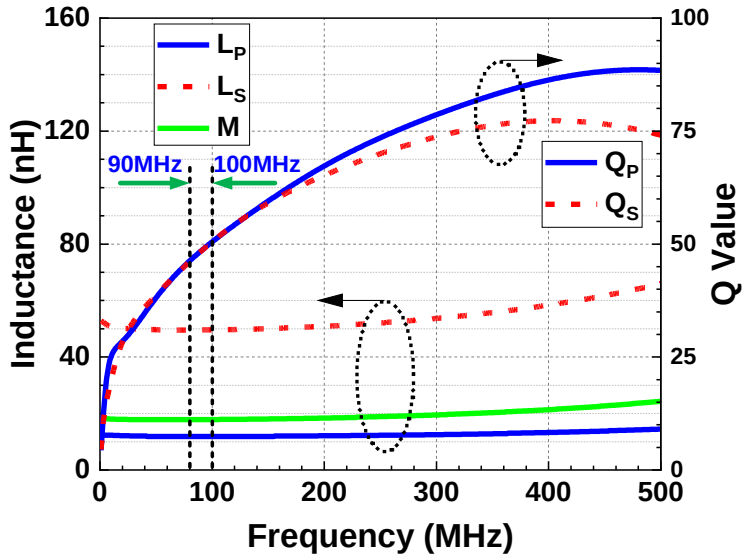
Voltage Series-Combining Transformer

3D View of the proposed isolated DC-DC









EM simulation:

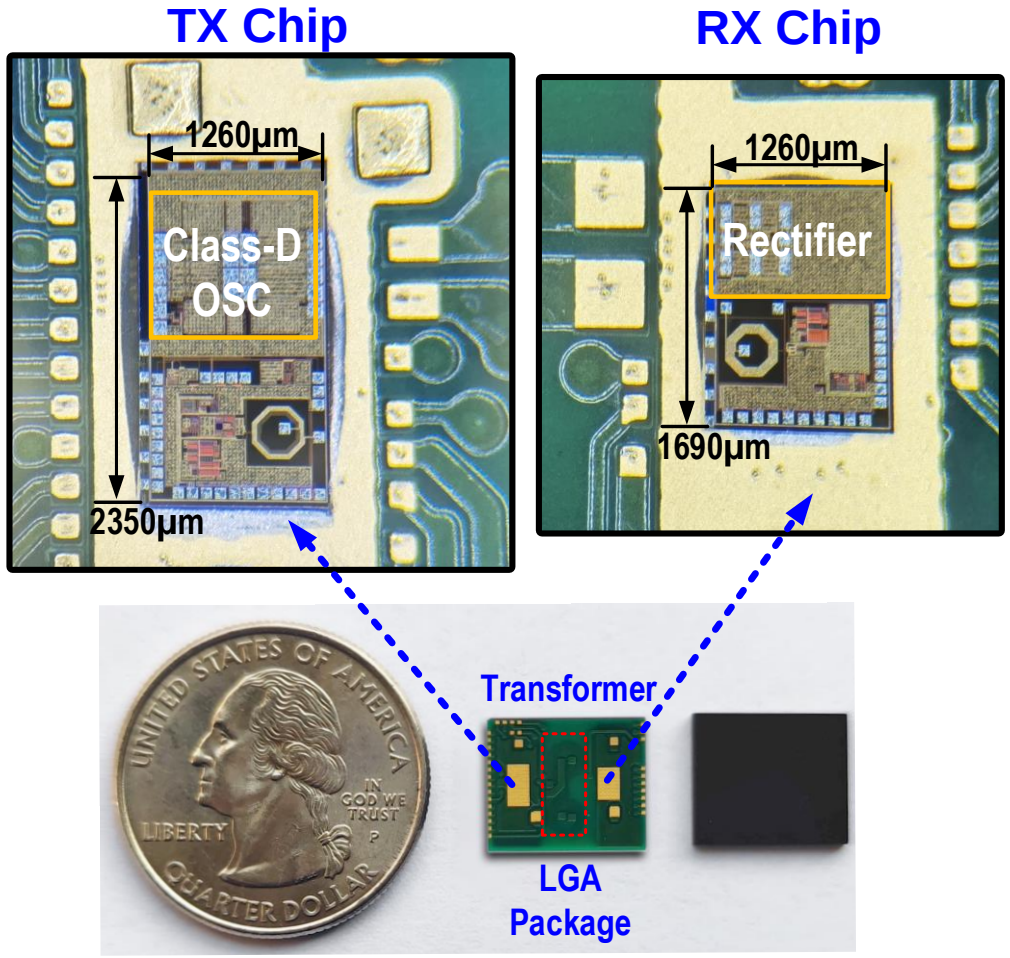
- ✓ $L_P/L_S/M$:11.9/49.6/17.8nH @90MHz
- ✓ $Q_{P/S}$:48.5@90MHz
- ✓ k=0.73

