A 15b Quadrature Digital Power Amplifier with Transformer-Based Complex-Domain Power-Efficiency Enhancement

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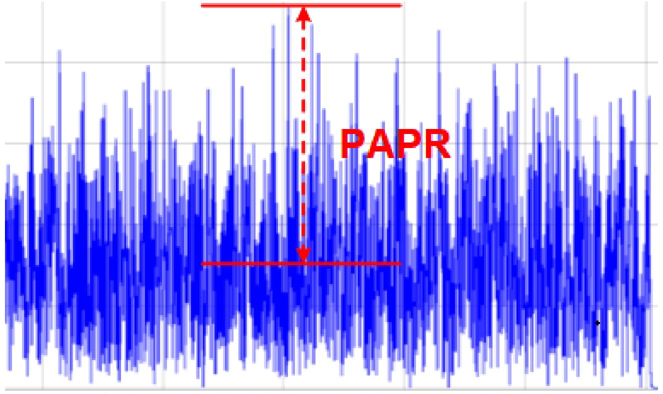
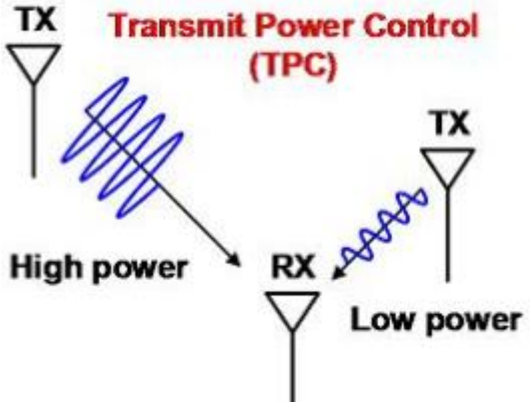
Outline

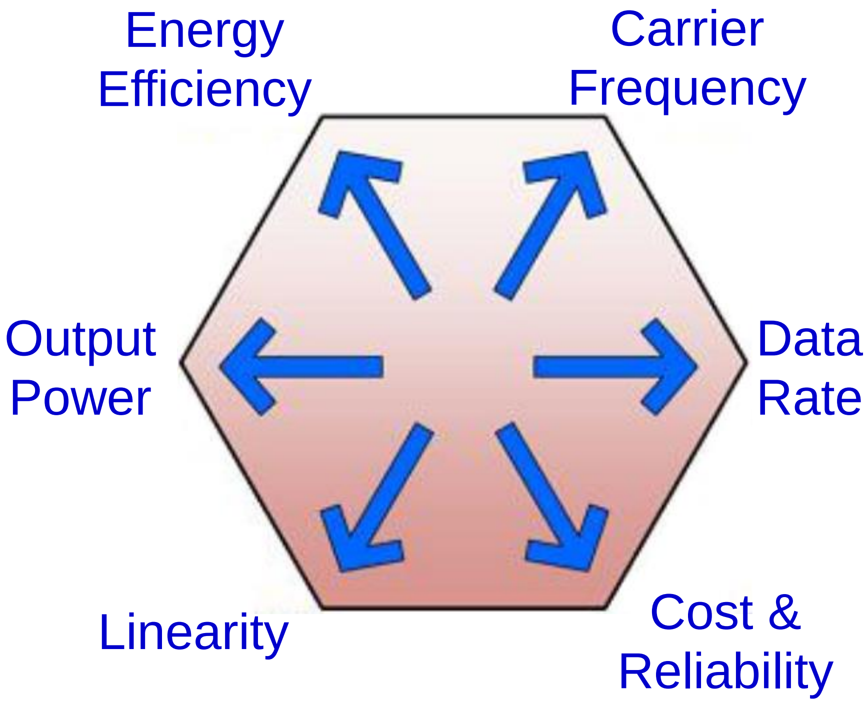
- **Motivation**
- **Operations of Transformer-Based Complex-Domain Cell Sharing and Load Modulation**
- **Circuit Implementation**
- **Measurement Results**
- **Conclusions**

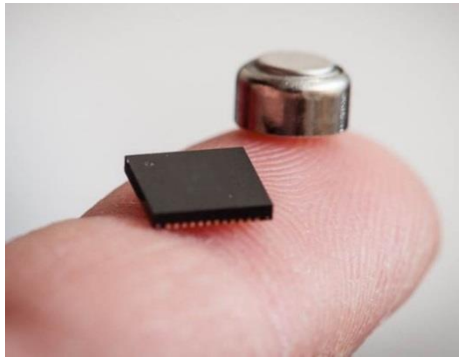
Design Challenges

- Scare spectrum resources and higher data rate: OFDM and higher-order QAM modulation (OFDM &1024QAM: >10dB PAPR)
- High output power for large link distance & wide range of Pout
- High peak/PBO efficiency for battery life and thermal management
- Compact and high integration for low cost

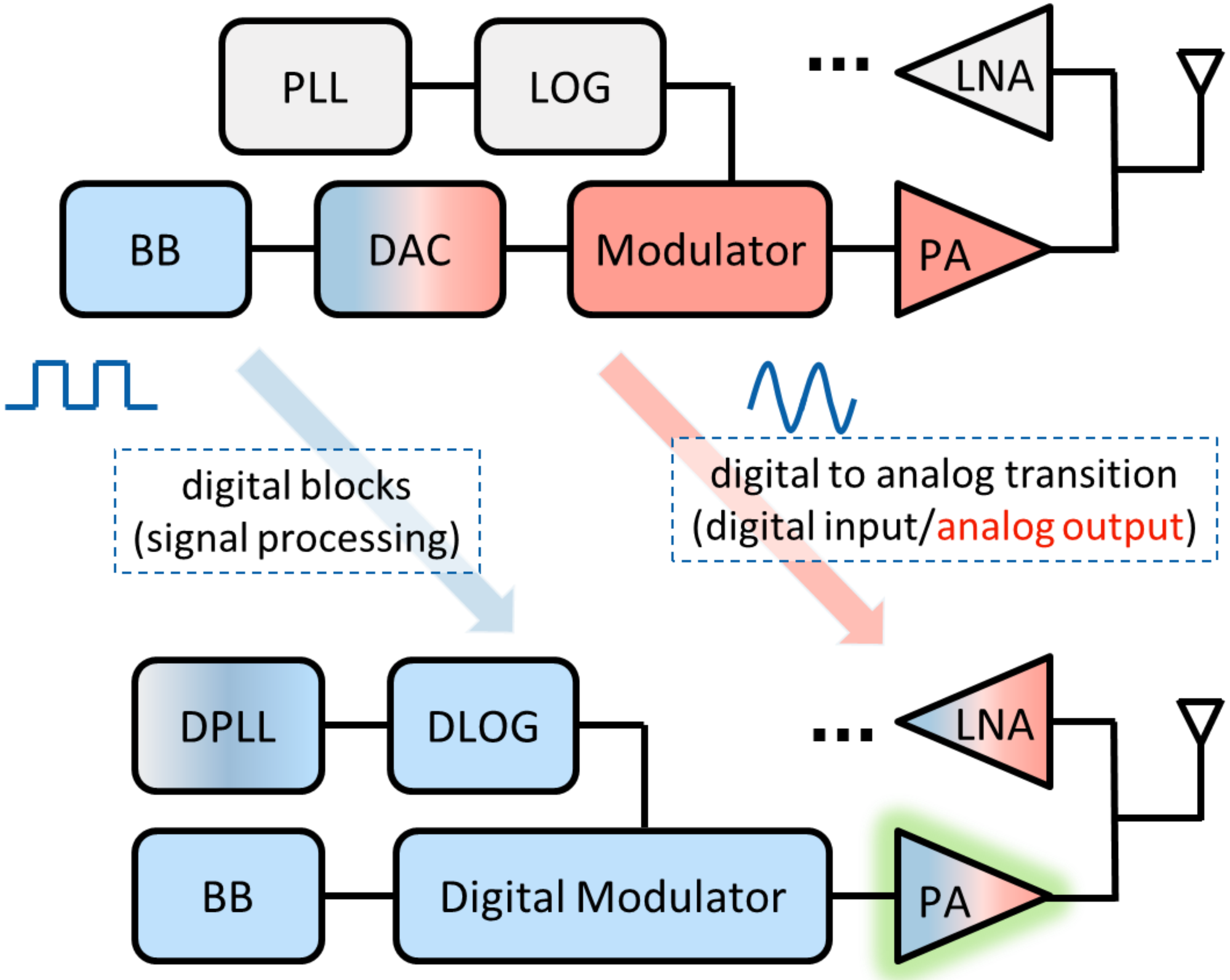






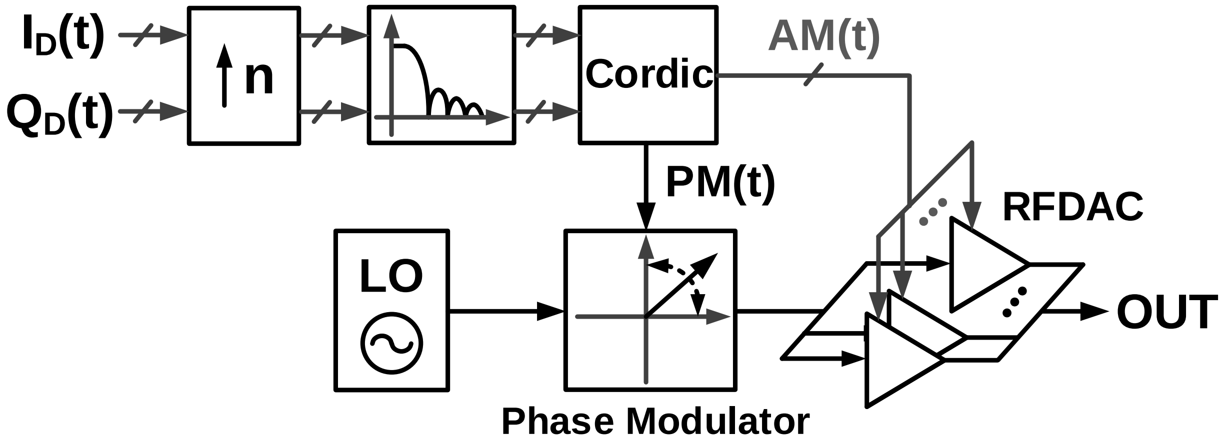


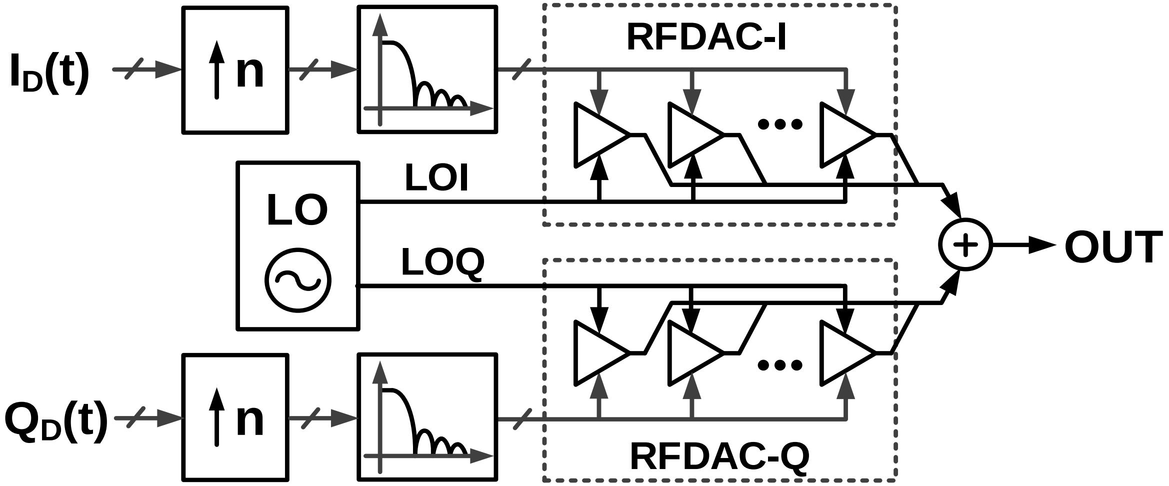
Scaling-Friendly Digital RF



- **Digital TX**
  - \+ Conventional TX sub blocks (DAC, filter, Mixer, DA & PA) <u>in a single block</u>
  - \+ Flexibility, MIMO & multi-standard TXs, Digital calibration
  - \+ Small area, high efficiency
  - \+ Compatible with CMOS scaling
  - – Quantization noise and sampling images

Digital Polar & Quadrature TXs





Digital polar TX

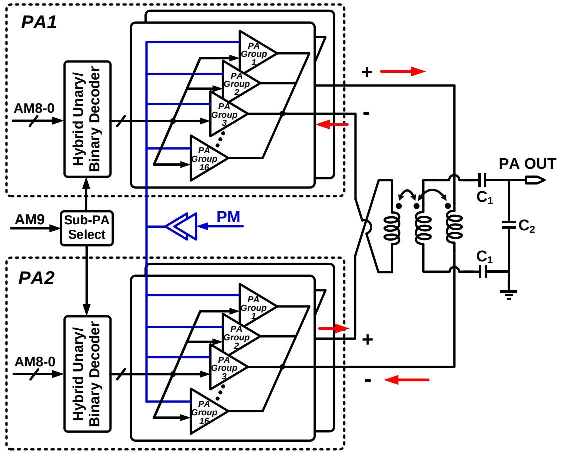
+ High Pout, high η
– BW expansion highly-linear phase modulator

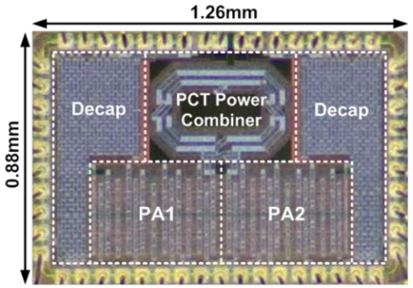
Digital quadrature TX

+ Wide BW; no CORDIC, phase modulator or AM-PM alignment
– I/Q combination limits Pout and η

Efficiency-Enhanced DPAs

Dual-Band Polar DPA with 6dB PBO η boost

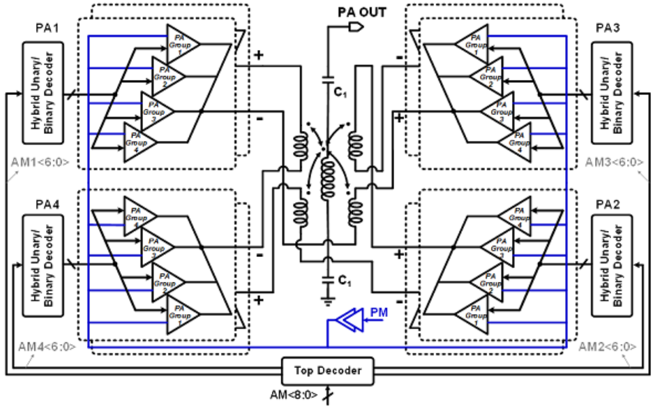


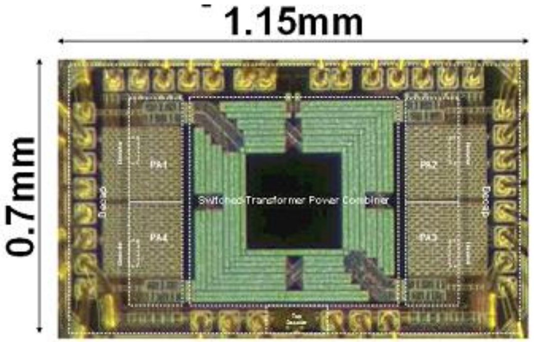


[Y. Yin, ISSCC’18]

[Y. Yin, JSSC’19]

Wideband Polar DPA with 0-18dB PBO η boost

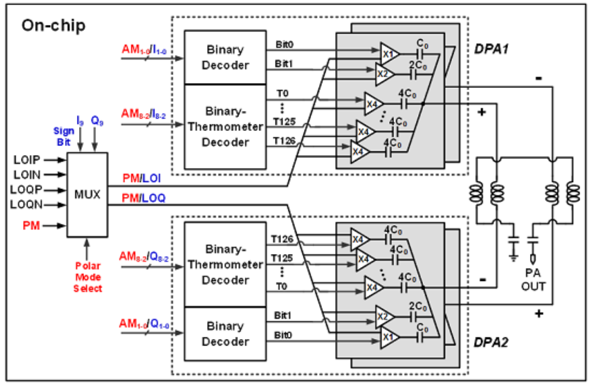


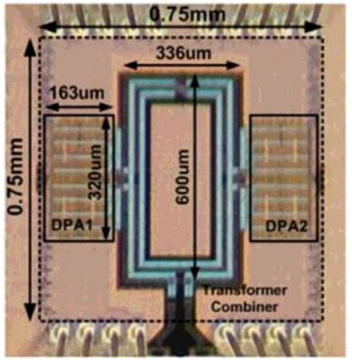


[L. Xiong, ISSCC’19]

[Y. Yin, JSSC’20]

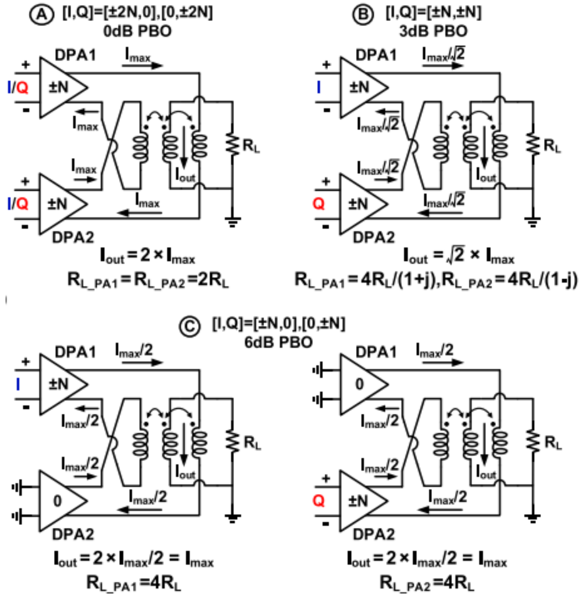
Polar/quadrature dual-mode reconfigurable DPA

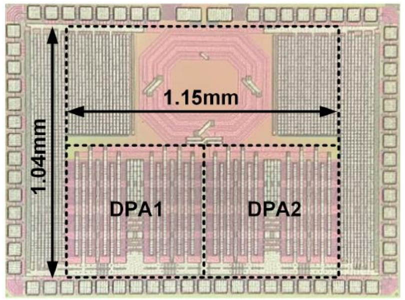




[Y. Yin, JSSC’19]

