

# Ultra-low Power Components for a 94 GHz Transceiver

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# Low Power ICs for mm-wave Imaging



High-resolution 94 GHz imaging radar

- DARPA MFRF [1]

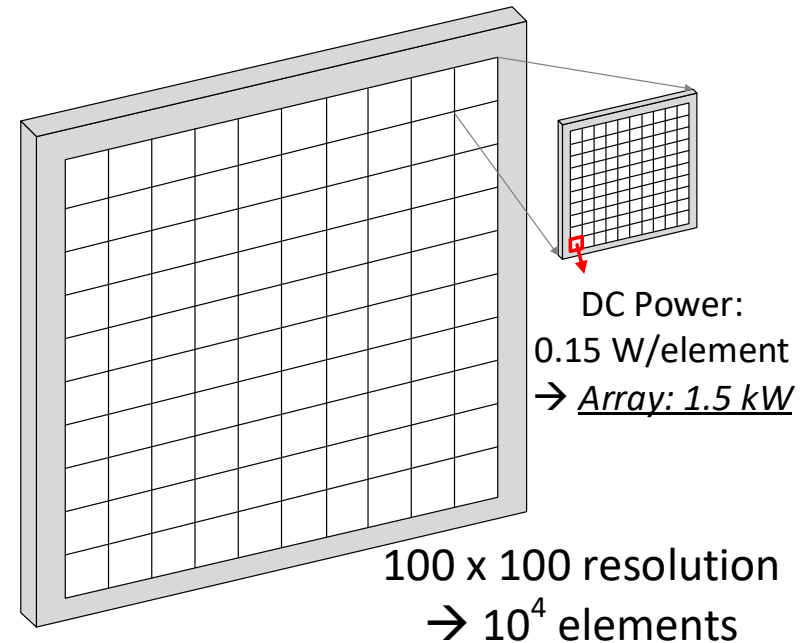
Large DC power consumption

→ Very low DC power array elements are required

Existing SiGe ICs

- 137 mW Tx, 137 mW Rx [2]

- 116 mW Tx, 160 mW Rx [3]



Ultra-low-power 94 GHz ICs:

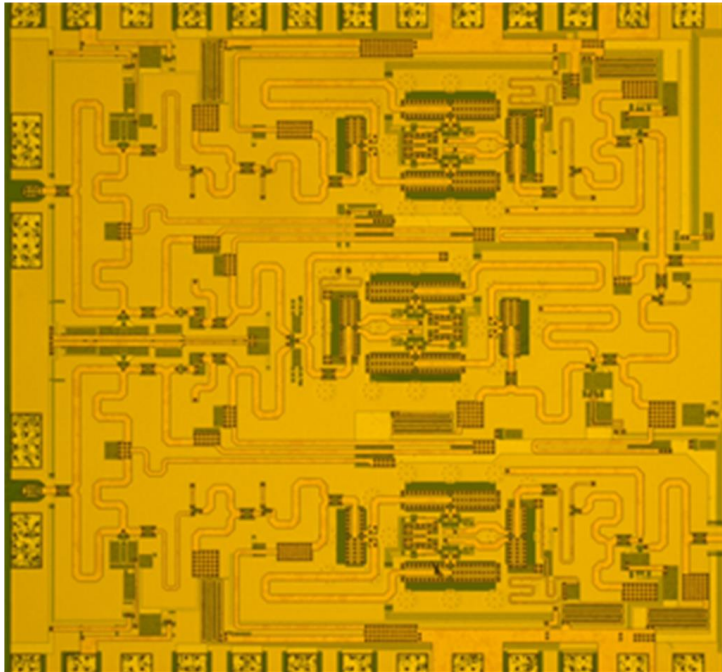
- Advanced InP HBT technology, low-power mm-wave design

[1] H. B. Wallace, *IEEE PAST 2013* (DARPA)

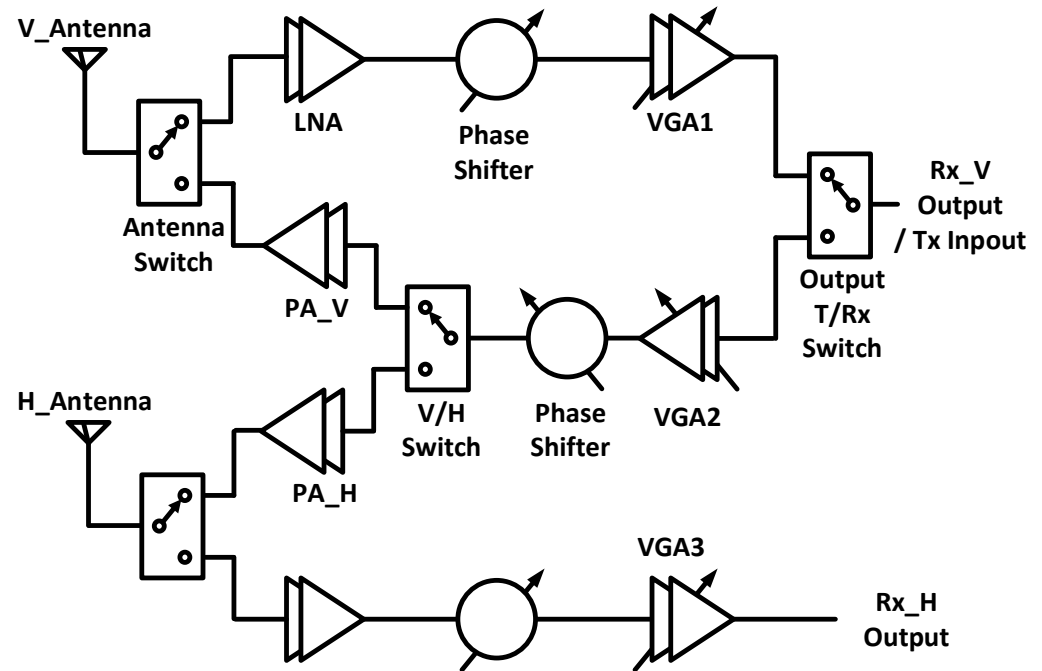
[2] F. Golcuk, et al., *IEEE Trans. Microw. Theory Tech.* (UCSD)

[3] A. Natarajan, et al., *IEEE Trans. Microw. Theory Tech.* (IBM)

# DARPA MFRF 94 GHz Array



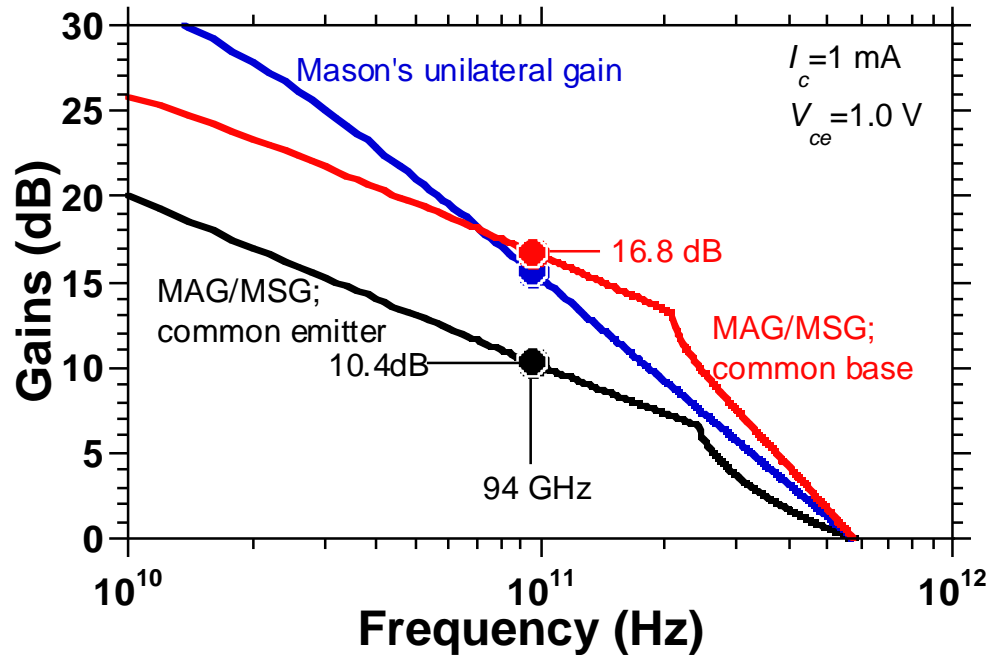
This work (InP HBT process)



DARPA dual-polarization array architecture

- Transmit either V or H polarization
- Receive both V and H polarization
- Save power: turn off the transmitter when receiving, vice-versa

# THz HBTs (Teledyne) for Low Power



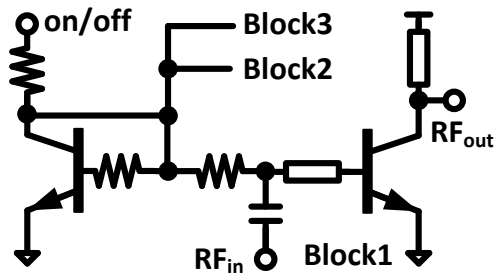
1.1 THz  $f_{\max}$  InP HBTs  $\rightarrow$  high gain per stage with low power

Low-power (1 V, 1 mA) bias,  $0.13 \times 3 \mu\text{m}^2$  HBT

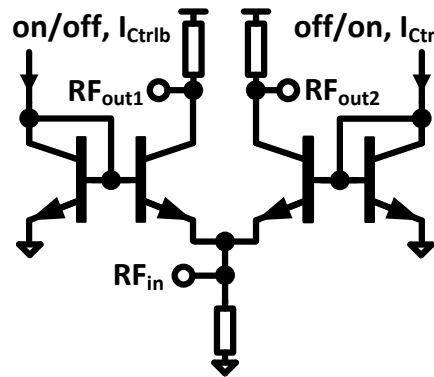
- 16.8 dB common base @ 1 mW DC  $\rightarrow$  16.8 dB/mW

- 10.4 dB common emitter @ 1 mW DC  $\rightarrow$  10.4 dB/mW

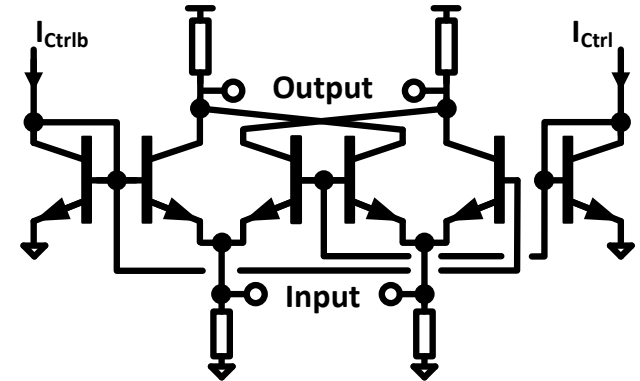
# Current Mirror Based Design



biasing



Controlling gain & switching



In the individual block:

Current mirror used for biasing, switching on/off, controlling gain

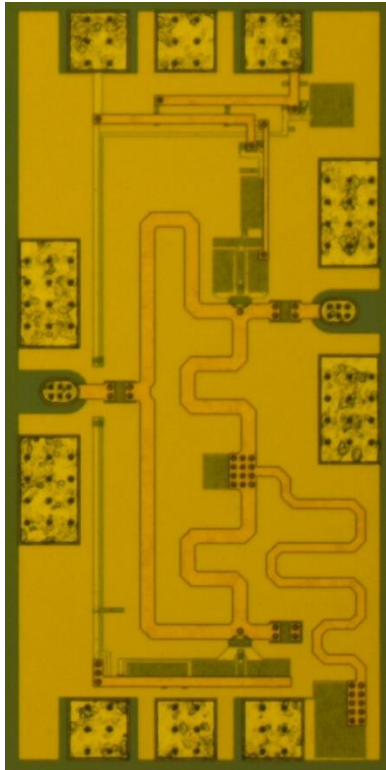
In the transceiver:

A mirror reference shared between several blocks: save power

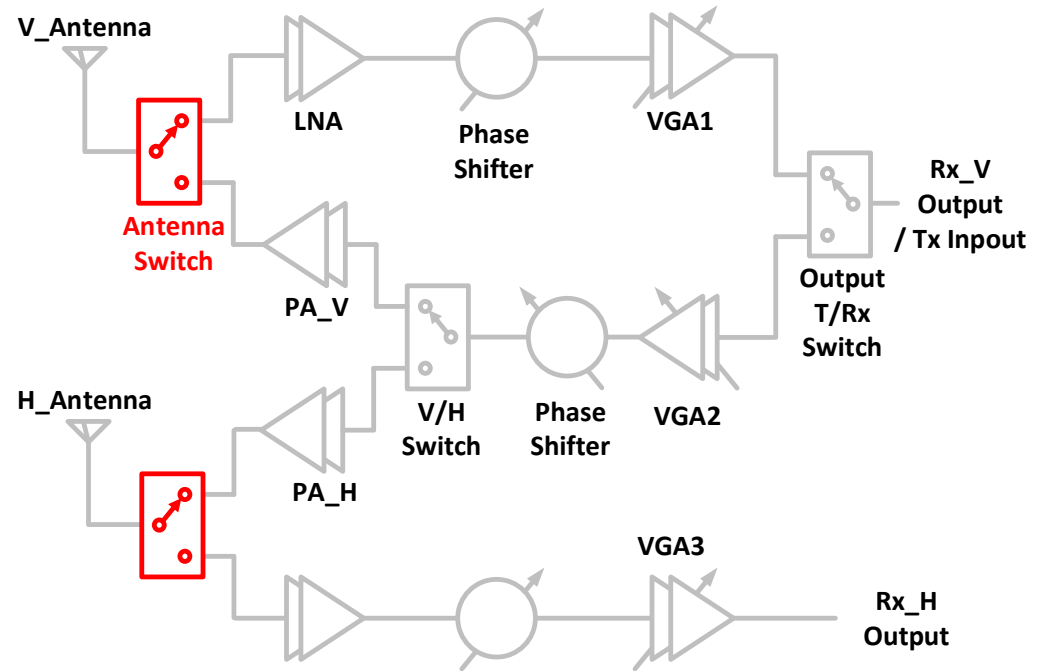
The mirror reference *is* the on/off switch for Tx/Rx modes and V/H polarizations

