Phased array innovations for 5G mmWave beamforming

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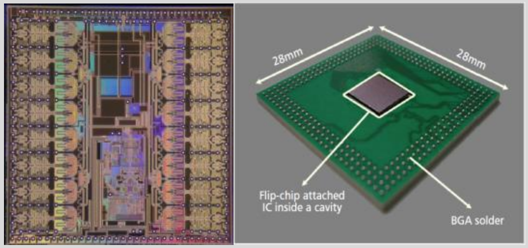
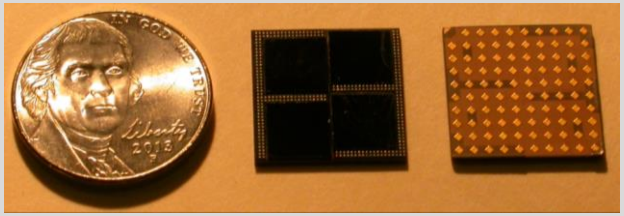
Toronto 5G Summit – November 2015

Enabling 5G: mmWave Silicon Integration and Packaging

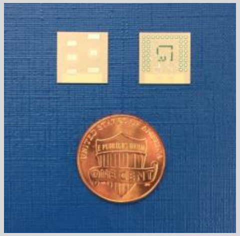
Overview of IBM Research's 10+ years of work on silicon-based mmWave radios, phased arrays, and Gb/s link demonstrations



mmWave WLAN – IBM 16-Element 60-GHz phased array



mmWave Backhaul – IBM 64-Element 94-GHz phased array

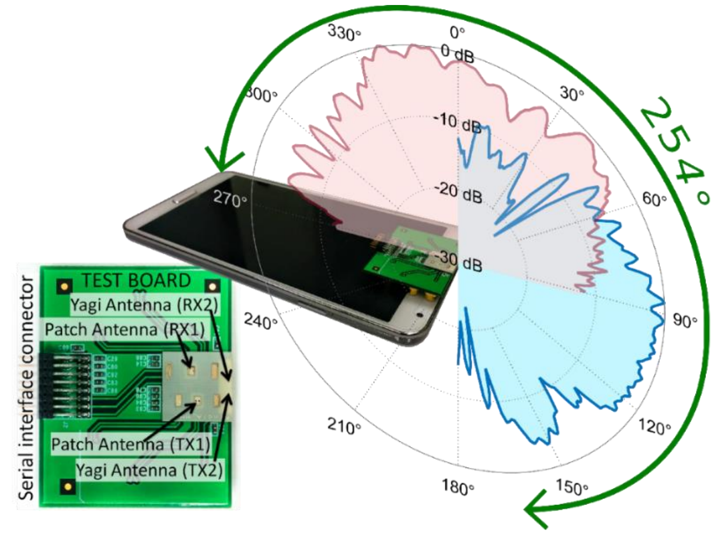


mmWave handset radio – IBM 60-GHz low-power TRX

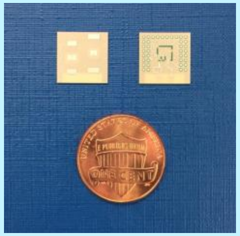
https://ieeetv.ieee.org/ieeetv-specials/toronto-5g-summit-2015-bodhisatwa-sadhu-enabling-5g-mmwave-silicon-integration-and-packaging?

Seattle 5G Summit – November 2016

mmWave Radio Design for Mobile Handsets



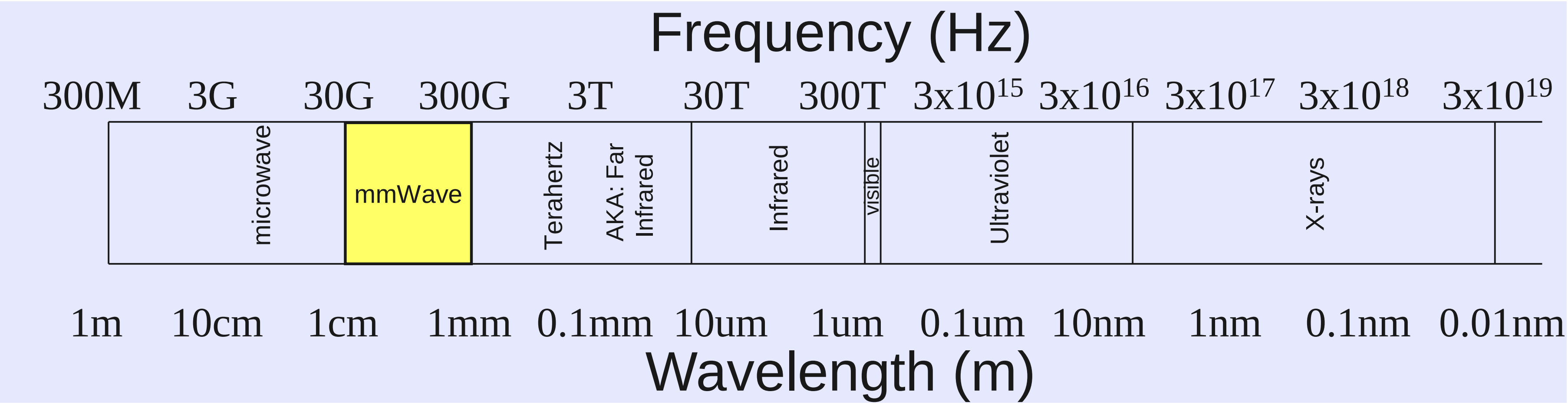
60-GHz (802.11ad), low-power (<250mW TX or RX), 32nm SOI CMOS TRX with switched beam antenna for wide spatial link coverage



mmWave handset radio – IBM 60-GHz low-power TRX

https://ieeetv.ieee.org/conference-highlights/seattle-5g-mmwave-radio-design-for-mobile-handsets?

Introduction to Millimeter-Wave (mmWave)



mmWave is defined as 30-300 GHz, or λ=10 mm to 1 mm

Higher Frequency

(1) More Bandwidth

(5% @ 60 GHz = 3 GHz)
(5% @ 6 GHz = 0.3 GHz)

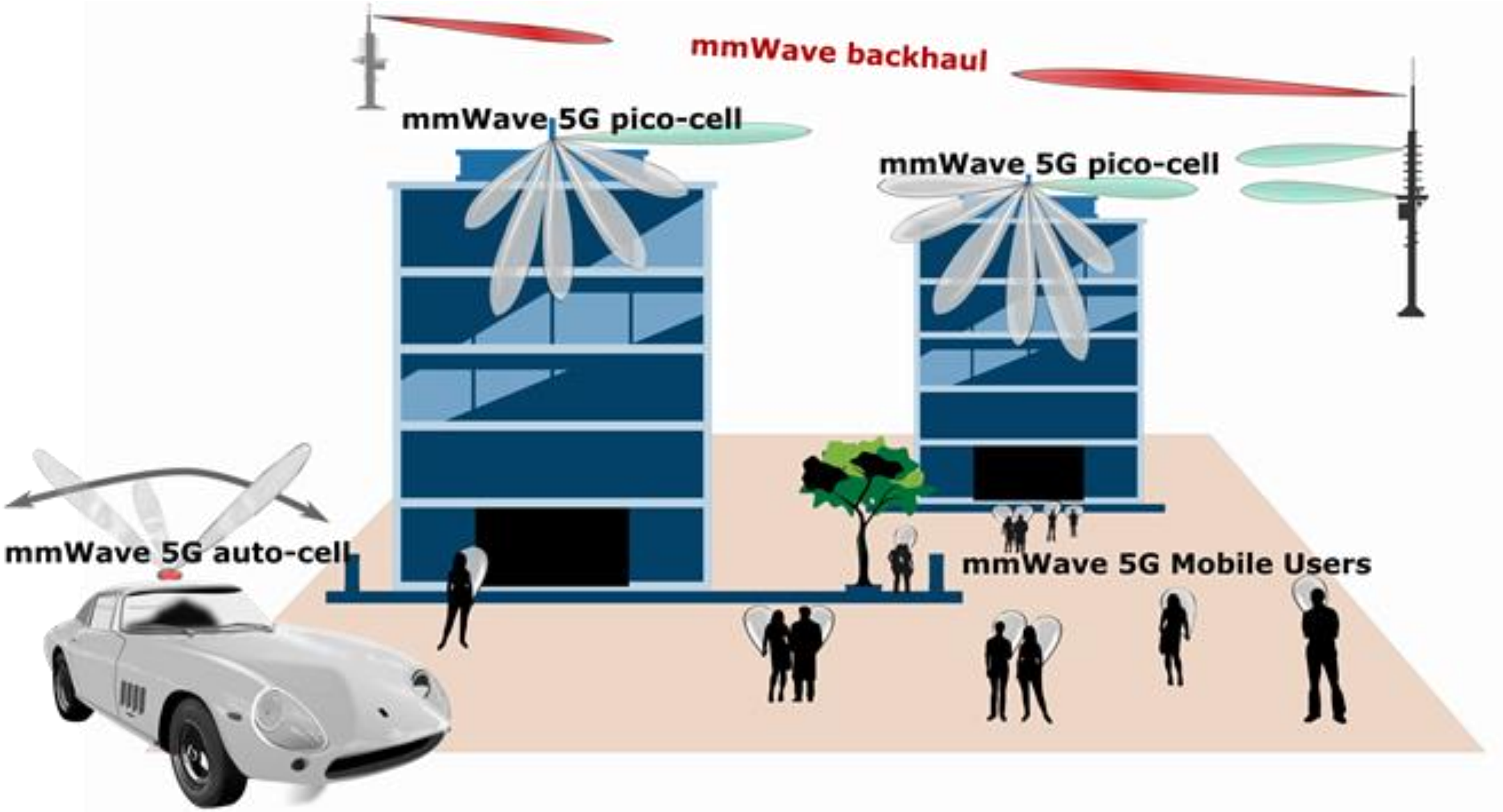
(2) Smaller Wavelength
- Integrate antenna in package
- Greater resolution radar/imager
- Directional propagation

Current applications:
- Gb/s short-range comm.
- Automotive radar
- Mobile backhaul
- Airport security
- **5G**

Key advantages of mmWave for 5G are higher data rates and spatial multiplexing

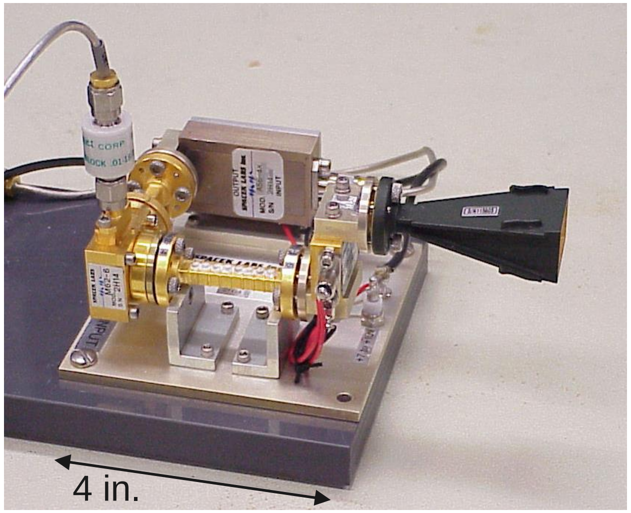
Gb/s mmWave Wireless Links:

Applications across the infrastructure stack

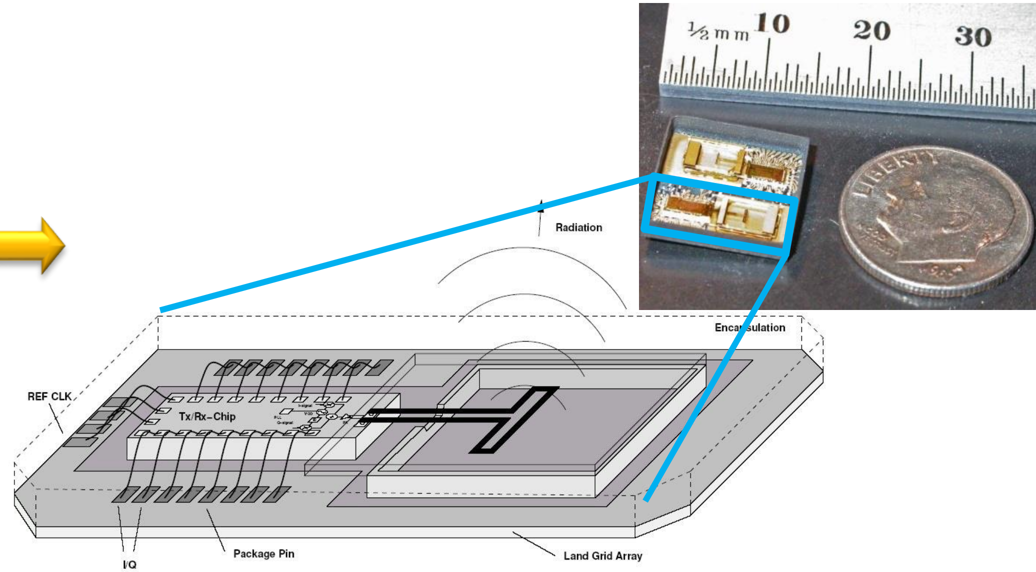


mmWave-based 5G network concept:
Ericsson: E. Dahlman, et al., “5G Radio Access,” Ericsson Review, June, 2014
Samsung: W. Roh, et al., "Millimeter-wave beamforming as an enabling technology for 5G cellular communications: theoretical feasibility and prototype results," in IEEE Communications Magazine, Feb, 2014

Enabling technology #1: Silicon integration of mmWave transceivers



Discrete 60-GHz Radio

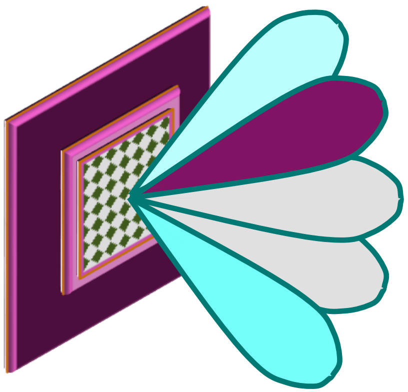


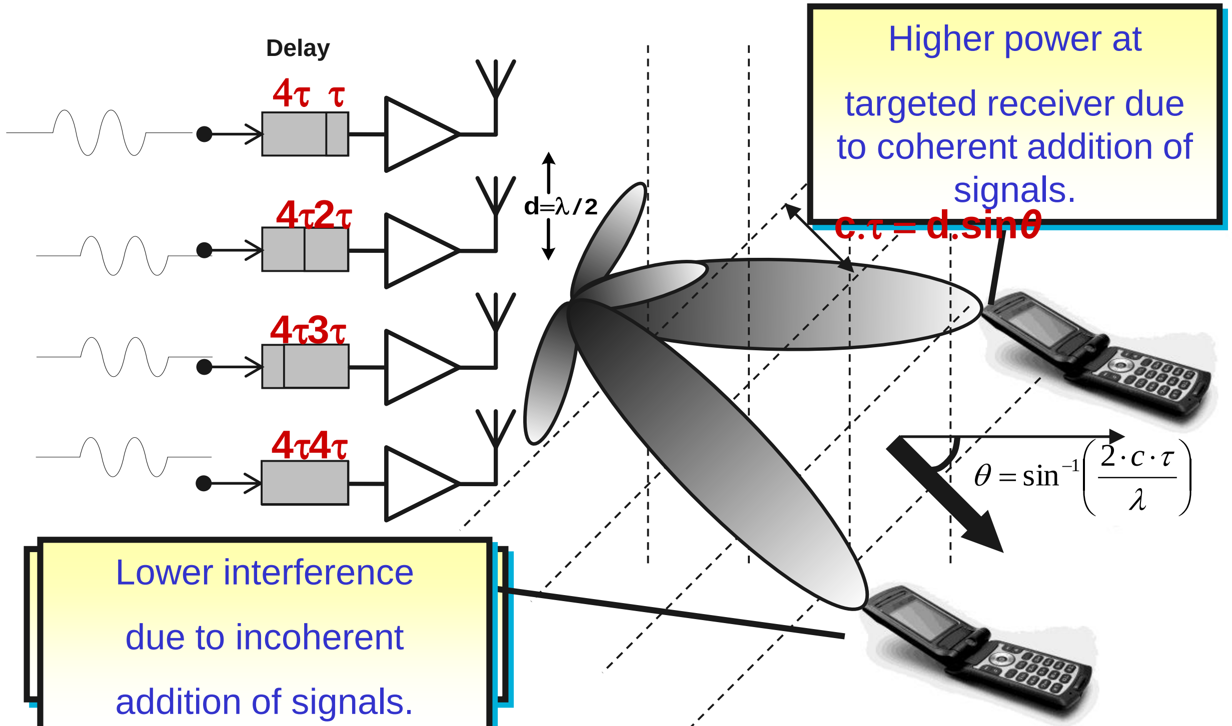
World's 1st monolithic mmWave Radio
IBM Research 2006

Cost: $1,500	**Cost: ~$15**
Size: 10's of cm	**Size: <10 mm**

Miniaturization and mass adoption of mmWave applications

Enabling technology #2: Integrated phased arrays for beam forming





With ***N*** element TX, if each element radiates ***P*** Watts,

Effective radiated power in target direction: ***N^2.P*** Watts.

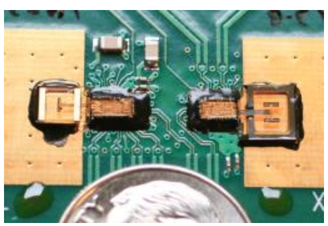
A. Natarajan, et al., JSSC 2005

14+ Year History of mmWave Subsystem Research at IBM

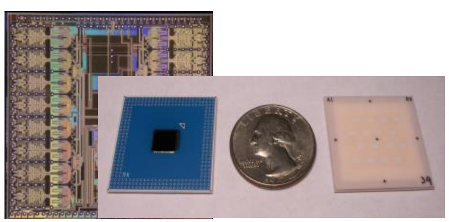
Leading-edge highly-integrated technology solutions to enable wireless communication and sensor systems with less volume, weight and cost

- 60-GHz Low-Power Radio in 32nm SOI
- 60-GHz SiGe Single-Element and Phased Array Radios
- 94-GHz Scalable Phased Array
- E-band Fixed-Beam Radio for Backhaul
- 5G

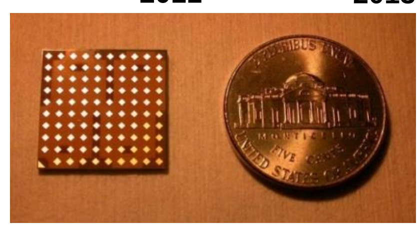
2003 | 2005 | 2007 | 2009 | 2011 | 2013 | 2015 | 2017



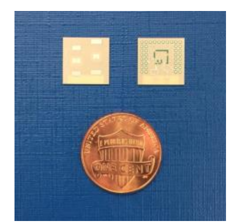
World's First Monolithic mmWave (60 GHz) Radio



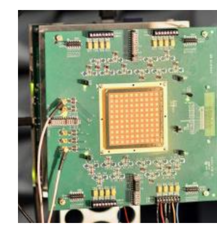
60GHz 16-Element Phased Array Transceiver Chip-Set



94-GHz 64-element Phased Array Transceiver



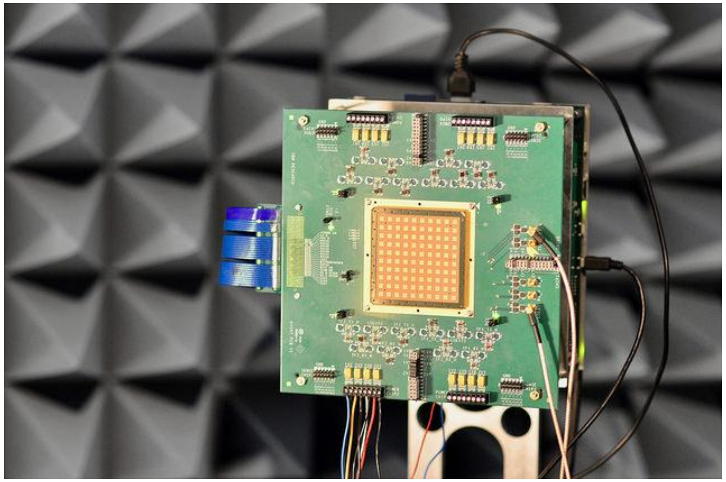
Low-power, Switched Beam 60GHz CMOS IC

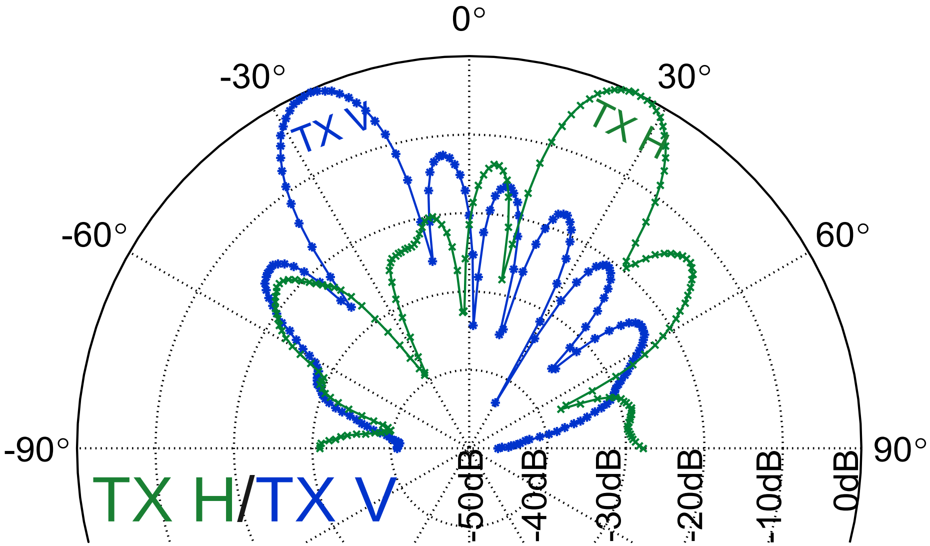


28-GHz 64-element Phased Array Transceiver

This Presentation: Reston, VA 5G Summit – August 2017
Phased array innovations for 5G mmWave beamforming