Quadrature DPA with complex-domain η boost



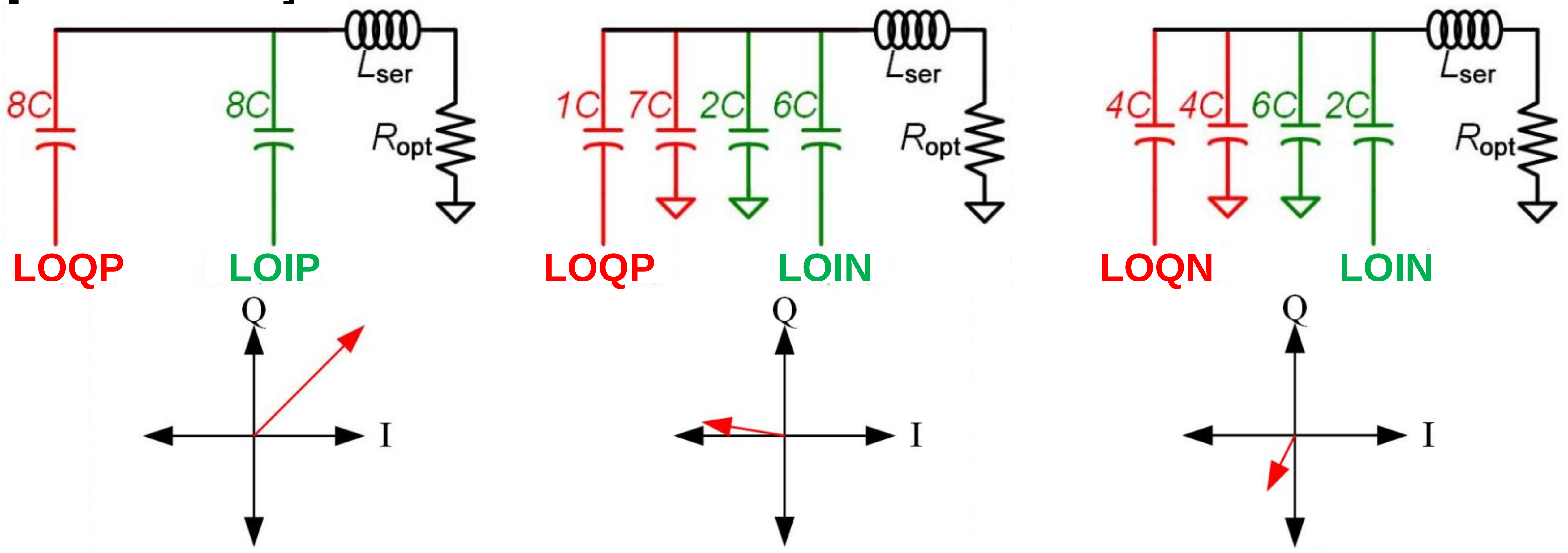


[D. Zheng, ISSCC’20]

[Y. Li, JSSC’21]

IQ Sharing (1/2)

[Yuan JSSC'16]



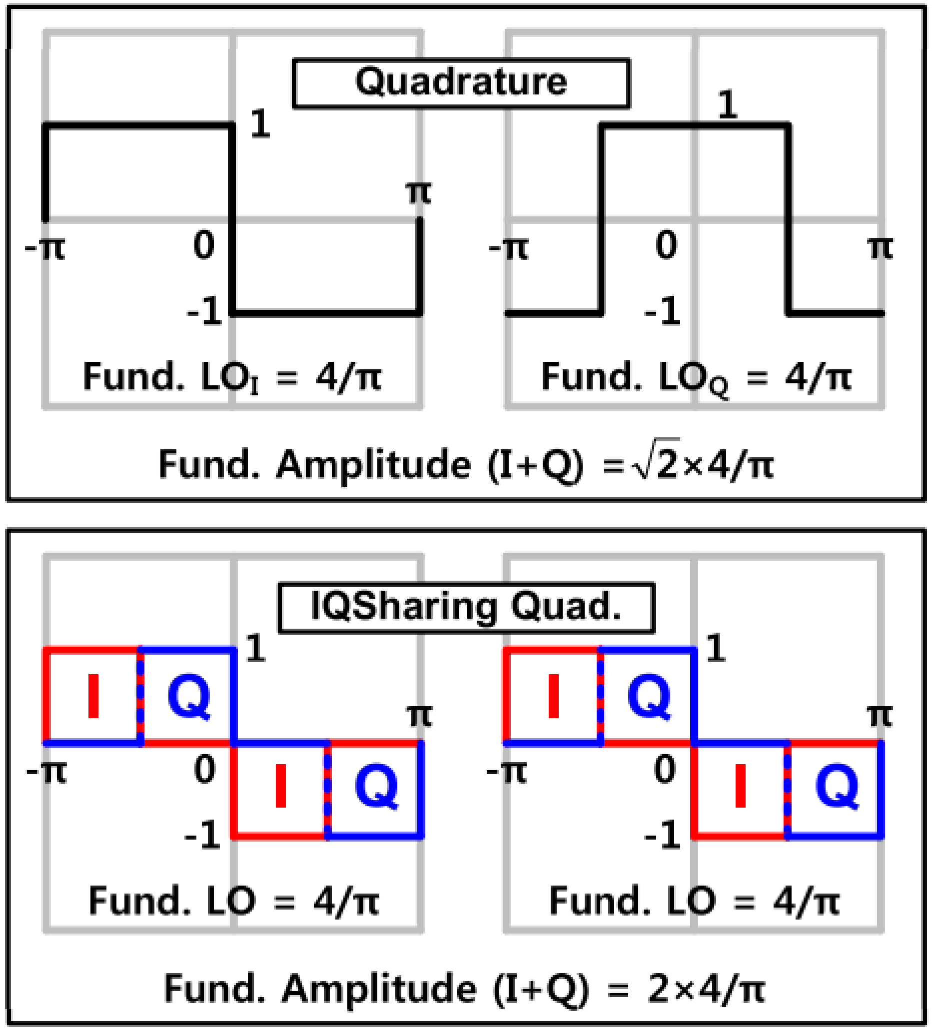
Output: 8 + j8 **Output: -6 + j1** **Output: -2 – j4**

Conventional quadrature:

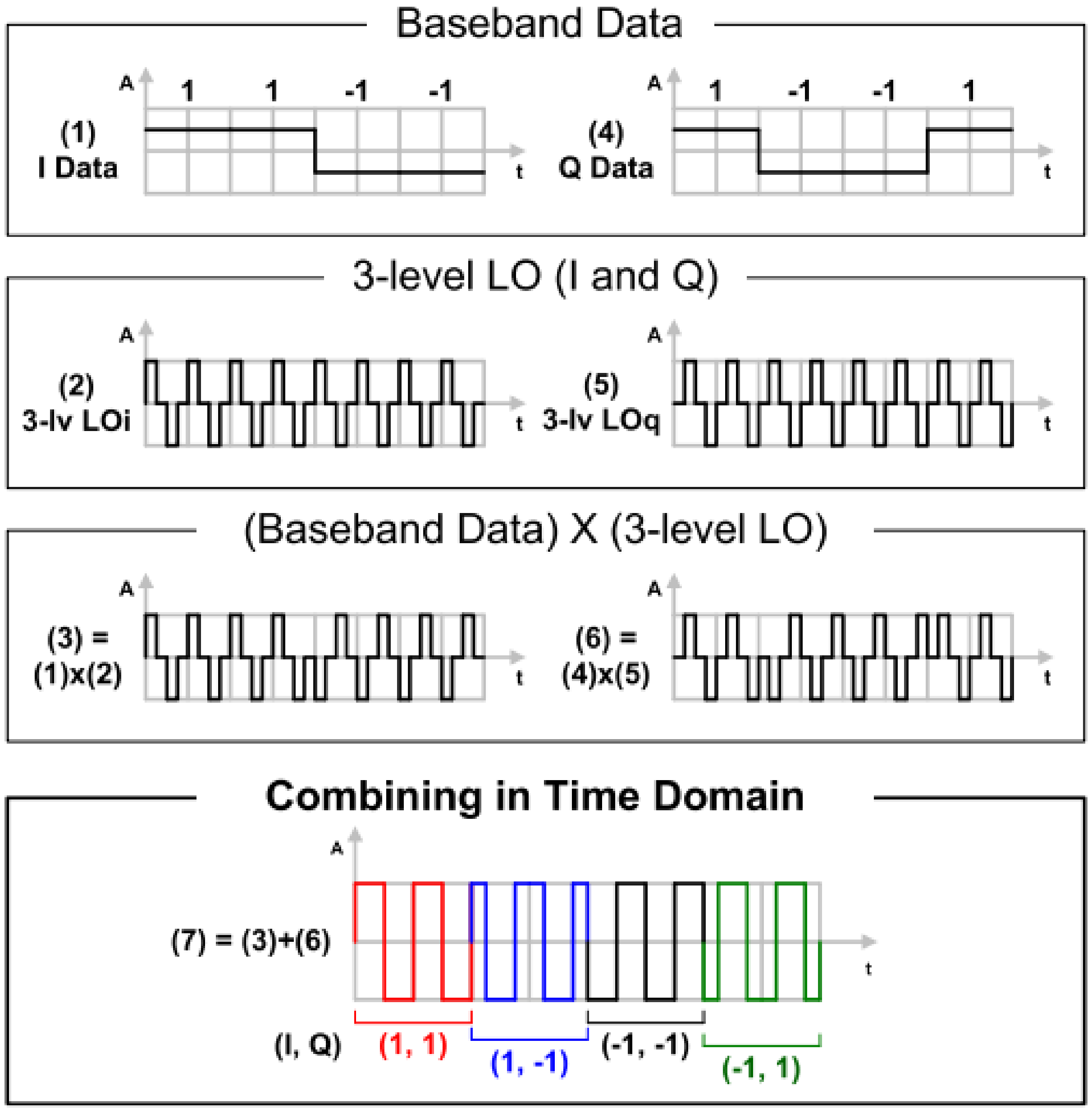
I PA cells can only be at state I, Q PA cells can only be at state Q

IQ Sharing (2/2)

[Jin JSSC'17]

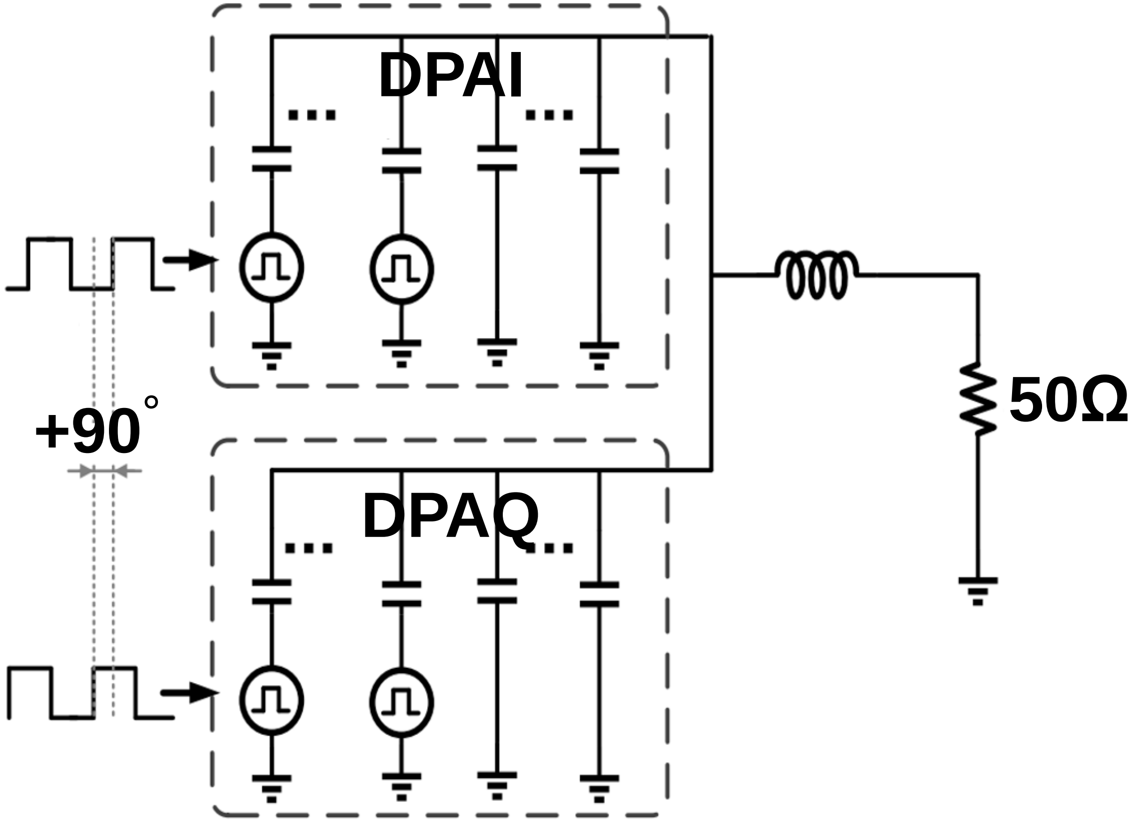


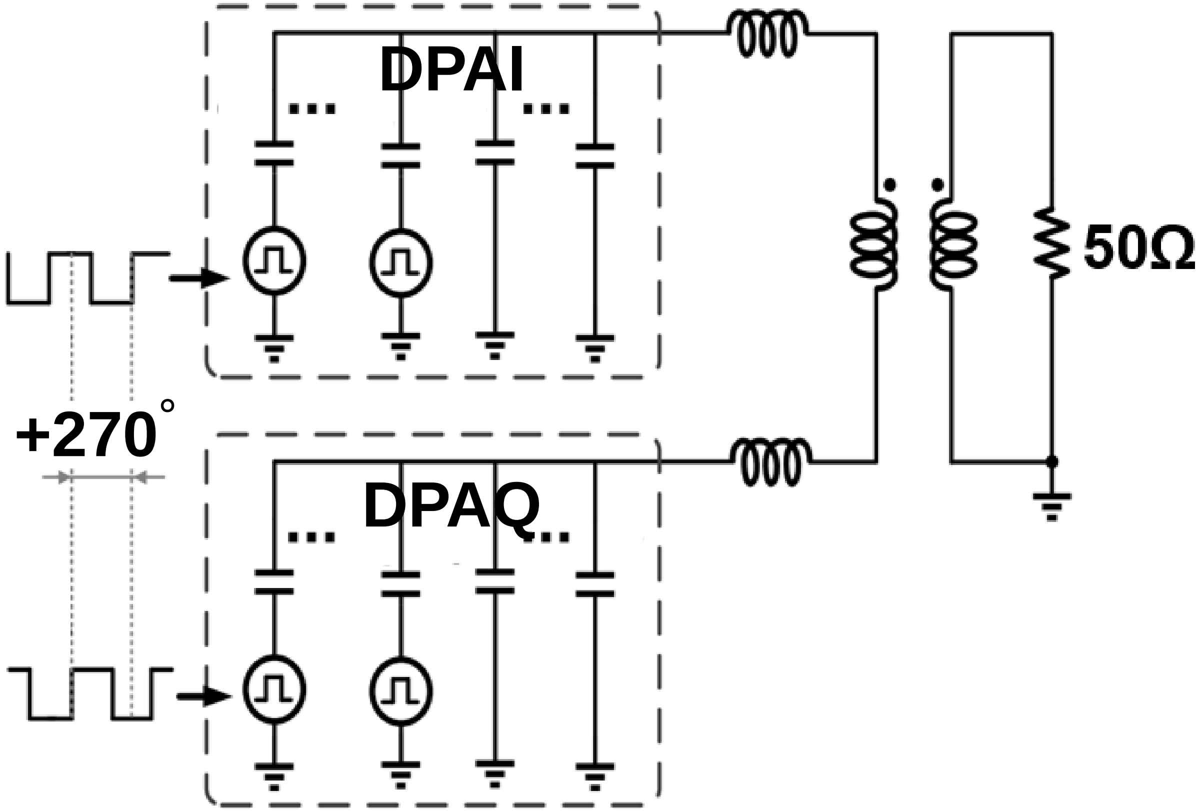
IQ time sharing



Transformer-based Load Modulation (1/3)

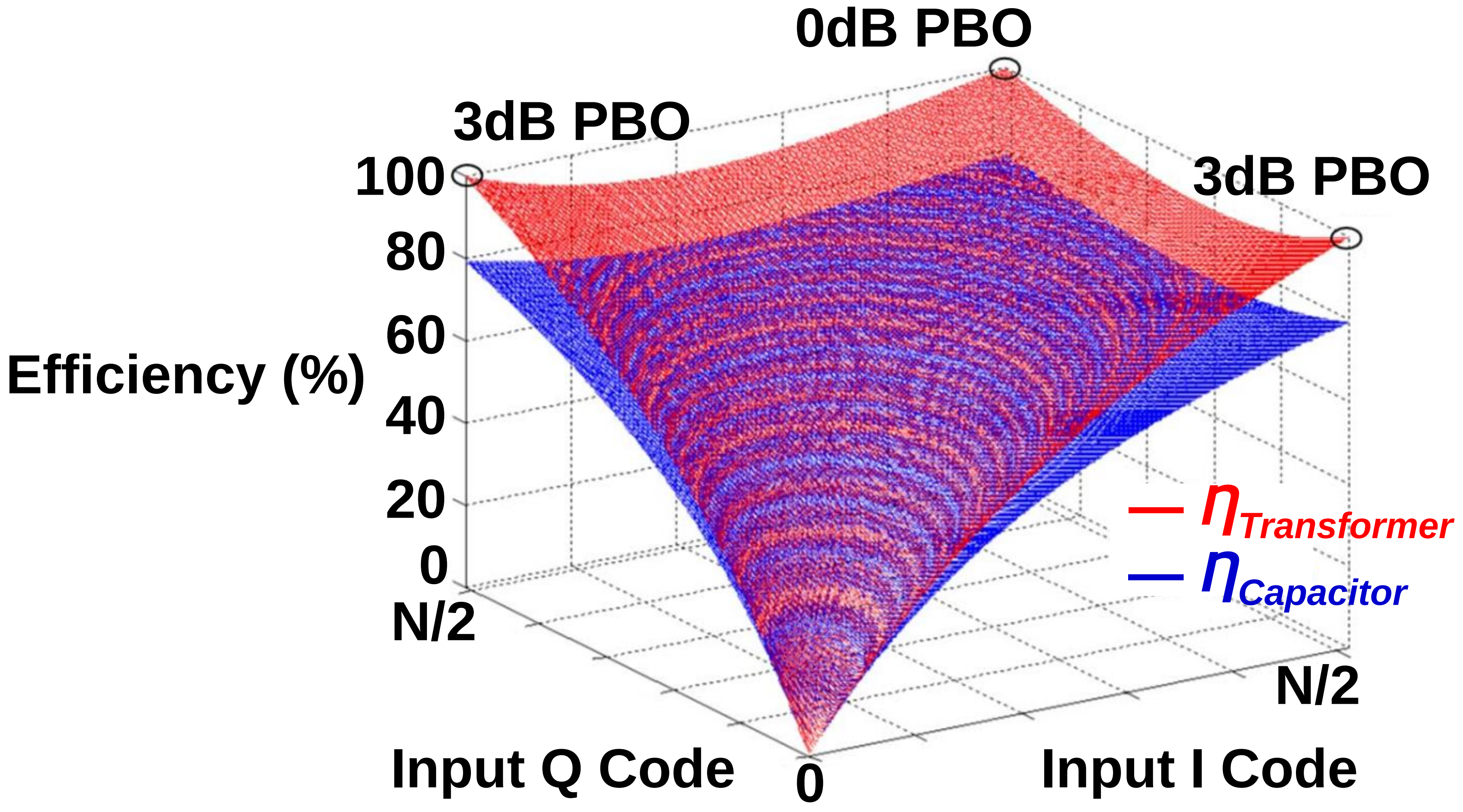
Capacitor-combined VS Transformer-combined





Transformer-based Load Modulation (2/3)