**Mirror-based designs: low voltage, low current → low power**

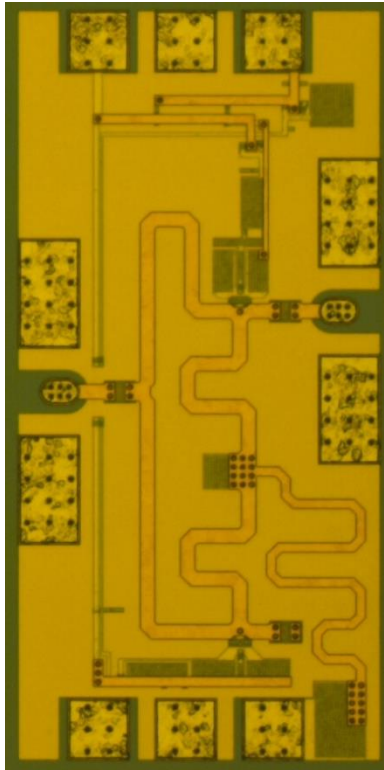
# Antenna Switch



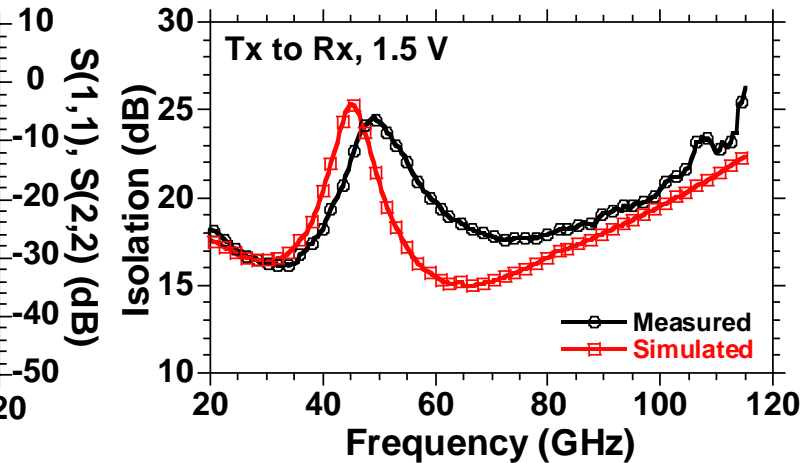
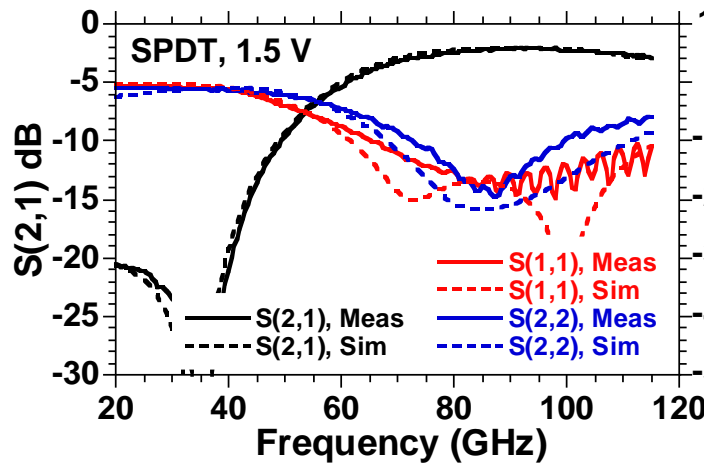
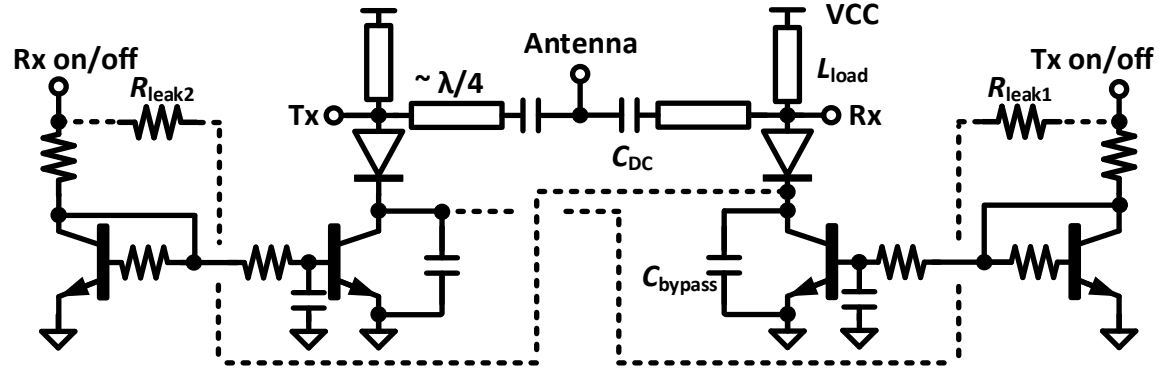
Size: 420 um x 860 um



# Antenna Switch



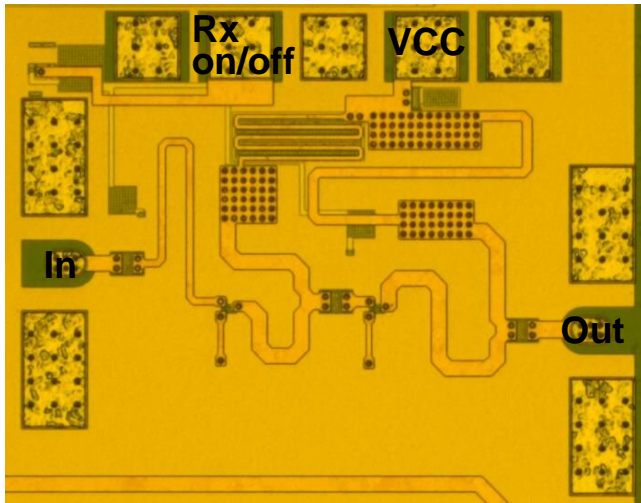
Size: 420  $\mu\text{m}$  x 860  $\mu\text{m}$



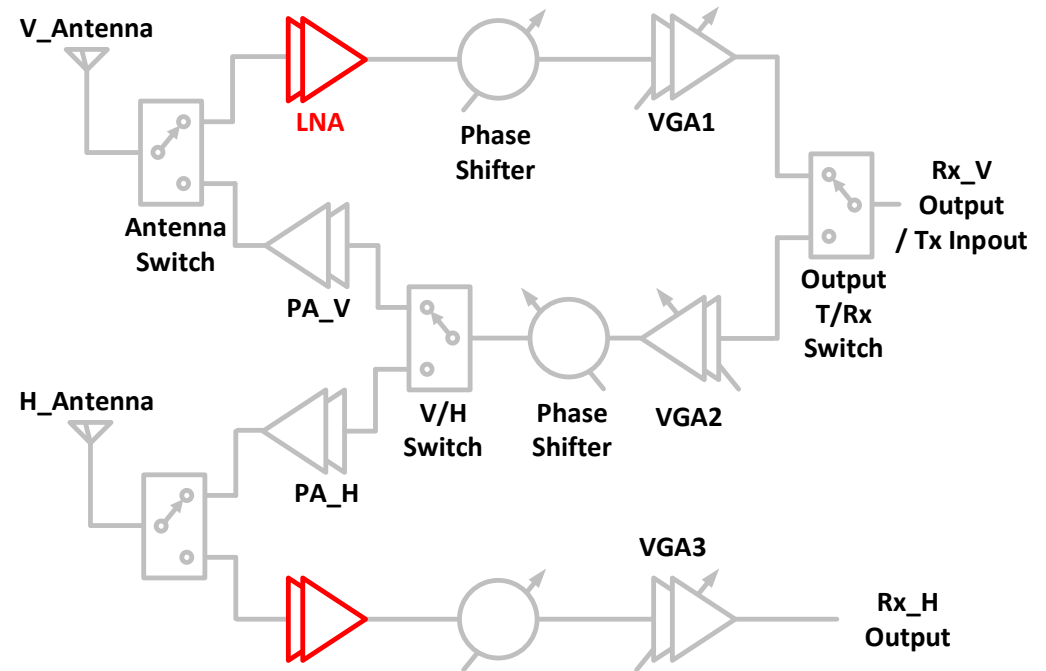
Switches between TRx

2 dB insertion loss, 19 dB isolation, 4.8 mW DC power (3.2 mA @ 1.5 V)

# Low Noise Amplifier (LNA)

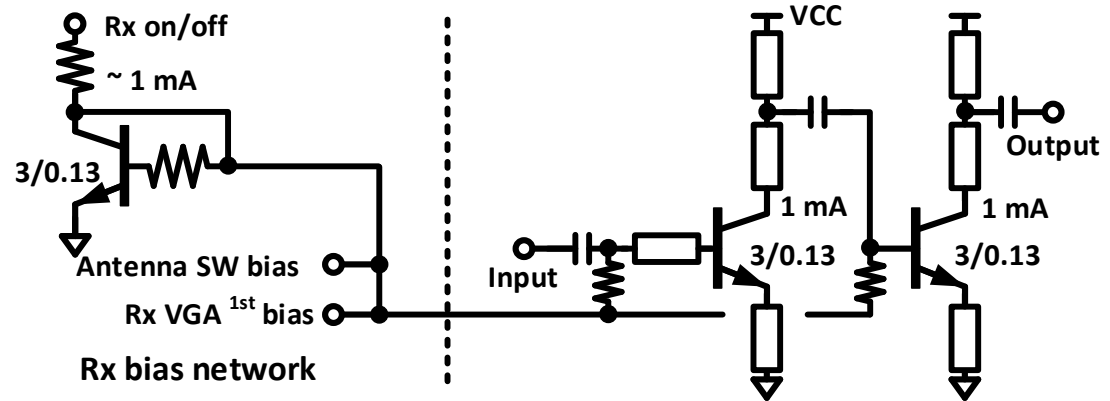
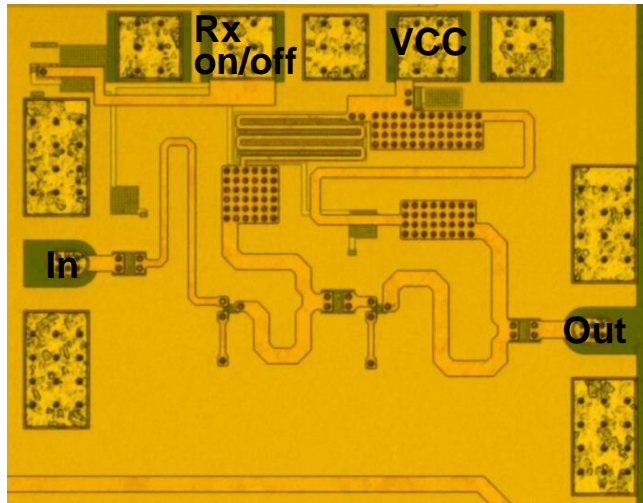


Size: 660 um x 510 um

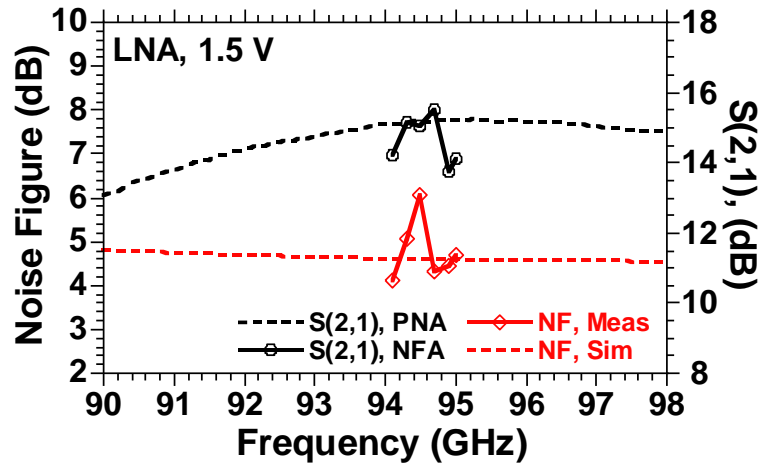
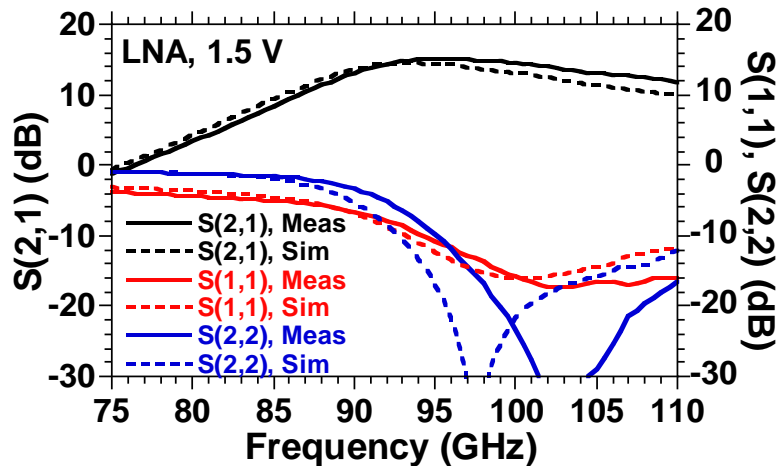




# Low Noise Amplifier (LNA)

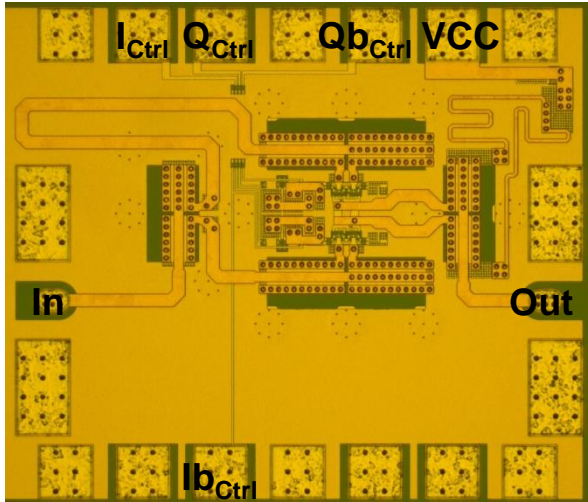


Size: 660 um x 510 um

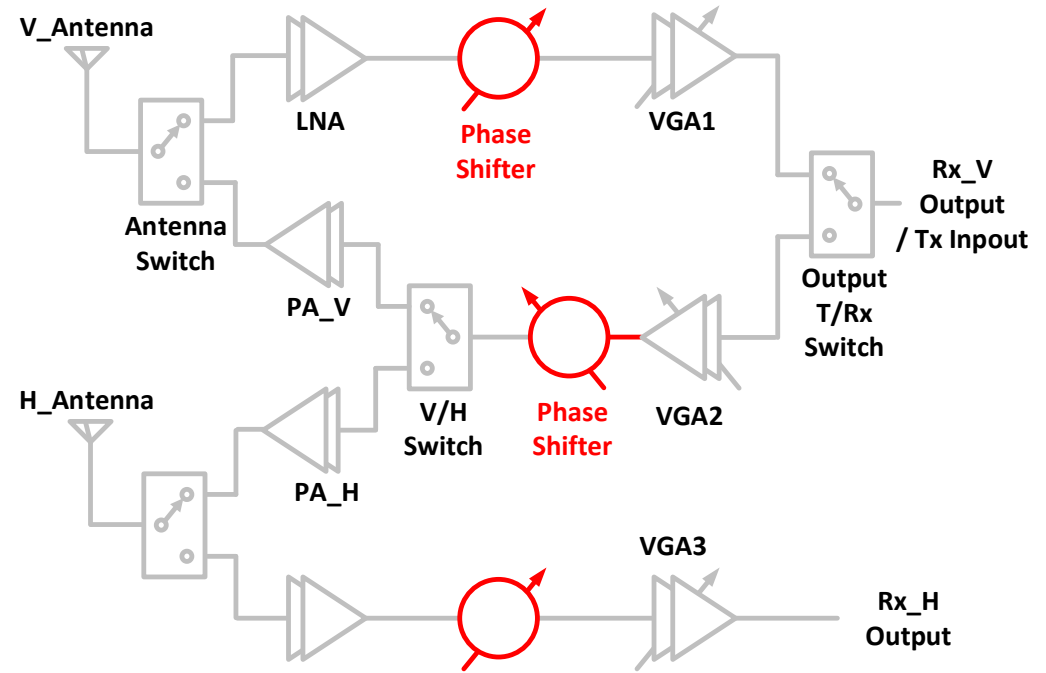


Two-stage CE amplifier biased by a current mirror  
 15.1 dB gain, NF < 6 dB, 3.5 mW DC power (2.3 mA @ 1.5 V)