- **28-GHz Phased Array Antenna Module co-developed by IBM and Ericsson**
- **Focus of this presentation is on innovative techniques to enable precise beamforming**
  - IC Architecture
  - Building blocks to enable orthogonal phase and amplitude control at each RF Frintend
  - Antenna-in-package implementation





Key 5G mmWave Challenges

Maximize TX range while minimizing form factor

Easy to control

Key challenges

Fine beam steering resolution

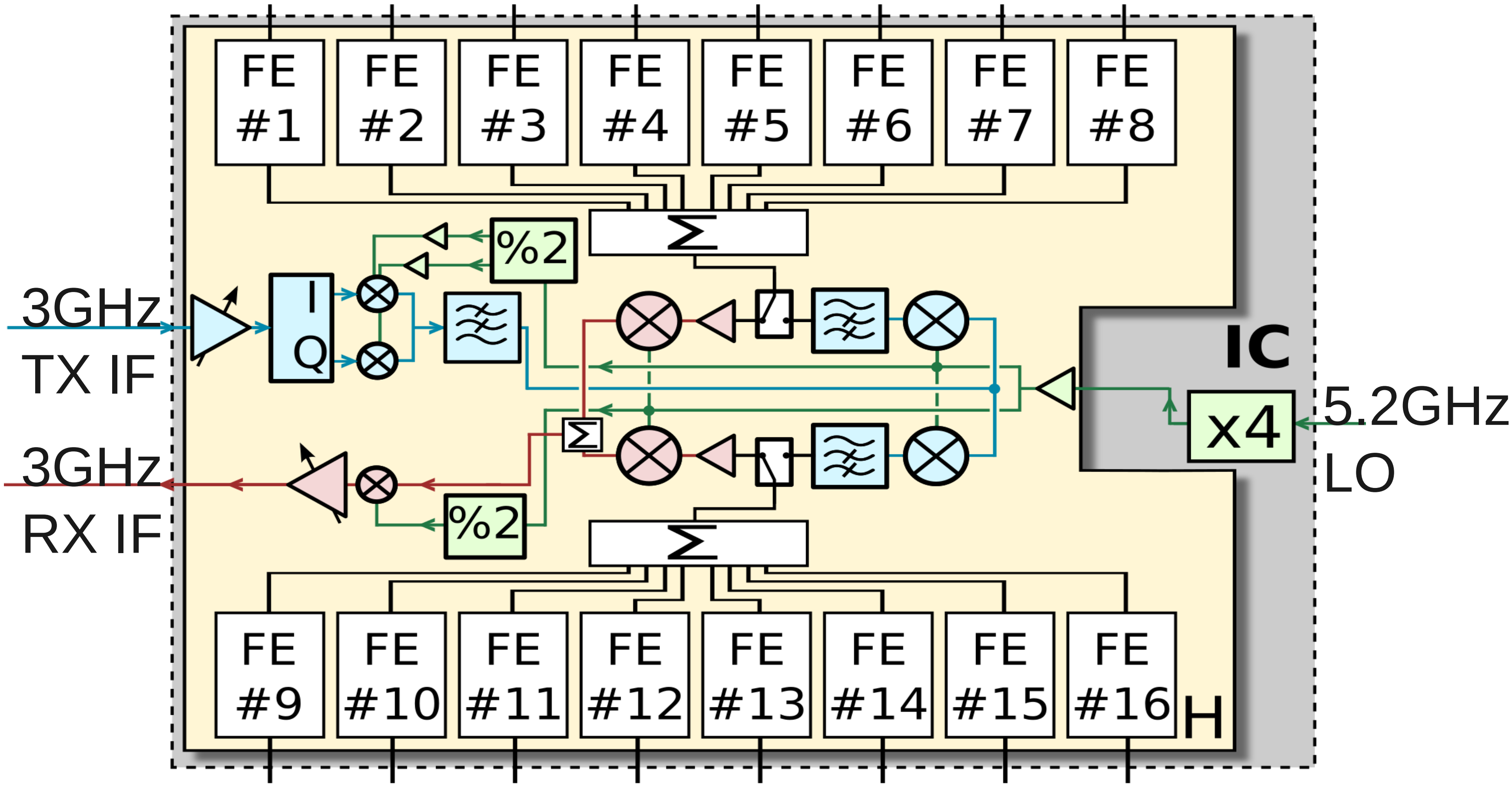
Support simultaneous beams

Key 5G mmWave Challenges…
… to IC Design Challenges

Key IC challenges

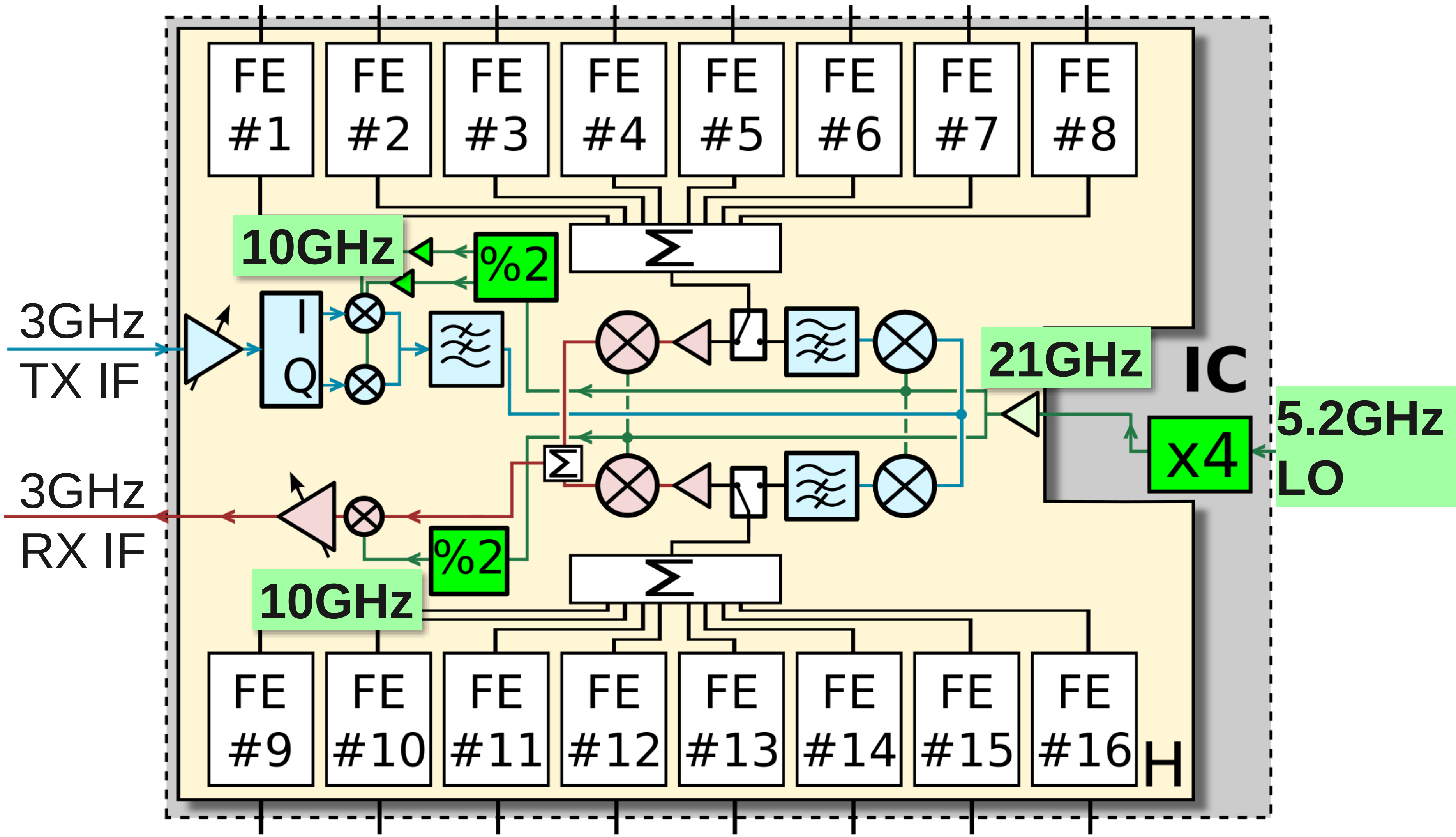
- Maximize TX output power, with TX/RX integration
- Orthogonal phase and gain control
- Fine phase resolution
- Support for two polarizations

IC Architecture: RF Phase Shifting
(single polarization shown for simplicity)

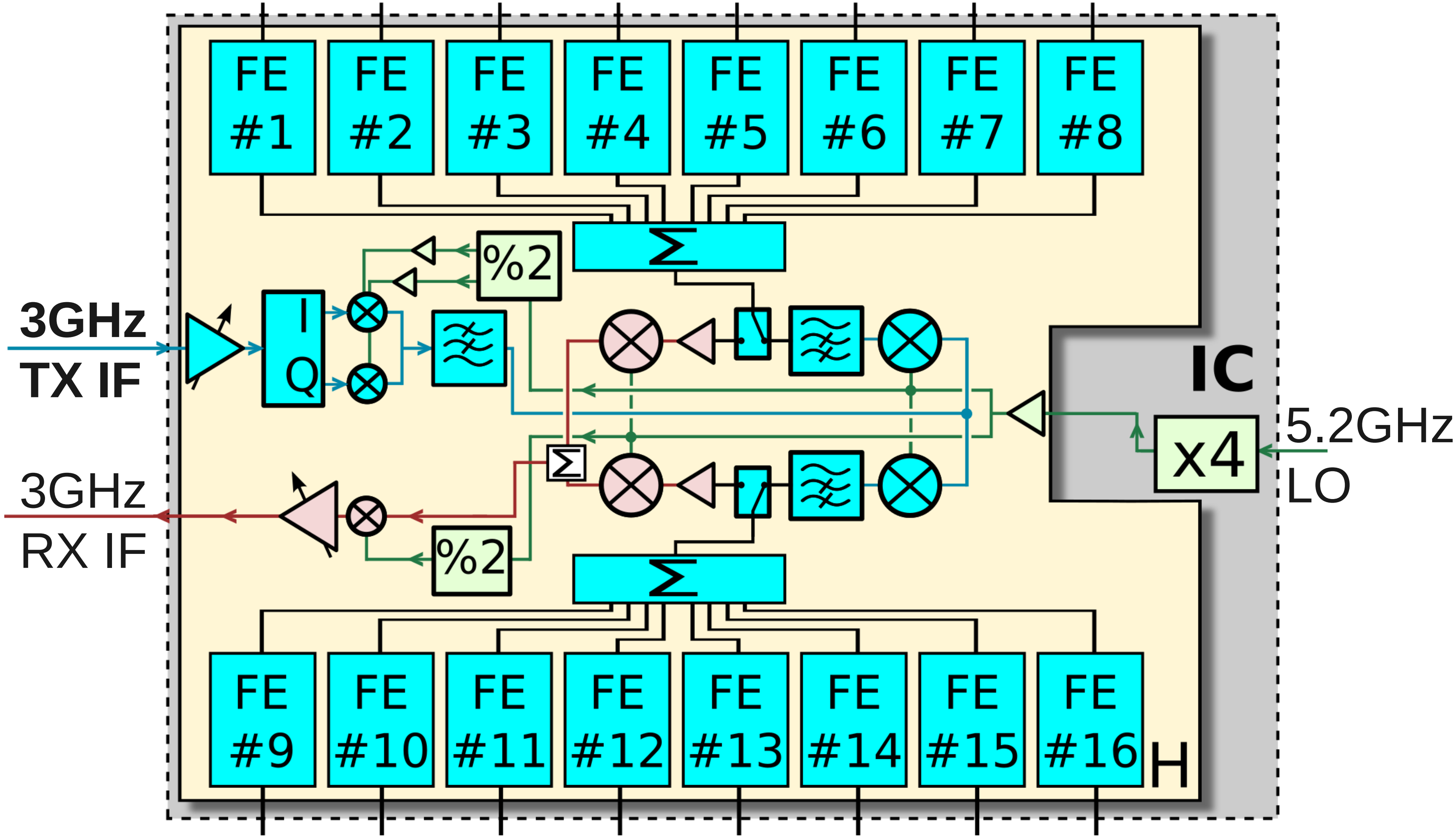


B. Sadhu, et al, "A 28GHz 32-Element Phased-Array Transceiver IC with Concurrent Dual Polarized Beams and 1.4 Degree Beam-Steering Resolution for 5G Communication", *IEEE ISSCC,* 2017.

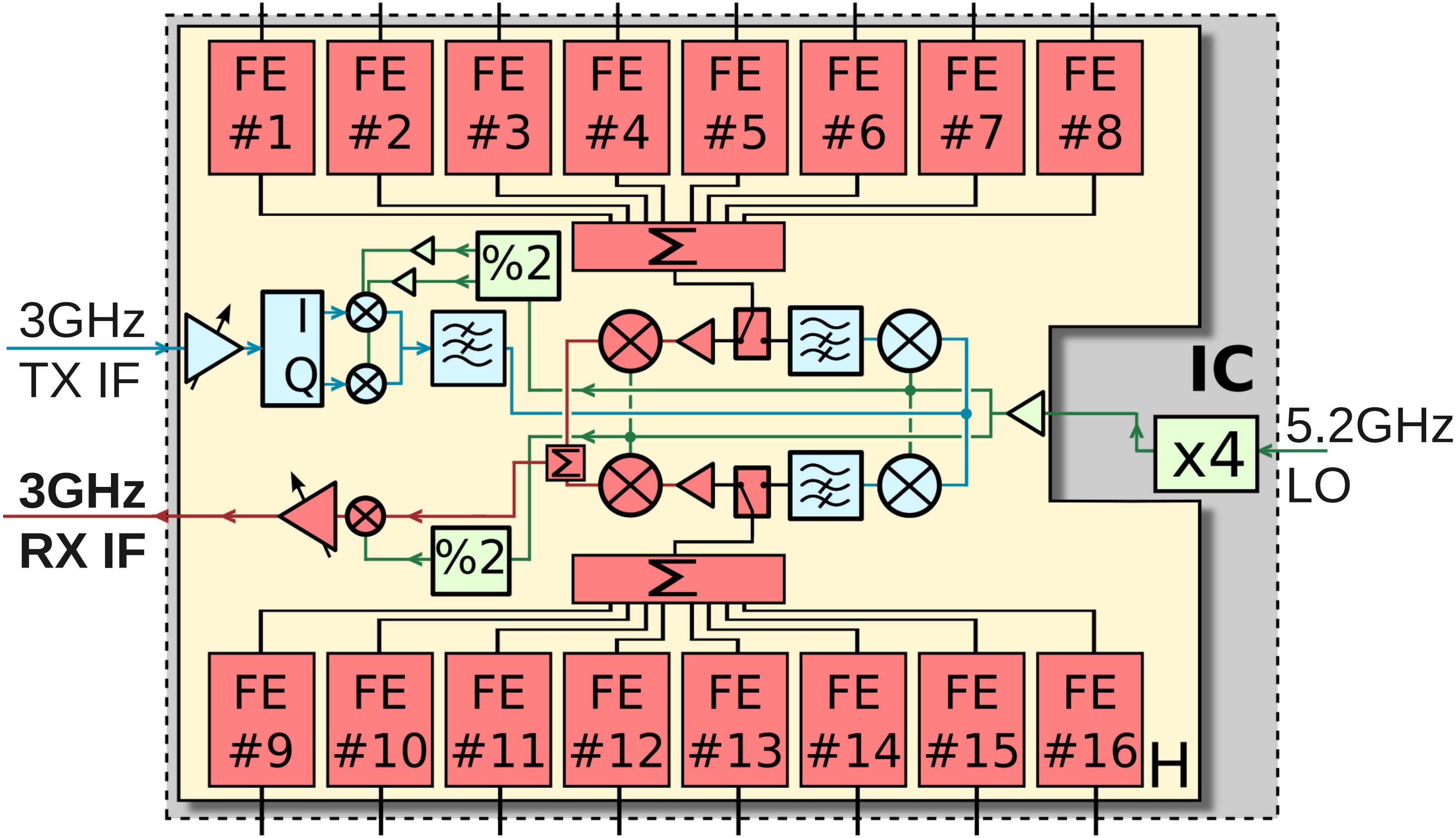
IC Architecture: LO Path



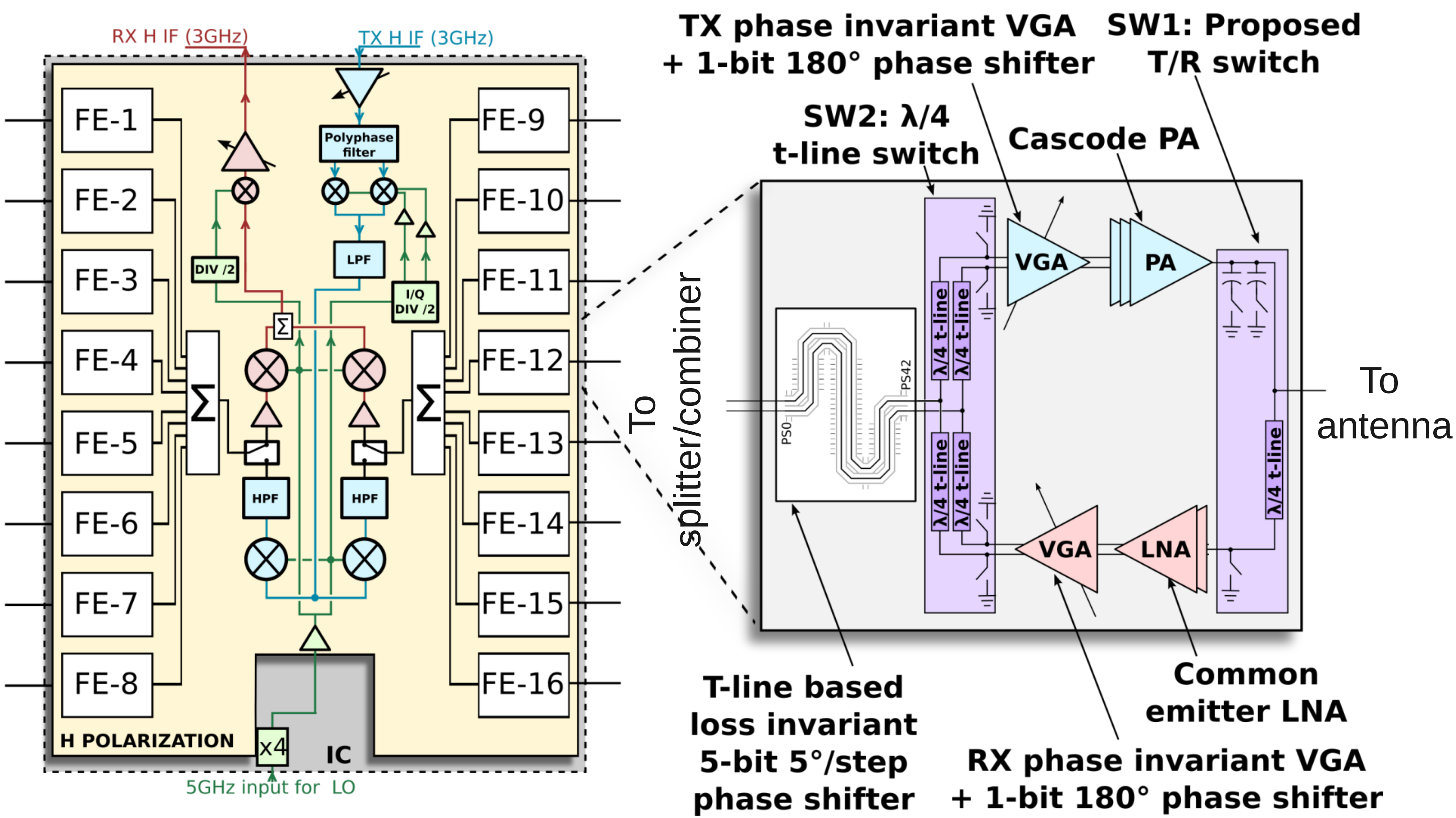
IC Architecture: TX Path



IC Architecture: RX Path



IC Architecture: Front-End



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Key 5G mmWave Challenges…
… to IC Design Challenges