Capacitor-combined VS Transformer-combined

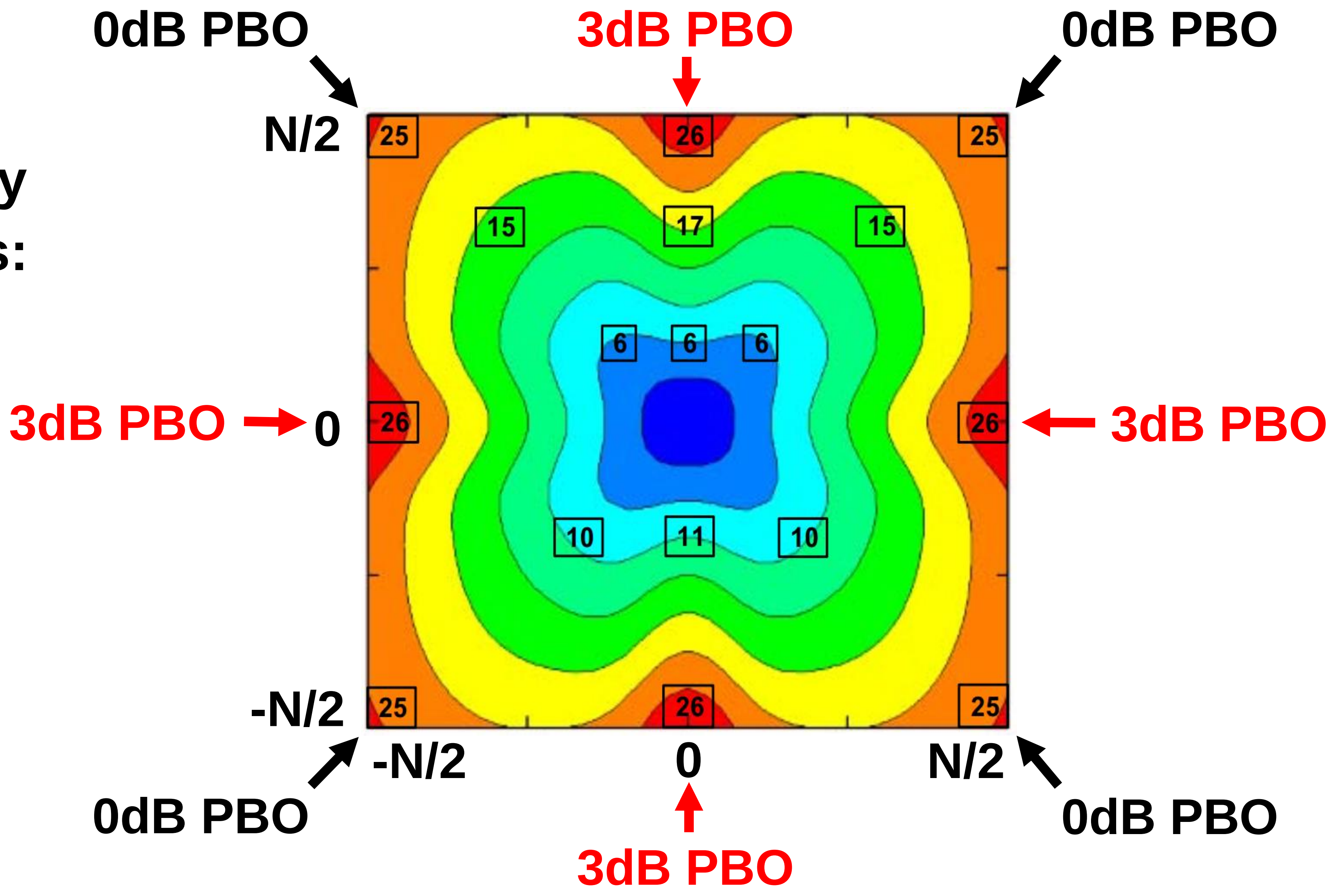


[Yin JSSC'19]

Transformer-based: 3 efficiency peaks in one quadrant

Transformer-based Load Modulation (3/3)

Efficiency Contours:



Transformer-based: 8 efficiency peaks in the I/Q complex plane

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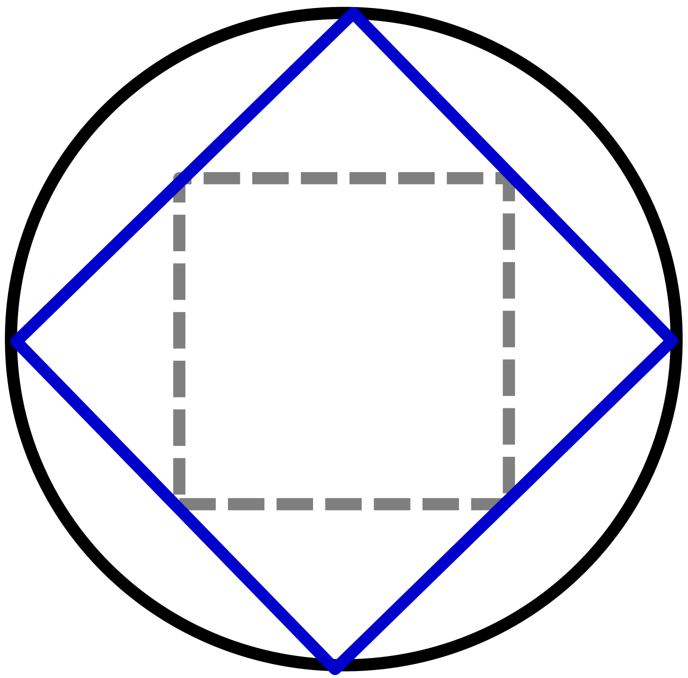
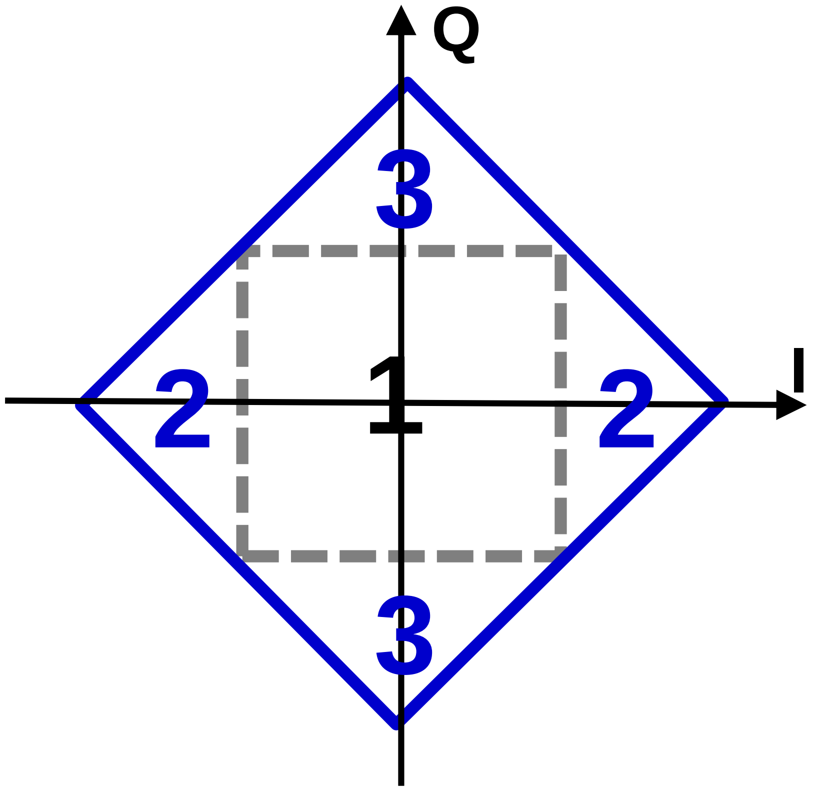
Transformer-based Cell Sharing





- Square : conventional quadrature
- Circle : polar
- Diamond: cell-shared quadrature

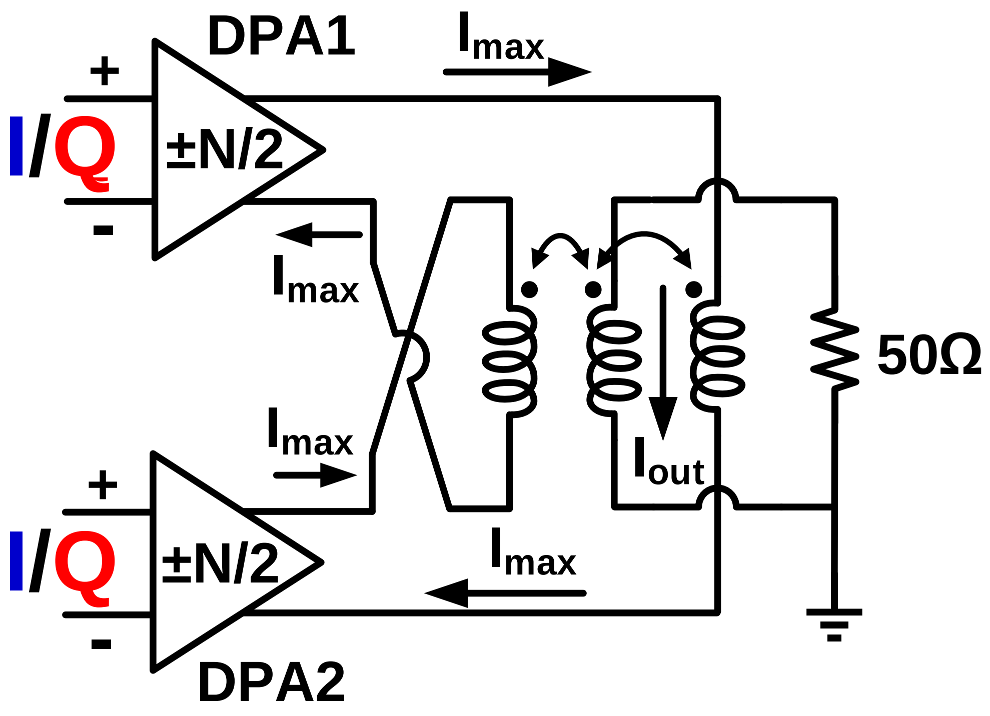
- 1: No cell sharing
- 2: Q PA cells are shared at state I
- 3: I PA cells are shared at state Q

Cell-shared quadrature:

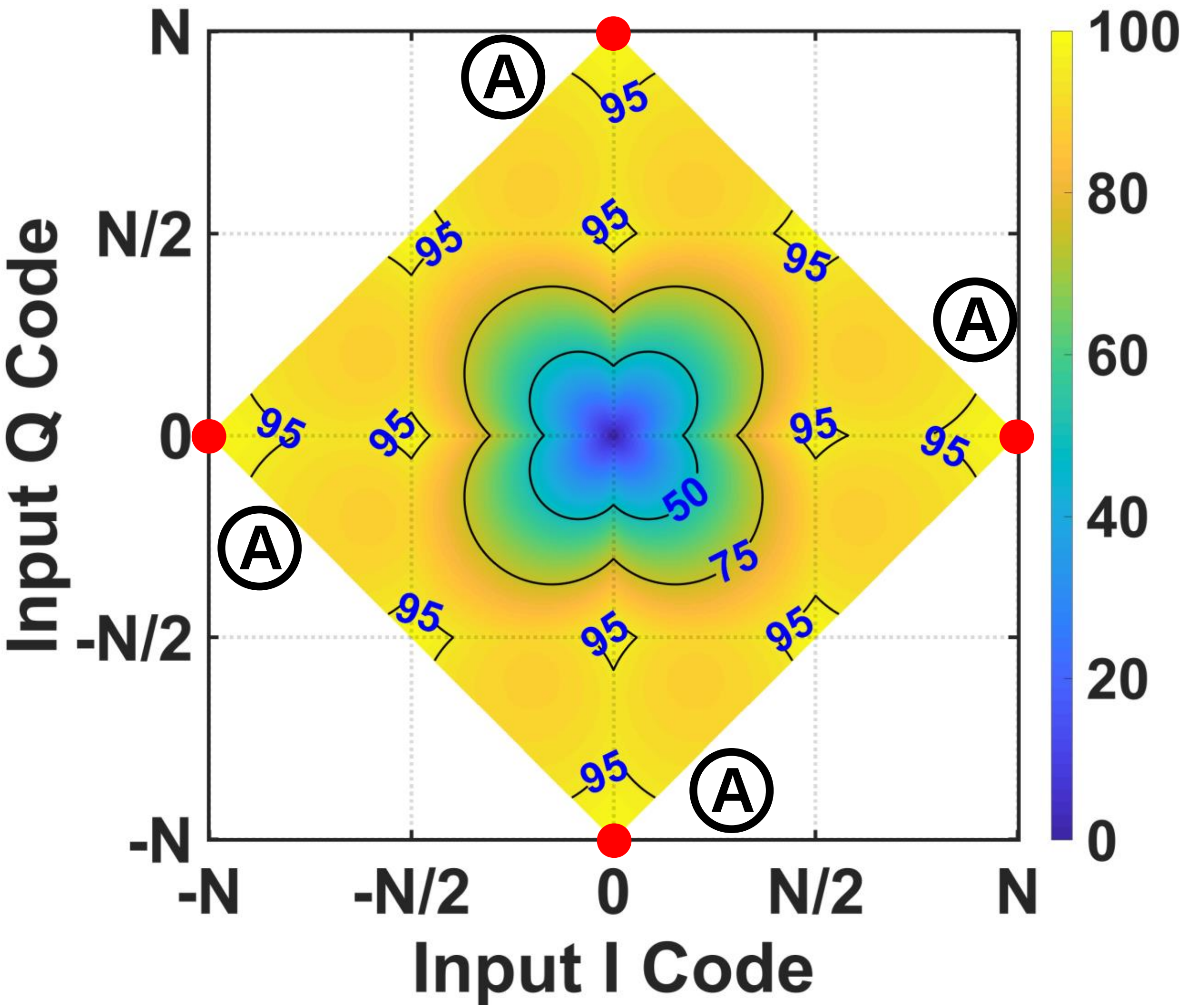
I PA cells can be at state I or state Q, Q PA cells can be at state I or state Q

Transformer-based load modulation @State A (1/2)

At state A (Four 0dB PBOs):

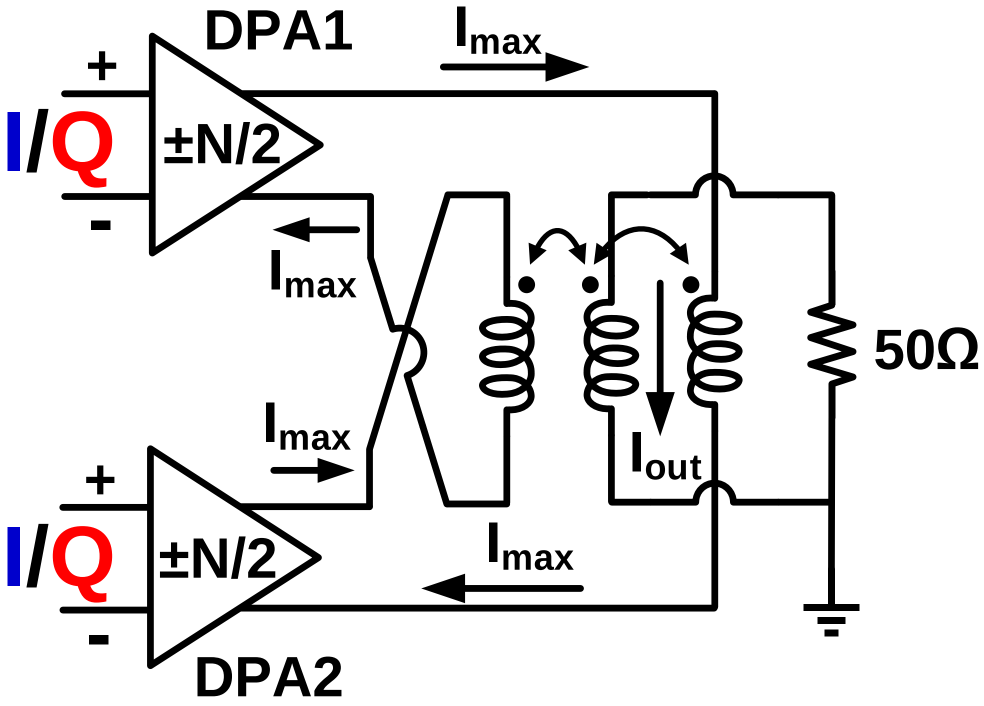


- $I_{out} = 2 \times I_{max}$
- $R_{L\_DPA1} = R_{L\_DPA2} = 50\Omega$

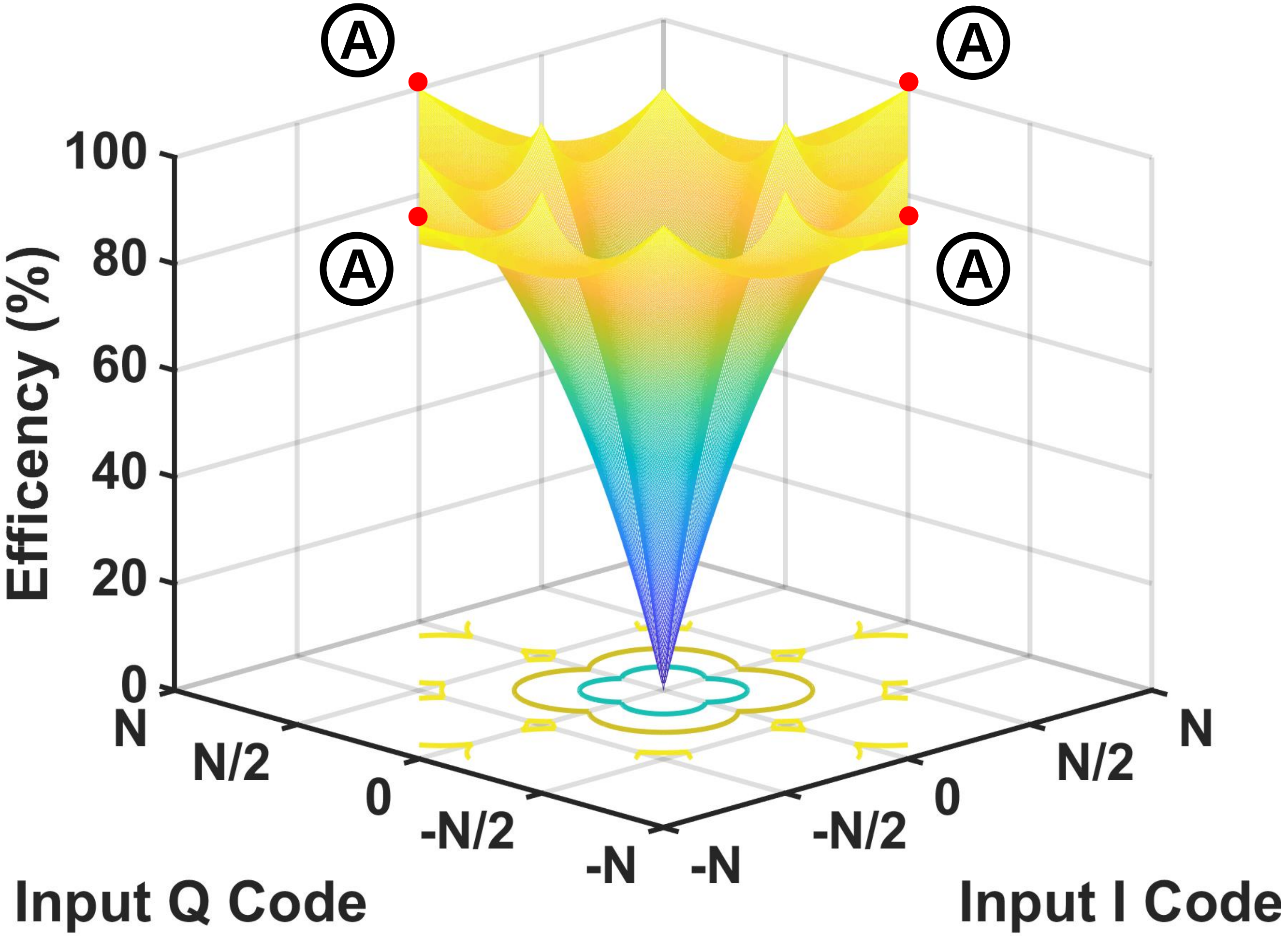


Transformer-based load modulation @State A (2/2)

