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

A High-Efficiency Transformer-in-Package Isolated DC-DC Converter Using Glass-Based Fan-Out Wafer-Level Packaging

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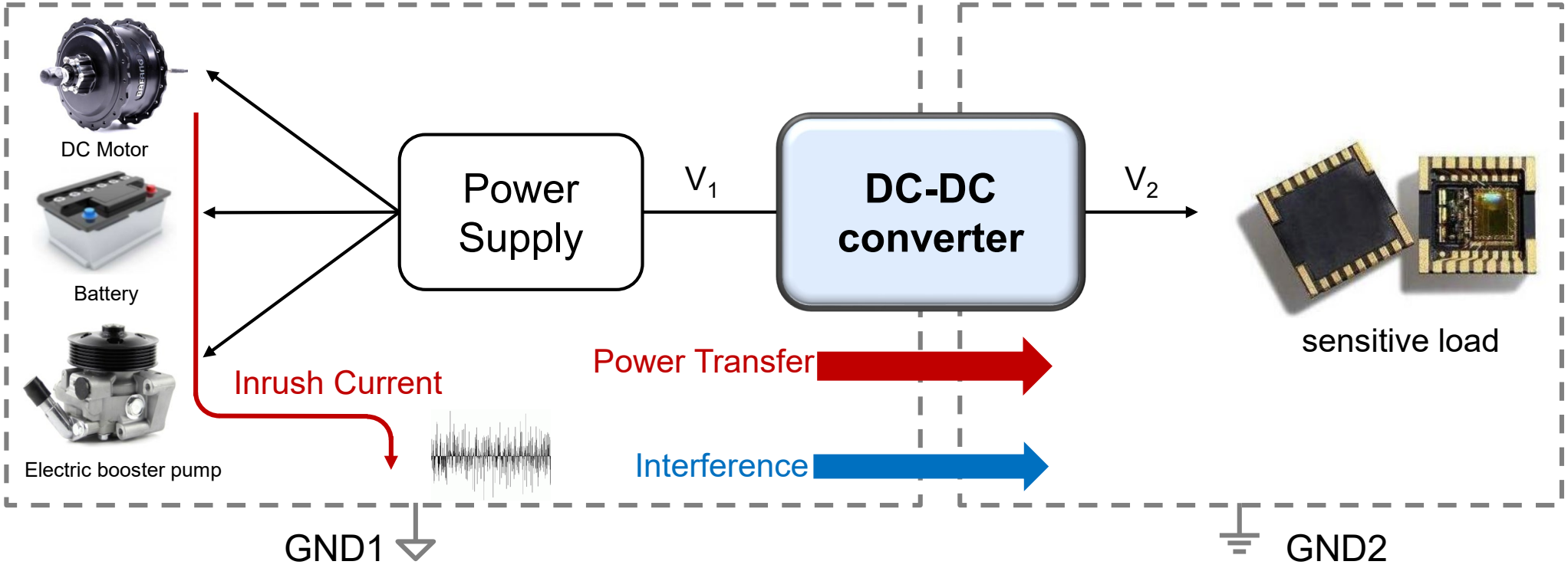
Outline

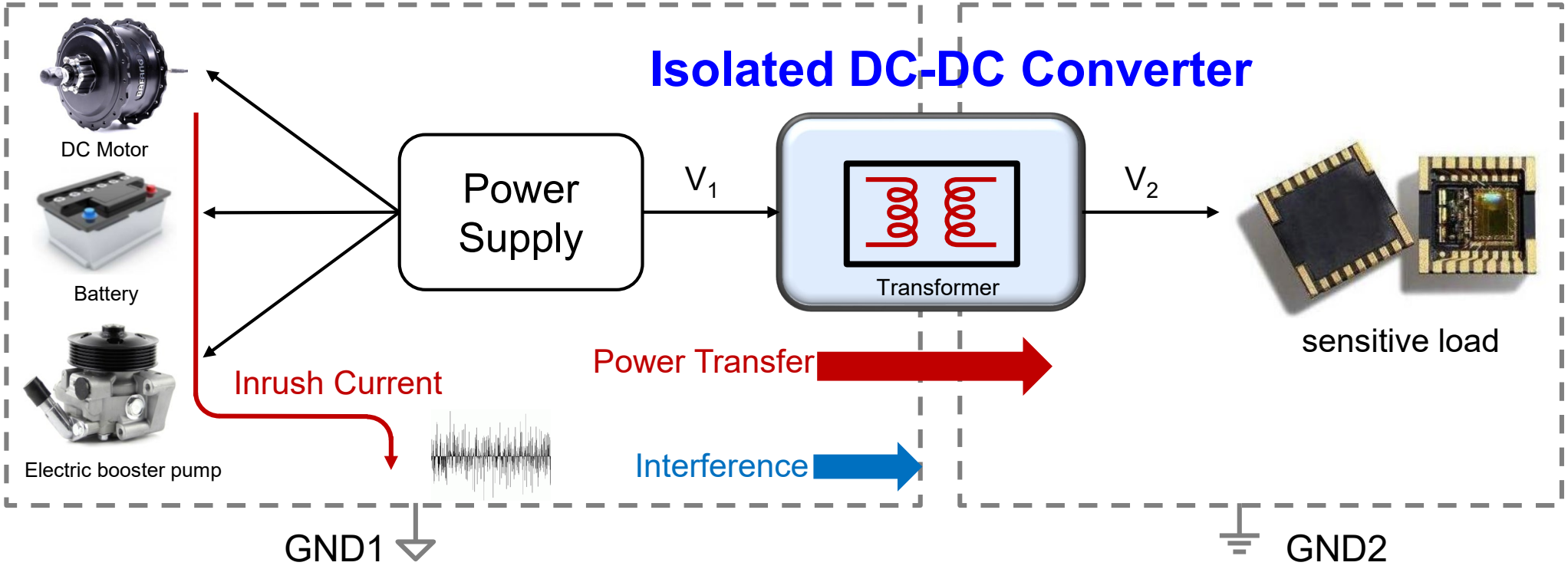
- **Motivation**
- **Proposed TiP FOWLP Isolated DC-DC converter**
  - System Architecture & TiP Solution
  - The Glass-based Transformer
  - Circuit Implementation
- **Measurement Results**
- **Conclusions**

Motivation



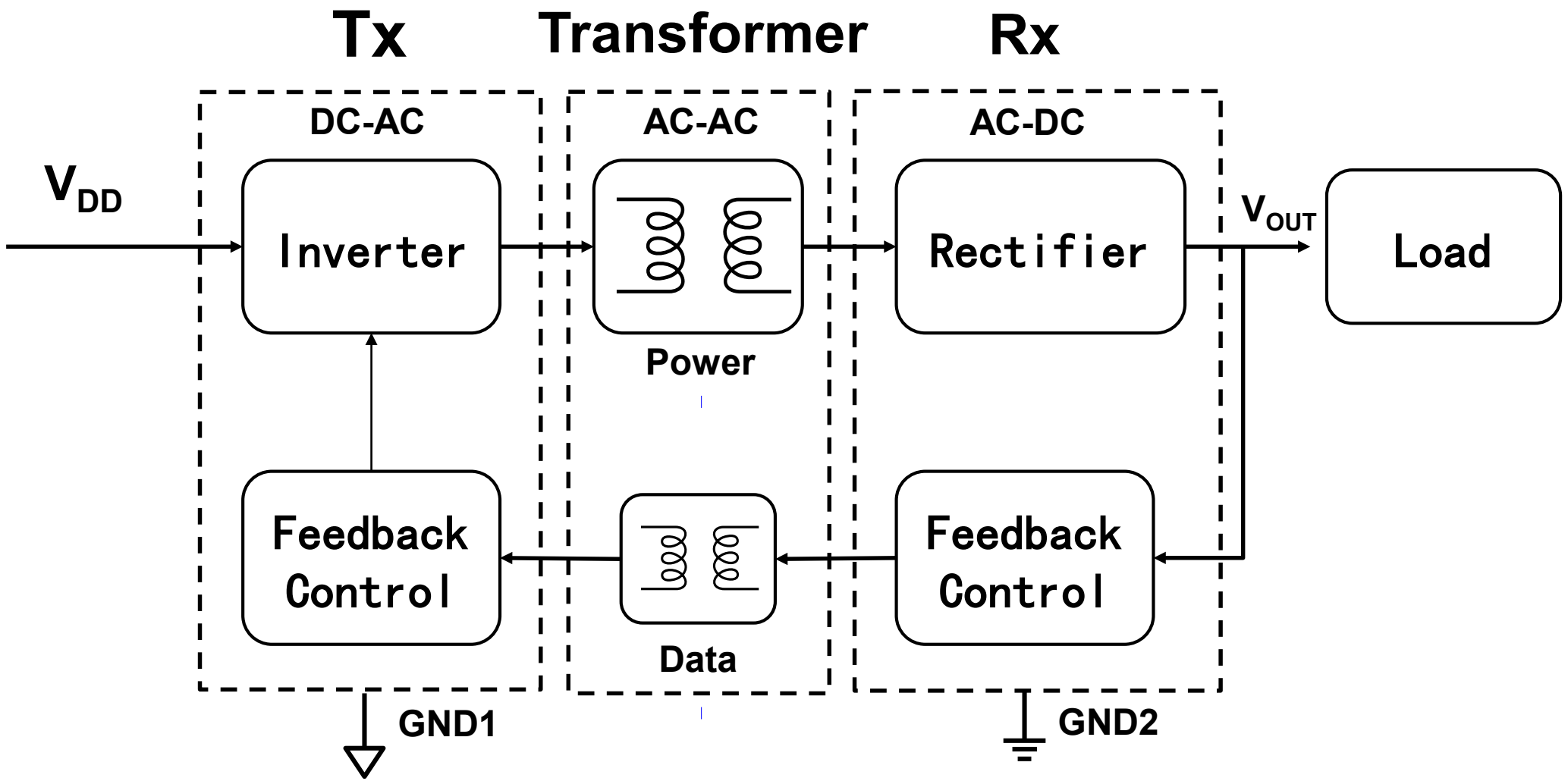
- Voltage breakdown ☹
- Potential inrush current ☹
- Common-mode noise ☹
- Human Safety ☹

Motivation



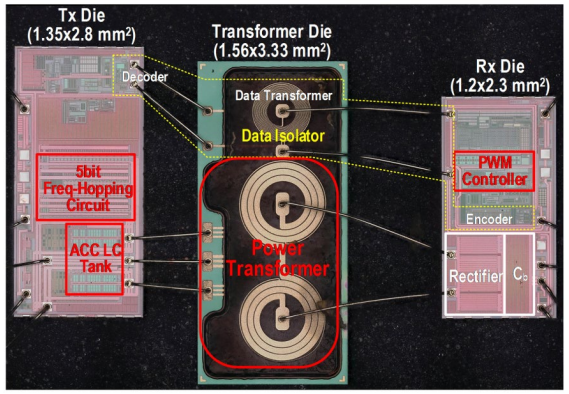
- Device and human safety ☺
- Data acquisition accuracy ☺
- System reliability ☺