Maximize TX output power, with TX/RX integration

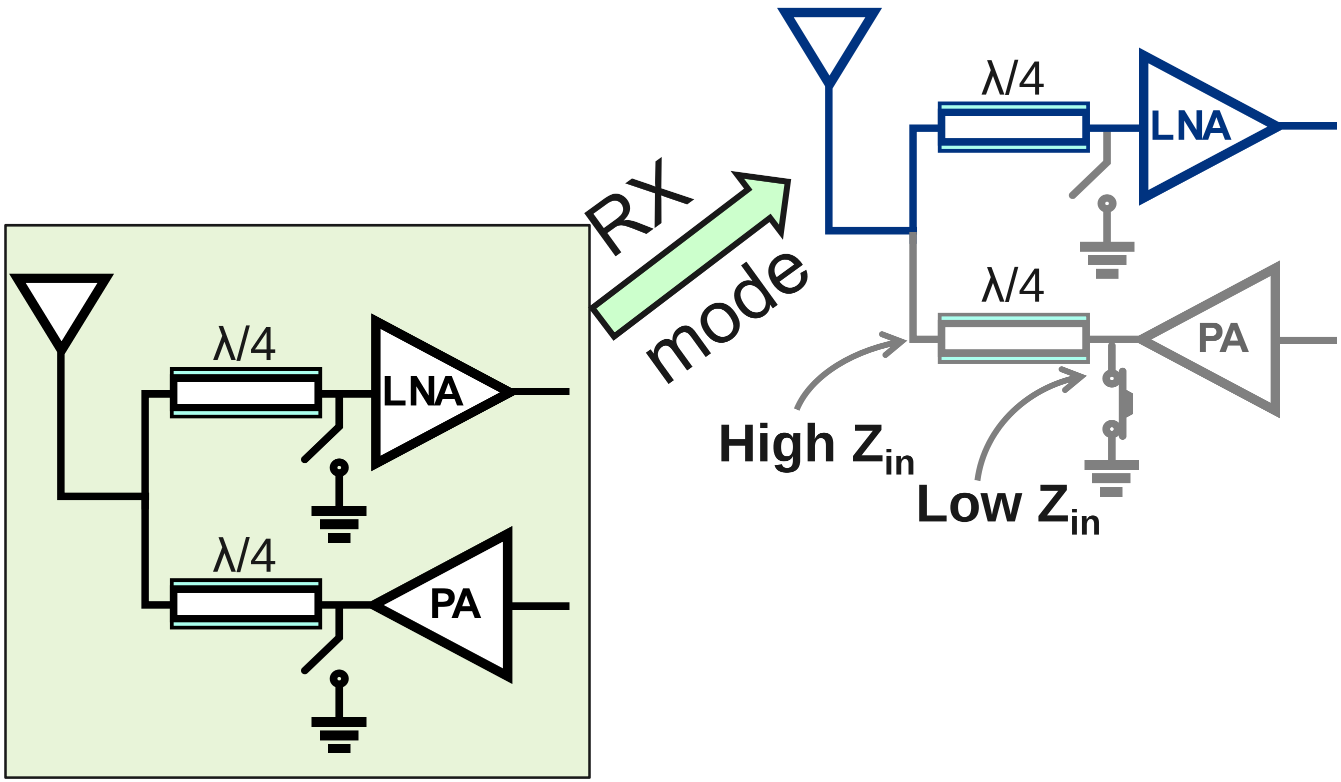
Orthogonal phase and gain control

Key IC challenges

Fine phase resolution

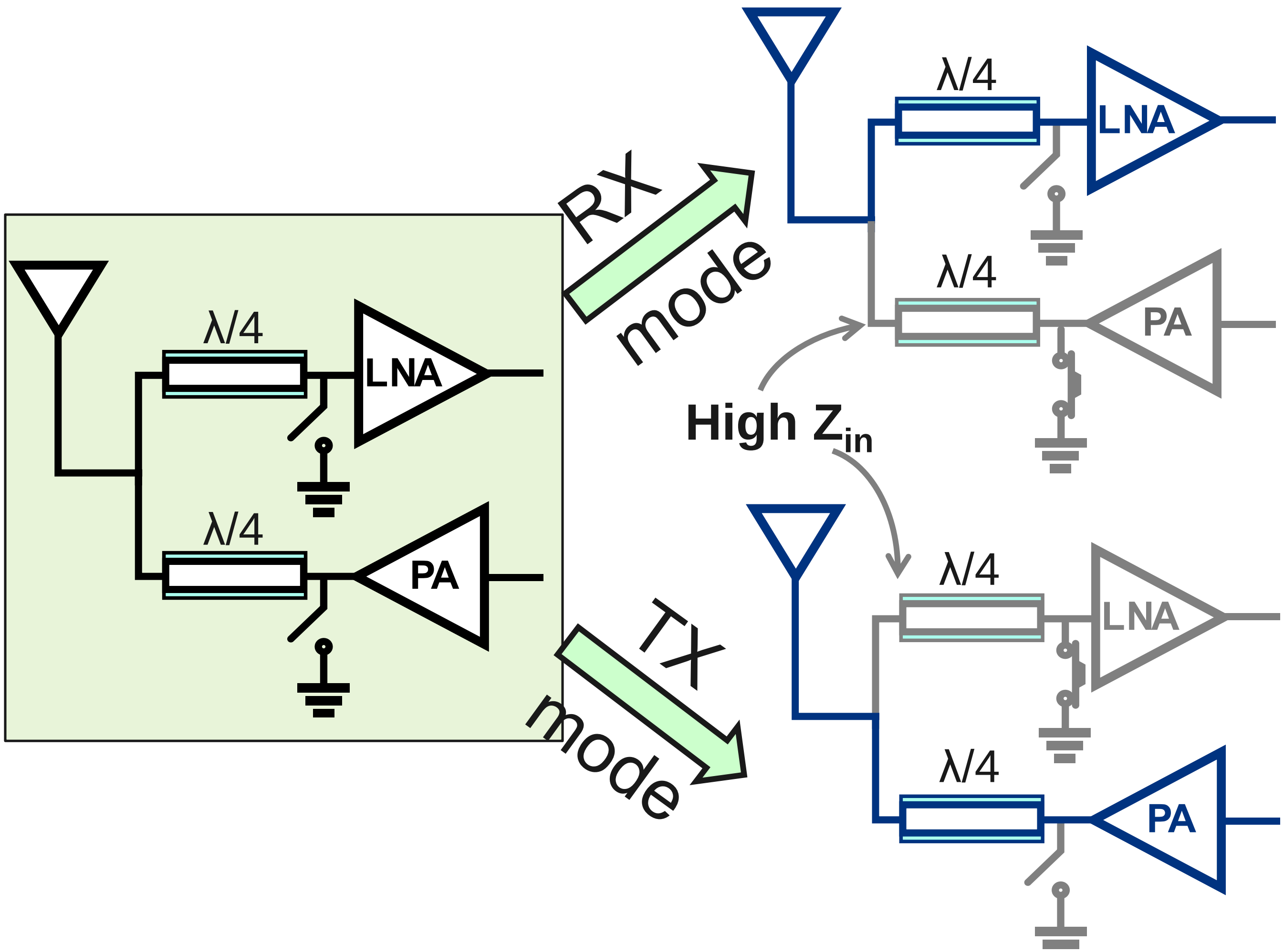
Support for two polarizations

How Does a Conventional l/4 TX/RX Switch Work?



Degrades RX noise figure by ~ 1.5dB

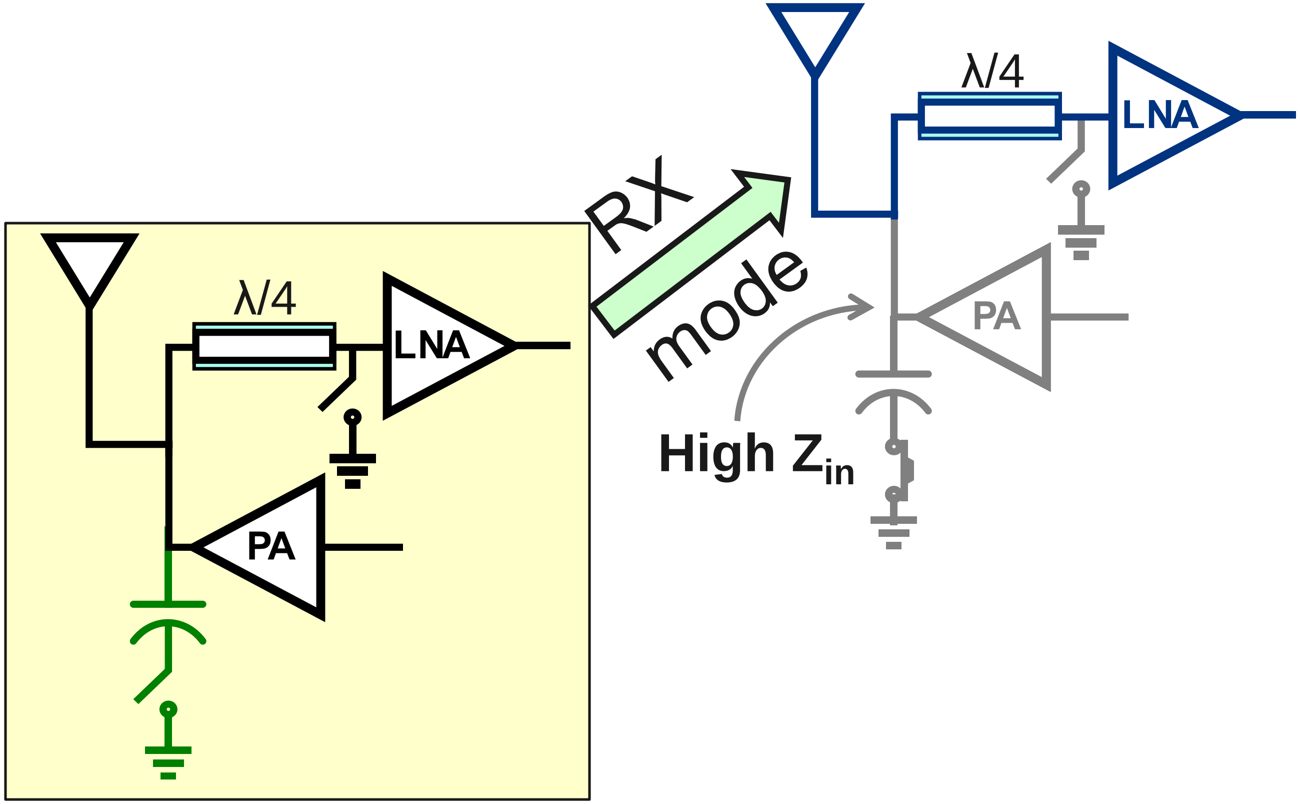
How Does a Conventional l/4 TX/RX Switch Work?