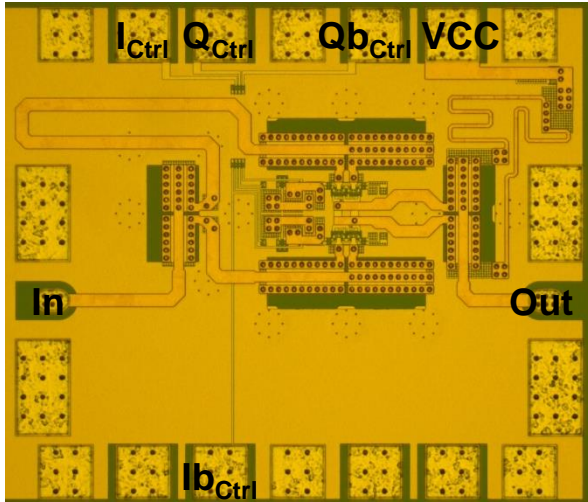
# Phase Shifter



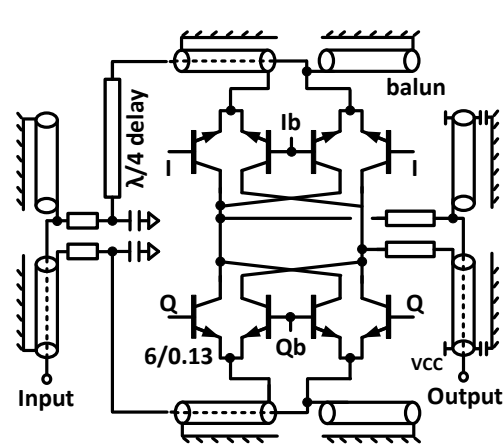
Size: 760 um x 640 um



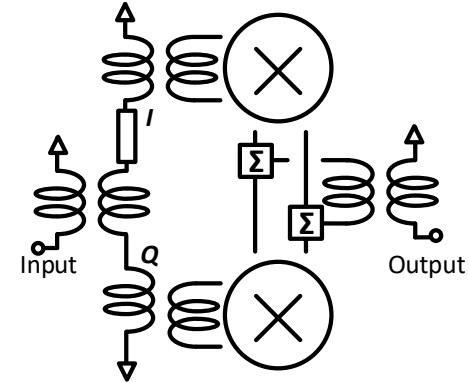
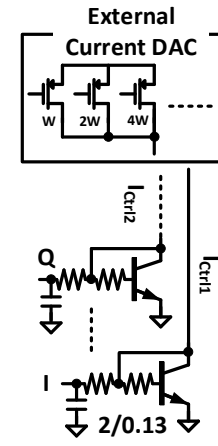
# Phase Shifter



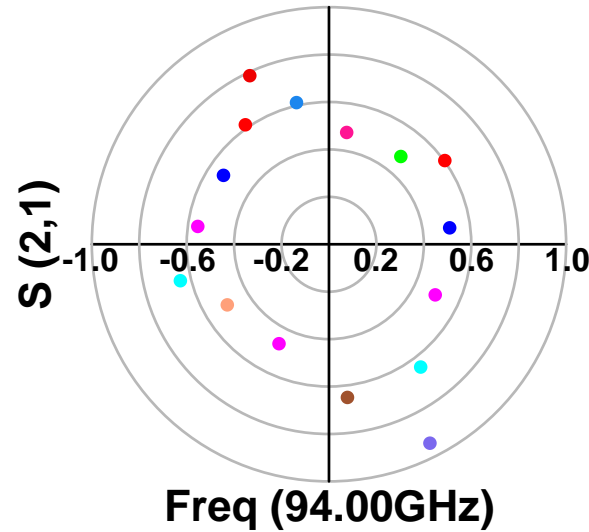
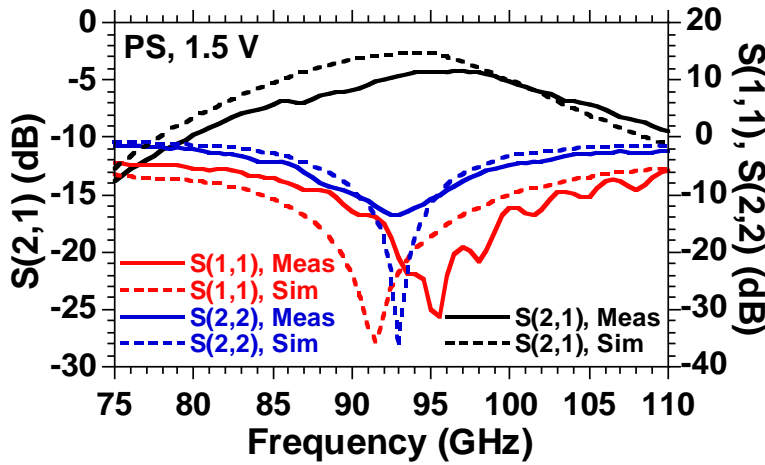
Size: 760  $\mu\text{m}$  x 640  $\mu\text{m}$



Sub-quarter wavelength balun<sup>[1]</sup>



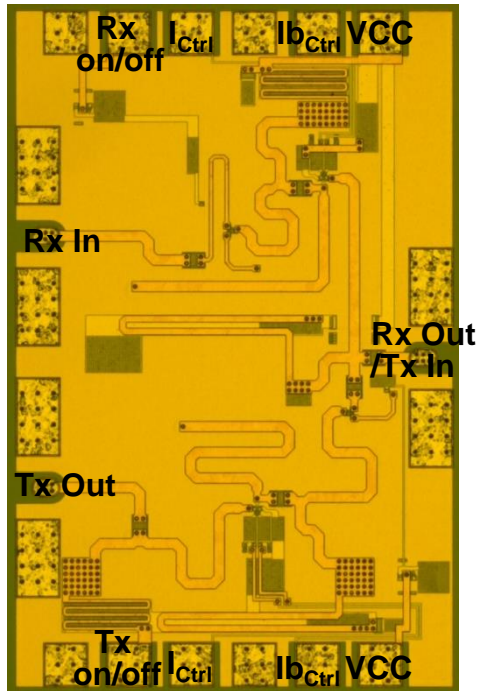
Block diagram



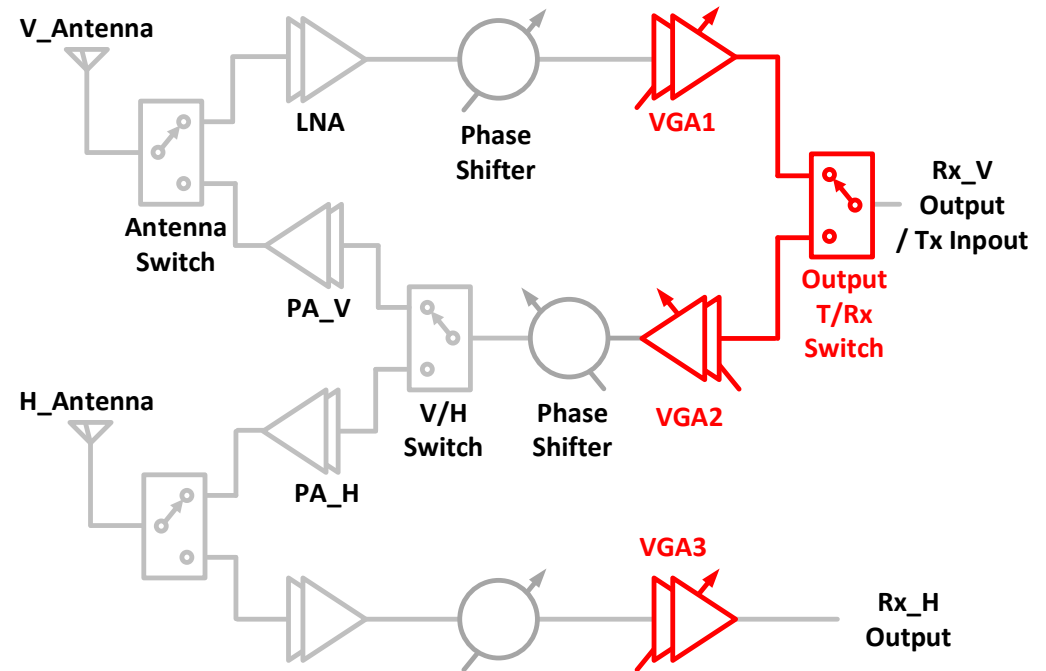
[1] H. Park, et al.,  
*IEEE J. Solid-State Circuits*  
(UCSB)

Active phase shifter controlled by current mirrors  $\rightarrow$  Current DACs  
3-7 dB loss,  $360^\circ$  phase shift, 6.5 mW DC power (4.3 mA @ 1.5 V)

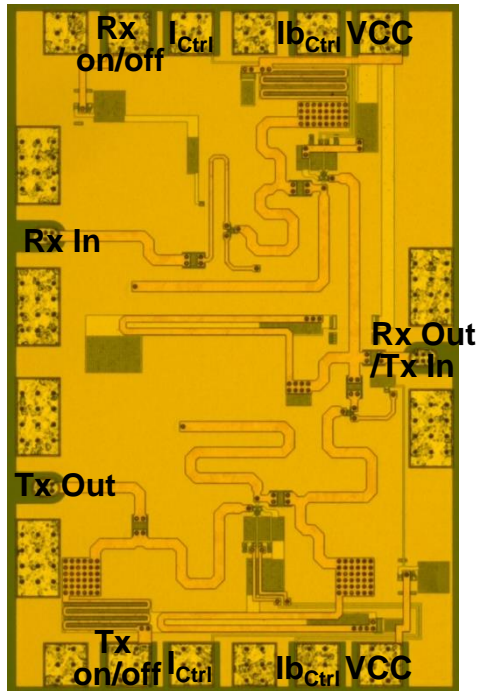
# Variable Gain Amplifier (VGA)



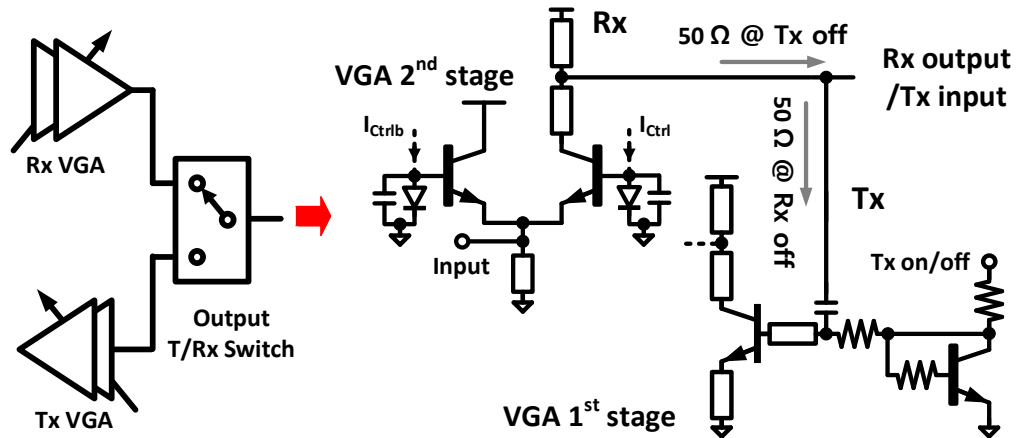
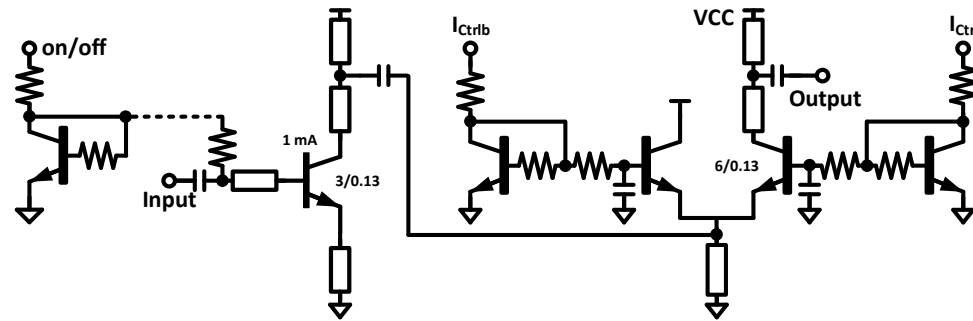
Size: 700 um x 1080 um



# Variable Gain Amplifier (VGA)



Size: 700  $\mu\text{m}$  x 1080  $\mu\text{m}$

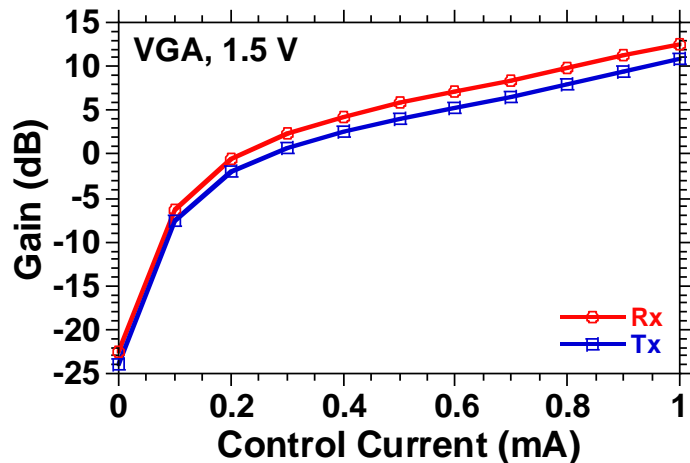
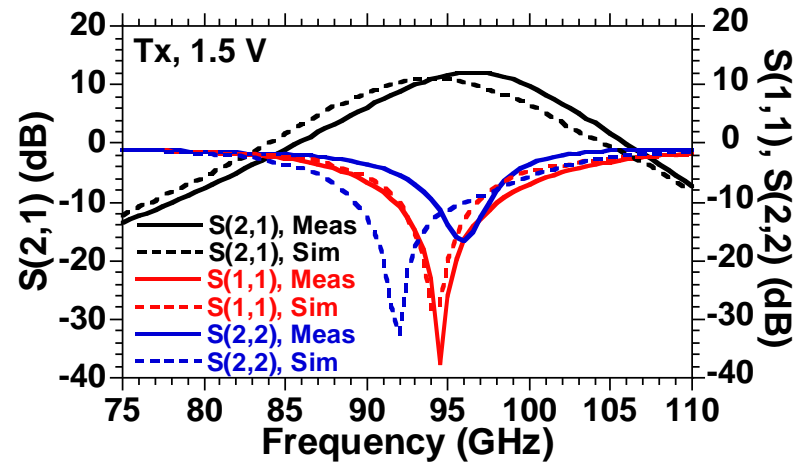
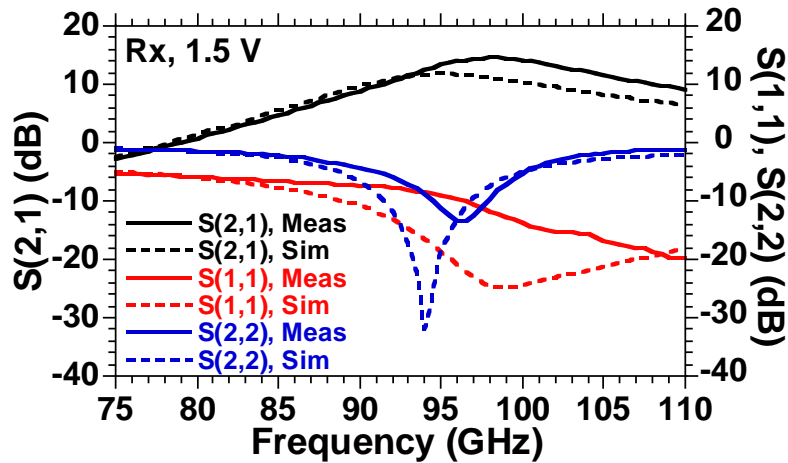


Gain is controlled by current mirrors

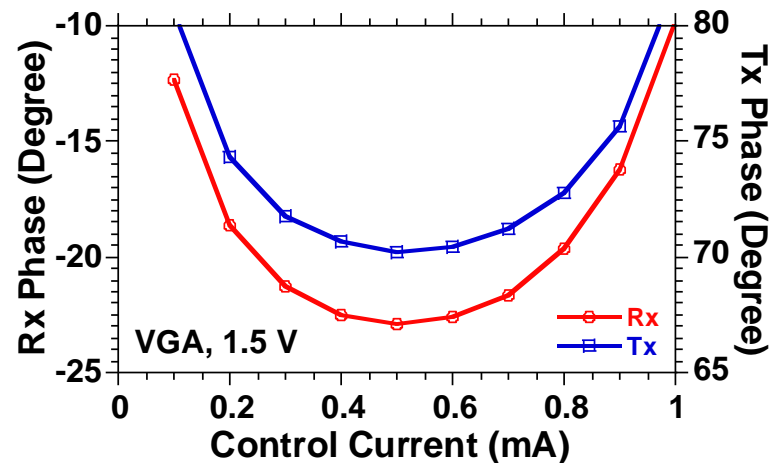
Tx or Rx modes are selected by tuning the appropriate stages on and off.