Block Diagram



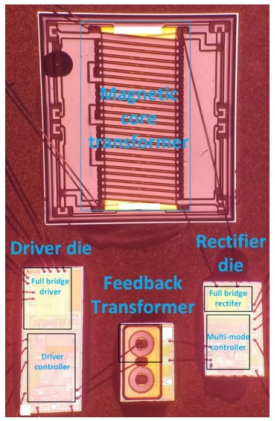
State-of-the-arts

Si-based Gold windings 6μm-thick



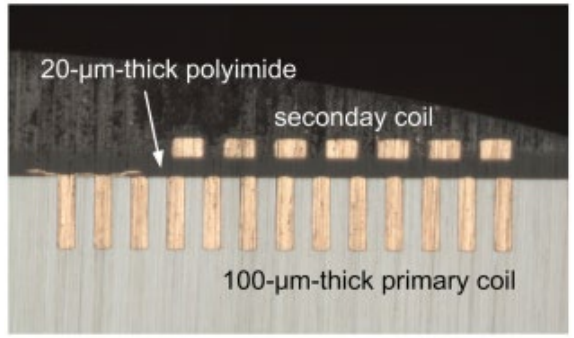
[W. Qin ISSCC'19]

Magnetic-core



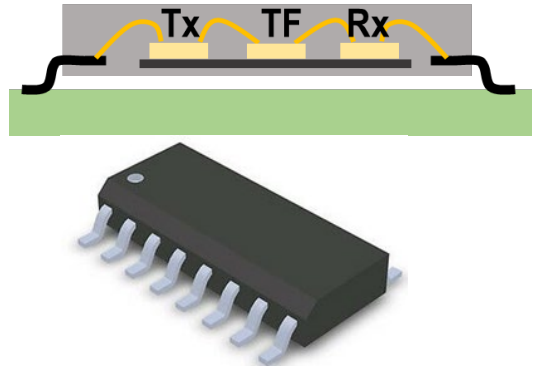
[Y. Zhuo ISSCC'19]

Si-embedded 100μm-Thick



[L. Li ISSCC'20]

SOIC Packaging



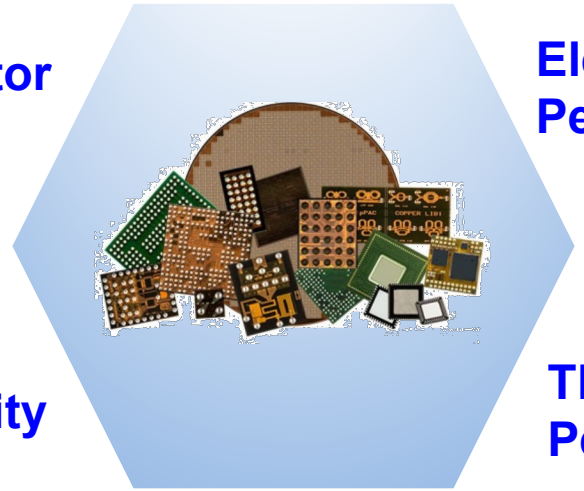
Reference	Freq. (MHz)	Quality factor	Transformer (TF) Size (mm^2)	Max. P_{OUT} (W)	Peak Efficiency
W. Qin ISSCC'19	160-210	6.8	5.2	0.8	34%
Y. Zhuo ISSCC'19	16-25	12	8.4	1.1	52%
L. Li ISSCC'20	11	16/7	4	0.165	34%

Design challenges for fully-integrated isolated DC-DC converters

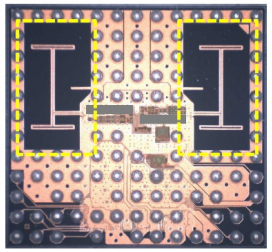
- Trade-off between size, cost and quality factor of transformer for high efficiency
- Compact form factor for high power density

Wafer-Level Packaging

Market drivers & Wafer Level Packaging capabilities



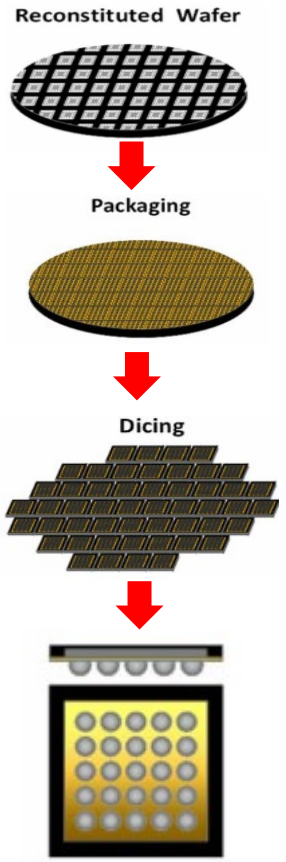
[Image from JCET]



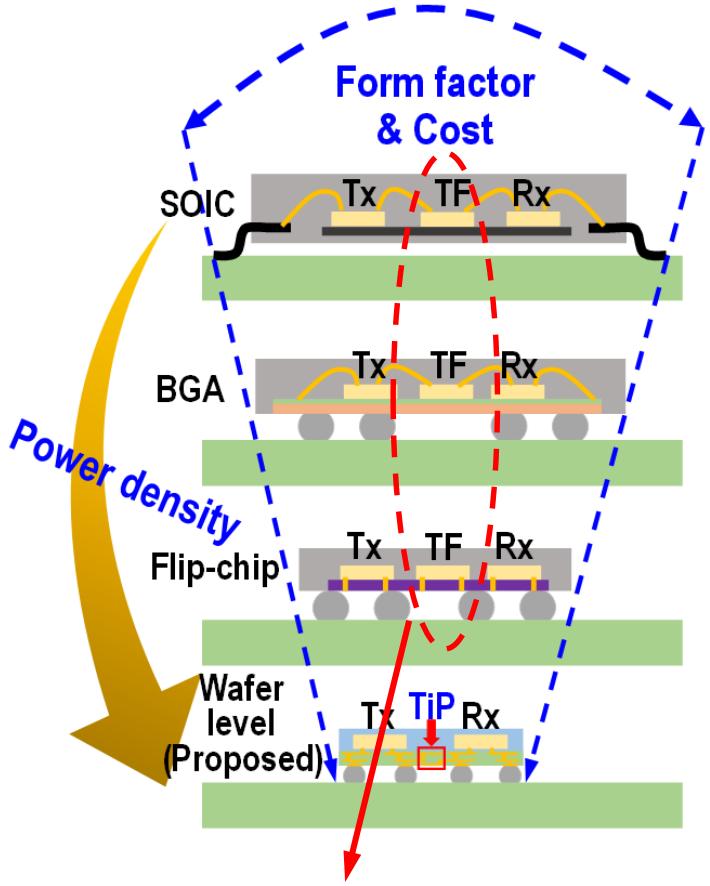
[MTK AIP ISSCC'2019]

[Infineon eWLB]

FOWLP process flow



[Hunt, J., ASE Group]



Implement the transformer using RDL to save one die?

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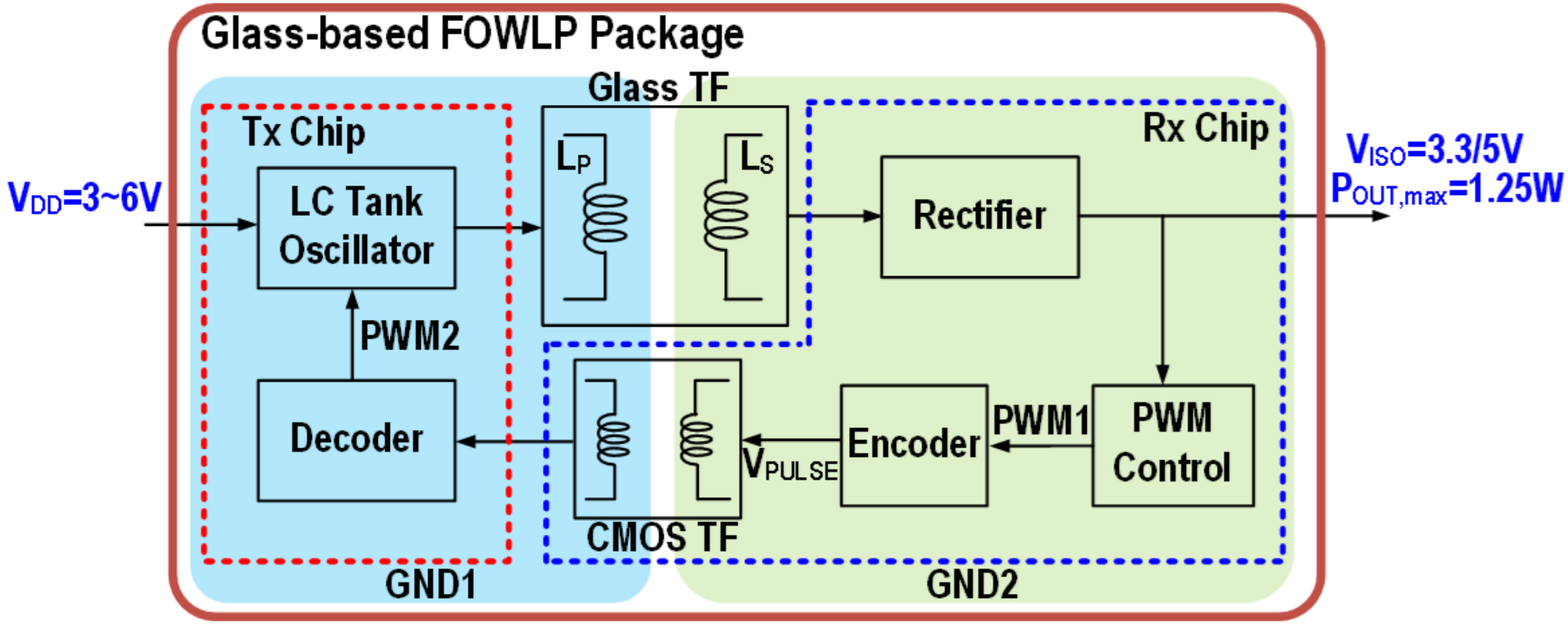
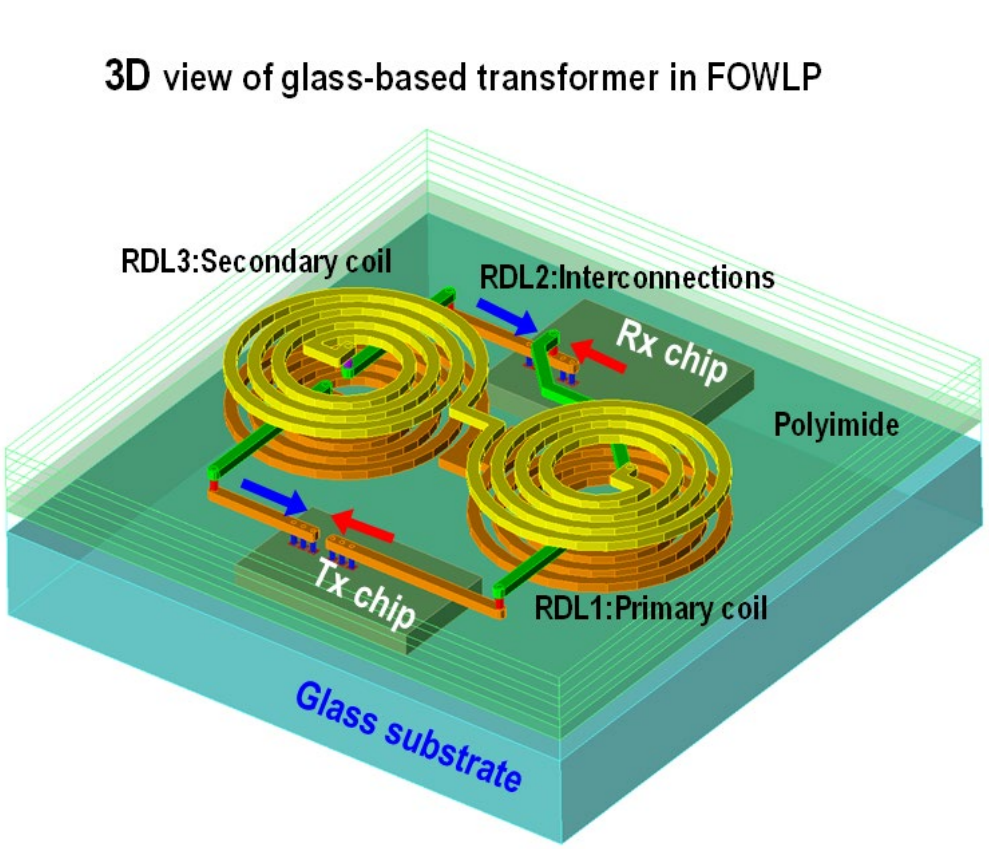
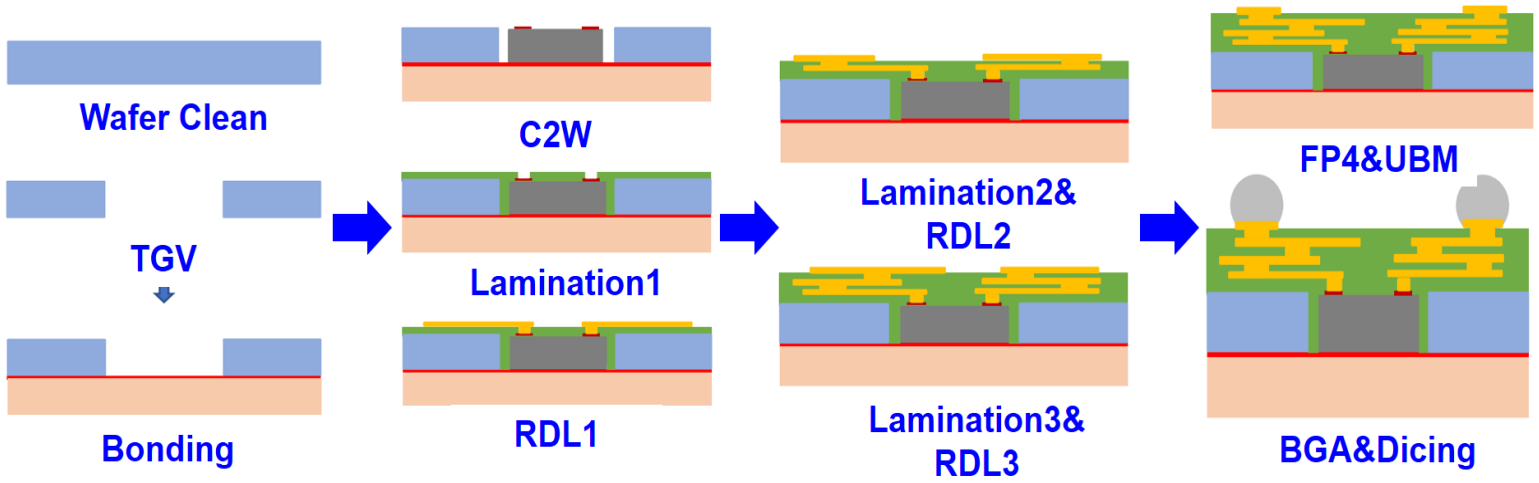
System Architecture