At state A (Four 0dB PBOs):



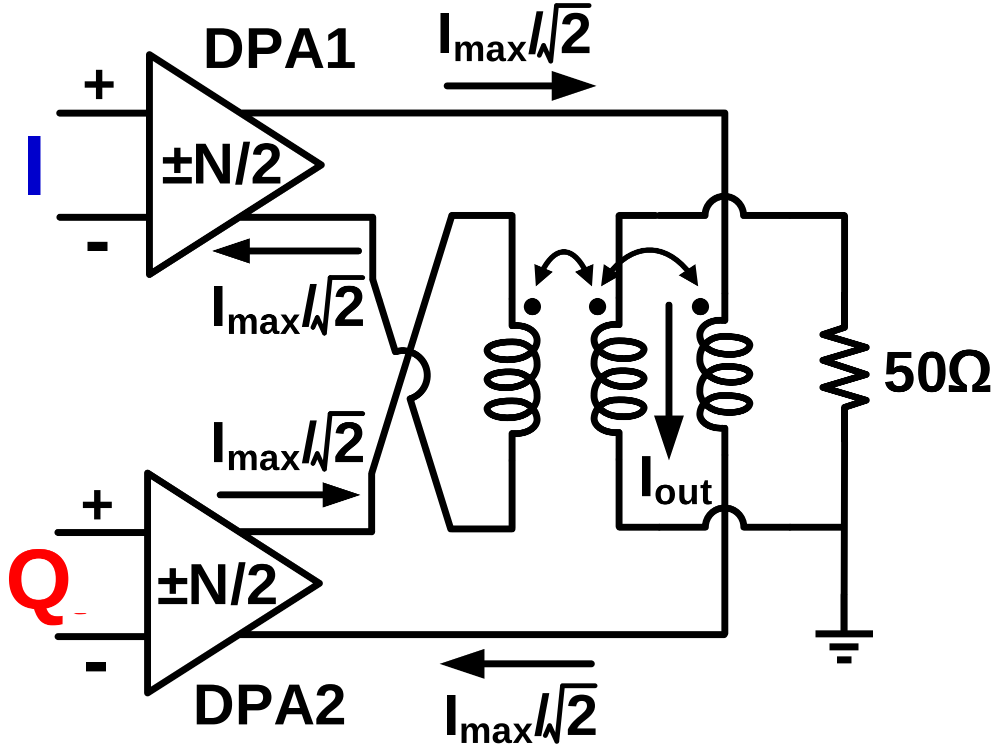
- $I_{out} = 2 \times I_{max}$
- $R_{L\_DPA1} = R_{L\_DPA2} = 50\Omega$



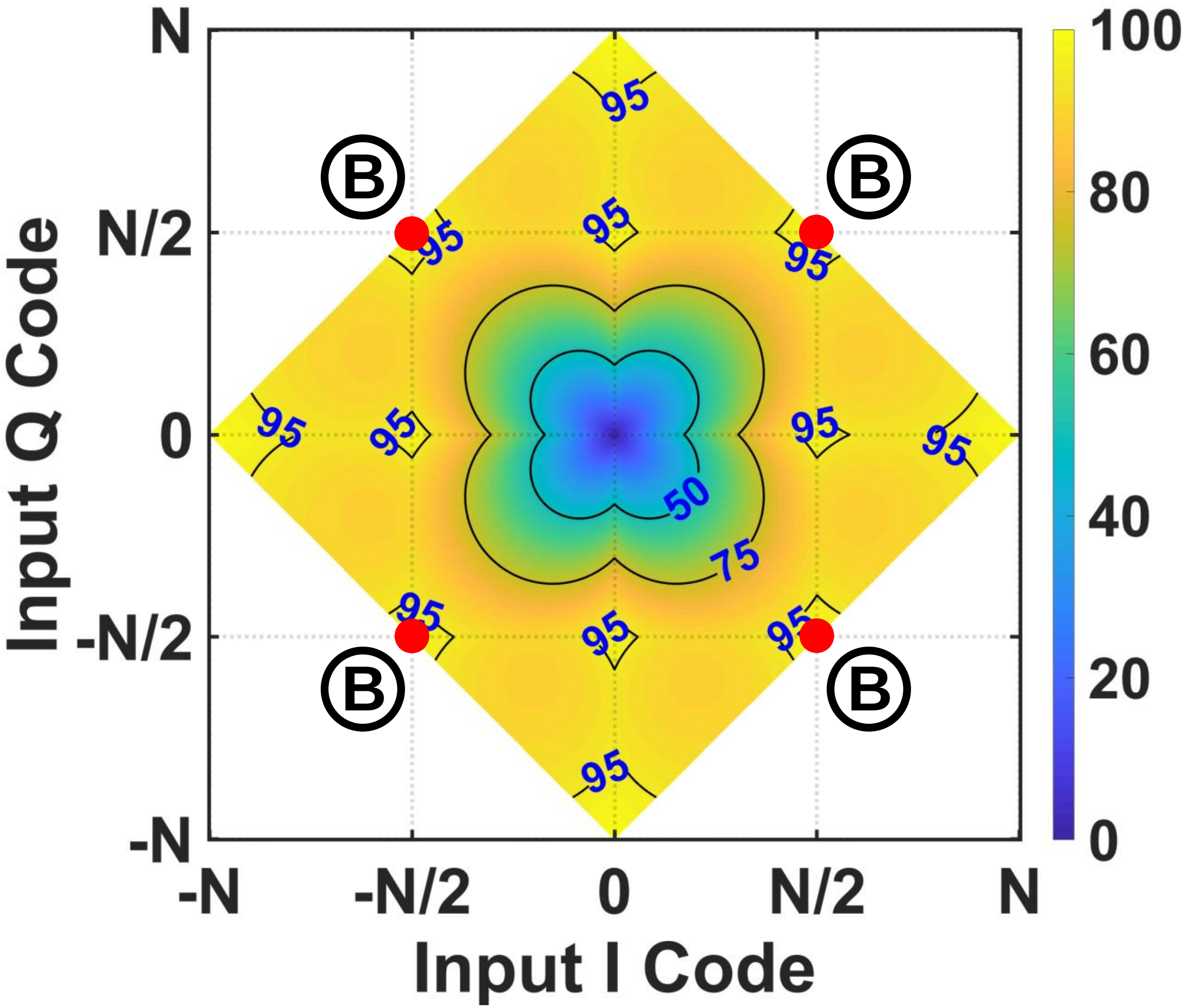
4 efficiency peaks

Transformer-based load modulation @State B (1/2)

At state B (Four 3dB PBOs):

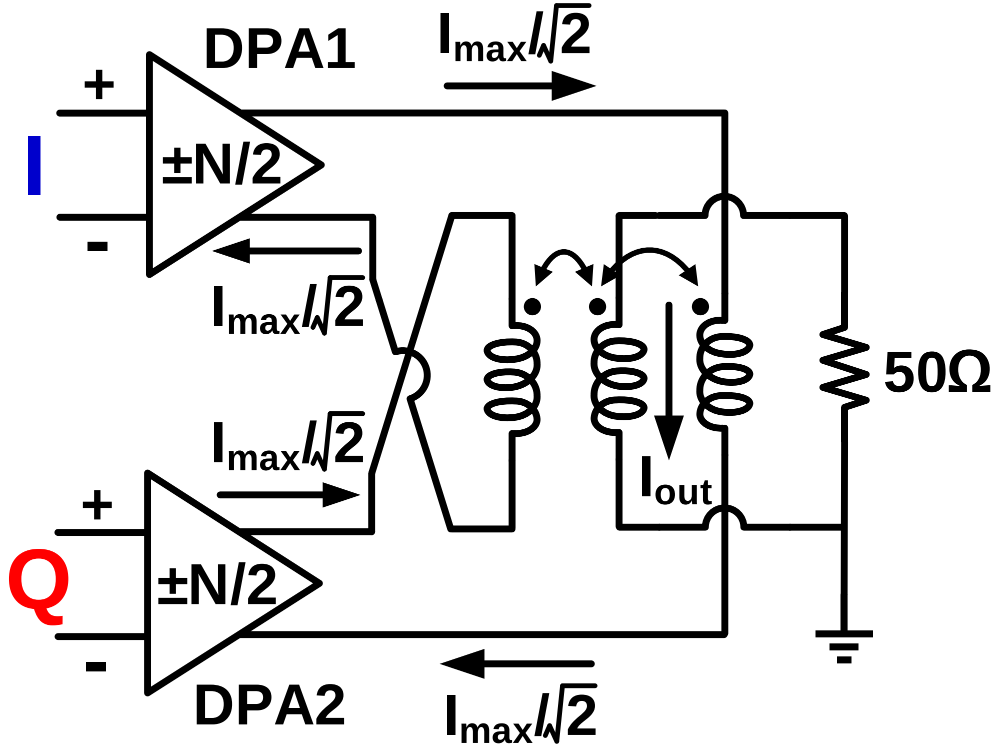


- $I_{out} = \sqrt{2} \times I_{max}$
- $R_{L\_DPA1} = R_{L\_DPA2} = 50\sqrt{2}\ \Omega$

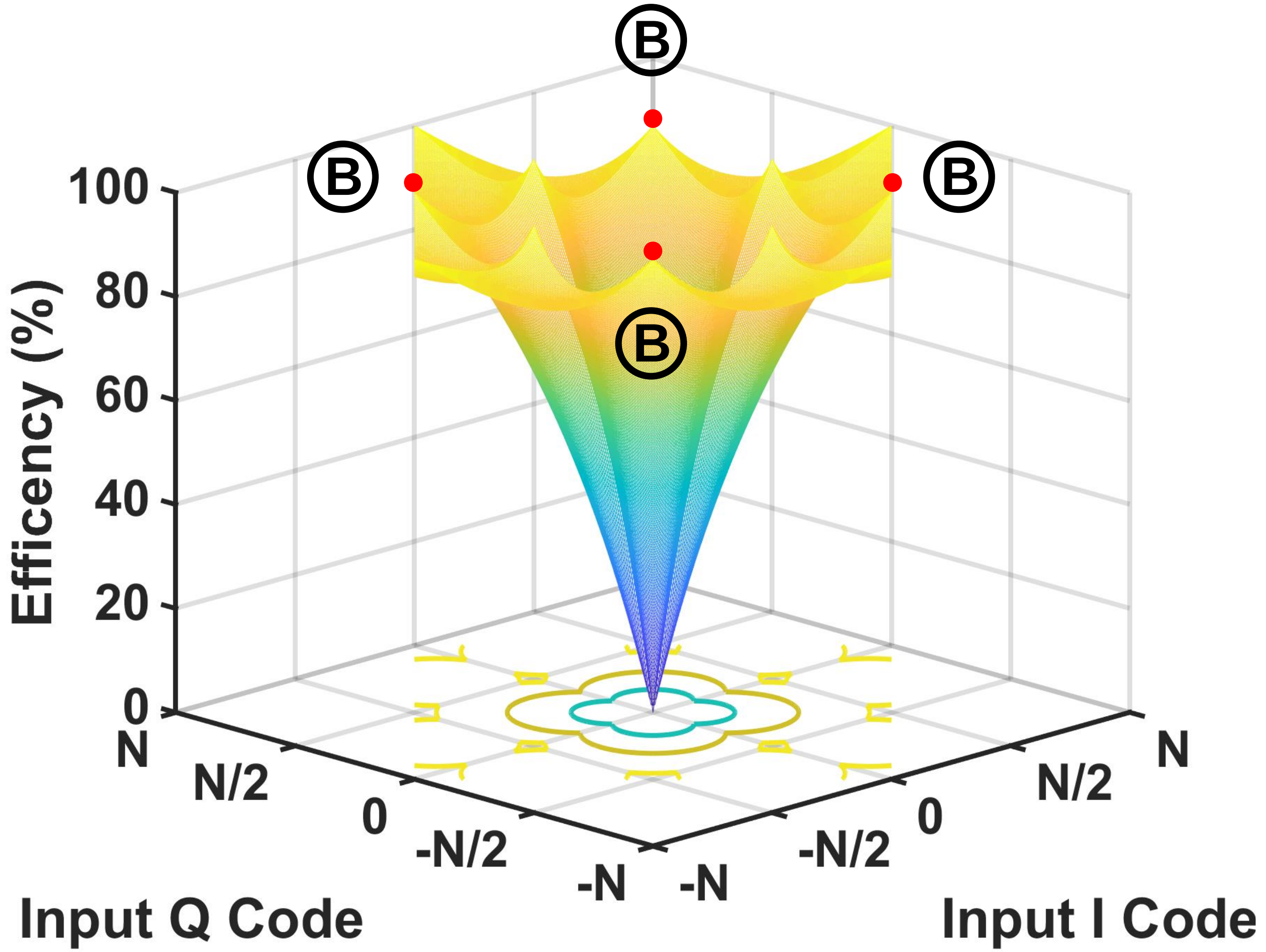


Transformer-based load modulation @State B (2/2)

At state B (Four 3dB PBOs):



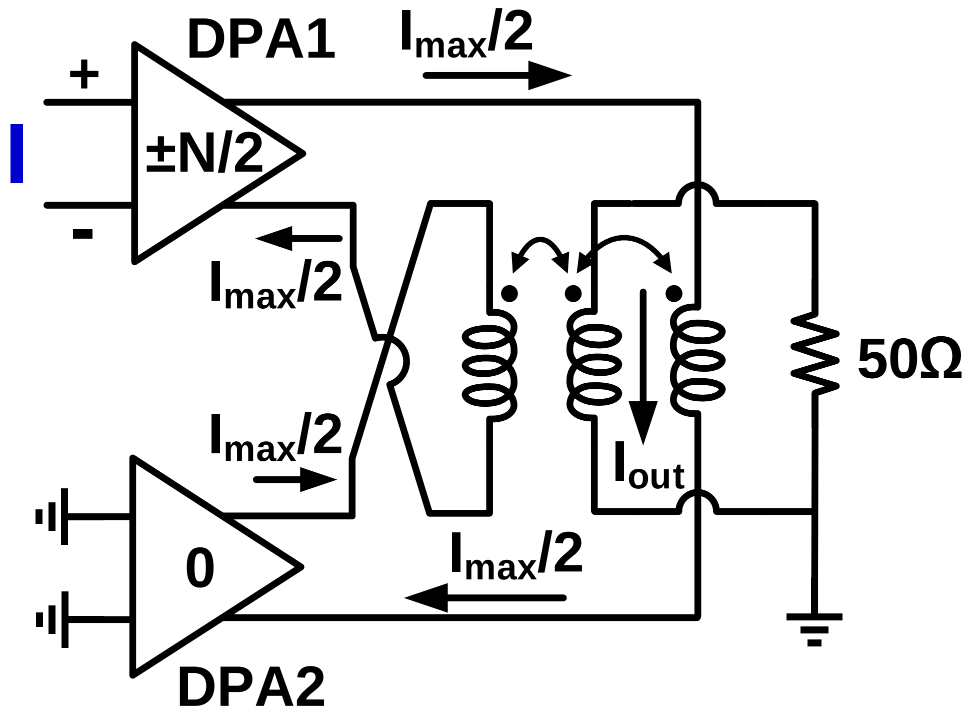
- $I_{out} = \sqrt{2} \times I_{max}$
- $R_{L\_DPA1} = R_{L\_DPA2} = 50\sqrt{2}\ \Omega$



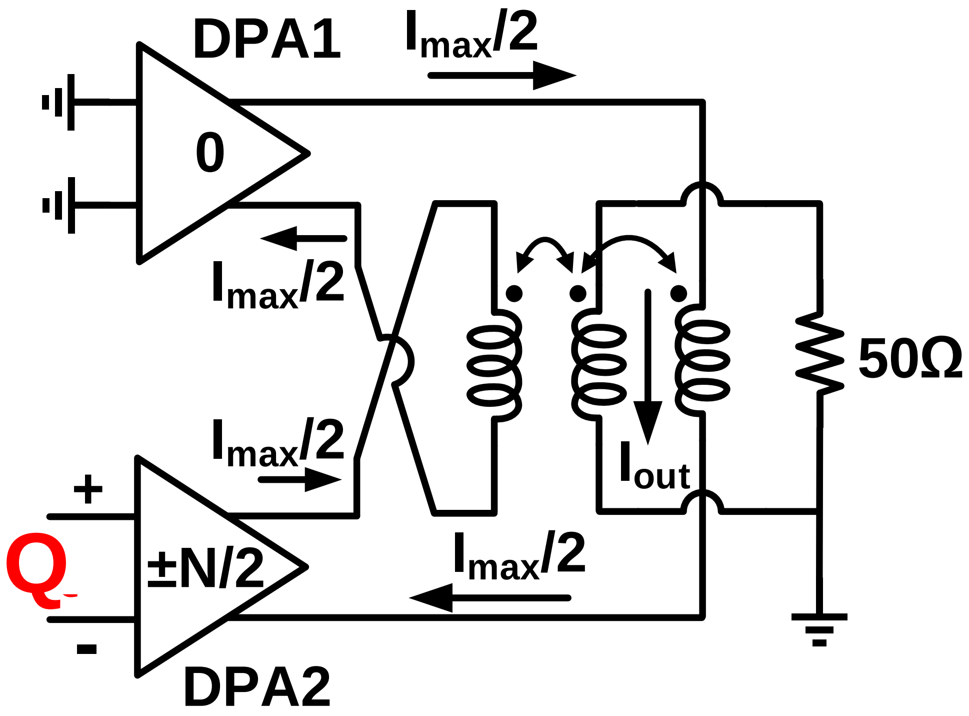
4 efficiency peaks

Transformer-based load modulation @State C (1/2)

At state C (Four 6dB PBOs):