Degrades RX noise figure by ~ 1.5dB

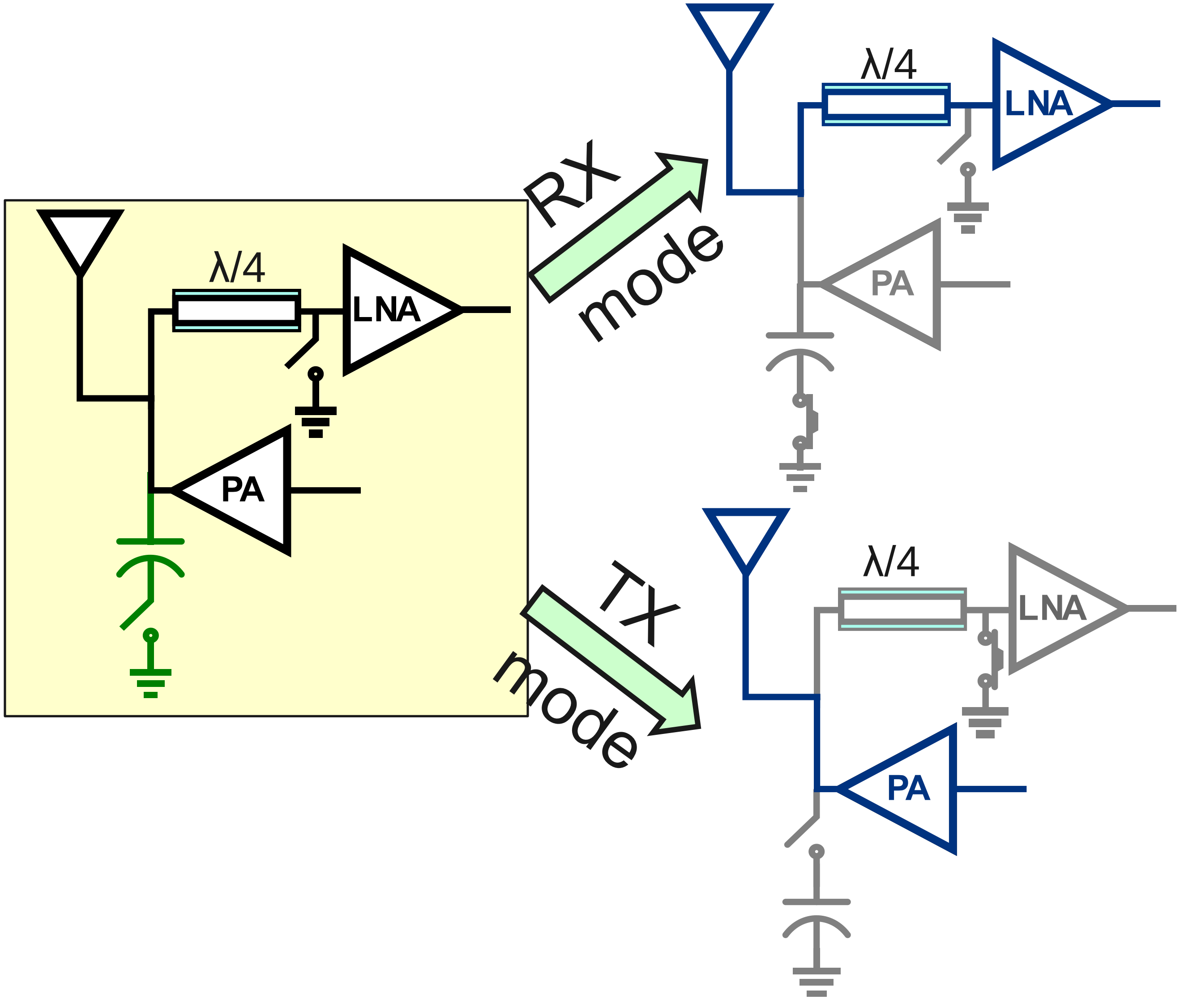
Degrades TX output power by ~ 1.5dB

Proposed Technique Cuts TX Losses



Degrades RX noise figure by ~ 2dB

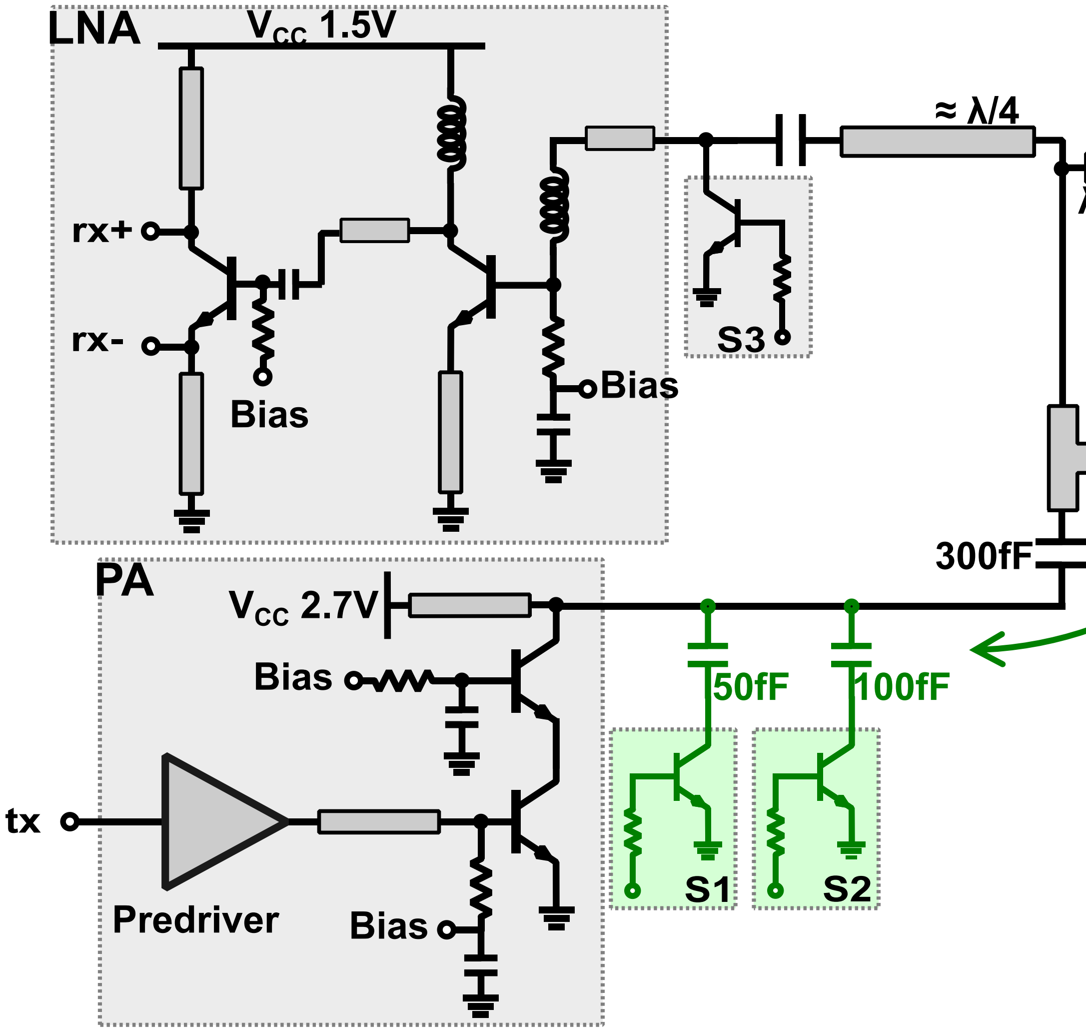
Proposed Technique Cuts TX Losses



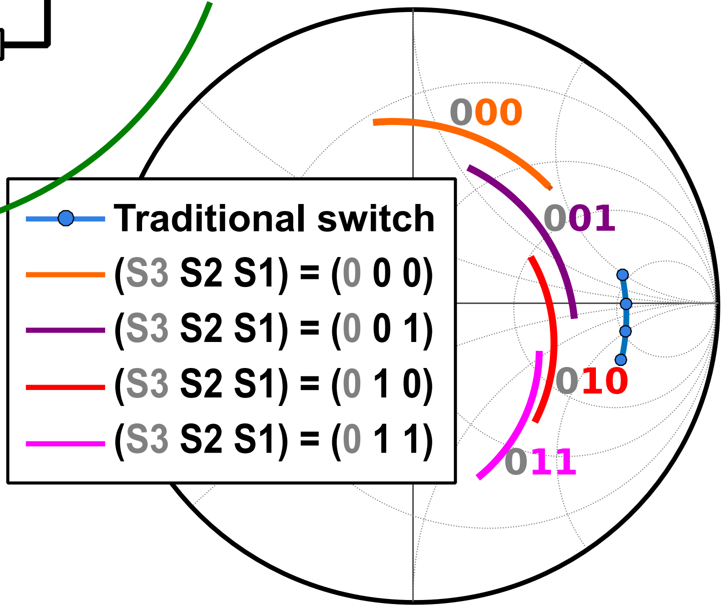
Degrades RX noise figure by ~ 2dB

Does not degrade TX output power

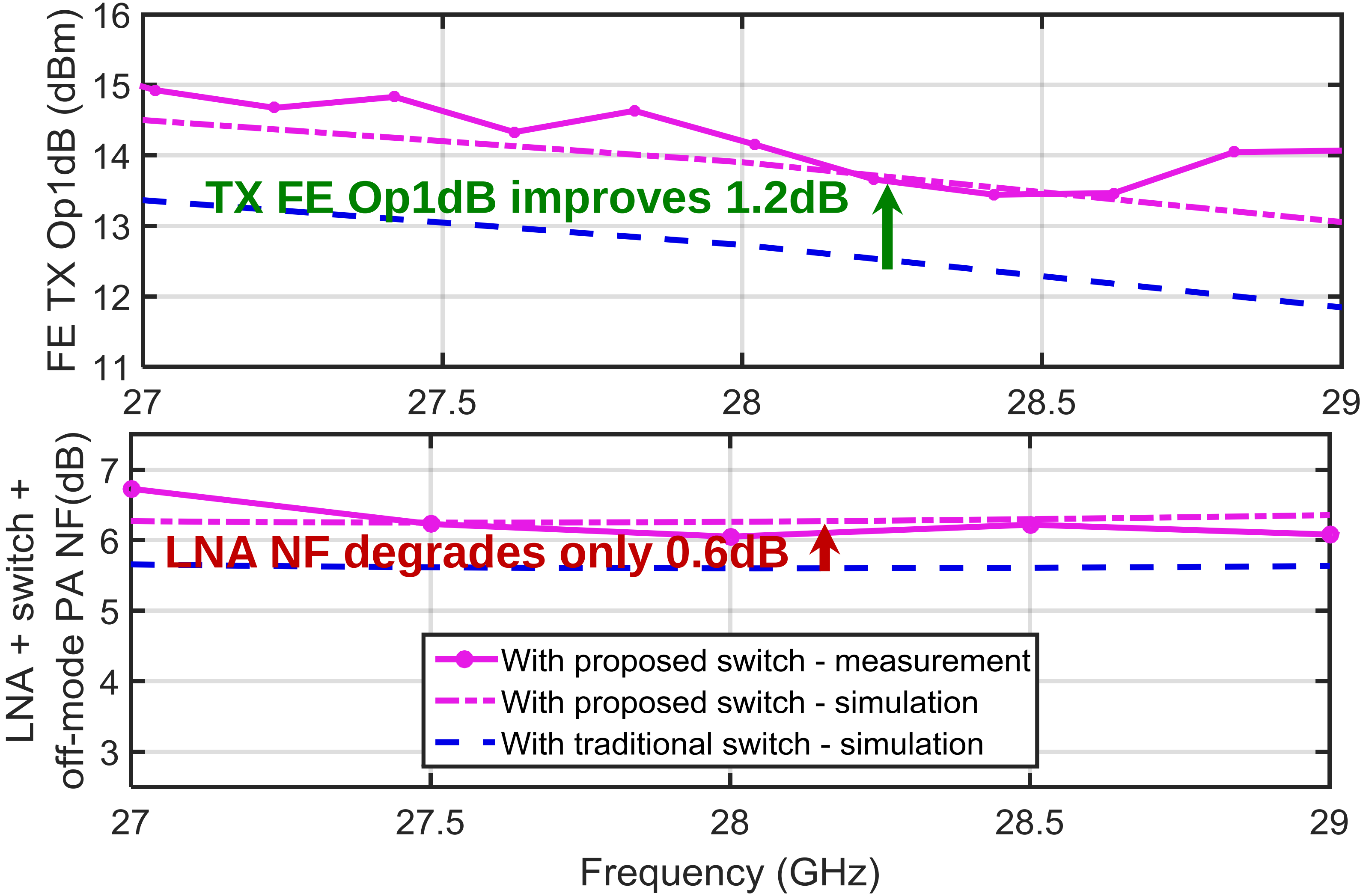
TX/RX Switch Circuit Details



RX mode Z $_{PA\_OFF}$
26GHz to 30GHz



TX/RX Switch Measurements



- 1.2dB translates to 23% power savings in the phased array IC in TX mode

Key 5G mmWave Challenges…
… to IC Design Challenges

Maximize TX output power, with TX/RX integration

Orthogonal phase and gain control

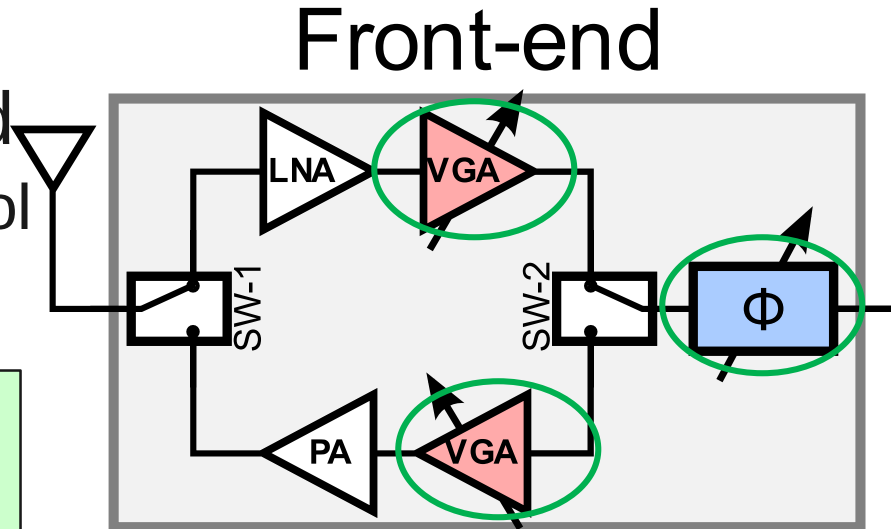
Key IC challenges

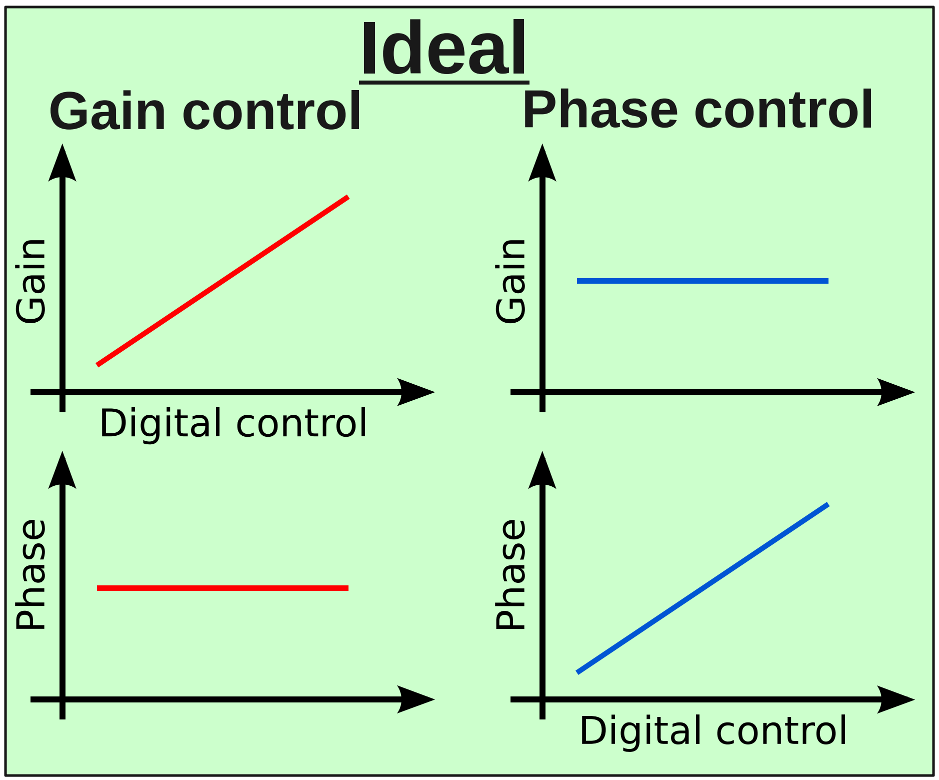
Fine phase resolution

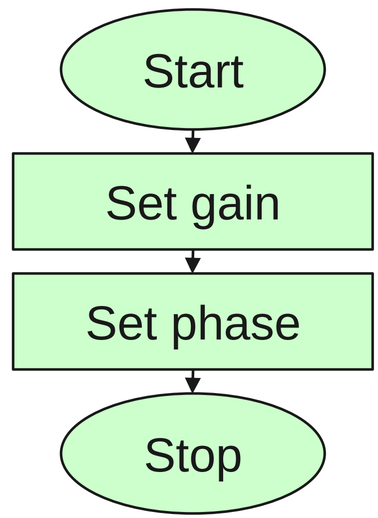
Support for two polarizations

Orthogonal Gain & Phase Control

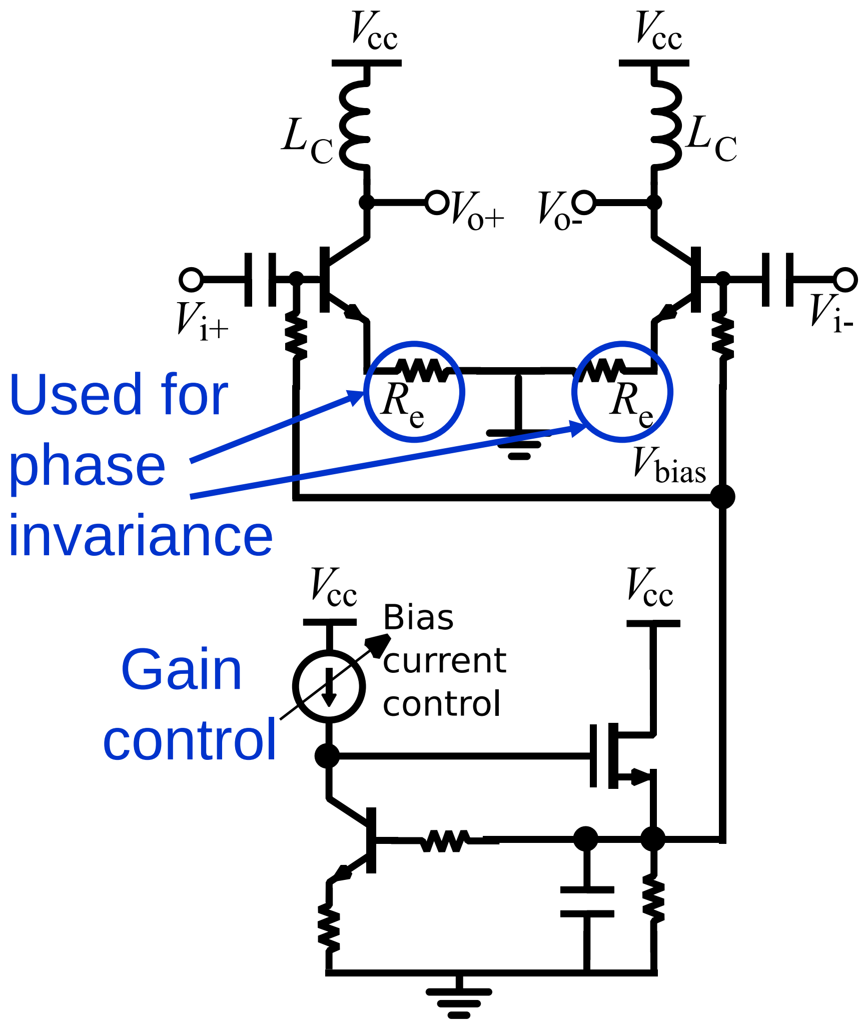
- Transmit/receive frontend
  - Phase invariant gain control
  - Loss invariant phase shift



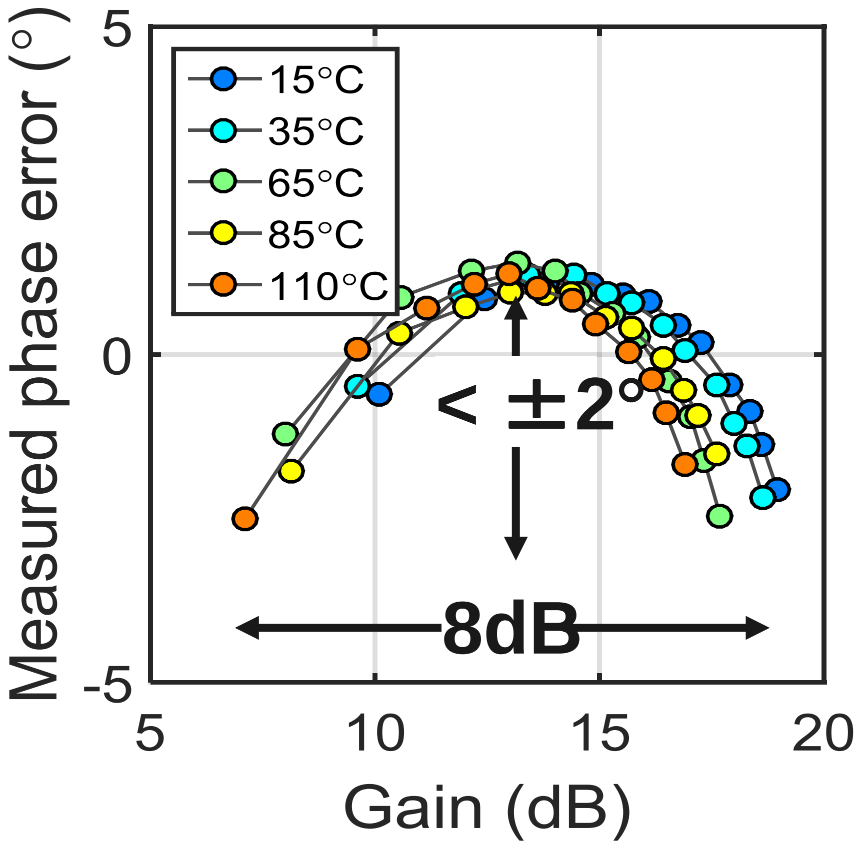




Phase Invariant Gain Control

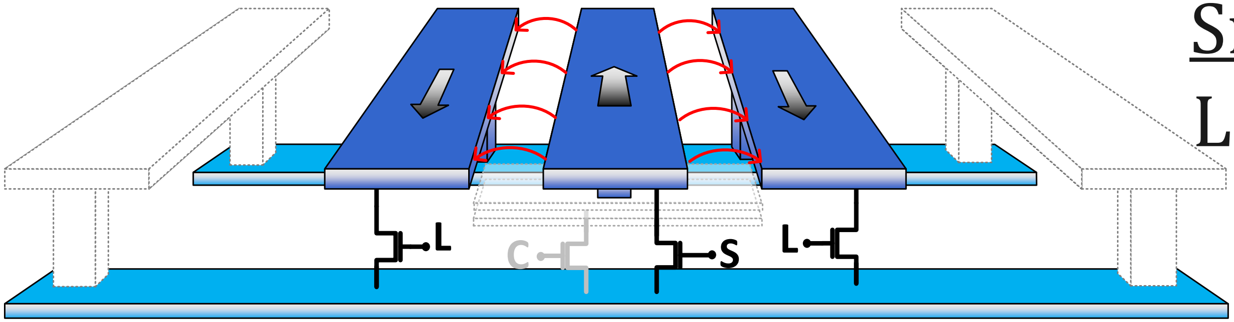


$$R_{e0} = \frac{c_\pi}{g_m c_{je}} = \frac{\tau_b}{c_{je}}$$



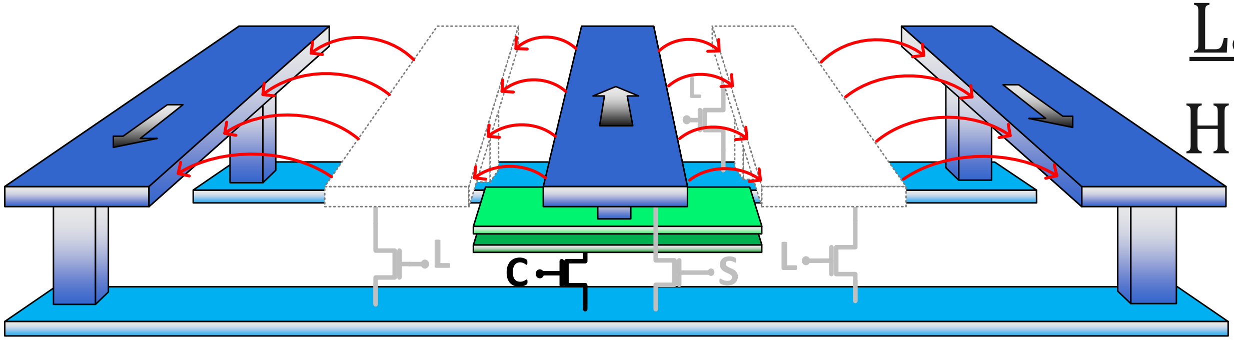
B. Sadhu, J. Bulzzachelli, and A. Valdes-Garcia, "A 28GHz SiGe BiCMOS phase invariant VGA", IEEE Radio Frequency Integrated Circuits Symposium, pp. 319-322, May 2016.

Phase Control Using Tunable Transmission Line Phase Shifter



<u>Small L, small C</u>

$$\text{Low Delay} = \sqrt{L_1 C_1}$$



<u>Large L, large C</u>

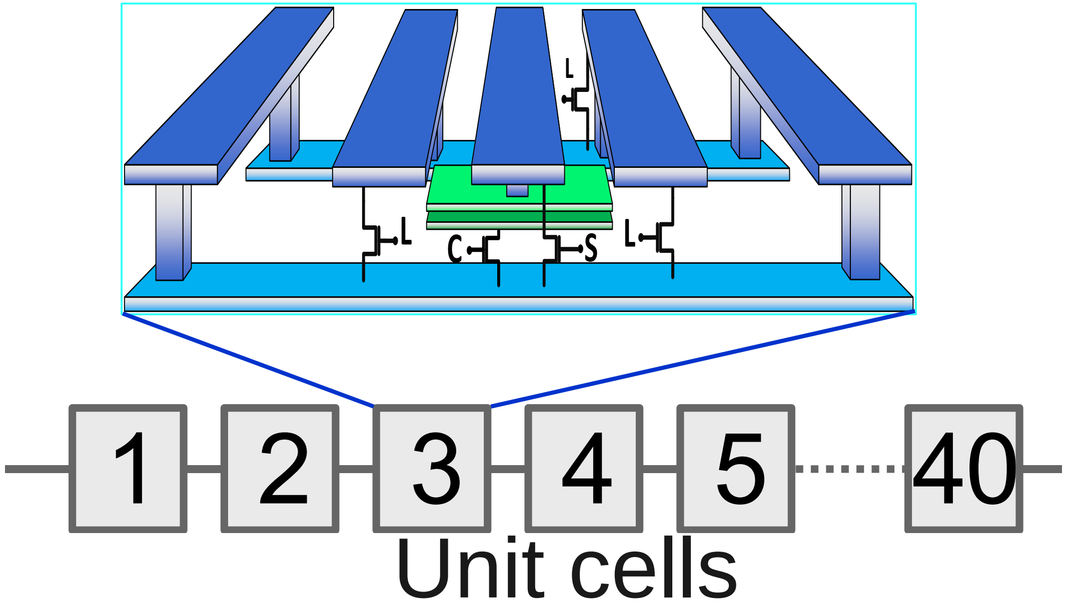
$$\text{High Delay} = \sqrt{L_2 C_2}$$

Constant characteristic impedance: $\sqrt{\frac{L_1}{C_1}} = \sqrt{\frac{L_2}{C_2}} = Z_o$

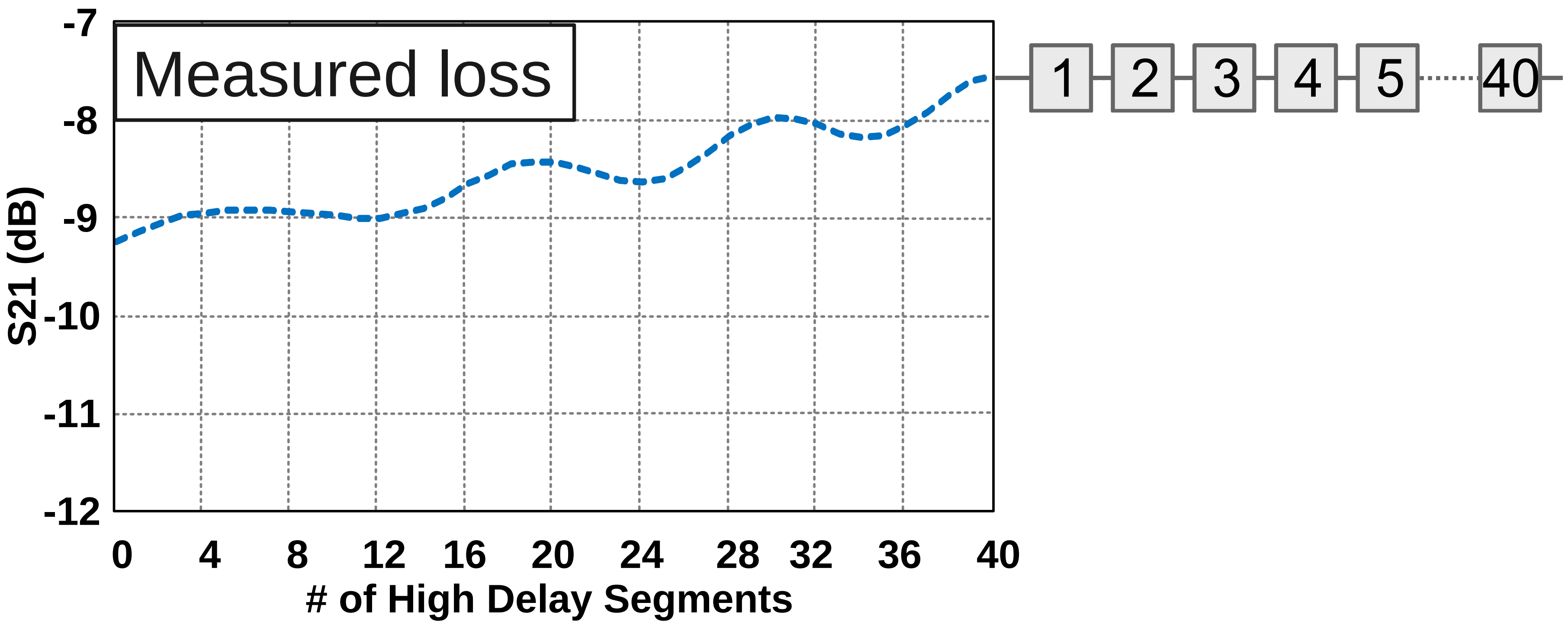
Y. Tousi and A. Valdes-Garcia, "A Ka-band Digitally-Controlled Phase Shifter with sub-degree Phase Precision", IEEE Radio Frequency Integrated Circuits Symposium, pp. 356-359, May 2016.

