MILLIMETER WAVE POWER AMPLIFIERS

STATE OF THE ART AND FUTURE TECHNOLOGY TRENDS

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ASSOCIATE PROFESSOR

SCHOOL OF ELECTRICAL & COMPUTER ENGINEERING

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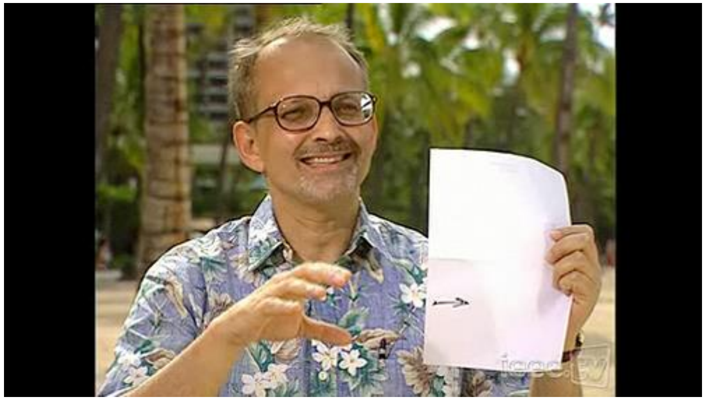

Asad Abiri, UCLA
ADC Operations

Charles Sodini, MIT
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Join the many others who have benefited from the IEEE SSCS

Willy Sansen (KU Leuven): “I joined the IEEE as a student … and got in touch with experts in the field. It is such a rewarding experience to be part of this network of microelectronic designers. It was essential for my career.”

Zhihua Wang (Tsinghua Univ.): “With a Solid-State Circuits Society membership, I am part of the SSCS family; I can attend conferences, communicate with top level experts… obtain cutting-edge technology information. All these activities are beneficial to career development”

Boris Murmann (Stanford Univ.):”My SSCS Membership have had a profound impact on my career. …it motivated me go on to graduate school. … In my work as an academic and industry consultant, I critically rely on the SSCS network … and stay up-to-date in our fast paced field”

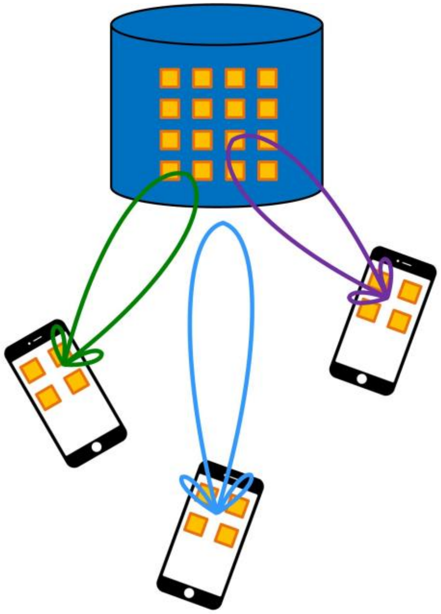
Advancing Technology for Humanity

Outline

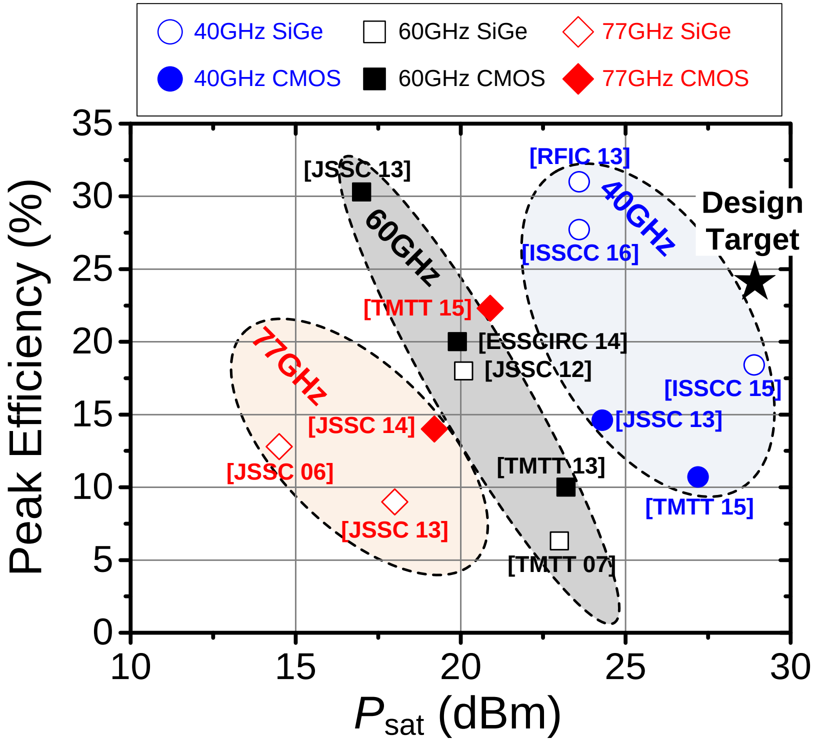
- Introduction
- State of the Art: Georgia Tech PA Survey (2000-present)
- Broadband Linear Efficient PAs
- Antenna-PA Co-Designs: Multi-Feed Mm-Wave Radiators
- Conclusion

Introduction

- **Need:** large output power and peak efficiency



$$Path\ Loss = 20\log_{10}(4\pi df/c)$$

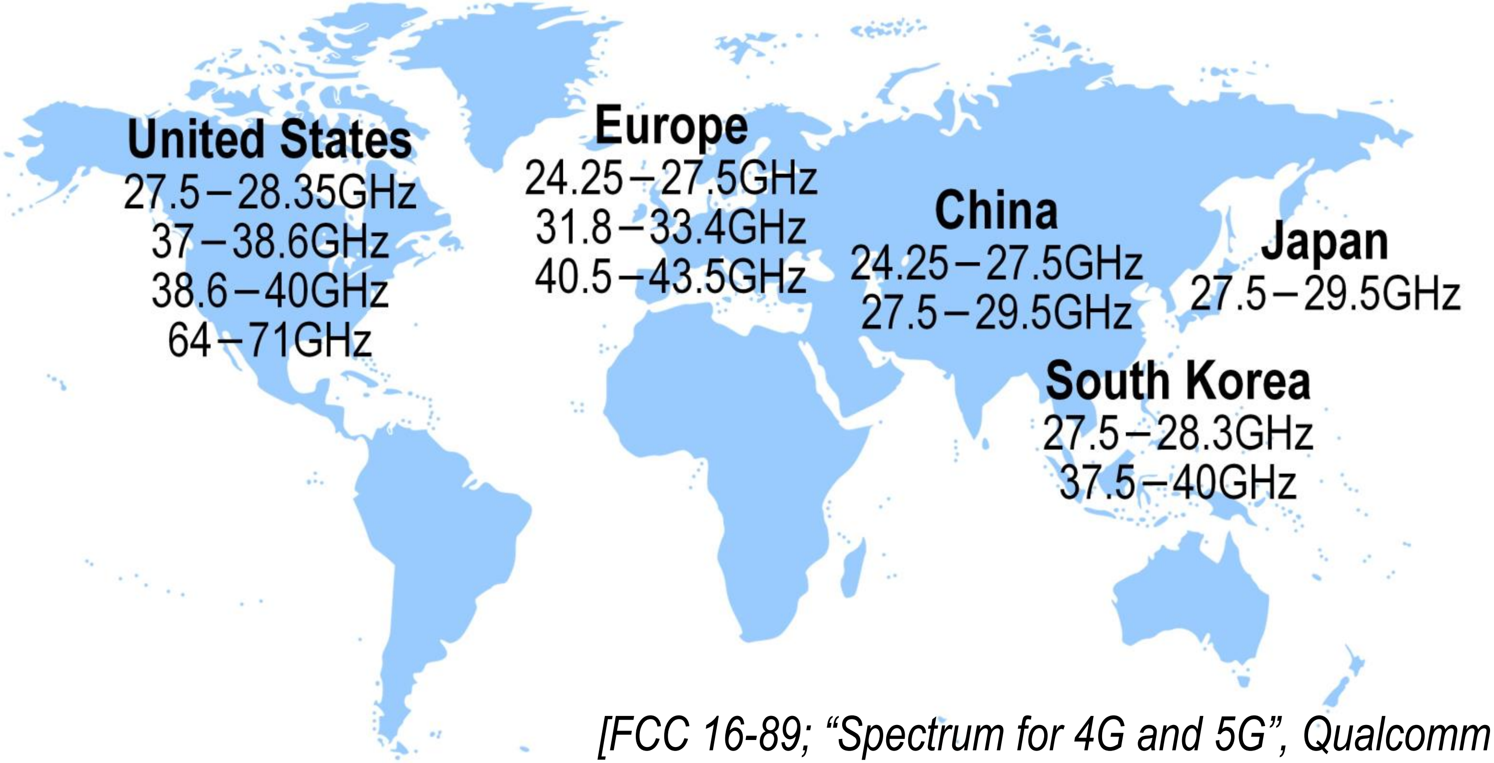


- Ensure sufficient link budget and compensate high path loss
- **Drain Efficiency** $\eta = P_{out}/P_{DC}$ and **Power Added Efficiency** $PAE = (P_{out} - P_{in})/P_{DC}$
- Thermal handling and device operation time

Introduction

- **Need:** broad or reconfigurable carrier bands

Potential 5G mm-wave bands



[FCC 16-89; "Spectrum for 4G and 5G", Qualcomm 2016]

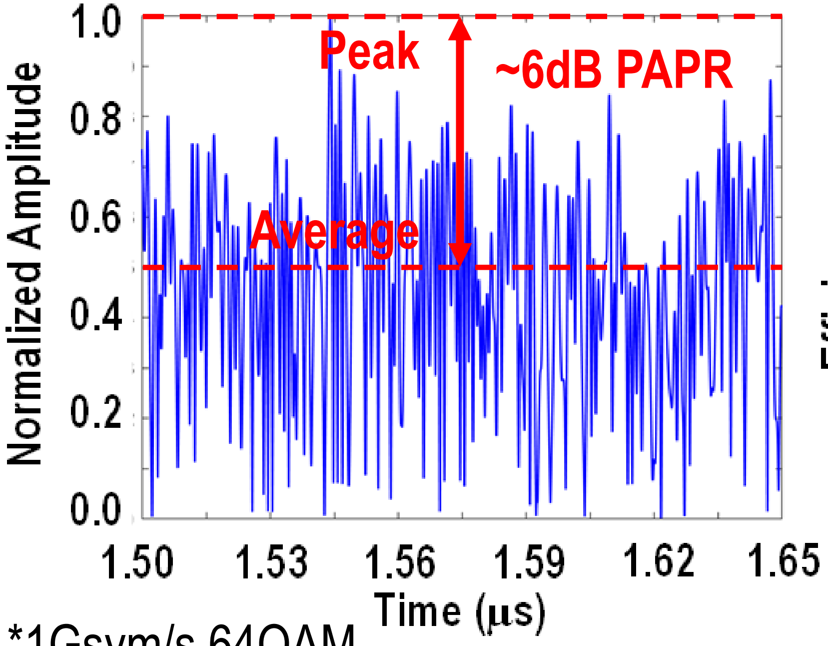
- Multi-standard communication or frequency reconfigurability and agility

Introduction

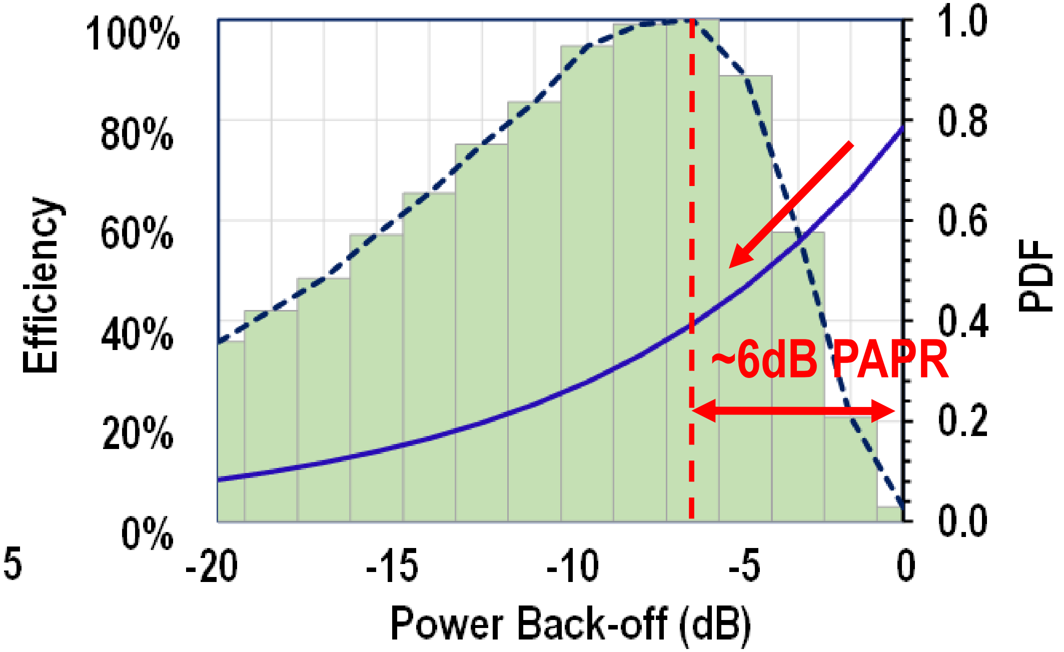
- **Need:** high back-off efficiency

PA Average Efficiency

$$\int \eta(P_{out}) \bullet pdf(P_{out})\, dP_{out}$$



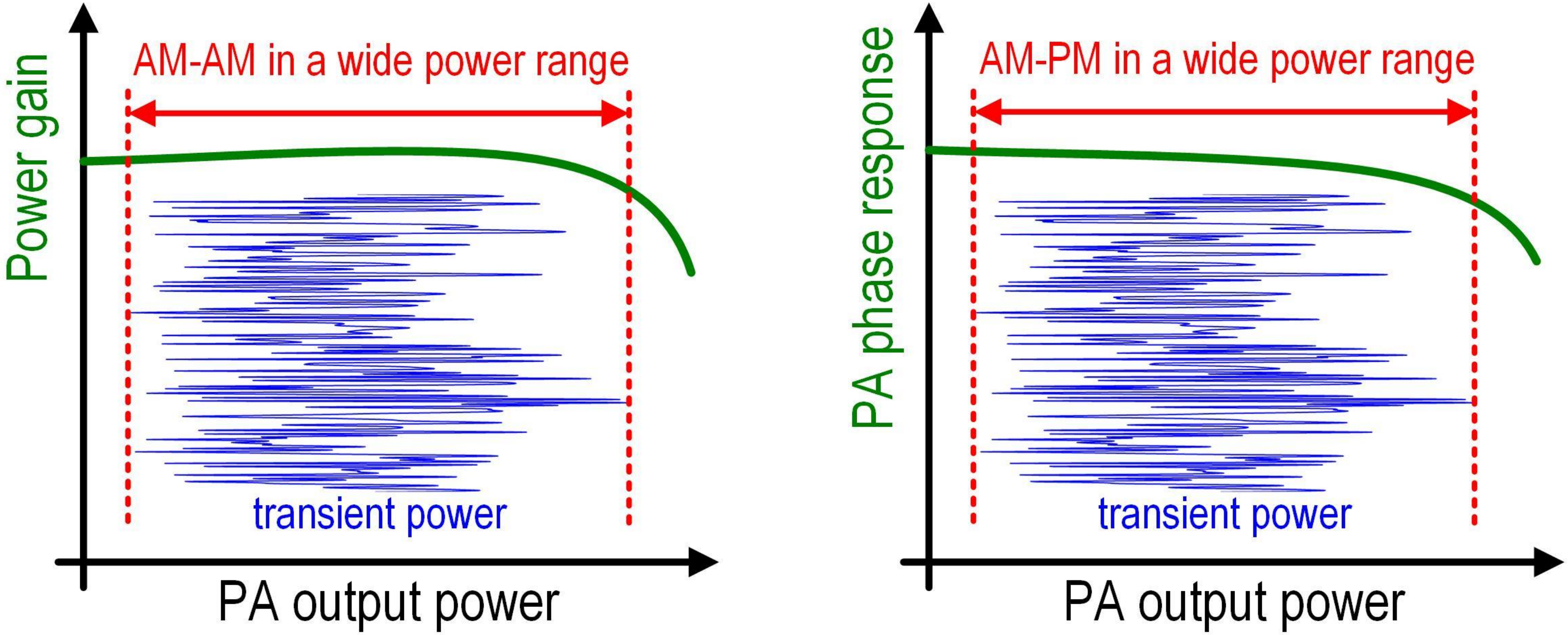
*1Gsym/s 64QAM



- Spectrum-efficient modulation (high-order QAM, OFDM) leads to high PAPR
- System average efficiency largely depends on the back-off efficiency

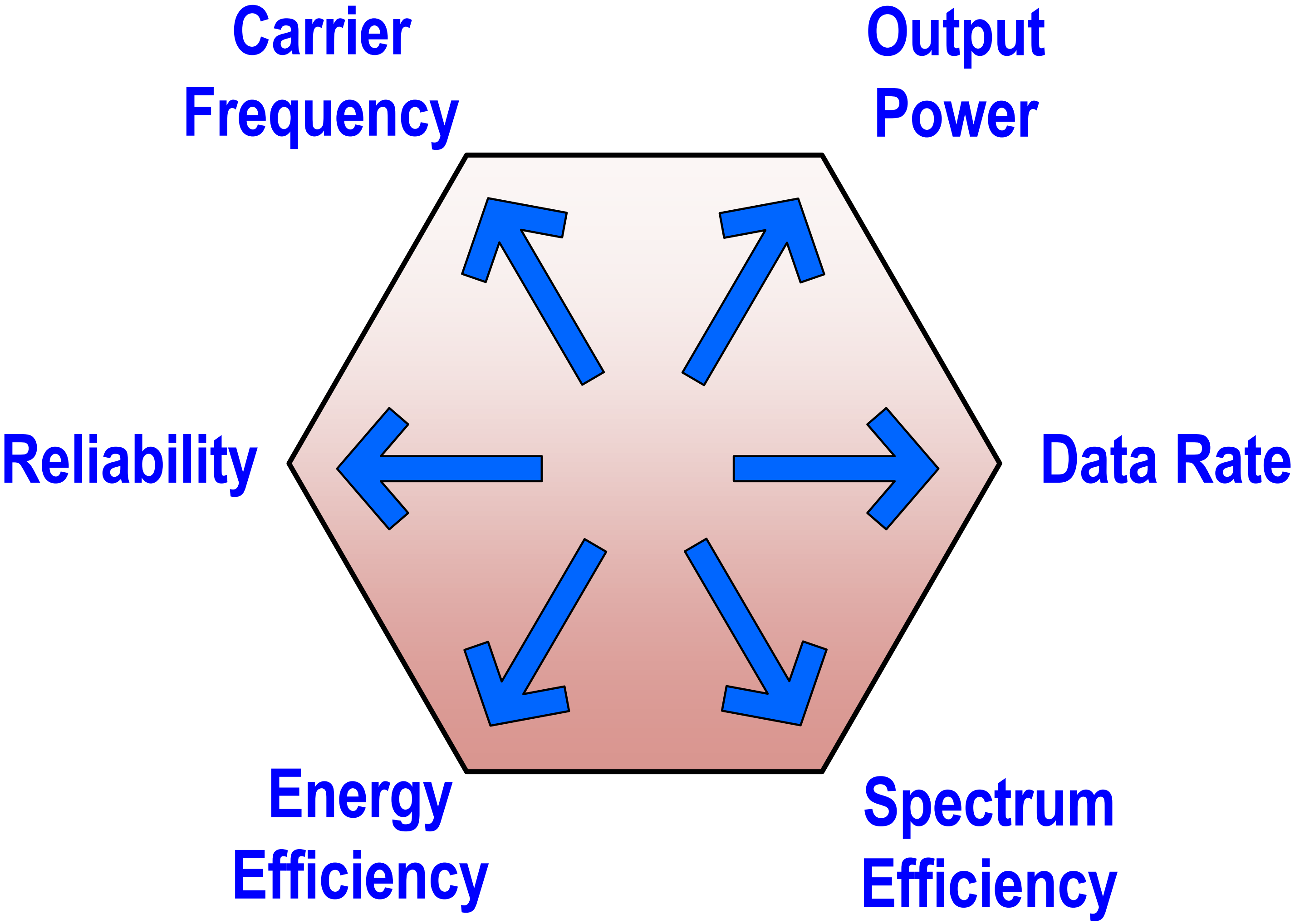
Introduction

- **Need:** high linearity

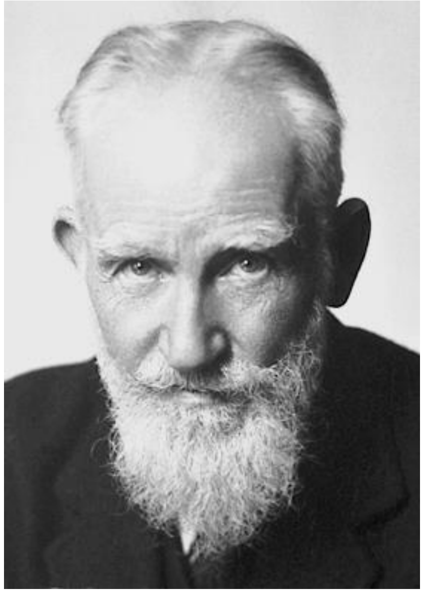


- Inherently linear for multi-Gbit/s complex modulations with minimum or even no digital pre-distortions (DPD)

Unreasonable Request for "Perfect" Mm-Wave PAs…



Unreasonable Request for “Perfect” Mm-Wave PAs…

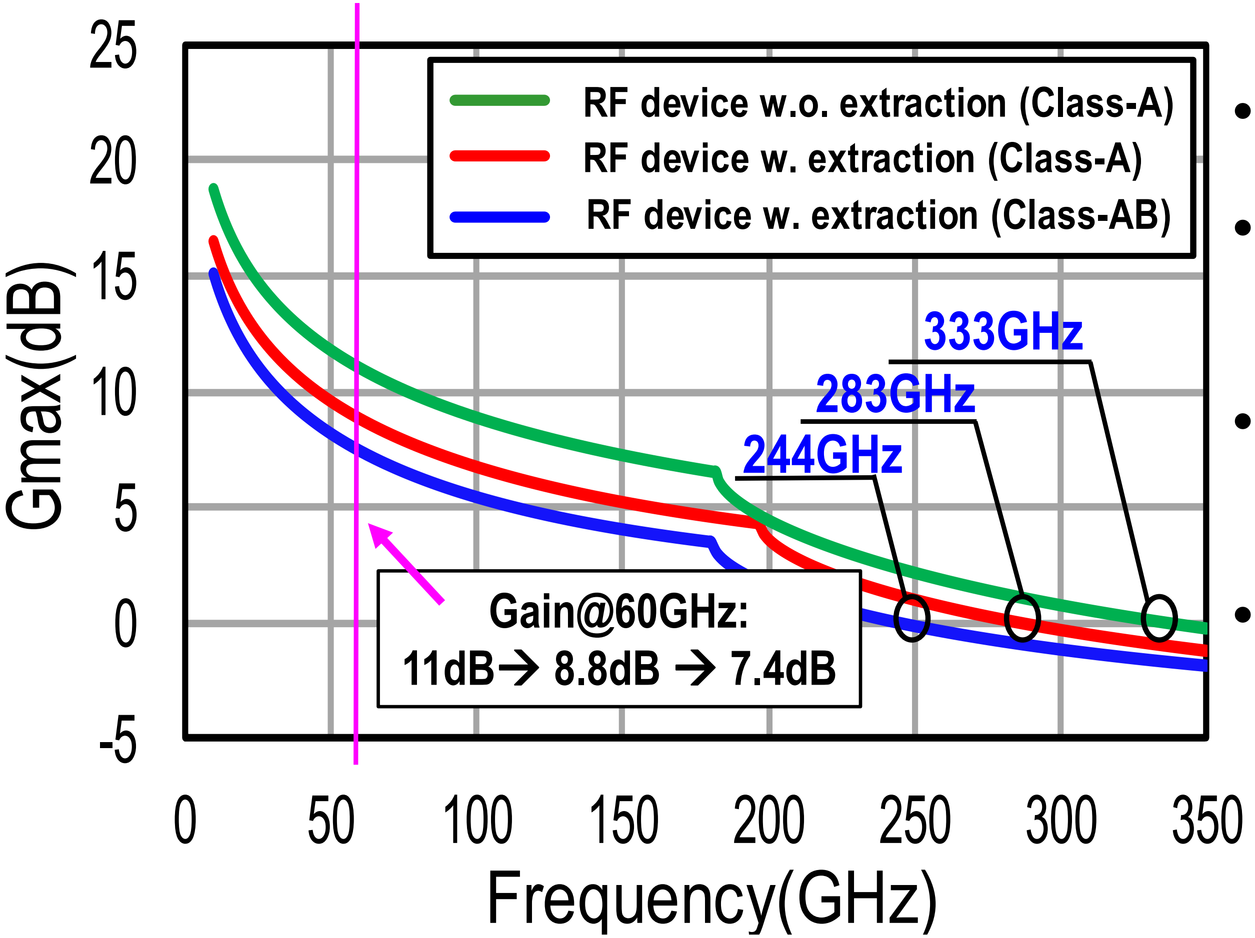


…The reasonable man adapts himself to the world. The unreasonable one persists in trying to adapt the world to himself. Therefore all progress depends on the unreasonable man…

— George Bernard Shaw (26 July 1856 – 2 November 1950), Nobel Prize Laureate for Literature in 1925.

Challenge 1: Gain, Stability, and Efficiency

Power Gain vs. Freq. for a Typical Scaled CMOS Device



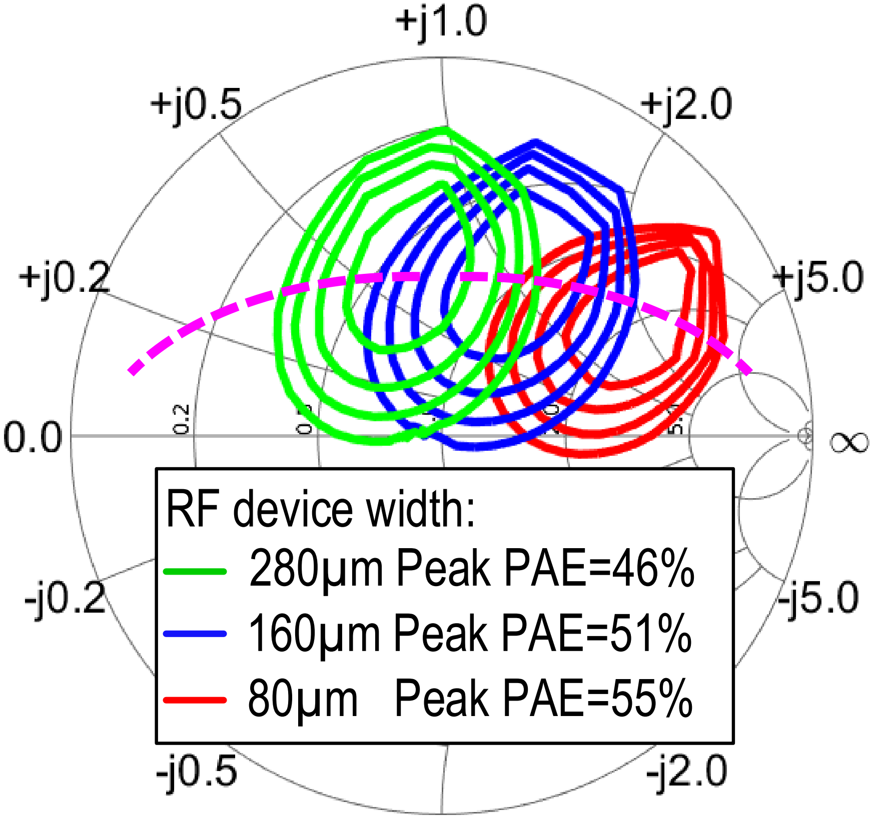
- Limited gain & f_{max}
- Small signal gain vs. large signal gain
- Multiple stages lowering $PAE=(P_{out}-P_{in})/P_{DC}$
- Stability for broadband PA

Challenge 2: Output Power and Efficiency

- Limited device output voltage swing (V_{DD}-V_{knee}) and power
- $P_{out} = \mathbf{i_{max}} \times (V_{DD}-V_{knee})/2$

  $= (V_{DD}-V_{knee})^2/2\mathbf{R_L}$
- Larger devices or more devices
- Lossy impedance transformation

Typical Optimum Load Impedance and Peak PAE† vs. Device Sizes @28GHz

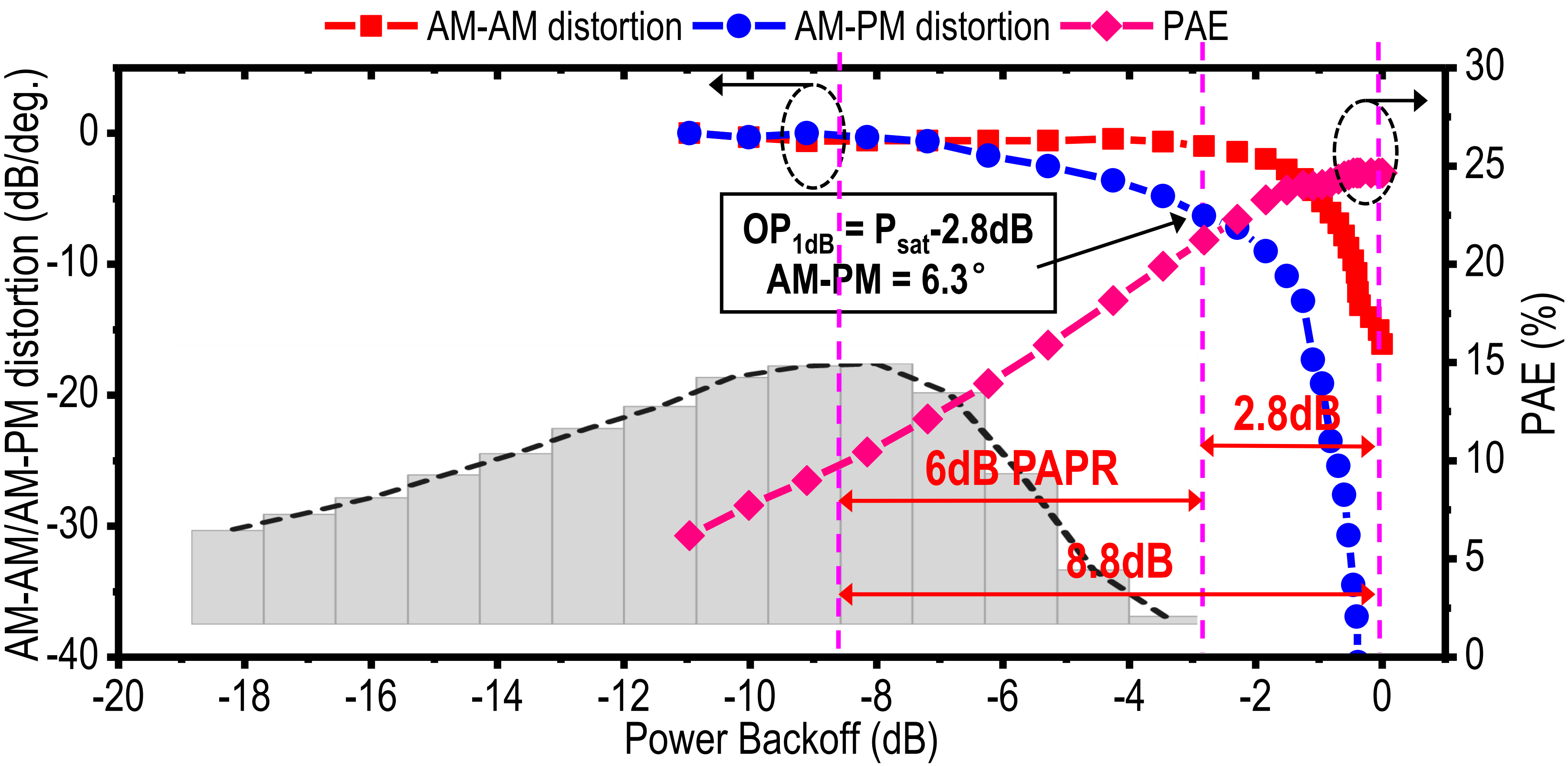


† Including PA output matching network passive loss

- I. Aoki, S. Kee, D. Rutledge, and A. Hajimiri, *IEEE T-MTT*, 2002.

Challenge 3: Efficiency and Linearity

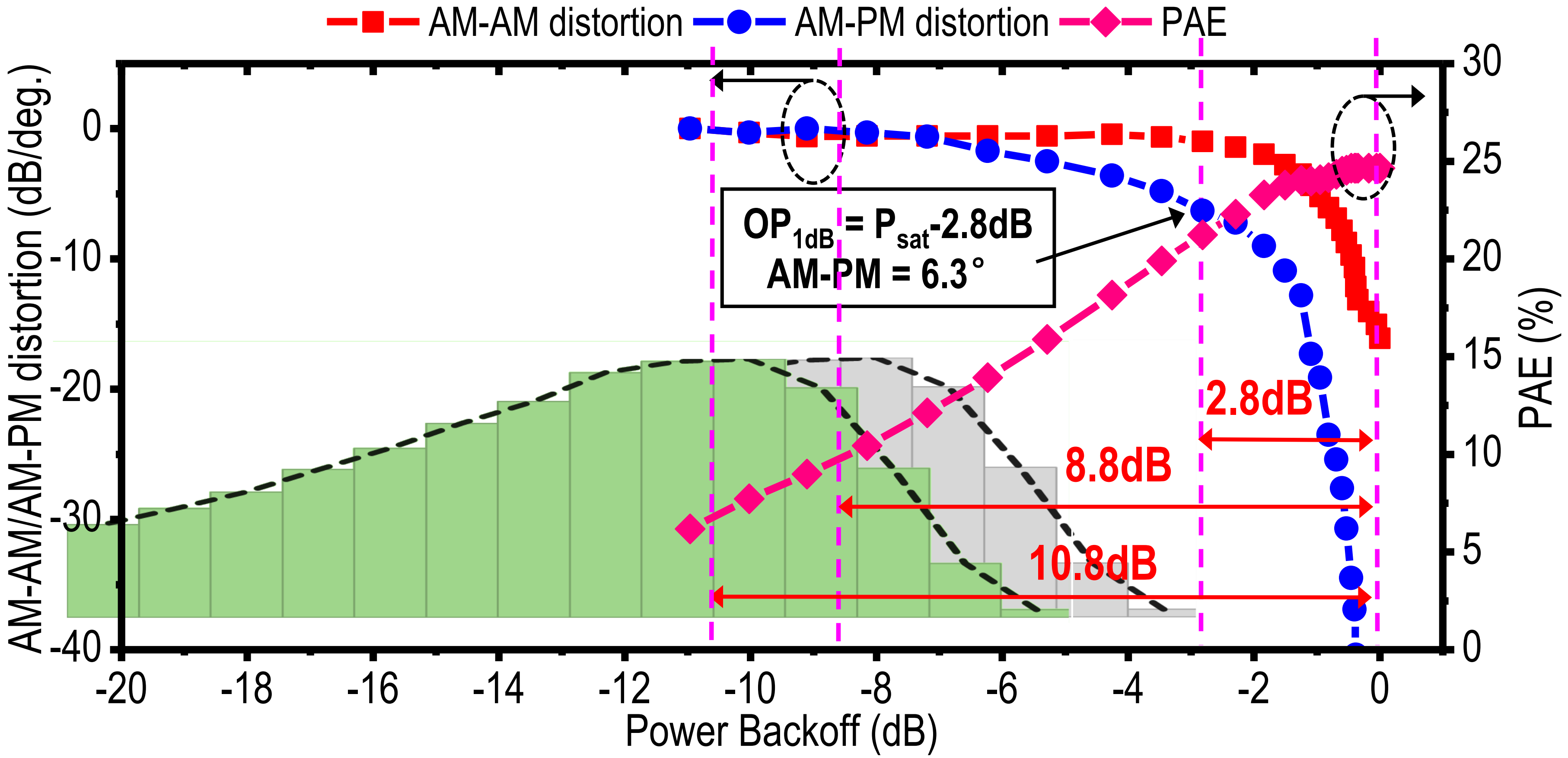
Measured AM-AM/AM-PM vs. P_{out} backoff for a typical CMOS 28GHz 18dBm Class-AB PA



- Avoid amplitude clipping over OP_{1dB} → An extra power back-off of 2.8dB
- **$P_{ave} = P_{sat}$ - 2.8dB - 6dB PAPR → - 8.8dB PBO → ~9% average PAE**

Challenge 3: Efficiency and Linearity

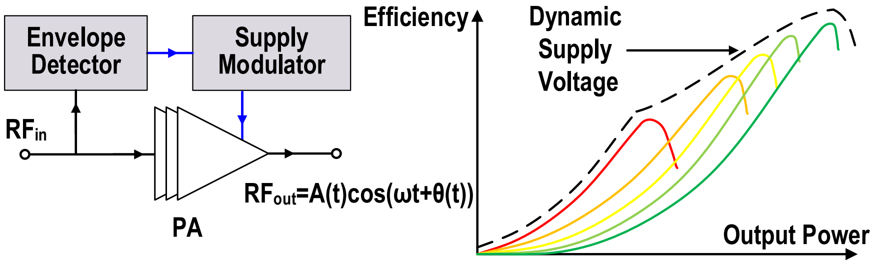
Measured AM-AM/AM-PM vs. P_{out} backoff for a typical CMOS 28GHz 18dBm Class-AB PA



- Avoid AM-PM distortion → An additional power back-off of ~2dB
- **$P_{ave} = P_{sat}$ - 2dB - 2.8dB - 6dB PAPR → - 10.8dB PBO → ~6% average PAE**

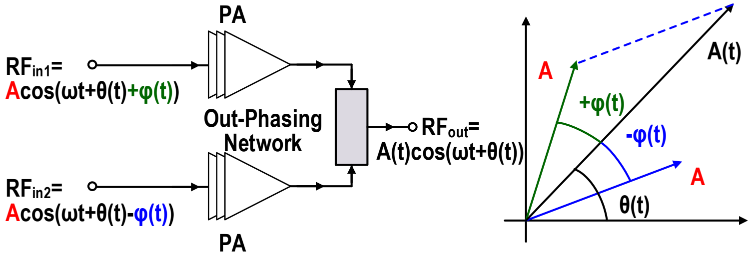
Challenge 4: Efficiency, Data Rate, Linearity

- **ET PAs**
  - Deep PBO efficiency enhancement
  - Supply modulator efficiency
  - AM supply BW (×3~×5) → Limited mod. BW (~150MHz)



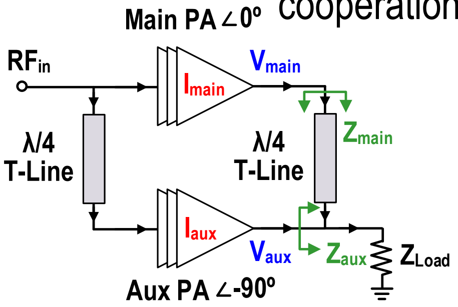
- Zoya Popovic, *IEEE Microwave Magazine,* May 2017.