The RF port impedance remains 50  $\Omega$

# VGA Measurements



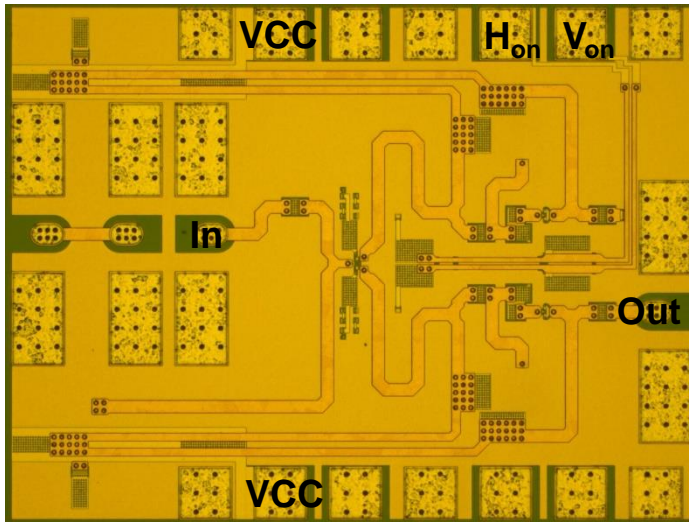
7 mW DC power (4.7 mA @ 1.5 V)  
12.5 dB gain



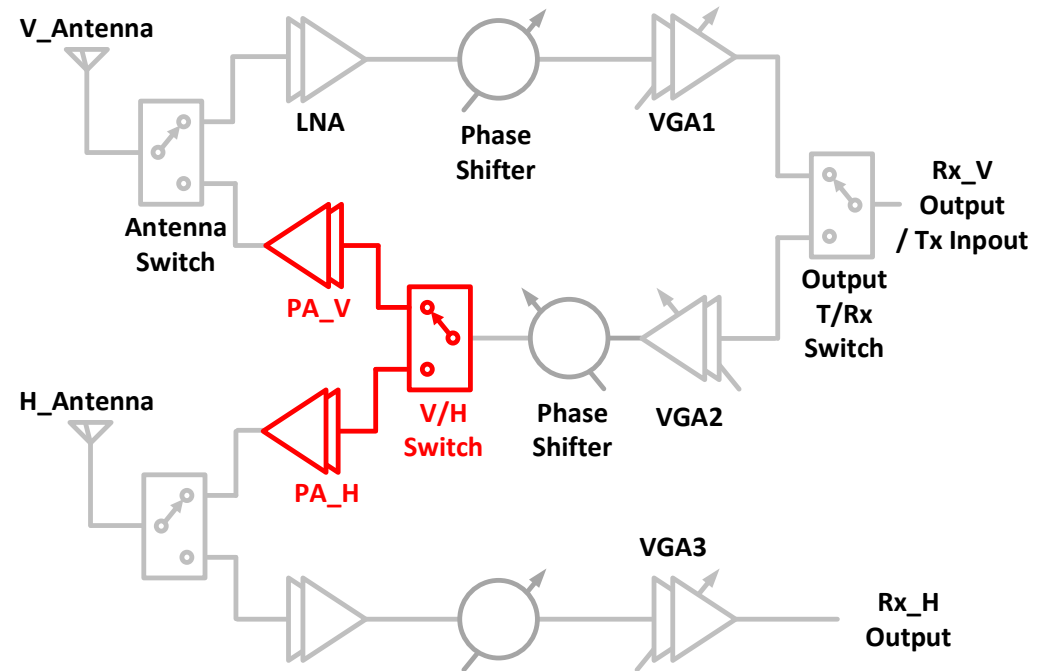
7 mW DC power (4.7 mA @ 1.5 V)  
10.9 dB gain

*\*at the maximum gain settings.*

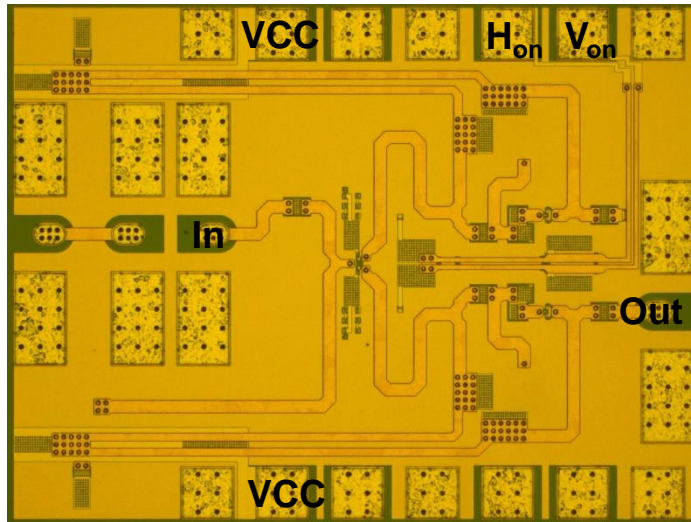
# Power Amplifier (PA)



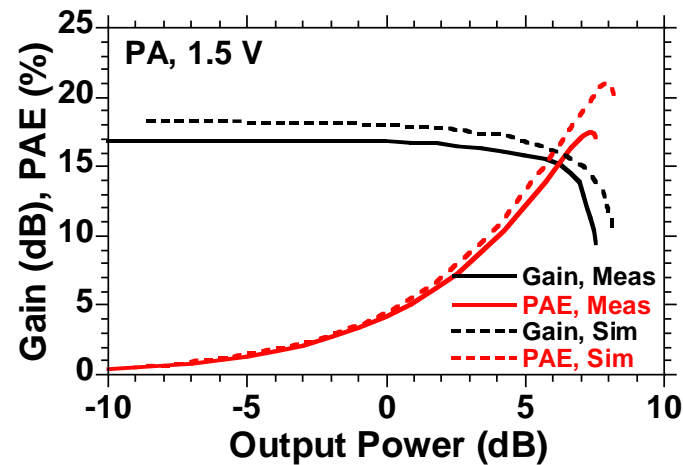
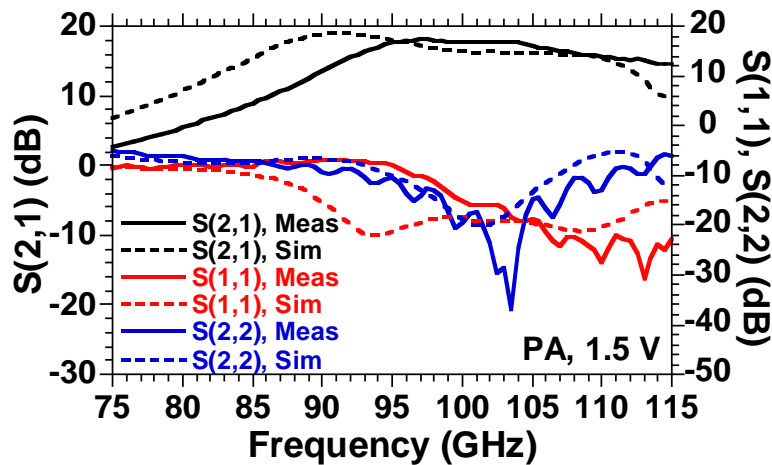
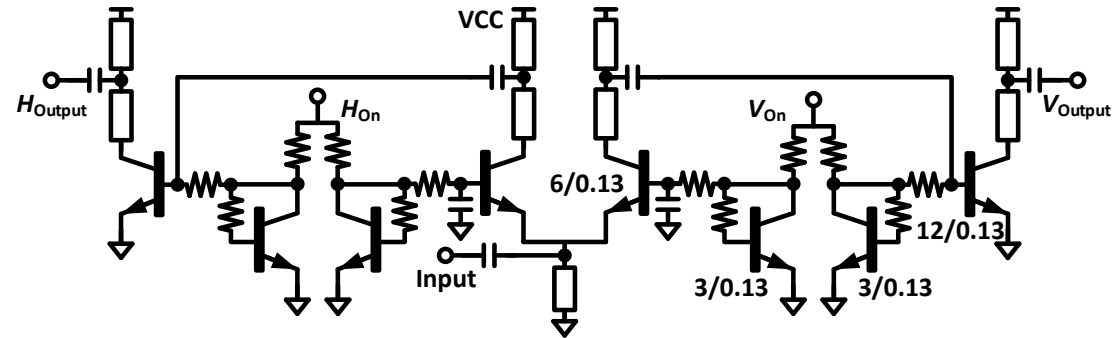
Size: 910 um x 680 um



# Power Amplifier (PA)



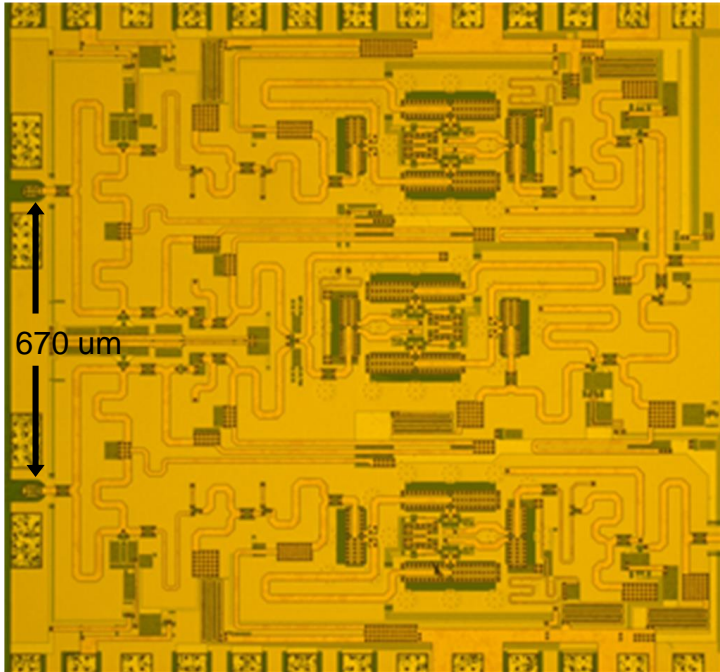
Size: 910  $\mu\text{m}$  x 680  $\mu\text{m}$



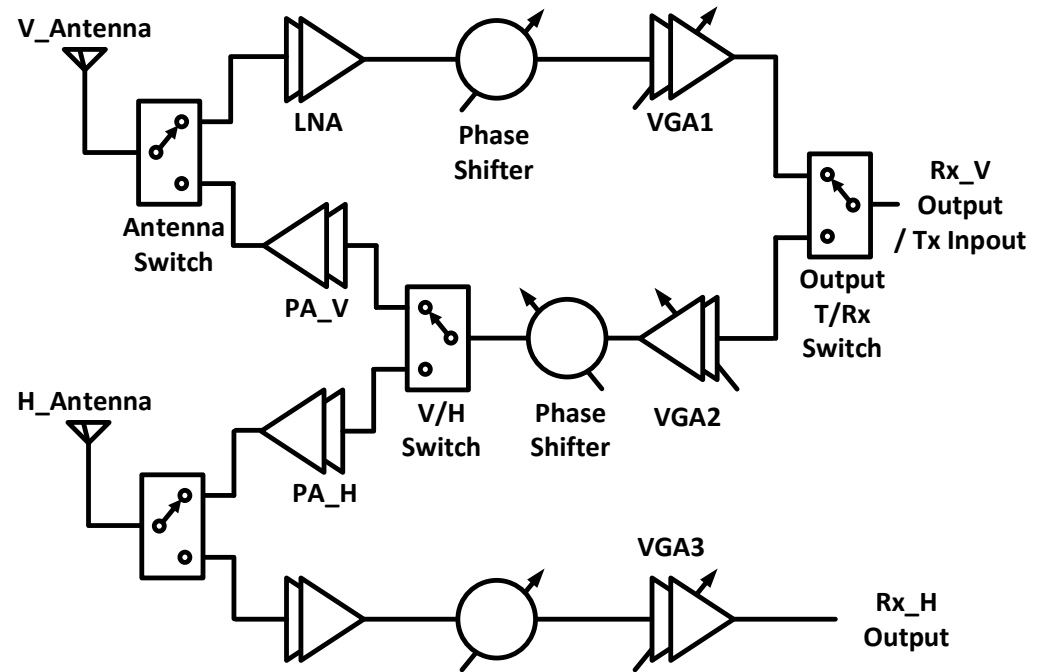
CB preamplifier with V and H polarization outputs switched by current mirrors  
 17 dB gain,  $P_{\text{sat}}$  7 dBm, PAE: 17 %, 22.5 mW DC power (15 mA @ 1.5 V)