Connecting T-Line Unit Cells in Phase Shifter

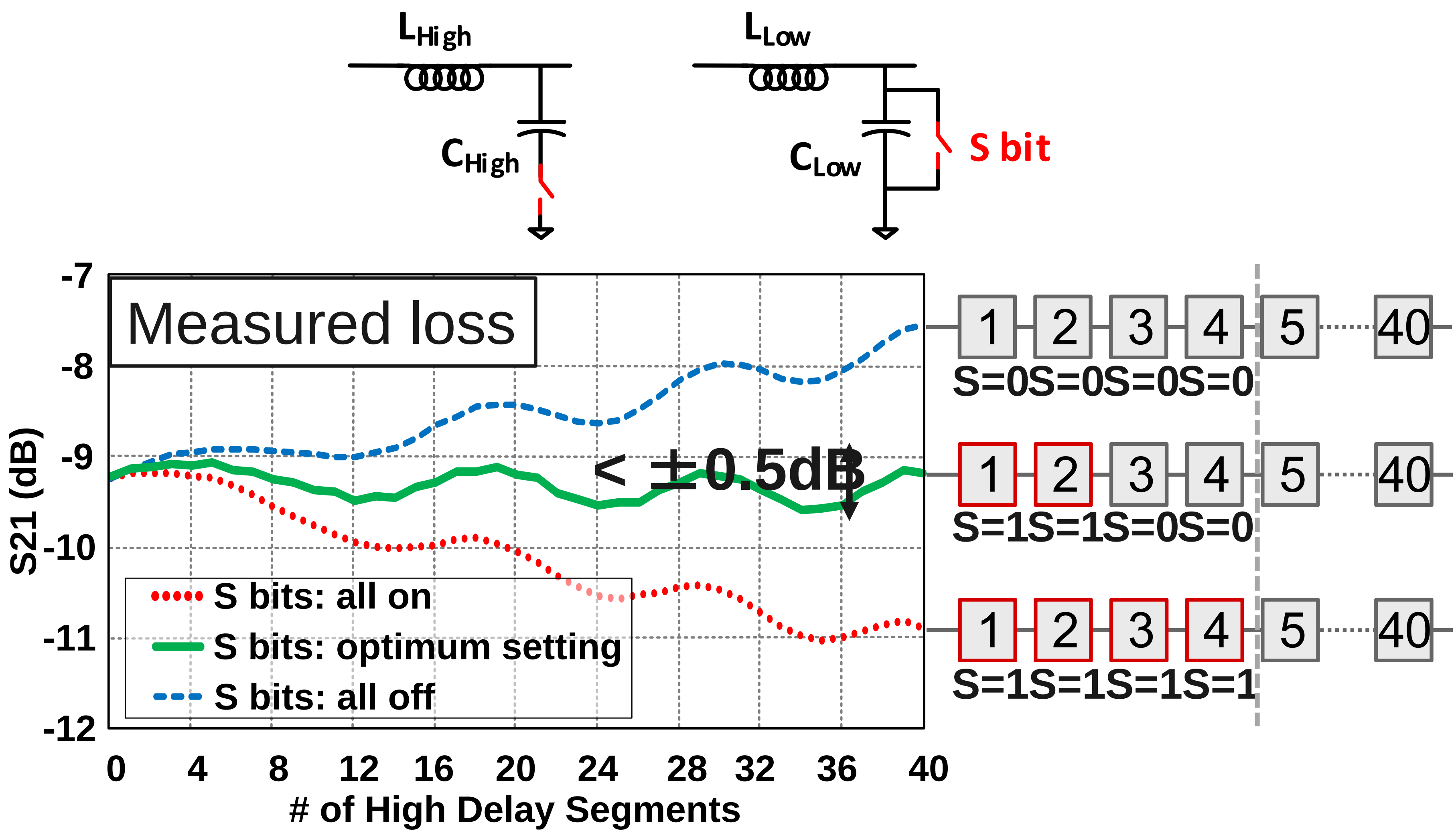
- Small phase steps
- Large phase range
- Fast switching
- Uniform steps



Enabling Loss Invariance in Phase Shifter



Enabling Loss Invariance in Phase Shifter



Key 5G mmWave Challenges…
… to IC Design Challenges

Maximize TX output power, with TX/RX integration

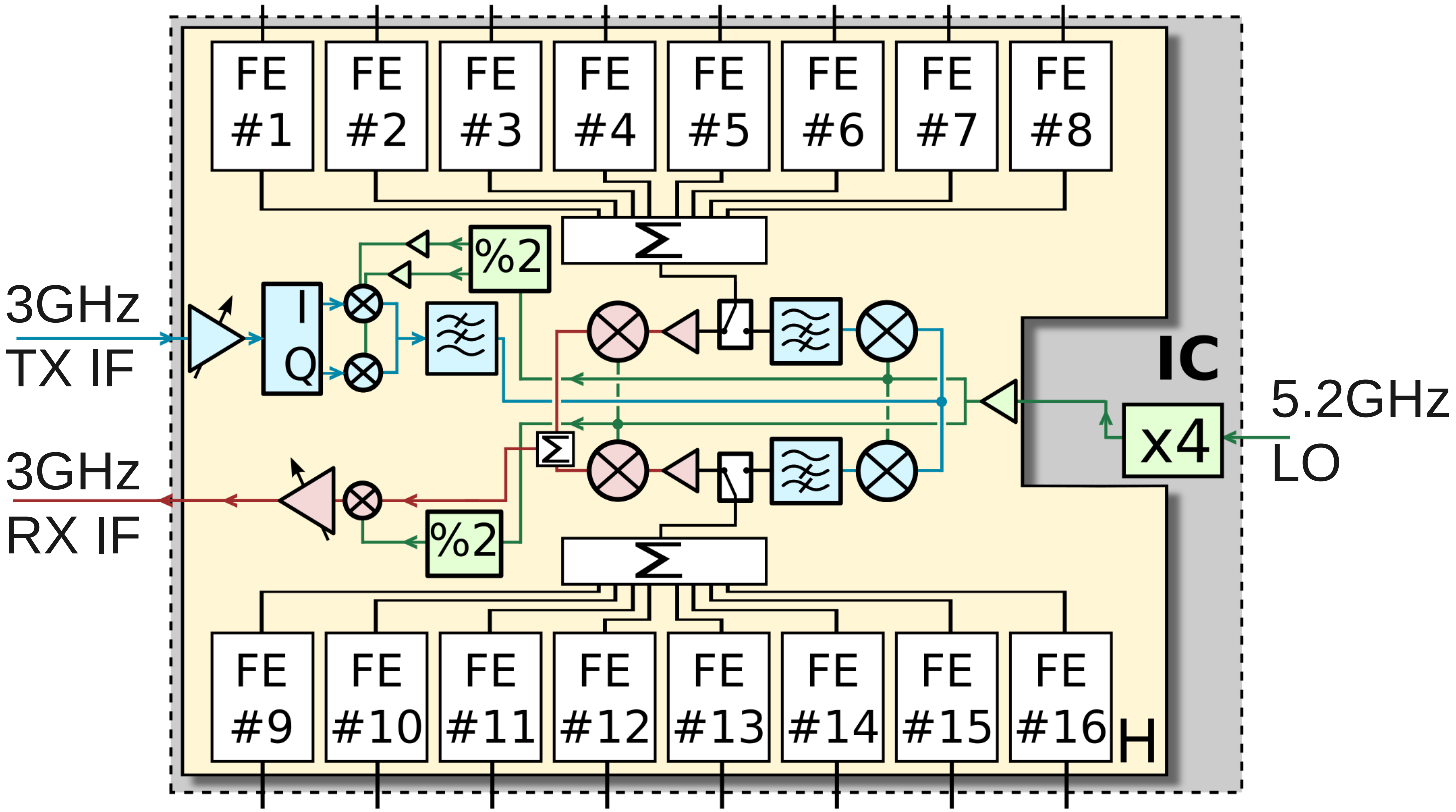
Orthogonal phase and gain control

Key IC challenges

Fine phase resolution

Support for two polarizations

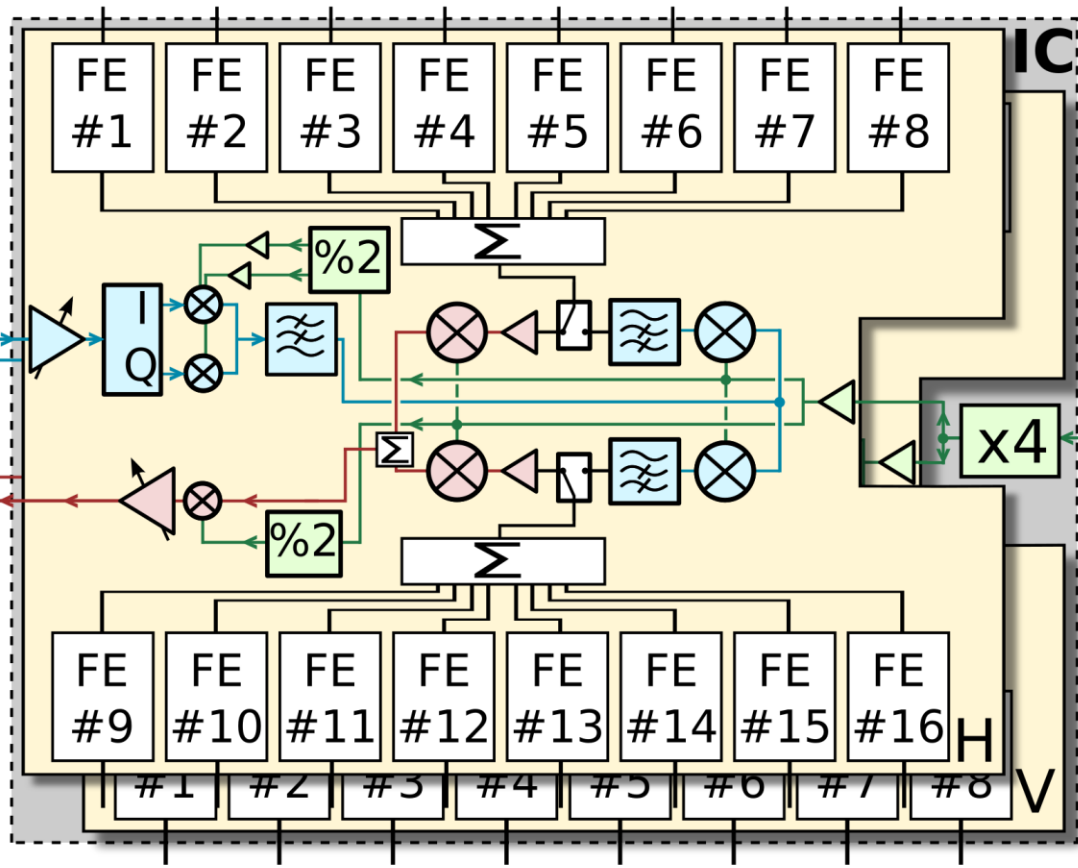
Dual-polarized IC Architecture: Single Polarization Slice



Dual-polarized IC Architecture: Two Identical 16-Element Slices

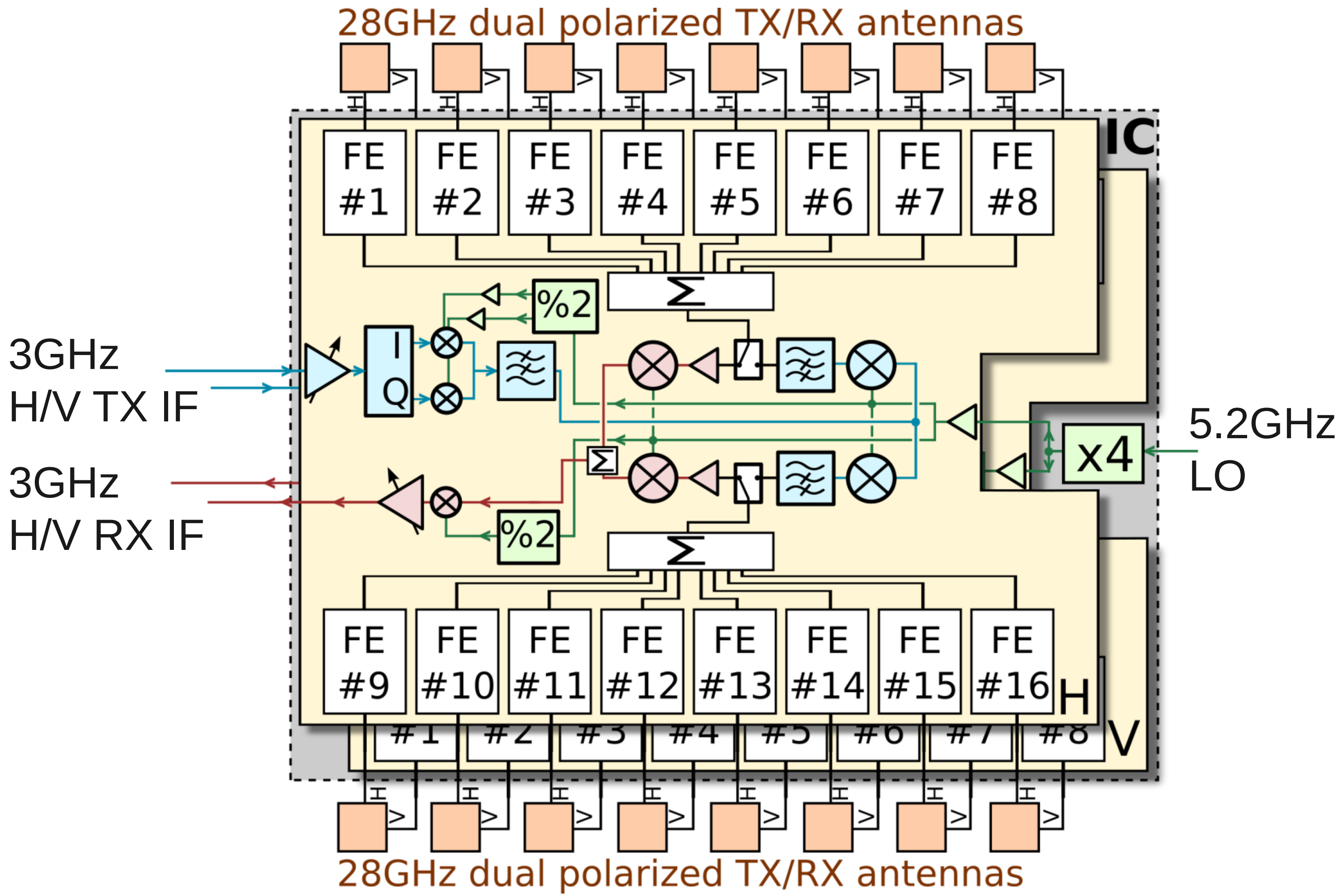
3GHz
H/V TX IF

3GHz
H/V RX IF



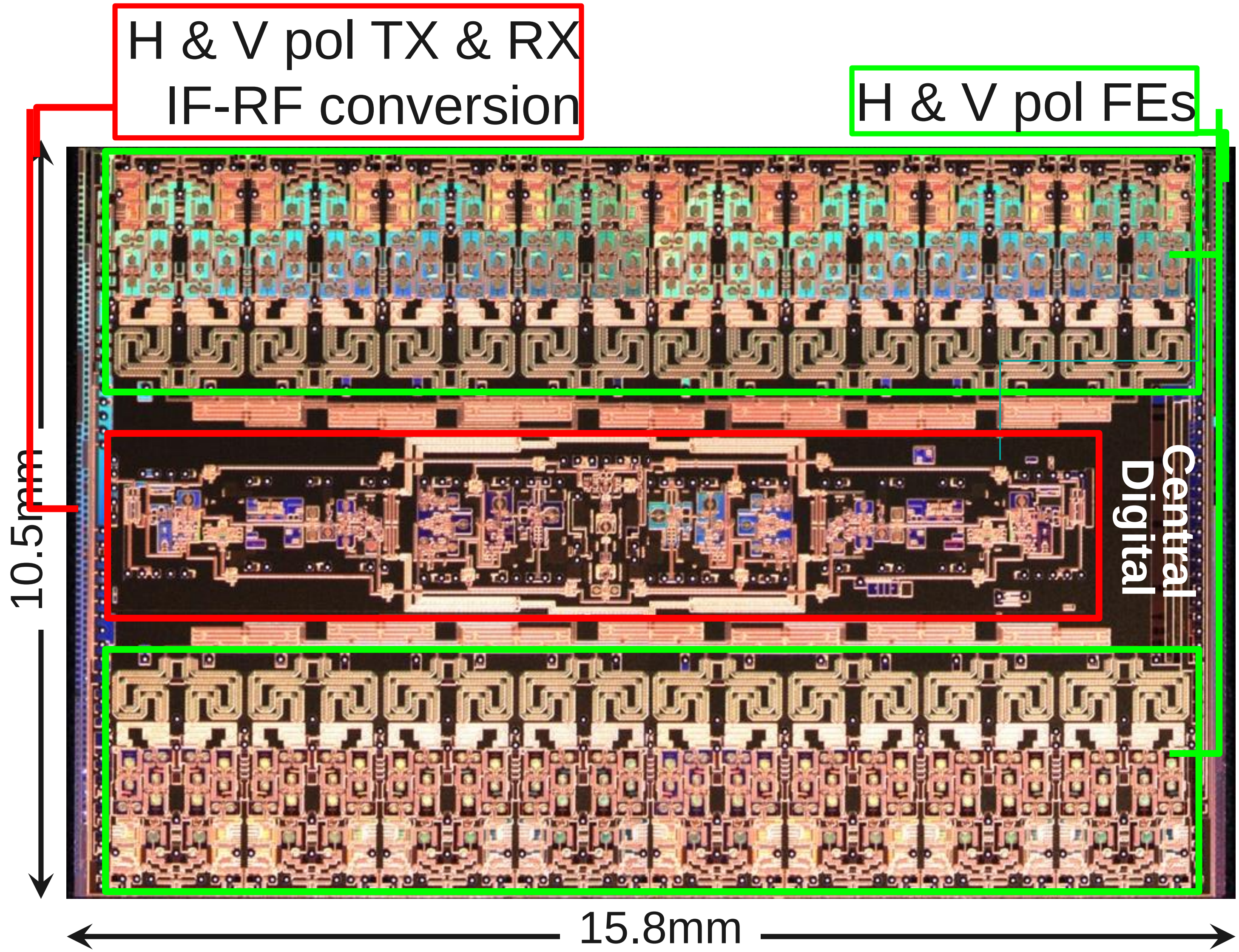
5.2GHz
LO

Dual-polarized IC Architecture:
32 Elements Feed 16 Dual-Pol Antennas



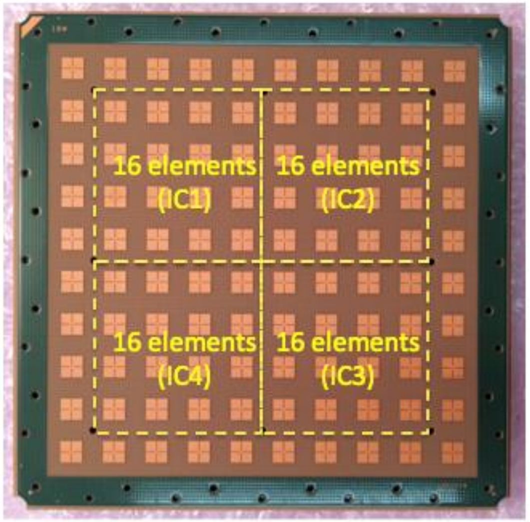
Implemented in SiGe 130nm BiCMOS, GF 8HP:

fT/fMAX = 200GHz/280GHz



Antenna-in-package and phased array scaling approach

Fully-Assembled 4-chip Antenna Module

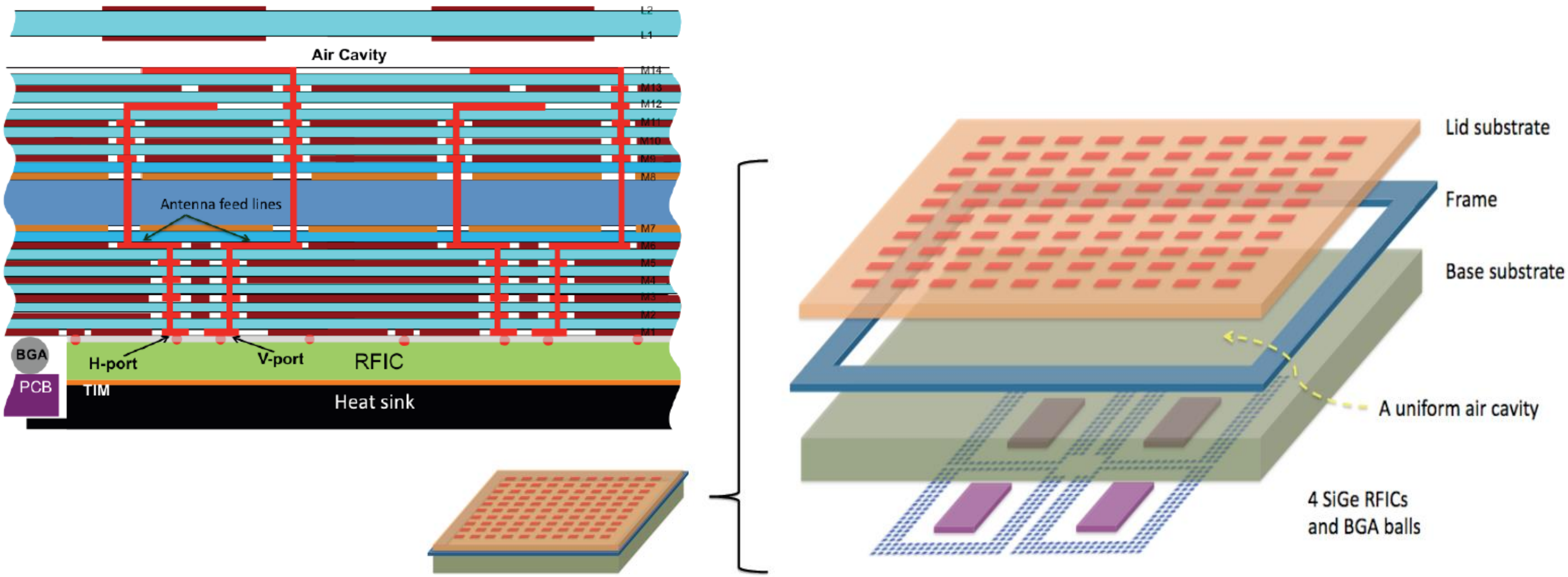


- Package dimensions: 70mm x 70mm x 2.7mm
- Flip-chip assembly for 4 ICs
- 655 BGA w/ 1.27mm pitch supporting multiple power domains, IF (TX & RX) and LO signals, Digital control and ref clock signals

- Phased array IC and package scalability concept introduced and demonstrated at 94GHz in A. Valdes-Garcia, *et al.*, RFIC 2013 and X. Gu, *et al.* ECTC 2014

- For 28GHz package details: X. Gu, D. Liu, C. Baks, O. Tageman, B. Sadhu, J. Hallin, L. Rexberg, and A. Valdes-Garcia, " A Multilayer Organic Package with 64 Dual-Polarized Antennas for 28GHz 5G Communication", *IEEE IMS*, June 2017.