- Two 1:1-coupled coils for a parallel-connected primary and a series-connected secondary
- Internal-metal layer-1 and layer-2 for primary and the secondary coils: **2-oz-thick and 200-μm-wide** copper traces ➔ **High Q Coils** ➔ **High Efficiency**

Outline

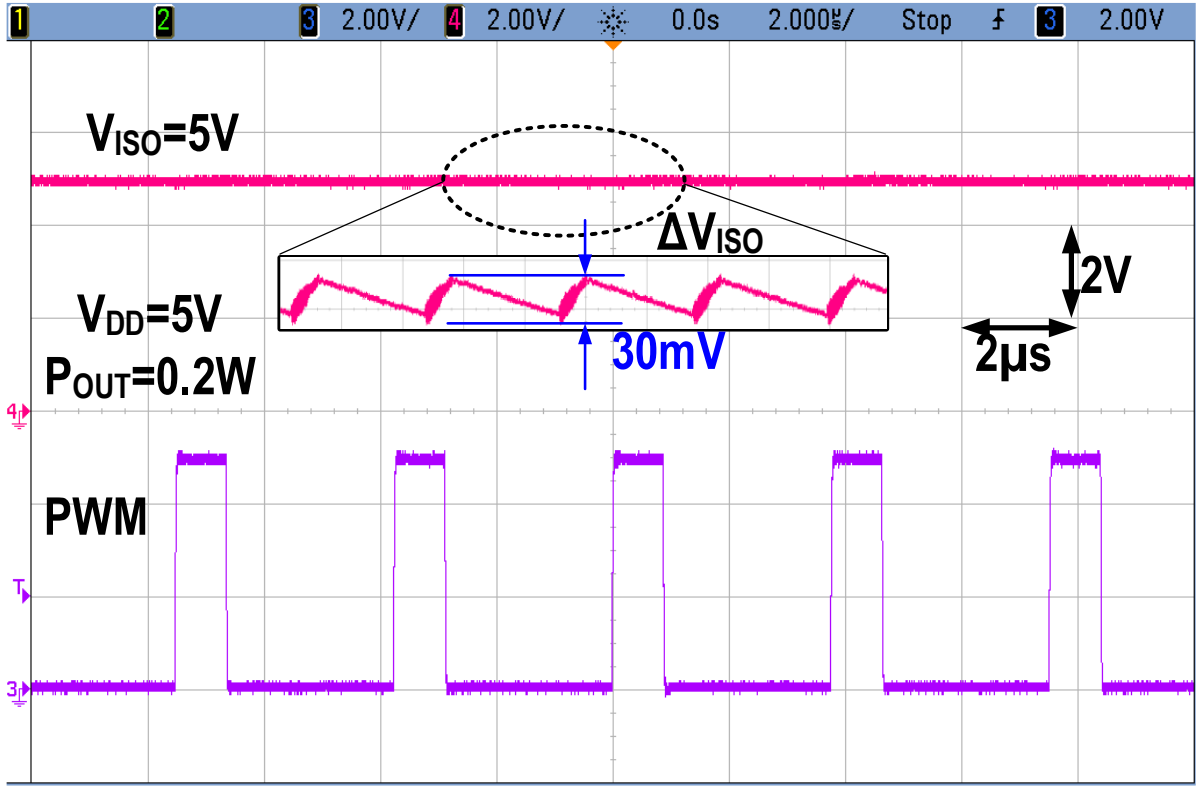
- Motivation and Challenges
- Proposed Low-EMI Isolated DC-DC converter
  - EMI Mechanism for Isolated DC-DC Converter
  - Proposed Cross-Coupled Shoot-Through-Free Class-D Oscillator
  - System Architecture and Voltage Series-Combining Transformer in LGA package substrate
- **Measurement Results**
- Conclusions