# Transceiver



Size: 1770 um x 1550 um



Transmit either V or H polarization

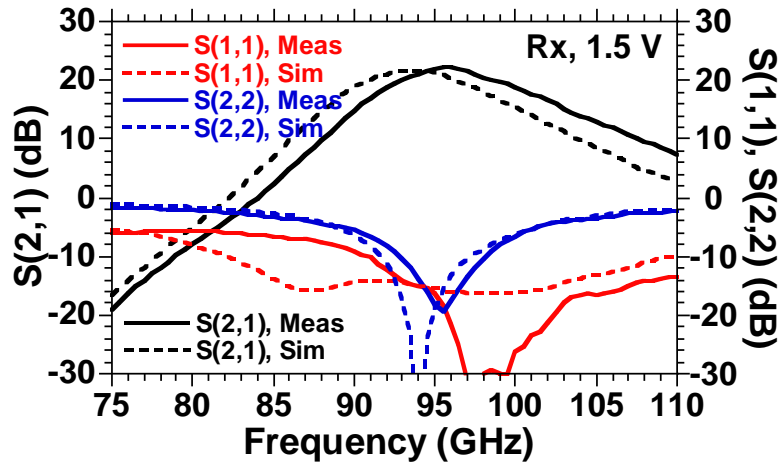
Receive both V and H polarization

A current mirror bias is shared between several blocks

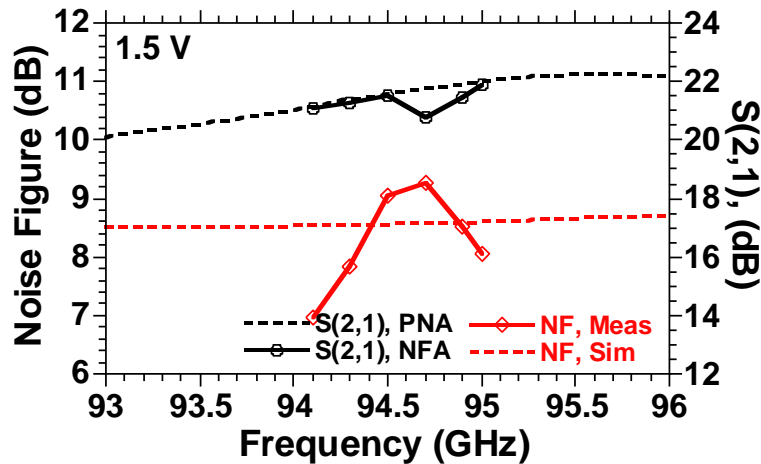
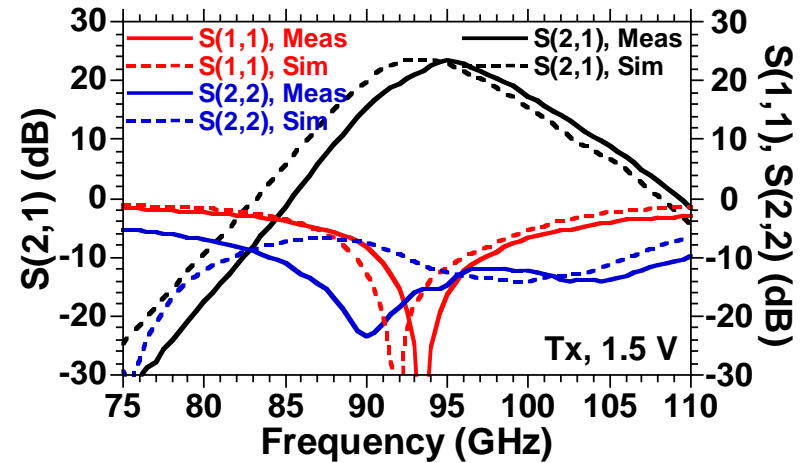
Mirrors are the on/off switch for Tx/Rx modes and V/H polarizations

# Transceiver Measurements

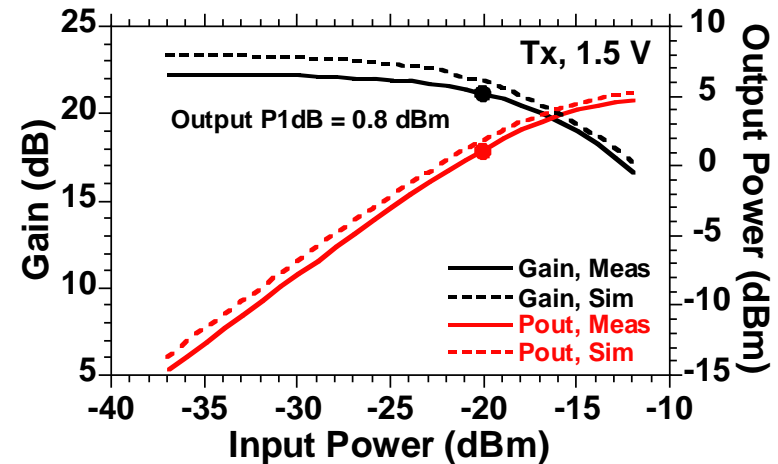
Receiver (V & H)



Transmitter (V or H)



39 mW DC power (26 mA @ 1.5 V)  
 Gain: 21 dB (V), 22 dB (H)  
 NF < 9.3 dB



40 mW DC power (26.5 mA @ 1.5 V)  
 Gain: 22.2 dB  
 $P_{\text{sat}}$ : 5 dBm

# Comparison

Single-channel	[1] SiGe	[2] SiGe	This Work, InP (1.5 V)	This Work, InP (1 V)
Frequency (GHz)	90-102	88-96	92-98	
Architecture	TRx	TRx	TRx	
Rx Gain (dB)	22-25	30	21	22
Rx NF (dB)	9 (excl. T/R switch)	8.5	< 9.3	< 8.9
Tx Gain (dB)	13	> 25	22	22
Tx Psat (dBm)	-5	>2	5	1.4
Tx DC Power	137 mW (1 Tx)	116 mW (1 Tx)	40 mW (1 Tx)	29 mW (1 Tx)
Rx DC Power	137 mW (2 Rx)	160 mW (2 Rx)	39 mW (2 Rx)	26 mW (2 Rx)
Area	1.9 mm <sup>2</sup> 2 Tx, 2 Rx	1.9 mm <sup>2</sup> 2 Tx, 2 Rx	2.7 mm <sup>2</sup> 2 Tx, 2 Rx (incl. pads)	
Technology f <sub>T</sub> , f <sub>max</sub> (GHz)	SiGe BiCMOS 200/270	SiGe BiCMOS 200/270	InP HBT 520/1100	

*\*ICs are biased with 1.5 V or 1.0 V supply, and with a 1.5 V mirror reference supply*

[1] F. Golcuk, et al., *IEEE Trans. Microw. Theory Tech.* (UCSD)

[2] A. Natarajan, et al., *IEEE Trans. Microw. Theory Tech.* (IBM)

# Ultra-Low Power Array Components



Ultra low power components and a transceiver  
for a 94 GHz dual-polarization phased-array

NF < 9.3 dB,  $P_{\text{sat}} > 1.4$  dBm with low DC power

1.5 V bias: **40 mW** receiver (V & H), **39 mW** transmitter (V or H),

1.0 V bias: **29 mW** receiver (V & H), **26 mW** transmitter (V or H)

Low power by:

1.1 THz InP HBTs

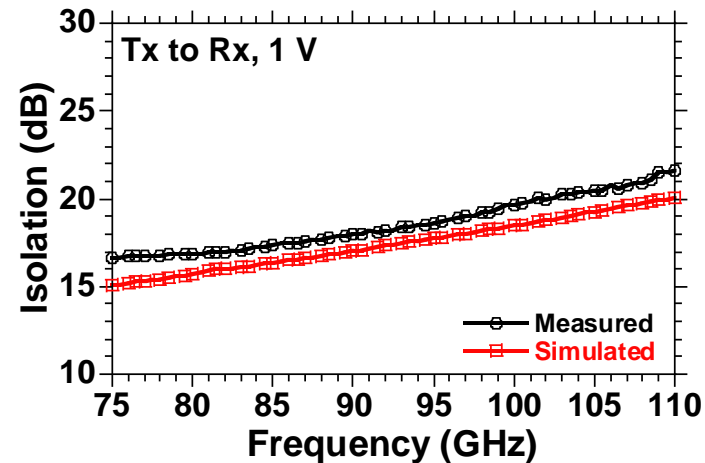
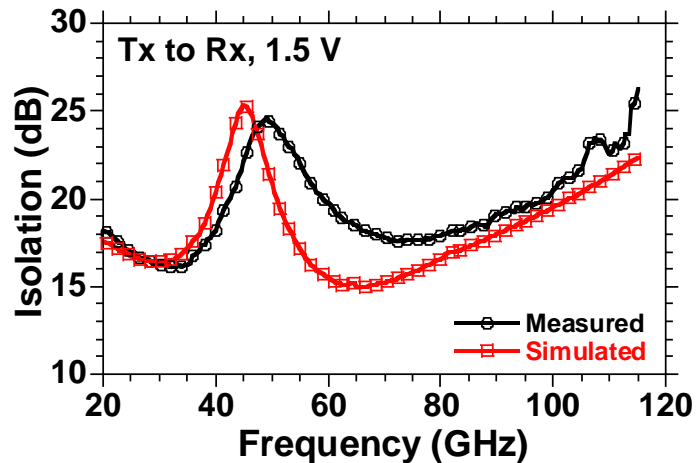
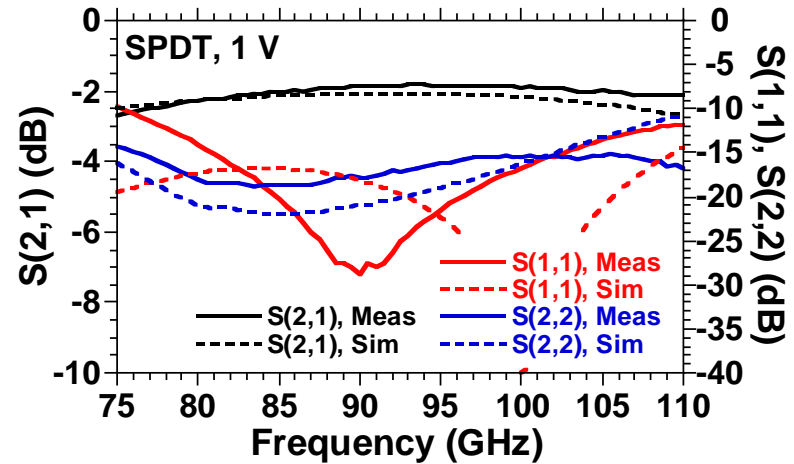
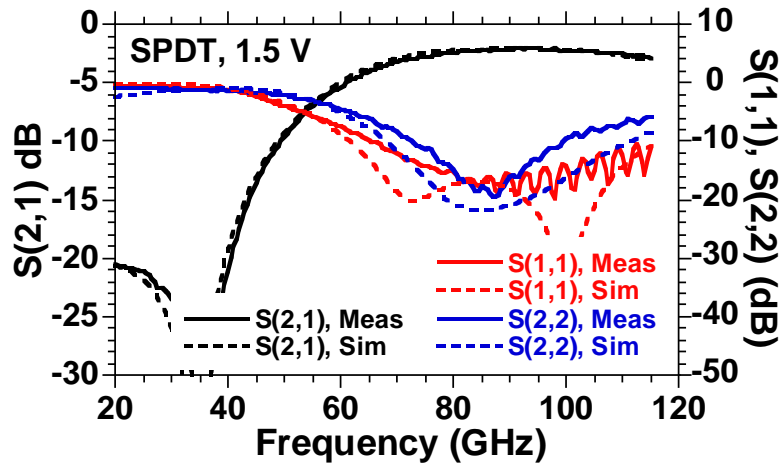
Current-mirror-based mm-wave IC design

We thank Teledyne Scientific & Imaging for IC fabrication.

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**Thank you**

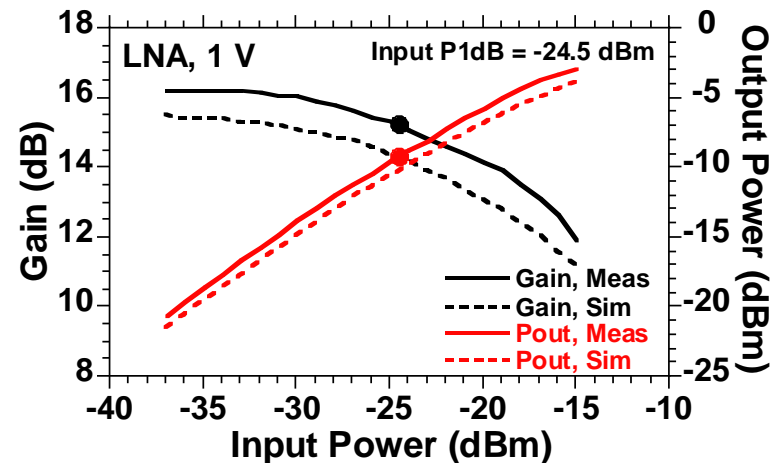
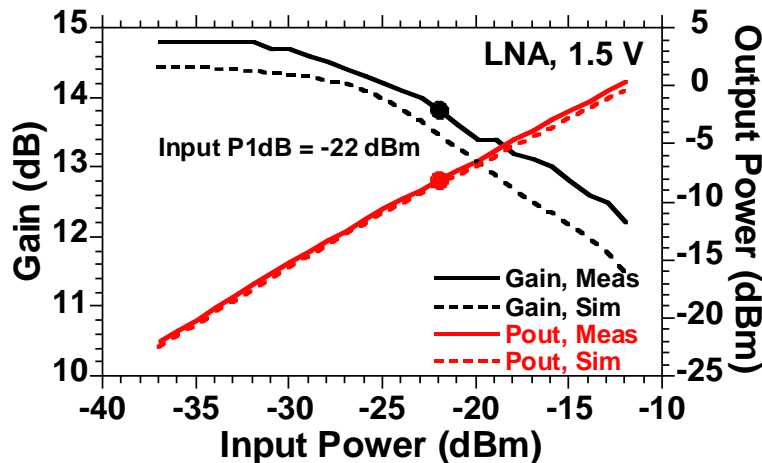
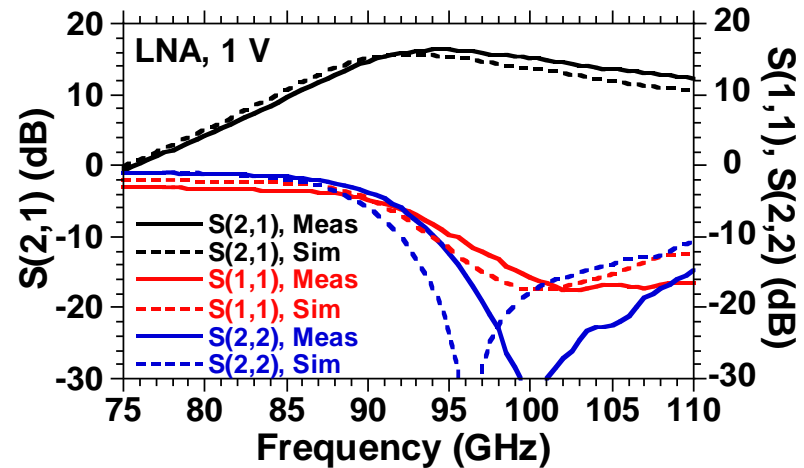
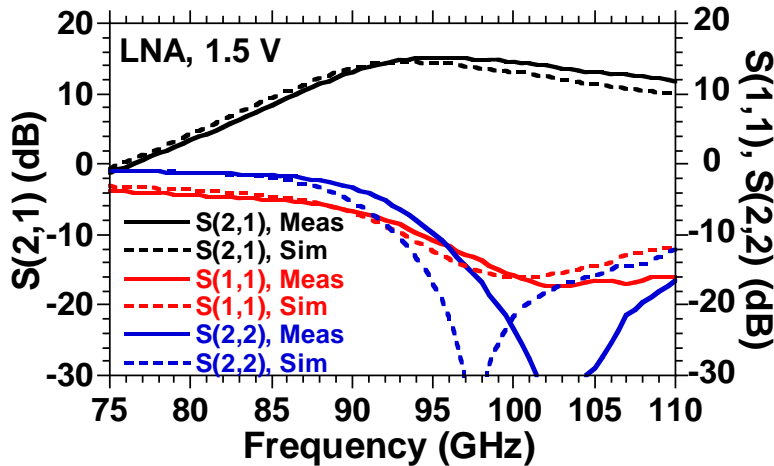
# Antenna Switch Measurements