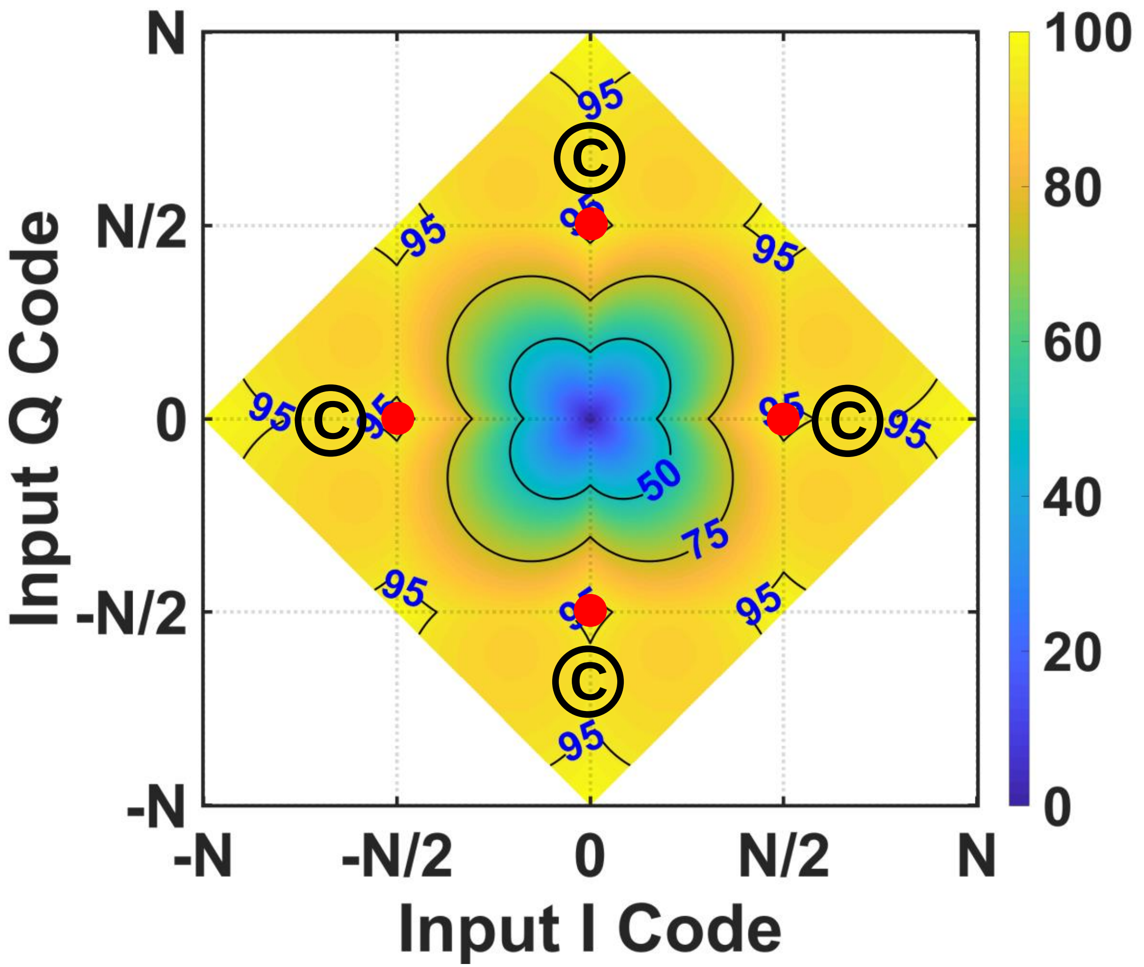
- $I_{out} = I_{max}$
- $R_{L\_DPA1} = 100\Omega$

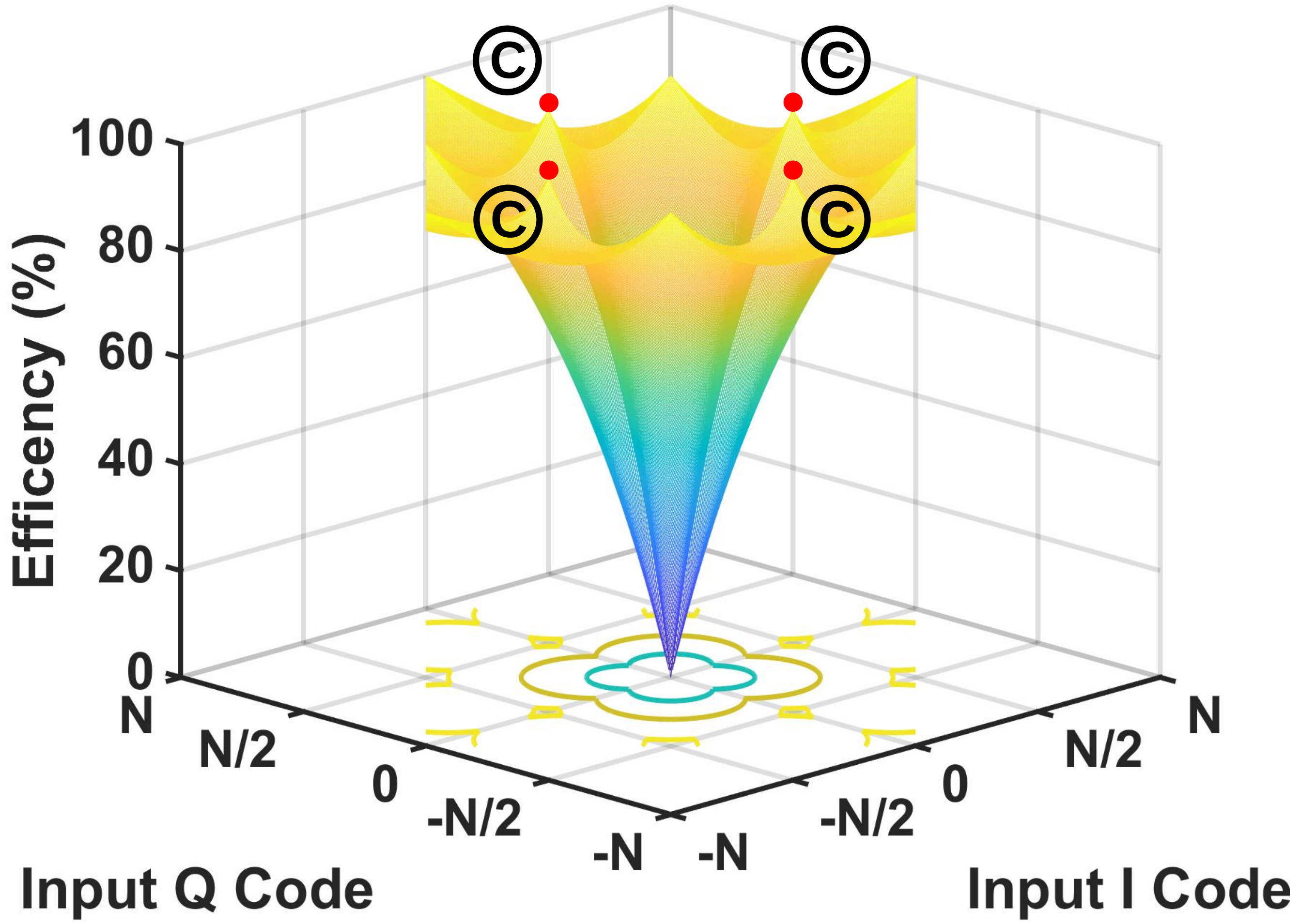


- $I_{out} = I_{max}$
- $R_{L\_DPA2} = 100\Omega$

Transformer-based load modulation @State C (2/2)

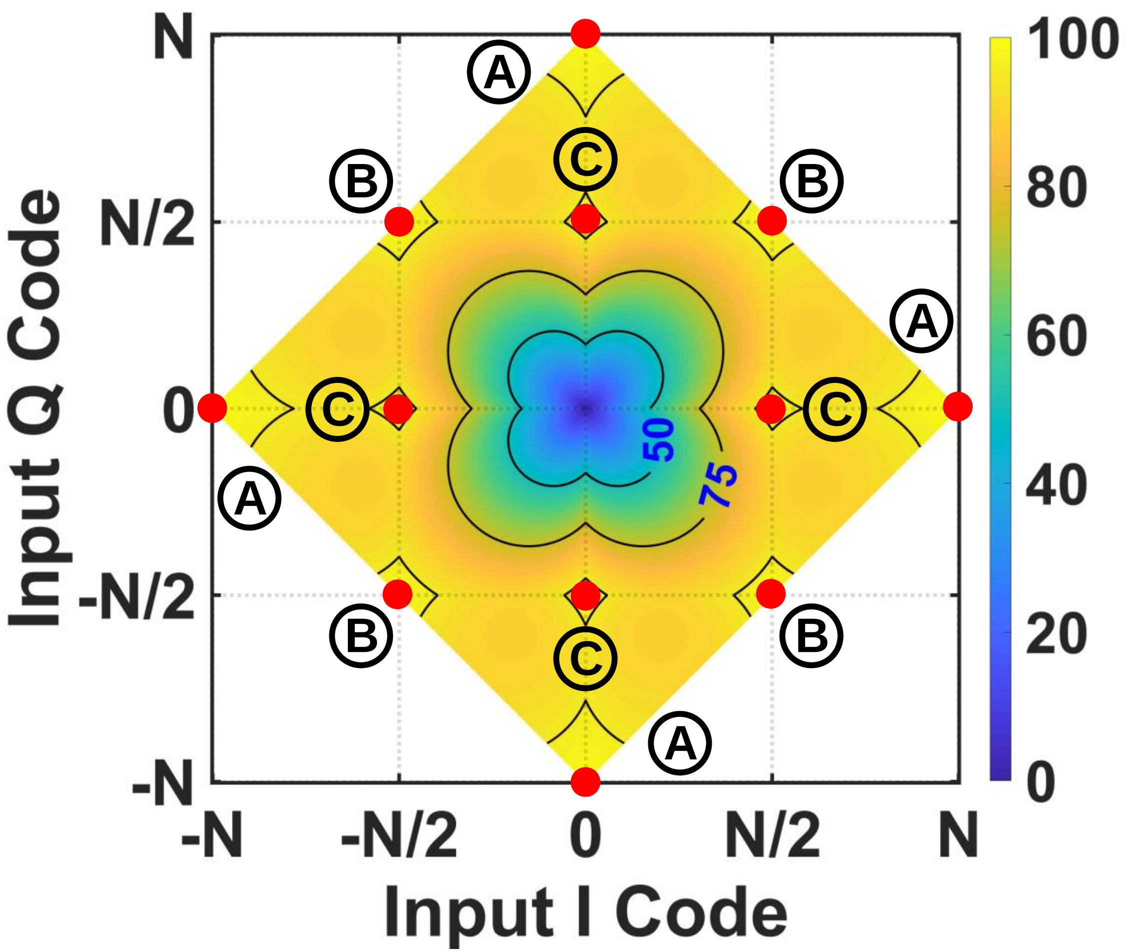
At state C (Four 6dB PBOs):

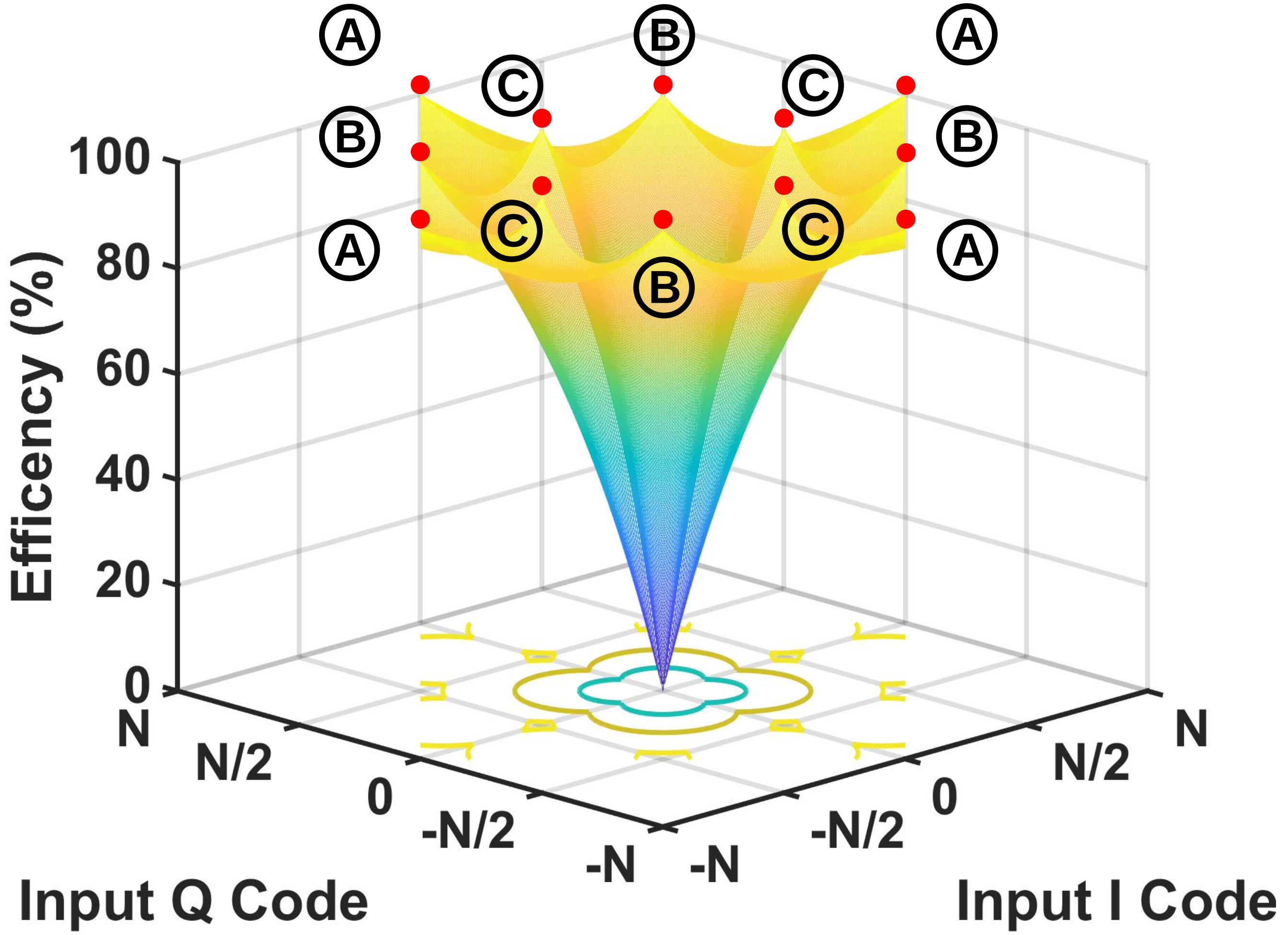




4 efficiency peaks

Transformer-Based Complex-Domain Cell Sharing and Load Modulation





- **The same peak output power as polar architecture**
- **12 efficiency peaks (A/B/C states) in the I/Q complex plane**

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- **Circuit Implementation**
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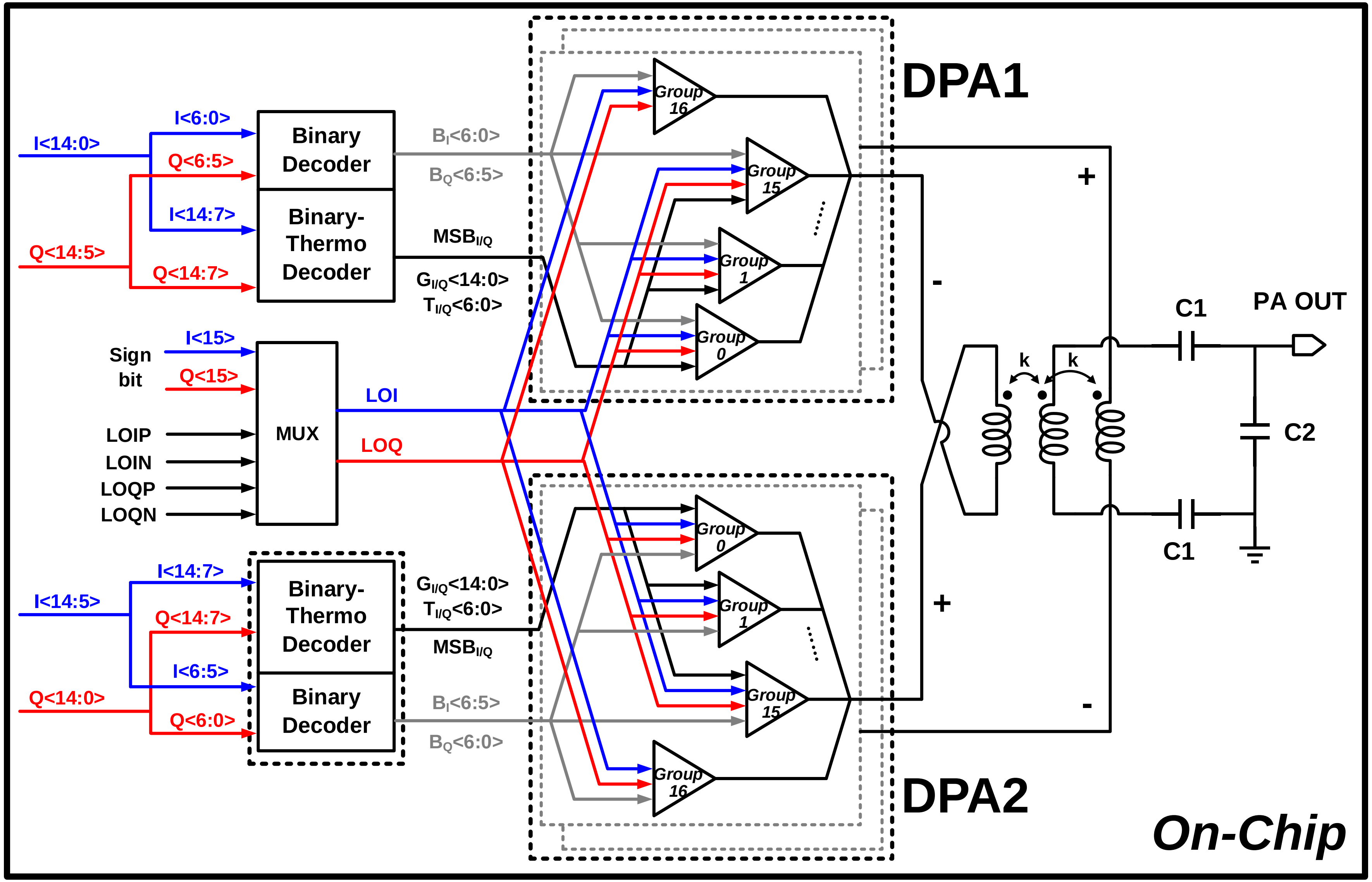
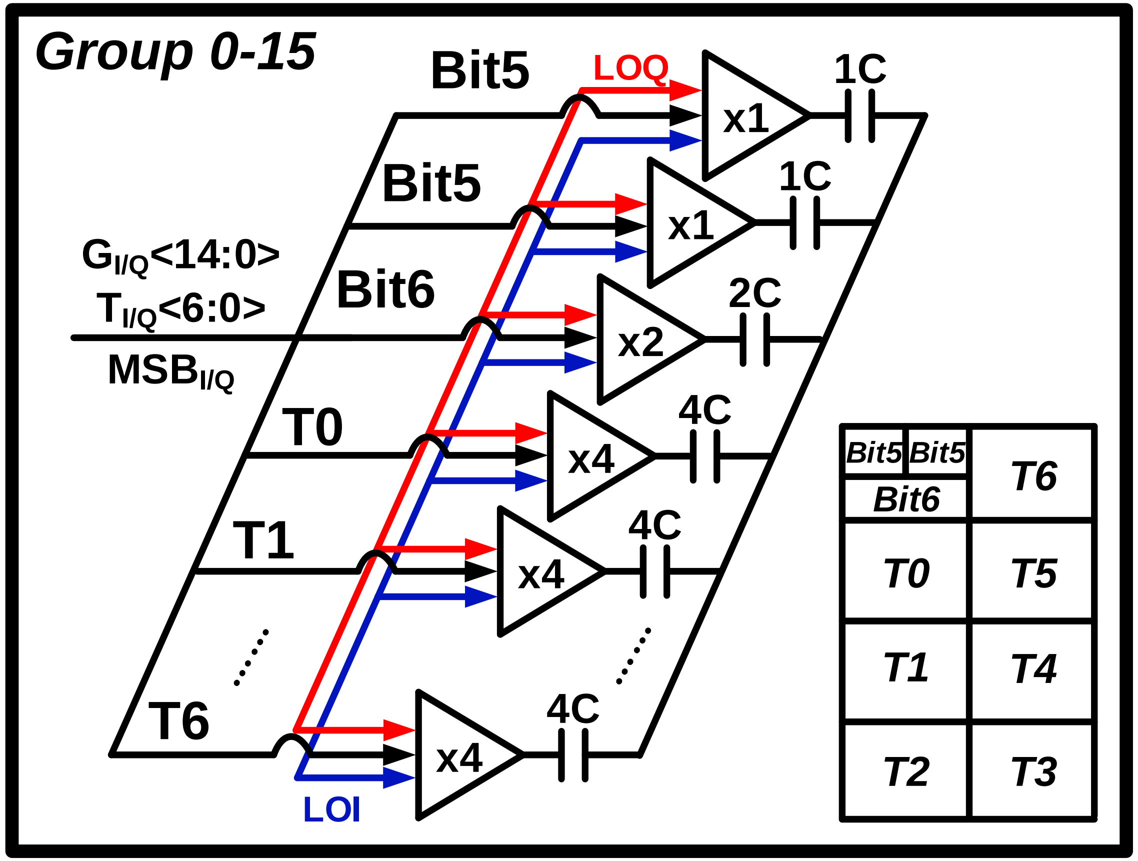
Block Diagram