Measured Results

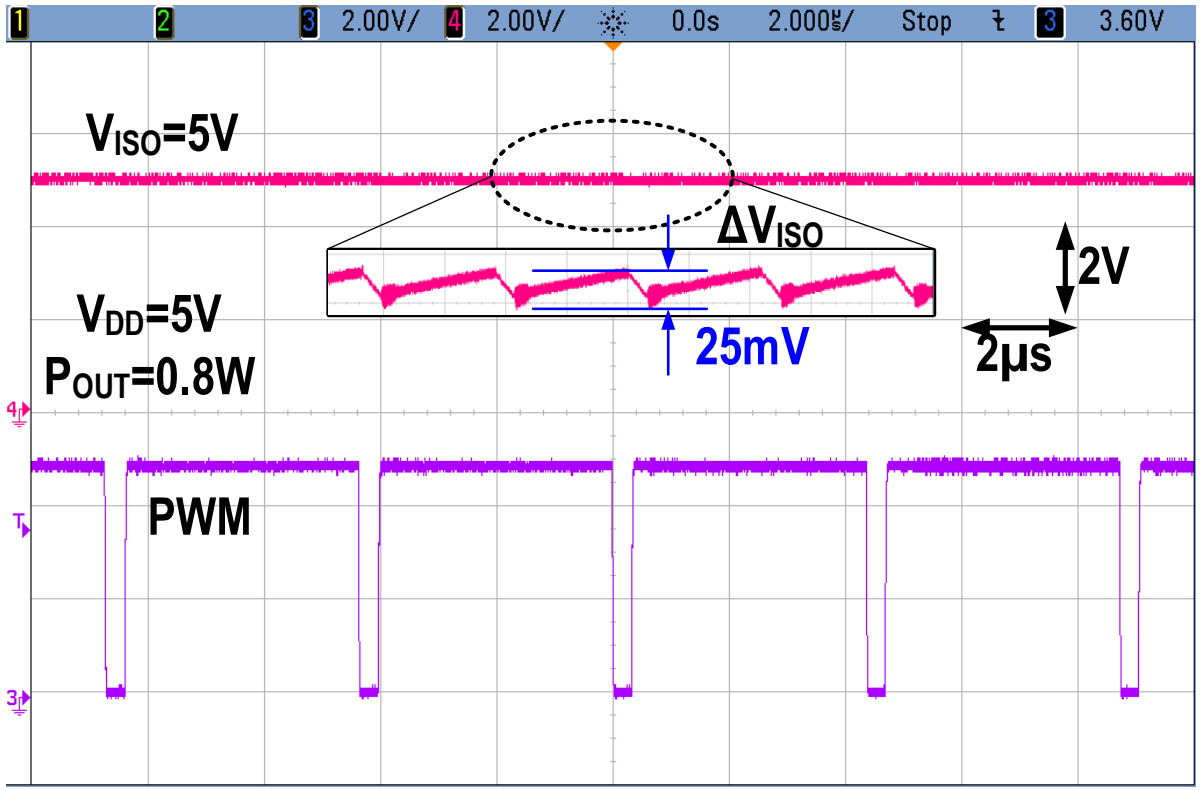


- 0.18μm BCD process
- Chip area:
  - TX :1260μm×2350μm
  - RX:1260μm×1690μm
- Package area:10mm×12mm