Power consumption: 3.2 mA @ 1.5 V  
 Insertion loss: 2 dB  
 Isolation: 19 dB @ 94 GHz

Power consumption: 2.8 mA @ 1 V  
 Insertion loss: 1.8 dB  
 Isolation: 18.5 dB @ 94 GHz

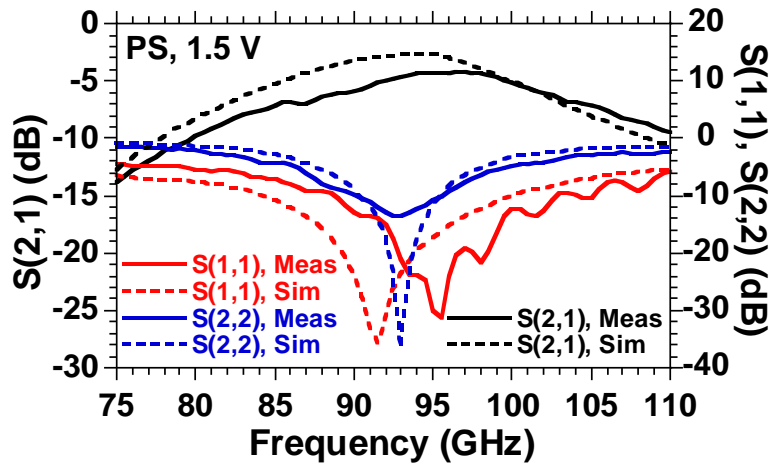
# LNA Measurements



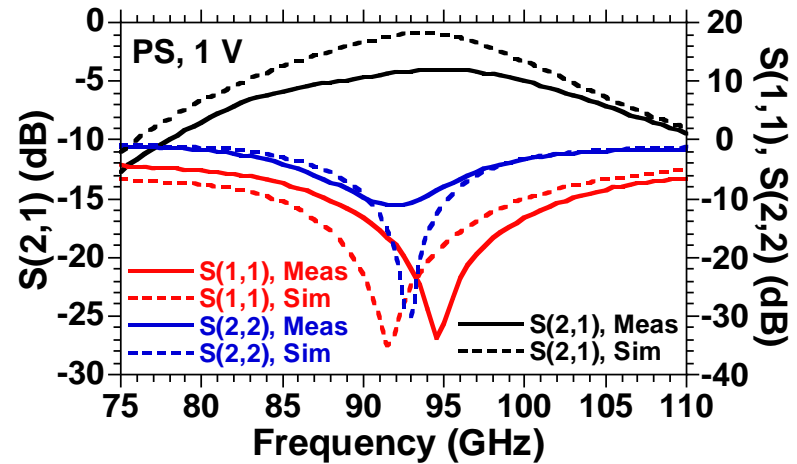
Power consumption: 2.3 mA @ 1.5 V  
 Gain: 15.1 dB @ 94 GHz  
 Peak gain: 15.2 @ 95 GHz

Power consumption: 2.0 mA @ 1 V  
 Gain: 16.3 dB @ 94 GHz (peak gain)

# Phase Shifter Measurements



Power consumption: 4.3 mA @ 1.5 V

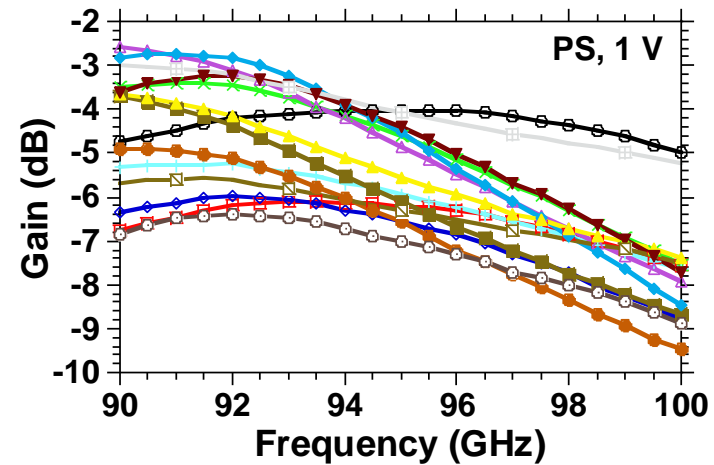
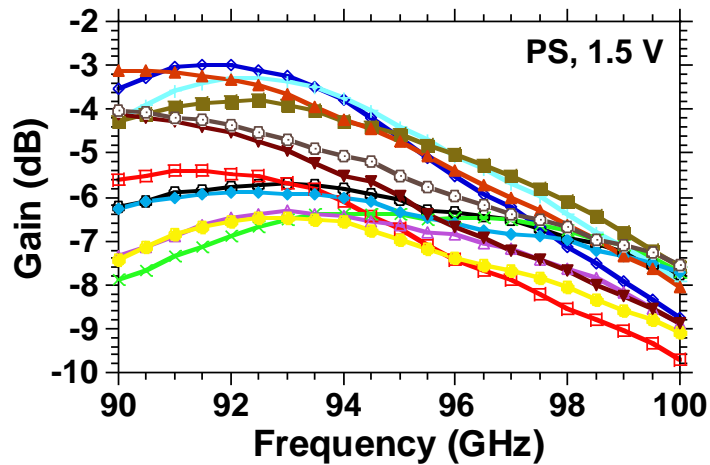
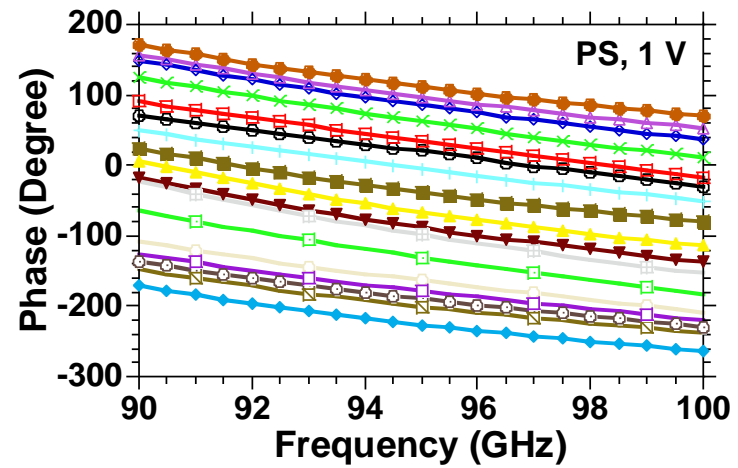
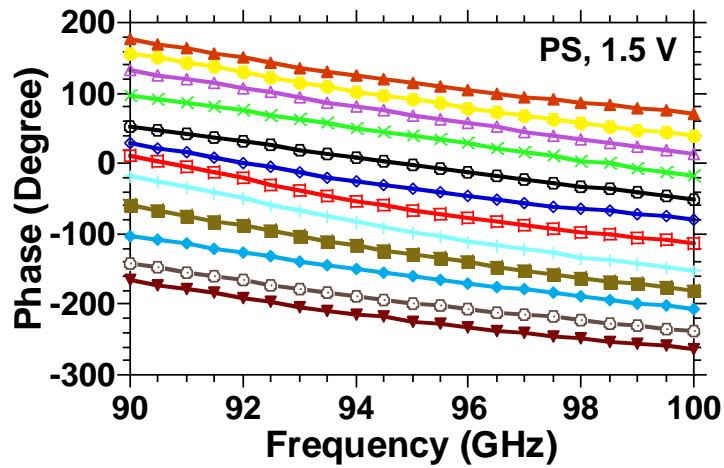


*\* $I_{Ctrl} = 0$  mA,  $Q_{Ctrl} = 0$  mA*

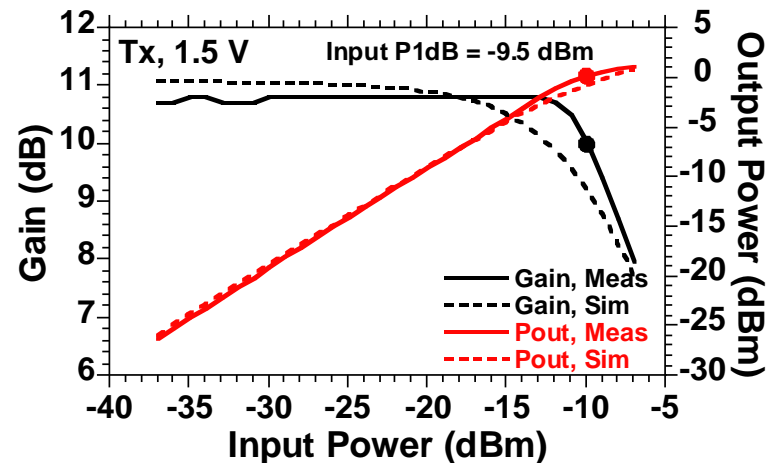
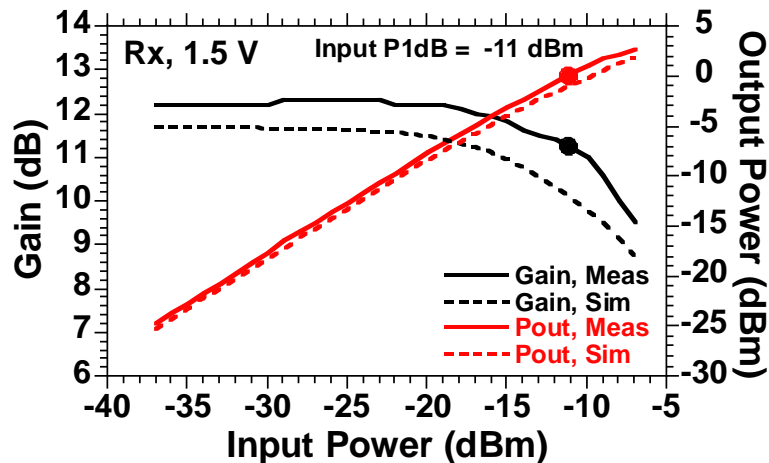
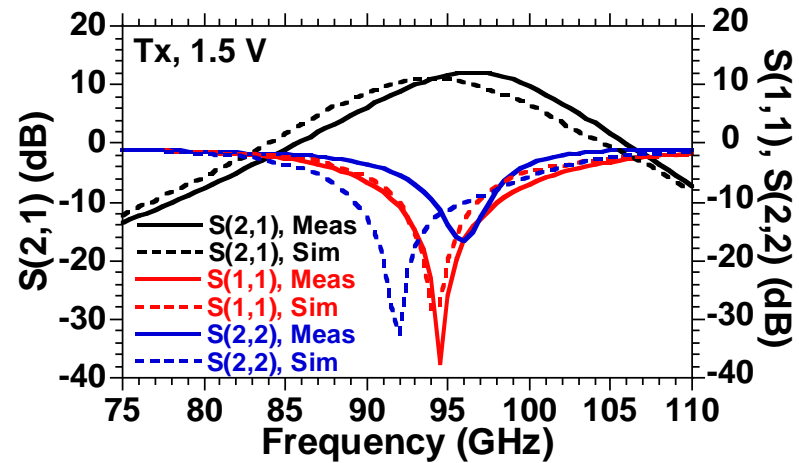
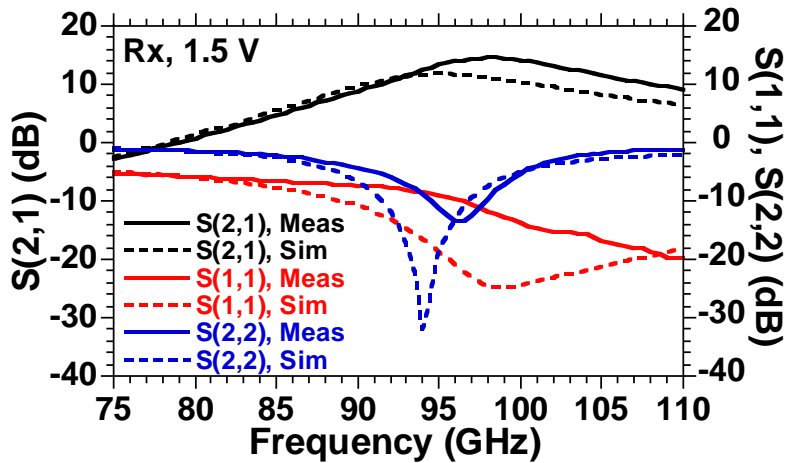
Power consumption: 4.2 mA @ 1 V