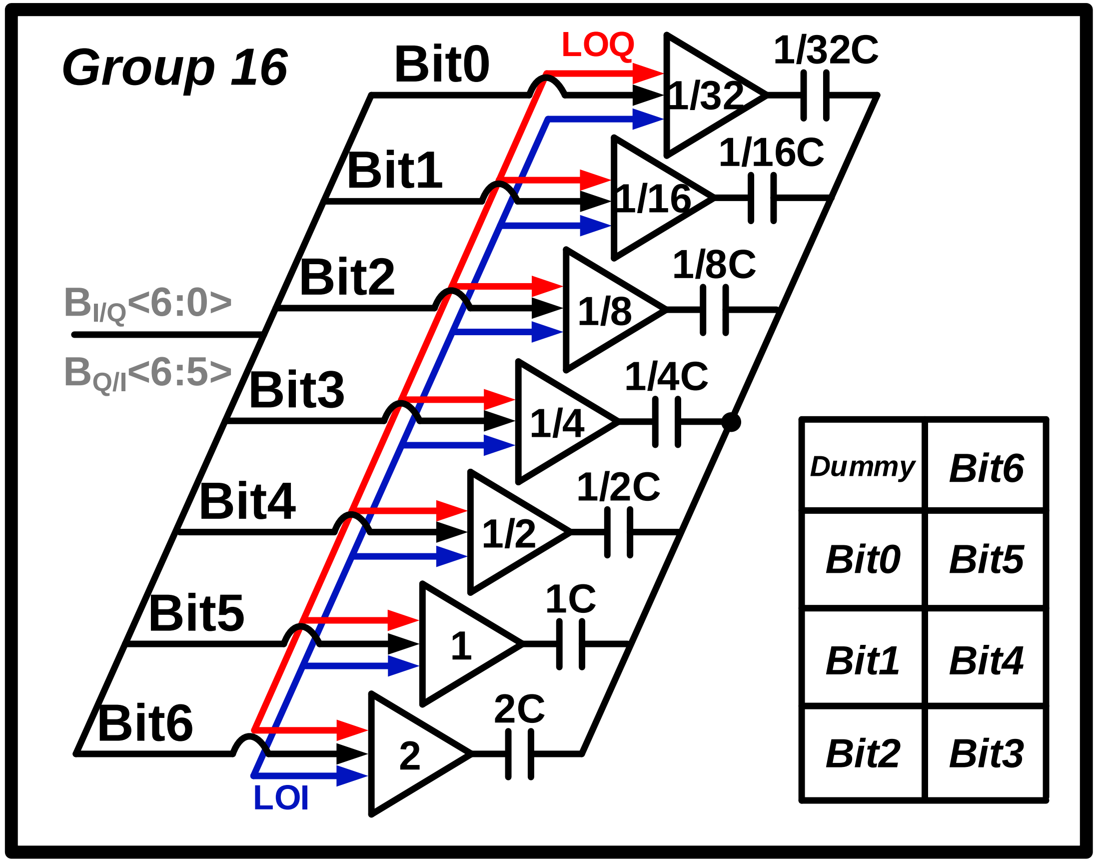


- 15-bit resolution: two 14-bit sub-DPAs with hybrid unary and binary arrays
- I/Q cell sharing: LOI and LOQ signals are fed into both sub-DPAs
- Compact parallel-combining transformer (PCT) power combiner

DPA Groups



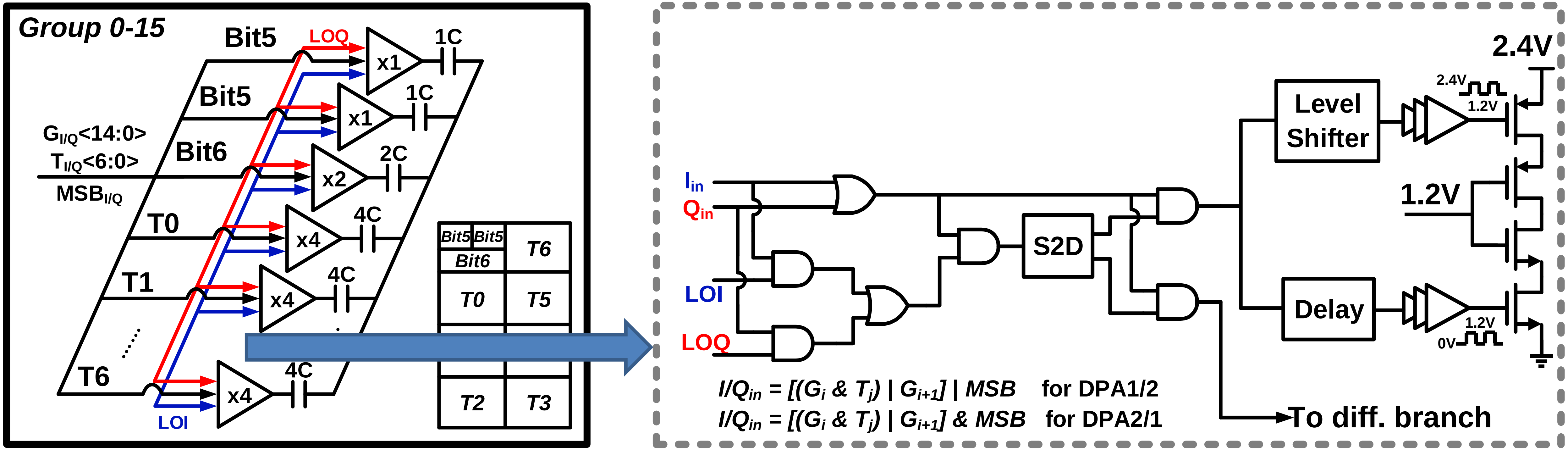
Group 0-15



Group 16

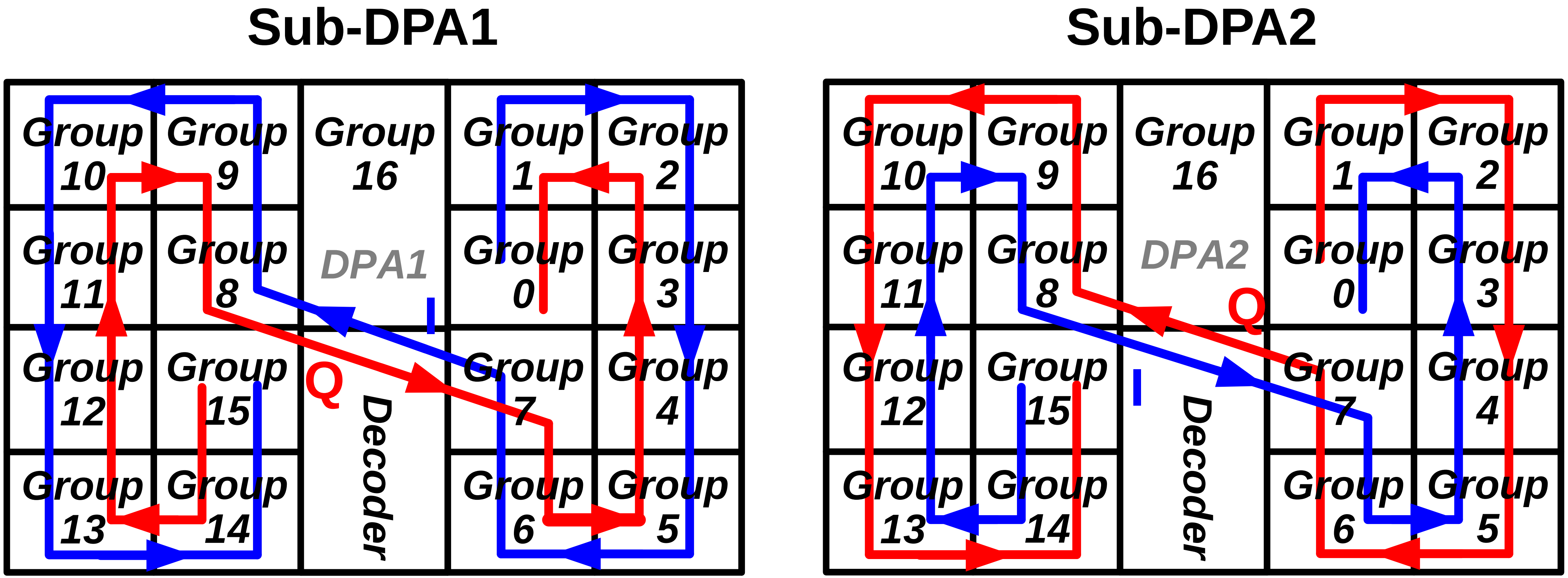
- Each sub-DPA: 16 hybrid groups (Group 0-15) and 1 binary group (Group 16)
- Each hybrid group: 7 thermo + 2-bit binary-coded cells

Differential Cascode Unit PA Cell



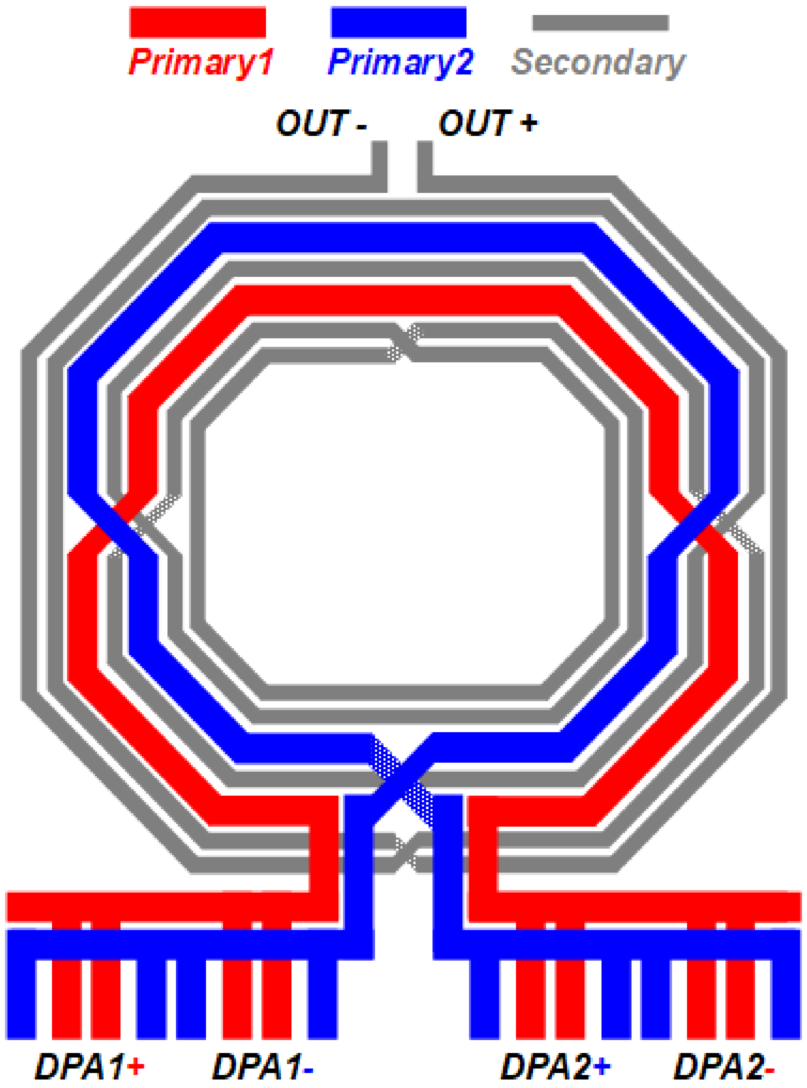
- **I/Q cell sharing: logic circuit selects the state (I or Q) of each unit PA**
- **Cascode inverter Class-D topology to obtain high output power**

DPA Group Floorplan

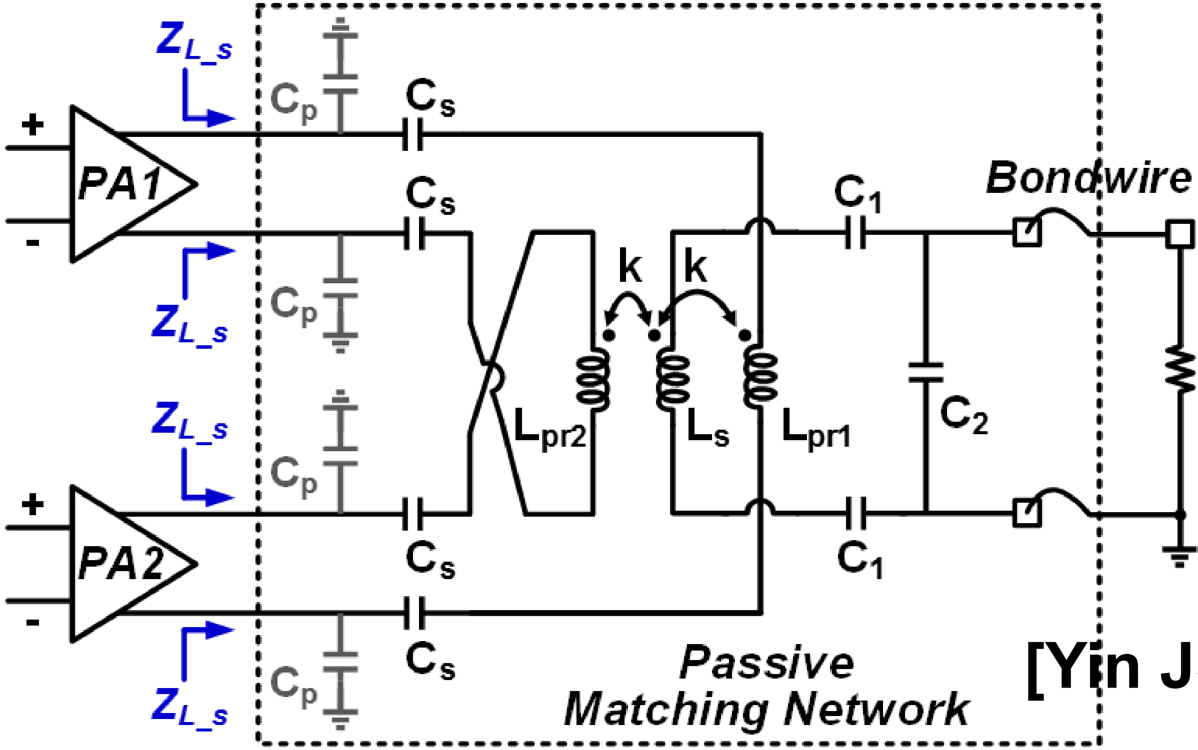


- **“Snake” traverse movement: improve the differential nonlinearity (DNL)**
- **I/Q cell sharing: I/Q signals have inverse movements**
- **Good symmetry in the switching sequence**

Matching Network (1/2)



- A compact single-transformer footprint
- Good differential symmetry
- Magnetic enhancement and increase Lpr
- Size reduction and lower loss



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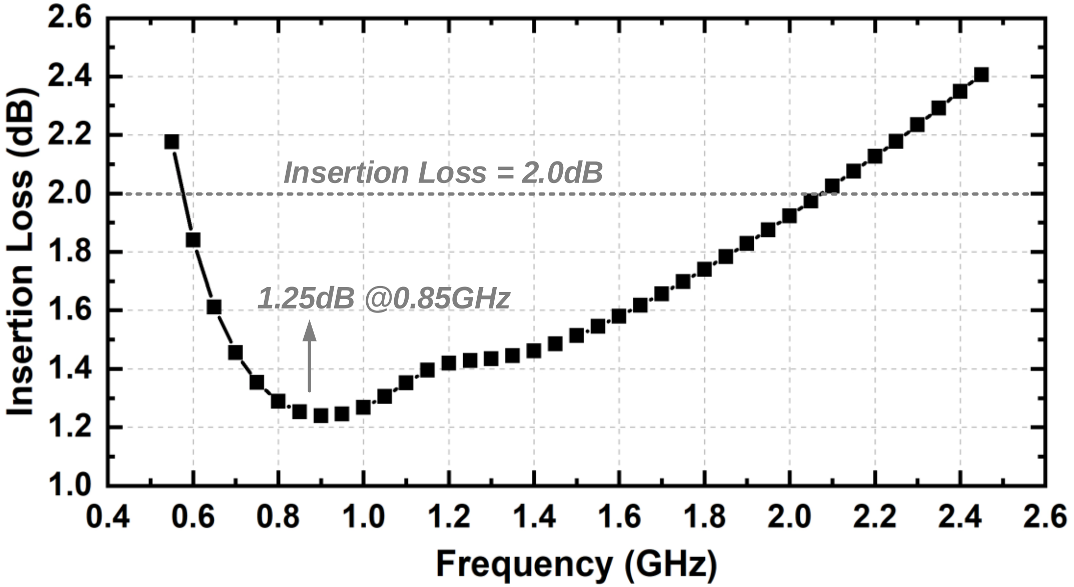
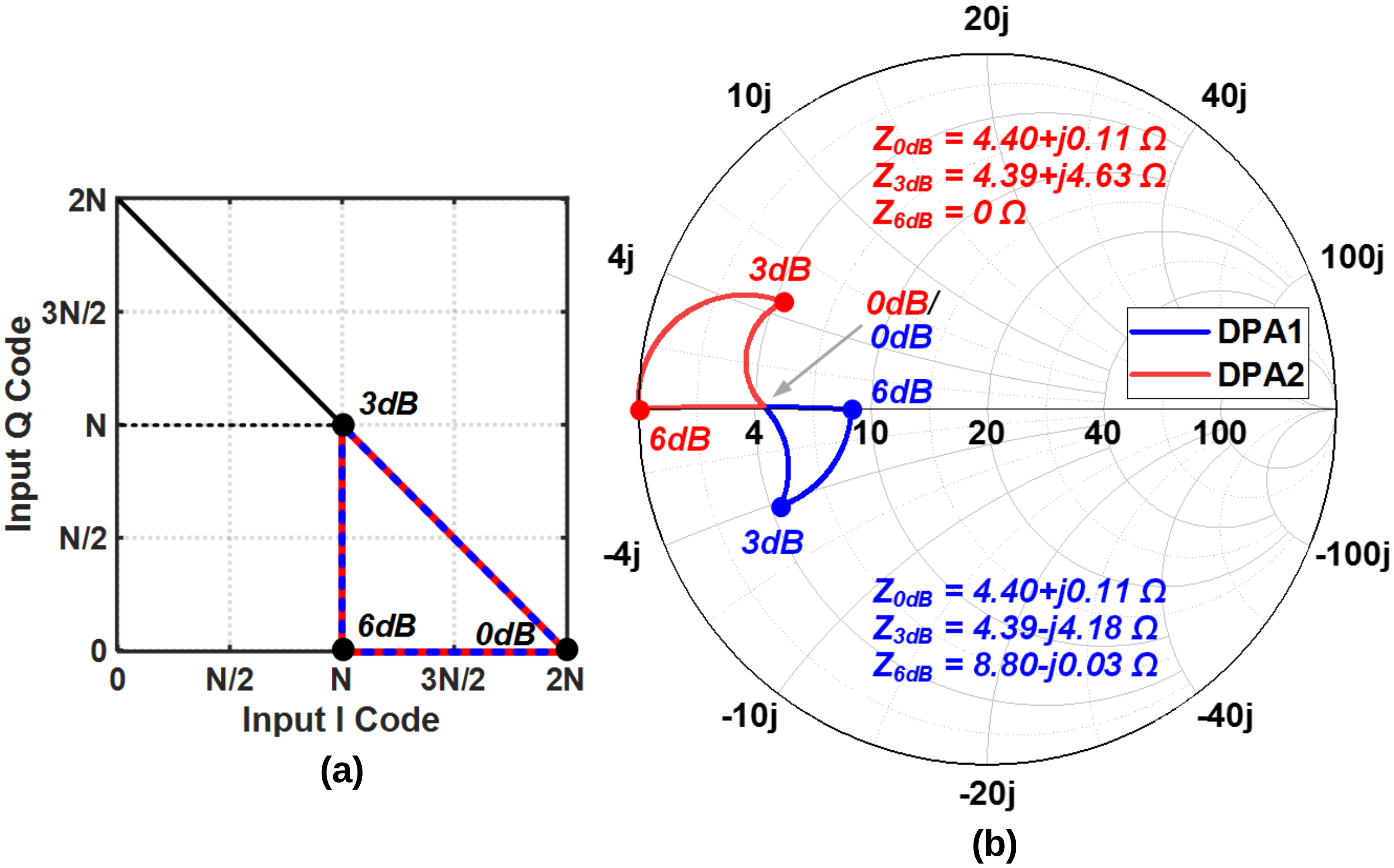
Matching Network (2/2)