Antenna-in-package Array with Air Cavity

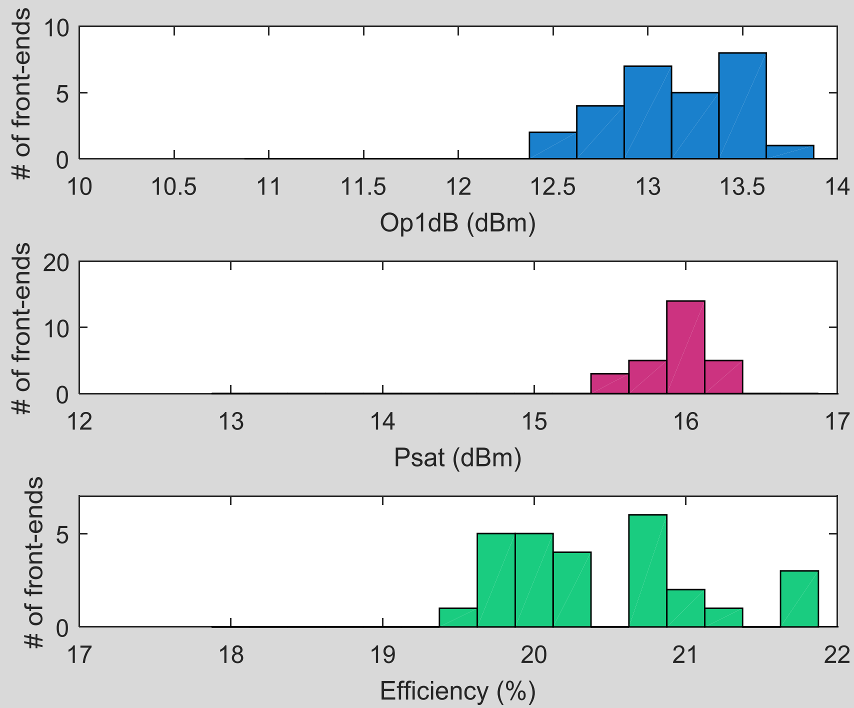


- Aperture coupled patch antenna
- Uniform air cavity between antenna patch and feed structure
- 14-layer base substrate based on organic buildup technology

Measurement Results

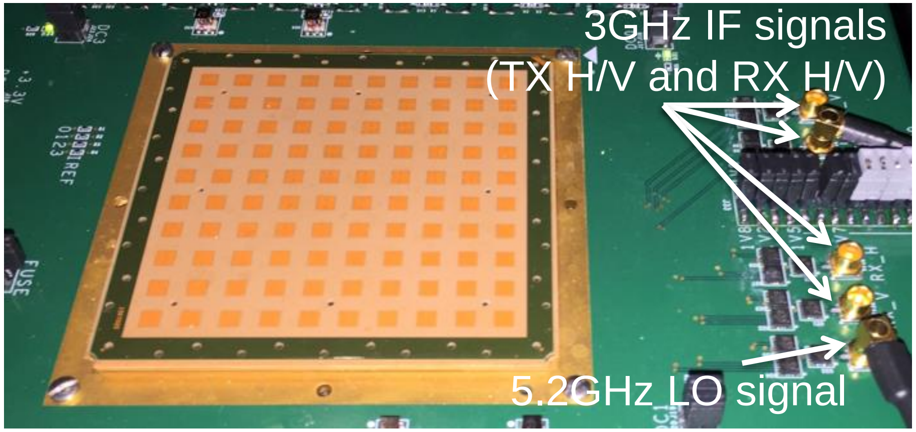
On-wafer Measurement Results

Single TX Path in Full IC: 27 Front-Ends Across 9 ICs

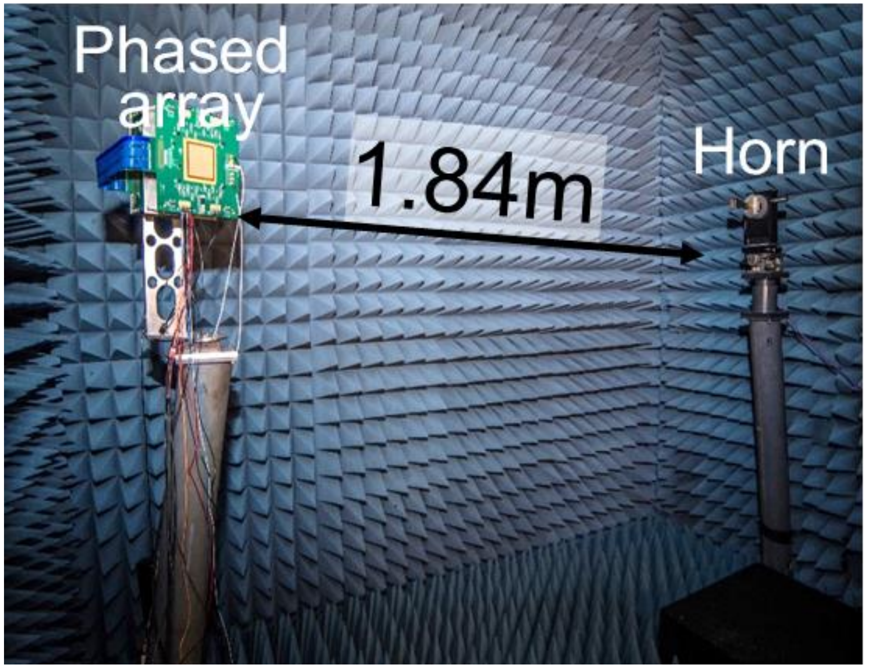


Full IC performance					
		1 sample			27 samples μ / σ
	Temperature	25C	65C	85C	25C
TX	Single-path gain ± Phase Invariant Gain Control (dB)	32 ±4.0	27 ±4.4	24 ±4.5	34 / 1.5 ± 4.0 / 0.2
TX	Single-path Op1dB (dBm)	14	14.1	13.9	13.5 / 0.4
TX	Single-path Psat (dBm)	16.4	16.6	16.2	16 / 0.2
TX	PA+switch peak efficiency measured in full IC (%)	22.1	20.1	20.8	20.5 / 0.6
TX	3dB BW (GHz)	2			
TX	Op1dB/Psat variation across 360° phase control (dB)	<0.1	<0.2	<0.5	
RX	Op1dB/Psat variation across 8dB gain control (dB)	<0.1	<0.5	<2	
RX	Single-path gain ± Phase Invariant Gain Control (dB)	34 ±4.0	31 ±4.4	28 ±4.5	35 / 0.6 ± 4.0 / 0.2
RX	3dB BW (GHz)	1.5			
Sub-block performance					
LNA NF (dB)		3.7	4.1	4.3	
LNA+switch+off-mode PA NF (dB)		6.0	6.6	6.9	
TX/RX VGA gain control (dB)		8	8.8	9.1	
TX/RX VGA phase variation (°)		±1.5	±2	±1.5	
Phase shifter phase control (°)		210	210	210	
Phase shifter loss variation (dB)		±0.1	±0.2	±0.4	
RX front end Ip1dB (dBm)		-22.5	-21.5	-21.5	

Over the Air Measurement Setup Using 4 IC Module

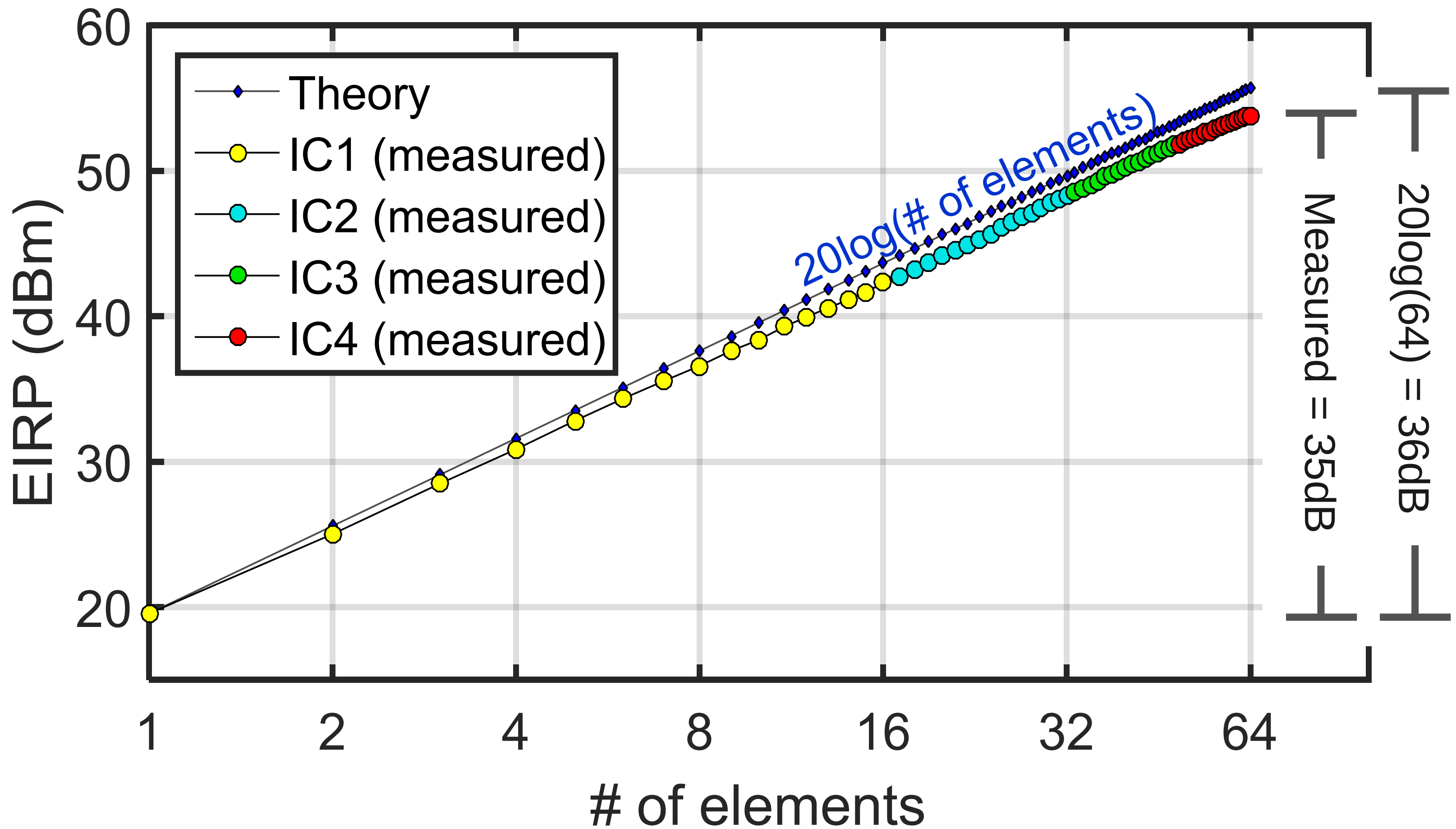


Evaluation board



Antenna chamber set-up

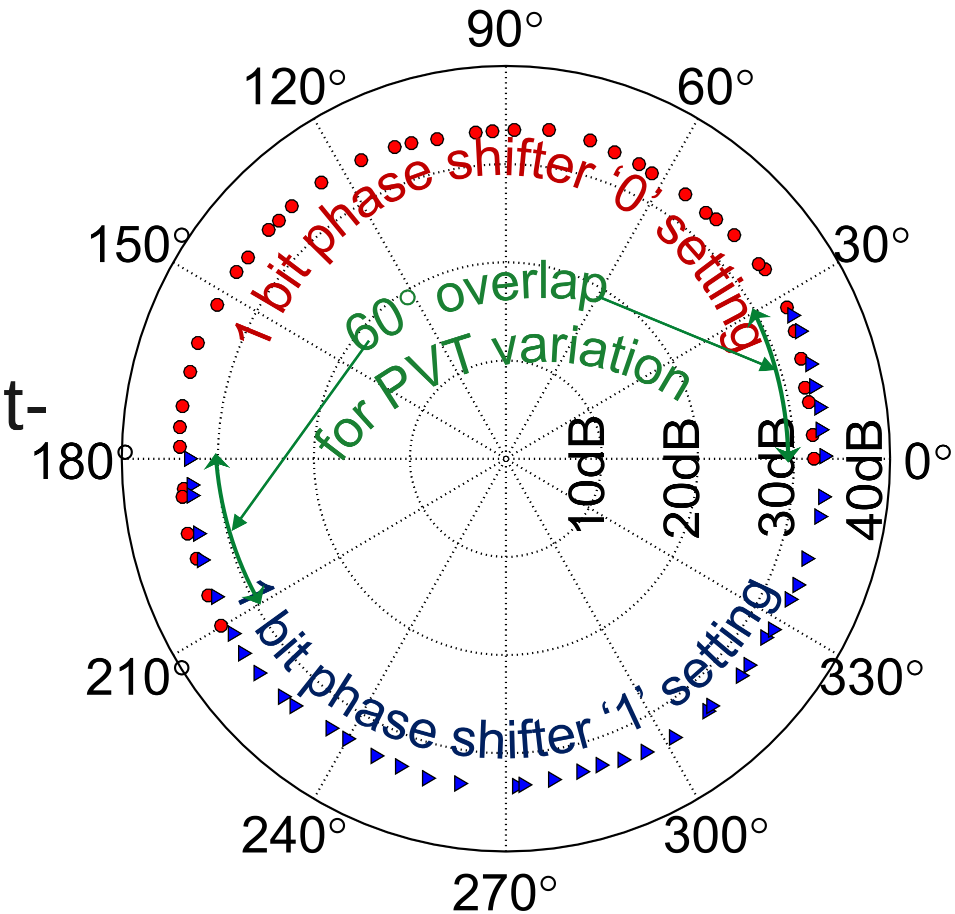
Measured 64 Element Progressive Element Turn On Without Calibration



Measured saturated EIRP in one polarization = 54dBm

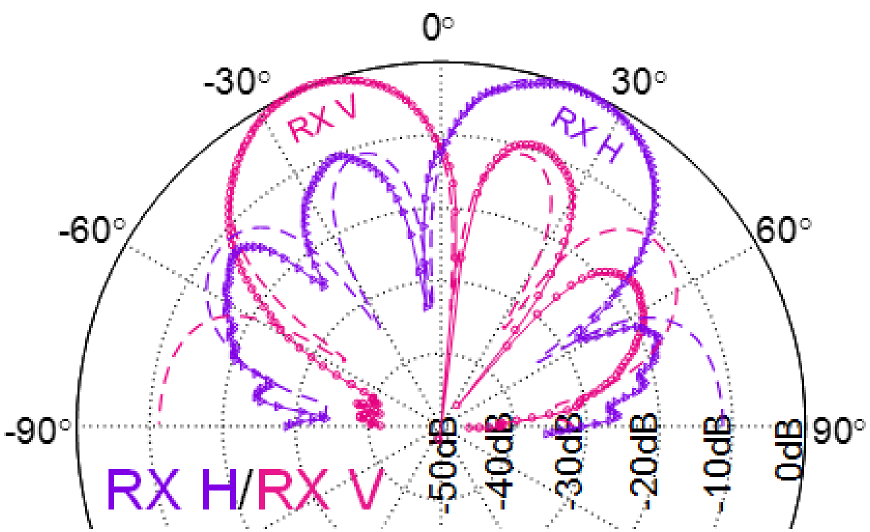
Measured Loss Invariant Phase Control in Phased Array

Gain variation per front-end < ±0.7dB across 360° phase control

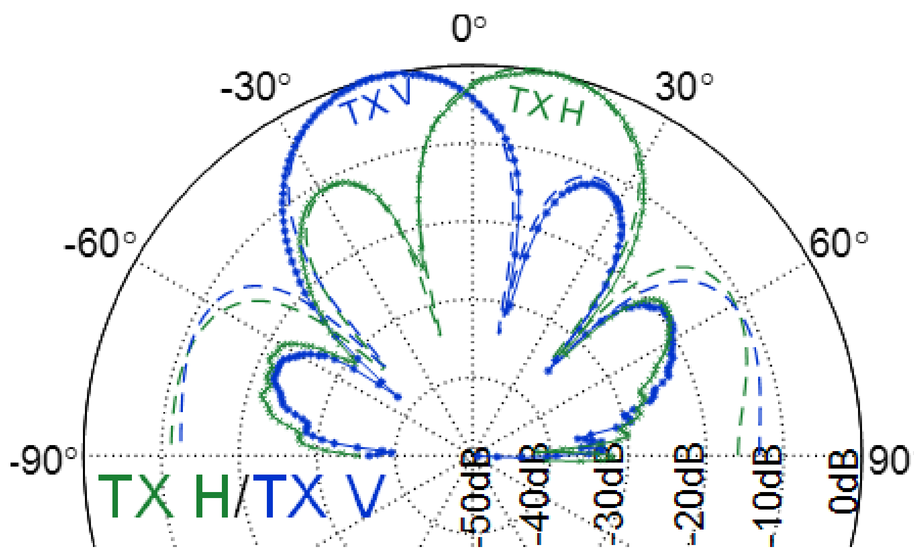


Measurements of 16 Element Beams from 1 IC

2 simultaneous beams in RX mode



2 simultaneous beams in TX mode

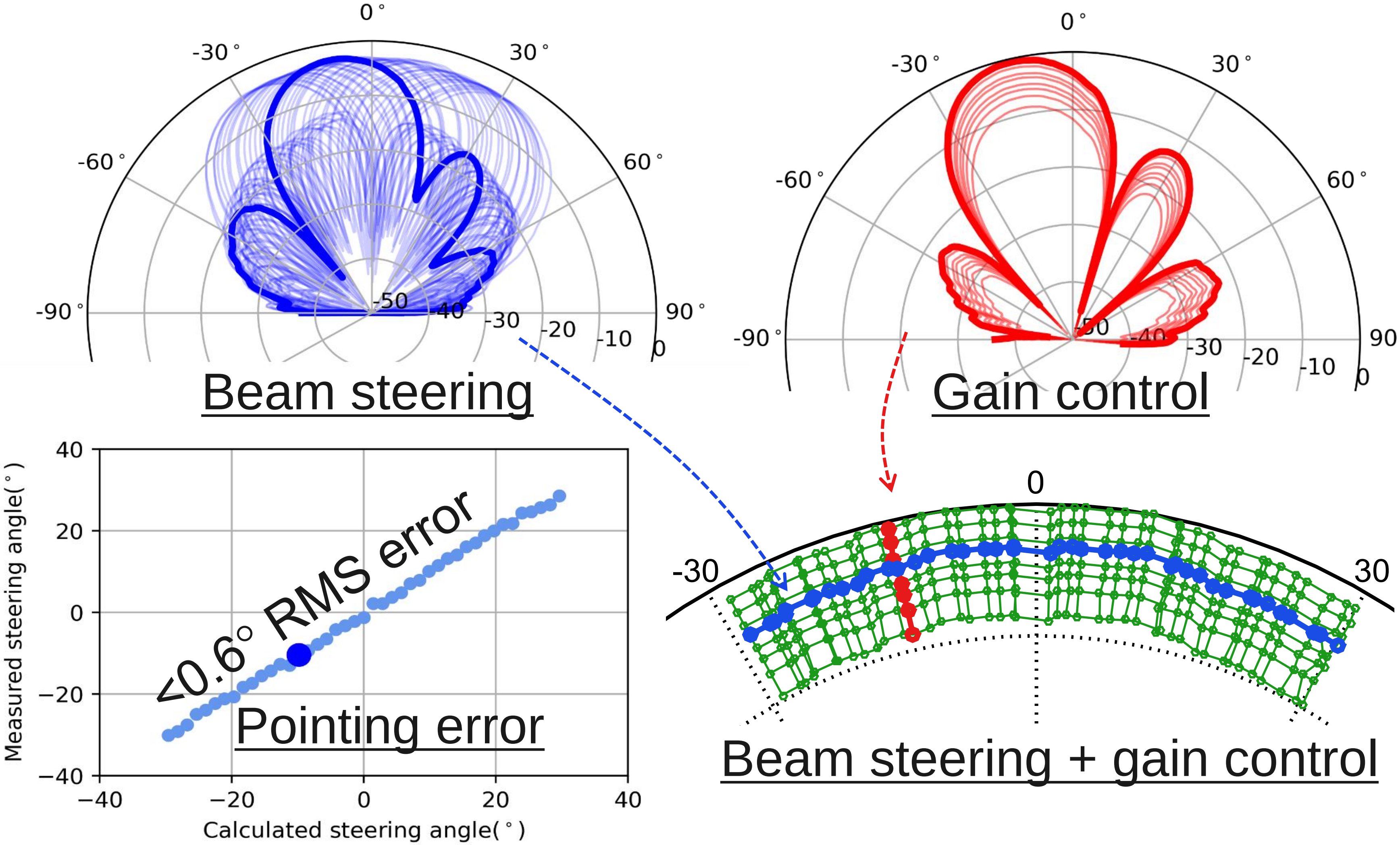


Measured radiation patterns

Ideal radiation patterns calculated with the same angular resolution available in the measurement setup