# Phase Shifter Measurements



# VGA Measurements

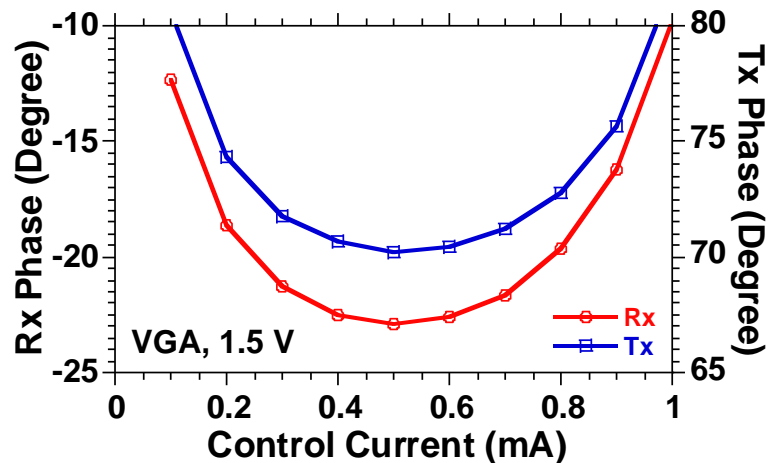
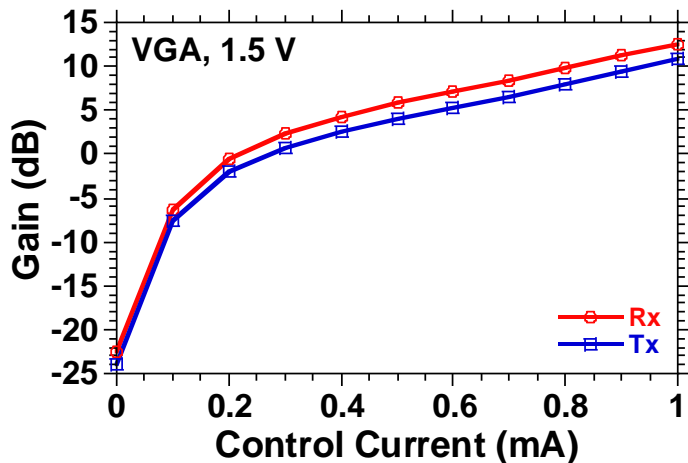
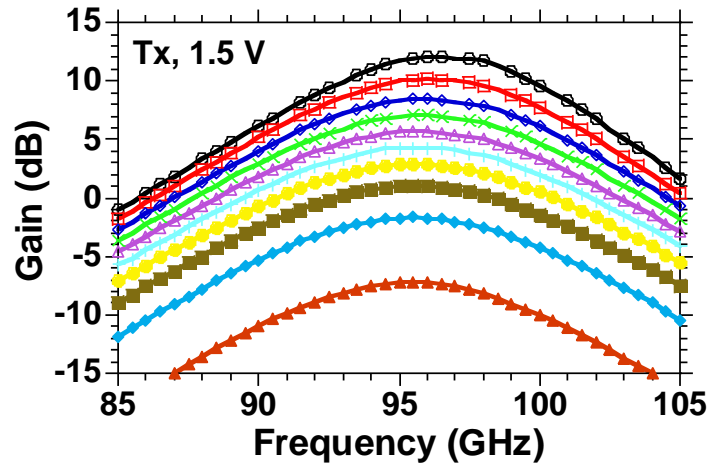
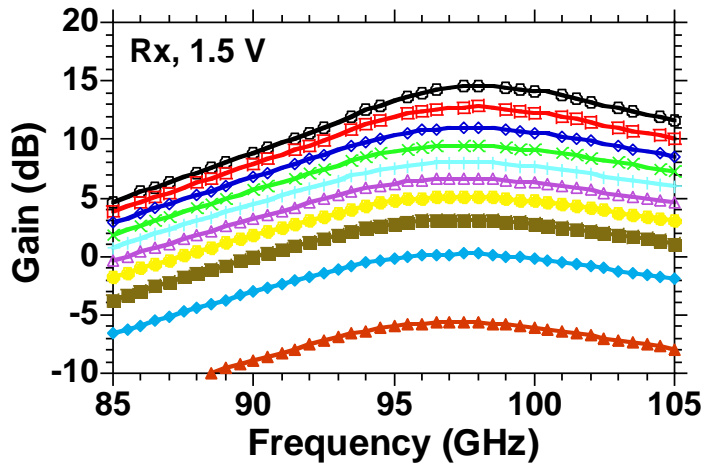


Power consumption: 4.7 mA @ 1.5 V  
 Gain: 12.5 dB @ 94 GHz  
 Peak gain: 14.6 @ 98 GHz

Gain: 10.9 dB @ 94 GHz  
 Peak gain: 12.1 dB @ 96 GHz

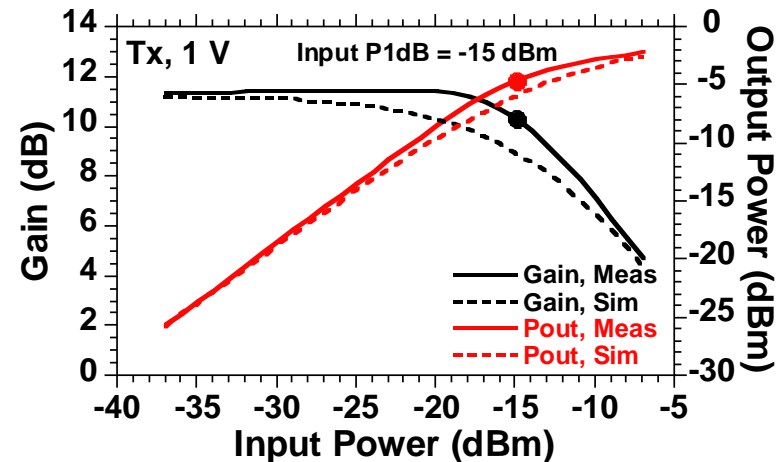
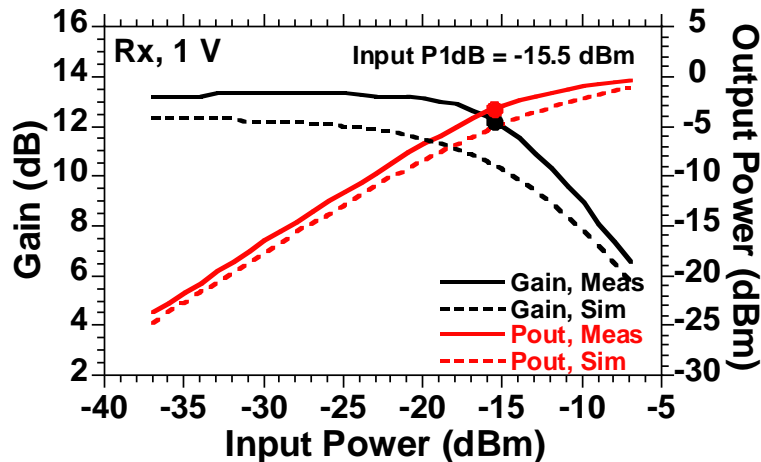
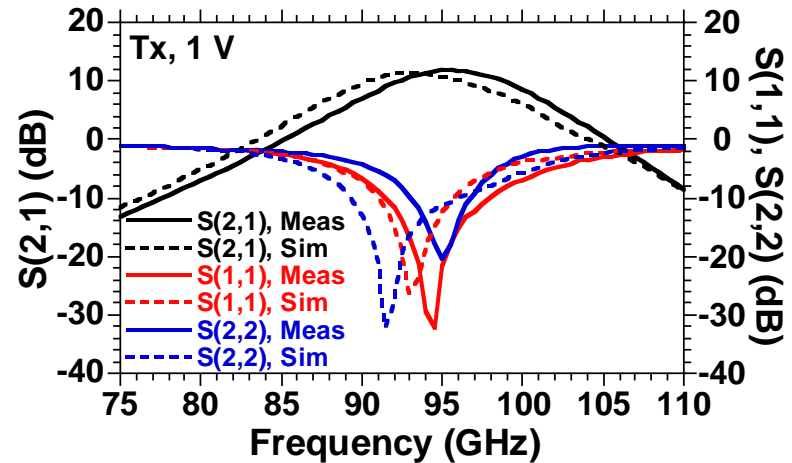
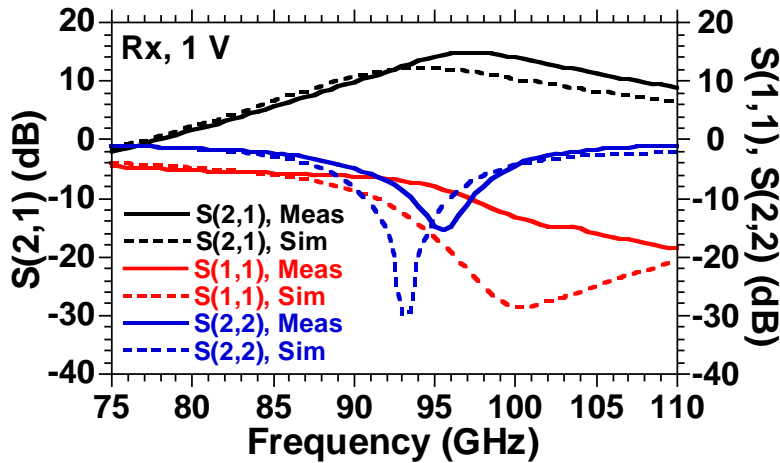
*\*at the maximum gain settings.*

# VGA Measurements



Over 7 dB gain adjustment (control current: 0.3-0.8 mA) with an associated 2 degrees the phase shift

# VGA Measurements

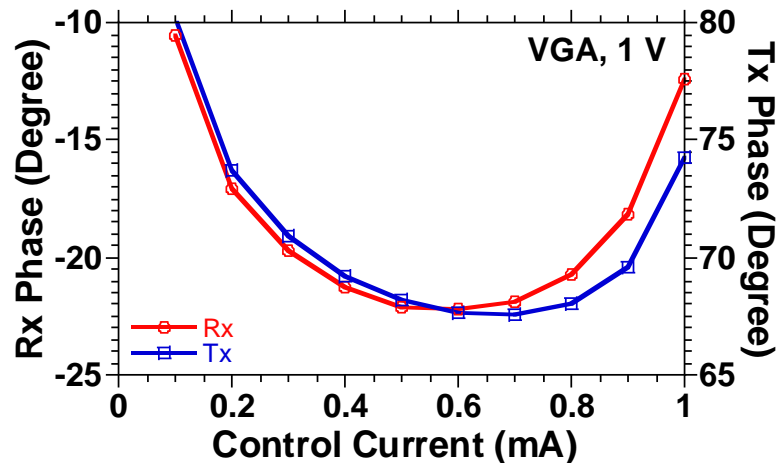
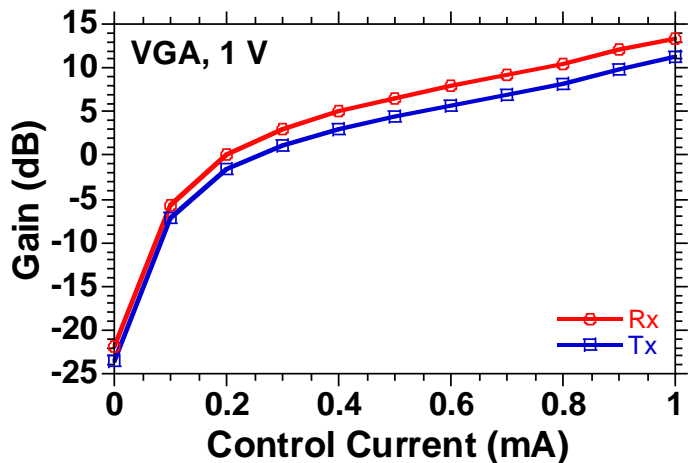
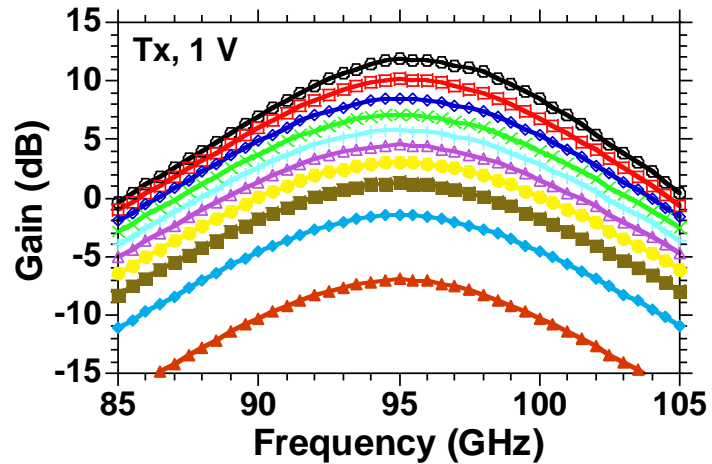
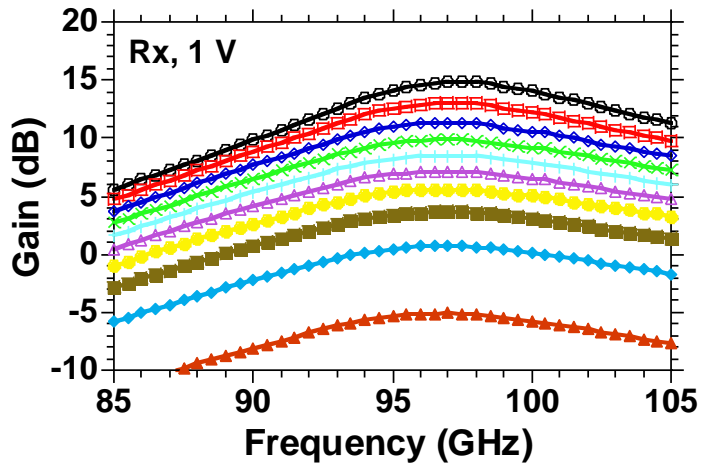


Power consumption: 4.6 mA @ 1.5 V  
 Gain: 13.4 dB @ 94 GHz  
 Peak gain: 14.9 @ 97 GHz

Gain: 11.4 dB @ 94 GHz  
 Peak gain: 11.8 dB @ 95 GHz

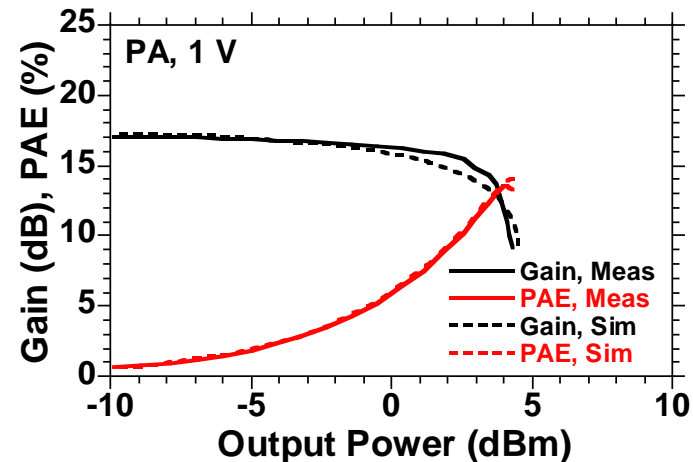
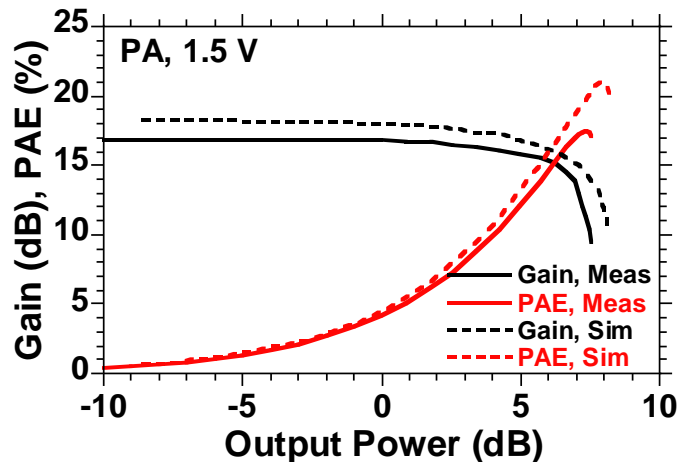
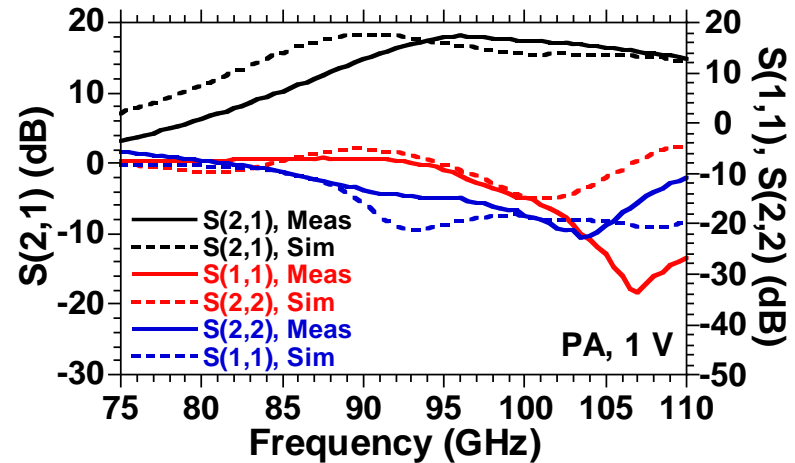
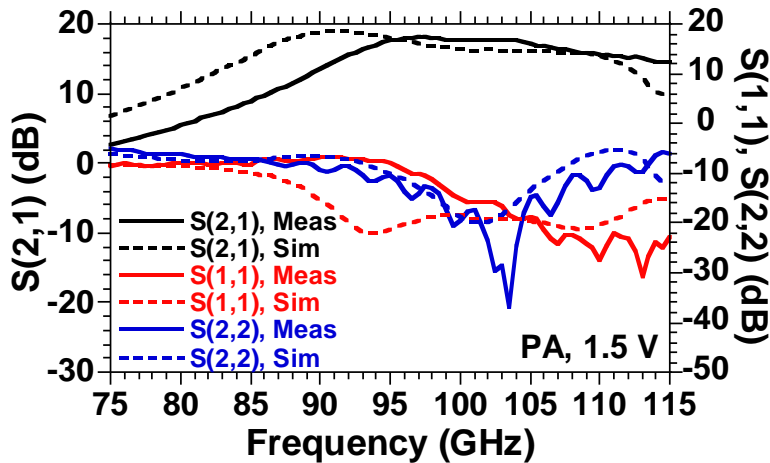
*\*at the maximum gain settings.*