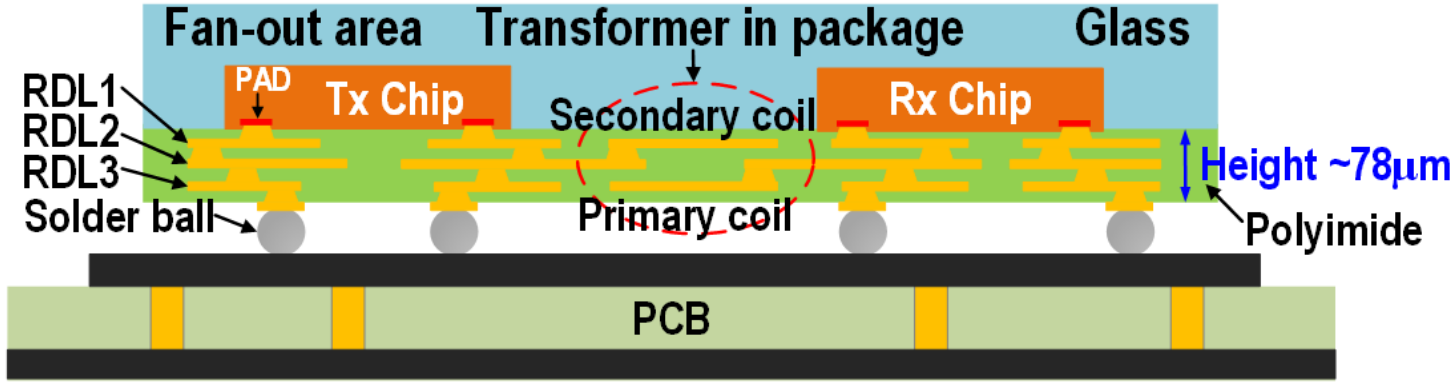


- Glass-based transformer (TF) in fan-out wafer level packaging (FOWLP)
- TX chip with wide V_{DD} range
- RX chip with on-chip TF for PWM digital isolator

Transformer-in-Package Solution



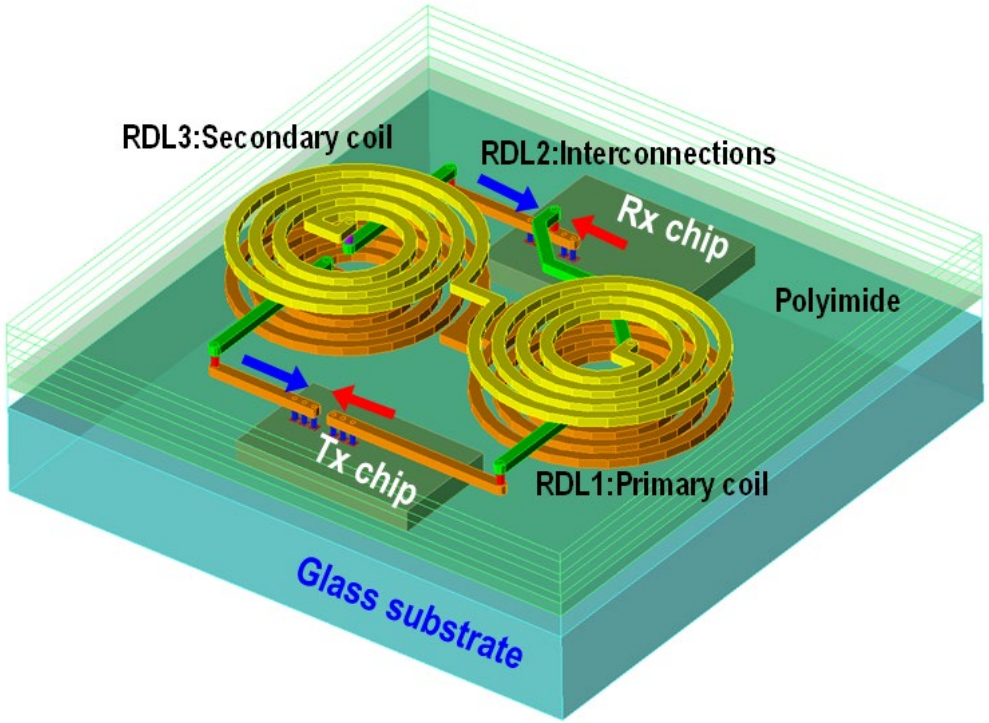




- The TX and RX chips are planted into the cavities with 300μm in the glass
- 3-RDL for TF and interconnections without extra TF chip