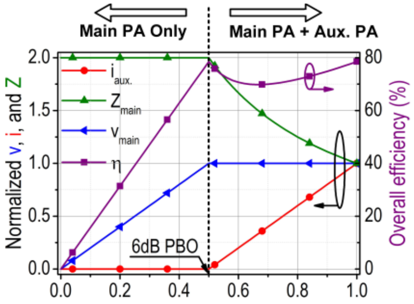
- **LINC PA Outphasing**
  - Deep PBO efficiency enhancement
  - DPD computation
  - Limited Chireix compensation BW
  - PM BW (×5~×7) → Limited mod. BW



- Hongtao Xu, et al., *IEEE J. Solid-State Circuits,* May 2011.
- T. Barton, et al., *IEEE T-MTT,* Apr. 2016.

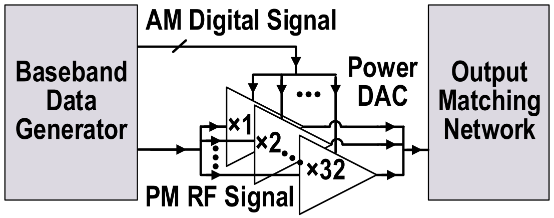
- **Doherty PAs**
  - PBO efficiency enhancement
  - Wideband modulation
  - Limited carrier BW and Main/Aux cooperation

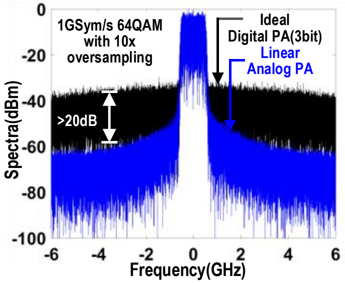




- B. Kim, et al., *IEEE Microwave Magazine,* Oct. 2006.
- S. Hu and H. Wang, *IEEE ISSCC,* 2017.

- **Digital PAs / Power DACs**
  - Versatile controls & high peak efficiency
  - Spurs, Limited ENOB, AM/PM sync
  - AM(×3~×5)/PM (×5~×7) BW expansion
  - Baseband computation





- K. Khalaf, et al., *IEEE J. Solid-State Circuits,* Jul. 2016.

Outline

- Introduction
- **State of the Art: Georgia Tech PA Survey (2000-present)**
- Broadband Linear Efficient PAs
- Antenna-PA Co-Designs: Multi-Feed Mm-Wave Radiators
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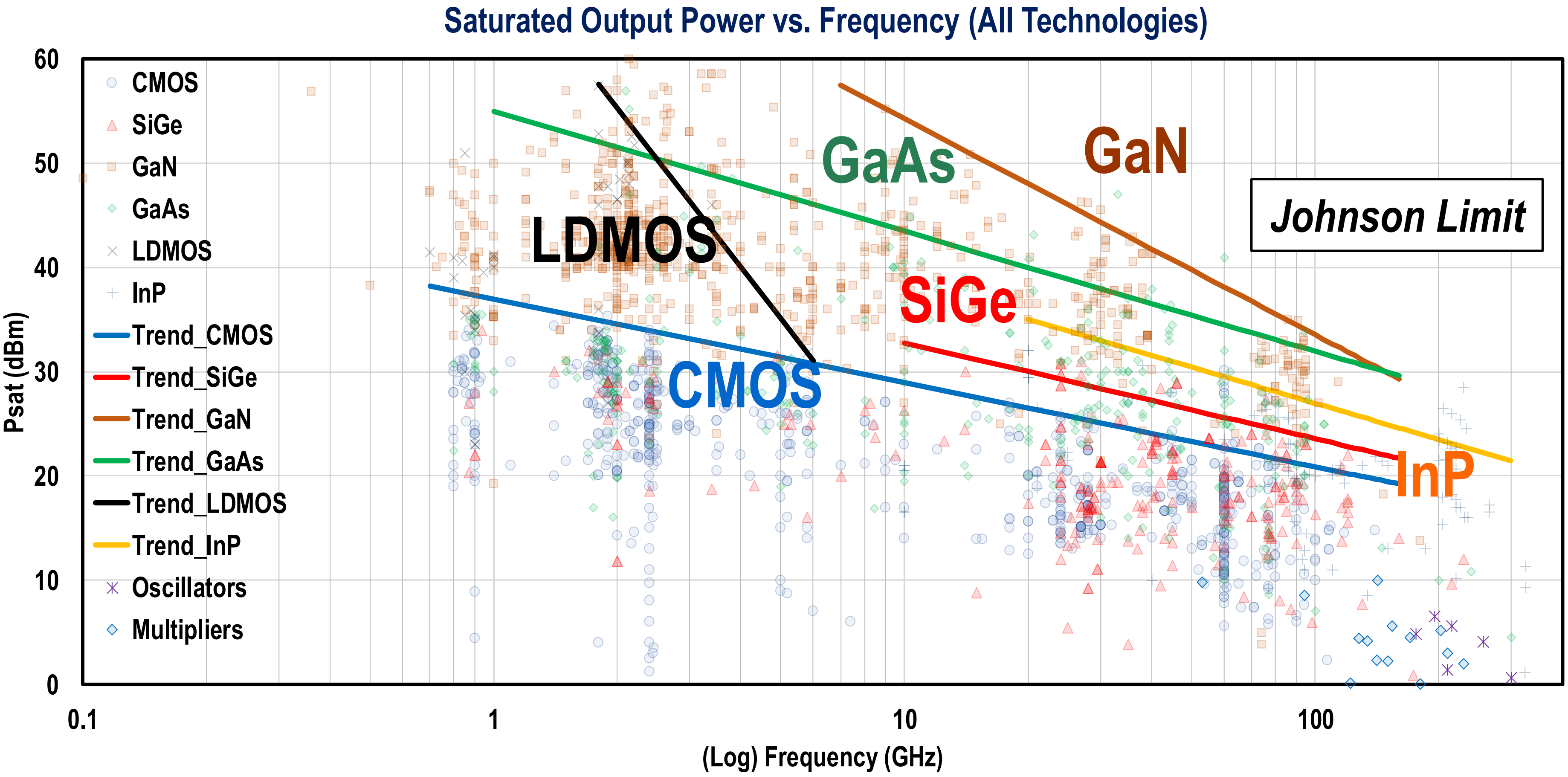
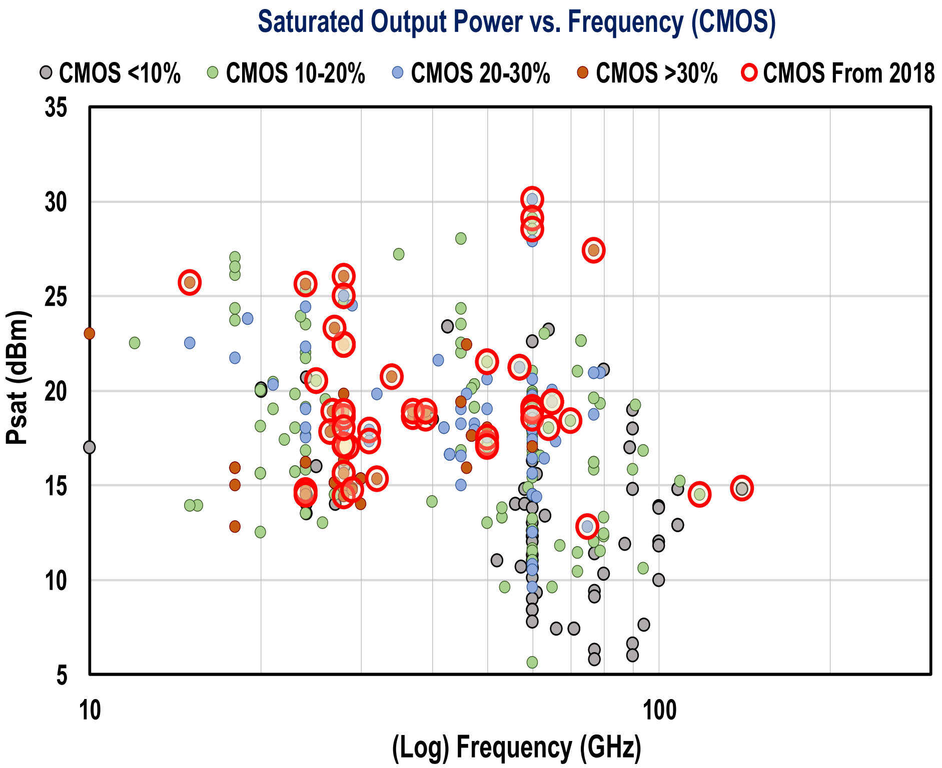
Georgia Tech PA Survey (2000-present)

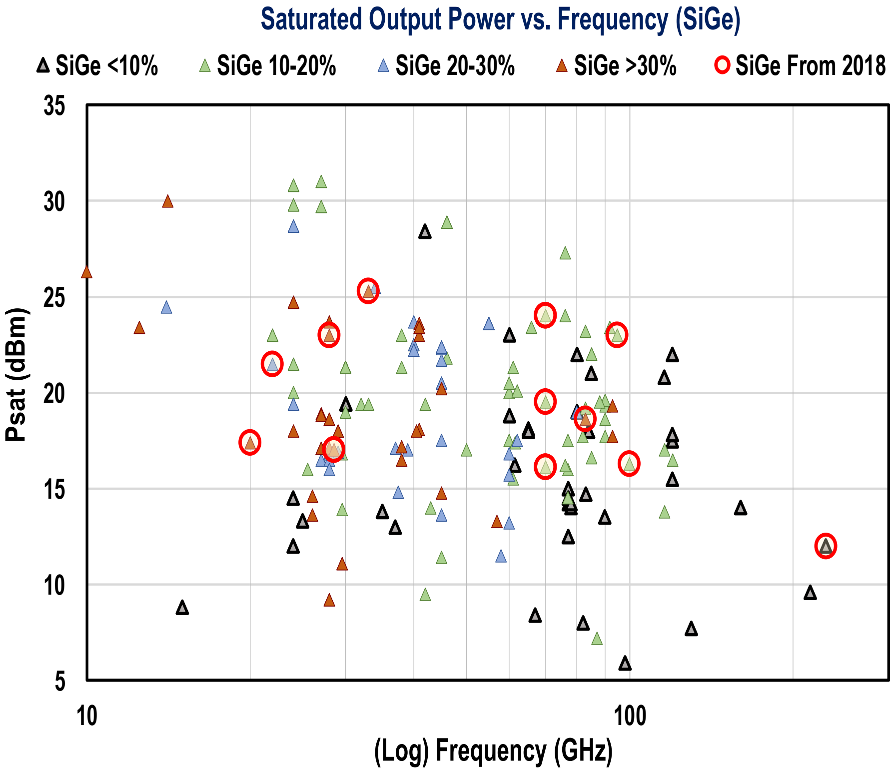
- CW/Modulation Performance: Frequency (0.5-200GHz), Technologies, P_{out}, PAE, EVM, etc.
- Version-3 available to the public at http://gems.ece.gatech.edu/PA_survey.html


Saturated Output Power vs. Frequency (All Technologies)

Georgia Tech PA Survey (2000-present)

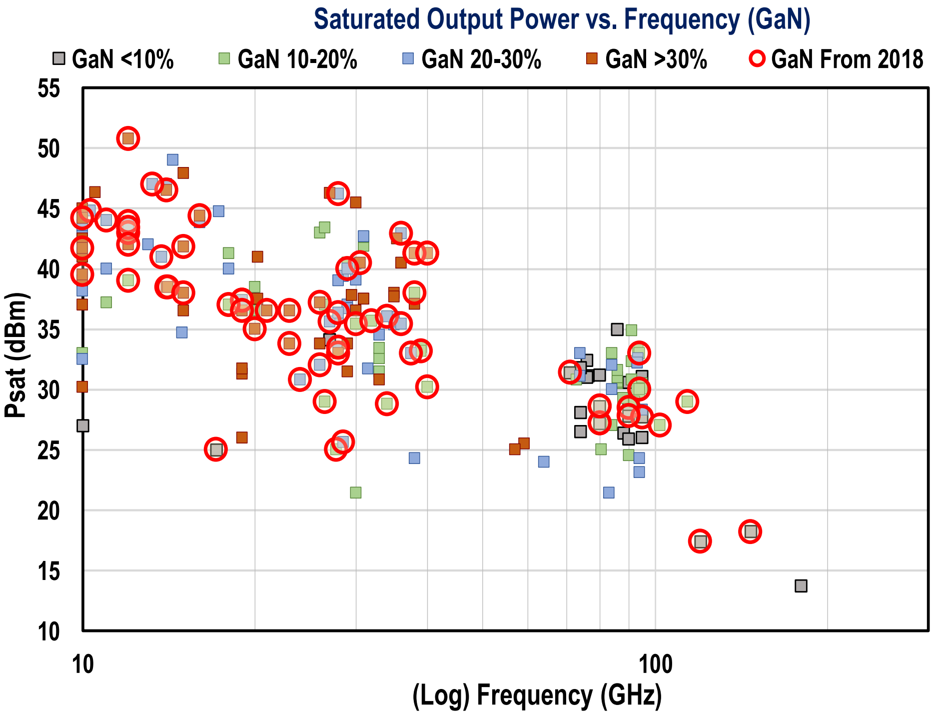
- State-of-the-Art PA P_{sat} vs. Frequency (CMOS and SiGe)

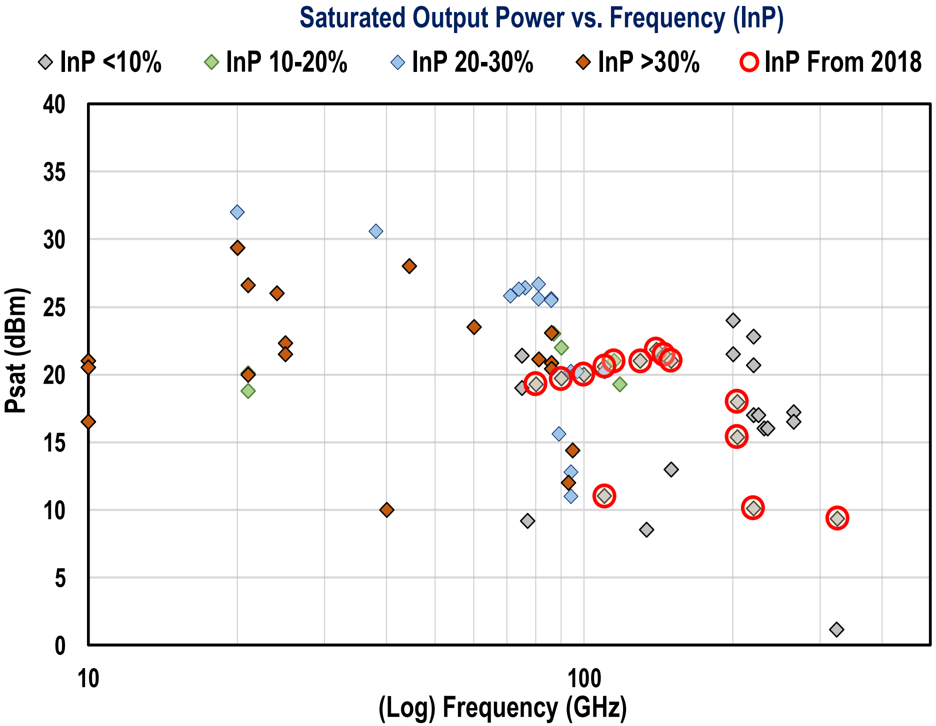




Georgia Tech PA Survey (2000-present)

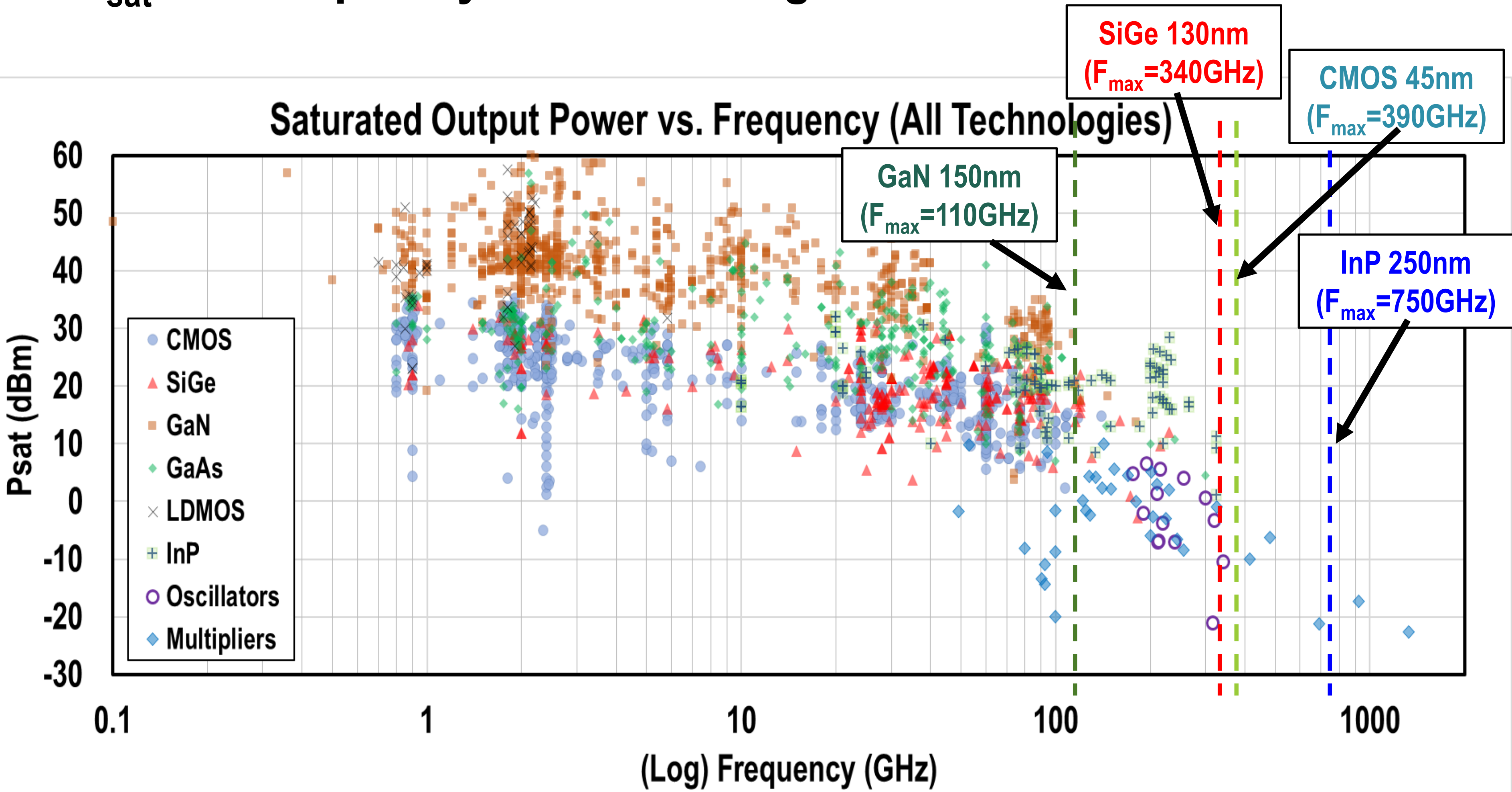
- State-of-the-Art PA P_{sat} vs. Frequency (GaN and InP)





Georgia Tech PA Survey (2000-present)

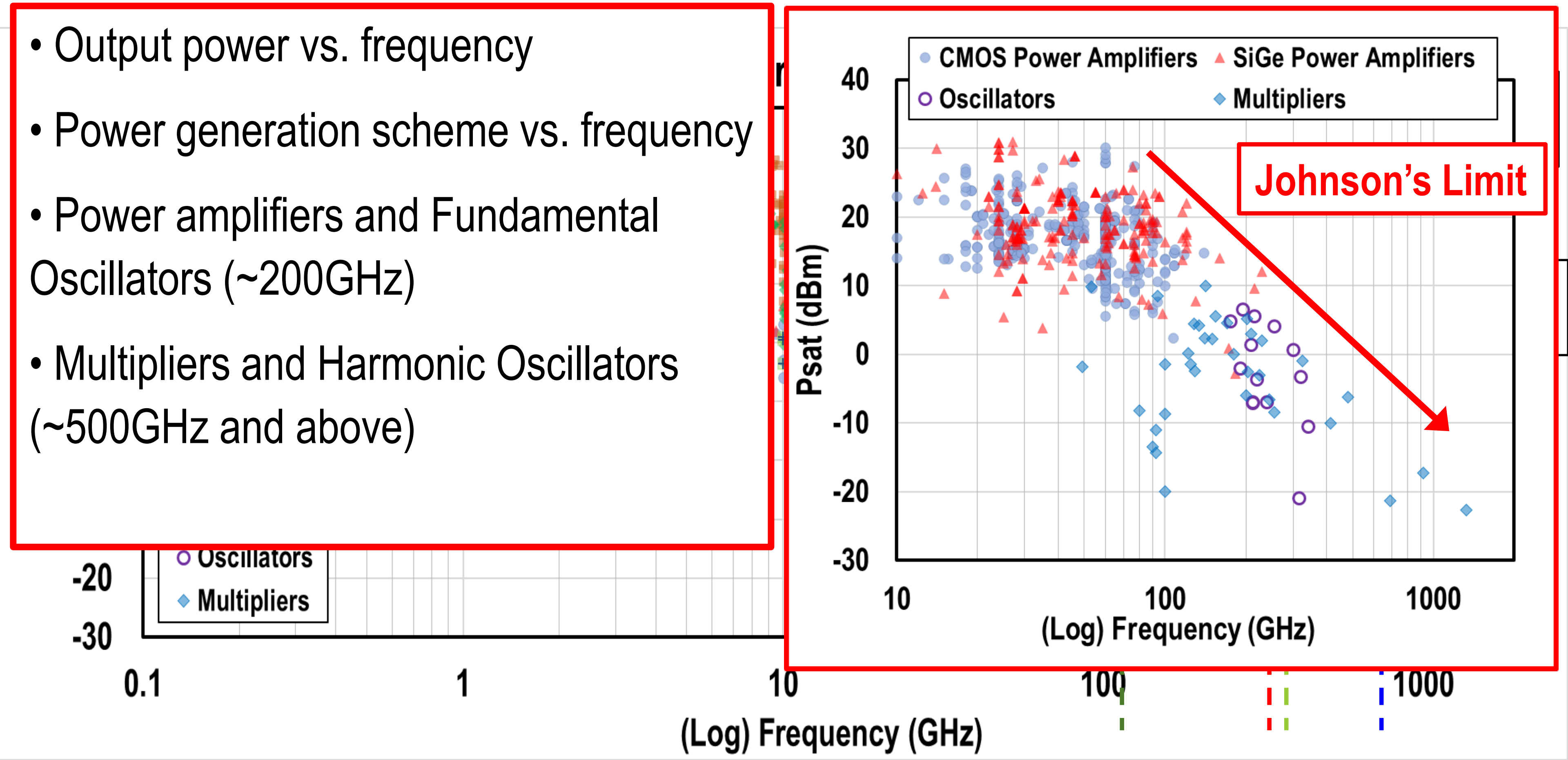
- P_{sat} vs. Frequency vs. Technologies



Georgia Tech PA Survey (2000-present)

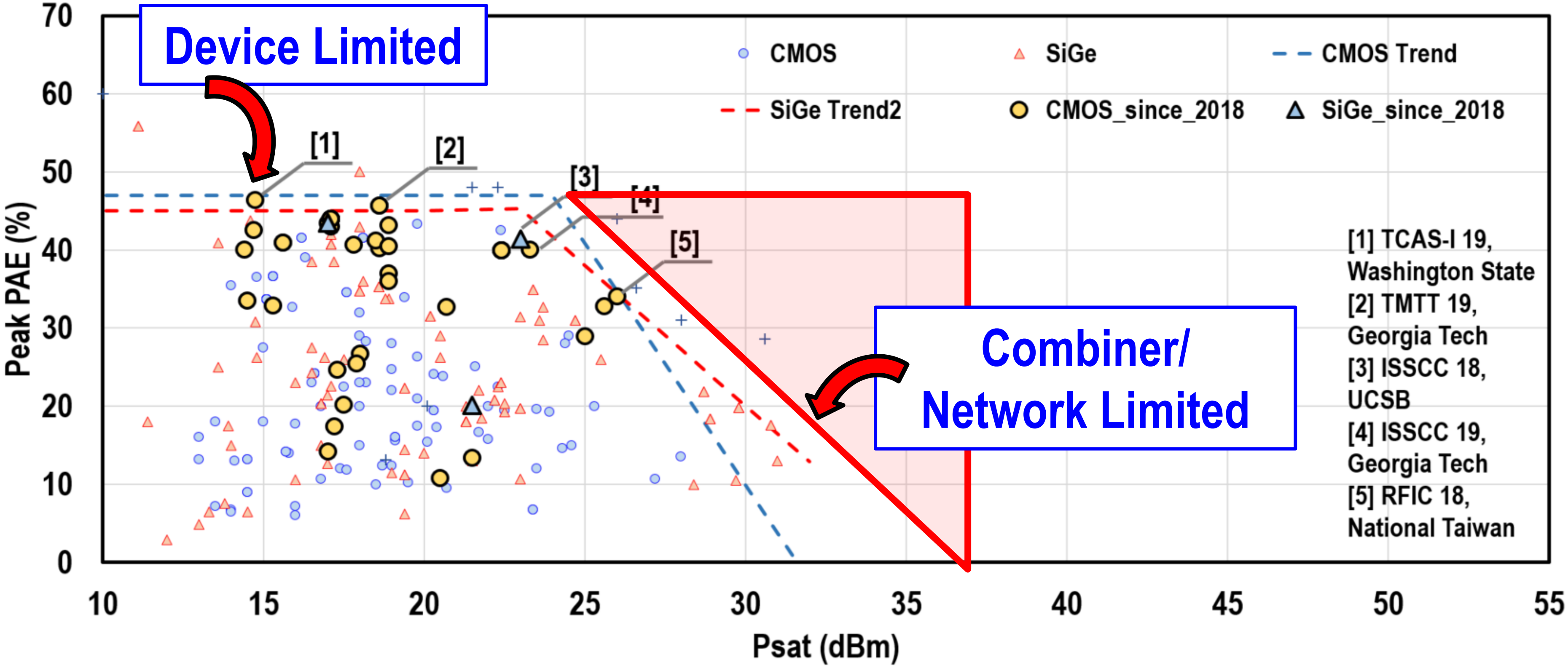
- P_{sat} vs. Frequency vs. Technologies

- Output power vs. frequency
- Power generation scheme vs. frequency
- Power amplifiers and Fundamental Oscillators (~200GHz)
- Multipliers and Harmonic Oscillators (~500GHz and above)



Georgia Tech PA Survey (2000-present) GEMS

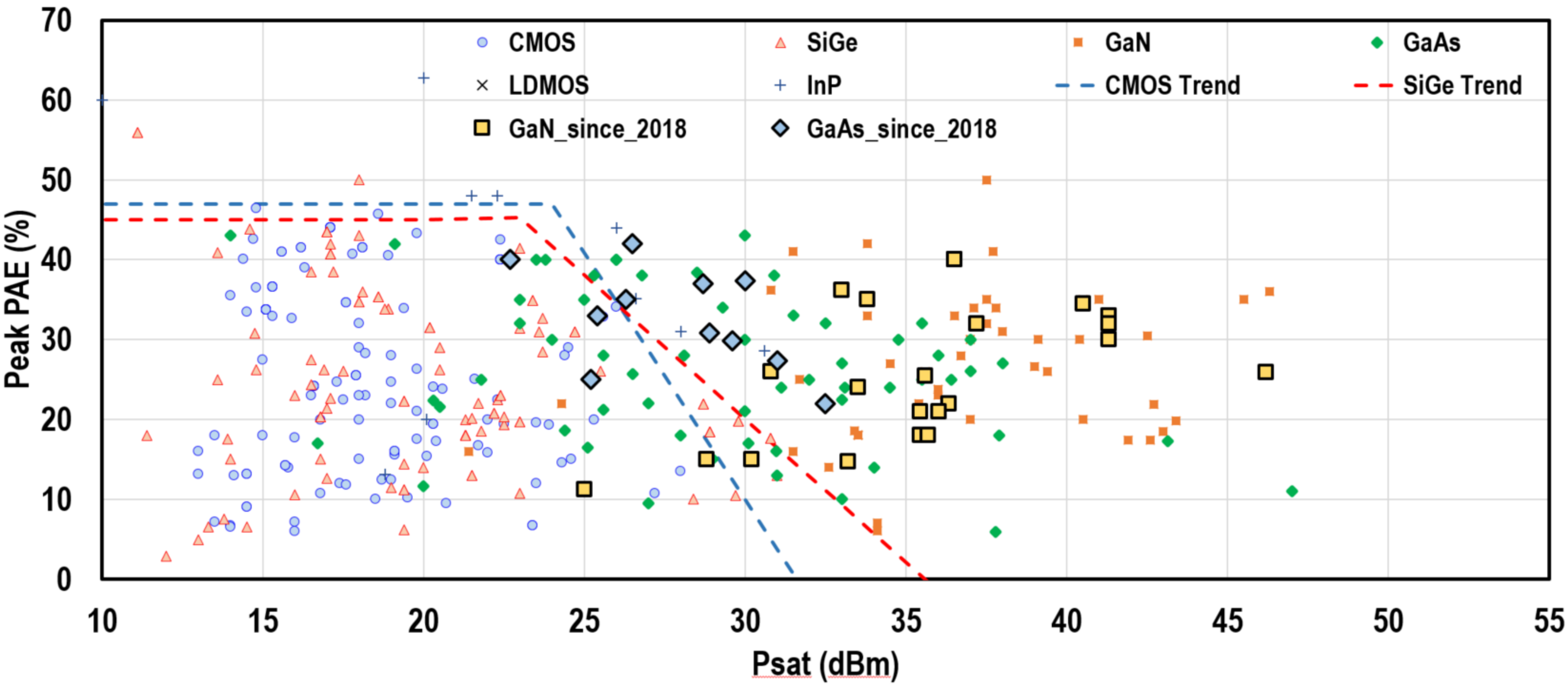
- **State-of-the-Art PA P_{sat} vs. Peak PAE (20-50GHz PAs)**



[1] TCAS-I 19, Washington State
[2] TMTT 19, Georgia Tech
[3] ISSCC 18, UCSB
[4] ISSCC 19, Georgia Tech
[5] RFIC 18, National Taiwan

Georgia Tech PA Survey (2000-present) GEMS

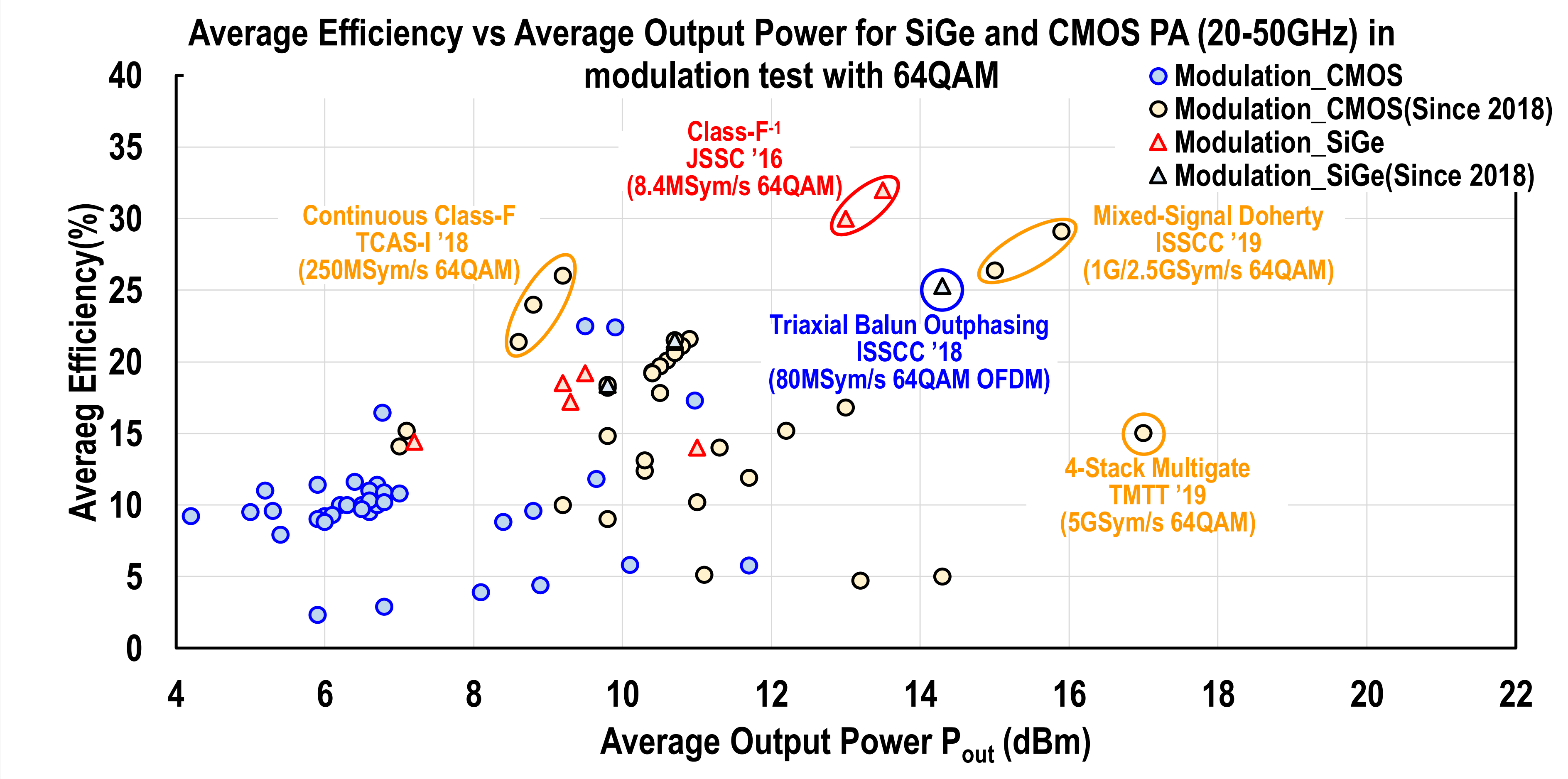
- State-of-the-Art PA P_{sat} vs. Peak PAE (20-50GHz PAs)



Georgia Tech PA Survey (2000-present) GEMS

- **20-50GHz CMOS/SiGe PAs with 64QAM modulation test**

PAs with MER<-20dB and >150MSym/s modulation rate. (Majority of the modulation signals have ~7dB PAPR. A few use OFDM 64QAM with ~9dB PAPR.)

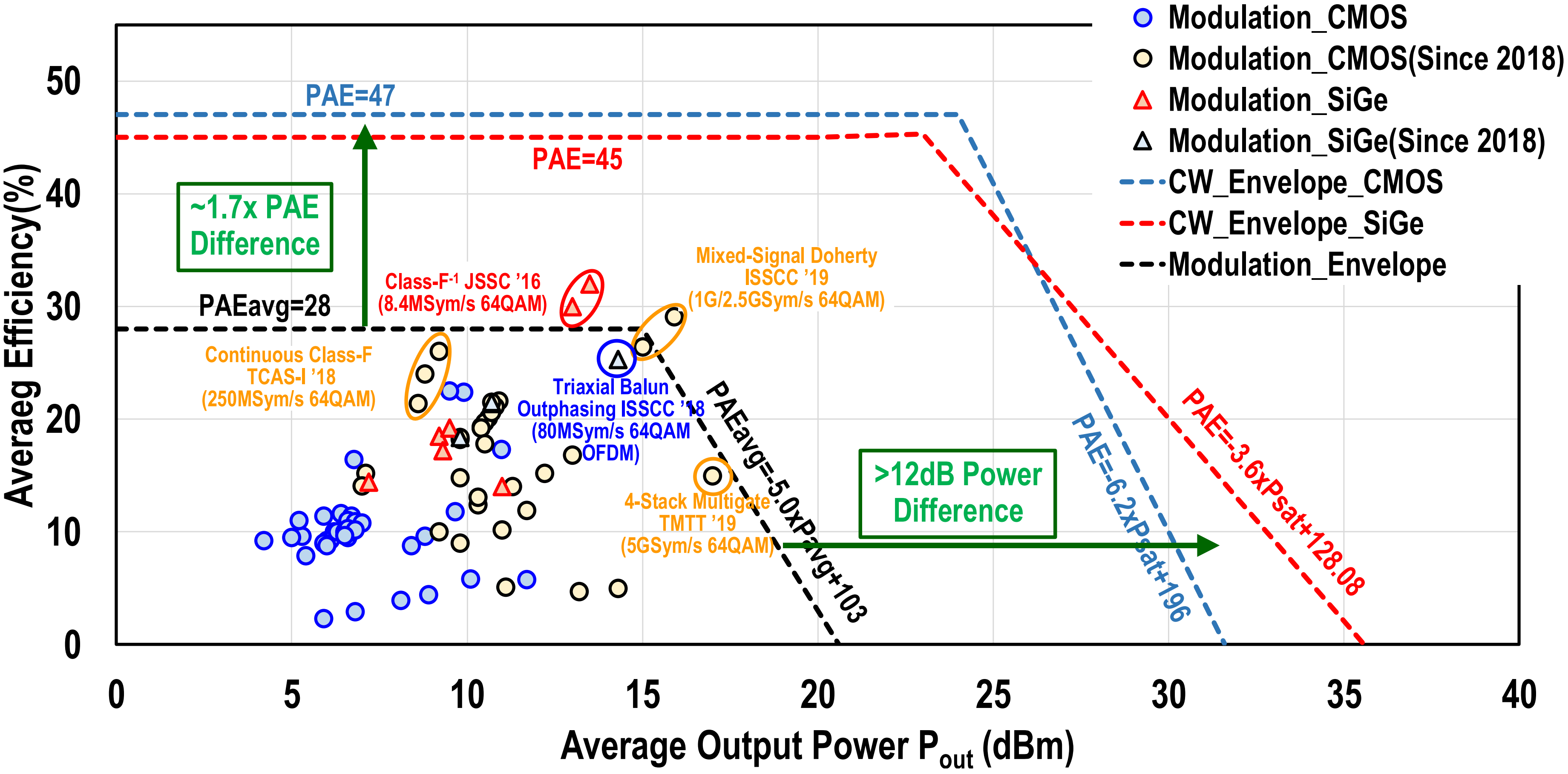


Georgia Tech PA Survey (2000-present)

- **20-50GHz CMOS/SiGe PAs with 64QAM modulation test**

  HUGE DIFFERENCE between P_{out} / PAE in modulation tests vs. CW operations.