Measured Results

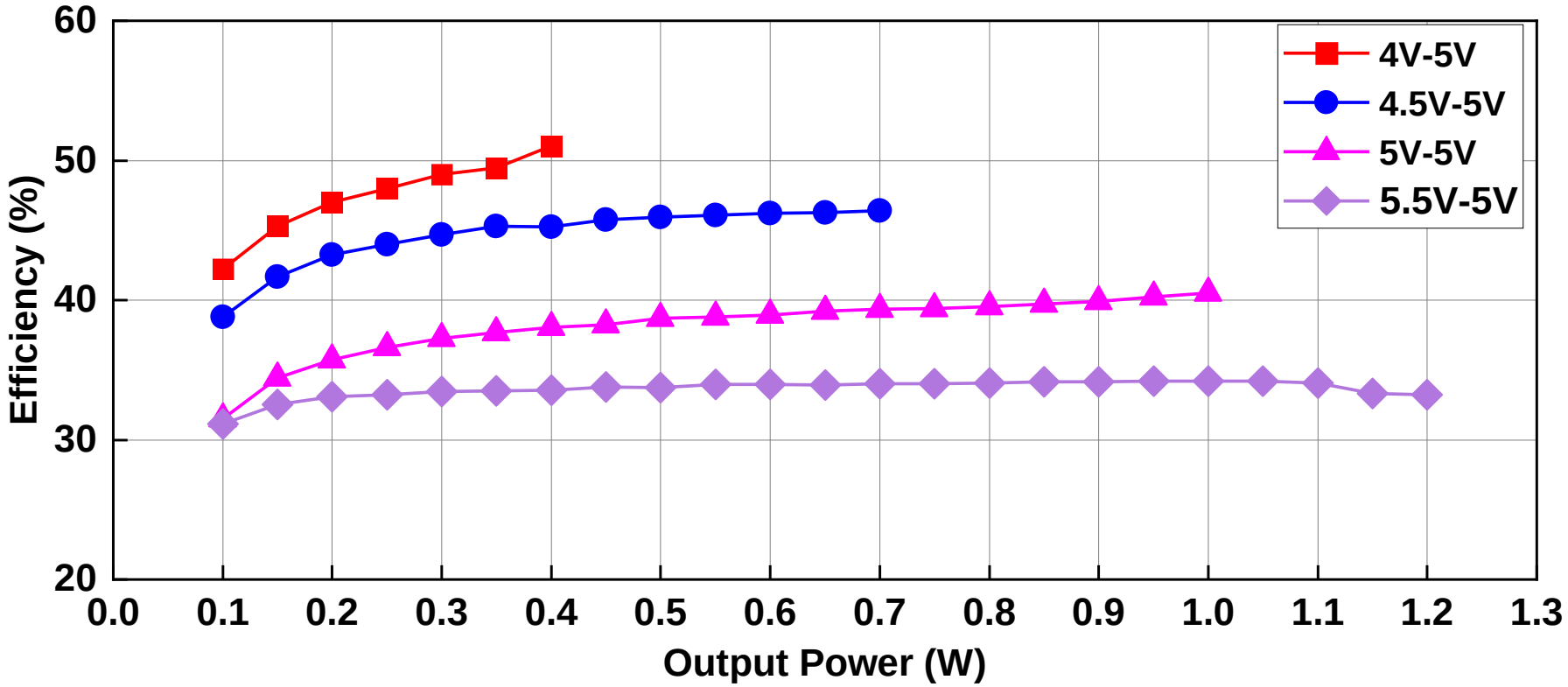


- V_{DD}=5V
- P_{OUT}=0.2W



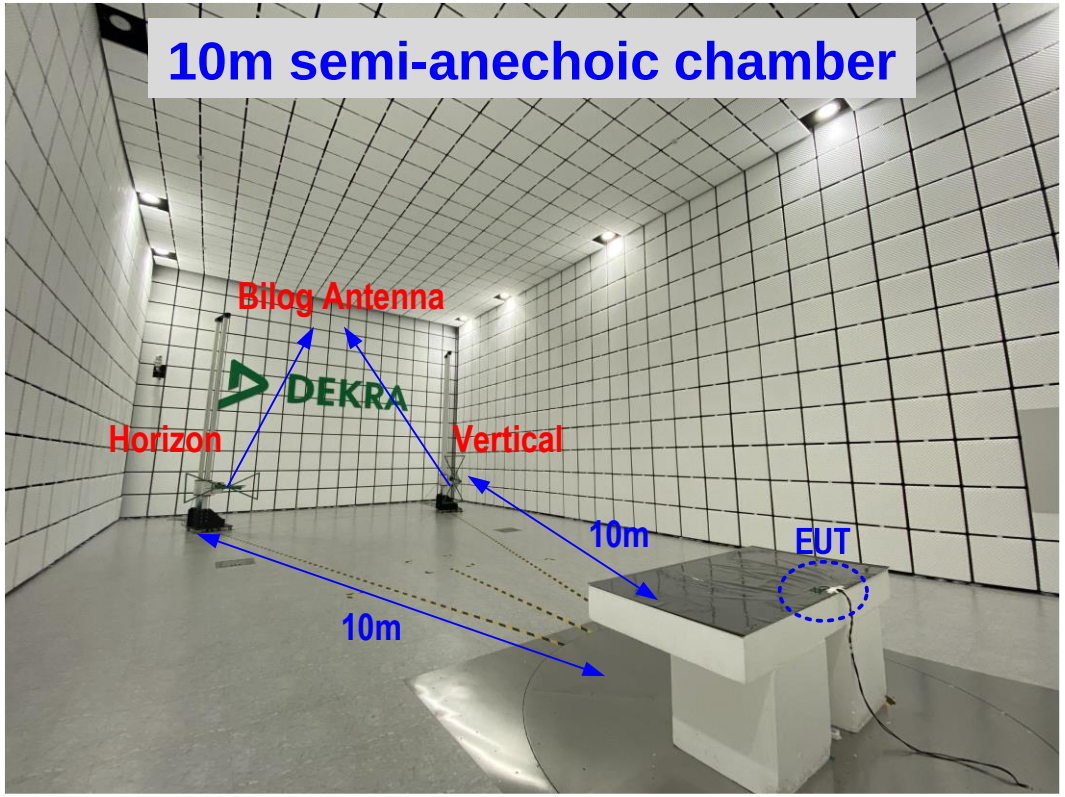
- V_{DD}=5V
- P_{OUT}=0.8W

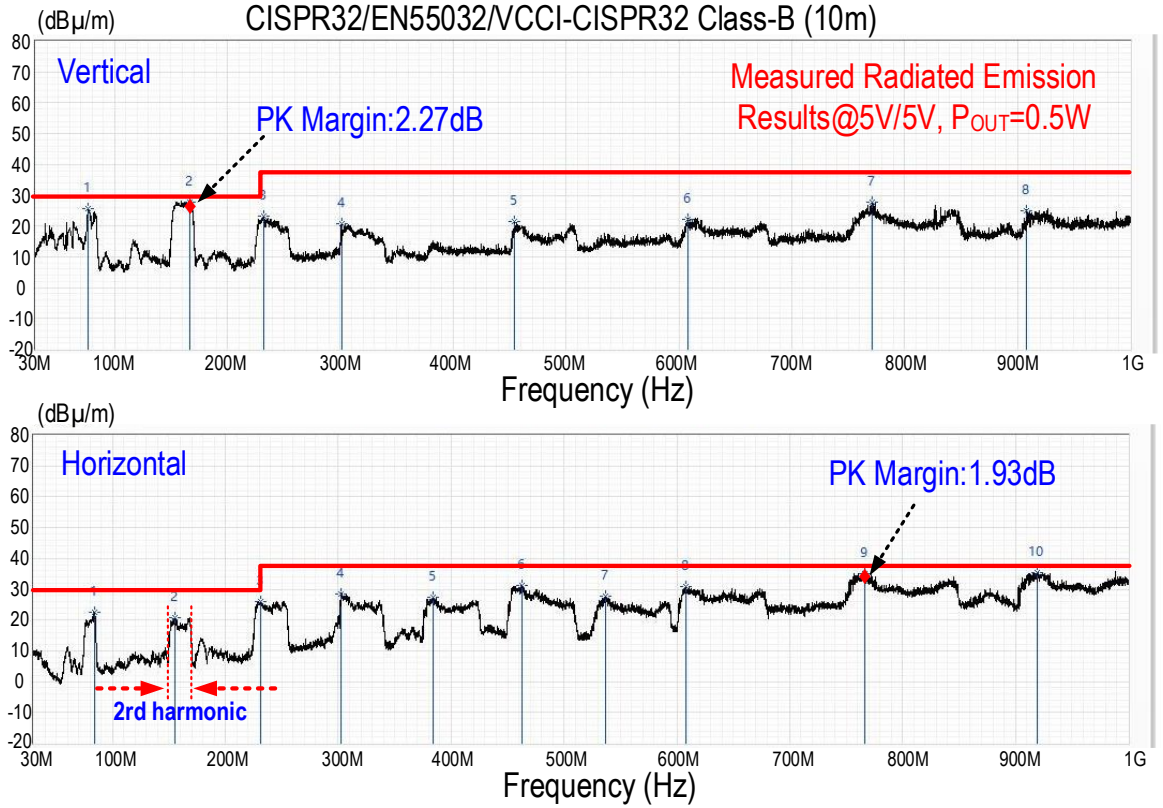
Measured Results



- V_{DD}/V_{ISO}=4V/5V: **Peak efficiency=51%@0.4W**
- V_{DD}/V_{ISO}=5V/5V: **Efficiency=41%@1W**
- **Maximum output power: 1.2W**

Measured Results





- Two-layer PCB without using any stitching capacitor
- Pass CISPR32 Class-B certification with 2.27dB peak margin in the vertical field and 1.93dB peak margin in the horizontal field

Comparison

Reference	ISSCC'19 [2]	ISSCC'19 [5]	ISSCC'20 [4]	ISSCC'21 [3]	**This work**