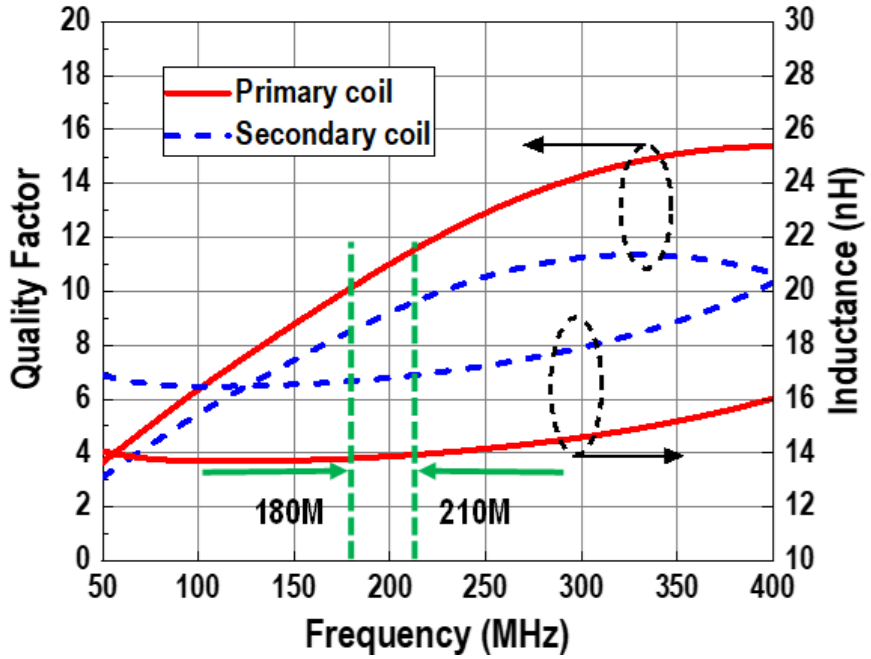
Glass-based Transformer

3D view of glass-based transformer in FOWLP

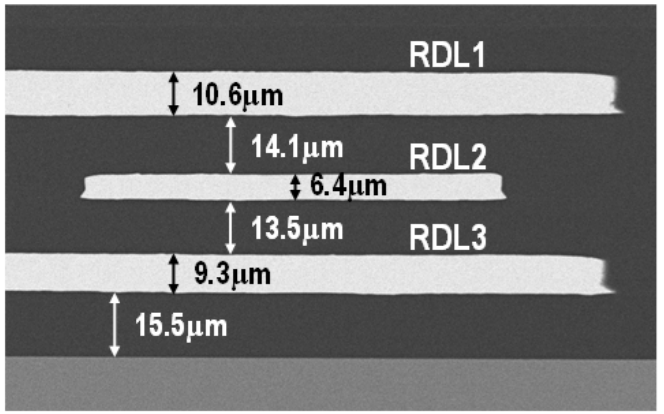


Q_P=10.3~11.6
Q_S=8.6~9.6
L_P=13.8nH
L_S=16.7nH
@180-210MHz

Electromagnetic-simulated results of glass-based transformer

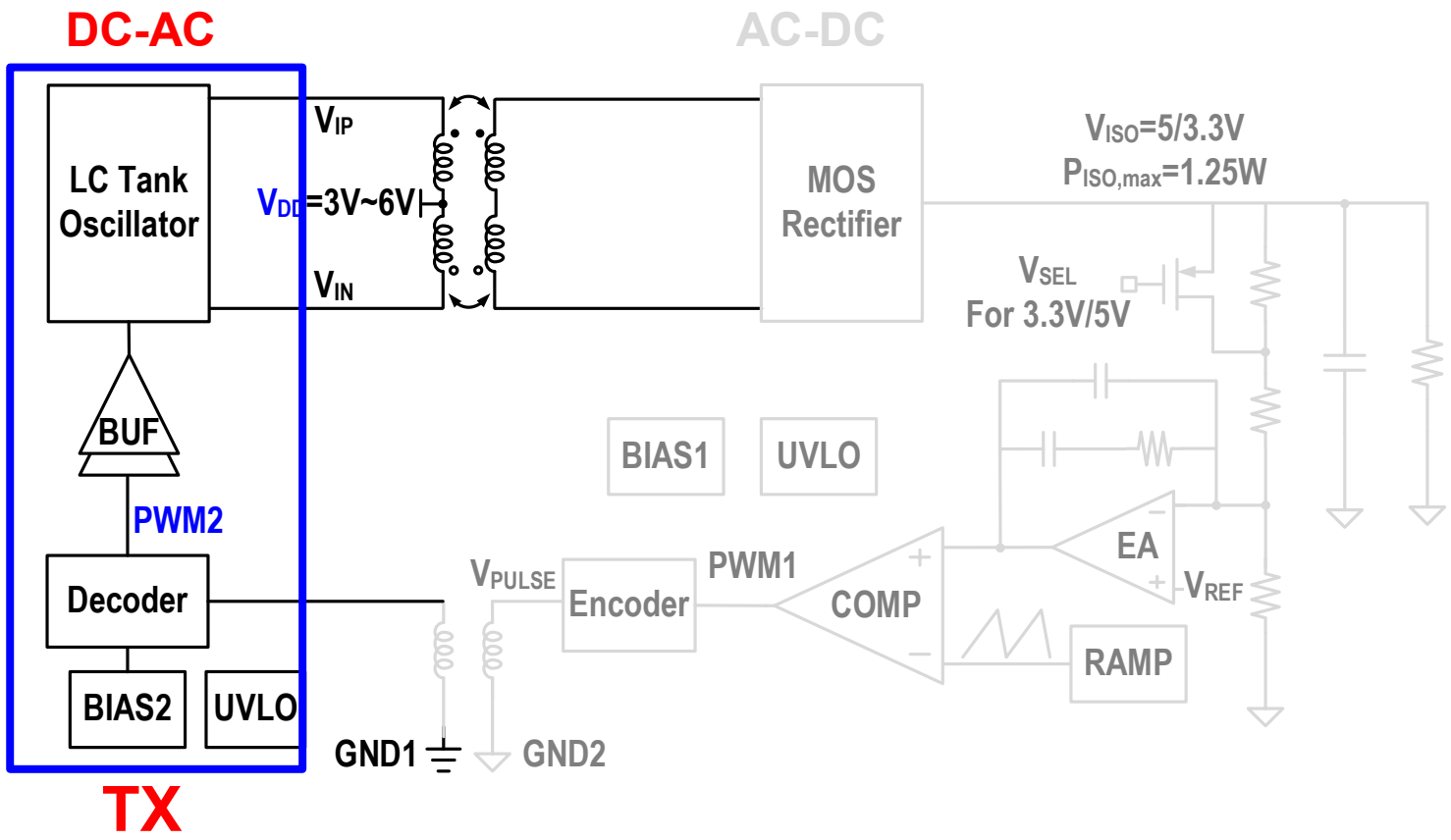


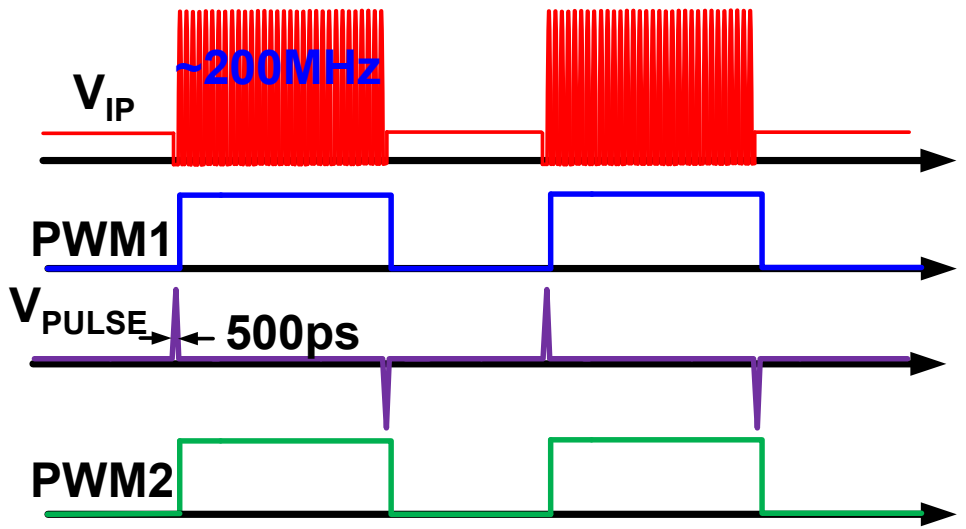
Cross section view of the glass-based transformer



- RDL1 and RDL3 for Primary and Secondary coils: 10-μm thick, 100-μm wide and 3.5 turns of windings
- Simulated coupling factor：0.8