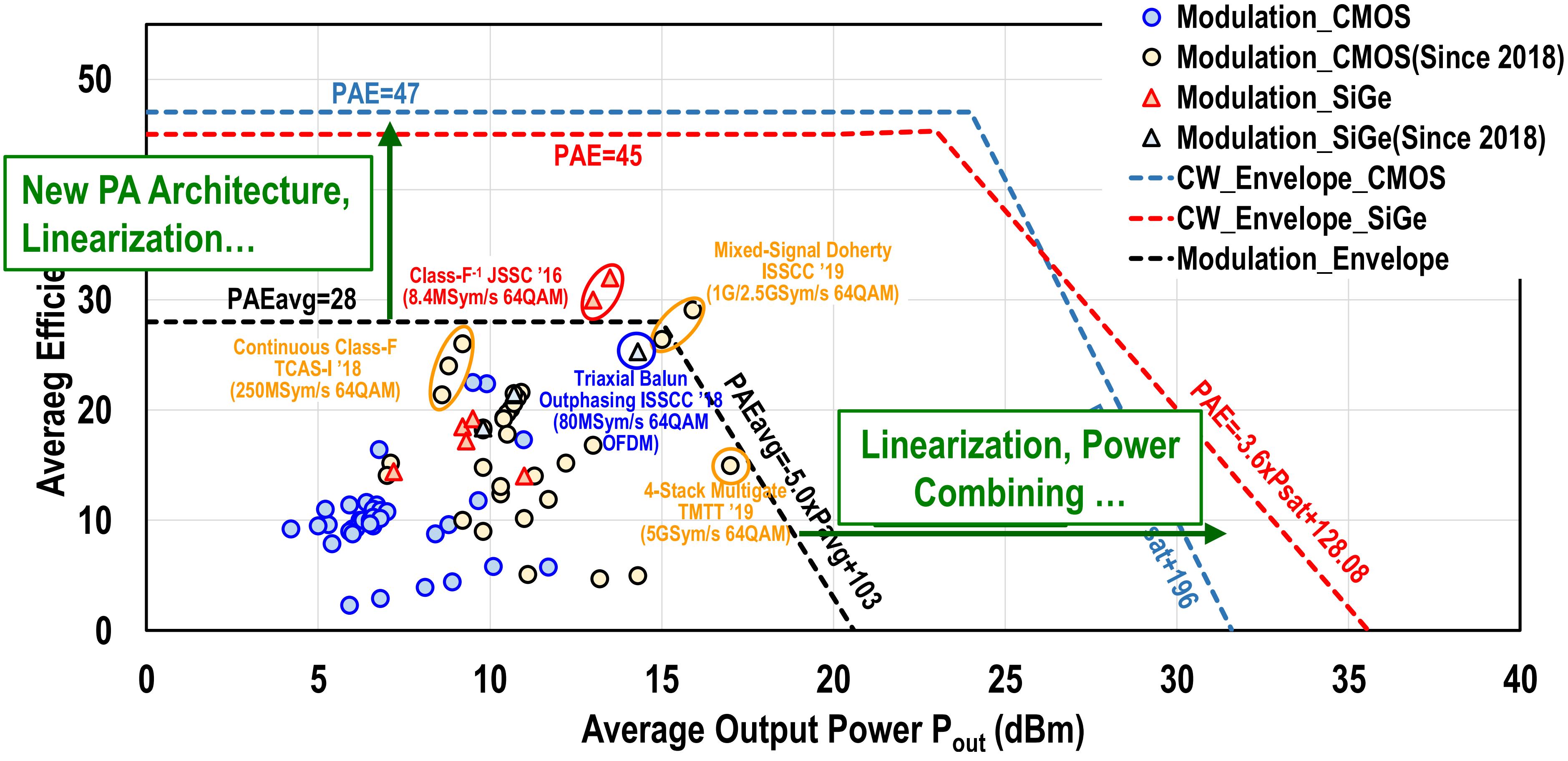
Modulation and CW Performance Comparison for SiGe and CMOS (20-50GHz)



Georgia Tech PA Survey (2000-present) GEMS

- 20-50GHz CMOS/SiGe PAs with 64QAM modulation test

To push the boundary of average P_{out} and PAE requires linearization techniques, power combining, and new architecture ……



Modulation and CW Performance Comparison for SiGe and CMOS (20-50GHz)

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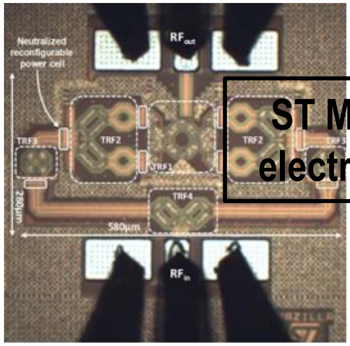
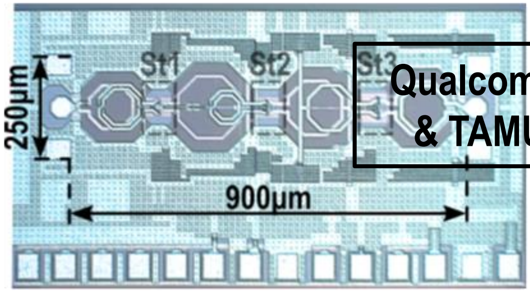
Mm-Wave Linear Class-AB PAs in Silicon

- **Balanced performance of efficiency, linearity, and modulation BW**
- **“RF-in-RF-out” PAs → System integration**



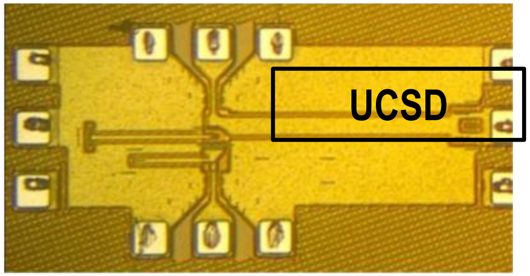
ST Micro-electronics

- A. Larie, *et al.*, *IEEE ISSCC 2015.*
- 60GHz Class AB/C in 28nm FD-SOI



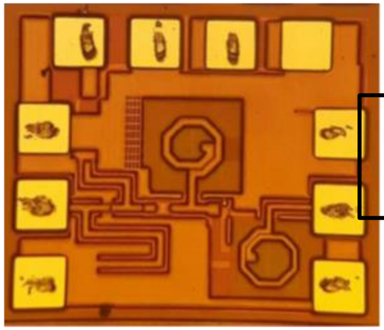
Qualcomm & TAMU

- S. Shakib, *et al.*, *IEEE ISSCC 2017*.
- 28GHz Class AB in 40nm CMOS



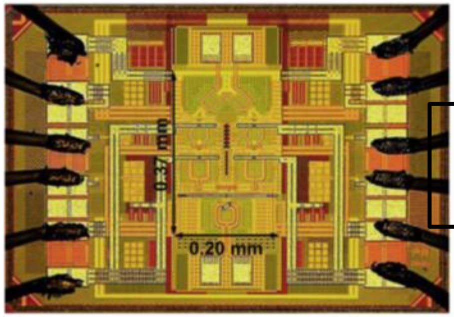
UCSD

- A. Agah, *et al.*, *IEEE RFIC 2012.*
- 45GHz Stacked Class AB in 45nm SOI



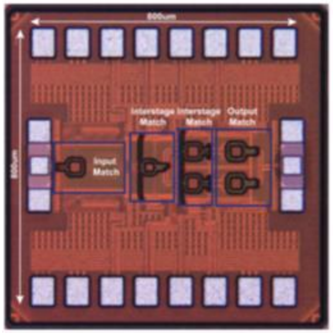
NC State

- A. Sarkar, B. Floyd, *IEEE T-MTT 2017.*
- 28GHz Class AB in 130nm SiGe



KU Leuven

- D. Zhao, P. Reynaert, *IEEE JSSC 2013.*
- 60GHz Class AB in 40nm CMOS

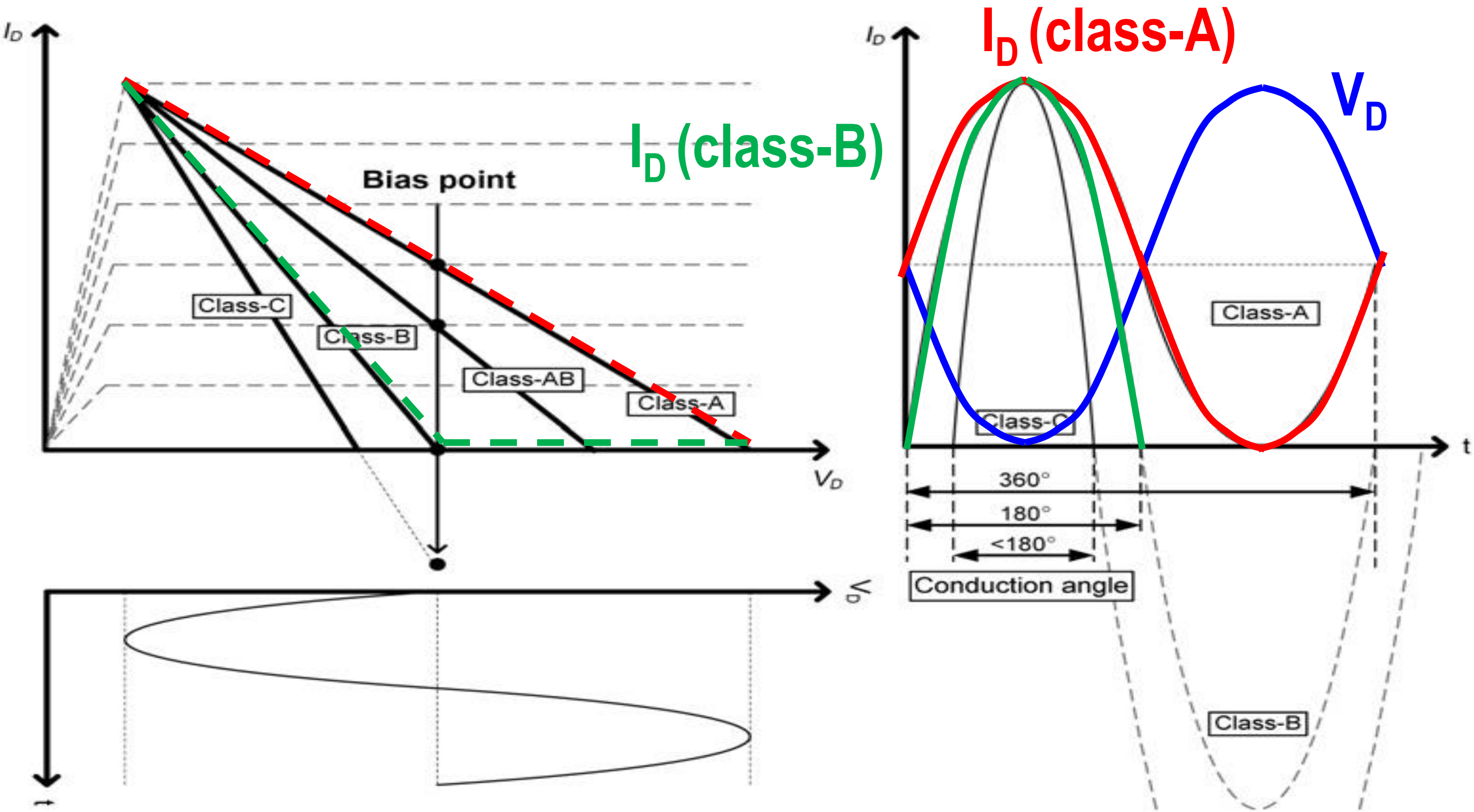


UC Berkeley & Intel

- S. Thyagarajan, A. Niknejad, C. D. Hull, *IEEE TCAS-I 2014*.
- 60GHz Class AB in 28nm CMOS

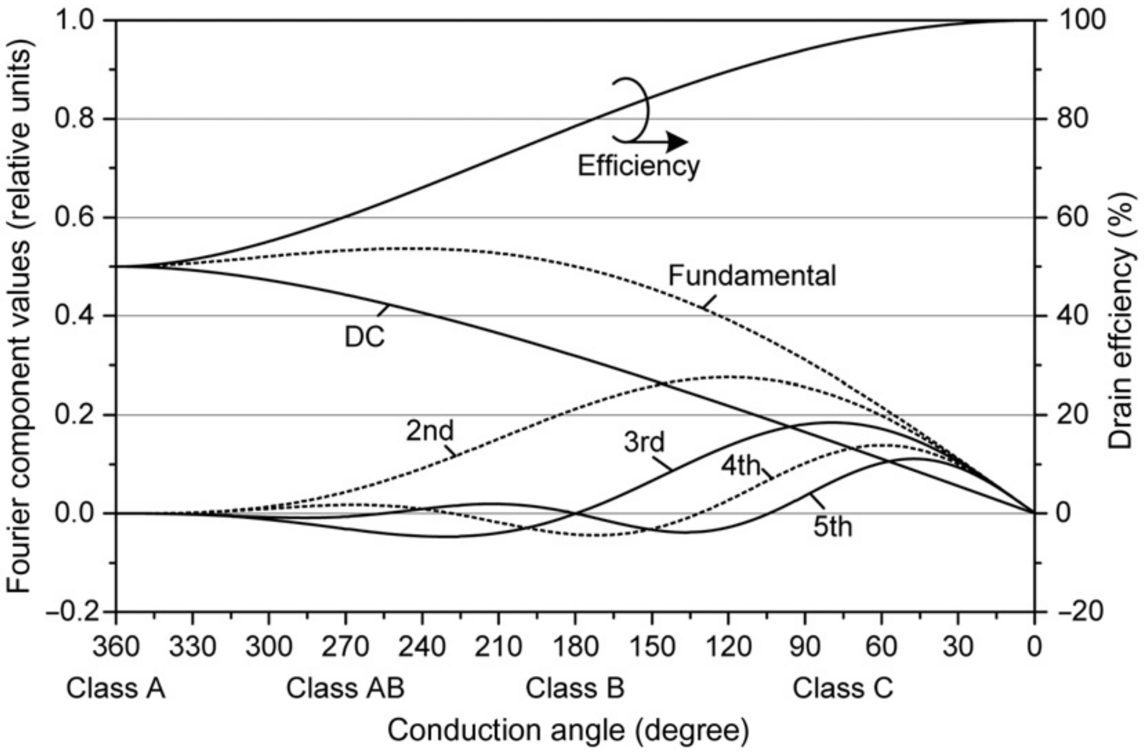
Power Amplifier Classes

- **Linear-Mode PAs: Classes A, B, AB, and C**
- Assume linear device, harmonic short termination, no triode



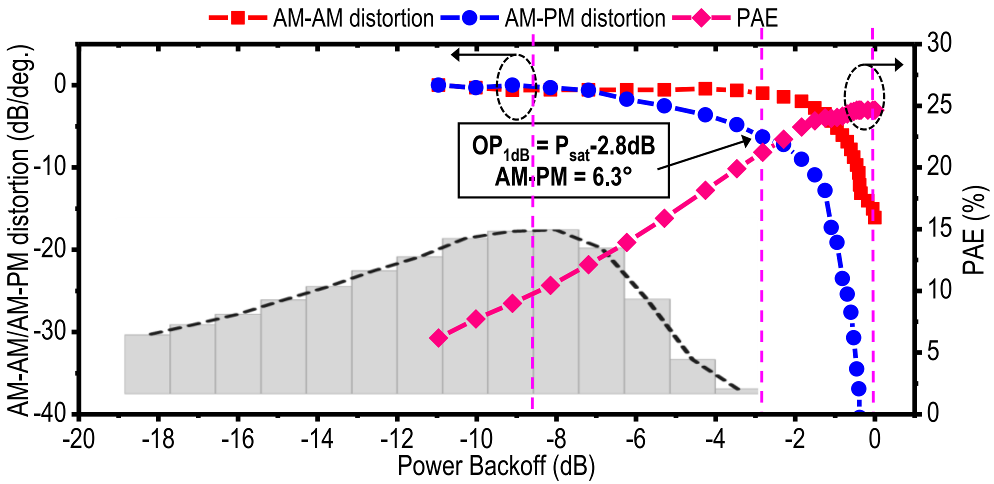
Power Amplifier Classes

Class	Conduction Angle	Bias Point	Efficiency (Max Theoretical)	Gain	Linearity	Output Power (Normalized)
A	360°	Higher than V_T	50%	Largest ↓ Lowest	Good ↓ Bad	1
AB	360°–180°		50–78.5%			Larger than 1 (max 1.15 at 240°)
B	180°	V_T	78.5%			1
C	180°–0°	Lower than V_T	78.5–100%			1 at 180° 0 at 0°



Power Amplifier Linearity

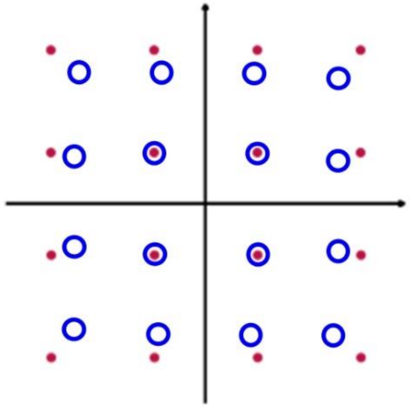
- **AM-AM and AM-PM distortions**



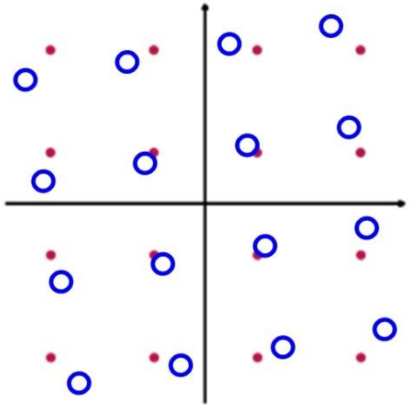
$OP_{1dB} = P_{sat}$-2.8dB
AM-PM = 6.3°

- In-band: Error Vector Magnitude (EVM)
- Out-of-band: Adjacent Channel Power Ratio (ACPR)

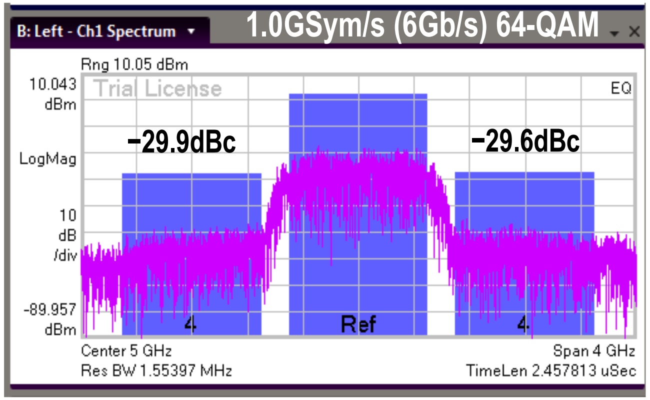
AM-AM



AM-PM



ACPR



1.0GSym/s (6Gb/s) 64-QAM

Rng 10.05 dBm

−29.9dBc

−29.6dBc

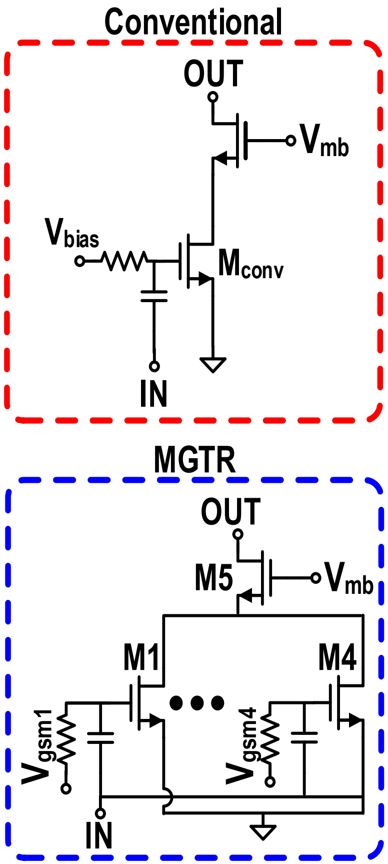
Center 5 GHz
Res BW 1.55397 MHz

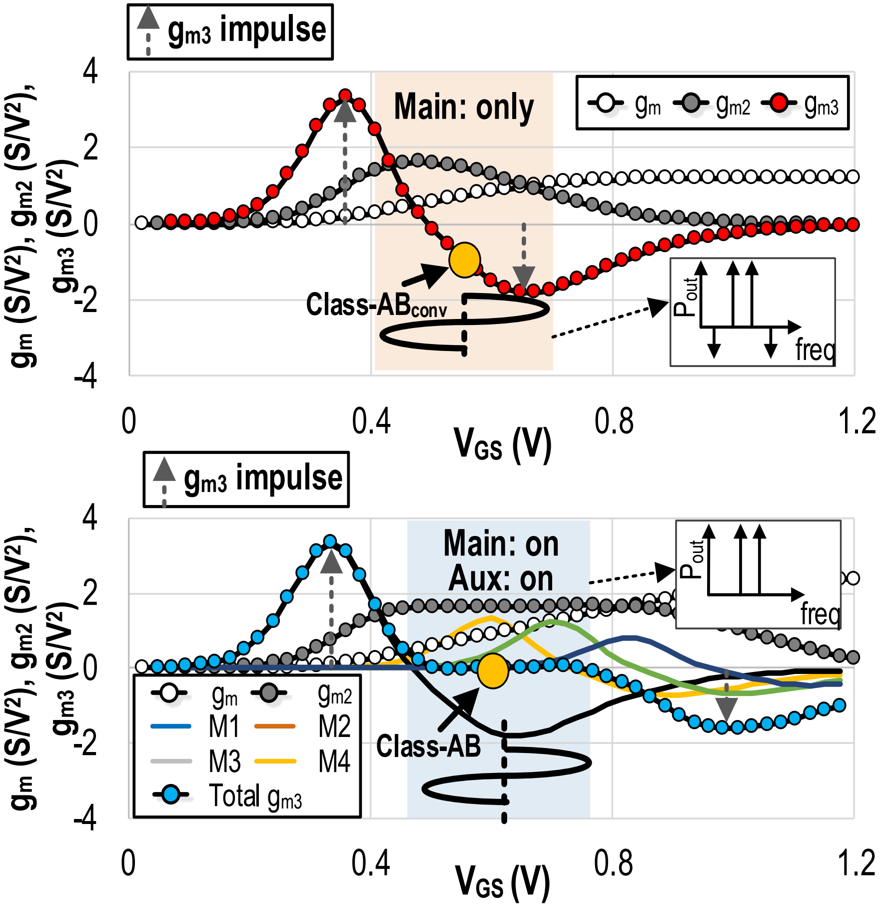
Span 4 GHz
TimeLen 2.457813 uSec

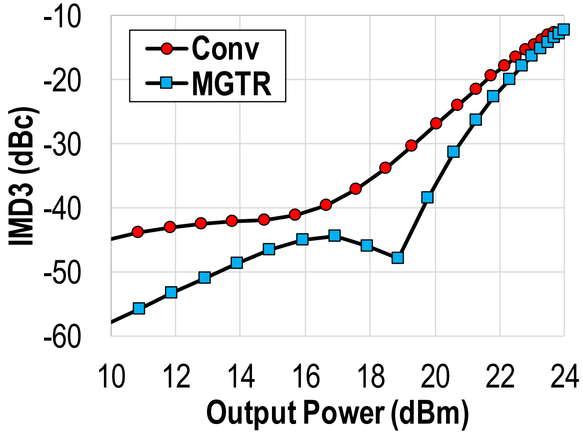
- Dynamic AM-AM/AM-PM and memory effect

Multi-Gated Transistors PA

- g_{m3} cancellation of PA stage
  - Negative g_{m3} of M1 (Class-AB) is cancelled-out by the positive g_{m3} of M2-M4 (Class-C) → **Wide near-zero g_{m3} region, suppressing IMD3**





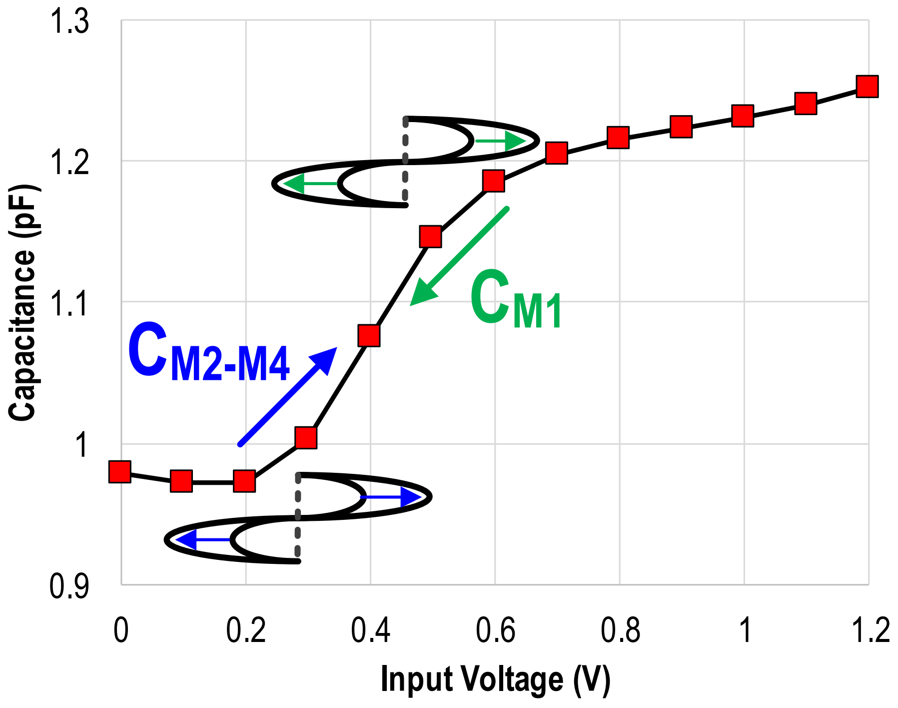


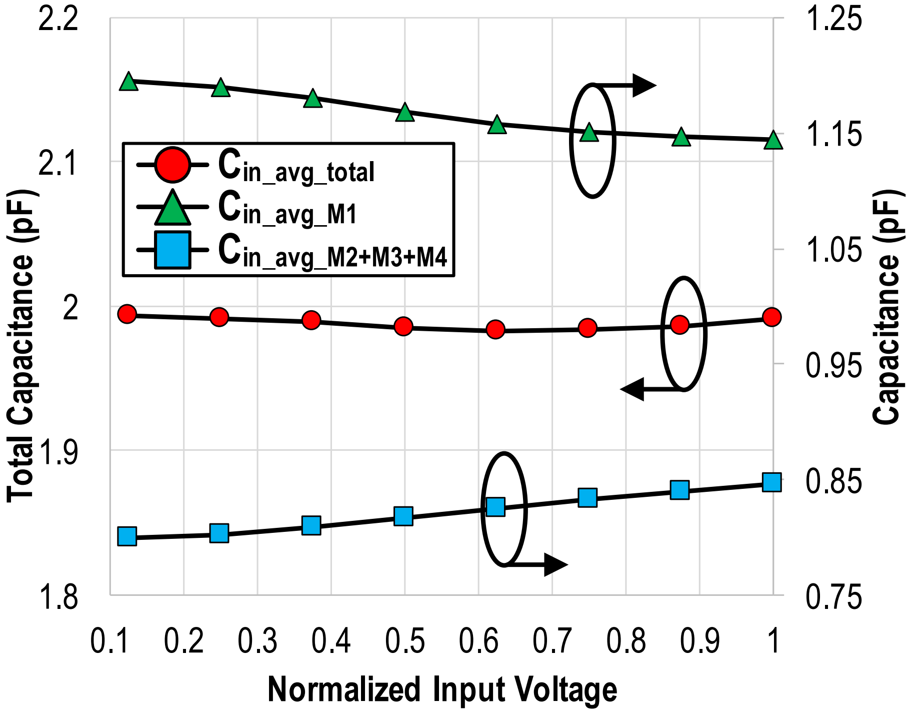
D. Jung, H. Zhao, and H. Wang, *IEEE IMS 2018* and *T-MTT 2019*.

Multi-Gated Transistors PA

- **Average input capacitance of PA stage**
  - Average input capacitance of M1 (Class-AB) ↓
  - Average input capacitance of M2-M4 (Class-C) ↑

→ Less average input capacitance variance of common source transistors

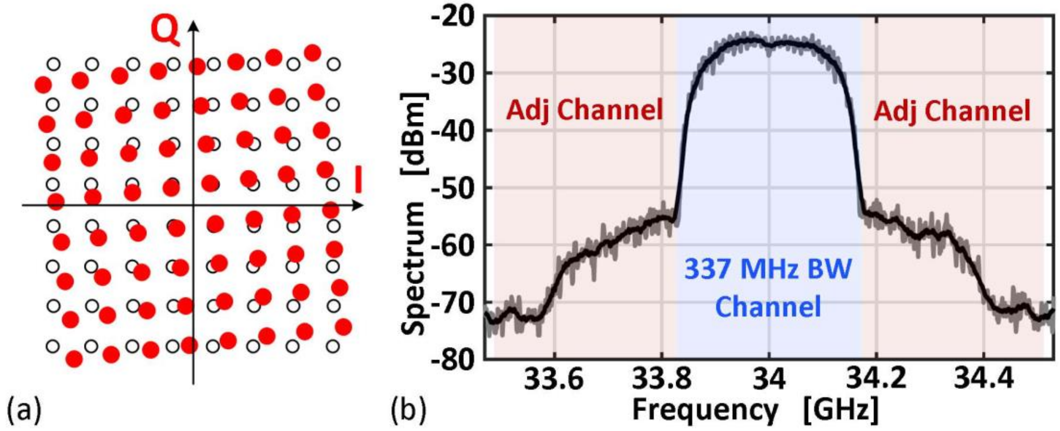




D. Jung, H. Zhao, and H. Wang, *IEEE IMS 2018* and *T-MTT 2019*.

PA AM-PM Distortion

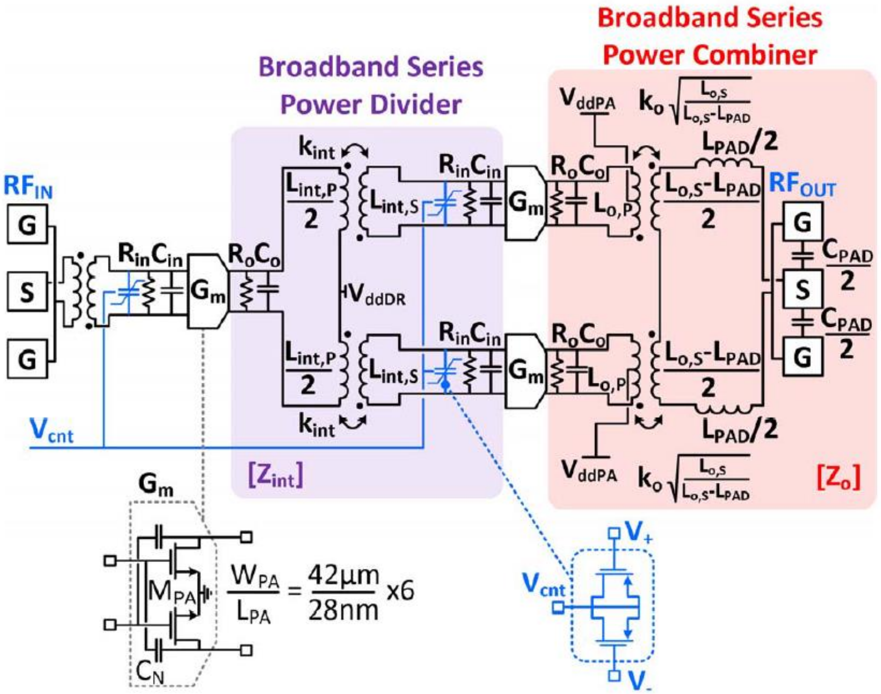
- **AM-PM distortion in complex modulation**

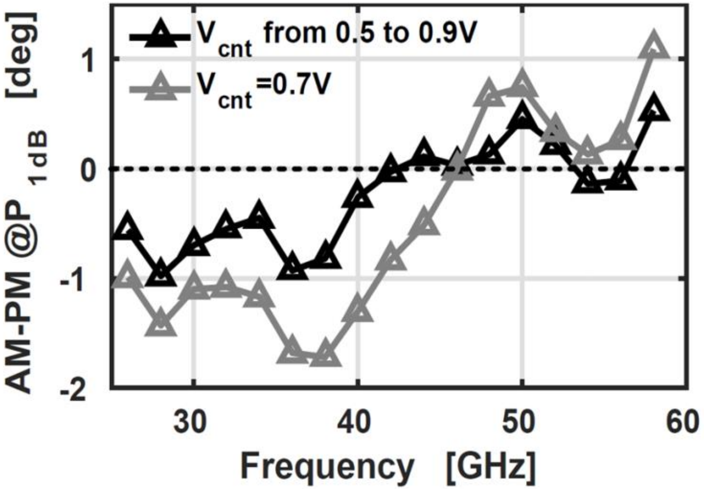


- **PA input device nonlinear capacitor**
- **PA input Miller capacitor and nonlinear g_m**
- **PA output device nonlinear capacitor**

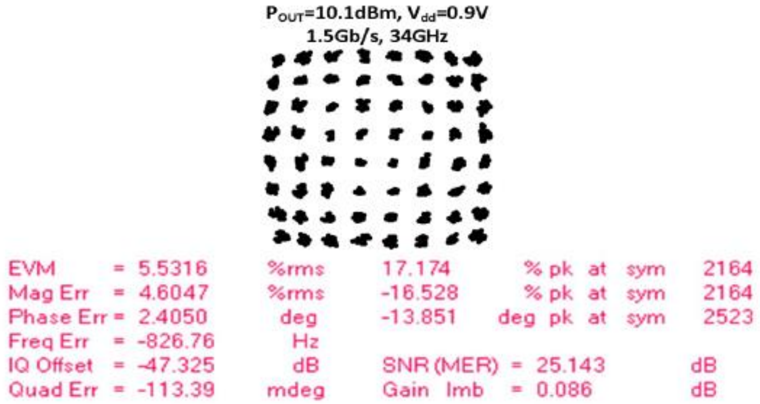
- M. Vigilante and P. Reynaert, JSSC 2018 and RFIC 2017
- J. Park, Y. Wang, S. Pellerano, C. Hull, H Wang, ISSCC 2017 and JSSC 2018
- S. Golara, S. Moloudi, and A. A. Abidi, TCAS-I 2017

PA AM-PM Distortion





- **PMOS varactor cancellation**
- **Wideband matching network**
- **PA-Driver AM-PM cancellation**

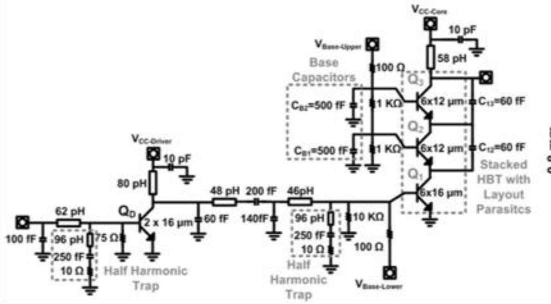

P_{OUT}=10.1dBm, V_{dd}=0.9V
1.5Gb/s, 34GHz

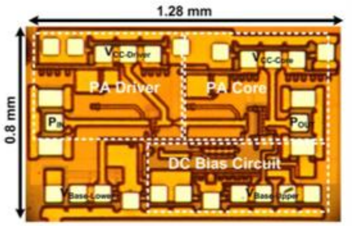
```
EVM        =  5.5316    %rms     17.174         % pk  at  sym   2164
Mag Err    =  4.6047    %rms    -16.528         % pk  at  sym   2164
Phase Err  =  2.4050     deg    -13.851     deg pk  at  sym   2523
Freq Err   =  -826.76     Hz
IQ Offset  =  -47.325     dB     SNR (MER)  =  25.143           dB
Quad Err   =  -113.39   mdeg     Gain  Imb  =  0.086            dB
```

- M. Vigilante and P. Reynaert, JSSC 2018 and RFIC 2017

Mm-Wave Switching PAs or Harmonically-Tuned PAs in Silicon

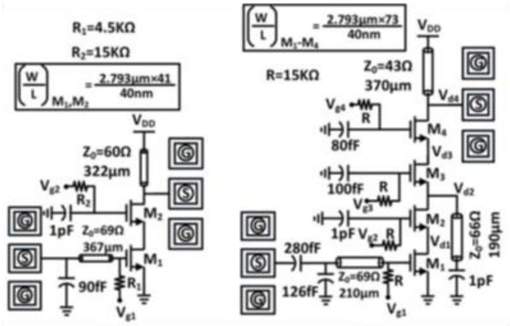
- **Superior efficiency and output power**

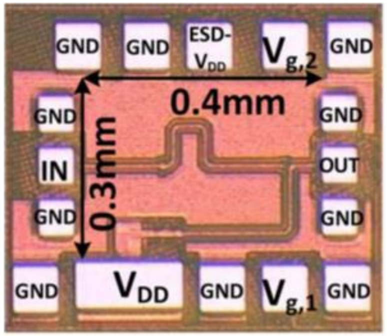


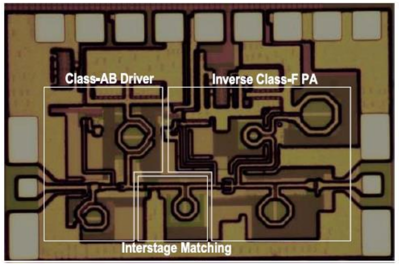


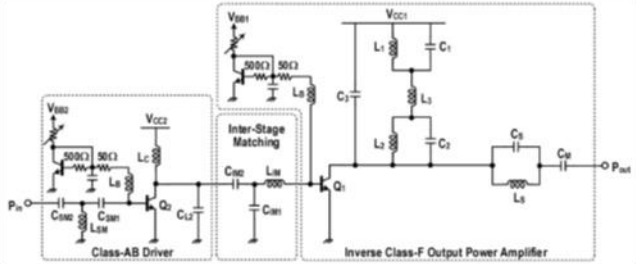
- K. Datta, H. Hashemi, *IEEE JSSC 2014*.
- **130nm SiGe (BV$_{CEO}$=1.7V, BV$_{CBO}$=5.9V)**
- **2-Stack Class-E @ 41GHz: P$_{sat}$ 23.4dBm, Peak PAE 31-34.9%.**