Simulated insertion loss of passive network



Simulated impedance trajectories of DPA1 and DPA2



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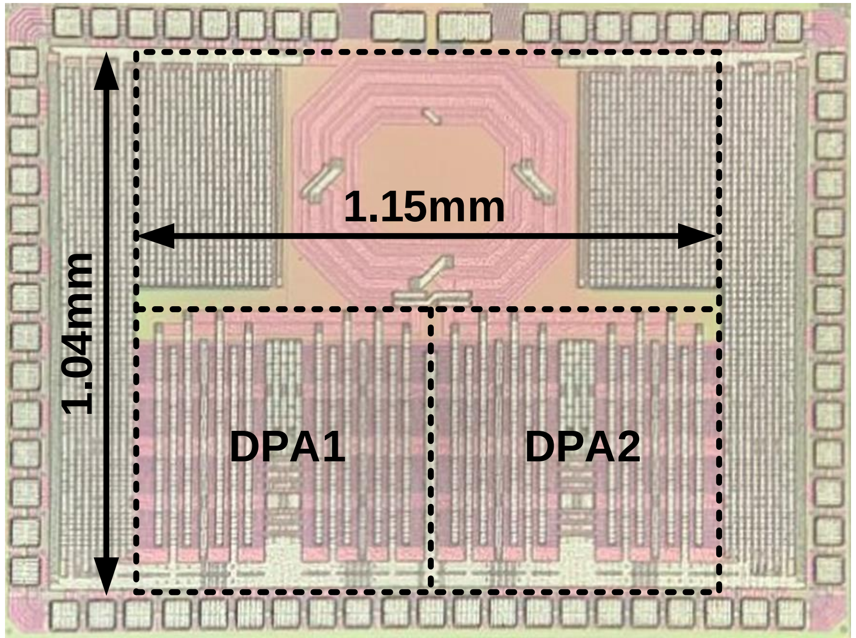
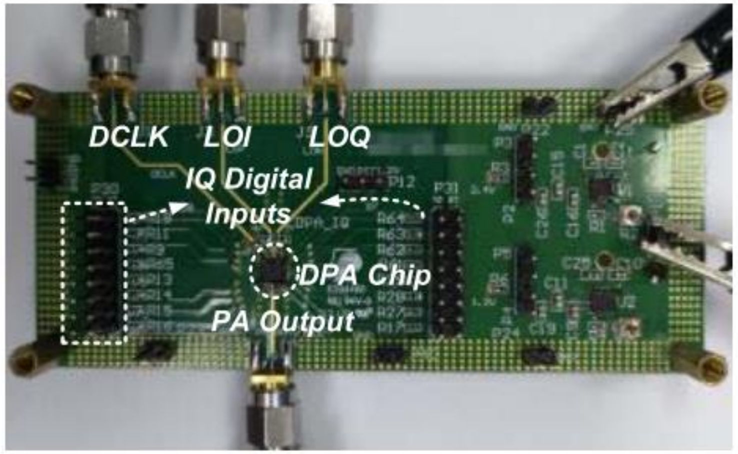
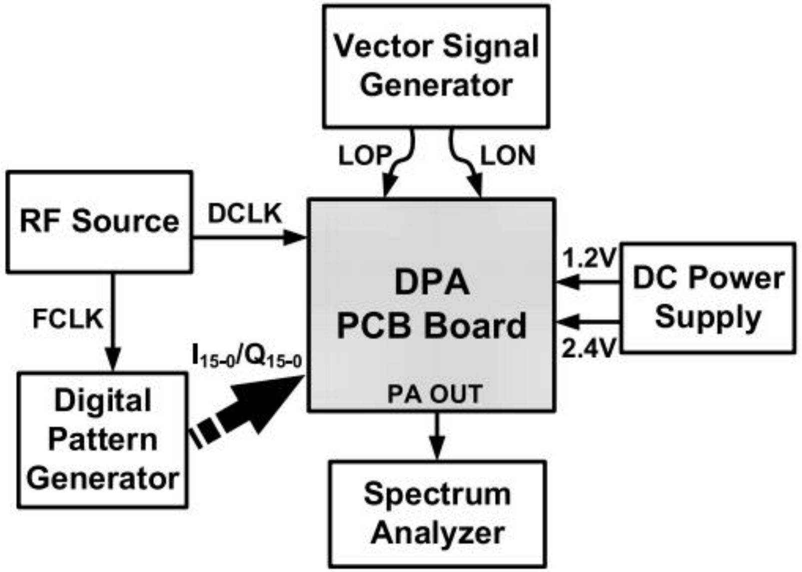
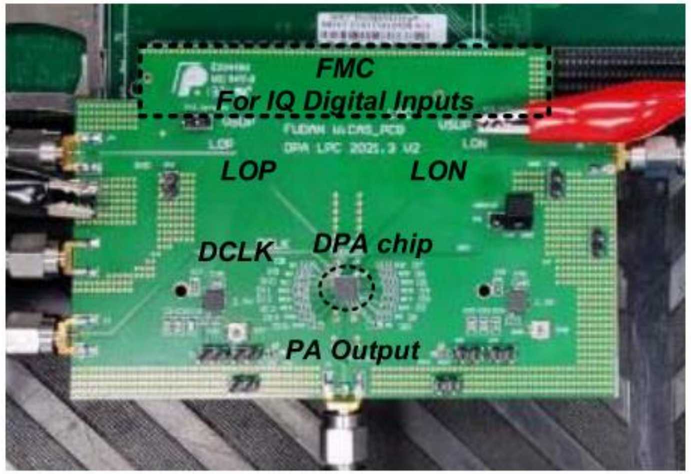
Chip Photo & Measurement Setup

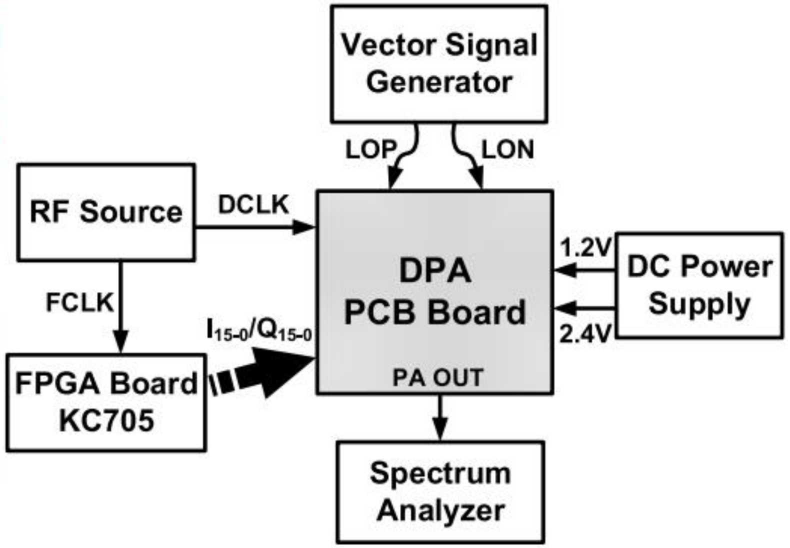




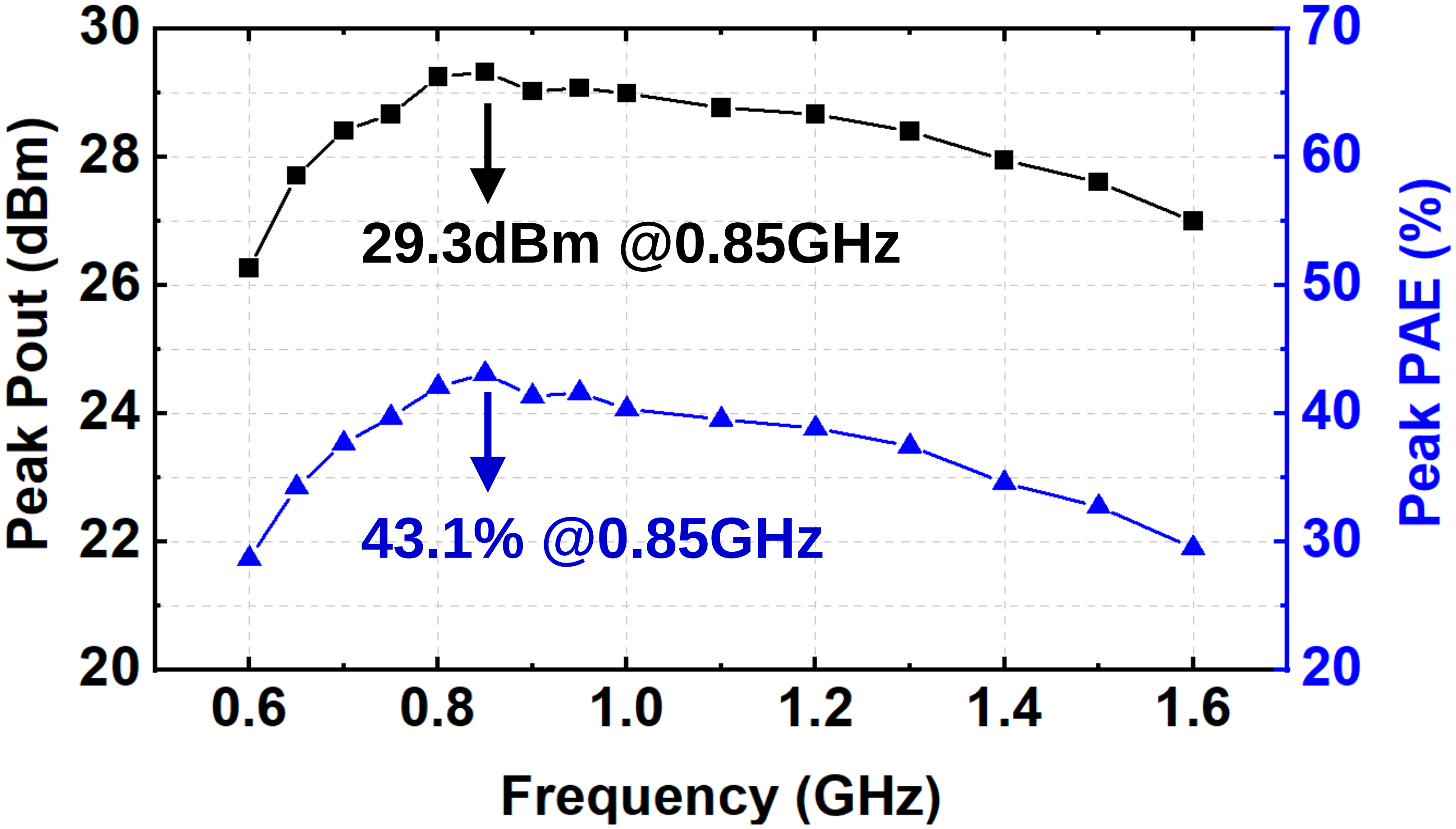


- 55nm CMOS
- Core area: 1.2mm^2
- Power supplies: 2.4V & 1.2V
- PAE = Pout / Pdc(all blocks)



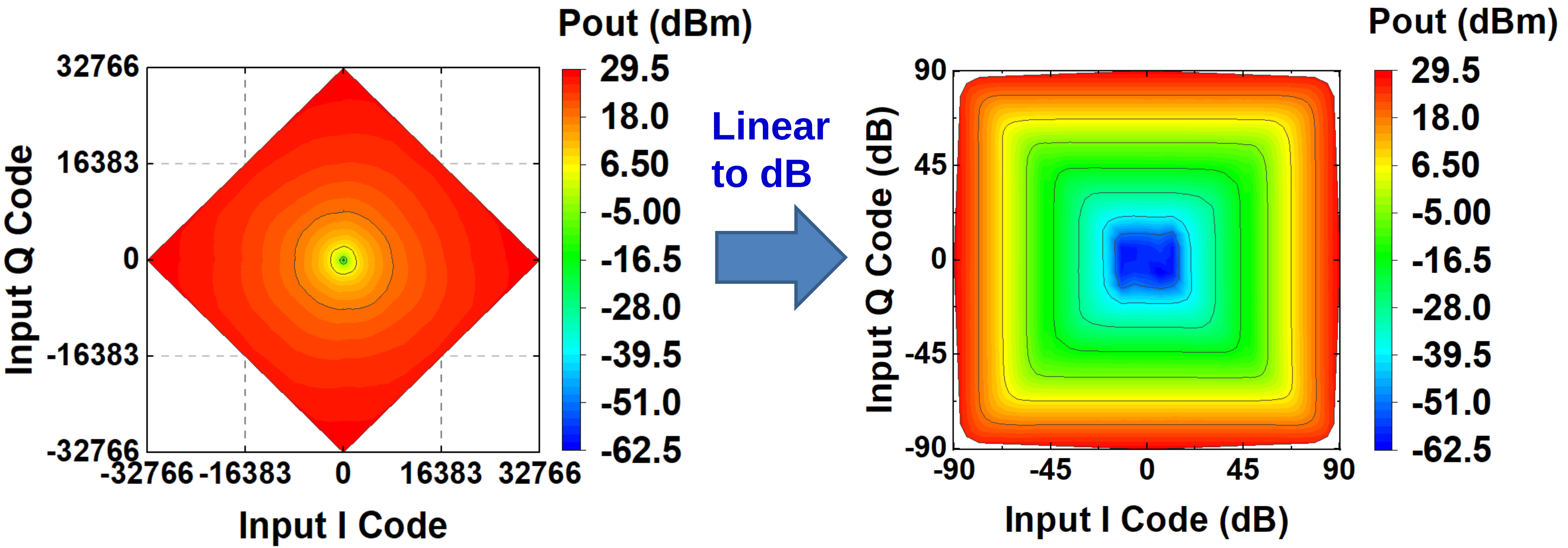


Measured CW Performance (1/3)



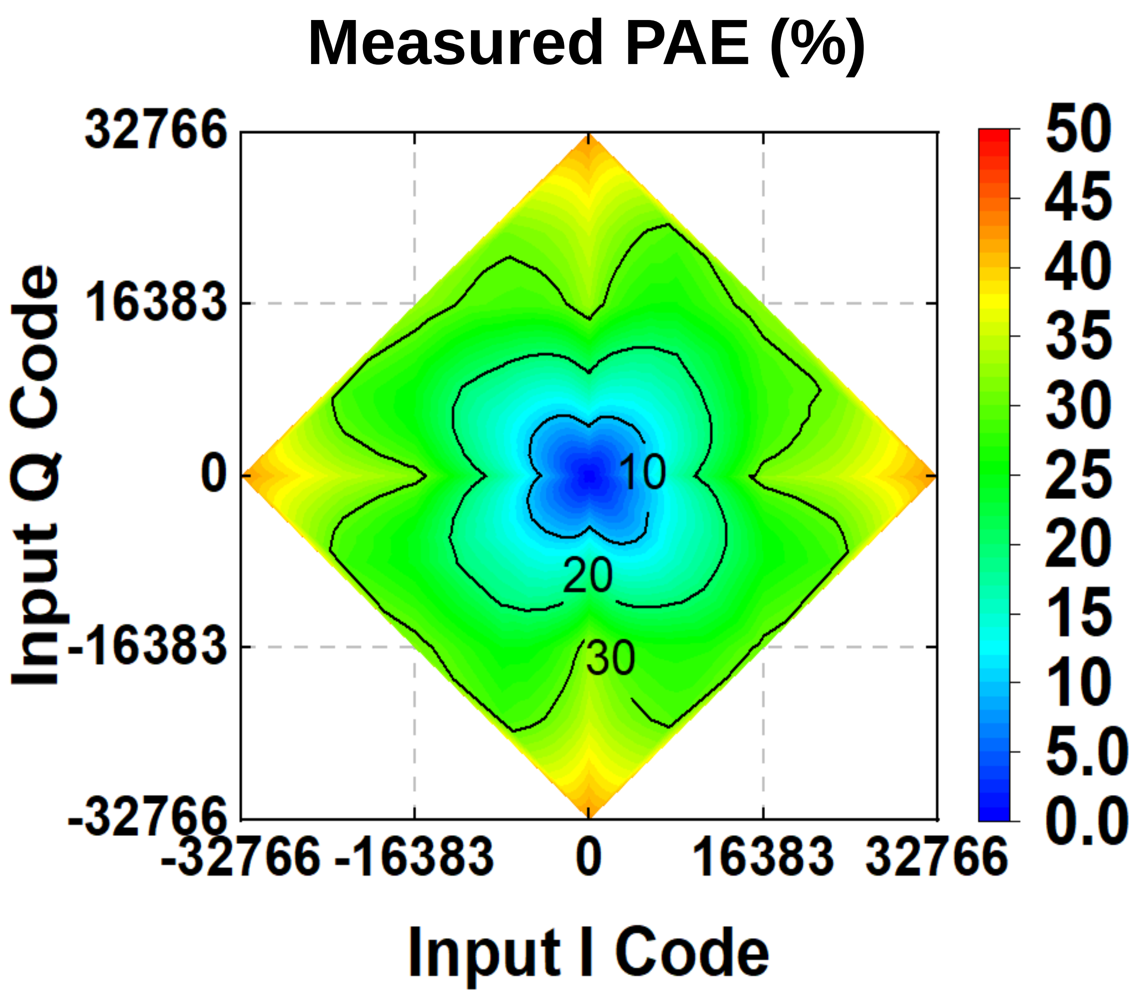
- **Peak Pout : 29.3dBm @0.85GHz**
- **Peak PAE : 43.1% @0.85GHz**

Measured CW Performance @0.85GHz (2/3)



- **Comparable peak Pout with polar architecture:**
  - **29.3dBm at state A where I/Q cell sharing is performed**