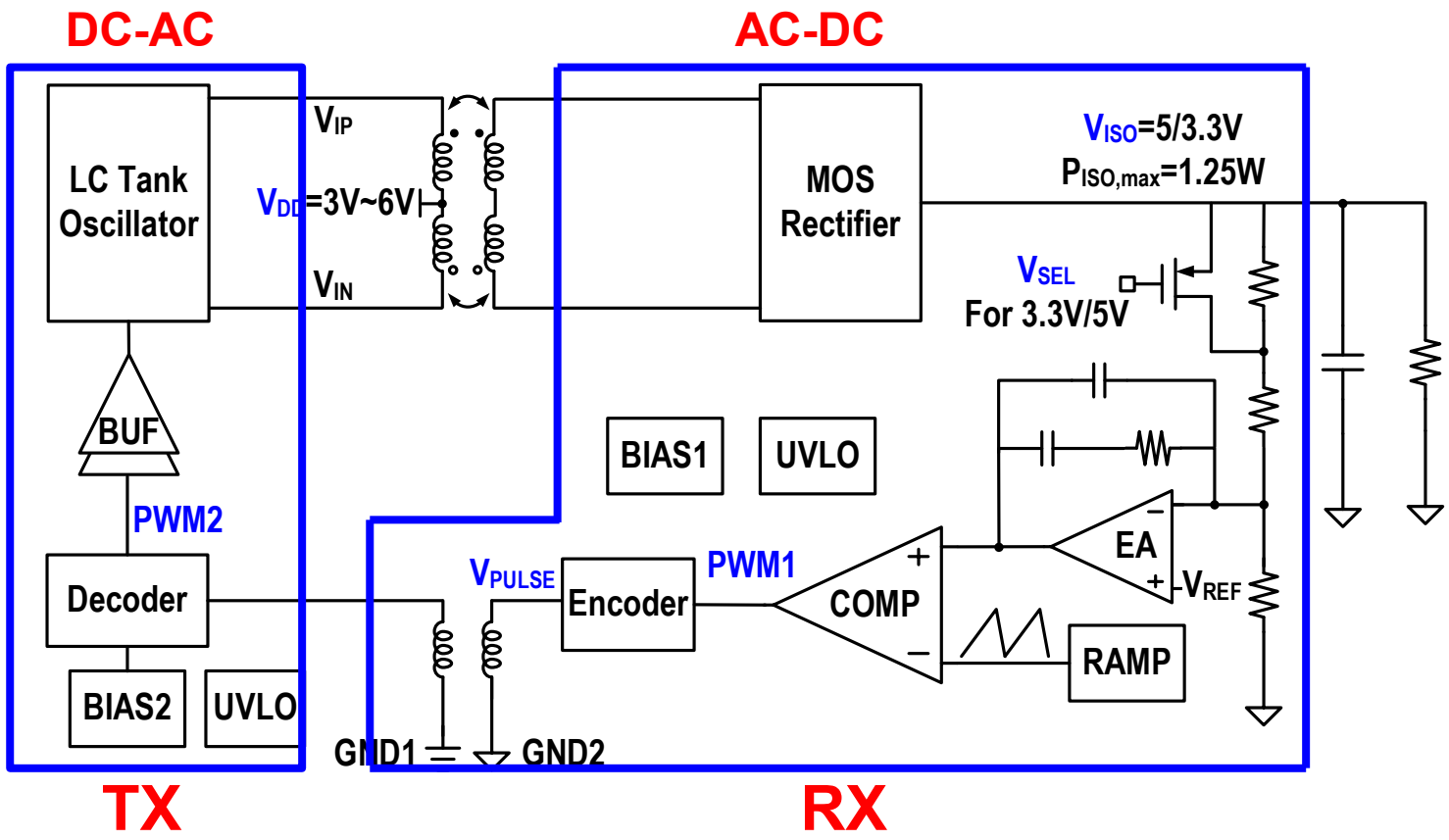
Circuit Implementation

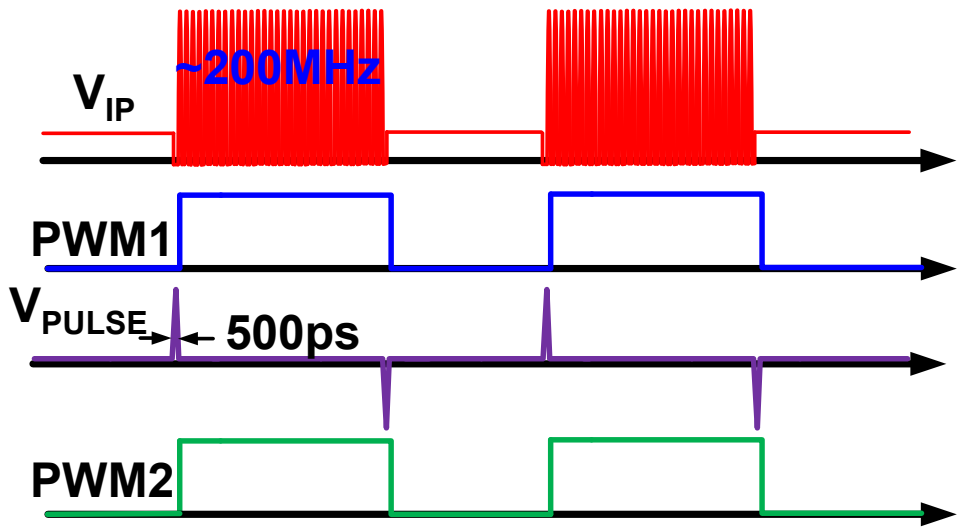




- LC tank oscillator operated at ~200MHz resonate frequency

Circuit Implementation

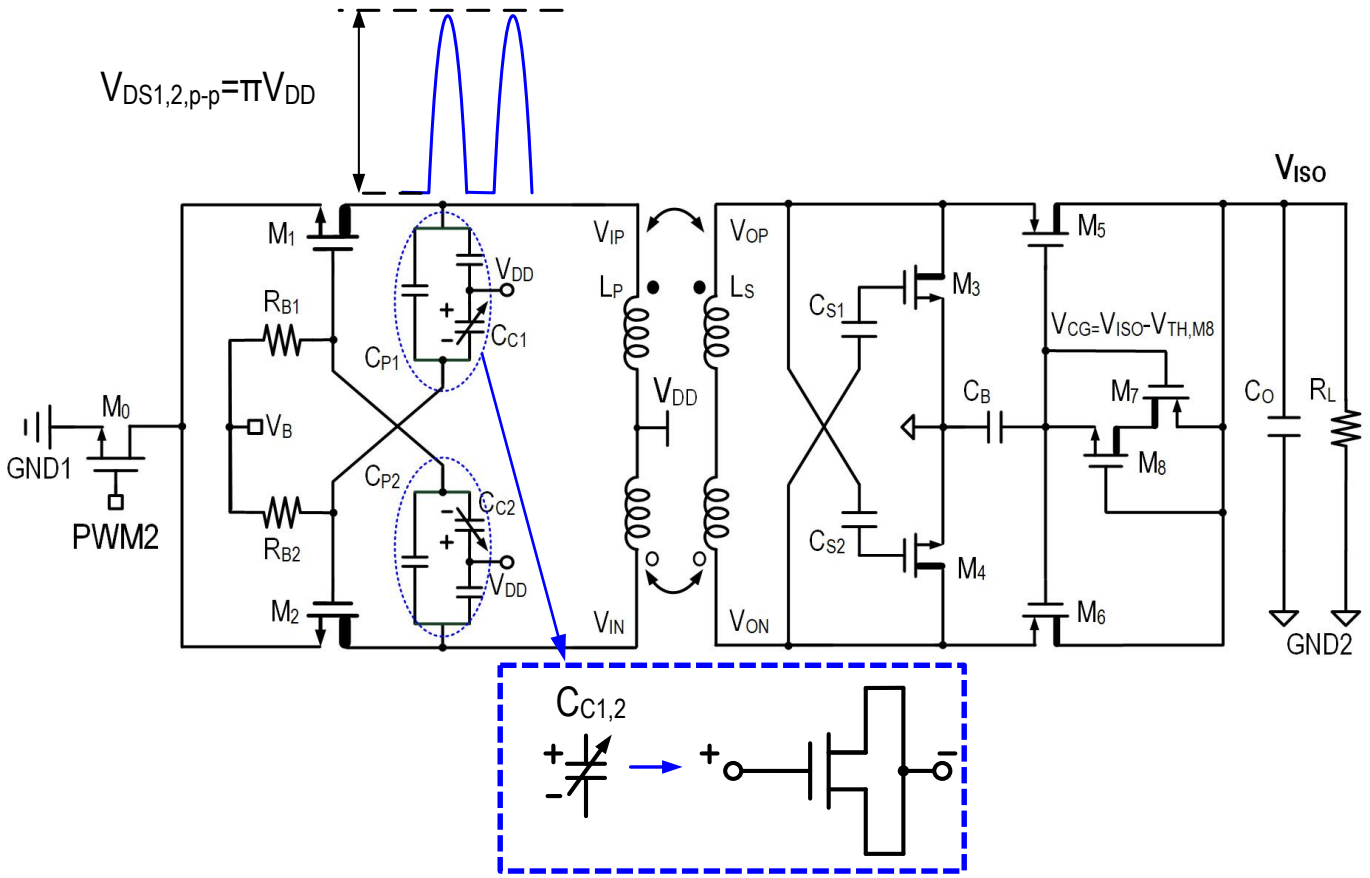


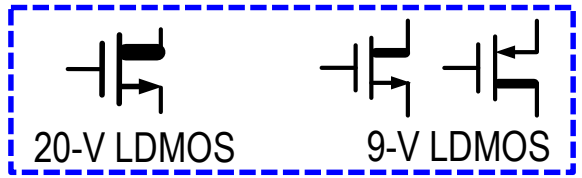


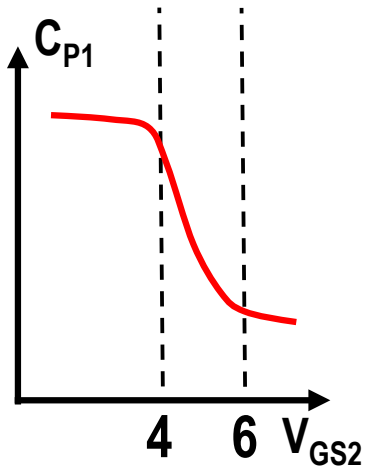
[S. Kaeriyama JSSC 2012]

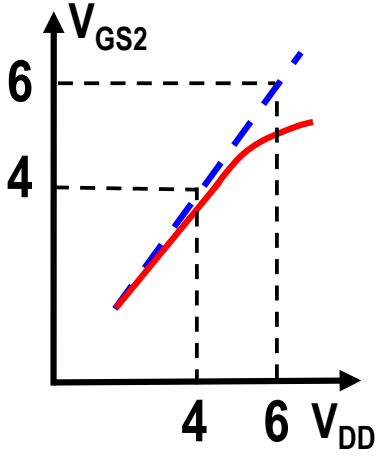
- PWM control with Type-II compensation
- PWM signal running at 625kHz is transmitted from RX to TX via a digital isolator

Power Stage



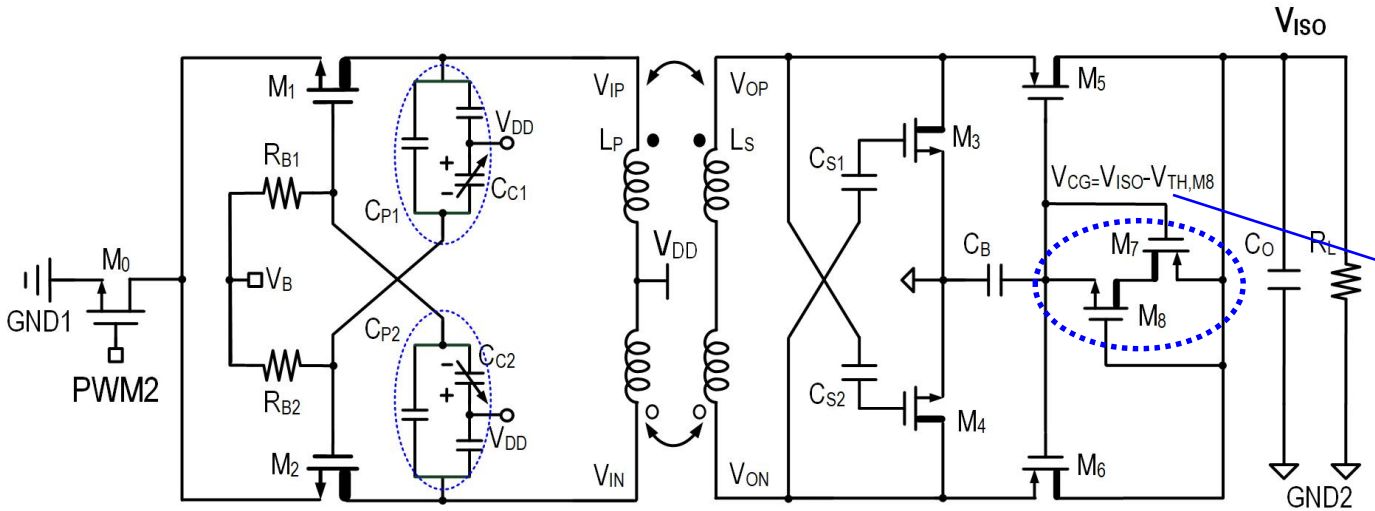


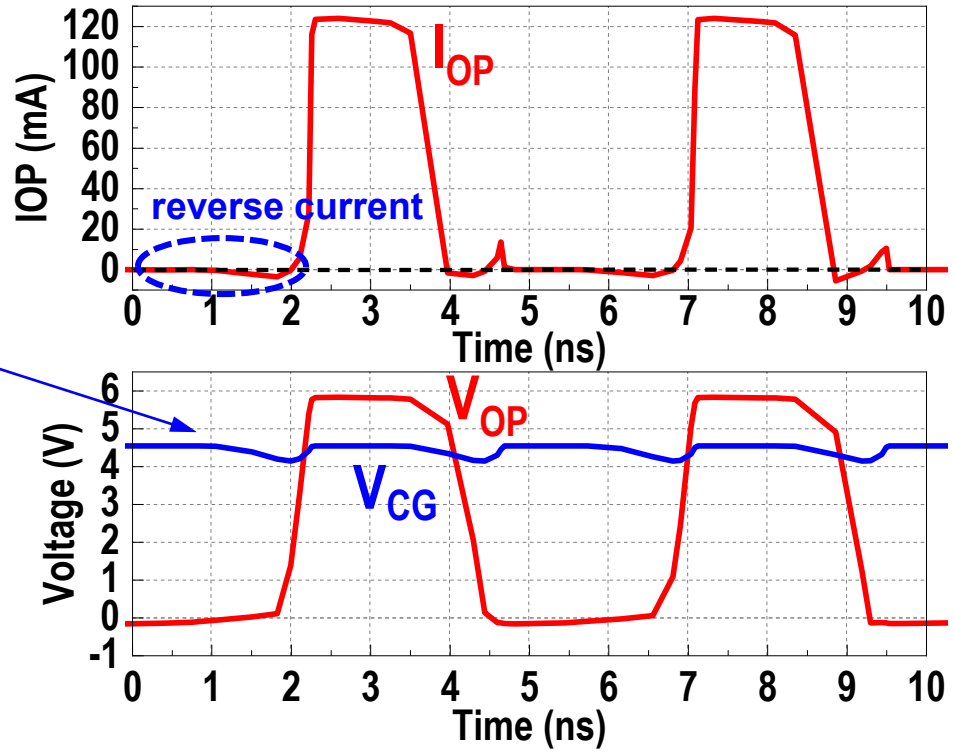




- 20V LDMOS for power transistor $M_{1,2}$
- The varactor section for wide supply voltage range of 3~6V