- A. Chakrabarti and H. Krishnaswamy, *IEEE JSSC 2014*.
- **45nm CMOS SOI (nominal V$_{DD}$=~1V)**
- **2-Stack Class-E @ 47GHz: P$_{sat}$ 17.6dBm, Peak PAE 34.6%.**







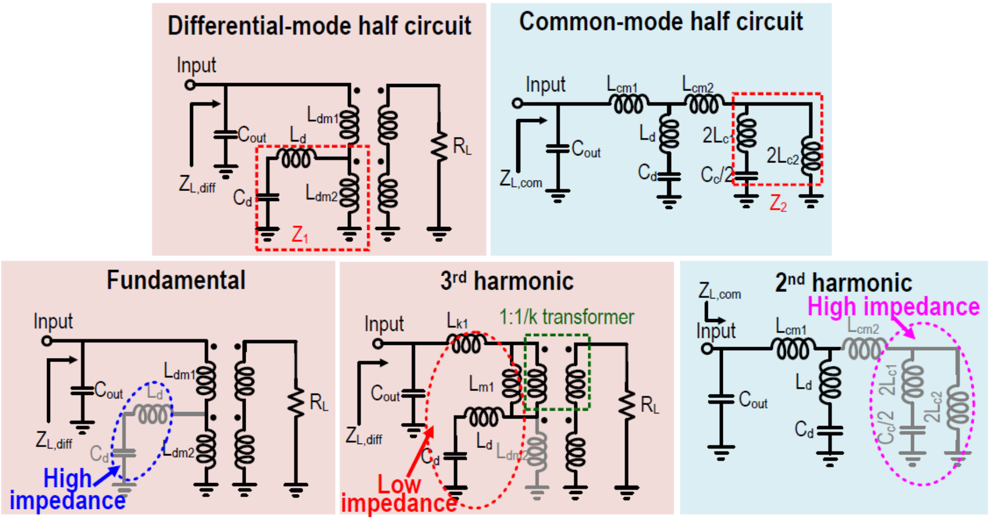


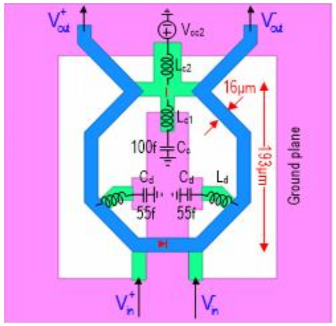
- S. Mortazavi, K.-J. Koh, *IEEE JSSC 2016*.
- **130nm SiGe (BV$_{CEO}$=1.7V, BV$_{CBO}$=5.9V)**
- **Class-F^{-1} @ 24GHz: P$_{sat}$ 18dBm, Peak PAE 50%.**

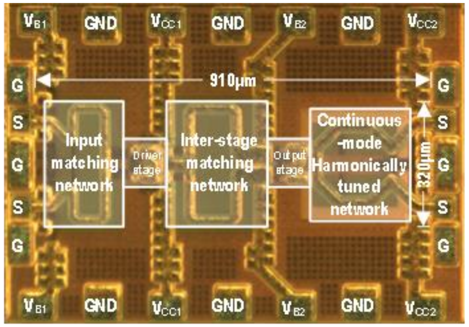
A Continuous-Mode F^{-1}-like Harmonic Tuning Broadband PA in SiGe

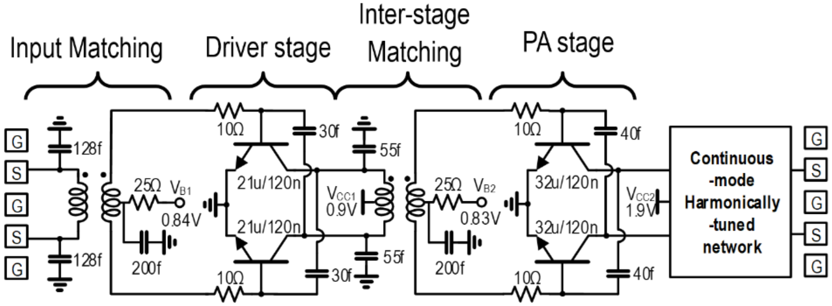
- **High modulation efficiency over a large carrier BW**
- **Ultra-compact**

Exploring and enhancing transformer parasitics

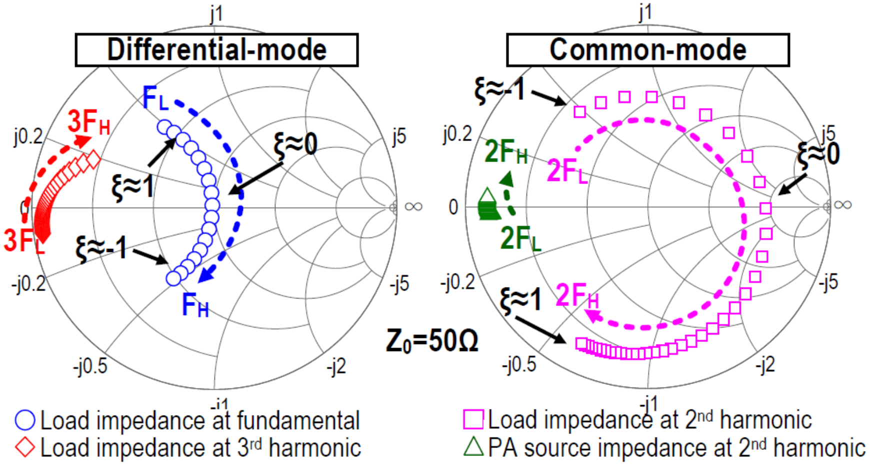








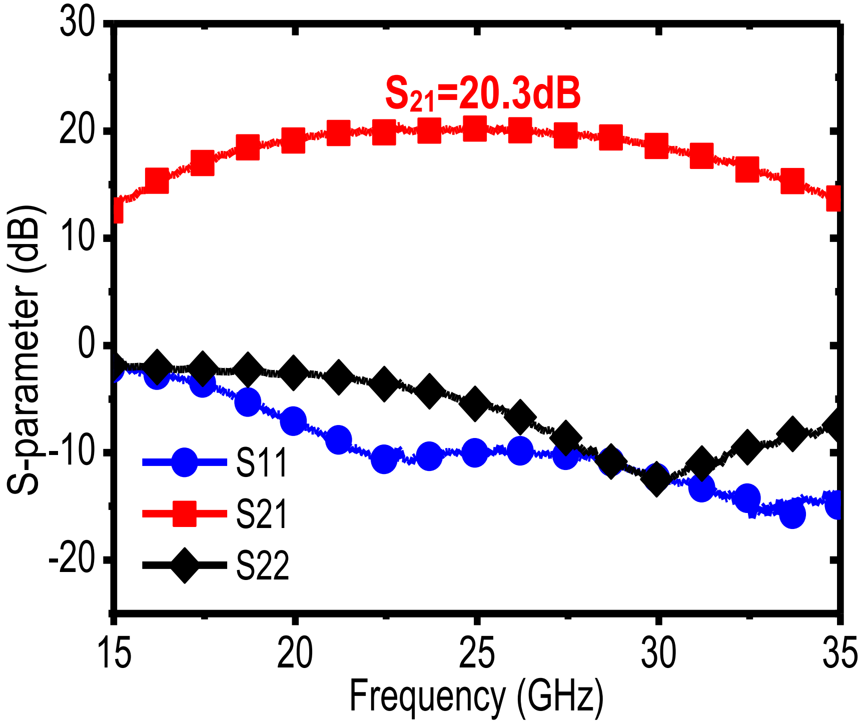
- Global Foundries 0.13μm SiGe
- Core area: 0.29mm^2



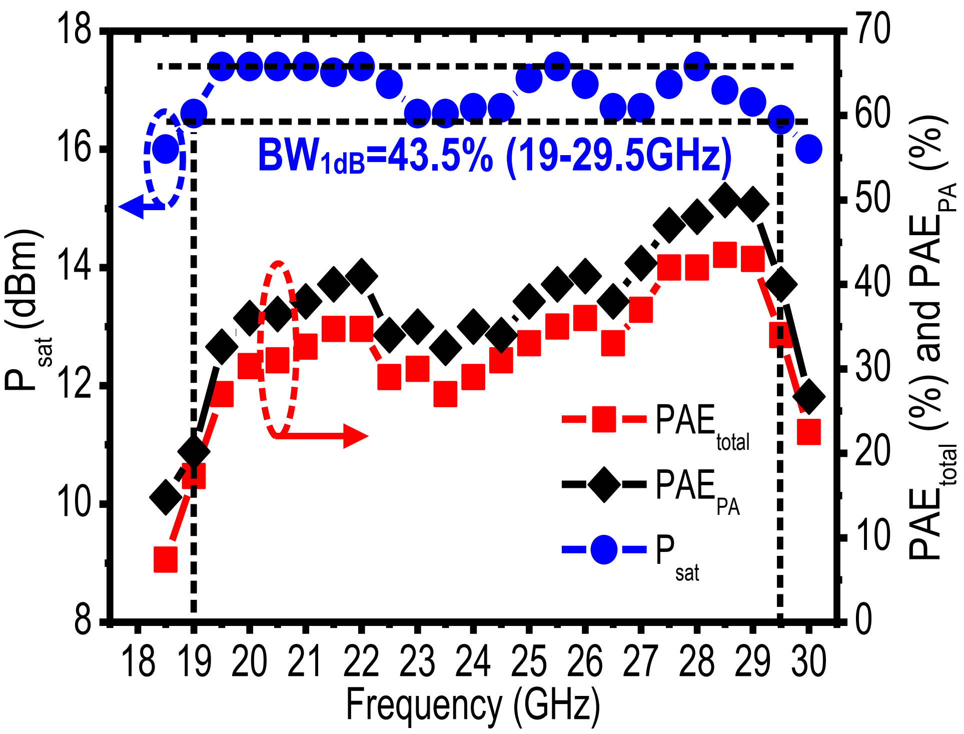
- T. Li, M. Huang, and H. Wang, *IEEE ISSCC 2018* and *IEEE T-MTT 2019*.

A Continuous-Mode F^{-1}-like Harmonic Tuning Broadband PA in SiGe

- **Small-signal CW**



- **Large-signal CW**



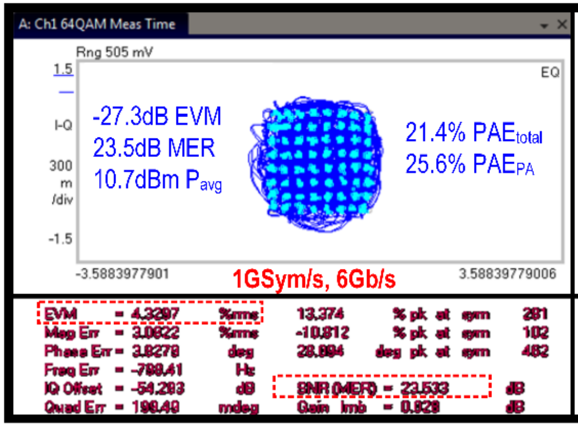
- **BW_{3dB} = 20.2~28.9GHz (35.4%)**
- **BW_{S11} = 21.5~39GHz (57.9%)**

- **P_{sat} 1dB BW = 19~29.5GHz (43%)**
- **Peak PAE = 45%**

- T. Li, M. Huang, and H. Wang, *IEEE ISSCC 2018* and *IEEE T-MTT 2019.*

A Continuous-Mode F^{-1}-like Harmonic Tuning Broadband PA in SiGe

- 64-QAM modulation at 28.5GHz (EVM < -25dB up-to 18Gb/s)

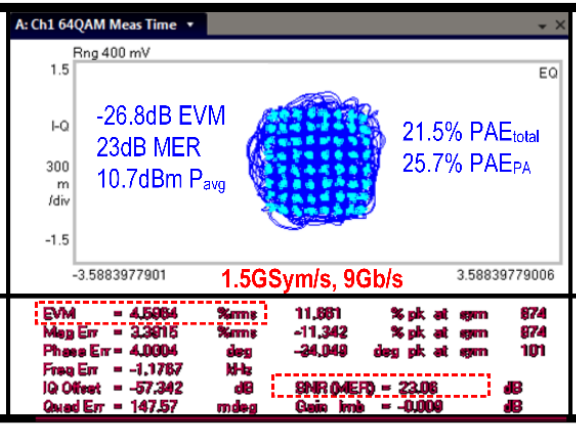


-27.3dB EVM
23.5dB MER
10.7dBm P_{avg}

21.4% PAE_{total}
25.6% PAE_{PA}

1GSym/s, 6Gb/s

```
EVM       = 4.3297   %rms    13.374      % pk  at  sym   281
Mag Err   = 3.0822   %rms    -10.812     % pk  at  sym   102
Phase Err = 3.8278   deg     28.894  deg pk  at  sym     482
Freq Err  = -798.41  Hz
IQ Offset = -54.283  dB      SNR (MER) = 23.533          dB
Quad Err  = 199.49   mdeg    Gain  Imb = 0.828           dB
```

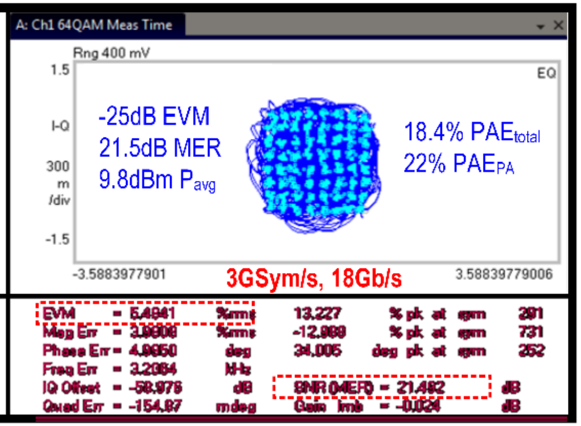


-26.8dB EVM
23dB MER
10.7dBm P_{avg}

21.5% PAE_{total}
25.7% PAE_{PA}

1.5GSym/s, 9Gb/s

```
EVM       = 4.5964   %rms    11.661      % pk  at  sym   874
Mag Err   = 3.3615   %rms    -11.342     % pk  at  sym   874
Phase Err = 4.0004   deg     -24.049 deg pk  at  sym     101
Freq Err  = -1.1767  kHz
IQ Offset = -57.342  dB      SNR (MER) = 23.06           dB
Quad Err  = 147.57   mdeg    Gain  Imb = -0.009          dB
```



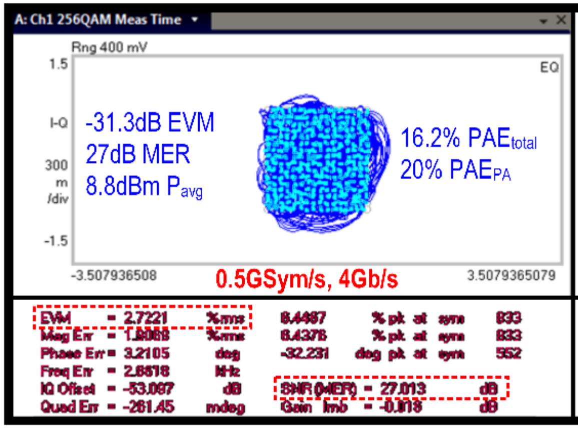
-25dB EVM
21.5dB MER
9.8dBm P_{avg}

18.4% PAE_{total}
22% PAE_{PA}

3GSym/s, 18Gb/s

```
EVM       = 5.4841   %rms    13.227      % pk  at  sym   291
Mag Err   = 3.9808   %rms    -12.988     % pk  at  sym   731
Phase Err = 4.9950   deg     34.005  deg pk  at  sym     252
Freq Err  = 3.2064   kHz
IQ Offset = -58.976  dB      SNR (MER) = 21.492          dB
Quad Err  = -154.87  mdeg    Gain  Imb = -0.024          dB
```

- 256-QAM modulation at 28.5GHz (EVM < -30.5dB up-to 8Gb/s)

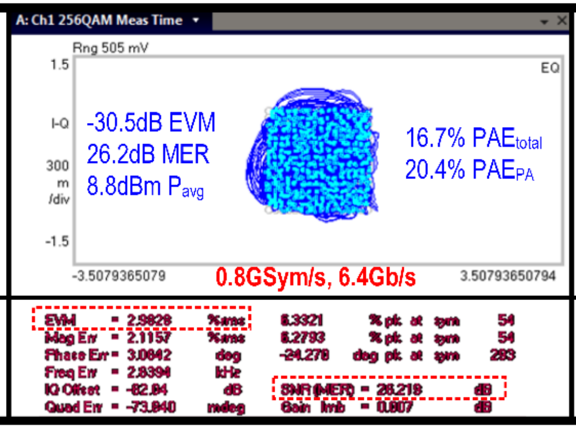


-31.3dB EVM
27dB MER
8.8dBm P_{avg}

16.2% PAE_{total}
20% PAE_{PA}

0.5GSym/s, 4Gb/s

```
EVM       = 2.7221   %rms    6.4487      % pk  at  sym   833
Mag Err   = 1.9068   %rms    6.4376      % pk  at  sym   833
Phase Err = 3.2105   deg     -32.231 deg pk  at  sym     552
Freq Err  = 2.6618   kHz
IQ Offset = -53.097  dB      SNR (MER) = 27.013          dB
Quad Err  = -261.45  mdeg    Gain  Imb = -0.018          dB
```

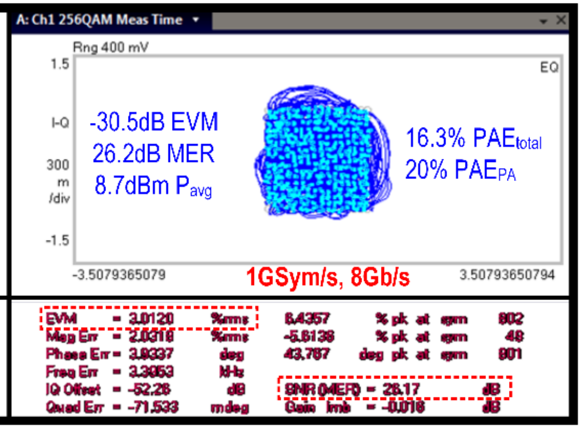


-30.5dB EVM
26.2dB MER
8.8dBm P_{avg}

16.7% PAE_{total}
20.4% PAE_{PA}

0.8GSym/s, 6.4Gb/s

```
EVM       = 2.9828   %rms    6.3321      % pk  at  sym   54
Mag Err   = 2.1157   %rms    6.2793      % pk  at  sym   54
Phase Err = 3.0842   deg     -24.278 deg pk  at  sym     283
Freq Err  = 2.8394   kHz
IQ Offset = -82.84   dB      SNR (MER) = 26.218          dB
Quad Err  = -73.840  mdeg    Gain  Imb = 0.007           dB
```



-30.5dB EVM
26.2dB MER
8.7dBm P_{avg}

16.3% PAE_{total}
20% PAE_{PA}

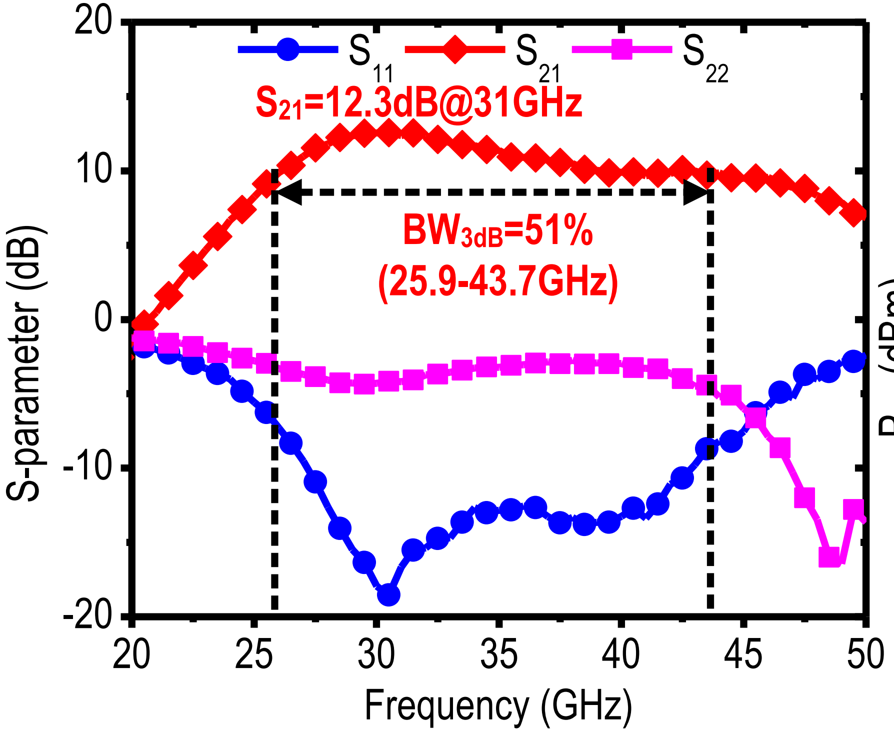
1GSym/s, 8Gb/s

```
EVM       = 3.0120   %rms    6.4357      % pk  at  sym   802
Mag Err   = 2.0318   %rms    -5.6138     % pk  at  sym   48
Phase Err = 3.9337   deg     43.767  deg pk  at  sym     801
Freq Err  = 3.3053   kHz
IQ Offset = -52.28   dB      SNR (MER) = 26.17           dB
Quad Err  = -71.533  mdeg    Gain  Imb = -0.016          dB
```

- T. Li, M. Huang, and H. Wang, *IEEE ISSCC 2018* and *IEEE T-MTT 2019.*

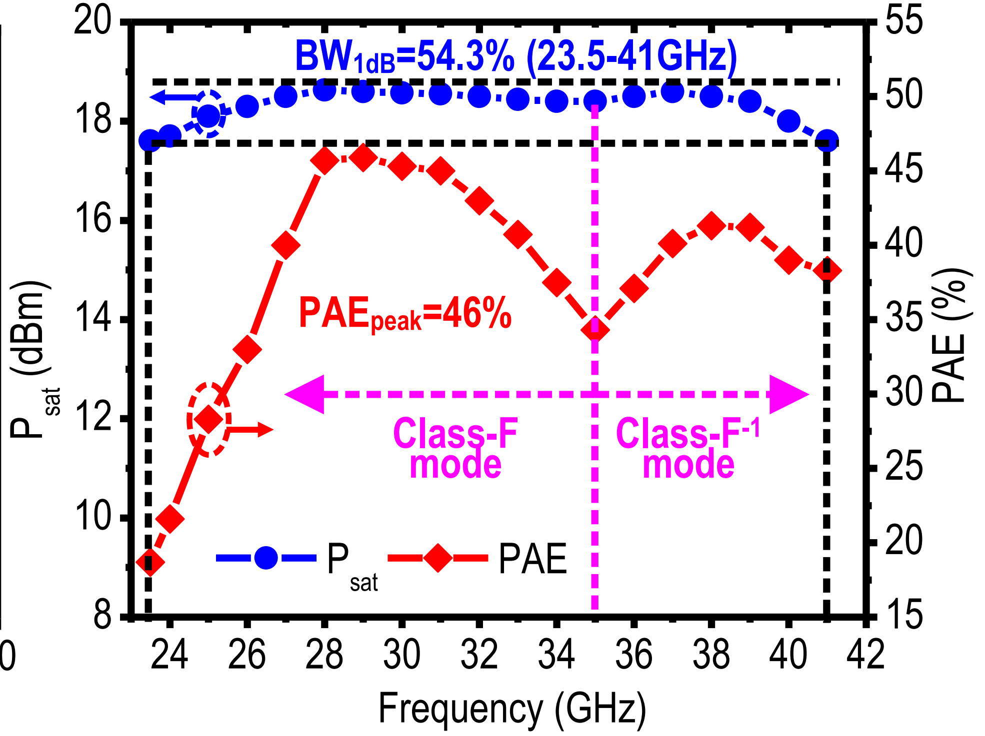
A Continuous-Mode Class F/F^{-1}-like Harmonic Tuning Broadband PA in 45nm CMOS SOI

- **Small-signal CW**



- **BW_{3dB}=25.9-43.7GHz (51%)**
- **BW_{S11}=27.3-43.2GHz (45.1%)**

- **Large-signal CW**

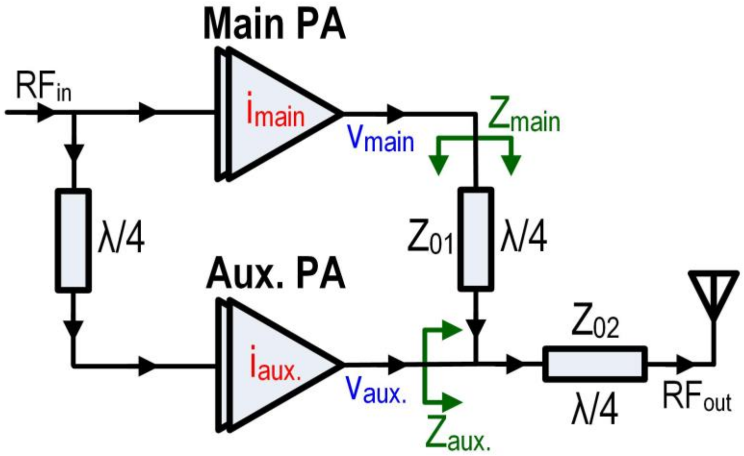


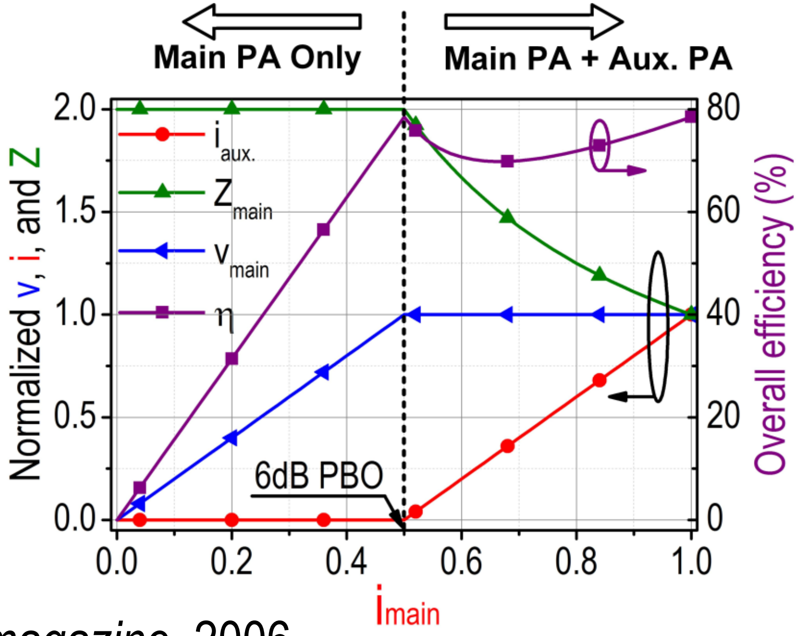
- **P_{sat} 1dB BW=23.5-41GHz (54.3%)**
- **Class F/F^{-1} Mode Transition at 35GHz**

- T. Li and H. Wang, *IEEE RFIC 2018* and *IEEE T-MTT 2019.*

Mm-Wave Doherty PAs or Doherty-Like PAs in Silicon

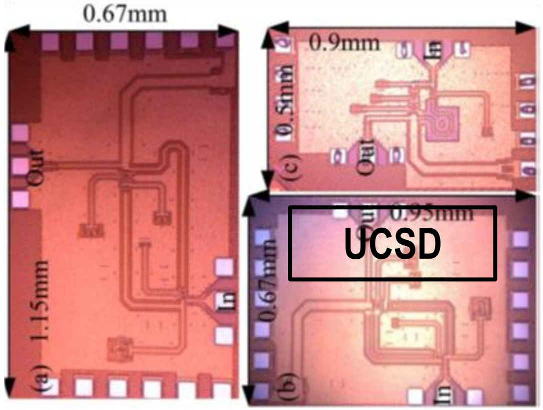
- **Doherty (General Active Load Modulation) PA – Power back-off efficiency enhancement**
  - ✓ Large modulation bandwidth → **Broadband 5G**
  - ✓ RF-in-RF-out operation → **Drop-in solution**
  - ✗ On-chip output passive network
  - ✗ Cooperation between two PA paths
  - ✗ Carrier bandwidth





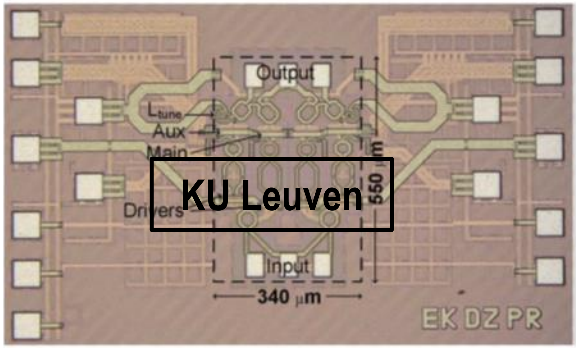
- B. Kim, J. Kim, I. Kim, J. Cha, *IEEE microwave magazine,* 2006.
- S. Hu, S. Kousai, and H. Wang, *IEEE T-MTT* 2015.

Example Mm-Wave Doherty PAs or Doherty-Like PAs in Silicon



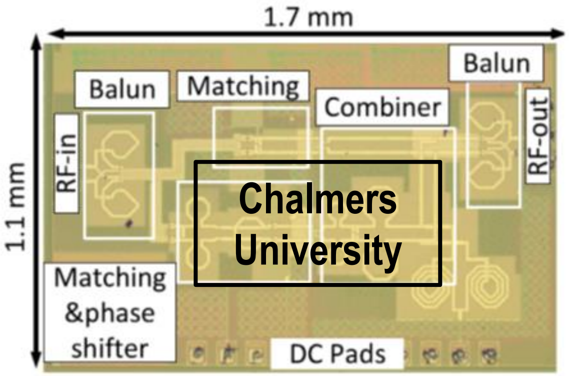
UCSD

- A. Agah, *et al.*, *IEEE JSSC 2013.*
- 45GHz Doherty PA in 45nm FD-SOI
- Active phase-shift for auxiliary path
- Stacked transistor PA core



KU Leuven

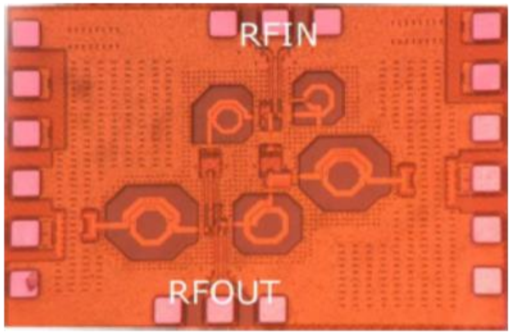
- E. Kaymaksut, D. Zhao, P. Reynaert, *IEEE T-MTT 2015.*
- 72GHz Doherty PA in 40nm CMOS
- XFMR series Doherty combiner



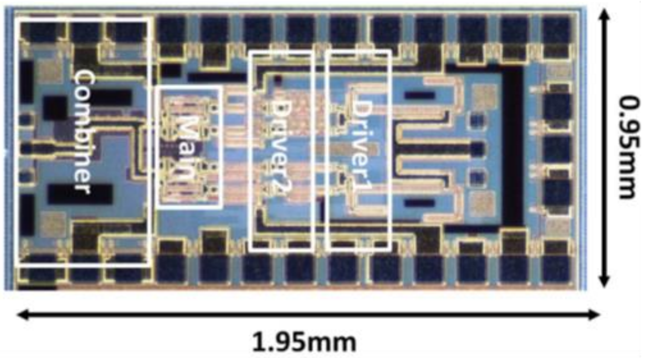
Chalmers University

- M. Özen, *et al.*, *IEEE MWCL 2017.*
- 20GHz Doherty PA in 130nm SiGe
- Low loss Doherty power combiner

UCSD



- N. Rostomyan, *et al.*, *IEEE MWCL 2018.*
- 28GHz Doherty PA in 45nm CMOS SOI
- Low loss Doherty power combiner

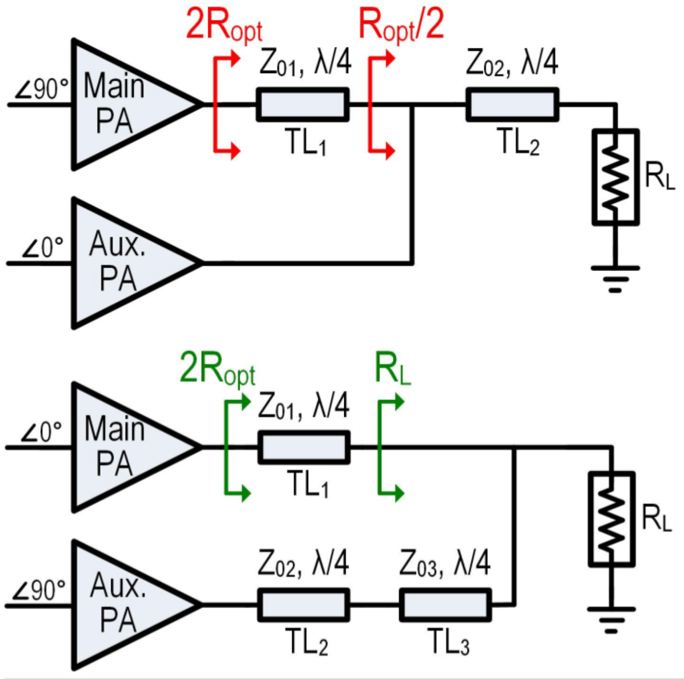


Princeton

- C. Chappidi, X. Wu, K. Sengupta, *IEEE JSSC 2018.*
- 30-50GHz Doherty-like PA in 130nm SiGe
- RF power DAC
- Multi-port network

Broadband Mm-Wave Doherty PA

- **Broadband and low-loss Doherty parallel combiner**



Conventional design

- ➢ Impedance transformation ratio of TL_1 at 6dB power back-off: **4**

$$Z_{01}=R_{opt},\ Z_{02}=\sqrt{R_L R_{opt}/2}$$

* R_{opt}=41.3Ω

Introduced design

- ➢ Impedance transformation ratio of TL_1 at 6dB power back-off: **1.65**

$$Z_{01}=Z_{02}=\sqrt{2R_L R_{opt}},\ Z_{03}=2R_L$$

✓ Enhanced passive efficiency in power back-off

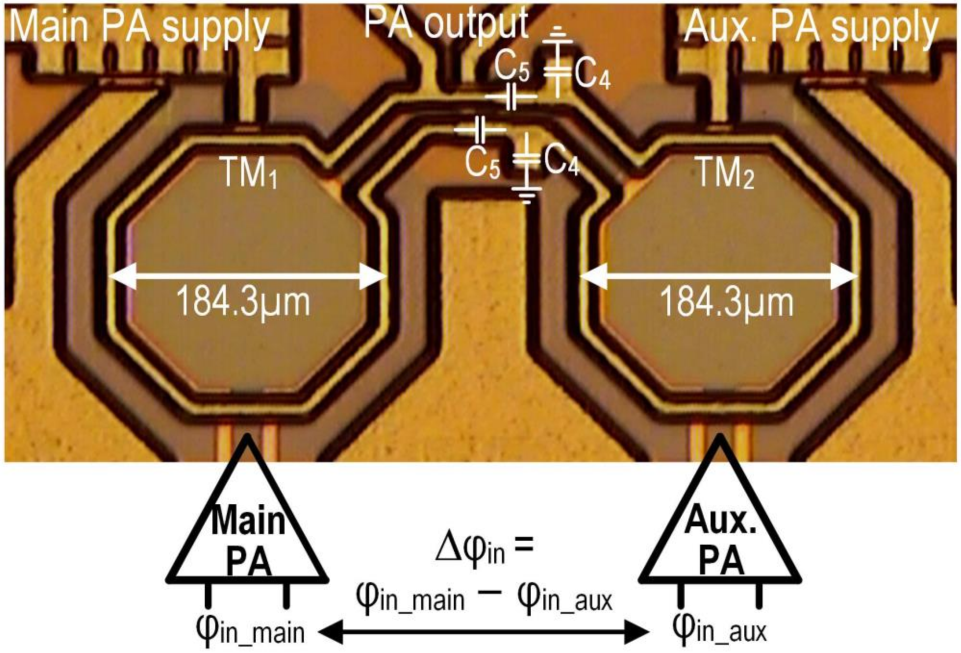
✓ Enlarged bandwidth

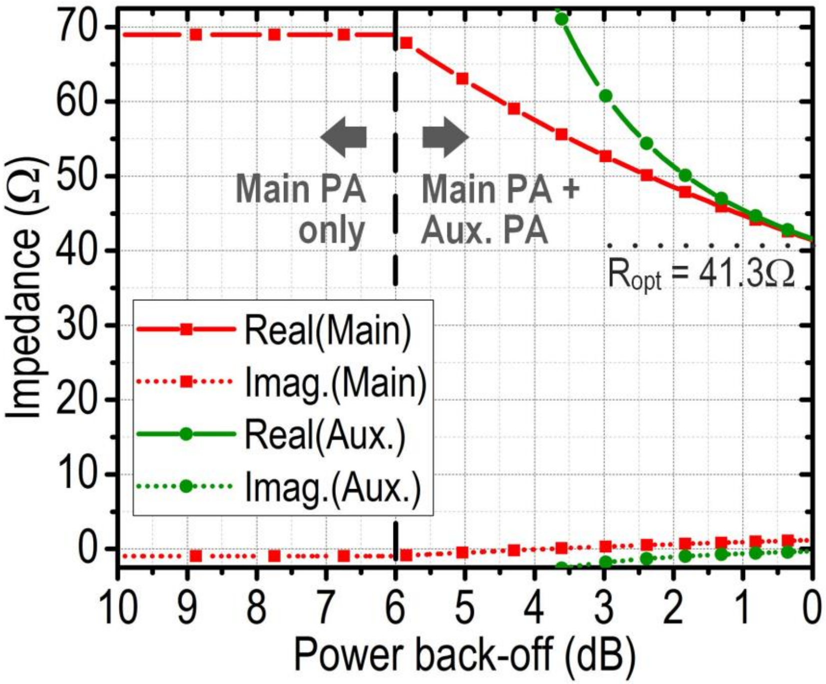
✗ Passive area

- A. Grebennikov, *et al.*, *IEEE T-MTT* 2012.