Technology	0.35μm BCD	0.35μm BCD	0.35μm BCD	0.18μm BCD	**0.18μm BCD**
Package (Size)	SOIC-8 (10mm×6mm)	SOIC-28 (10mm×18mm)	N/A	FOWLP (5mm×5mm)	**LGA Package (10mm×12mm)**
Transformer Type	Coreless	Magnetic-Core	Coreless	Coreless (in Package)	**Coreless (in Package)**
Input Voltage	4.5~5.5V	4.5~5.5V	3.3V	3~6V	**4~5.5V**
Output Voltage	3.3V~5V	5V	3.3V	3.3V/5V	**5V**
Max. P_{OUT}	0.8W	1.1W	0.165W	1.25W	**1.2W**
Peak Efficiency	34%	52%	34%	46.5%	**51%**
EMI Performance*	Pass Class-B Limit with Frequency Hoping (without Stitching Cap)	Pass Class-B Limit with Two External Capacitors (without Stitching Cap)	N/A	N/A	**Pass Class-B Limit (without Stitching Cap and Frequency Hopping)**

*EMI Performance is evaluated to CISPR-32 (CISPR-22) Class B Certification and Input-output Ratio is 5V to 5V.

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Conclusions

Proposed fully-integrated isolated DC-DC converter:

- **Symmetrical cross-coupled Class-D oscillator that greatly improves the EMI performance**
- ✓ **Meets the CISPR-32 Class B standard on a two-layer PCB without using any stitching capacitor**
- **Shoot-through-free with high efficiency and low cost**
- ✓ **51% peak efficiency, 1.2W maximum output power**

Thank You !