Power Stage

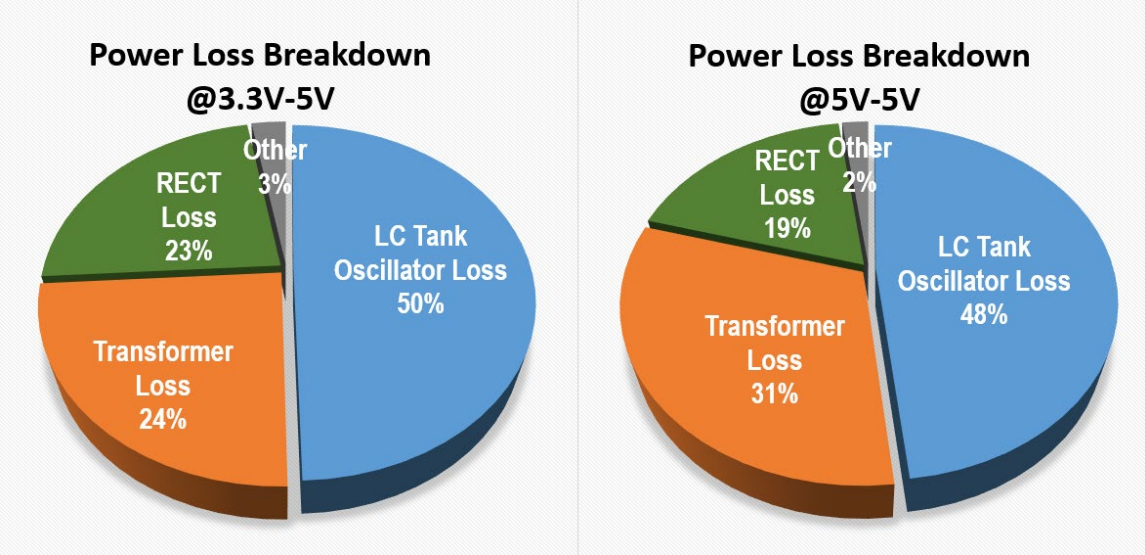




- **Fully-bridge MOS rectifier with common-gate bootstrapped for preventing the reverse current**

Power Loss Breakdown

Simulated power loss breakdown



Simulated efficiency

Condition @250mW	$\eta_{LC\ Tank\ Osc}$	η_{TF}	$\eta_{Rectifier}$	$\eta_{Overall}$
3.3V-5V	75.6%	84.1%	82%	52.1%
5V-5V	73.5%	76.7%	82%	46.2%

- Simulated power loss breakdown of the proposed converter
- Increased loss of TF results in reduced efficiency of TF at 5V-5V mode

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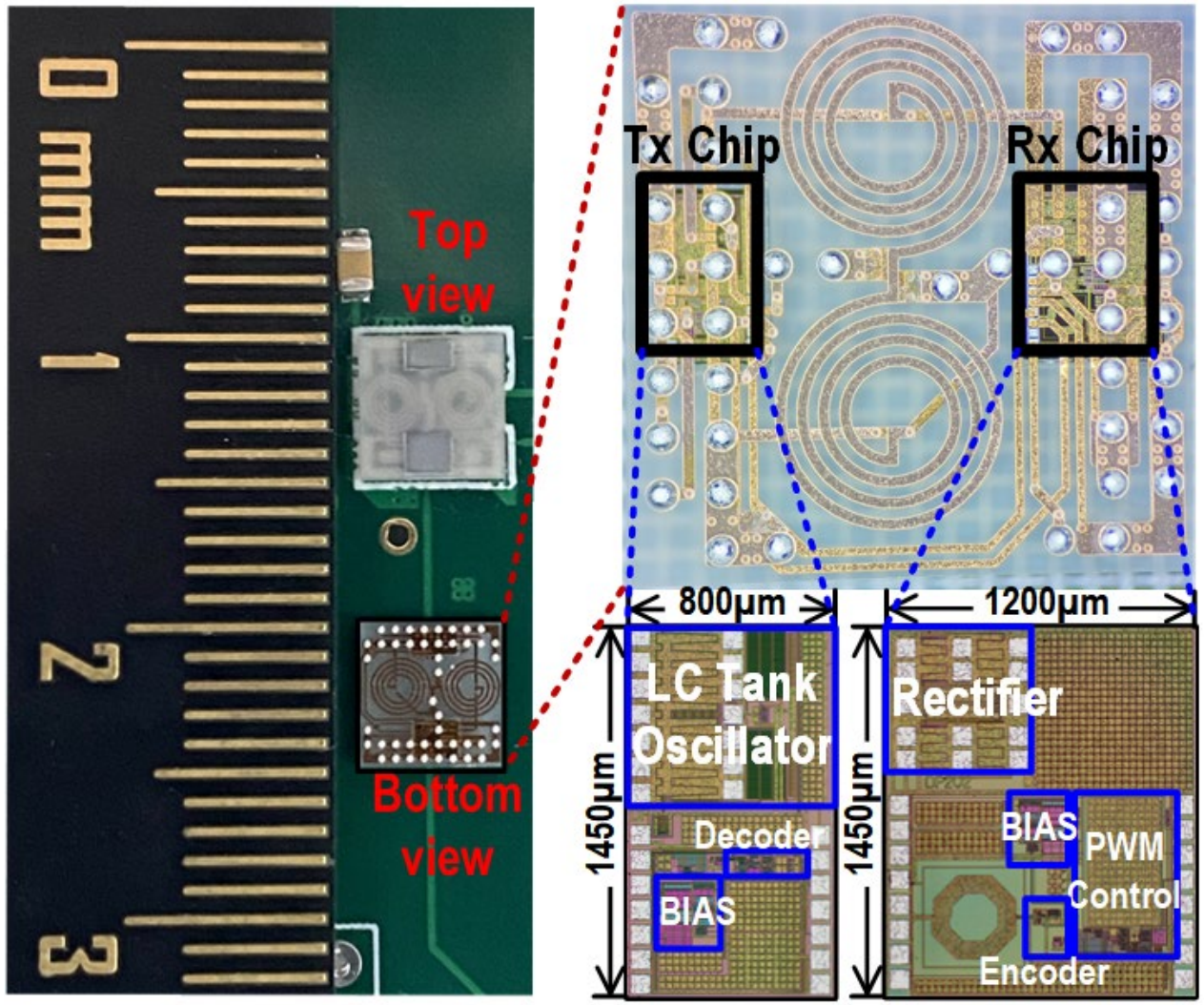
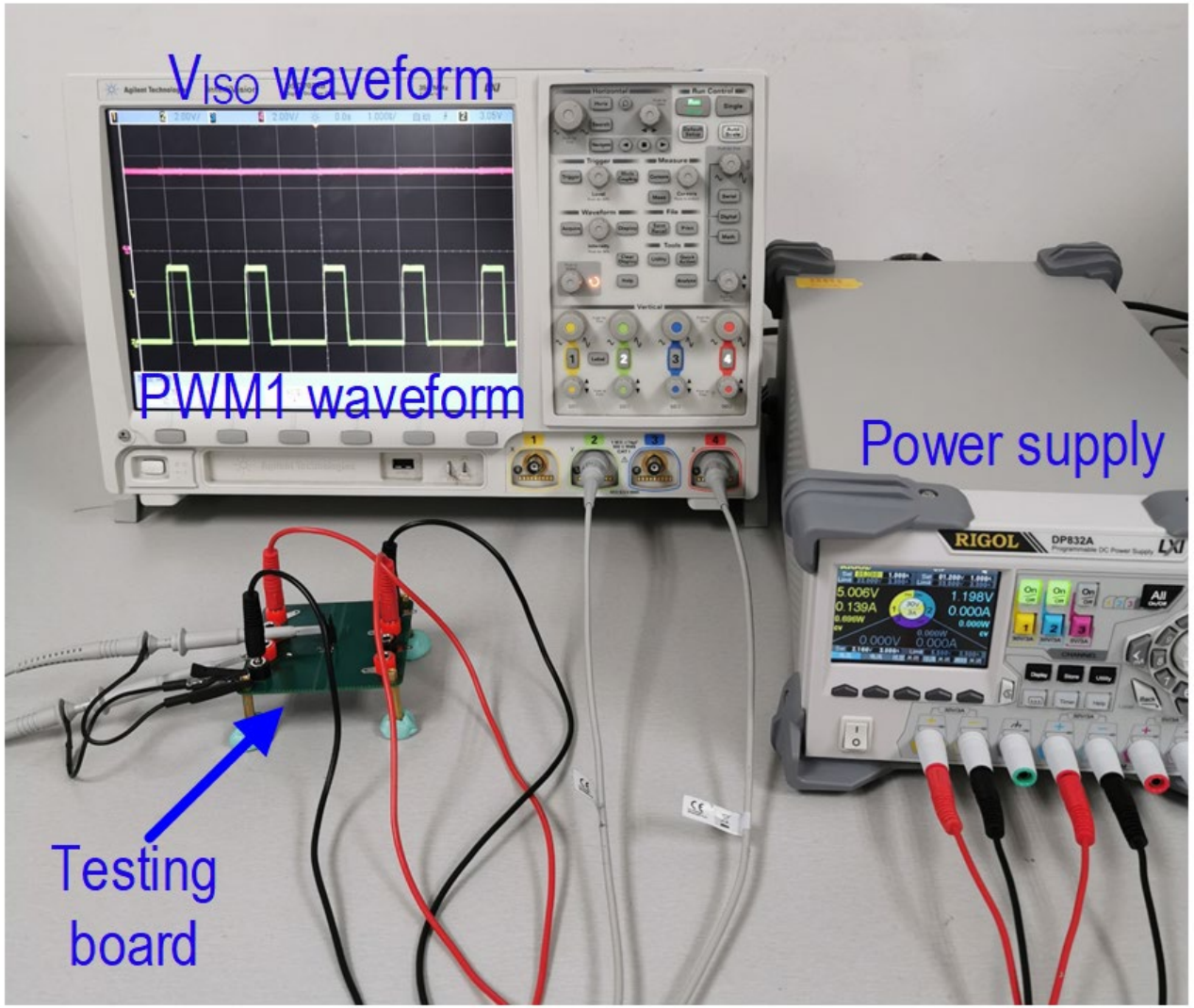
Measurement Results