Broadband Mm-Wave Doherty PA

- **Introduced design** – Broadband/low-loss Doherty parallel combiner
  - ✓ Compact
  - ✓ Desired Doherty load modulation
  - ✓ Enhanced passive efficiency in power back-off
  - ✓ Extended bandwidth

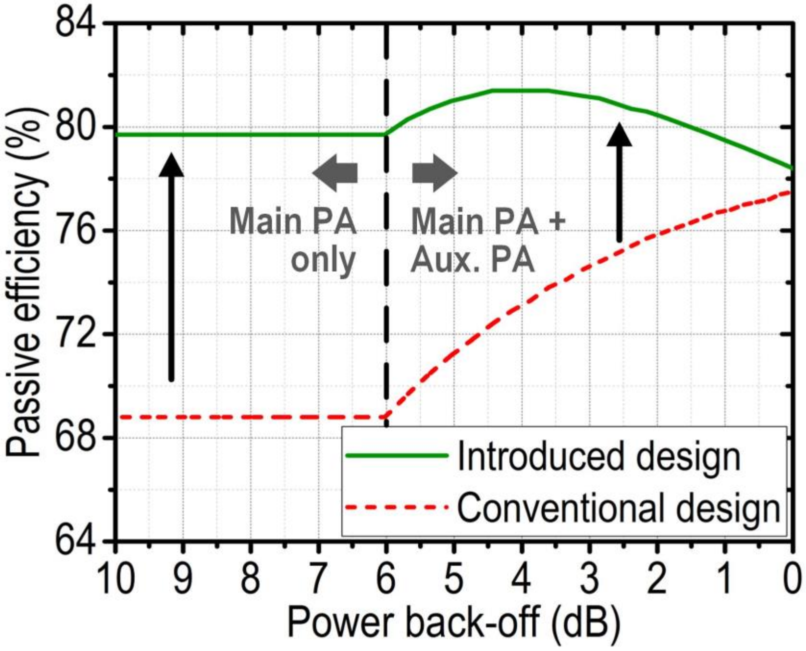


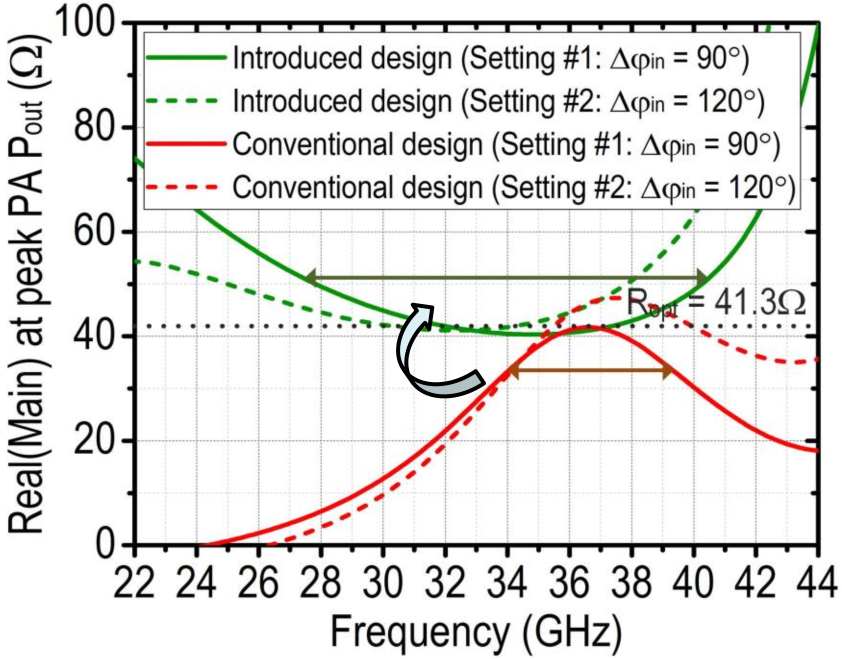


- S. Hu, F. Wang, and H. Wang, *IEEE ISSCC* 2017 and *JSSC 2019*.

Broadband Mm-Wave Doherty PA

- **Introduced design** – Broadband/low-loss Doherty parallel combiner
  - ✓ Compact
  - ✓ Desired Doherty load modulation
  - ✓ Enhanced passive efficiency in power back-off
  - ✓ Extended bandwidth

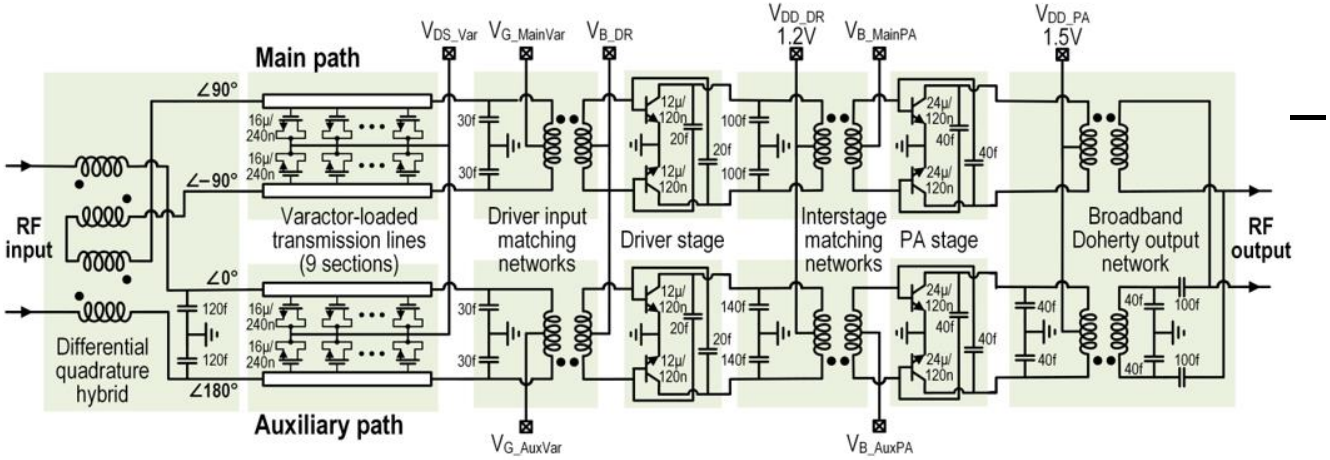


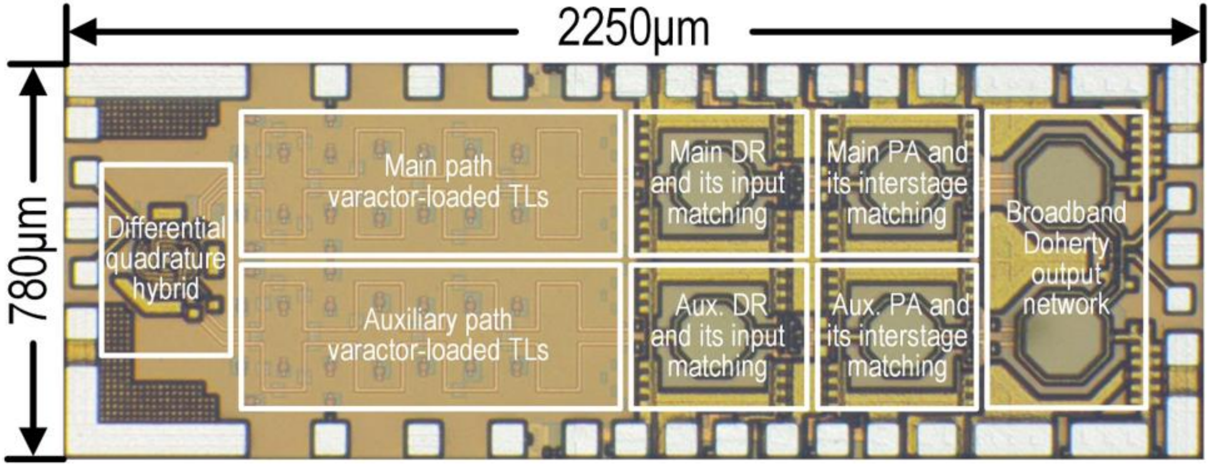


- S. Hu, F. Wang, and H. Wang, *IEEE ISSCC* 2017 and *JSSC 2019*.

Broadband Mm-Wave Doherty PA

- **World-first 28/37/39GHz multiband Doherty PA for 5G MIMO**



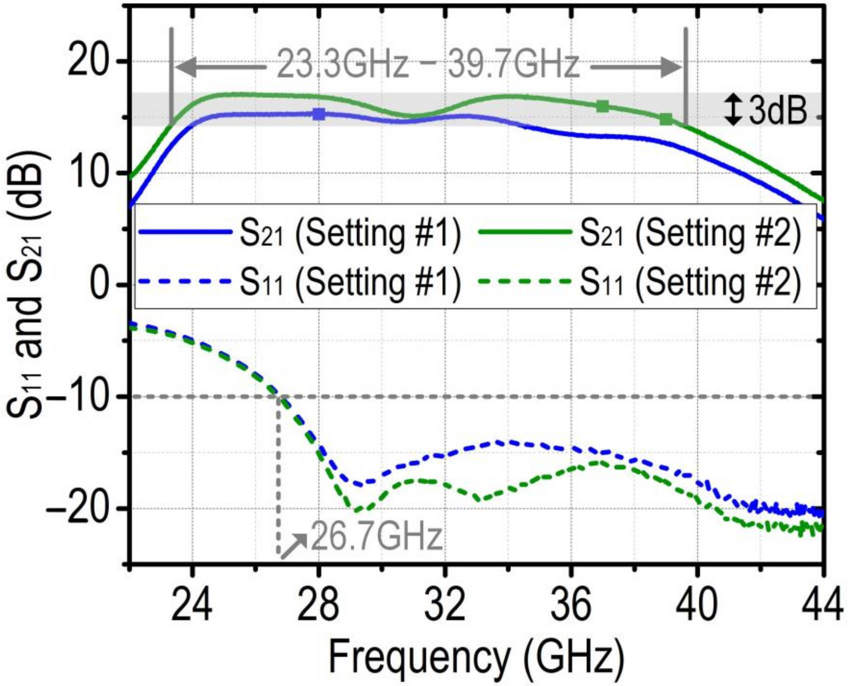


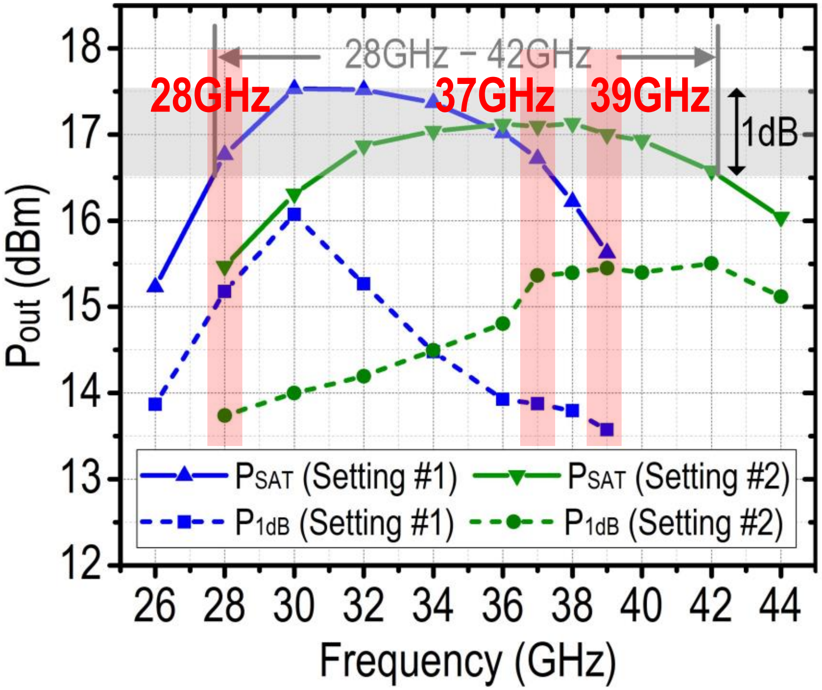
– Global Foundries 130nm SiGe BiCMOS

- S. Hu, F. Wang, and H. Wang, *IEEE ISSCC* 2017 and *JSSC 2019*.

Broadband Mm-Wave Doherty PA

- **CW measurements – Small-signal and large-signal**
  - Reconfigurable operation covers three 5G bands of 28/37/39GHz.



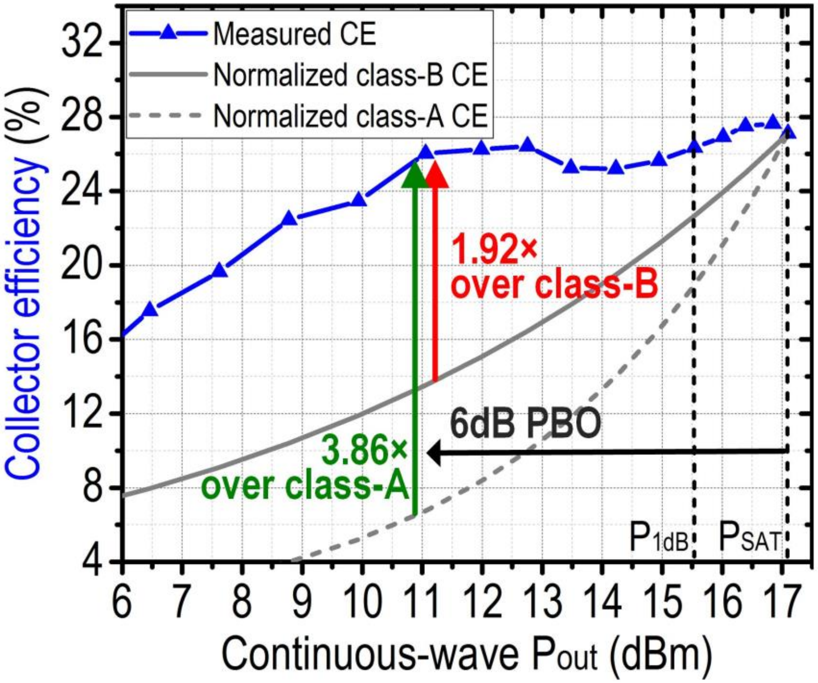


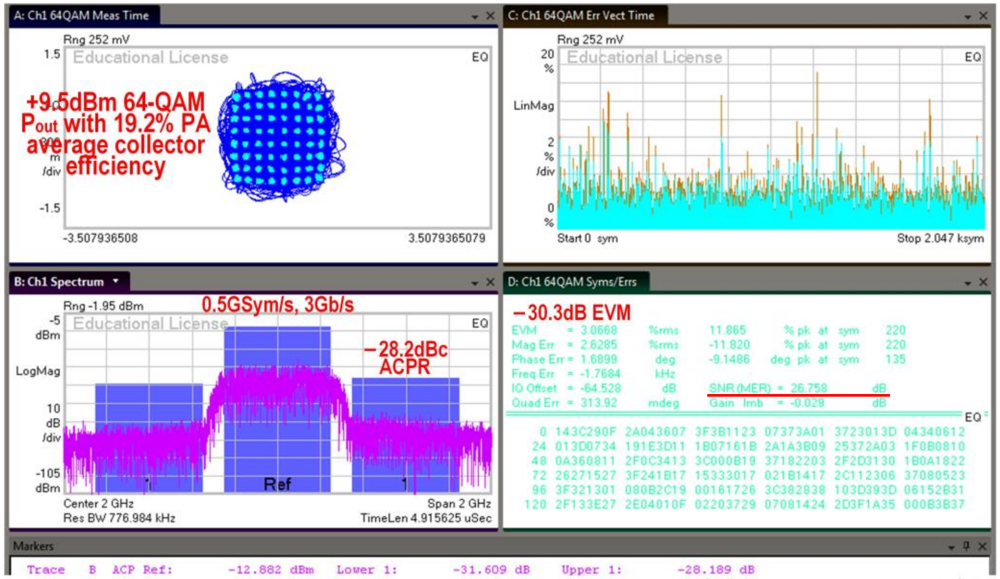
	Target band(s)	$V_{DS\_Var} - V_{G\_MainVar}$	$V_{DS\_Var} - V_{G\_AuxVar}$	$\Delta\varphi_{in} = \varphi_{in\_main} - \varphi_{in\_aux}$
Setting #1	28GHz	0.5	0	120°
Setting #2	37GHz, 39GHz	0	0.5	90°

- S. Hu, F. Wang, and H. Wang, *IEEE ISSCC* 2017 and *JSSC 2019*.

Broadband Mm-Wave Doherty PA

- **CW measurements – Power back-off at 37GHz**
  - +17.1dBm P_{sat}, +15.5dBm P_{1dB}, 27.6% peak CE
  - 1.92× efficiency enhancement over class-B at 6dB PBO
  - 500MSym/s 64QAM (3Gb/s) without digital predistortion (DPD)





+9.5dBm 64-QAM P_{out} with 19.2% PA average collector efficiency

0.5GSym/s, 3Gb/s

−28.2dBc ACPR

−30.3dB EVM

```
EVM       =  3.0668    %rms     11.865      % pk  at  sym    220
Mag Err   =  2.6285    %rms    -11.820      % pk  at  sym    220
Phase Err =  1.6899     deg    -9.1486   deg  pk  at  sym    135
Freq Err  = -1.7684     kHz
IQ Offset = -64.528      dB    SNR (MER) =  26.758        dB
Quad Err  =  313.92    mdeg    Gain  Imb  =  -0.029        dB

  0  143C290F  2A043607  3F3B1123  07373A01  3723013D  04340612
 24  013D0734  191E3D11  1B07161B  2A1A3B09  25372A03  1F0B0810
 48  0A360811  2F0C3413  3C000B19  37182203  2F2D3130  1B0A1822
 72  26271527  3F241B17  15333017  021B1417  2C112306  37080523
 96  3F321301  080B2C19  00161726  3C382838  103D393D  06152B31
120  2F133E27  2E04010F  02203729  07081424  2D3F1A35  000B3B37
```

```
Trace   B  ACP Ref:      -12.882 dBm   Lower 1:      -31.609 dB    Upper 1:      -28.189 dB
```

* LO for the external mixers = 39GHz

- S. Hu, F. Wang, and H. Wang, *IEEE ISSCC* 2017 and *JSSC 2019*.

Pushing the Doherty PA Further

- **Doherty / Doherty-like PA**

🙂 PBO efficiency enhancement, wideband mod. BW

☹ Cooperation between Main and Aux PA path

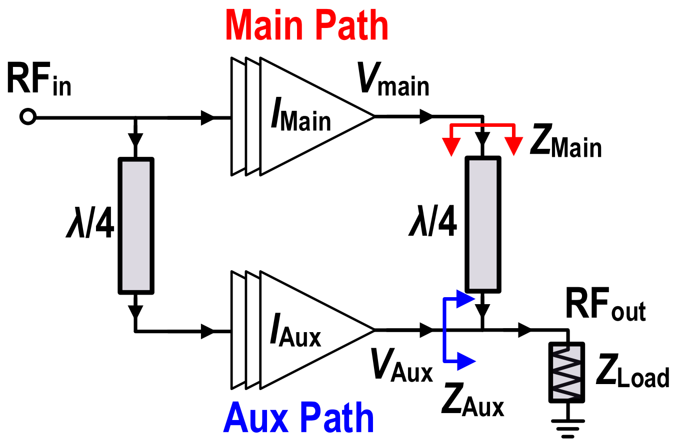
- **Polar Digital PA/TX (Power DAC)**

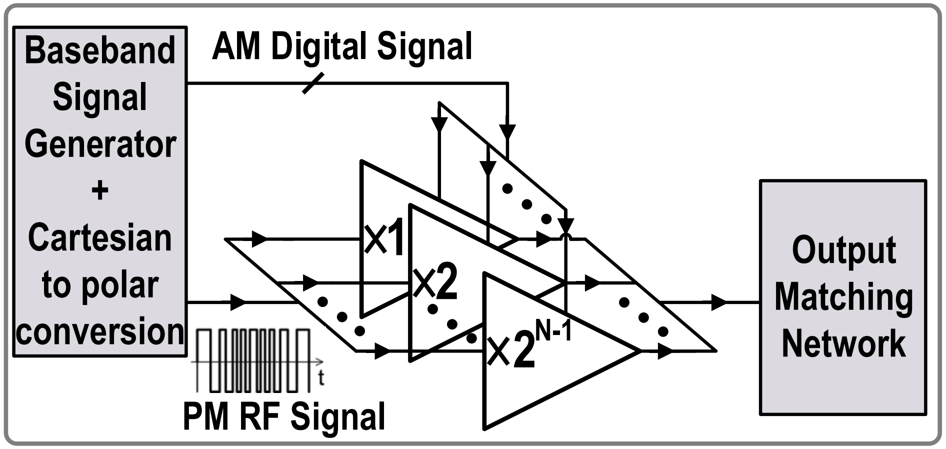
🙂 Precise control and reconfiguration

☹ AM-/PM-path bandwidth expansions

☹ Out-of-band (OOB) images and in-band noise

☹ Limited ENOB for mm-wave digital PA





[S. Hu, H. Wang, *et al.*, *IEEE TMTT*, vol. 63, no. 2, pp. 580-597, Feb. 2015.]

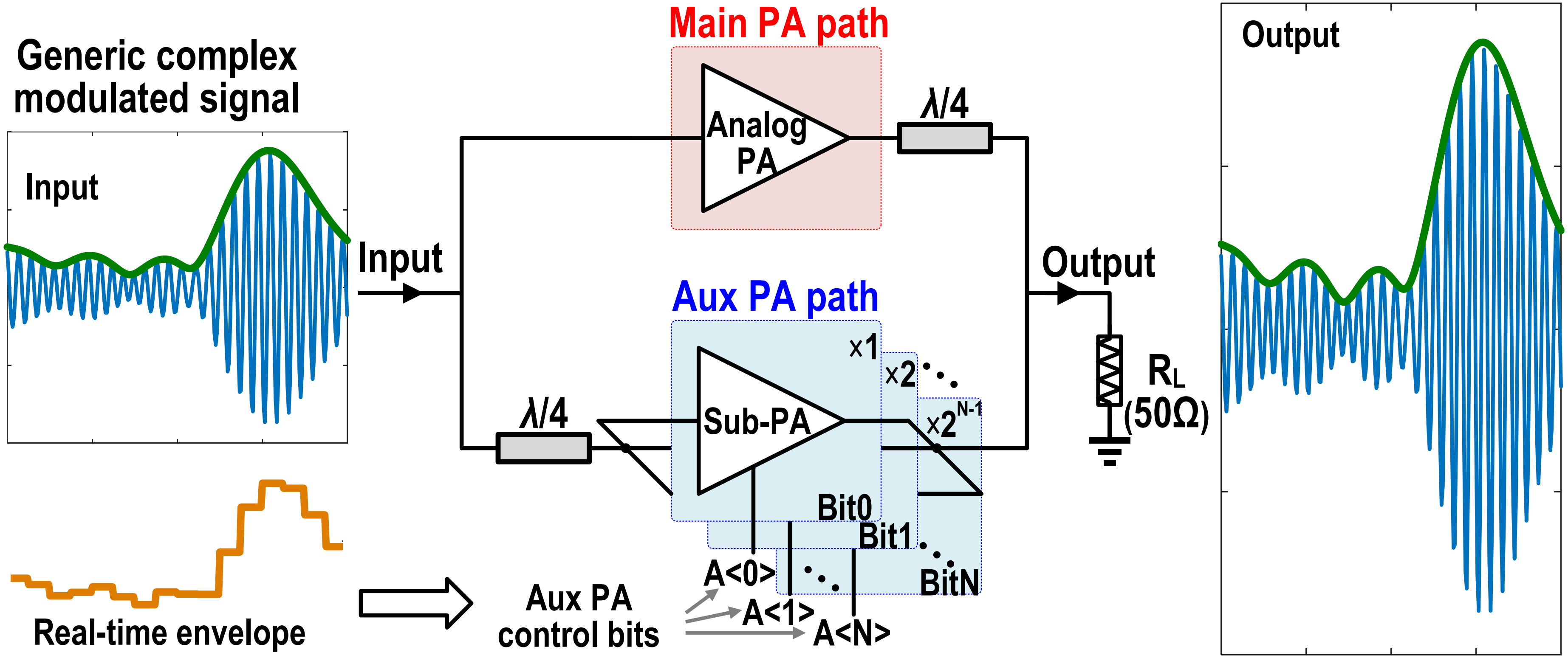
New Doherty PA/TX Architecture?

Mixed-Signal Doherty PA Architecture

- **Conceptual Schematic for Mixed-Signal Doherty PA**

  (1) Main path: analog PA   Aux path: array of binary-weighted PA cells

  (2) Input signal: generic complex modulated signal (NOT constant envelop signal)

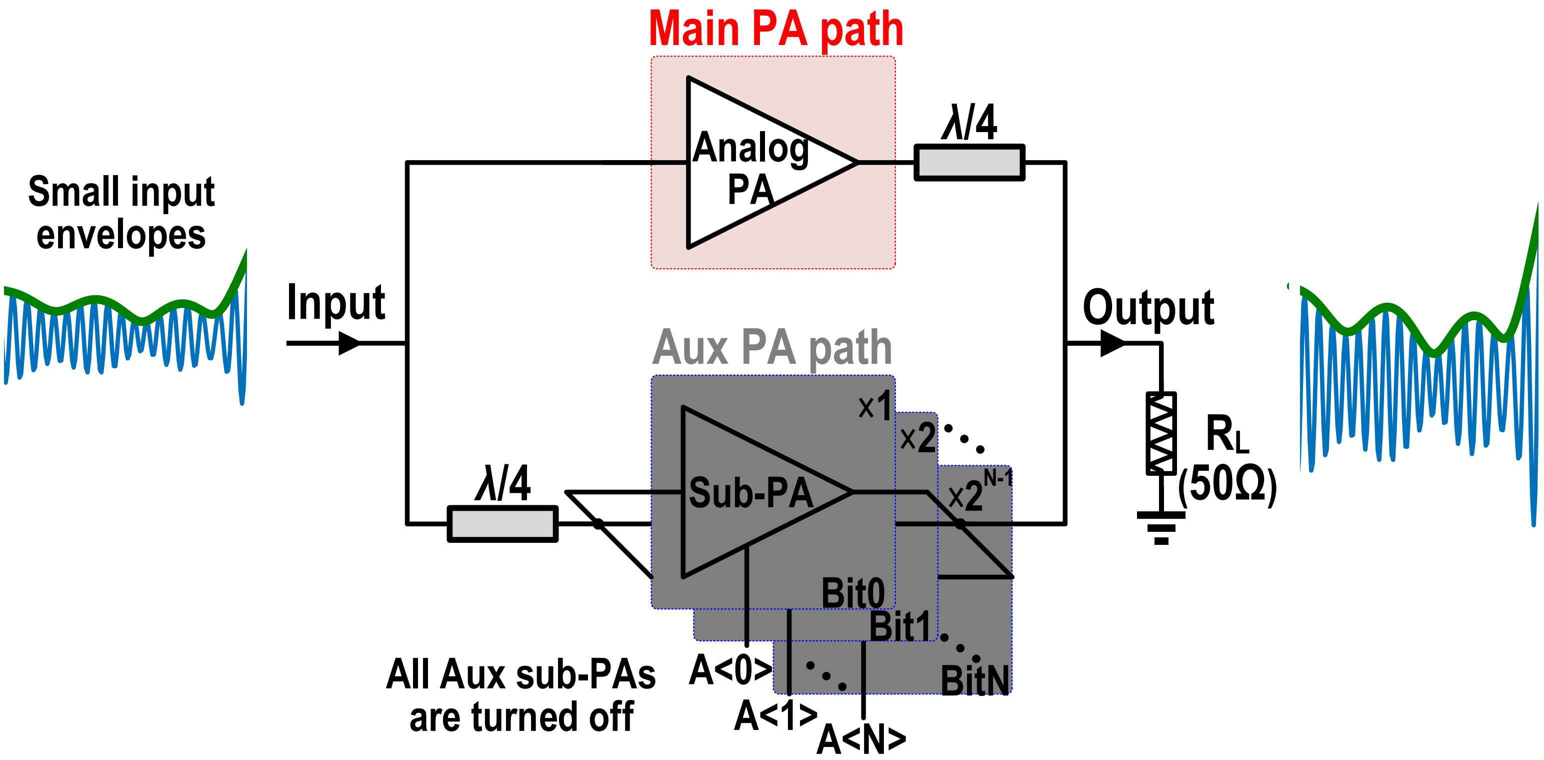


- F. Wang, T. Li, and H. Wang, *IEEE ISSCC* 2019.

Mixed-Signal Doherty PA Architecture

- **Small input envelopes: Analog Regime**

Only Main path analog PA is turned on → Operating as an analog PA

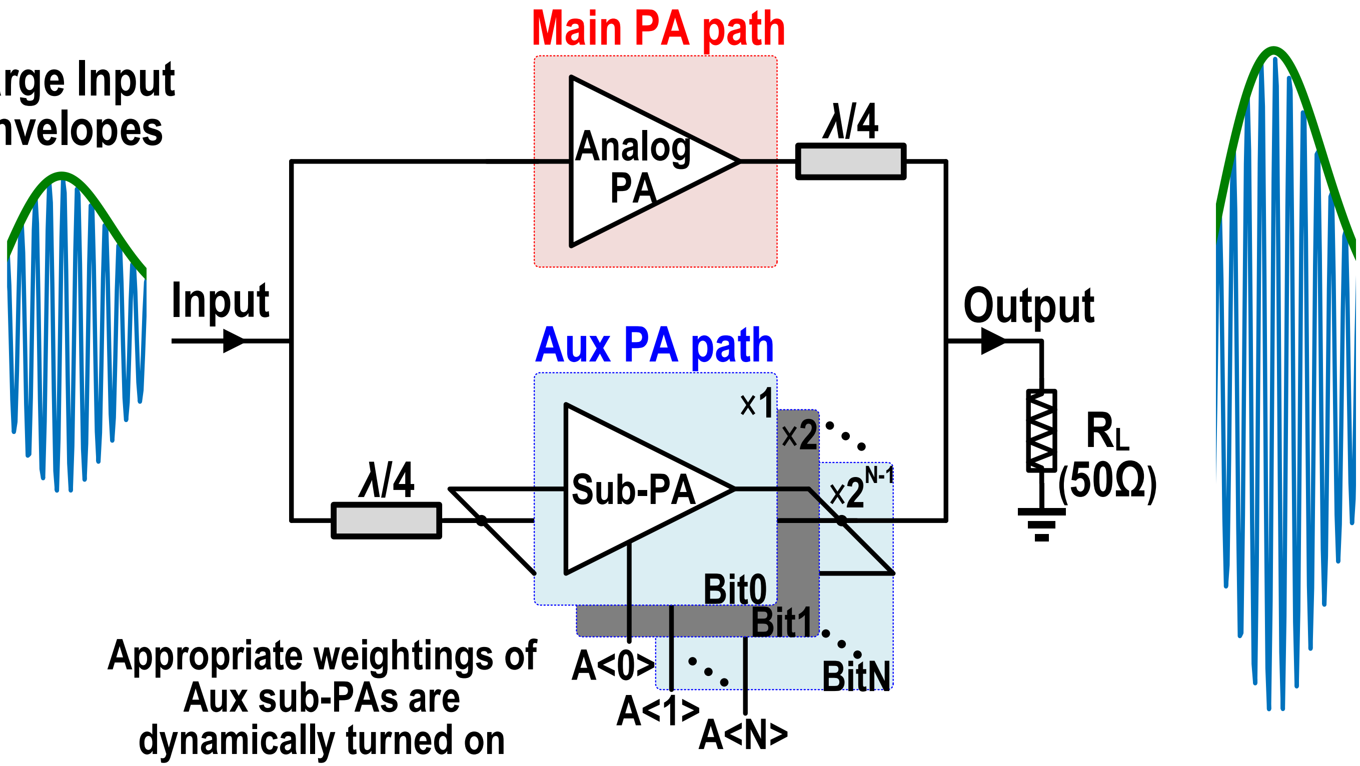


- F. Wang, T. Li, and H. Wang, *IEEE ISSCC* 2019.

Mixed-Signal Doherty PA Architecture

- **Large input envelopes: Mixed-Signal Regime**

→ Aux sub-PAs are dynamically turned on.



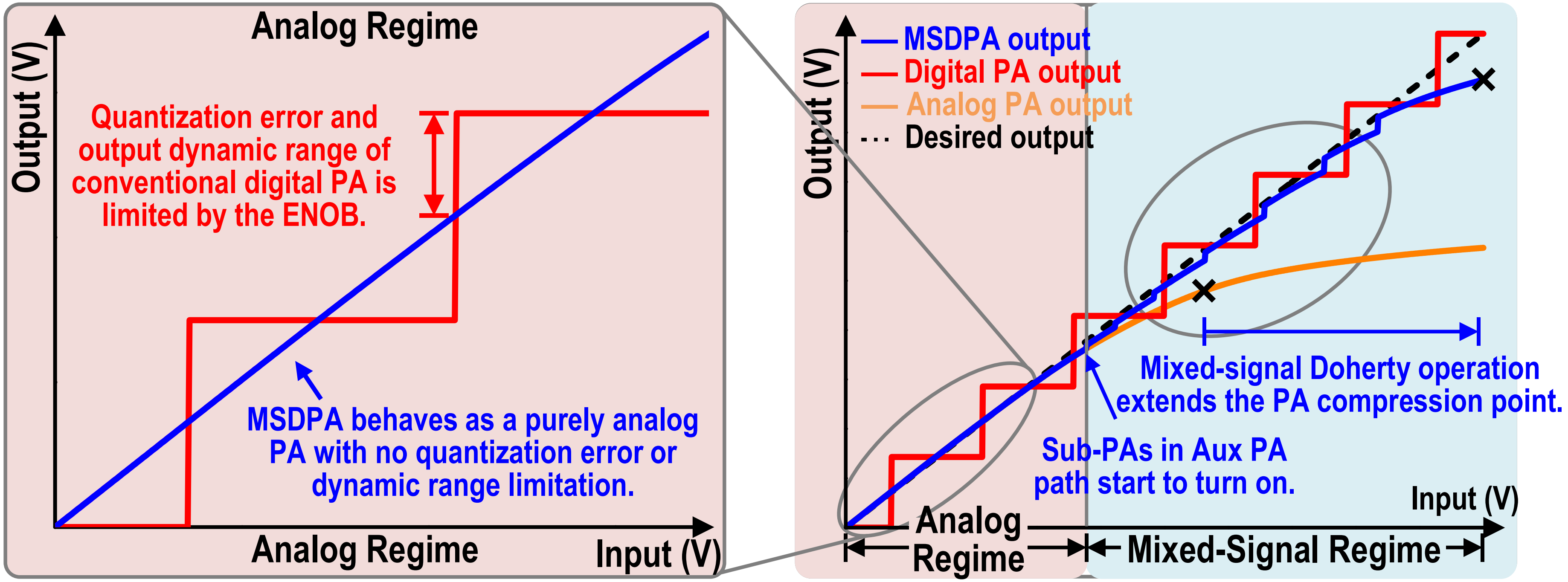
Appropriate weightings of Aux sub-PAs are dynamically turned on

- F. Wang, T. Li, and H. Wang, *IEEE ISSCC* 2019.

Unique Advantages of Mixed-Signal Doherty PA

- **Small Input Envelopes: Analog Regime**

A large dynamic range with no quantization error or LSB limitation, unlike digital PA

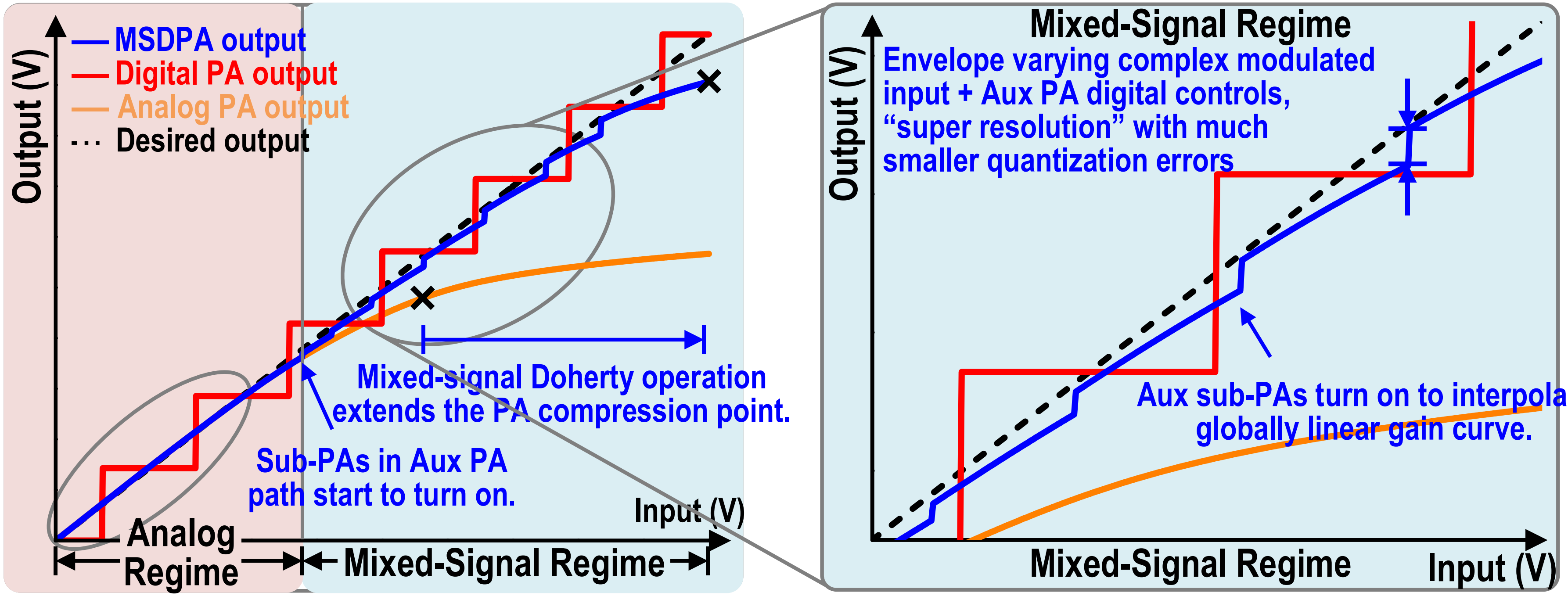


- F. Wang, T. Li, and H. Wang, *IEEE ISSCC* 2019.

Unique Advantages of Mixed-Signal Doherty PA

- **Large Input Envelopes: Mixed-Signal Regime**

The output envelope is interpolated by both envelope-varying input and real-time Aux PA digital controls. → Largely suppressing quantization errors



Mixed-signal Doherty operation extends the PA compression point.