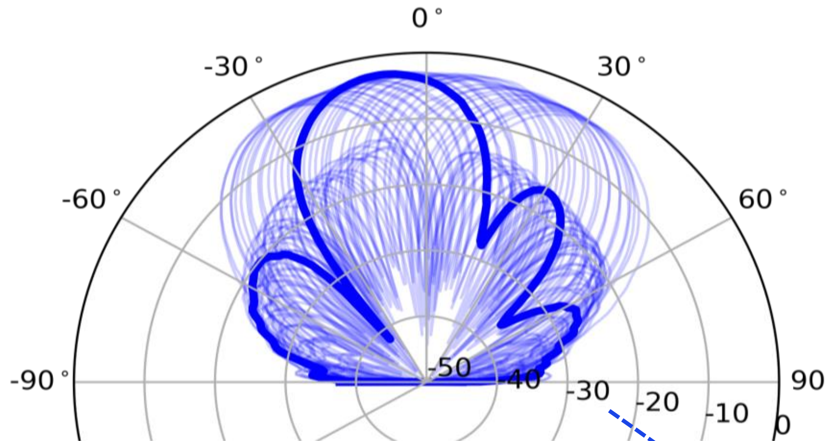
Results obtained without requiring array calibration

Measured Beam Steering Control

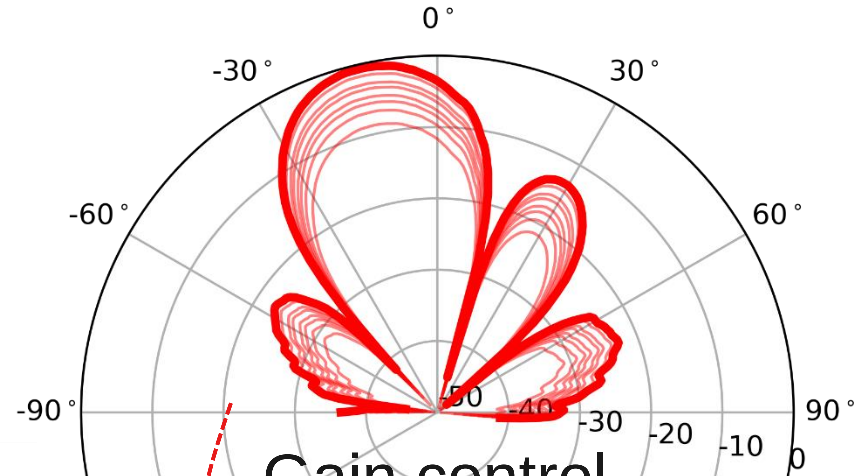


Results obtained without requiring array calibration

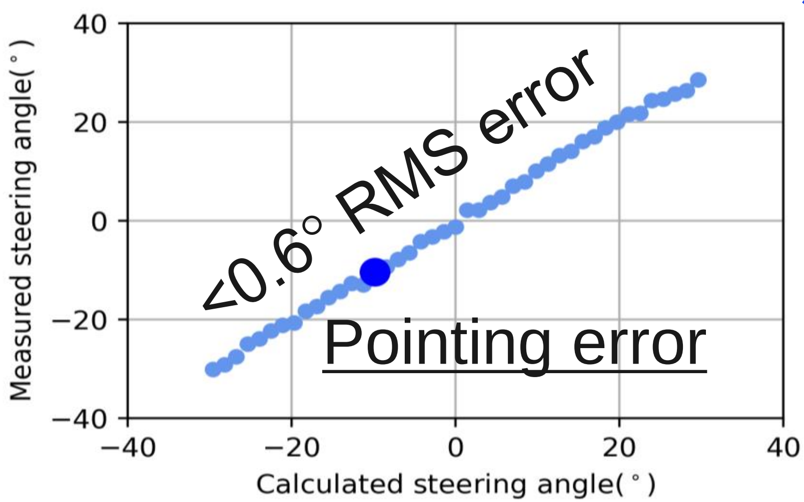
Measured Beam Steering Control



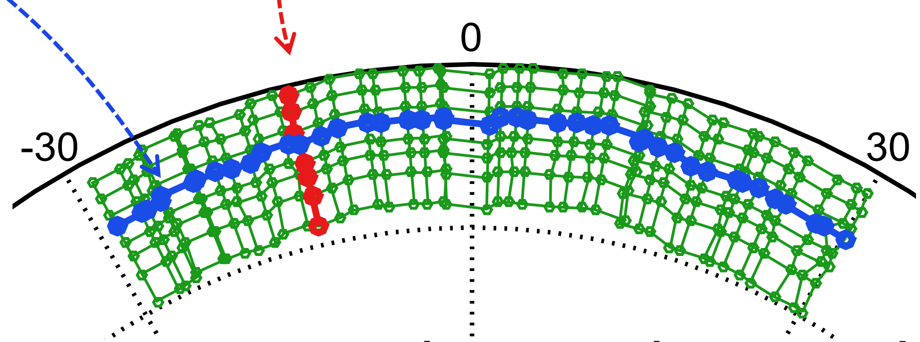
Beam steering



Gain control



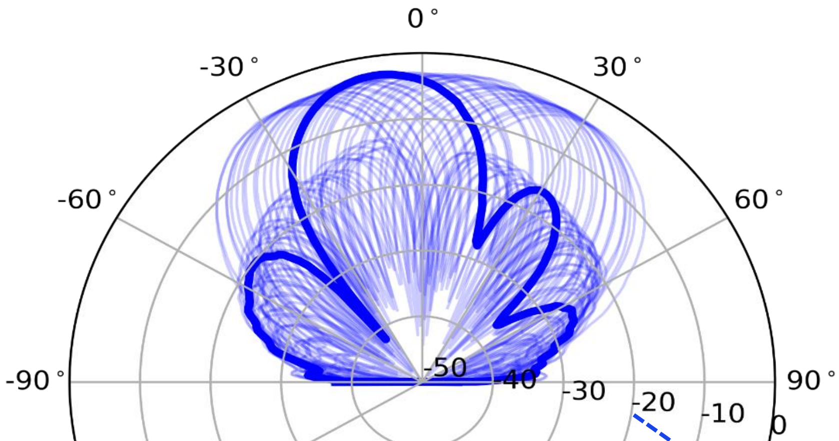
Pointing error



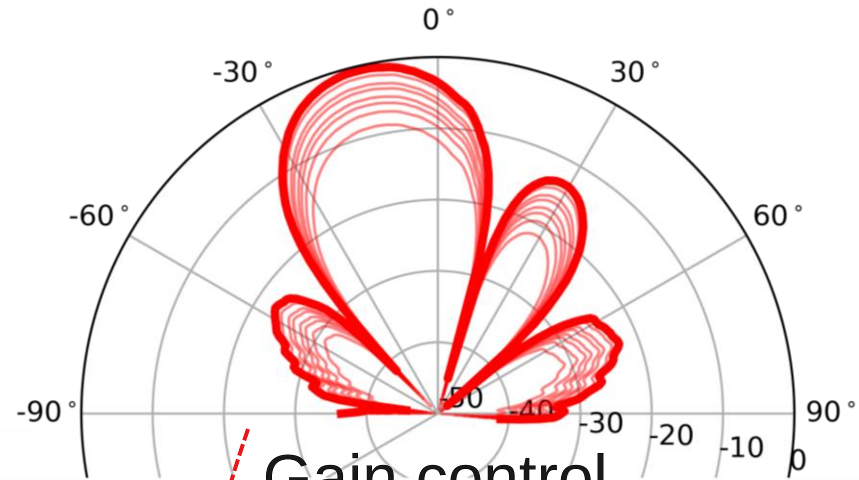
Beam steering + gain control

Results obtained without requiring array calibration

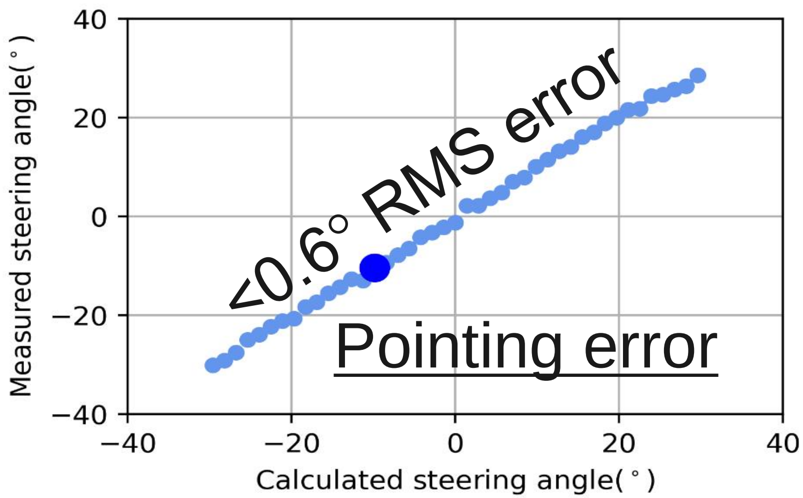
Measured Beam Power Control

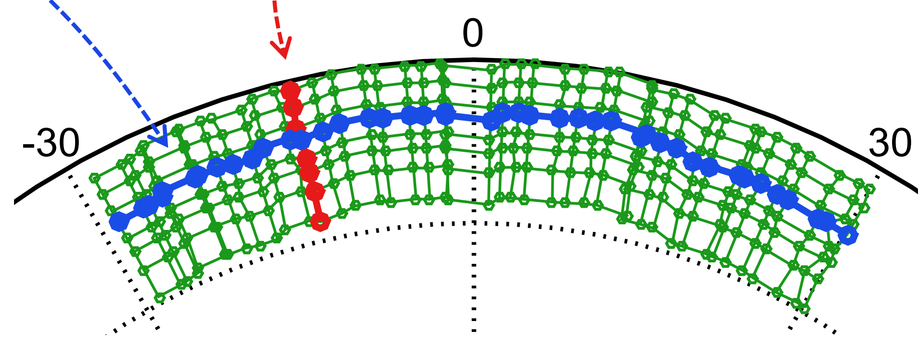


Beam steering



Gain control



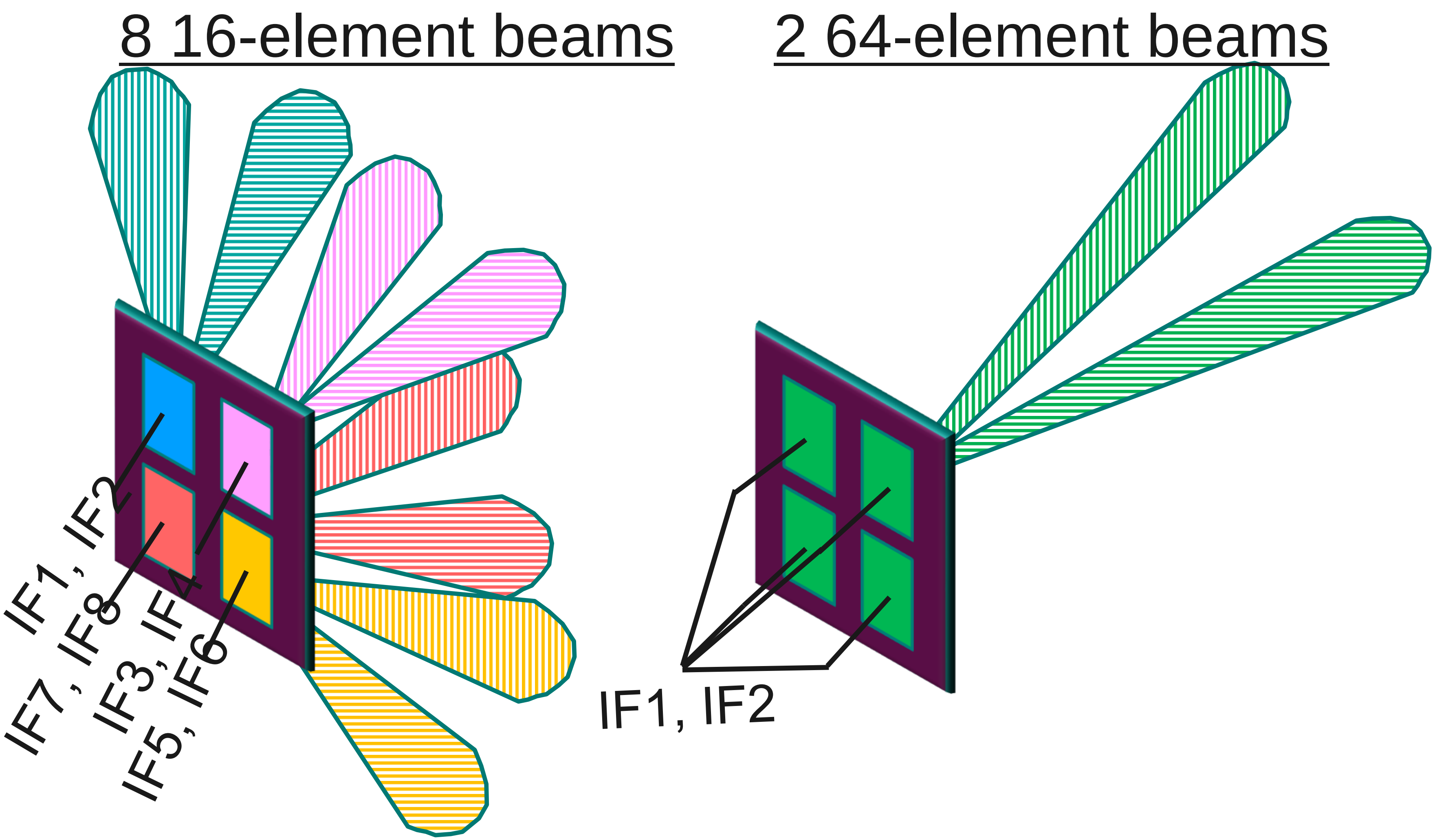


Beam steering + gain control

Results obtained without requiring array calibration

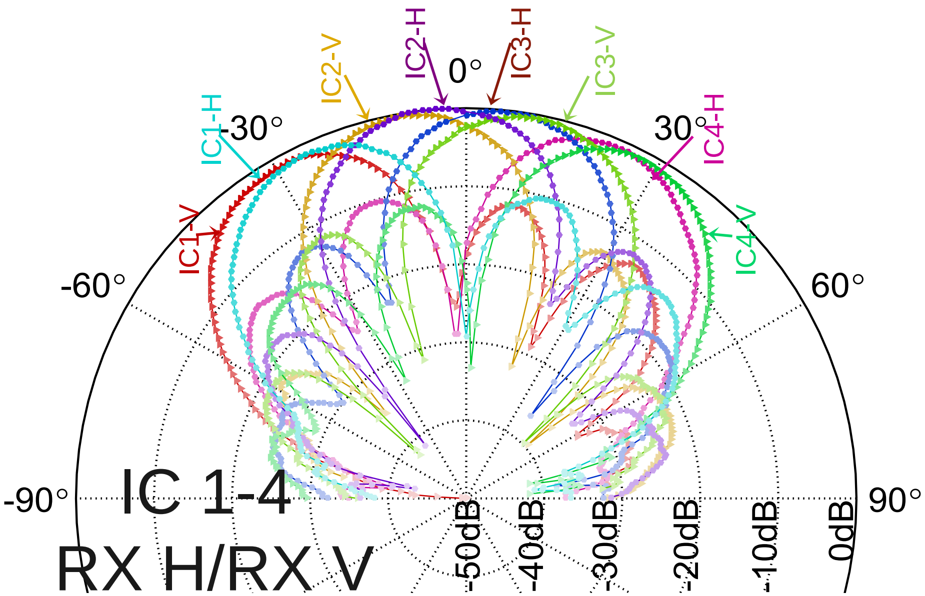
Beam-Forming Options in TX/RX

Total TRX elements per module (4 ICs) = 128

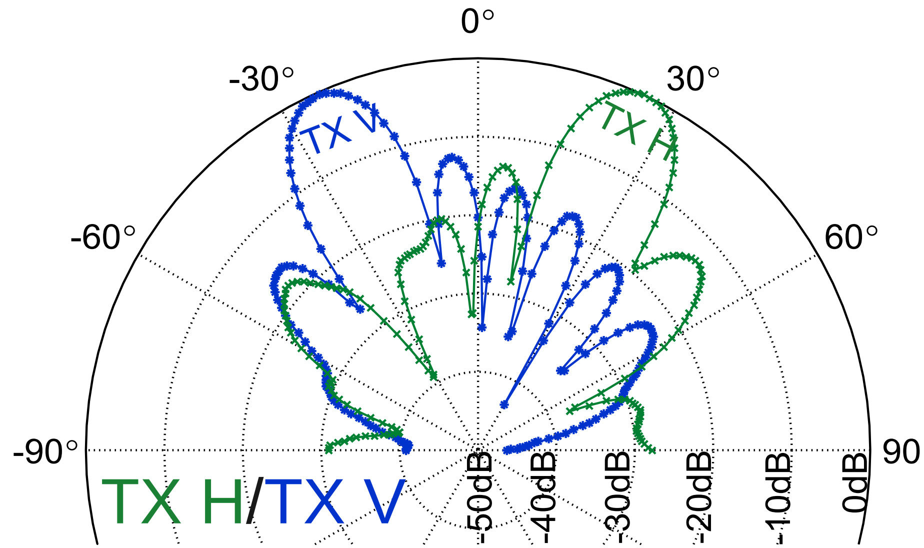


Measurements of Reconfigurable Beams from a Module (4 ICs)

8 16-element beams



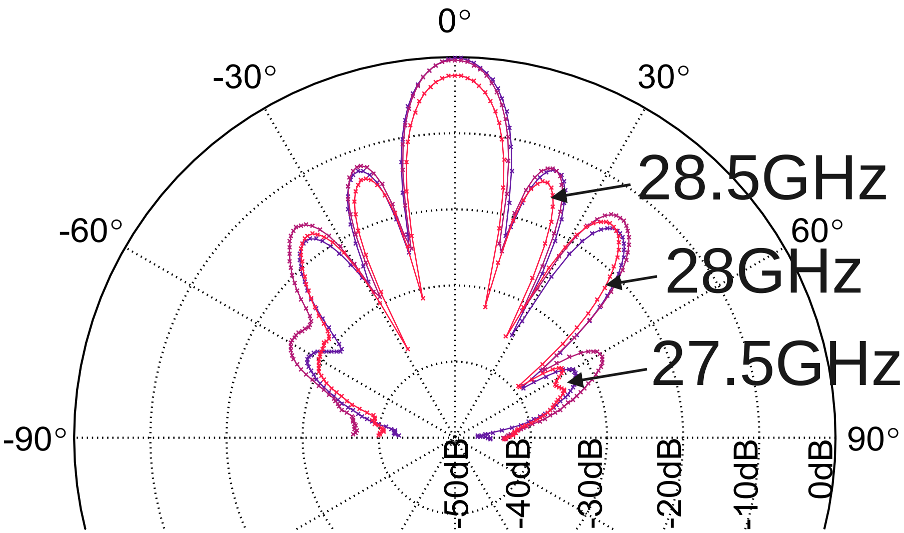
2 64-element beams



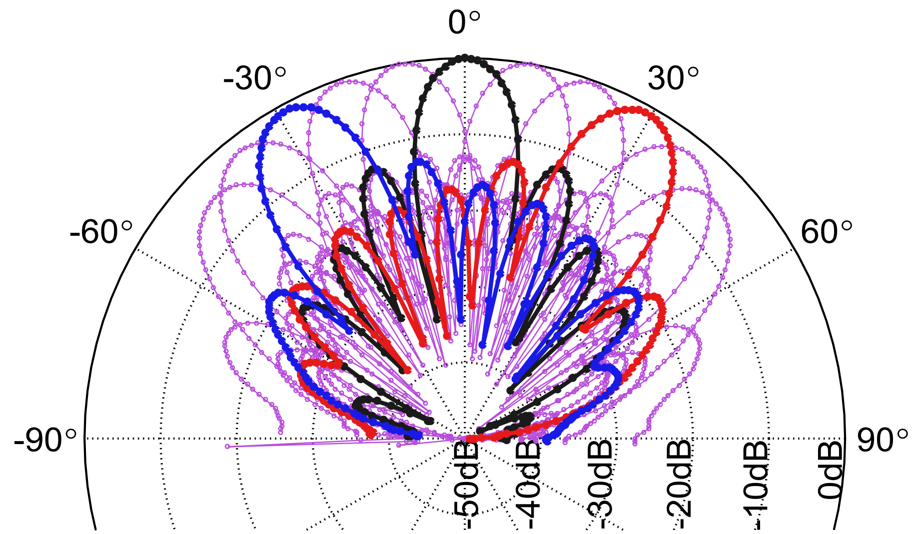
Results obtained without requiring array calibration