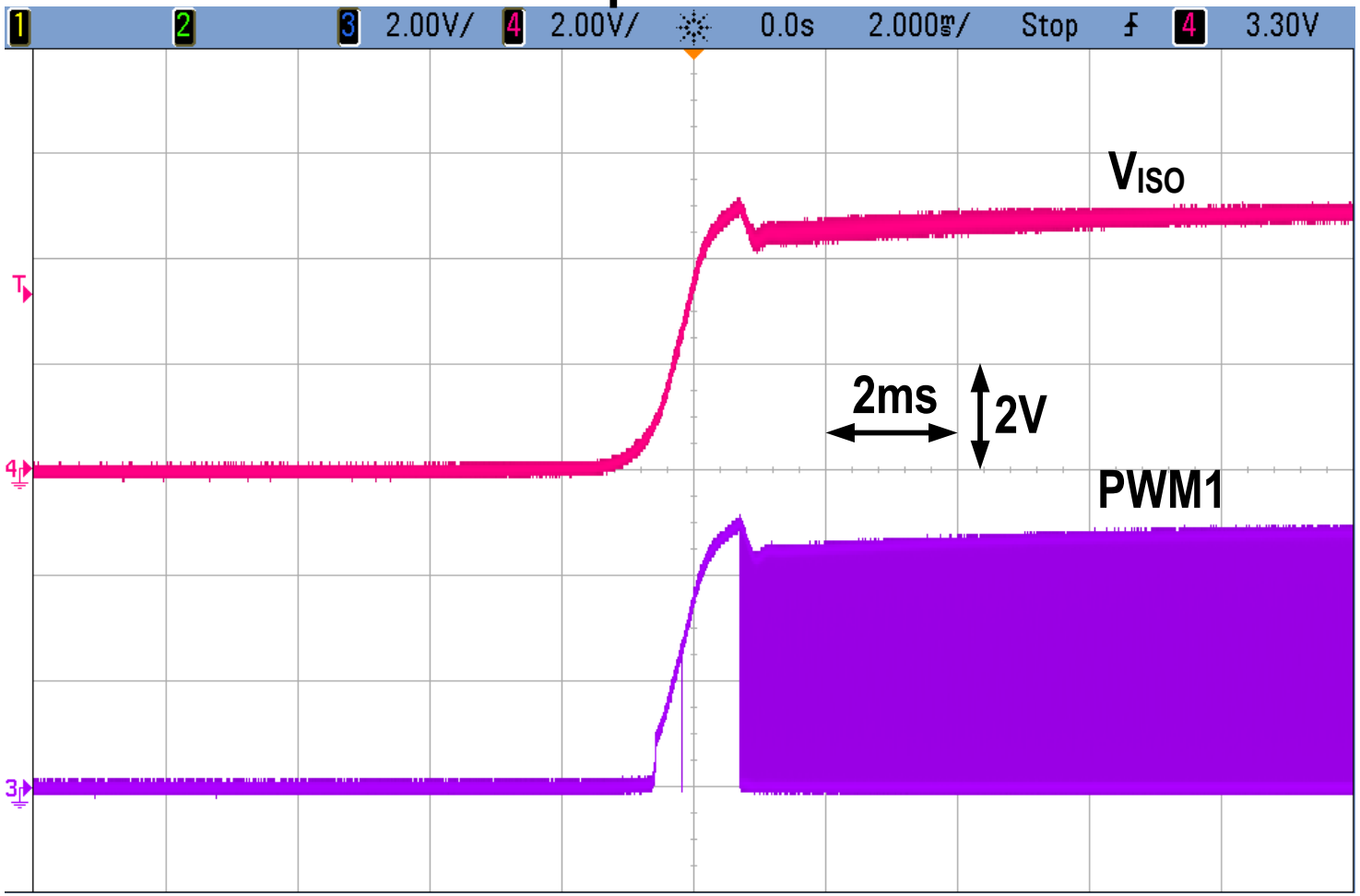
- 0.18μm BCD process
- Chip area:
  - TX :0.8mm×1.45mm
  - RX:1.2mm×1.45mm
- TF area:2mm×4mm
- Package area:5mm×5mm