Sub-PAs in Aux PA path start to turn on.

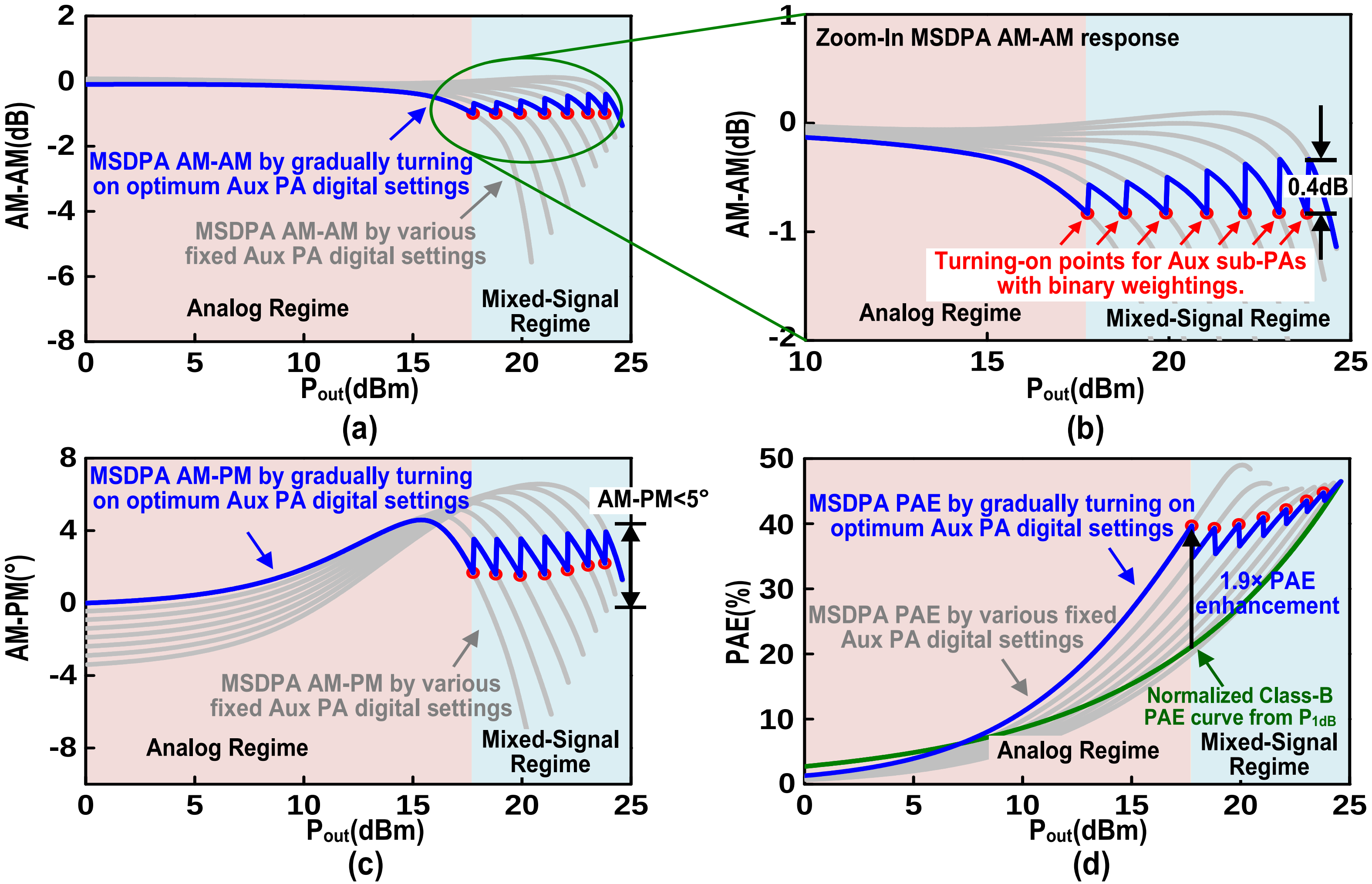
Envelope varying complex modulated input + Aux PA digital controls, "super resolution" with much smaller quantization errors

Aux sub-PAs turn on to interpolate globally linear gain curve.

- F. Wang, T. Li, and H. Wang, *IEEE ISSCC* 2019.

Unique Advantages of Mixed-Signal Doherty PA

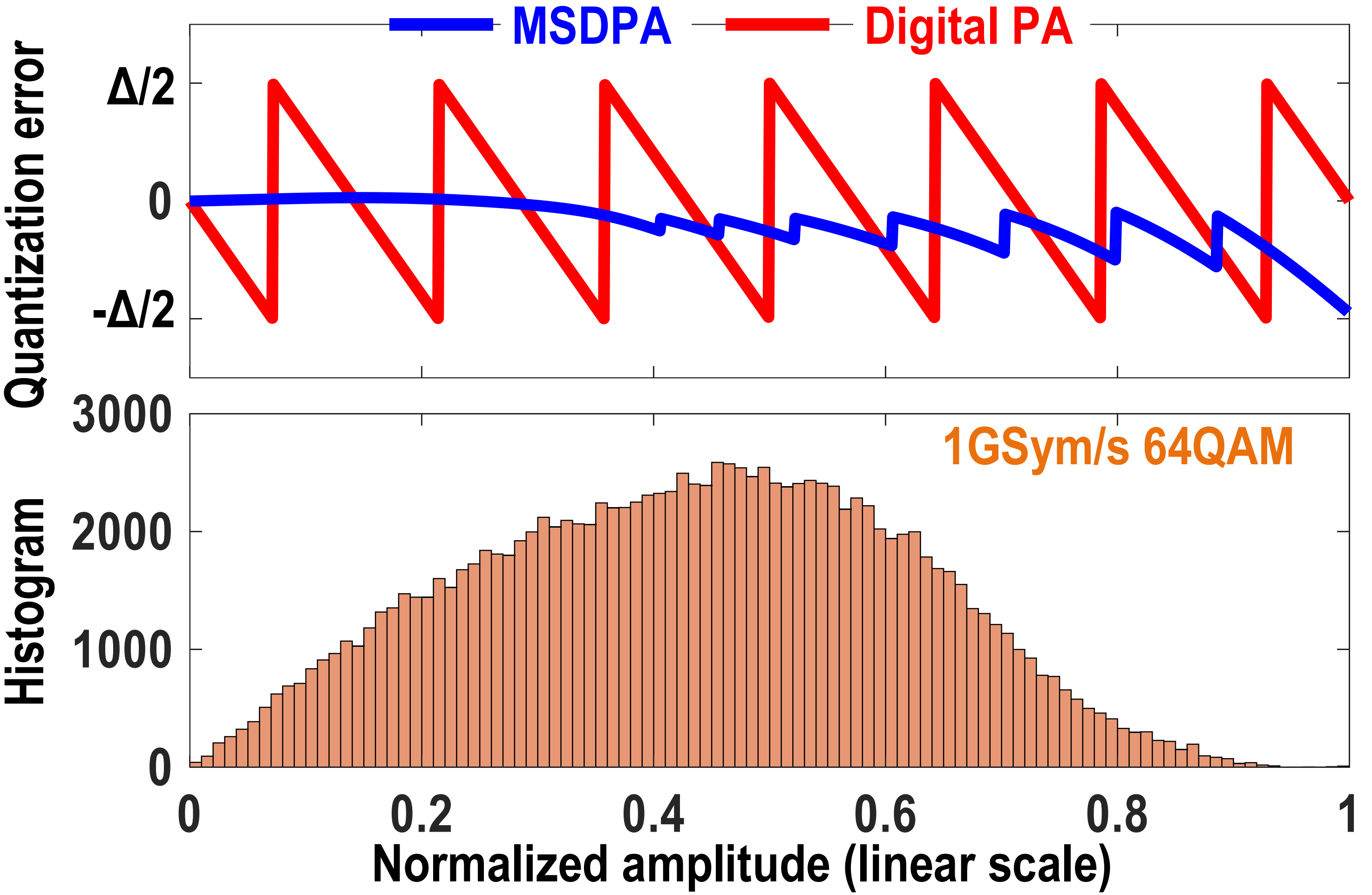
- **Mixed-Signal Doherty PA (3-bit) Gain, Phase, and Efficiency**



- F. Wang, T. Li, and H. Wang, *IEEE ISSCC* 2019.

Unique Advantages of Mixed-Signal Doherty PA

- Quantization Errors: Mixed-Signal Doherty PA vs. Digital PA (3-bits)



- F. Wang, T. Li, and H. Wang, *IEEE ISSCC* 2019.

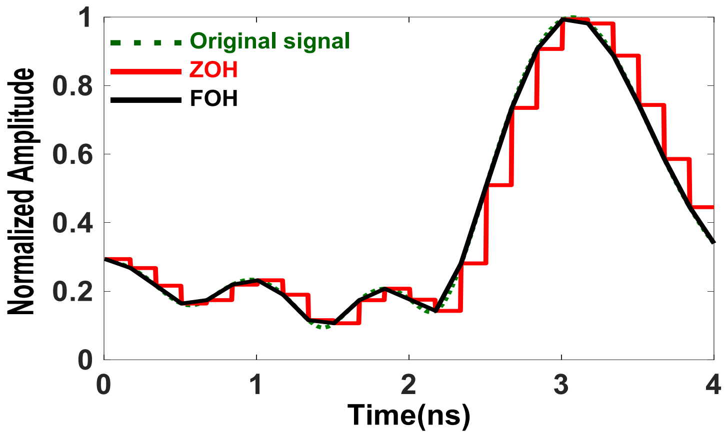
Unique Advantages of Mixed-Signal Doherty PA

• Signal Interpolation and Sampling Images

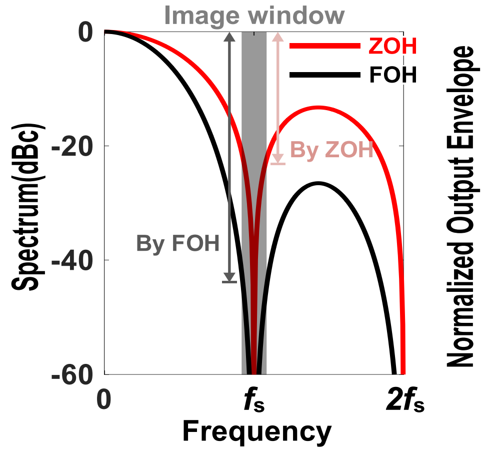
- Zeroth-Order-Hold (ZOH) vs. First-Order-Hold (FOH) systems

  Time domain: Stair-case vs. Linear-interpolation

  Freq. domain: $|\mathrm{Sinc}(f/f_s)|^2$ vs $|\mathrm{Sinc}(f/f_s)|^4$

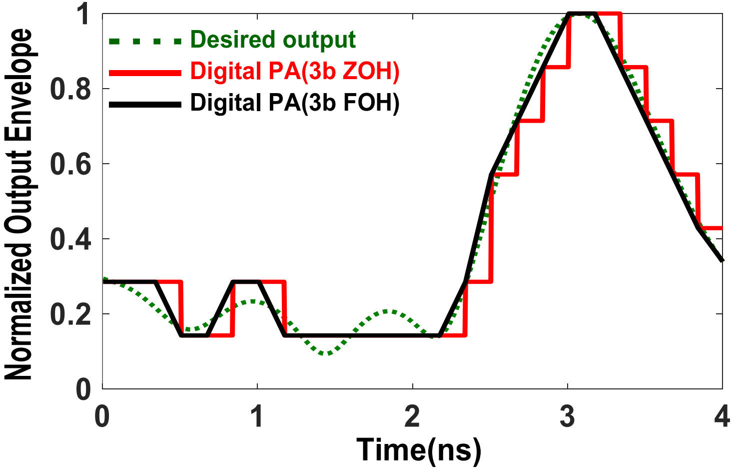


(a)

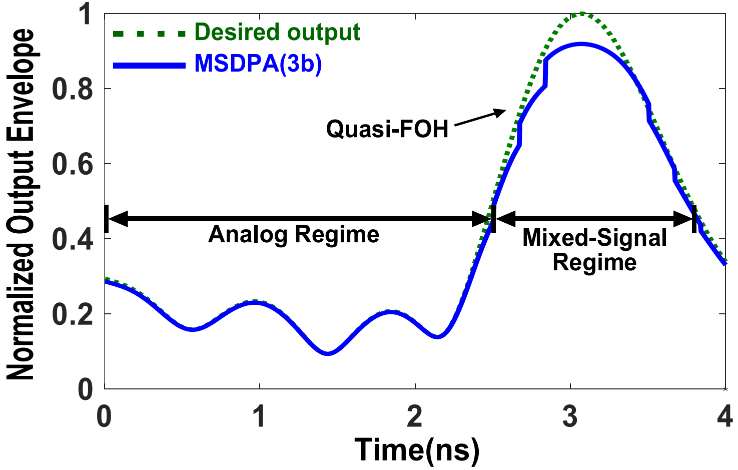


(b)

- Conventional digital PA (3-bit) vs. Mixed-signal Doherty PA (3-bit)



(c)

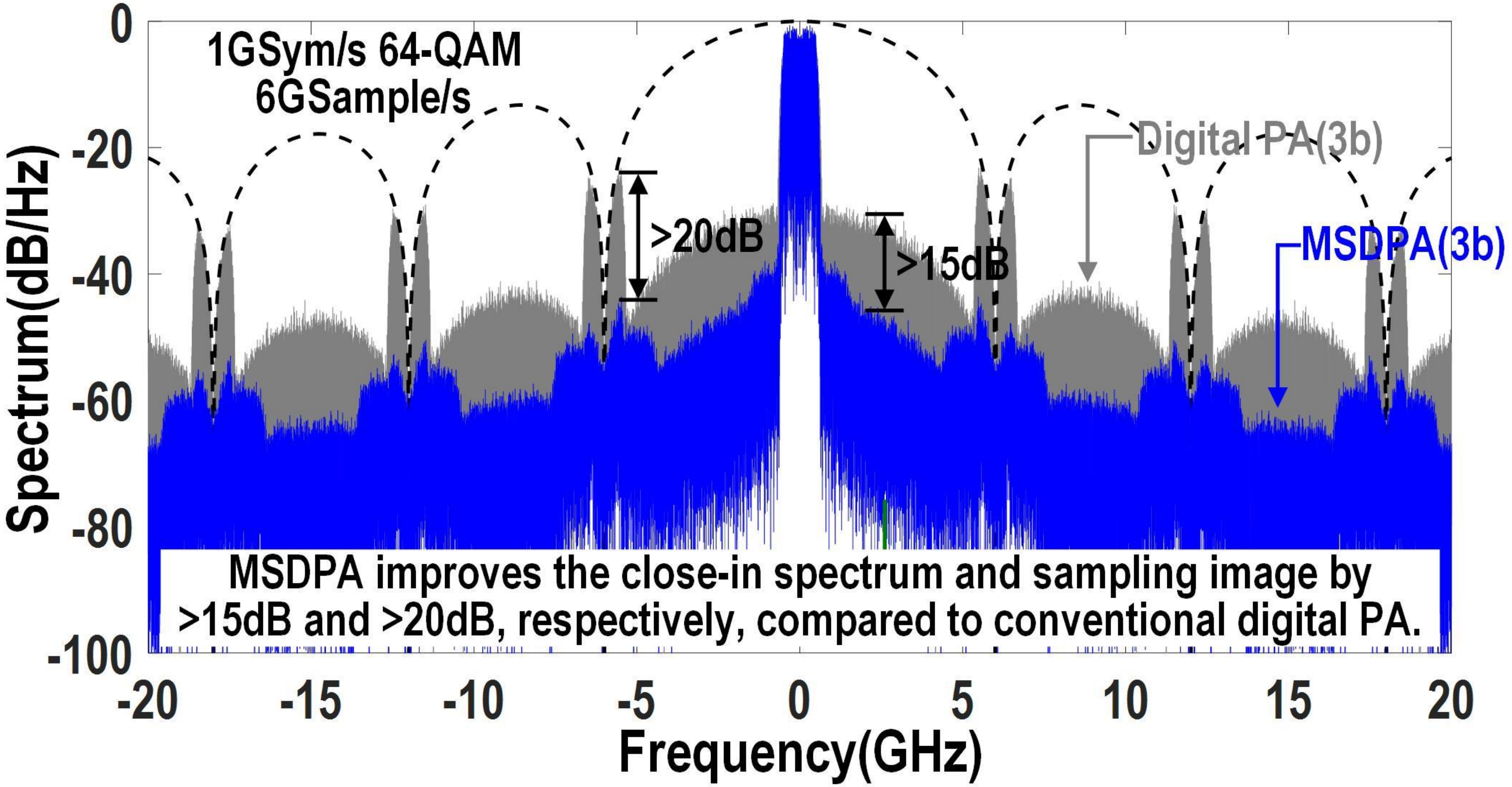


(d)

- F. Wang, T. Li, and H. Wang, *IEEE ISSCC* 2019.

Unique Advantages of Mixed-Signal Doherty PA

- Close-in spectrum and sampling images: Mixed-signal Doherty PA (3-bit) vs. Digital PA (3-bit)

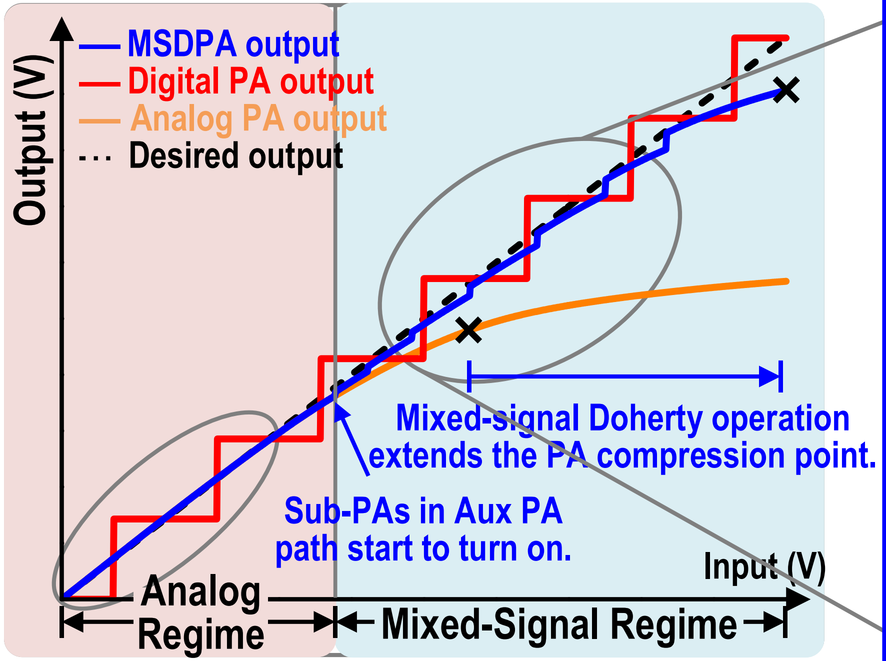


MSDPA improves the close-in spectrum and sampling image by >15dB and >20dB, respectively, compared to conventional digital PA.

- F. Wang, T. Li, and H. Wang, *IEEE ISSCC* 2019.

Unique Advantages of Mixed-Signal Doherty PA

- **“Super Resolution”:** With the same number of bits, mixed-signal Doherty PA achieves superior linearity than conventional digital PA.



Why Super Resolution?

(1) Small input envelopes: An analog PA with large dynamic range and no quantization error.

(2) Large input envelopes: Output envelopes by both envelope-varying input and real-time Aux PA digital controls. **Quasi “First-Order Hold (FOH)”** → Much smaller quantization errors and sampling images

(3) Non-uniform quantization

- F. Wang, T. Li, and H. Wang, *IEEE ISSCC* 2019.

Prototype Implementation

- **28GHz Mixed-Signal Doherty PA with only 3-bit Aux controls (ISSCC2019, ISSCC2017, JSSC2019)**

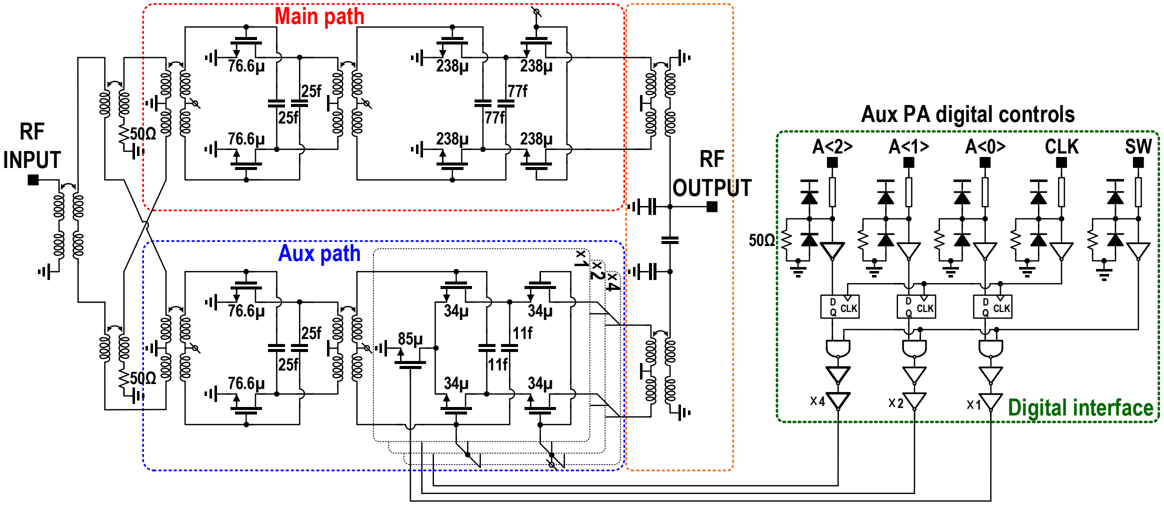
  Cascoded PA stage (476µm/40nm) and V_{DD} = 2.0 V

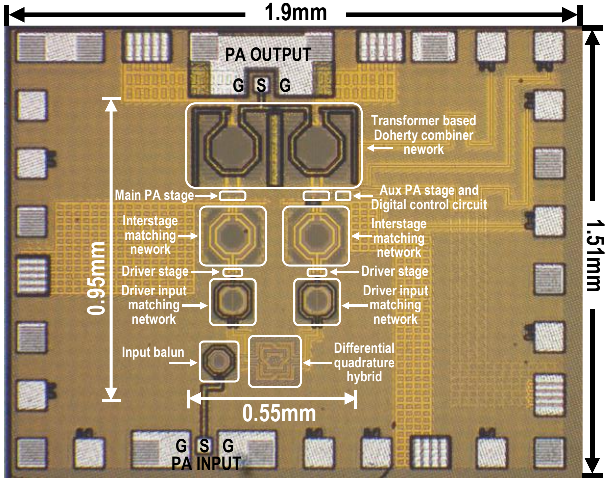
  CS driver stage (153.2µm/40nm) and V_{DD} = 1.0 V

- **Chip microphotograph**

  45nm SOI CMOS process

  0.53mm^2 core area

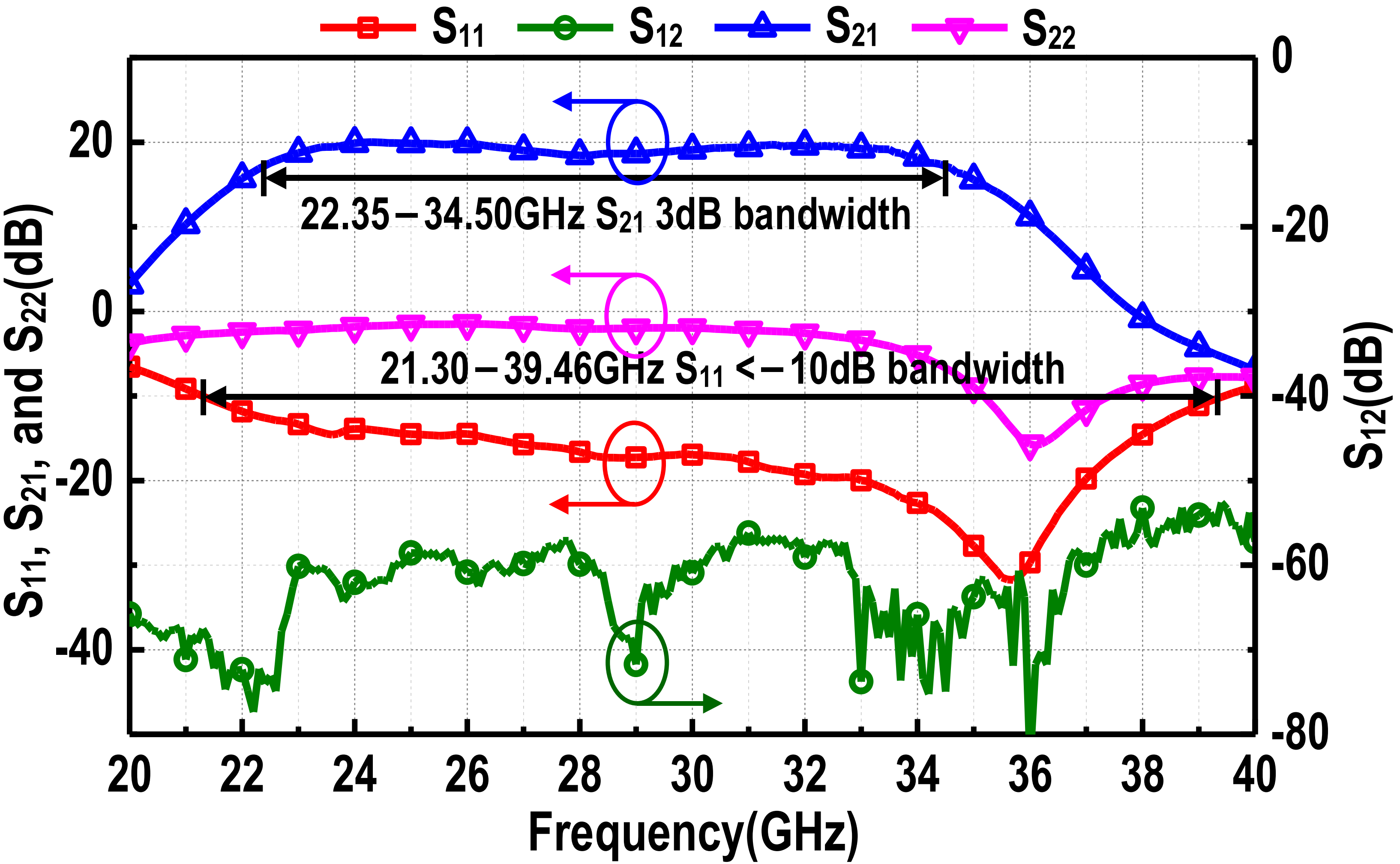




- F. Wang, T. Li, and H. Wang, *IEEE ISSCC* 2019.

Experimental Results

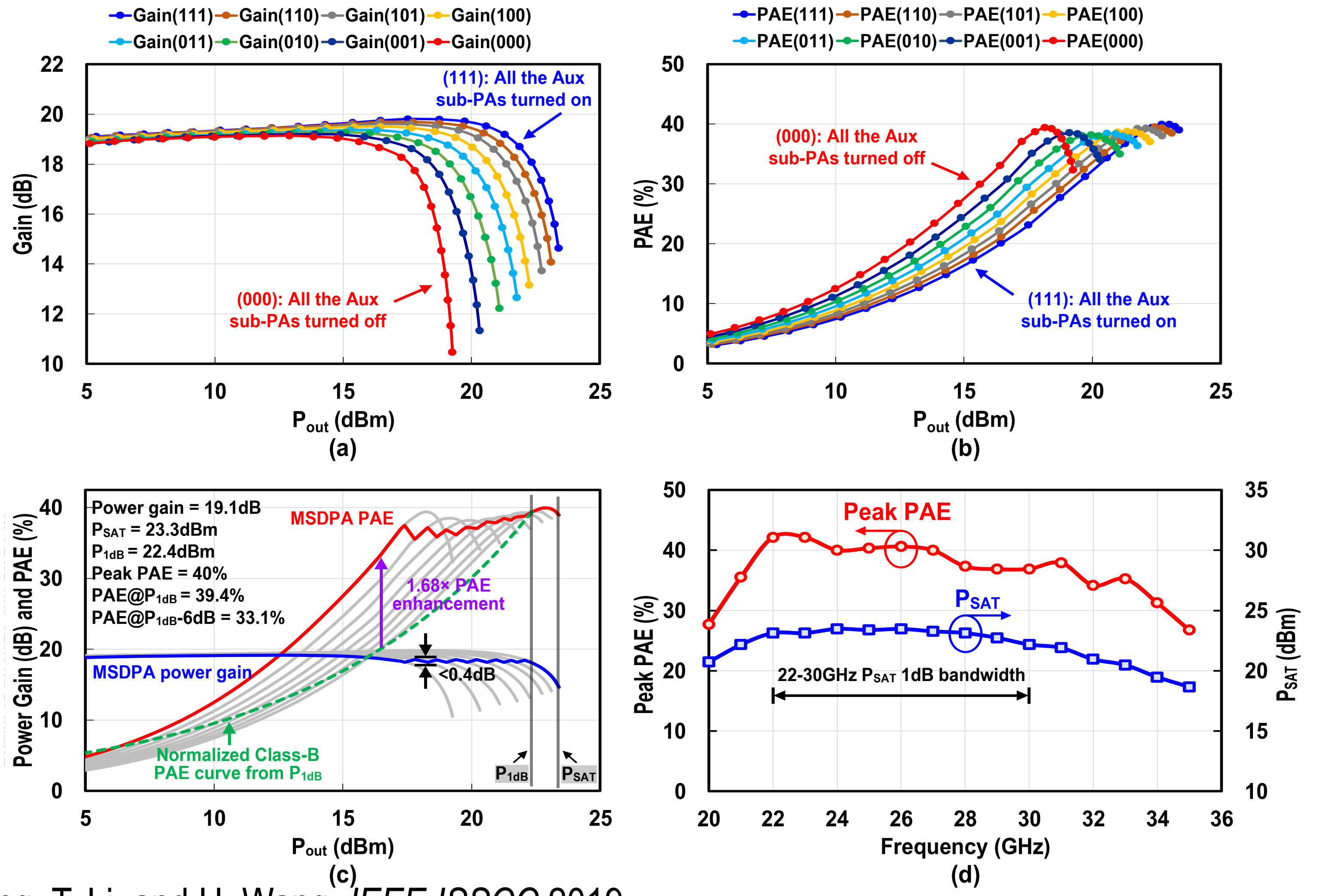
- **Small-Signal CW Measurement**



- F. Wang, T. Li, and H. Wang, *IEEE ISSCC* 2019.

Experimental Results

- **Large-Signal CW Measurements at 28GHz**

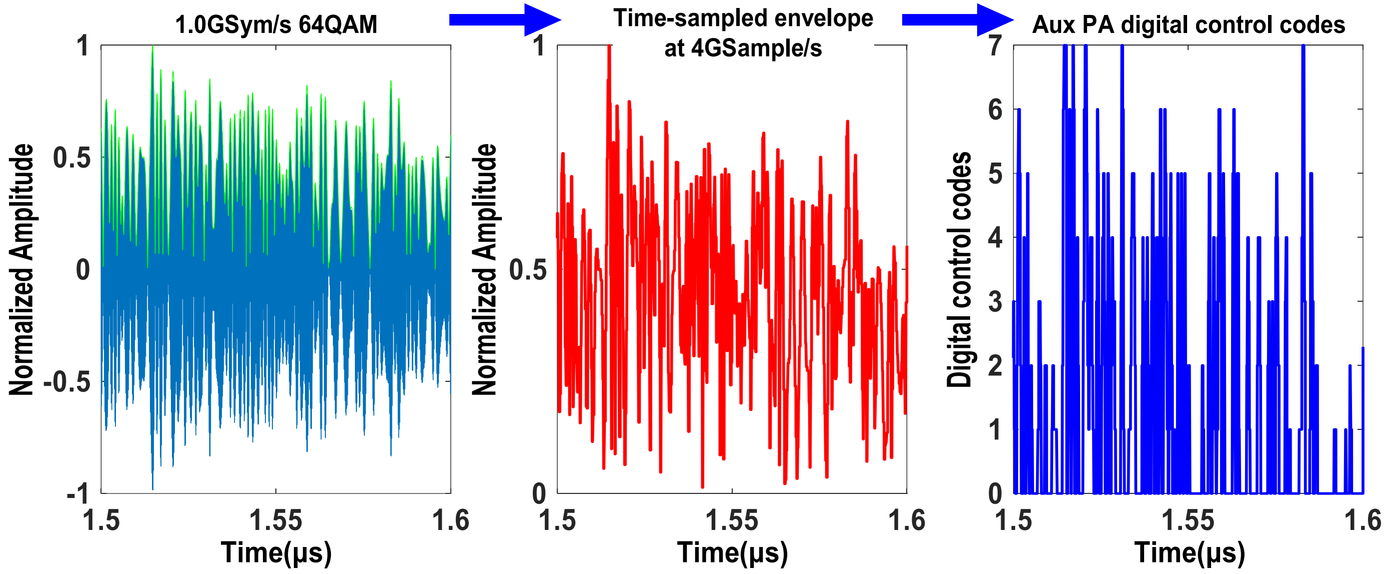


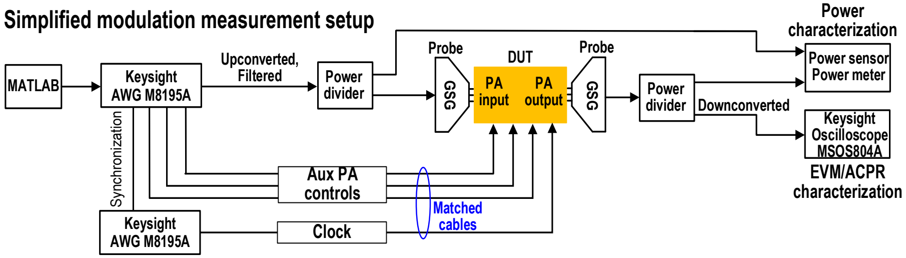
(a) (b) (c) (d)

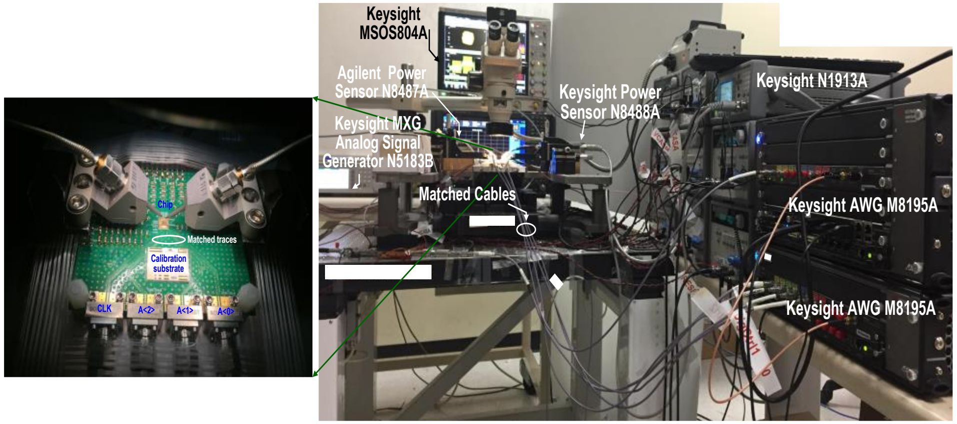
- F. Wang, T. Li, and H. Wang, *IEEE ISSCC* 2019.

Experimental Results

- **Modulation measurement setup**





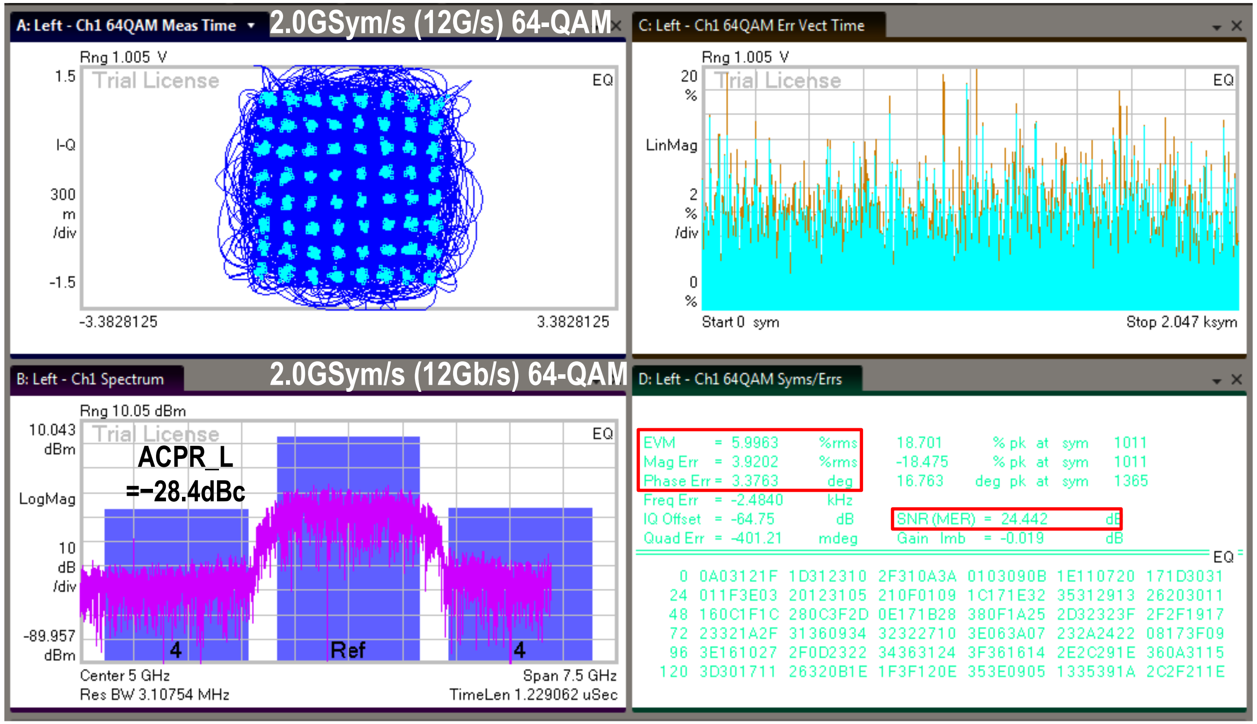


- F. Wang, T. Li, and H. Wang, *IEEE ISSCC* 2019.