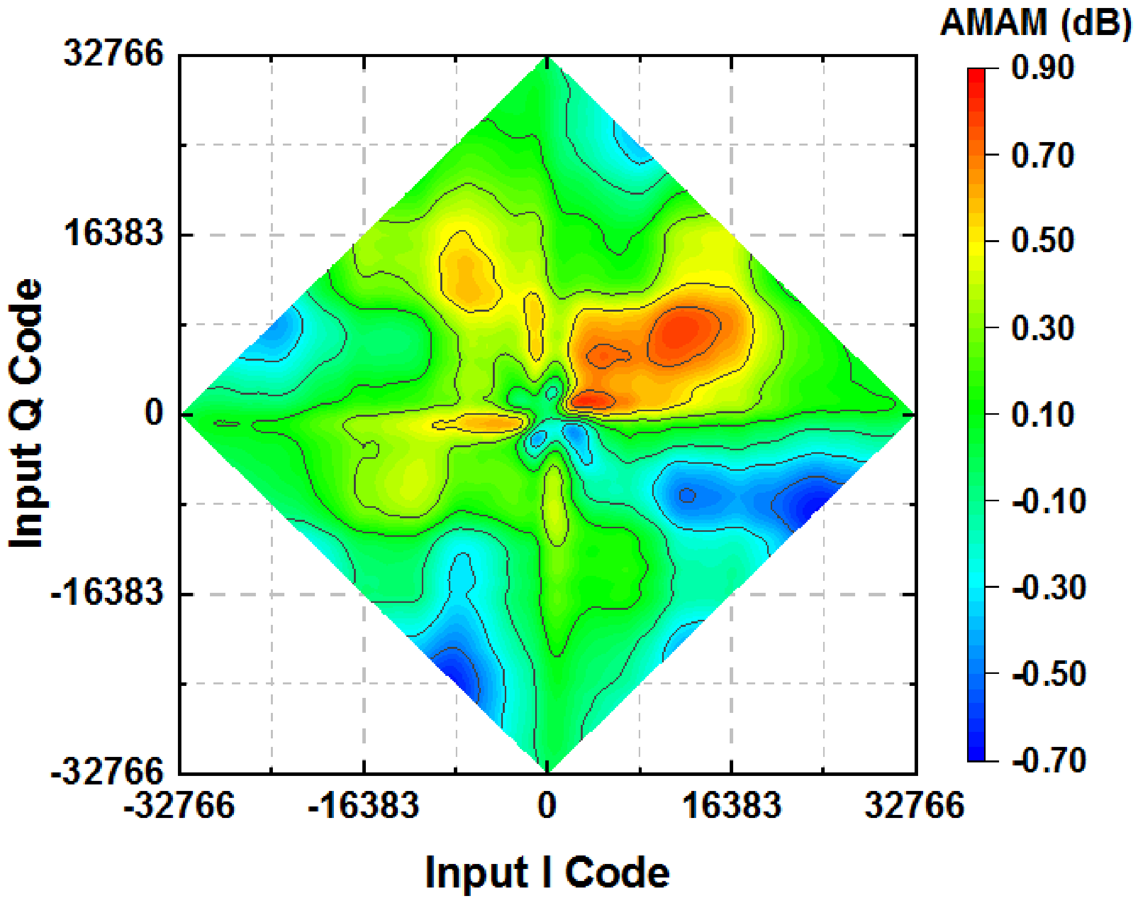
Measured CW Performance @0.85GHz (3/3)

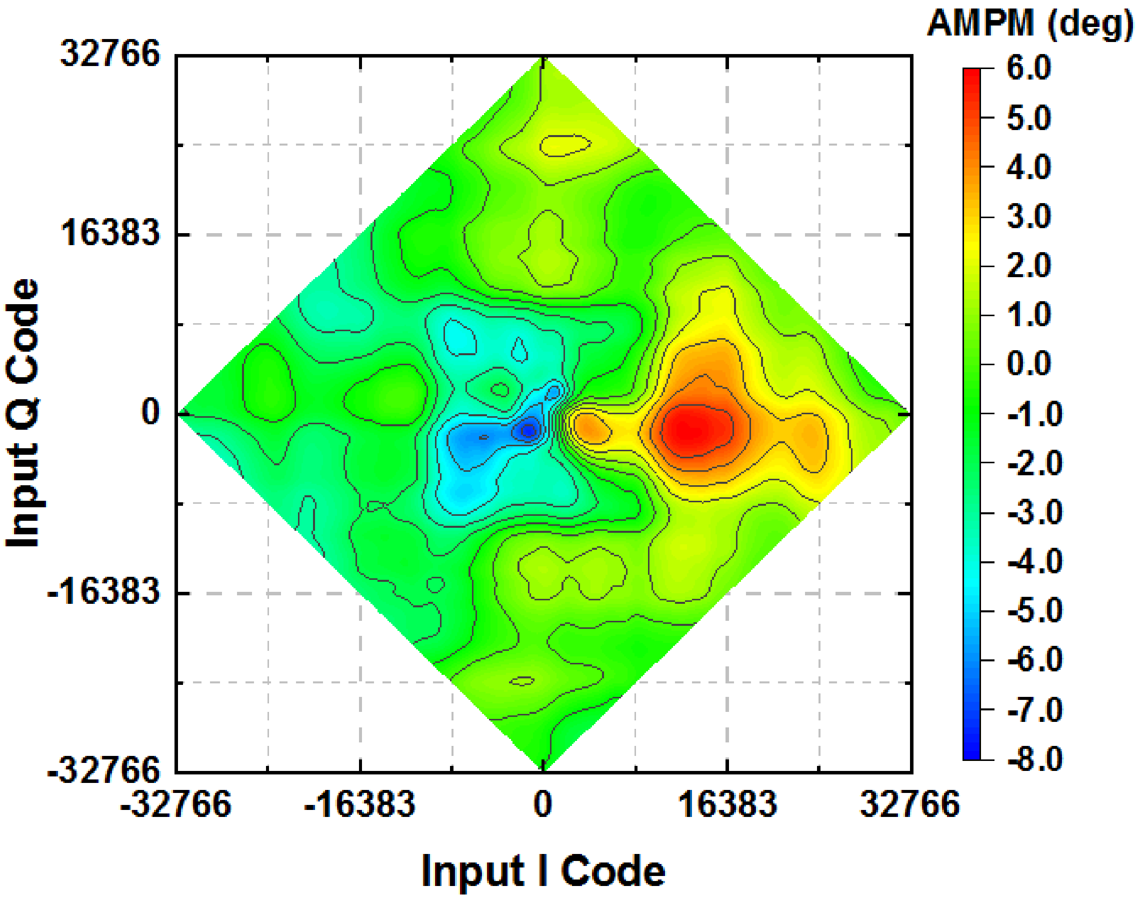


- **Comparable peak PAE with polar architecture:**
  - **43.1% at state A where I/Q cell sharing is performed**
- **Transformer-based cell sharing and load modulation:**
  - **Efficiency enhancement at state A, B and C**
  - **Average efficiency is effectively improved**

Measured AM-AM & AM-PM Nonlinearity

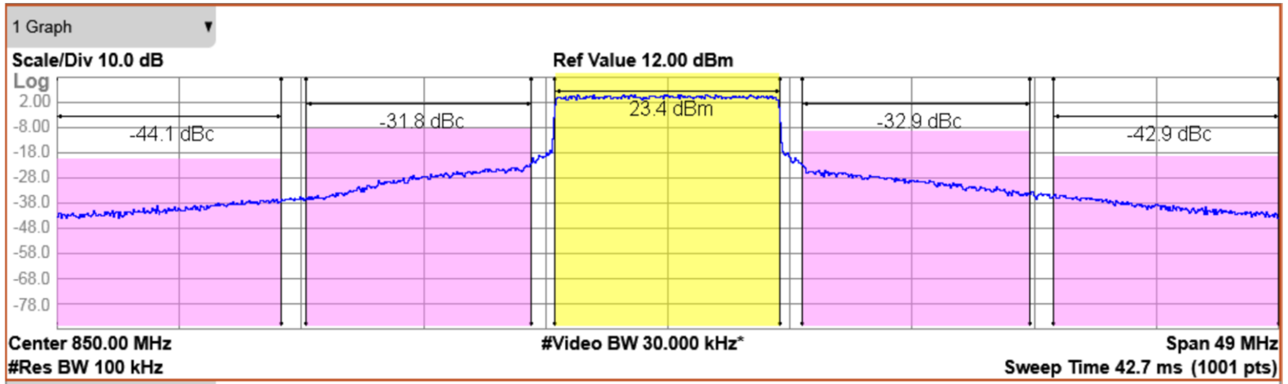
For 15-bit diamond:





- **AM-AM distortion: 1.6dB**
- **AM-PM distortion: 14.0°**

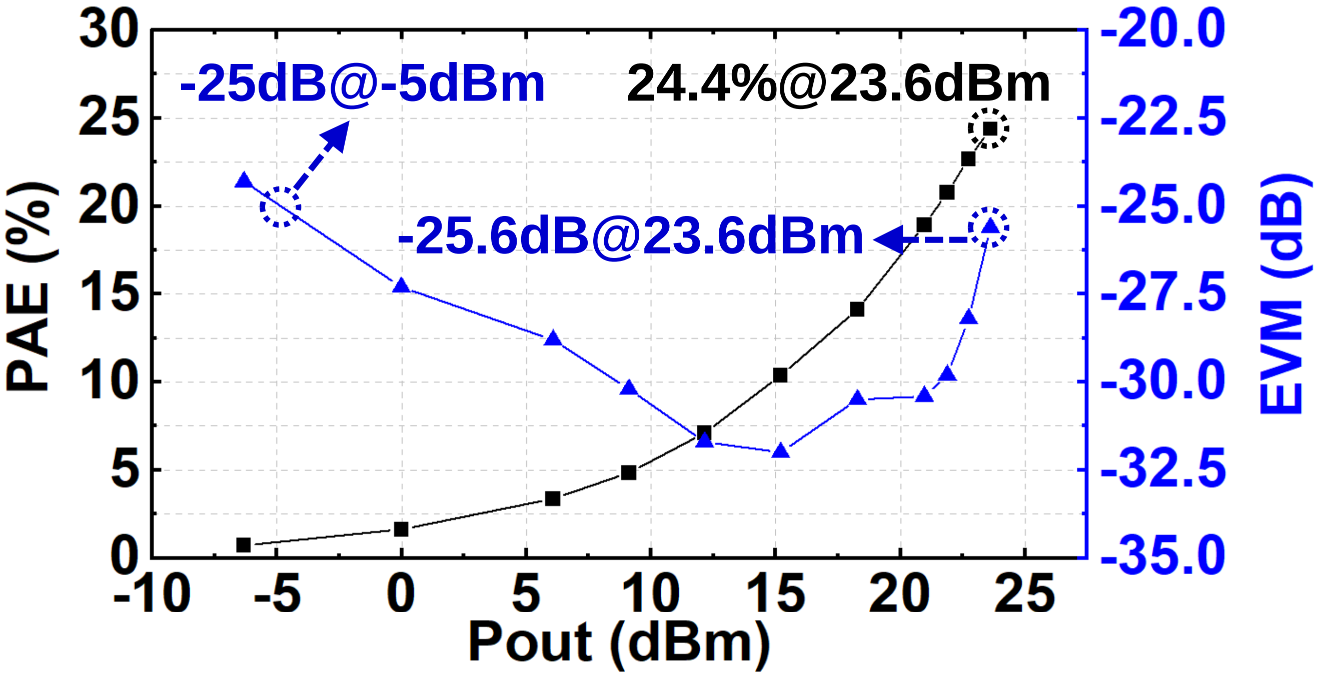
Measured 10MHz 64-QAM LTE Signal



2 Metrics

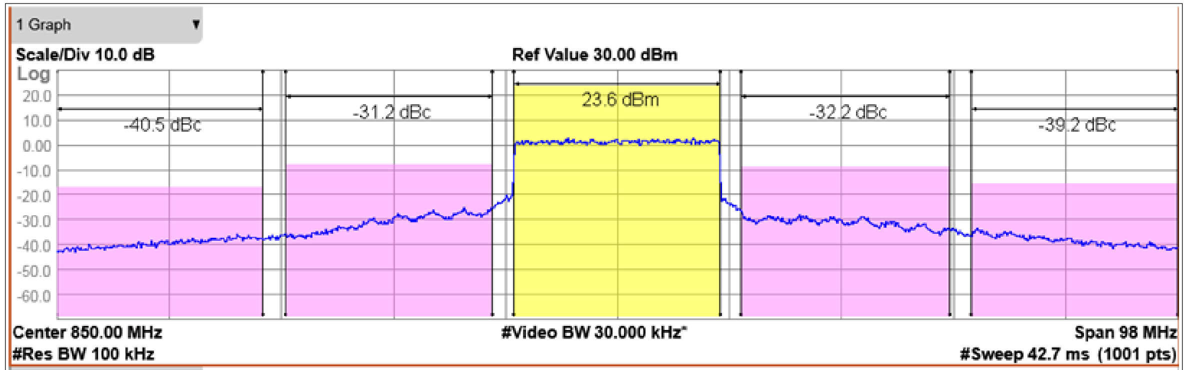
Total Car Pwr	23.396 dBm/9.000 MHz
Total PSD	---

			Lower				Upper				
			ACP		Ref Carrier		ACP		Ref Carrier		
	Offs Freq	Integ BW	dBc	dBm	dBm	Car #	dBc	dBm	dBm	Car #	Filter
A	10.00 MHz	9.000 MHz	-31.80	-8.405	23.40	1	-32.94	-9.546	23.40	1	-3 dB
B	20.00 MHz	9.000 MHz	-44.10	-20.71	23.40	1	-42.92	-19.52	23.40	1	-3 dB



- **W/O any digital predistortion (DPD)**
- **LTE 10MHz 64-QAM:**
  - **Pout: 23.4dBm**
  - **PAE: 24.0%**
  - **EVM: -26.0dB**
  - **Wide dynamic power range from -5dBm to 23.6dBm**

Measured 20MHz LTE/WLAN Signals



2 Metrics

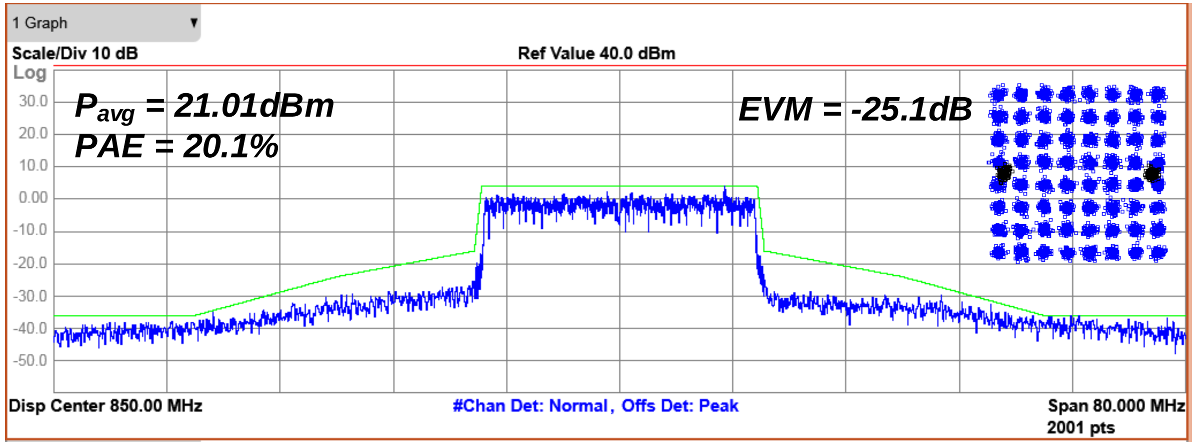
Total Car Pwr	23.556 dBm/18.00 MHz
Total PSD	---

Measure Trace	Trace 1
Trace Type	Trace Average (Active)

			Lower				Upper				
			ACP		Ref Carrier		ACP		Ref Carrier		
	Offs Freq	Integ BW	dBc	dBm	dBm	Car #	dBc	dBm	dBm	Car #	Filter
A	20.00 MHz	18.00 MHz	-31.23	-7.672	23.56	1	-32.17	-8.611	23.56	1	-3 dB
B	40.00 MHz	18.00 MHz	-40.55	-17.00	23.56	1	-39.27	-15.71	23.56	1	-3 dB

P_{avg} = 23.56dBm
PAE = 24.1%

EVM = -25.4dB



P_{avg} = 21.01dBm
PAE = 20.1%

EVM = -25.1dB

2 Table

Ref Carrier Power	Spectrum Peak Ref
21.01 dBm / 19.5 MHz	3.94 dBm

			Lower			Upper		
Start Freq	Stop Freq	Integ BW	dB	ΔLimit(dB)	Freq (Hz)	dB	ΔLimit(dB)	Freq (Hz)
9.750 MHz	10.25 MHz	100.0 kHz	-25.08	(-9.28)	-10.15 M	-24.83	(-9.93)	10.12 M
10.25 MHz	20.00 MHz	100.0 kHz	-33.80	(-6.09)	-19.65 M	-33.81	(-6.82)	18.77 M
20.00 MHz	30.00 MHz	100.0 kHz	-38.98	(-0.51)	-28.72 M	-40.10	(-1.01)	29.24 M
30.00 MHz	40.00 MHz	100.0 kHz	-41.74	(-1.74)	-31.64 M	-40.05	(-0.05)	32.48 M

- **LTE 20MHz 64QAM w/o DPD:**
  - **Pout: 23.6dBm**
  - **PAE: 24.1%**
  - **EVM: -25.4dB**

- **WLAN 20MHz 64QAM w/o DPD:**
  - **Pout: 21.0dBm**
  - **PAE: 20.1%**
  - **EVM: -25.1dB**

Outline

- Motivation
- Operations of Transformer-Based Complex-Domain Cell Sharing and Load Modulation
- Circuit Implementation
- Measurement Results
- **Conclusions**

Comparison with Prior Works

	This Work	JSSC 2016 [1]	JSSC 2017 [2]	ISSCC 2017 [3]	RFIC 2019 [7]
Architecture	**Quadrature with Complex-Domain load modulation**	Class-G Quadrature	Quadrature with IQ sharing	Quadrature with IQ sharing	Quadrature with Class-G Doherty
On-chip Balun	**1 transformer**	No	No	1 transformer	2 transformers
Frequency (GHz)	**0.85**	2.0	0.8	2.5	2.2
Resolution (bit)	**15**	7	6	11	12
Peak Pout (dBm)	**29.3**	20.5	13.9	28.6	27.8
Peak PAE (%)	**43.1**	20	40.4	35	32.1
Modulation Signal	**LTE 10MHz, 64QAM**	LTE 10MHz, 64QAM	LTE 10MHz, 16QAM	WLAN 20MHz	20-MHz SingleCarrier 1024 QAM
Pavg (dBm)	**23.6**	14.5	6.97	17.3	21
PAE (%)	**24.4**	12.2	29.1	11	18.4
EVM (dB)	**-25.6**	-28.9	-25.9	-27.3	-43
W/ DPD	**No**	Yes	Yes	No	Yes
Supply Voltage (V)	**1.2/2.4**	1.2/2.4	1.1	1.1	2.55/1.25
Die Area (mm^2)	**1.15×1.04**	1.75×1	1.66×0.66	1×1	1.07*0.845
Technology	**55nm CMOS**	65nm RF CMOS	28nm CMOS	28nm CMOS	65nm CMOS

†Results measured with a 50ohm GSG probe.

Conclusions

- **A 15b quadrature DPA with transformer-based complex-domain cell sharing and load modulation is presented.**
- **A PCT power combiner is introduced for high output power, back-off efficiency enhancement and compact implementation.**
- **The quadrature DPA achieves:**
  - **15b resolution, 29.3dBm peak Pout, 43.1% peak PAE**
  - **12 efficiency peaks in the I/Q complex plane**
  - **Comparable average Pout and average PAE with polar DPA**
  - **Wide dynamic power range w/o DPD**

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