Measurement Results



Measurement Results

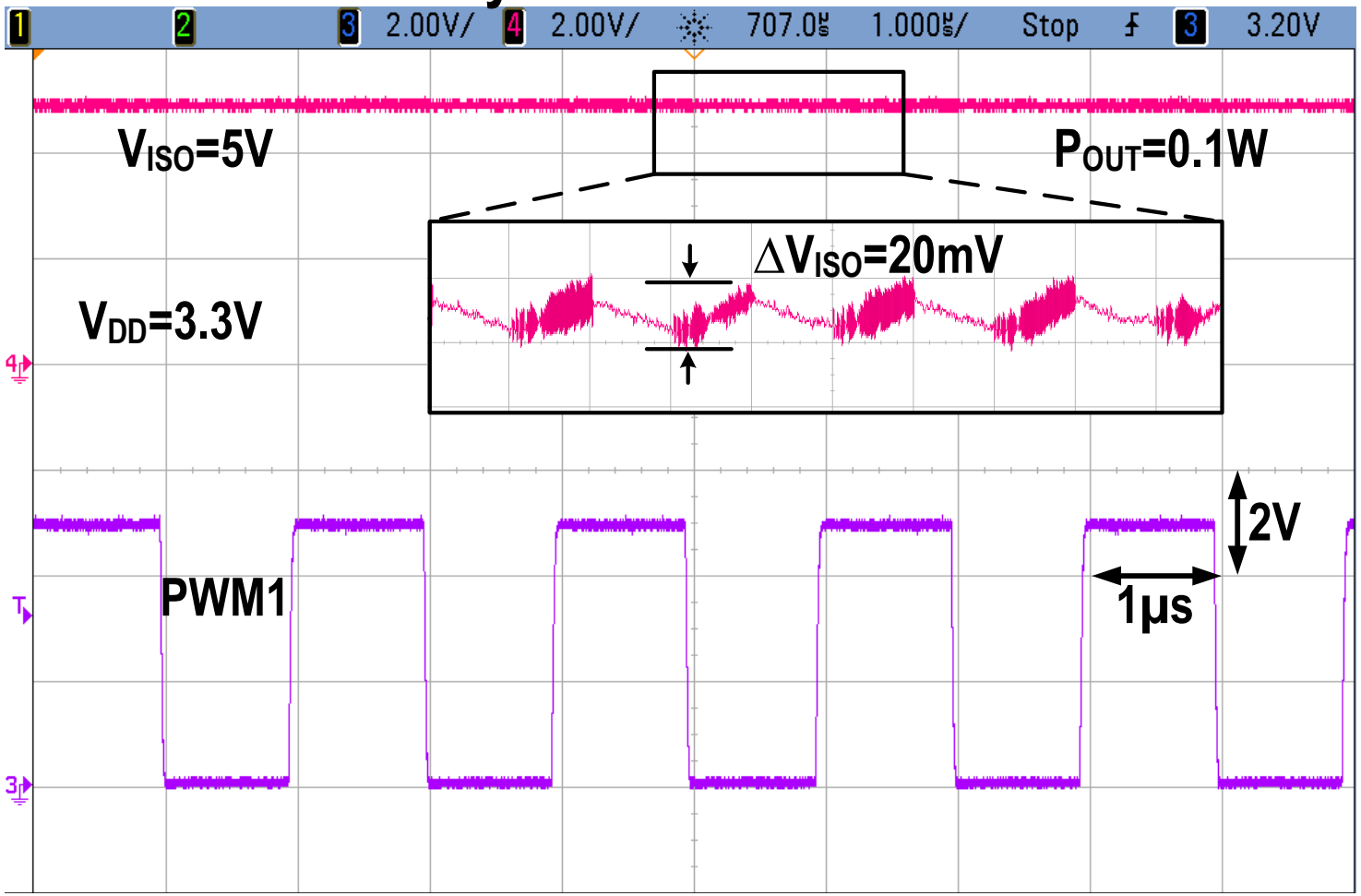
Start-up measurement



Measurement Results

- V_{DD}=3.3V
- P_{OUT}=0.1W

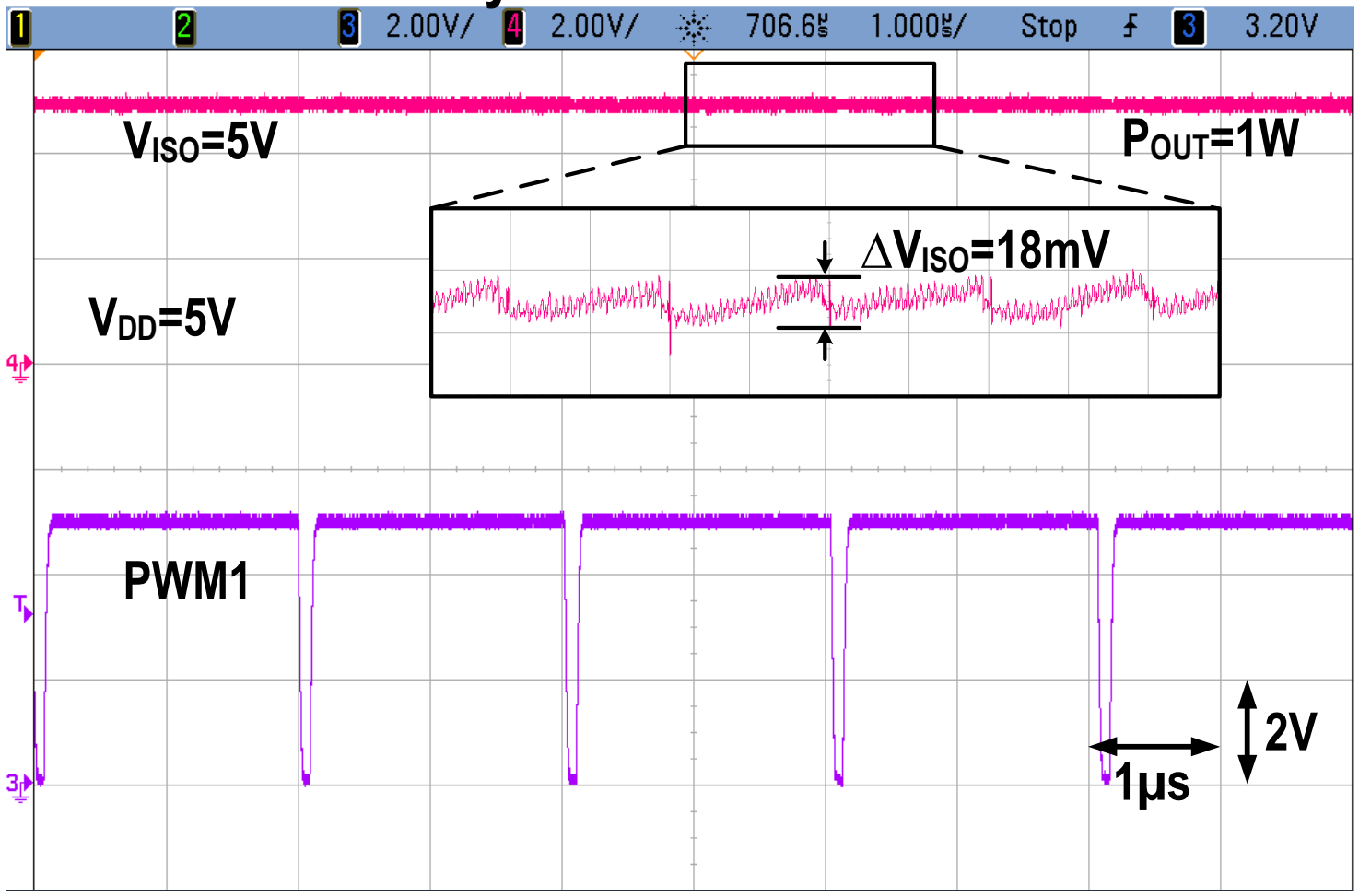
Steady-state measurement



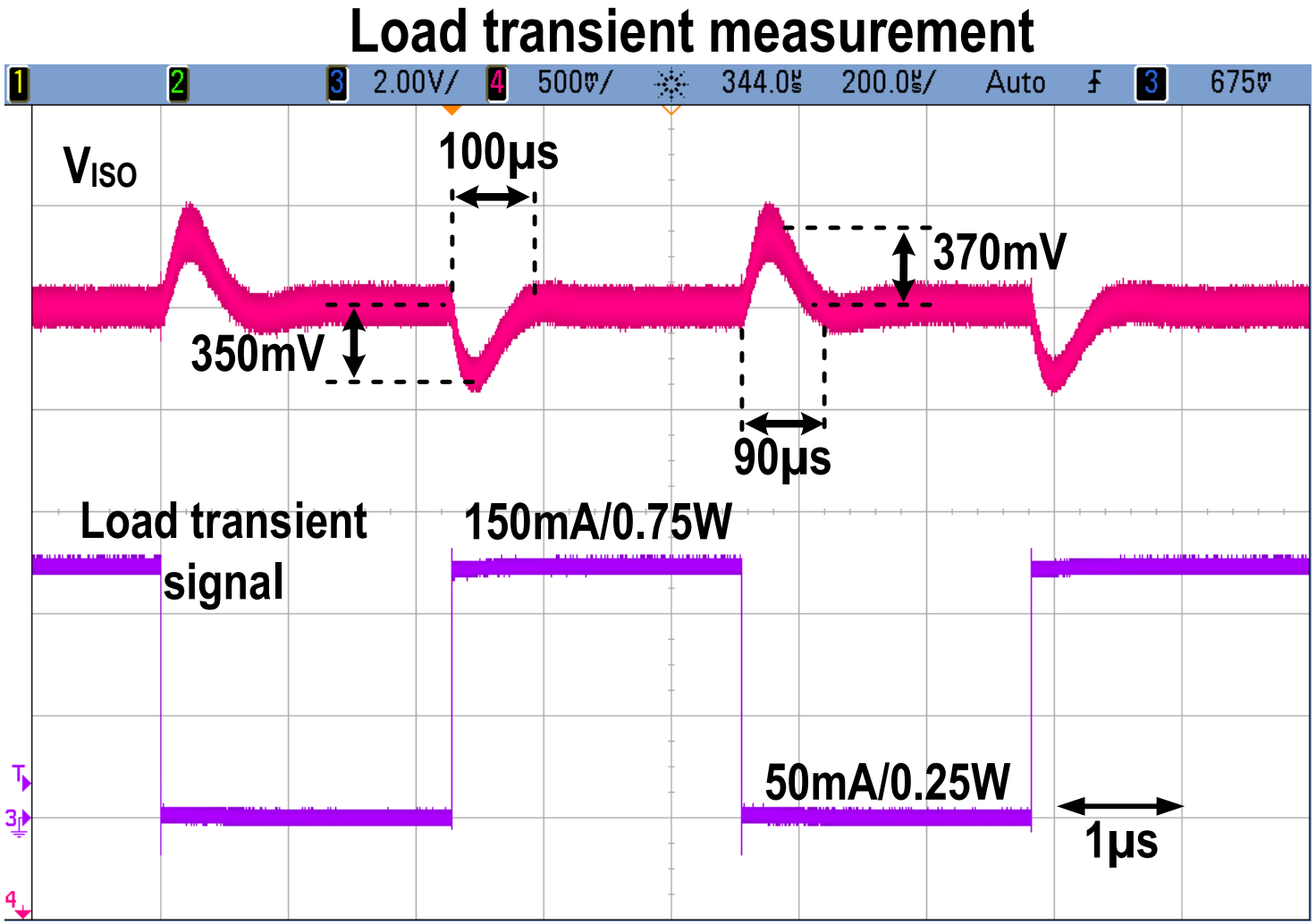
Measurement Results

- V_{DD}=5V
- P_{OUT}=1W

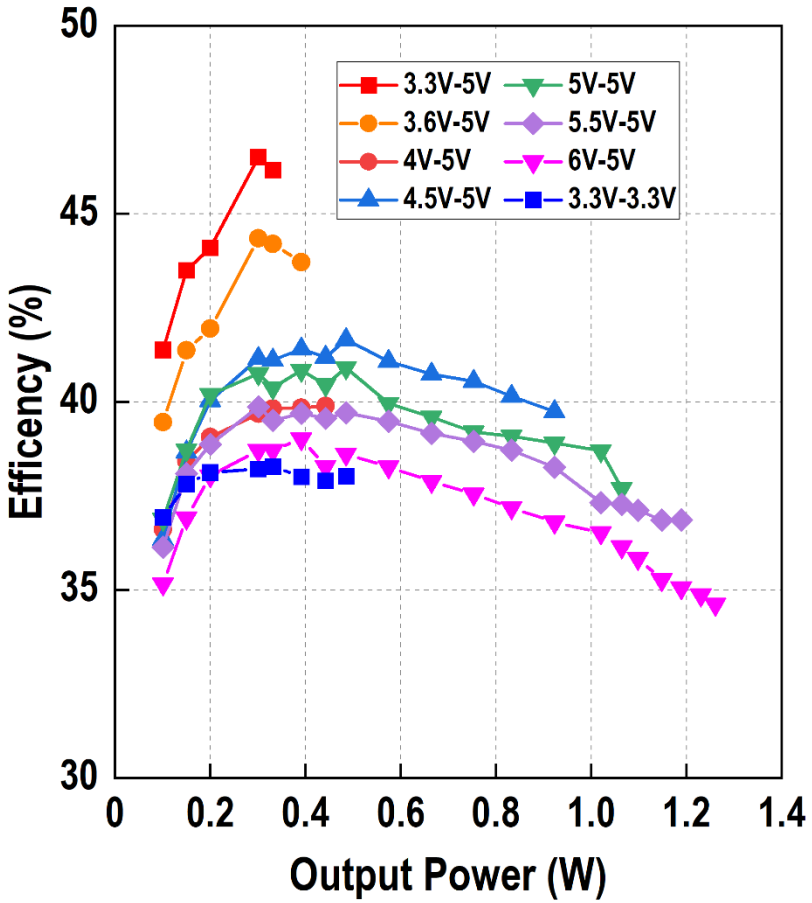
Steady-state measurement

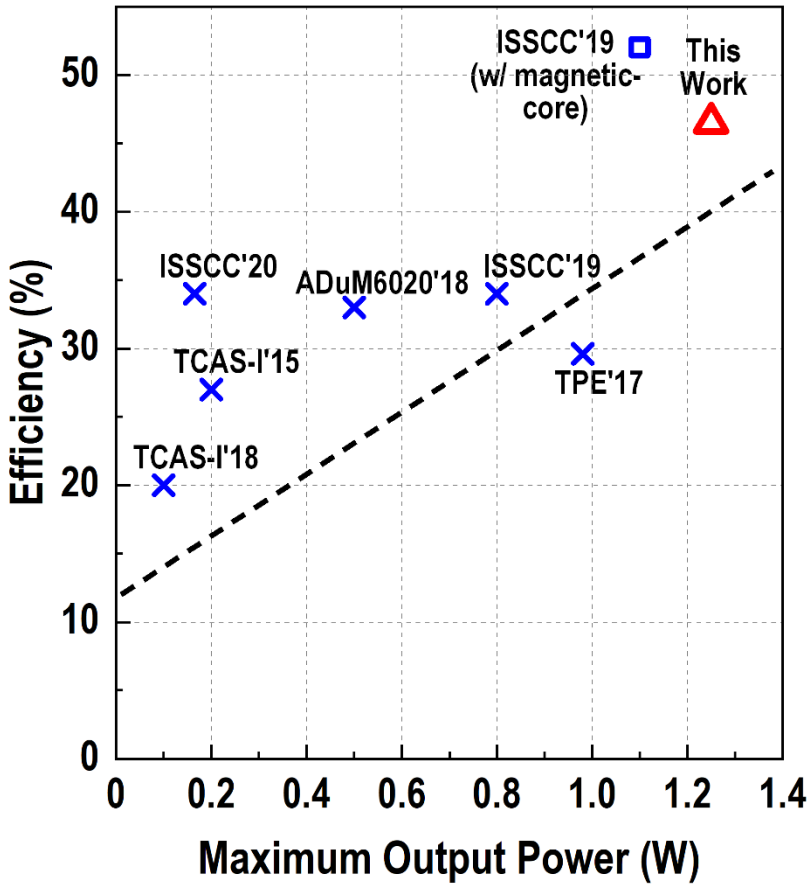


Measurement Results



Measurement Results





- V_{DD}/V_{ISO}=3.3V/5V: peak efficiency=46.5%@0.3W
- V_{DD}/V_{ISO}=5V/5V: efficiency>36.9%@0.1W~1.05W

Comparison

Reference	TCASI'18 [6]	ADuM6020'18 [7]	ISSCC'19 [2]	ISSCC'19 [3]	ISSCC'20 [4]	**This work**
Technology	0.35μm BCD	N/A	0.35μm BCD	0.35μm BCD	0.35μm BCD	**0.18μm BCD**
Transformer Type	Coreless	N/A	Coreless	Magnetic-Core	Coreless	**Coreless**
Input Voltage	3.3V	5V	4.5-5.5V	4.5-5.5V	3.3V	**3-6V**
Output Voltage	2.4V-3.3V	5V/3.3V	3.3V-5V	5V	3.3V	**3.3V/5V**
Max. P_{OUT}	0.093W	0.5W	0.8W	1.1W	0.165W	**1.25W**
Peak Efficiency	19%	33%	34%	52%	34%	**46.5%**
No. of Die	2	N/A	3	4	3	**2**
Package (Size)	N/A	SOIC-16 (10mm*13mm)	SOIC-8 (10mm*6mm)	SOIC-28 (10mm*18mm)	N/A	**Glass-based FOWLP (5mm*5mm)**
Power Density*	N/A	3.85mW/mm^2	13.33mW/mm^2	6.11mW/mm^2	N/A	**50mW/mm^2**

*Power density is calculated by dividing the maximum output power by the package size

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Technology	0.35μm BCD	N/A	0.35μm BCD	0.35μm BCD	0.35μm BCD	**0.18μm BCD**
Transformer Type	Coreless	N/A	Coreless	Magnetic-Core	Coreless	**Coreless**
Input Voltage	3.3V	5V	4.5-5.5V	4.5-5.5V	3.3V	**3-6V**
Output Voltage	2.4V-3.3V	5V/3.3V	3.3V-5V	5V	3.3V	**3.3V/5V**
Max. P_{OUT}	0.093W	0.5W	0.8W	1.1W	0.165W	**1.25W**
Peak Efficiency	19%	33%	34%	52%	34%	**46.5%**
No. of Die	2	N/A	3	4	3	**2**
Package (Size)	N/A	SOIC-16 (10mm*13mm)	SOIC-8 (10mm*6mm)	SOIC-28 (10mm*18mm)	N/A	**Glass-based FOWLP (5mm*5mm)**
Power Density*	N/A	3.85mW/mm^2	13.33mW/mm^2	6.11mW/mm^2	N/A	**50mW/mm^2**

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Conclusions

- A TiP solution for isolated DC-DC converters by using glass-based FOWLP to achieve 46.5% peak efficiency and 1.25W maximum P_{OUT} in a compact 5mm×5mm package
- A high-Q transformer (TF) and the interconnections can be both formed by using RDLs without an extra TF chip, and the system only needs two dies (the Tx chip and the Rx chip)
- A varactor section in LC tank oscillator is proposed to cope with a wide V_{DD} range of 3~6V

Acknowledgments

- This work was supported in part by the National Key R&D Program of China under Grant No. 2019YFB2204800 and the Strategic Priority Research Program of Chinese Academy of Sciences under Grant No. XDB44000000
- The authors would like to thank Xiamen Sky Semiconductor for package fabrication support

Thank You!