Experimental Results

- **Modulation Measurements: EVM and ACPR**

  2.0GSym/s (12Gb/s) 64-QAM without predistortion



```
EVM       =  5.9963     %rms     18.701      % pk  at  sym   1011
Mag Err   =  3.9202     %rms     -18.475     % pk  at  sym   1011
Phase Err =  3.3763      deg     16.763    deg pk  at  sym   1365
Freq Err  =  -2.4840     kHz
IQ Offset =  -64.75       dB     SNR (MER)  =  24.442          dB
Quad Err  =  -401.21    mdeg     Gain  Imb  =  -0.019          dB
                                                                EQ
  0  0A03121F  1D312310  2F310A3A  0103090B  1E110720  171D3031
 24  011F3E03  20123105  210F0109  1C171E32  35312913  26203011
 48  160C1F1C  280C3F2D  0E171B28  380F1A25  2D32323F  2F2F1917
 72  23321A2F  31360934  32322710  3E063A07  232A2422  08173F09
 96  3E161027  2F0D2322  34363124  3F361614  2E2C291E  360A3115
120  3D301711  26320B1E  1F3F120E  353E0905  1335391A  2C2F211E
```

First demonstration of 64-QAM modulation with only 3-bit digital controls

P_{avg}=15.6dBm

PAE_{avg}=27.8%

$P_{DC,digital}$ = 9mW

rms EVM=−24.4dB

EVM = 6.00 %rms

Mag Err = 3.92 %rms

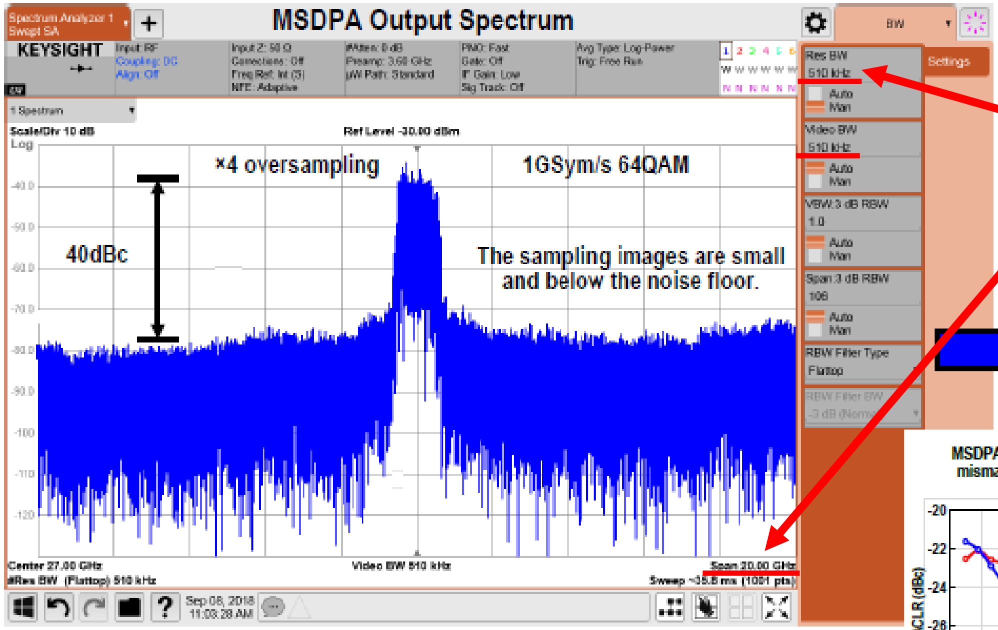
Phase Err = 3.38 deg

MER = 24.4 dB

- F. Wang, T. Li, and H. Wang, *IEEE ISSCC* 2019.

Experimental Results

- **Modulation Measurements: Out-of-Band Spurs and Delay Mismatch Effects**



Spectrum Analyzer 1
Swept SA

MSDPA Output Spectrum

KEYSIGHT

Input: RF
Coupling: DC
Align: Off

Input Z: 50 Ω
Corrections: Off
Freq Ref: Int (S)
NFE: Adaptive

#Atten: 0 dB
Preamp: 3.60 GHz
µW Path: Standard

PNO: Fast
Gate: Off
IF Gain: Low
Sig Track: Off

Avg Type: Log-Power
Trig: Free Run

1 Spectrum

Scale/Div 10 dB
Log

Ref Level -30.00 dBm

Center 27.00 GHz
#Res BW (Flattop) 510 kHz

Video BW 510 kHz

Span 20.00 GHz
Sweep ~35.8 ms (1001 pts)

Sep 08, 2018
11:03:28 AM

BW

Res BW
510 kHz

Video BW
510 kHz

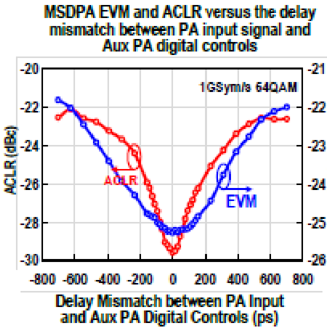
VBW:3 dB RBW
1.0

Span:3 dB RBW
106

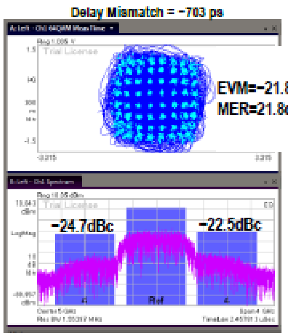
RBW Filter Type
Flattop

RBW Filter BW
-3 dB (Normal)

- 1G sym/s 64QAM with ×4 oversampling
- Resolution BW = 510 kHz
- Frequency Span = 20 GHz
- **~40dBc OOB floor without DPD**
- **No major sampling images observed**

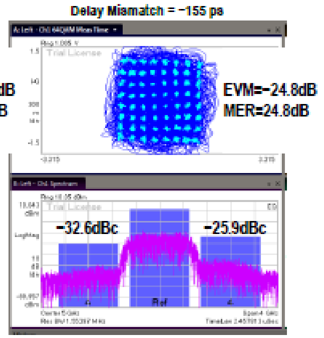


MSDPA EVM and ACLR versus the delay mismatch between PA input signal and Aux PA digital controls



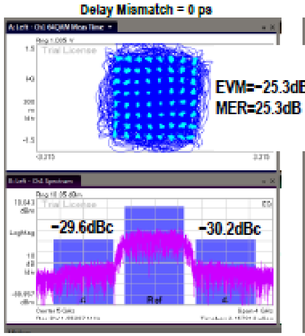
Delay Mismatch = −703 ps

EVM=−21.8dB
MER=21.8dB



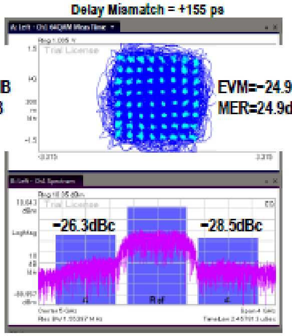
Delay Mismatch = −155 ps

EVM=−24.8dB
MER=24.8dB



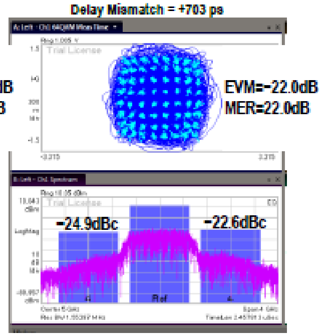
Delay Mismatch = 0 ps

EVM=−25.3dB
MER=25.3dB



Delay Mismatch = +155 ps

EVM=−24.9dB
MER=24.9dB



Delay Mismatch = +703 ps

EVM=−22.0dB
MER=22.0dB

- 1G sym/s 64QAM with ×4 oversampling
- For delay mismatch (PA input vs. Aux. PA controls) <±10% symbol period (±100ps), rms EVM<-25dB and ACLR<-27dBc
- ACLR is more sensitive than EVM for delay mismatches

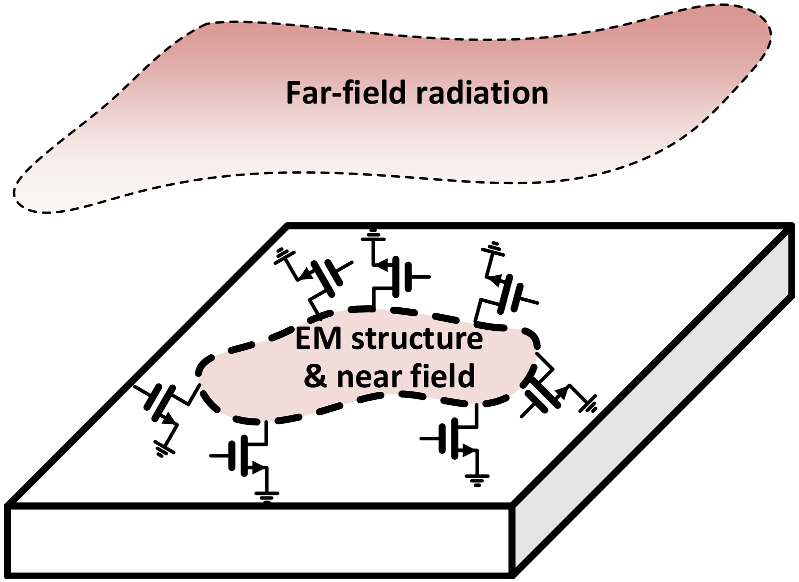
Outline

- Introduction
- State of the Art: Georgia Tech PA Survey (2000-present)
- Broadband Linear Efficient PAs
- **Antenna-PA Co-Designs: Multi-Feed Mm-Wave Radiators**
- Conclusion

Merging Antennas with Electronics?

Can we synergistically merge antennas/EMs together with active circuits?

- **Novel hybrid antenna-electronics with "On-Radiator" functions**
  - (1) Power Combining/Splitting
  - (2) Impedance Scaling and Filtering
  - (3) Active Load Modulation
  - (4) Reconfigurability

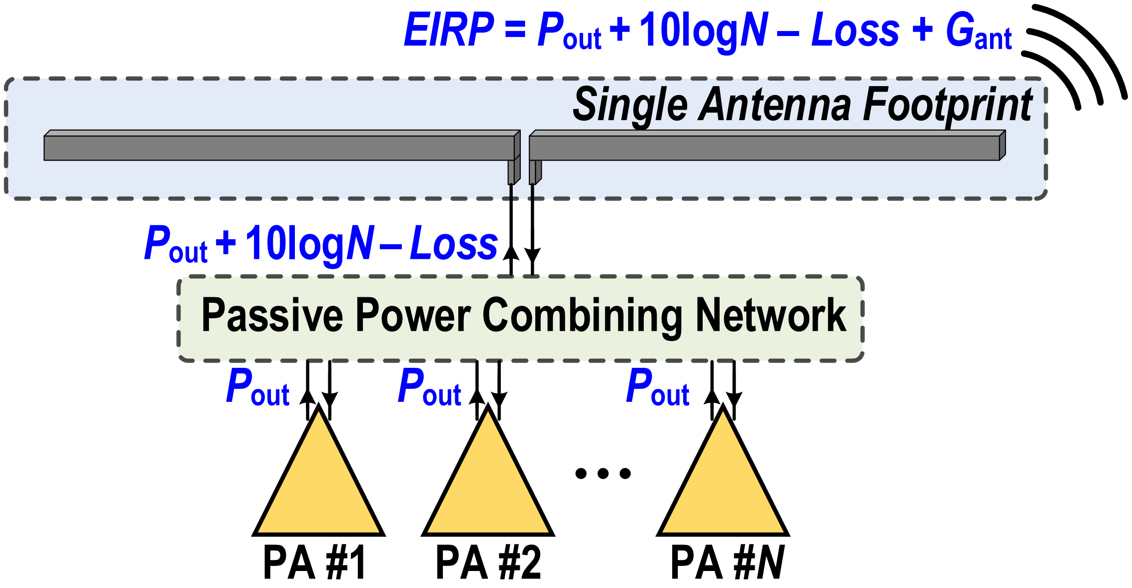


- R. King and T. Wu, "The Cylindrical Antenna with Arbitrary Driving Point," *IEEE T-AP, Sept. 1965.*
- S. Bowers, A. Hajimiri, "Multi-Port Driven Radiators," *IEEE T-MTT, Dec. 2013.*
- H. Wang, T. Chi, H. Nguyen, S. Li, J. Park, *et al., IEEE APS/URSI 2016, T-AP 2017, ISSCC 2017, ISSCC 2018, RFIC 2018.*

Multi-Feed Radiator for Direct On-Antenna Power Combining

- Conventional power combining technique I

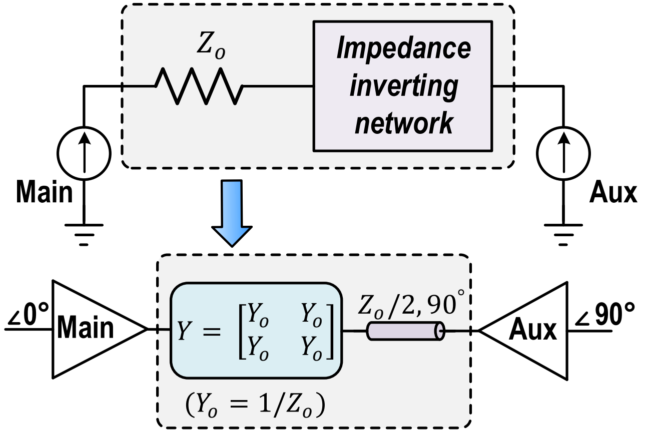
Passive on-chip/on-package combining networks

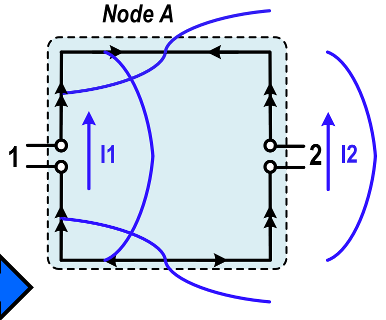


✗
- Lossy passive combiner degrades efficiency, especially with large number of power devices and high impedance-transformation ratio

Dual-Feed Mm-Wave Doherty Radiator

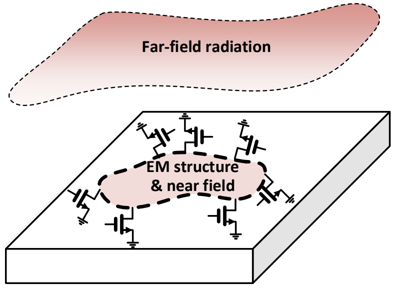
Series Doherty Architecture

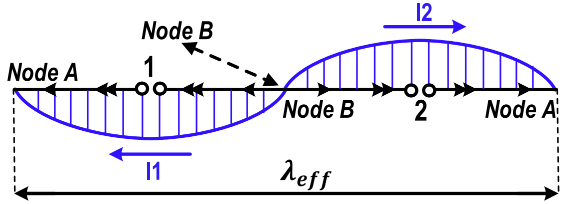




$$Y = \begin{bmatrix} Y_o & Y_o \\ Y_o & Y_o \end{bmatrix}$$

$$\text{where } Y_o = 1/Z_{rad}$$

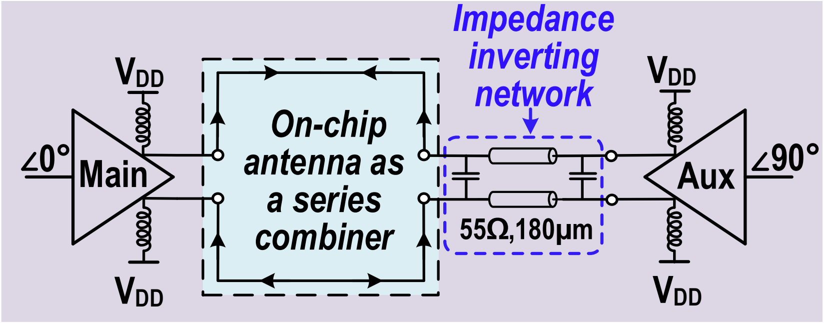




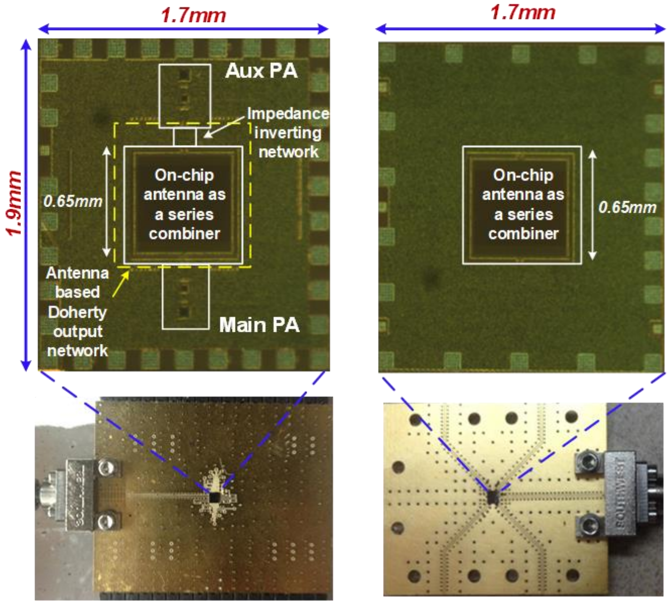
Standing-wave current distribution

Dual-feed loop antenna =
Radiator + ***Differential series combiner***

On-Antenna Doherty Radiator



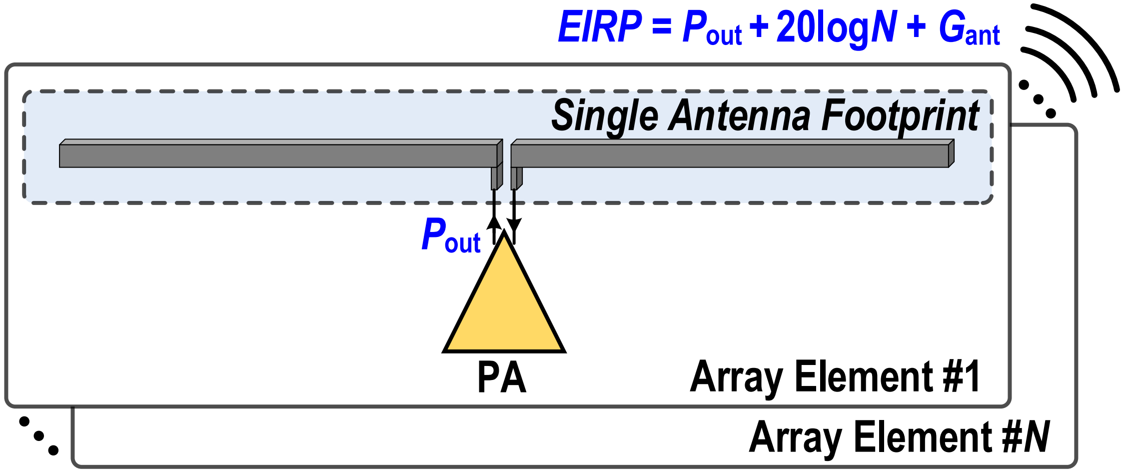
- H. T. Nguyen, T. Chi, S. Li, H. Wang, *IEEE ISSCC 2018 and IEEE JSSC 2018.*



Multi-Feed Radiator for Direct On-Antenna Power Combining

- Conventional power combining technique II

Spatial power combining by large-scale antenna arrays



$EIRP = P_{out} + 20\log N + G_{ant}$

Single Antenna Footprint

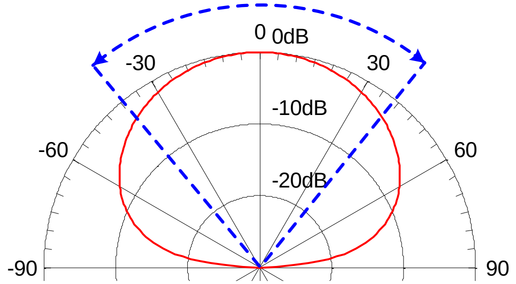
P_{out}

PA

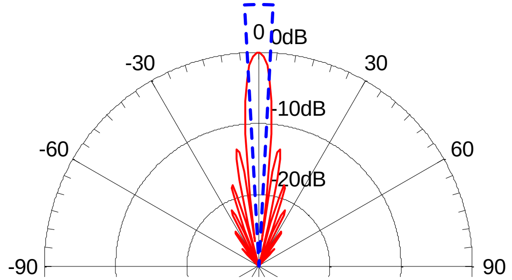
Array Element #1

Array Element #*N*

Single-Element 0.5λ Dipole
Half-Power Beamwidth = 78º



16-Element 0.5λ Dipole Array
Half-Power Beamwidth = 6º



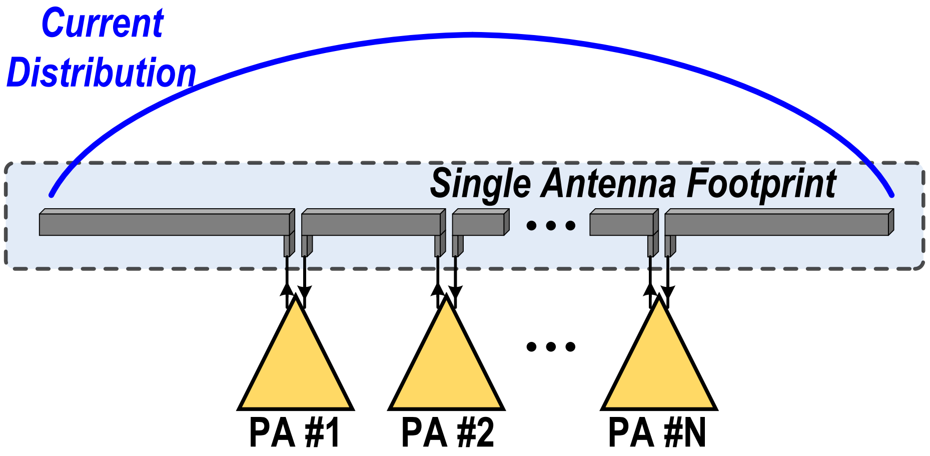
✓ • Ideally lossless and 20log*N* EIRP enhancement

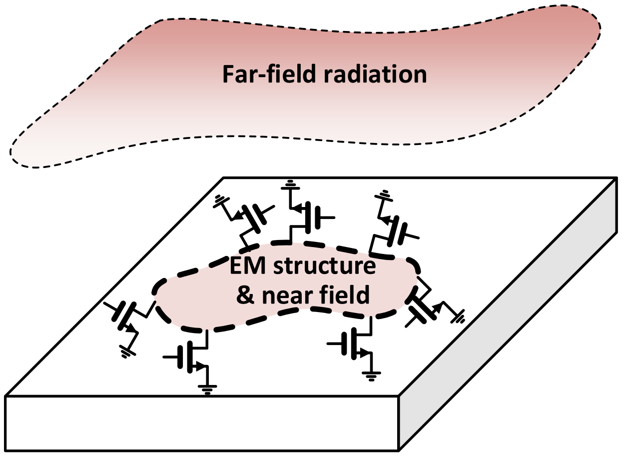
✗ • Large antenna panel size

✗ • Narrow antenna beamwidth → complicates Tx/Rx alignment for dynamic and mobile applications

Multi-Feed Radiator for Direct On-Antenna Power Combining

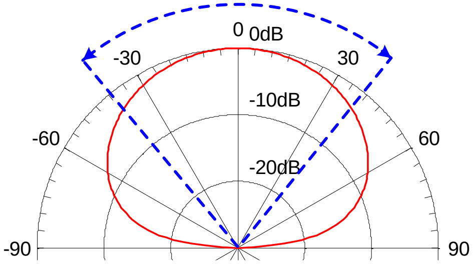
- Multifeed antenna (MFA) driven by multiple power amplifiers





- ✓ Power combining direct on antenna → boost output power
- ✓ Simplify impedance transformation → increase efficiency
- ✓ Single antenna footprint → maintain field of view
- ✓ Employed in an array → further increase EIRP or beam-steering

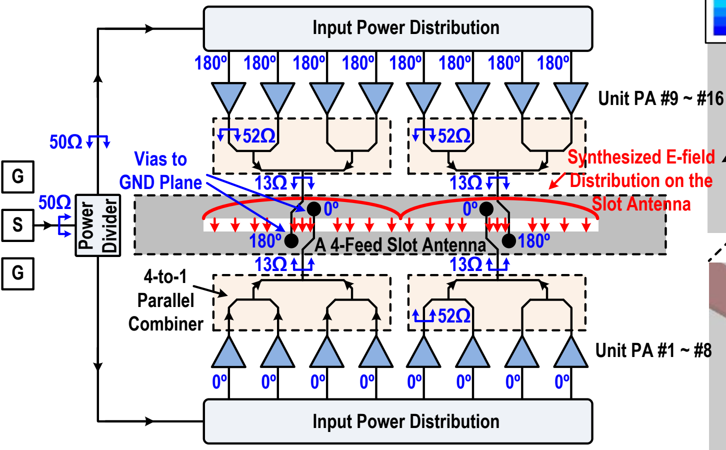
Single-Element 0.5λ Dipole
Half-Power Beamwidth = 78º

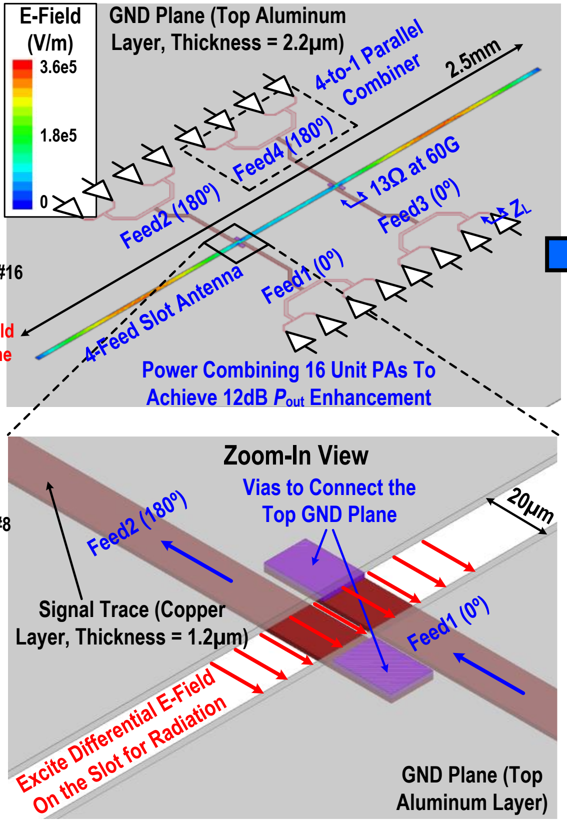


- T. Chi *et al.*, *AP-S 2016, T-AP 2017, ISSCC 2017, IMS 2018*]

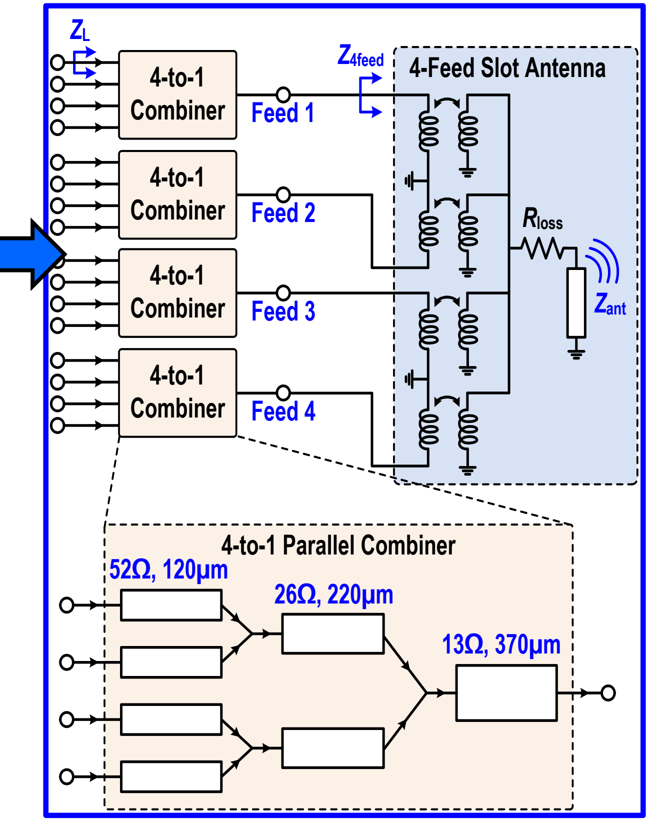
60GHz On-Chip Linear Radiator

- Linear radiator (antenna + 16 PAs) at 60GHz in 45nm CMOS SOI





“On-Antenna” Close-to-Ideal Parallel Combiner

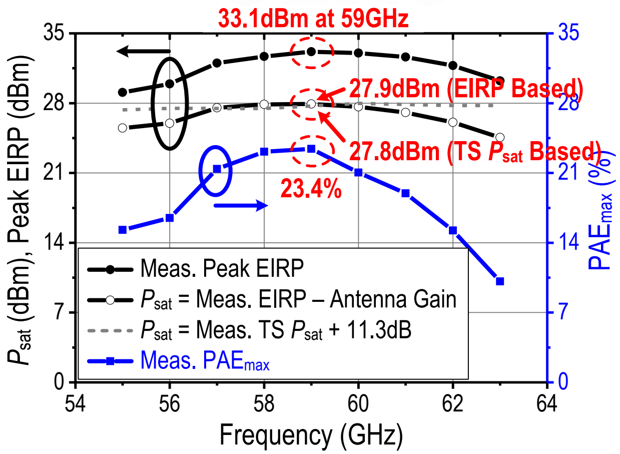


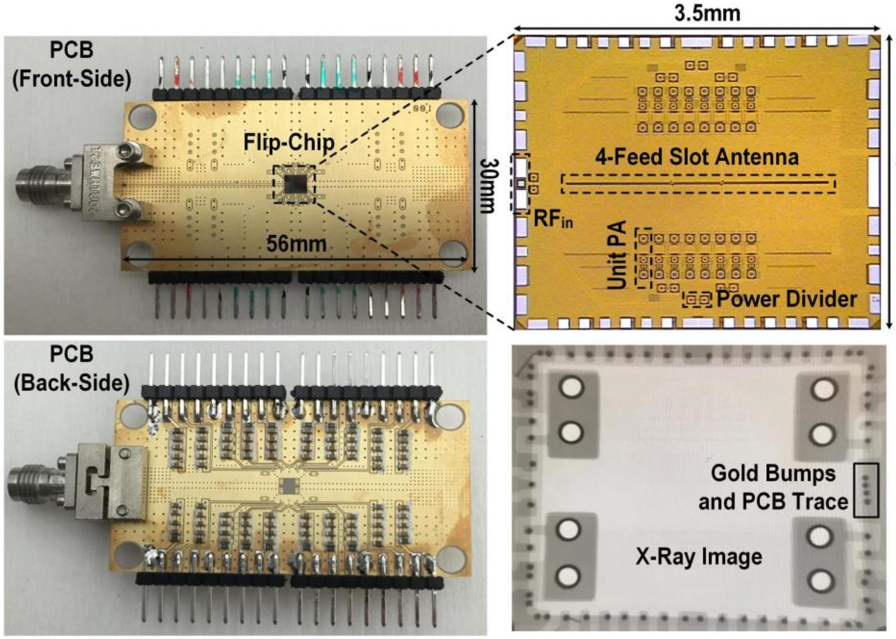
- T. Chi *et al.*, *ISSCC*, Feb. 2017.

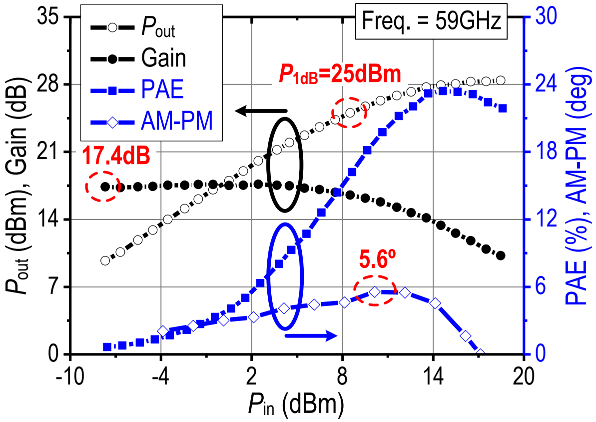
60GHz On-Chip Linear Radiator

- Linear radiator (antenna + 16 PAs) at 60GHz in 45nm CMOS SOI

Highest reported output power + efficiency

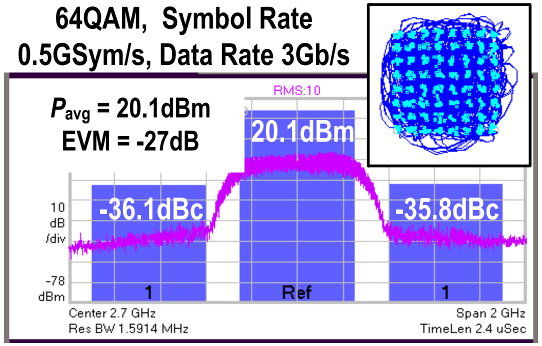






High linearity

64QAM, Symbol Rate 0.5GSym/s, Data Rate 3Gb/s

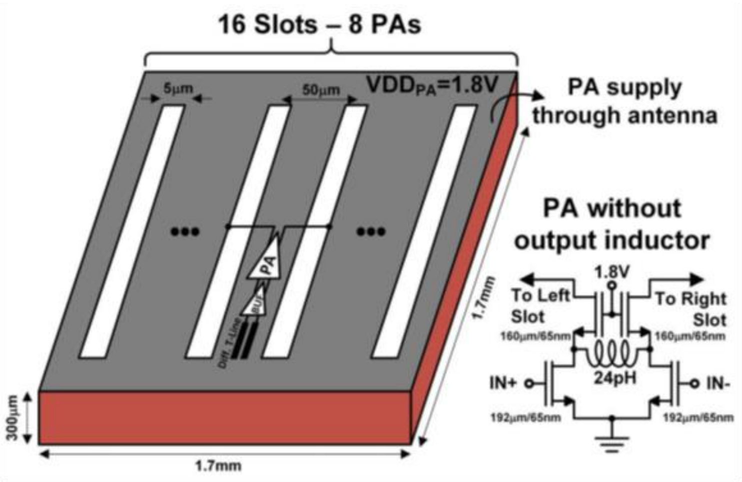


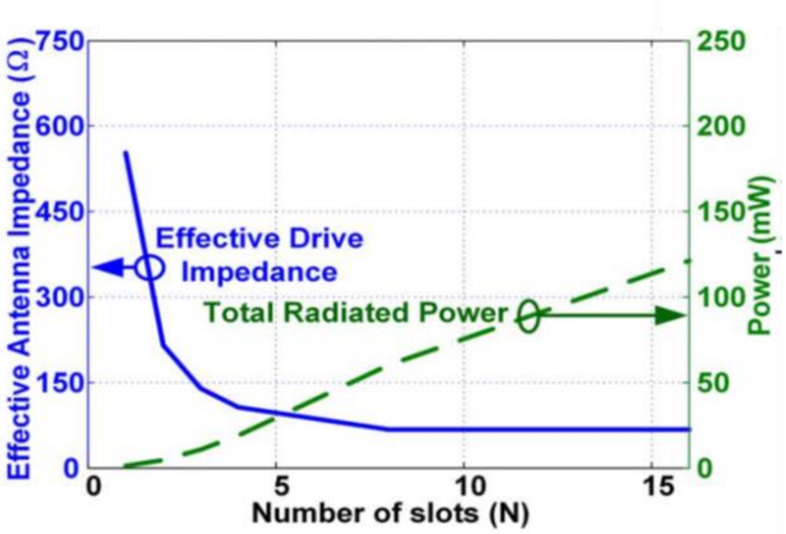
High-speed complex modulation

- T. Chi *et al.*, *ISSCC*, Feb. 2017.

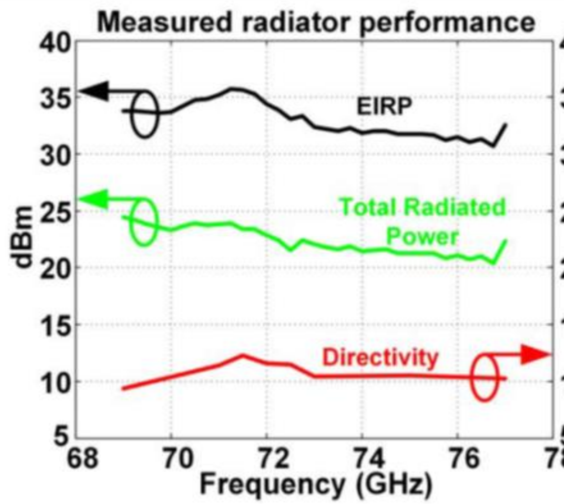
Direct On-Antenna Power Combining

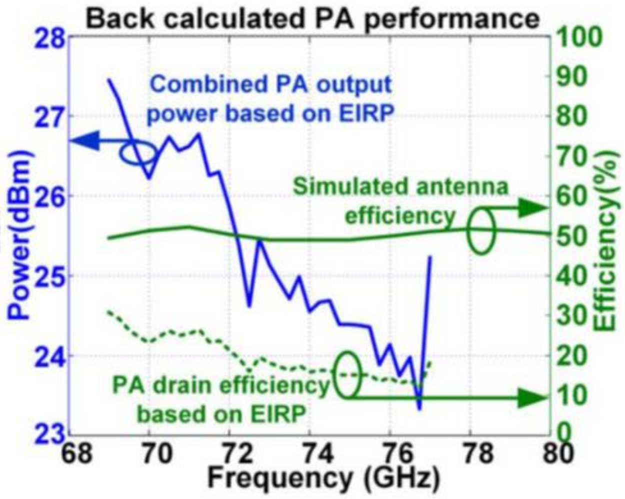
- **A 69-79GHz CMOS multi-port radiator with +35.7dBm CW EIRP**

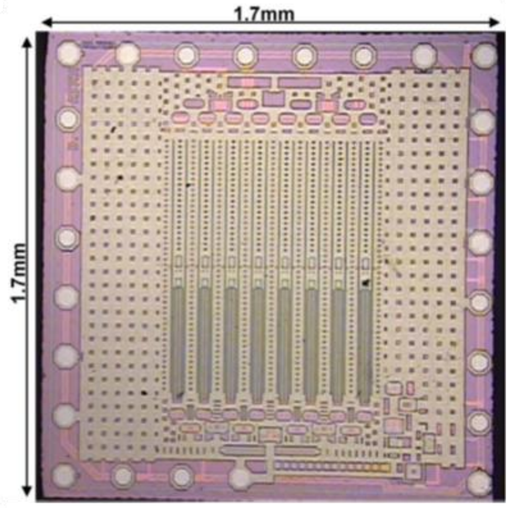




- B. Abiri, A. Hajimiri, *IEEE ISSCC 2018.*



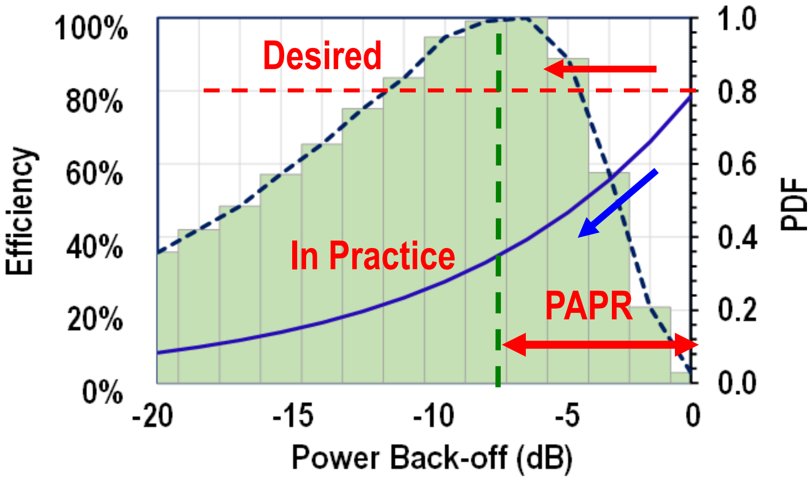




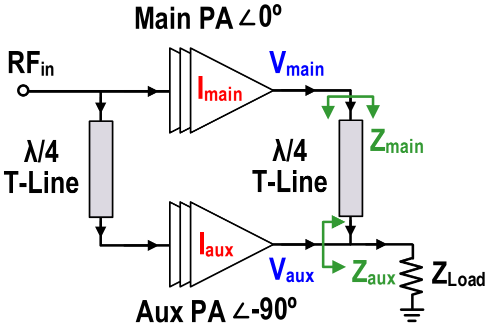
Multi-Feed Radiator for Direct On-Antenna Active Load Modulation

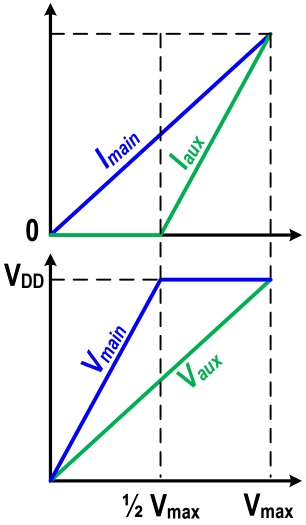
- Advanced “on-antenna” active load modulation transmitters?