Measured 64-element Beam-Steering

Beam across frequency

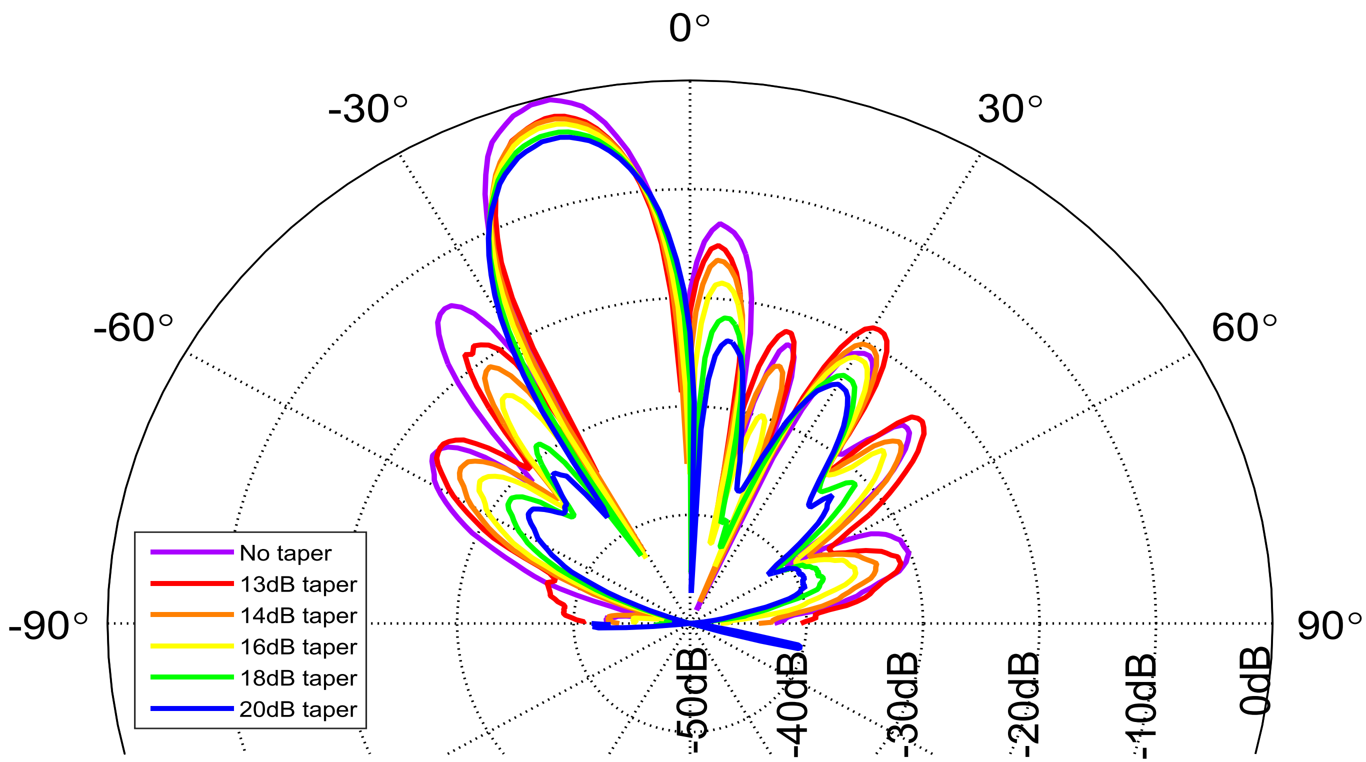


±50° beam steering
(w/ <10dB sidelobes w/o tapering)



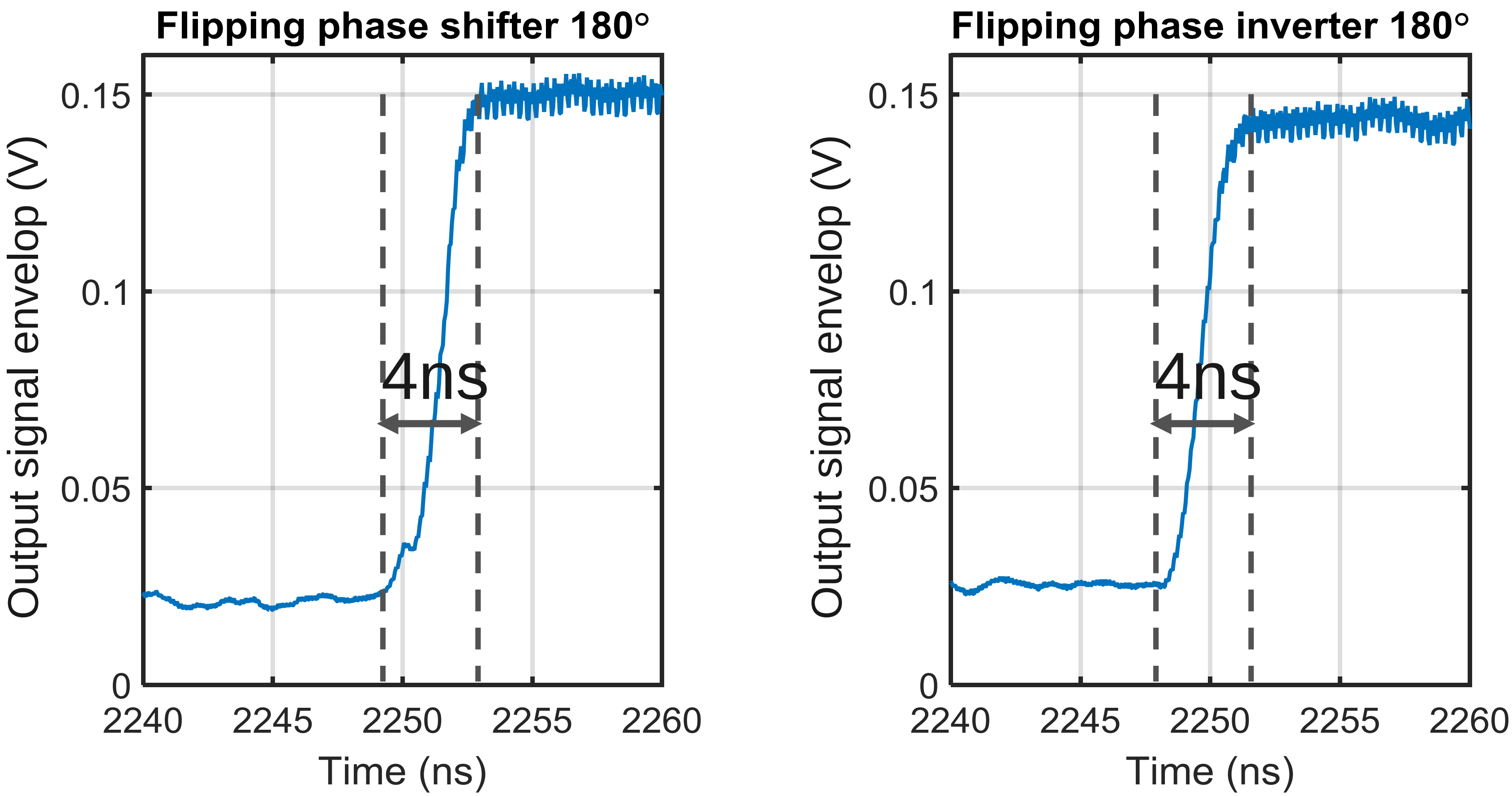
Results obtained with one-step element to element calibration; uncalibrated results similar

Tapering Measurement Results



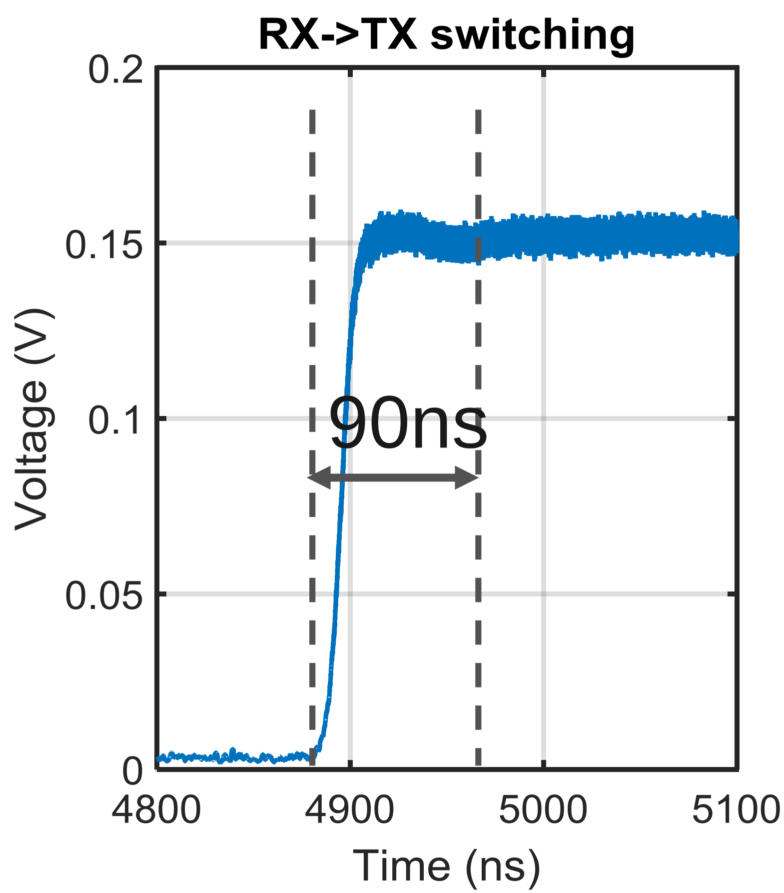
Measurement is performed in RX mode with 64 elements in H pol
Tapering uses VGA control and Taylor window

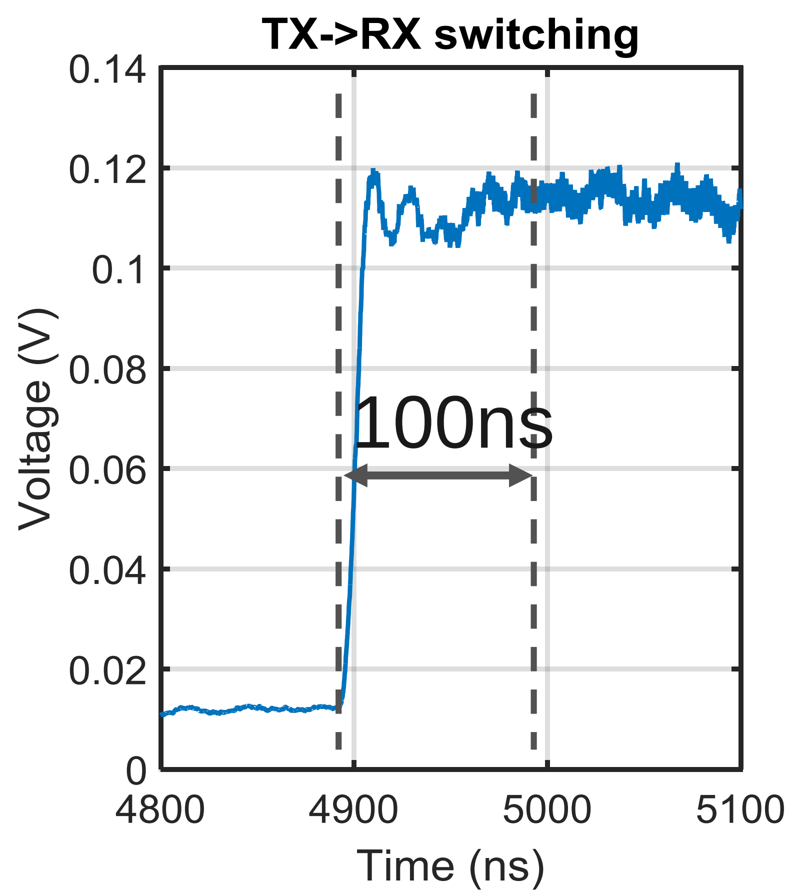
Measured Beam Switching Speed



Beam switching speed is <4ns

Measured TX↔RX Switching Speed





TX↔RX switching speed is <100ns

Performance Summary and Comparison for Published 28GHz Si-based Packaged Phased-Array TRX

	This work (ISSCC 2017 / IMS 2017)	**Anokiwave (AWMF-0129 Datasheet)**	**UCSD (RFIC 2017)**	**LG (RFIC 2017)**	**UCSD (IMS 2017)**
Number of Antennas	64	64	32	8	4
Simultaneous polarizations	**2**	**1**	**1**	**2**	**1**
FE Elements in Package/Board	**128**	**64**	**32**	**16**	**4**
Number of ICs	4	8	8	2	1
Input Interface	**IF 3GHz**	**Not published**	**RF 28GHz**	**Baseband**	**RF 28GHz**
EIRP per polarization	**54dBm (Psat)**	**50dBm (P1dB)**	**41dBm (P1dB) @29GHz**	**31.5dBm (Psat)**	**24.5dBm (P1dB) @29GHz**
DC power per polarization	13.2W(RX) + 20.4W(TX) @54dBm EIRP	18W (average)	4.2W (RX) + 6.4W(TX)	0.4W(RX) + 0.68W(TX) @24dBm EIRP	0.42W(RX) + 0.8W(TX)
IC Technology	GF SiGe 8HP 130nm	Not published	Jazz SBC18H3 SiGe BiCMOS	TSMC 28nm RF CMOS	Jazz SBC18H3 SiGe BiCMOS

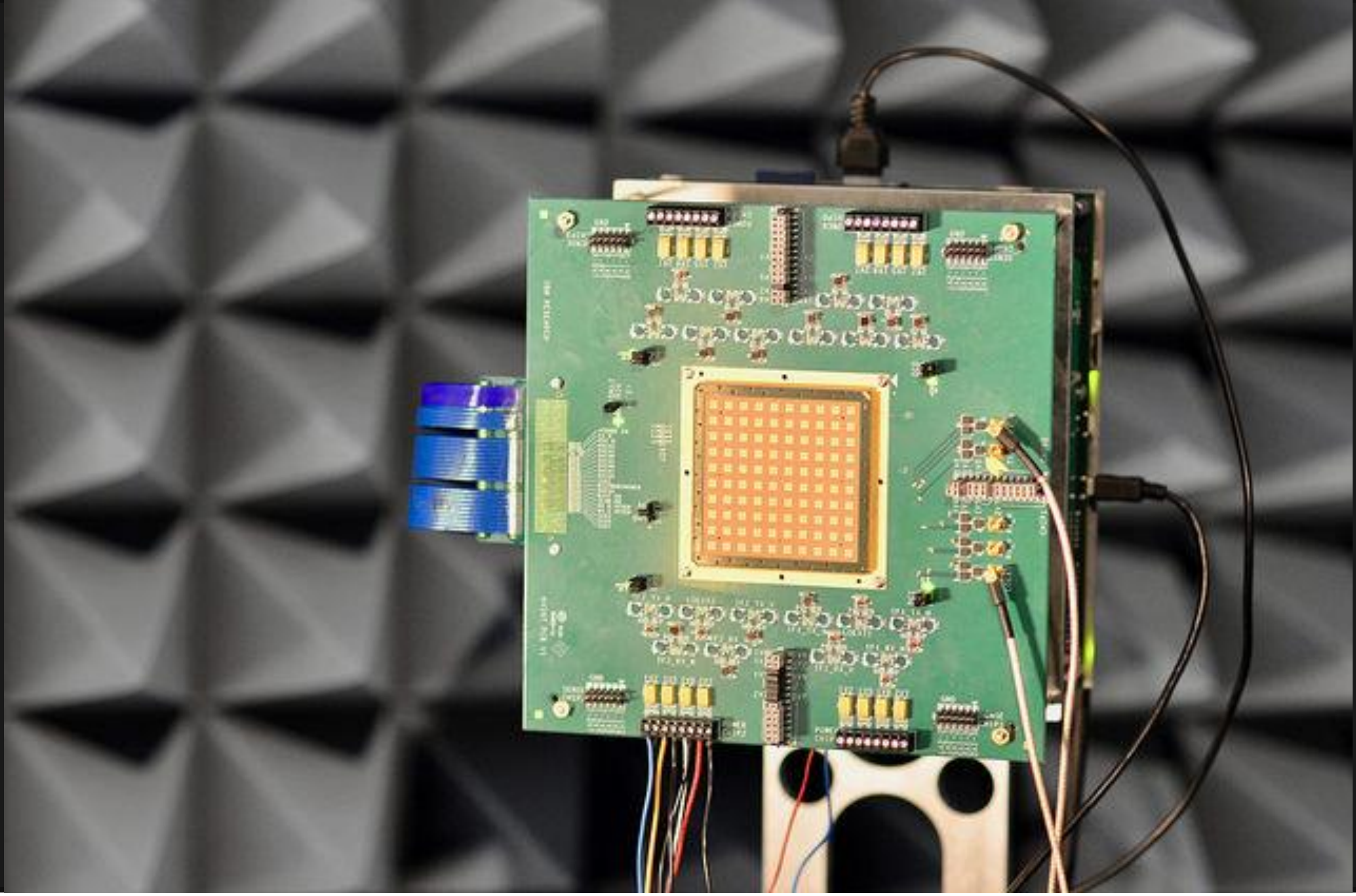
Summary and Conclusions

- **First reported** mmWave 5G base-station IC in a multi-IC antenna-in-package module (ISSCC 2017)
- **Proposed TRX switch improves EIRP** without sacrificing power consumption
- **Orthogonal phase and amplitude control** for efficient beam control
- **High resolution beam steering** with low side-lobes based on fine phase shift resolution

Acknowledgments

B. Sadhu[1], Y. Tousi[1], J. Hallin[2], S. Sahl[3], S. Reynolds[1], Ö. Renström[3], K. Sjögren[2], O. Haapalahti[3], N. Mazor[4], B. Bokinge[3], G. Weibull[2], H. Bengtsson[3], A. Carlinger[3], E. Westesson[5], J.-E. Thillberg[3], L. Rexberg[3], M. Yeck[1], X. Gu[1], D, Friedman[1], C. Baks[1], D. Liu[1], Y. Kwark[1], M. Wahlen[3], A. Ladjemi[3], A. Malmcrona[3].

[1]IBM T. J. Watson Research Center, Yorktown Heights, NY
[2]Ericsson, Lindholmen, Sweden
[3]Ericsson, Kista, Sweden
[4]IBM Research, Haifa, Israel
[5]Ericsson, Lund, Sweden



‘Ultimately though, we should expect mmWave systems to become as inexpensive and ubiquitous as 2.4- and 5-GHz WLAN systems are today. Some of the early companies developing products in the mmWave space will succeed and become profitable, and some will fail. **But the end result will be “millimeter-waves for the masses.”’** - Advanced Millimeter Wave Technologies: Antenna, Packaging and Circuits, Wiley Press, 2009

References

1. B. Sadhu, Y. Tousi1, J. Hallin, S. Sahl, S. Reynolds, O. Renstrom, K. Sjorgren, O.Haapalahti, N. Mazor, B. Bokinge, G. Weibull, H. Bengttson, A. Carlinger, E. Westesson5, J.-E. Thillberg, L. Rexberg, X. Gu, Daniel Friedman, and A. Valdes-Garcia, "A 28GHz 32-Element Phased-Array Transceiver IC with Concurrent Dual Polarized Beams and 1.4 Degree Beam-Steering Resolution for 5G Communication", *IEEE International Solid-State Circuits Conference,* 2017.

2. X. Gu, D. Liu, C. Baks, O. Tageman, B. Sadhu, J. Hallin, L. Rexberg, and A. Valdes-Garcia, " A Multilayer Organic Package with 64 Dual-Polarized Antennas for 28GHz 5G Communication", *IEEE International Microwave Symposium*, June 2017.

3. Y. Tousi and A. Valdes-Garcia, “A Ka-band Digitally-Controlled Phase Shifter with sub-degree Phase Precision”, IEEE Radio Frequency Integrated Circuits Symposium, pp. 356-359, May 2016.

4. B. Sadhu, J. Bulzzachelli, and A. Valdes-Garcia, “A 28GHz SiGe BiCMOS phase invariant VGA”, IEEE Radio Frequency Integrated Circuits Symposium, pp. 319-322, May 2016.

To Learn More…

- IBM Presentation at IEEE 5G Summit November 2015.

  "Enabling 5G: mmWave Silicon Integration and Packaging"

  - Slides: http://www.5gsummit.org/docs/slides/Bodhisatwa-Sadhu-5GSummit-Toronto-11142015.pdf
  - Video:

    https://ieeetv.ieee.org/ieeetv-specials/toronto-5g-summit-2015-bodhisatwa-sadhu-enabling-5g-mmwave-silicon-integration-and-packaging?

- IBM presentation at IEEE 5G Summit November 2016

  "mmWave radio design for mobile handsets"

  - Video:

    https://ieeetv.ieee.org/conference-highlights/seattle-5g-mmwave-radio-design-for-mobile-handsets?

- IBM-Ericsson announcement on phased array for 5G:

  http://www-03.ibm.com/press/us/en/pressrelease/51542.wss