  → **TX system back-off efficiency**

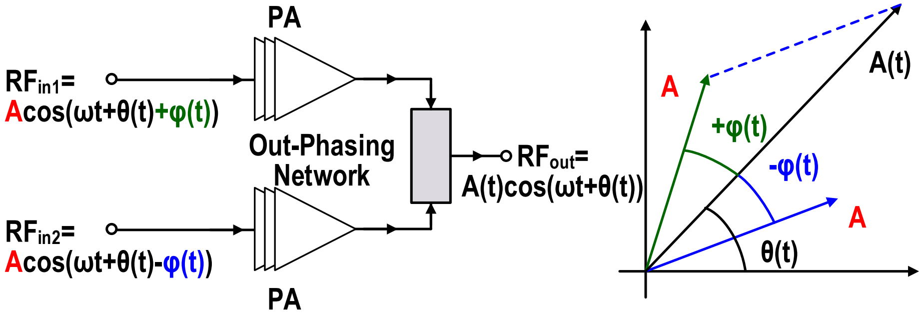


- **Doherty Linear TX Architecture**





- **Outphasing Nonlinear TX Architecture**



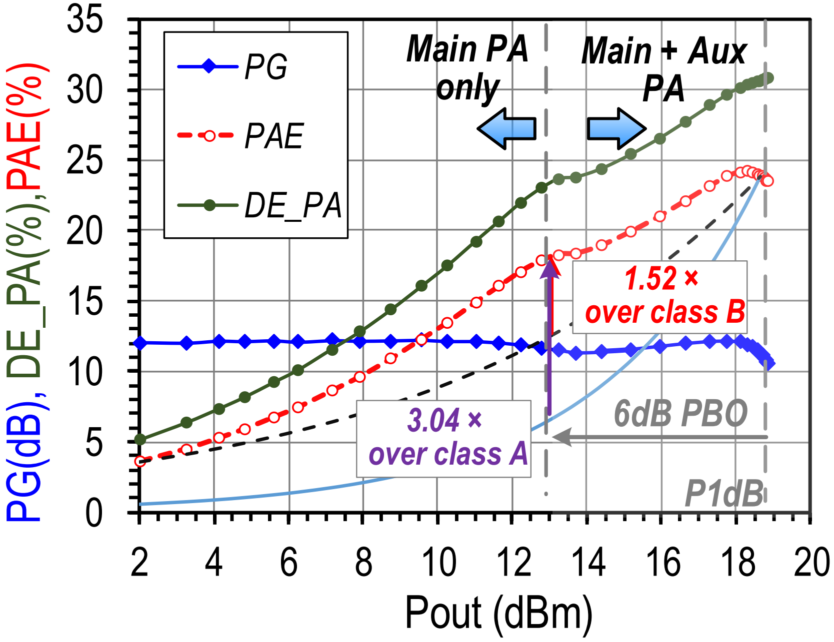
- B. Kim, et al., *IEEE Microwave Magazine*, Oct. 2006.
- S. Hu and H. Wang, *IEEE ISSCC*, 2017.

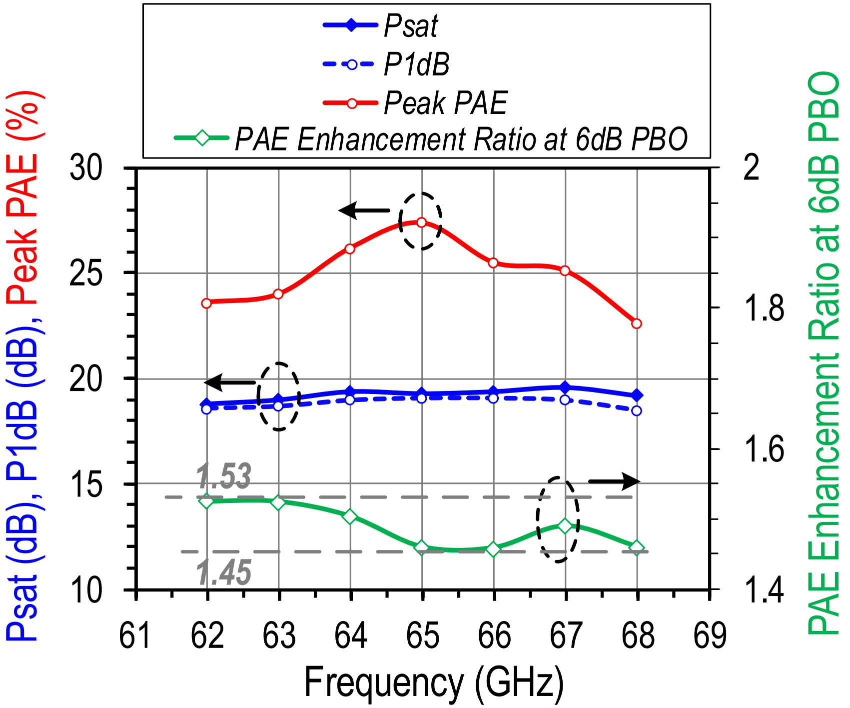
- Hongtao Xu, et al., *IEEE J. Solid-State Circuits*, May 2011.
- T. Barton, et al., *IEEE T-MTT*, Apr. 2016.

60GHz Doherty Radiator

- **CW measurement**
  - At 63GHz, +18.8 dBm P_{1dB}, 24% $PAE_{0dB\ PBO}$ and 18.3% $PAE_{6dB\ PBO}$
  - 1.52 × PAE enhancement over class-B at 6dB PBO
  - 1.45-1.53 × PAE enhancement over class-B at 6dB PBO

Carrier Frequency = 63GHz





- H. T. Nguyen, T. Chi, S. Li, H. Wang, *IEEE ISSCC 2018 and IEEE JSSC 2018.*

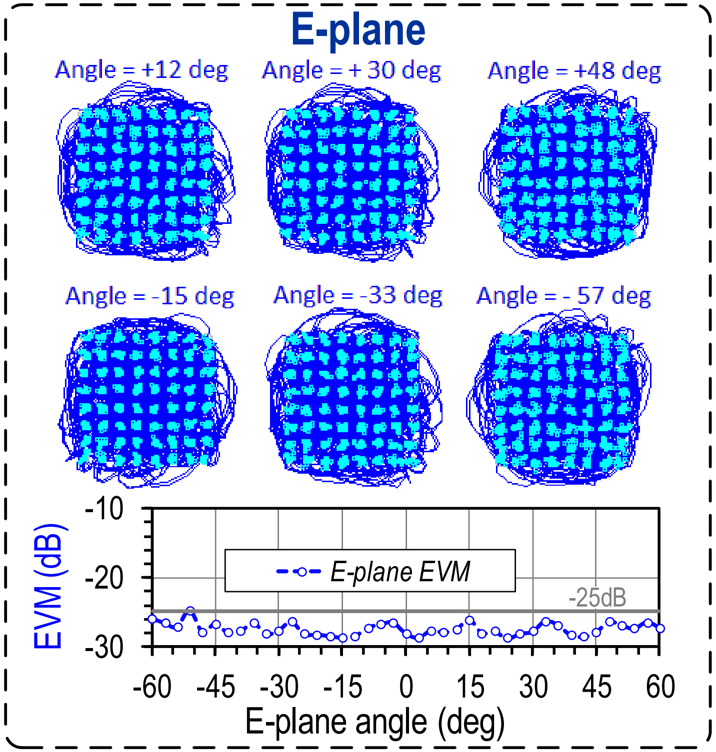
60GHz Doherty Radiator

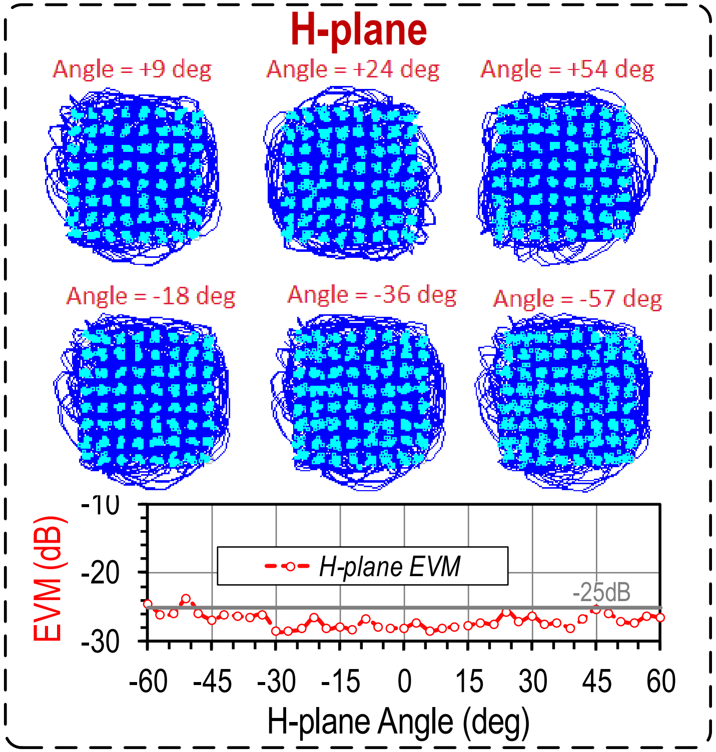
- **Modulation measurement**

The Doherty radiator combines the power on the antenna before radiation

→ Maintaining constellation over the *entire antenna FoV*

Undistorted modulation (in both E-plane and H-plane) over full FoV

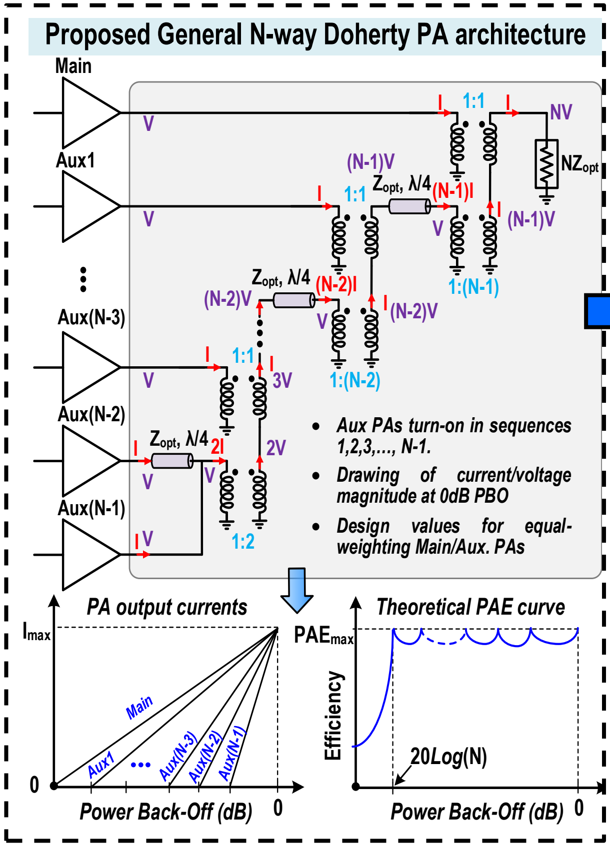




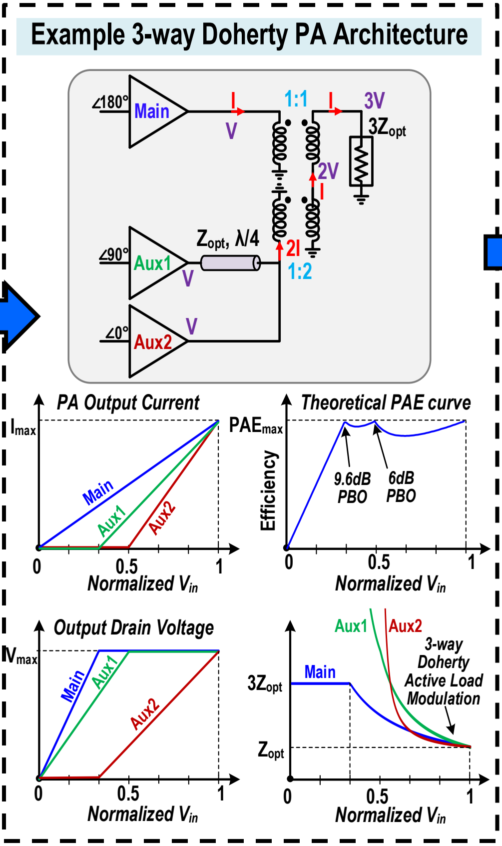
- H. T. Nguyen, T. Chi, S. Li, H. Wang, *IEEE ISSCC 2018 and IEEE JSSC 2018.*

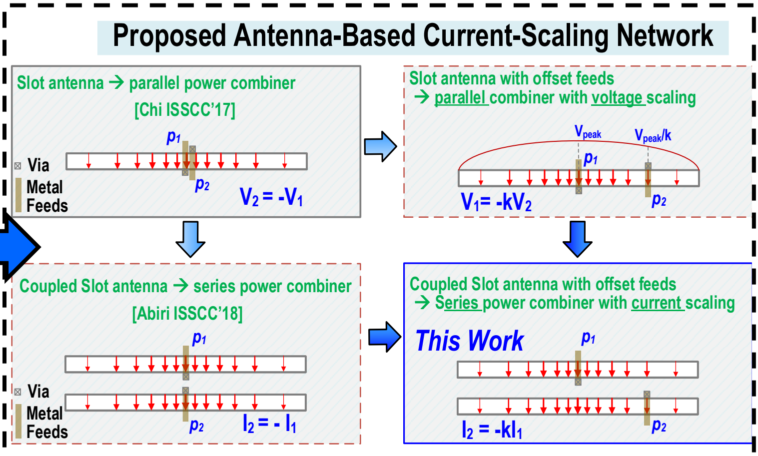
Multi-Antenna Coupling for N-Way Mm-Wave High-Order Doherty Radiator

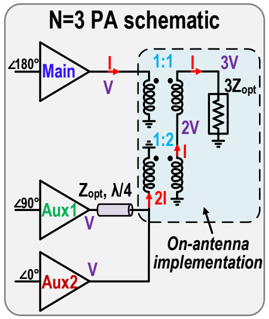
- Realizing ***general N-Way Doherty TX*** on radiator

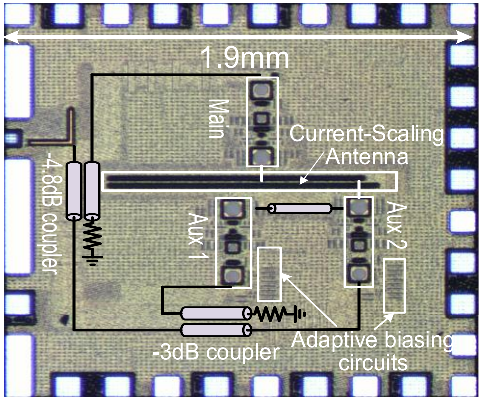


- Aux PAs turn-on in sequences 1,2,3,..., N-1.
- Drawing of current/voltage magnitude at 0dB PBO
- Design values for equal-weighting Main/Aux. PAs







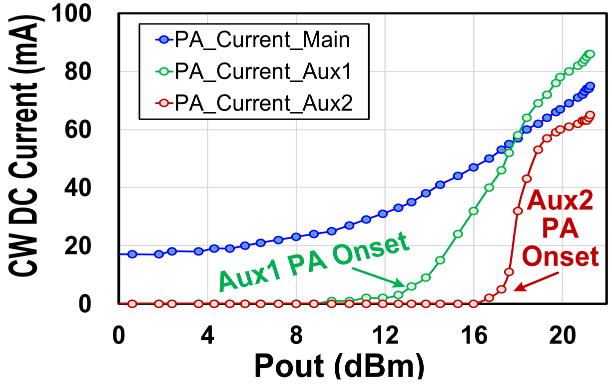


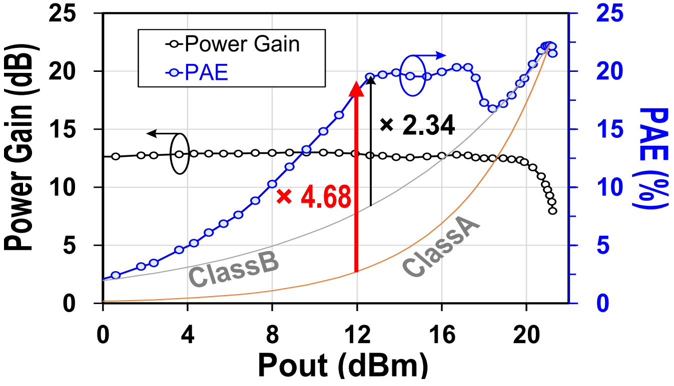
- H. T. Nguyen and H. Wang, *IEEE ISSCC 2019.*

Multi-Antenna Coupling for N-Way Mm-Wave High-Order Doherty Radiator

- **Measurements**

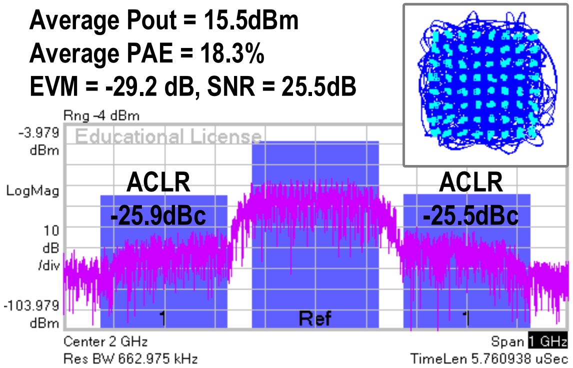
3-way Doherty Radiator CW Performance



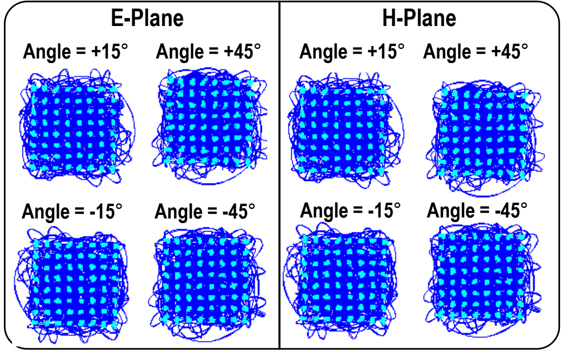


64-QAM 250MSym/s 1.5Gbit/s

Average Pout = 15.5dBm
Average PAE = 18.3%
EVM = -29.2 dB, SNR = 25.5dB

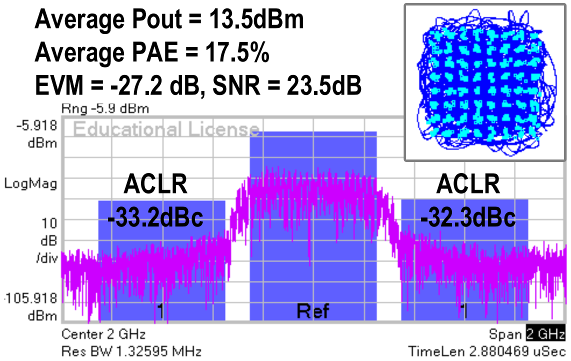


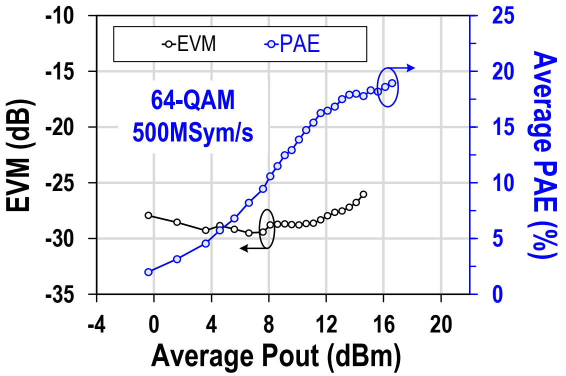
Average Pout = 12.8dBm , Average PAE = 17.5%



64-QAM 500MSym/s 3Gbit/s

Average Pout = 13.5dBm
Average PAE = 17.5%
EVM = -27.2 dB, SNR = 23.5dB

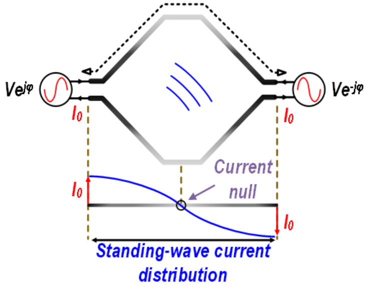




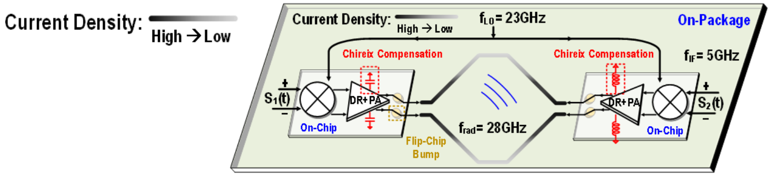
- H. T. Nguyen and H. Wang, *IEEE ISSCC 2019.*

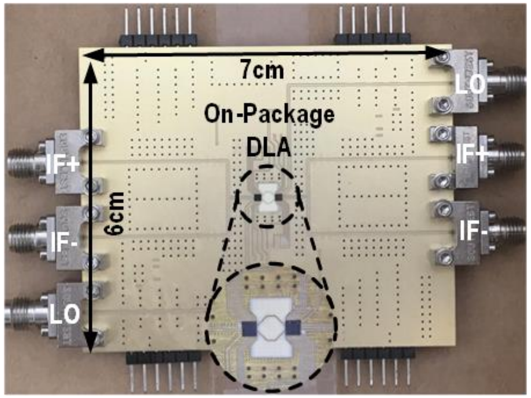
Multi-Feed Antenna for Nonlinear Chireix Outphasing Mm-Wave Transmitter

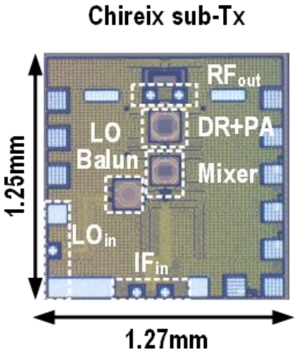
- Realizing high-efficiency ***Chireix Outphasing TX*** on radiator



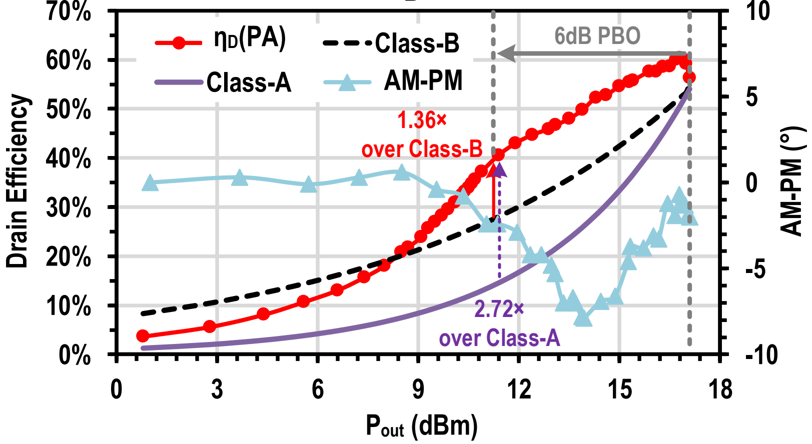
Dual-feed loop antenna = ***Radiator*** + ***Outphasing TX Combiner***



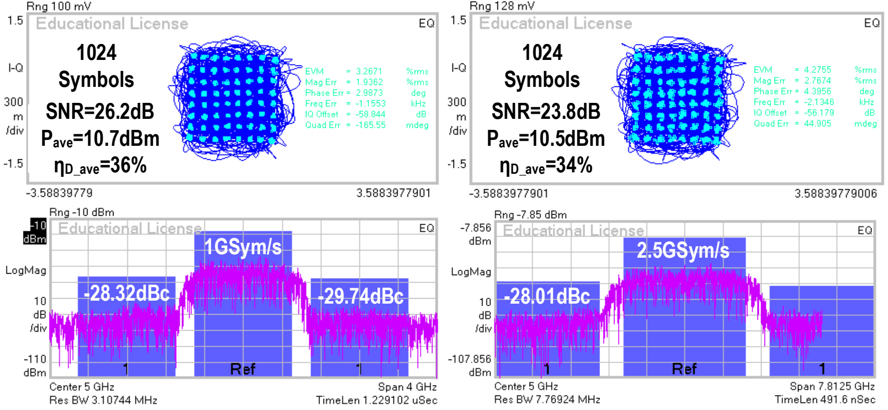




@ 28GHz P_{sat} η_D(PA) = 56%, 6dB PBO η_D(PA) = 38%



64-QAM 1Gsym/s and 2.5Gsym/s



1024 Symbols
SNR=26.2dB
P_{ave}=10.7dBm
η_{D_ave}=36%

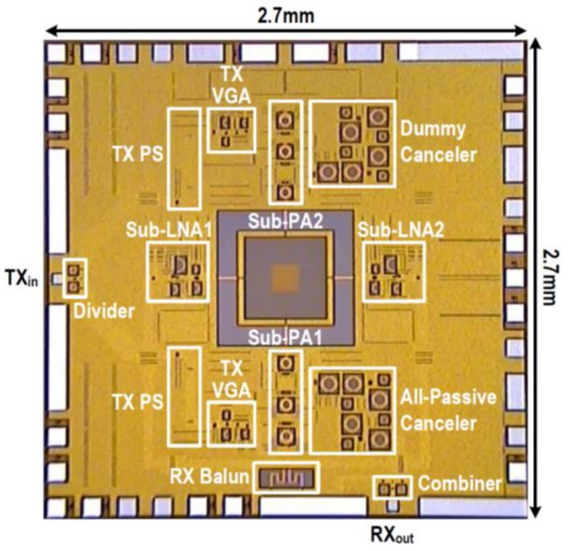
```
EVM        =  3.2671   %rms
Mag Err    =  1.9362   %rms
Phase Err  =  2.9873    deg
Freq Err   =  -1.1553   kHz
IQ Offset  =  -58.844    dB
Quad Err   =  -165.55  mdeg
```

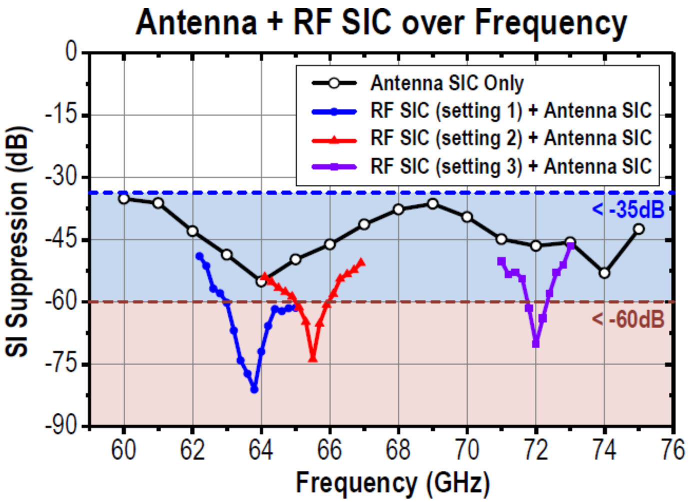
1024 Symbols
SNR=23.8dB
P_{ave}=10.5dBm
η_{D_ave}=34%

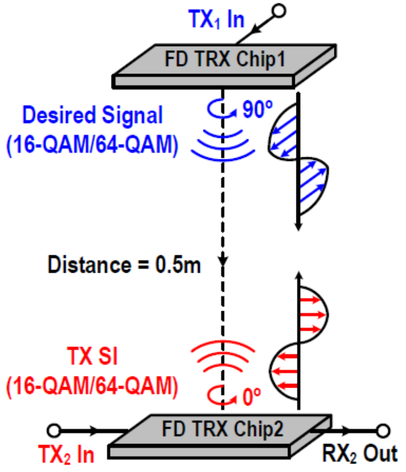
```
EVM        =  4.2755   %rms
Mag Err    =  2.7674   %rms
Phase Err  =  4.3956    deg
Freq Err   =  -2.1346   kHz
IQ Offset  =  -56.179    dB
Quad Err   =  44.905   mdeg
```

- S. Li, T. Chi, T. Huang, H. Nguyen, and H. Wang, *IEEE RFIC 2018 and JSSC 2019.* — ***RFIC Best Student Paper Award***

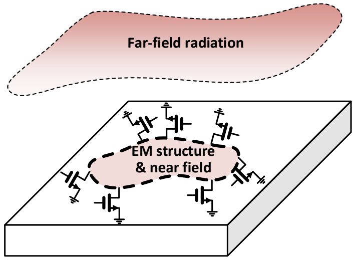
World-First Mm-Wave Polarization-Duplex TRX + Chip-to-Chip Demonstration







- Globalfoundries 45nm CMOS SOI
- No digital pre-distortion (DPD), channel equalization, or digital cancellation



- T. Chi, J. Park, S. Li, and H. Wang, *ISSCC* 2018, *JSSC* 2018

Desired Signal
P_{avg} = 9dBm
f_c = 63.1GHz

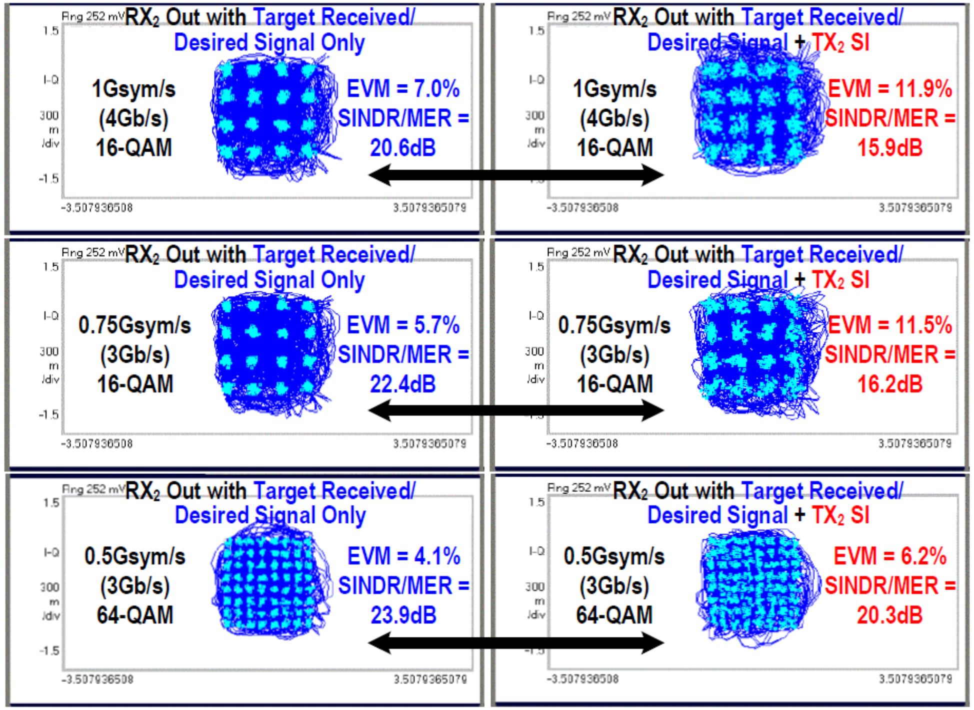
TX SI
P_{avg} = 2dBm
f_c = 63.1GHz

Desired Signal
P_{avg} = 9dBm
f_c = 63.3GHz

TX SI
P_{avg} = 5dBm
f_c = 63.3GHz

Desired Signal
P_{avg} = 9dBm
f_c = 63.1GHz

TX SI
P_{avg} = 2dBm
f_c = 63.1GHz



Outline

- Introduction
- State of the Art: Georgia Tech PA Survey (2000-present)
- Broadband Linear Efficient PAs
- Antenna-PA Co-Designs: Multi-Feed Mm-Wave Radiators
- **Conclusion**

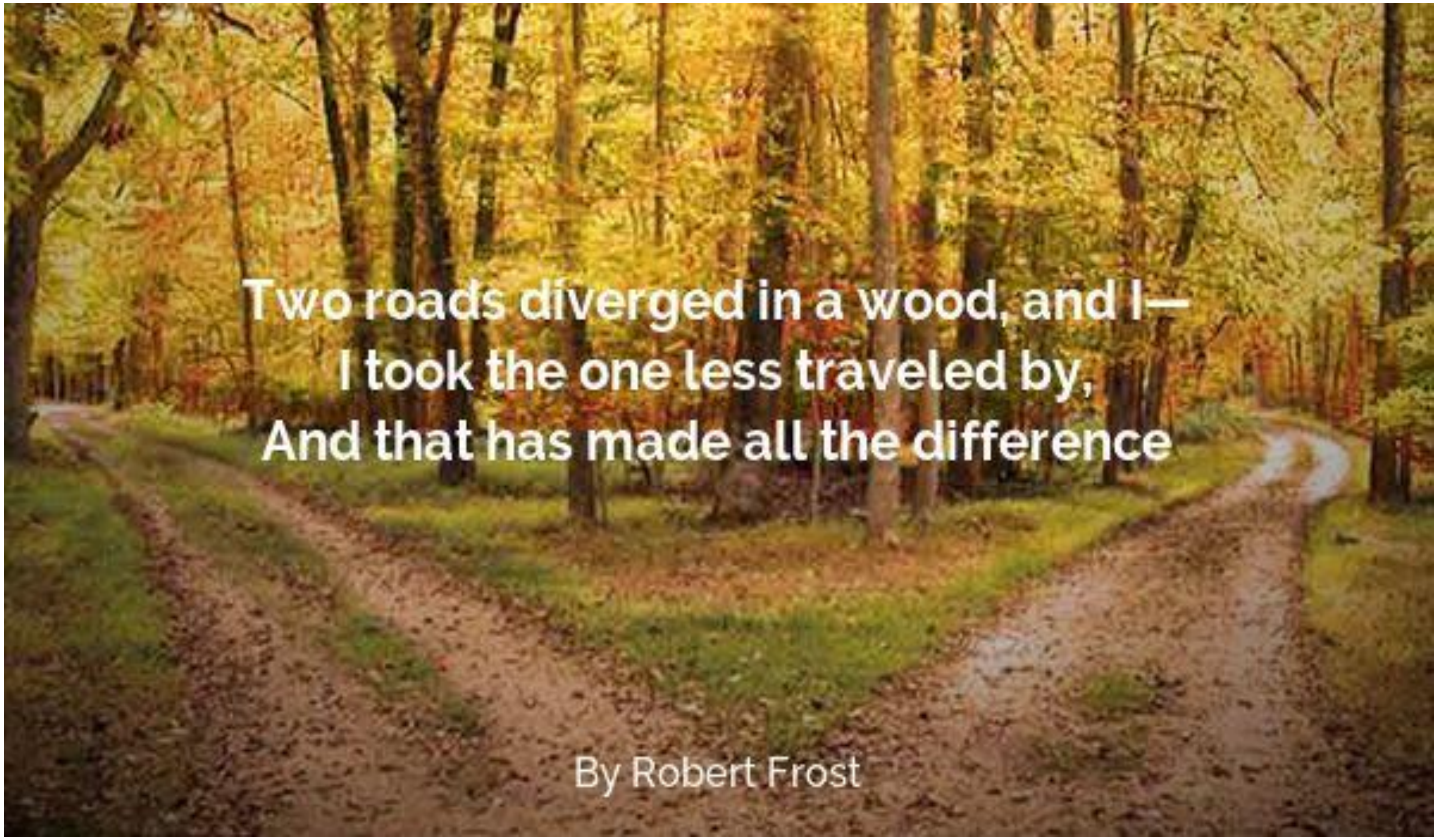
Conclusion and Future Directions

- **Trade-offs of Carrier Bandwidth, Efficiency, Linearity, and Modulation Rate**
- **Future Directions**
  - **Architecture:**
    - ➢ Broadband, linear, and efficient PA architectures
    - ➢ Antenna-PA/TX/RX co-designs
    - ➢ Compound semiconductor PA and heterogeneous integration
  - **Reliability:** Silicon PA in MIMO arrays
  - **Linearization:** Low overhead Gbit/s DPD

Acknowledgement

- DARPA, NSF, DoD, and Industry Sponsors
- Global Foundries for chip fabrication
- Members of Georgia Tech GEMS Lab

Thank you!



Two roads diverged in a wood, and I—
I took the one less traveled by,
And that has made all the difference

By Robert Frost

Thank you!