# VGA Measurements



Over 7 dB gain adjustment (control current: 0.3-0.8 mA) with an associated 2 degrees the phase shift

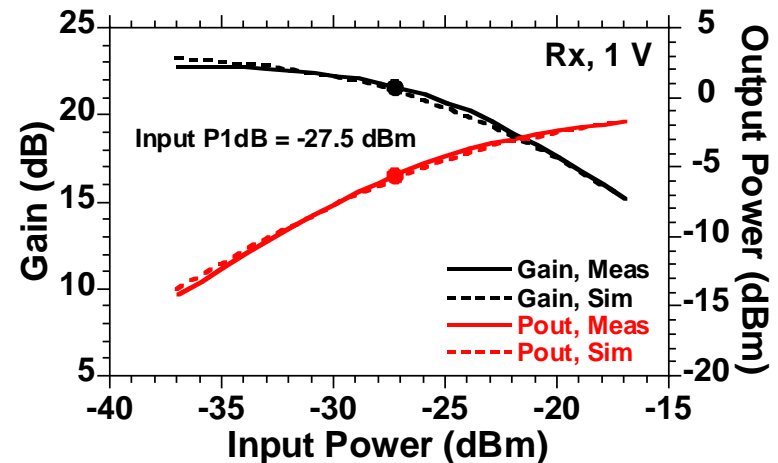
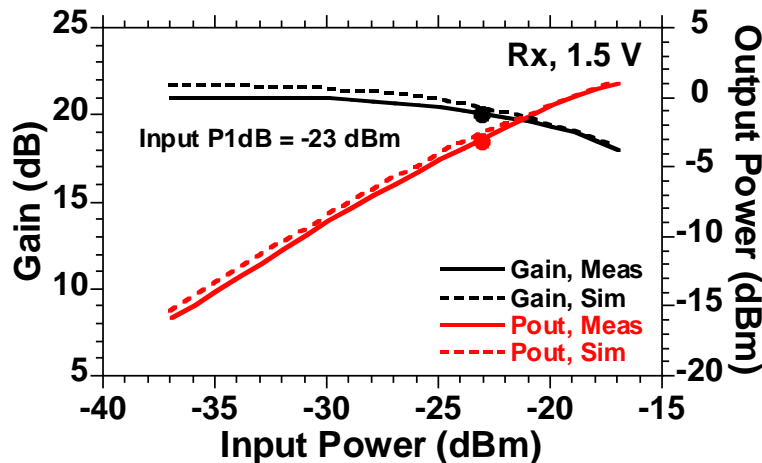
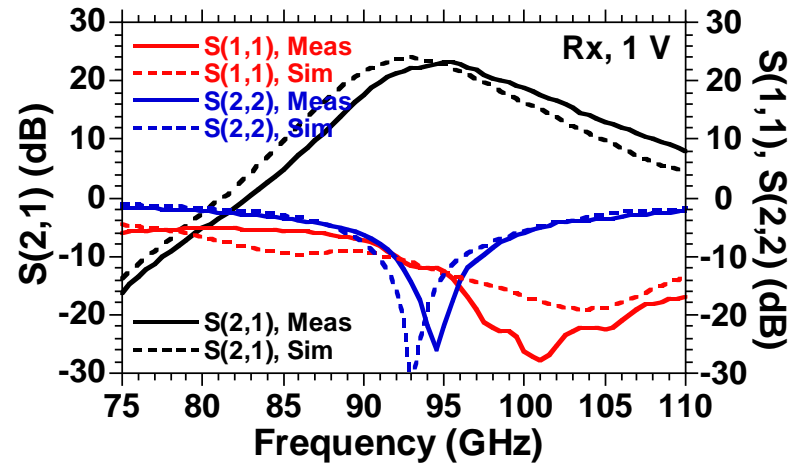
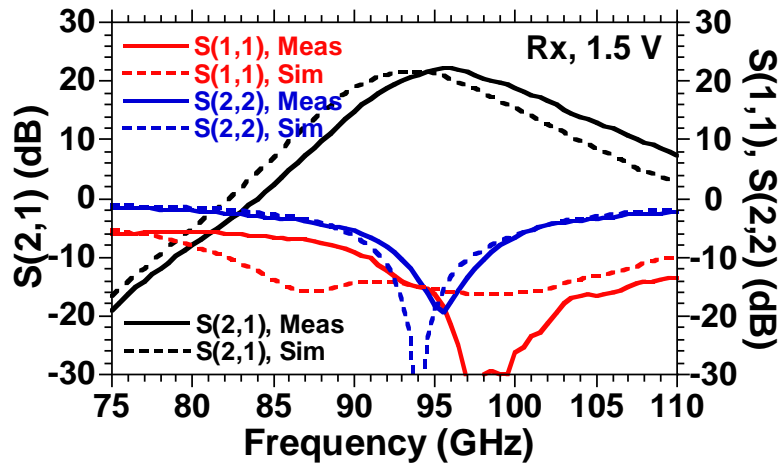
# PA Measurements



Power consumption: 15 mA @ 1.5 V  
 Gain: 17 dB @ 94 GHz  
 Output P3dB: 6.9 dBm, PAE: 17 %

Power consumption: 11.4 mA @ 1 V  
 Gain: 17 dB @ 94 GHz  
 Output P3dB: 3.5 dBm, PAE: 12.7 %

# Transceiver Measurements



## Dual-polarization simultaneous reception

Power consumption: 26 mA @ 1.5 V

Gain: 21 dB (V)

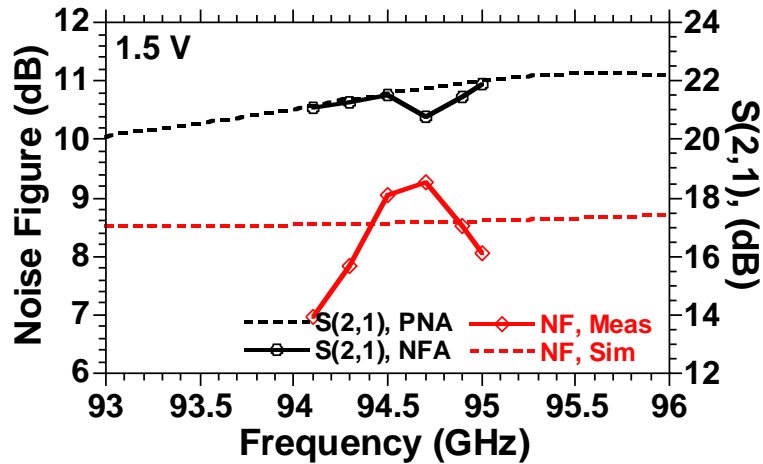
Input P1dB: -23 dBm (V)

Power consumption: 25.8 mA @ 1 V

Gain: 22.7 dB (V)

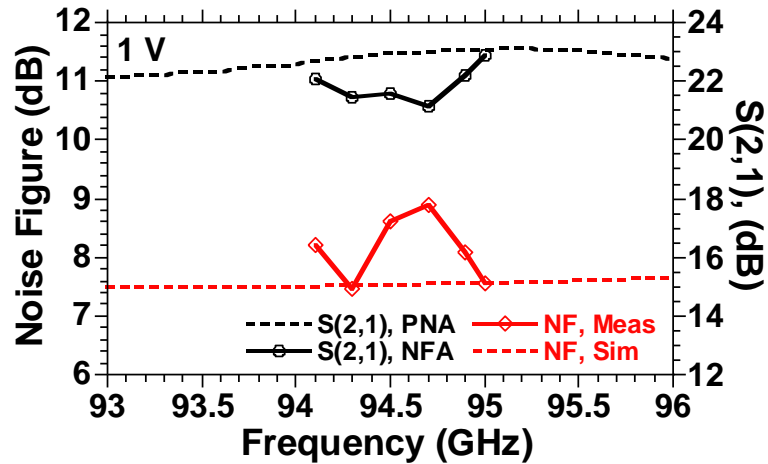
Input P1dB: -27.5 dBm (V)

# Transceiver Measurements



Gains measured by PNA and NFA are matched to each other

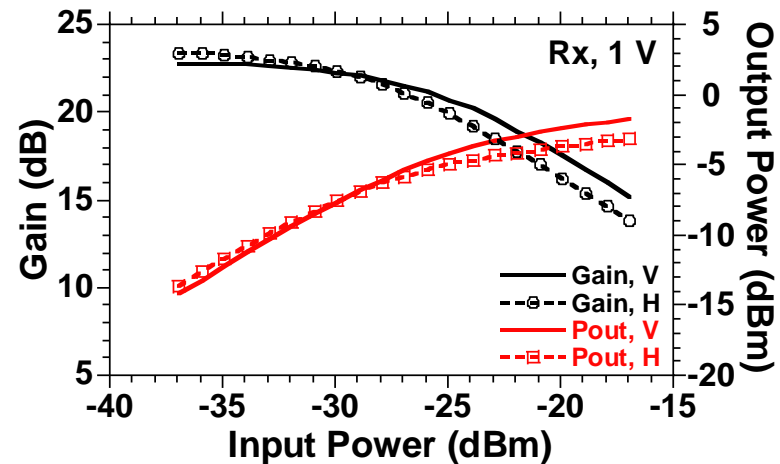
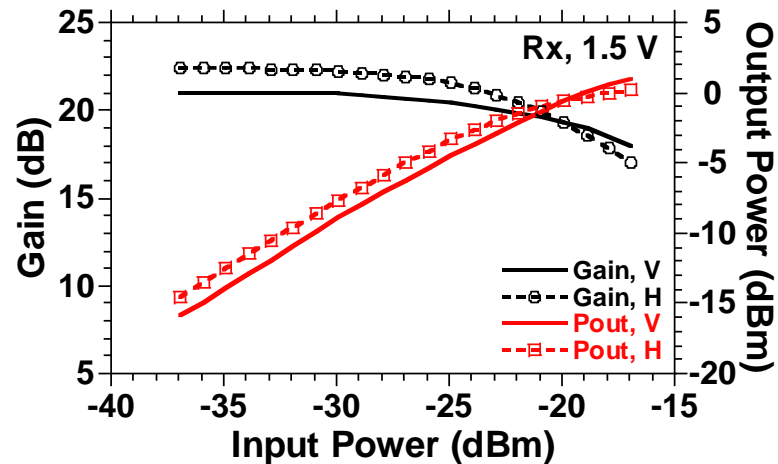
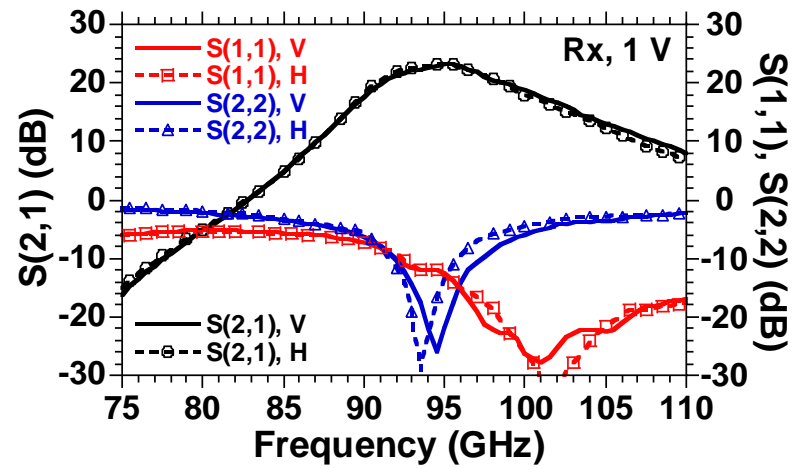
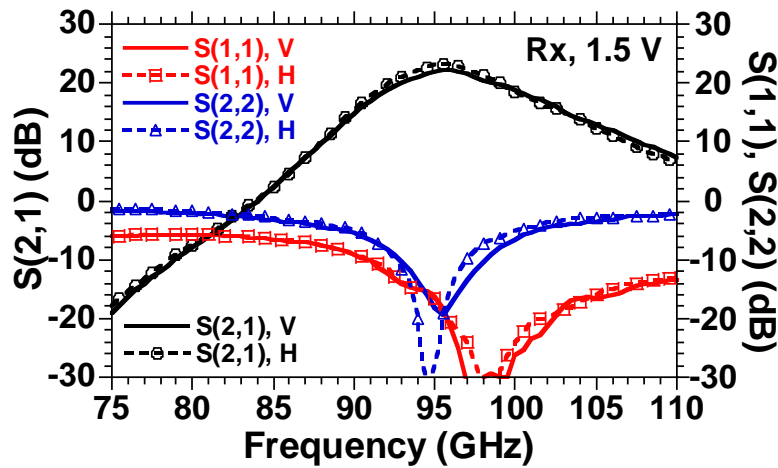
Noise figure < 9.3 dB



Noise figure < 8.9 dB

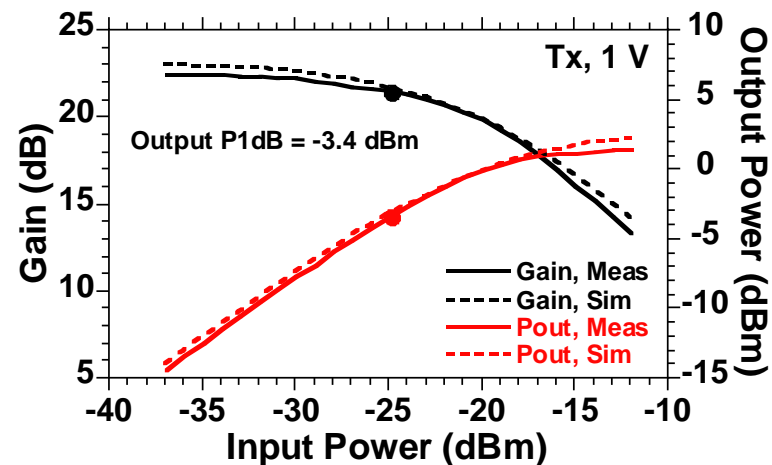
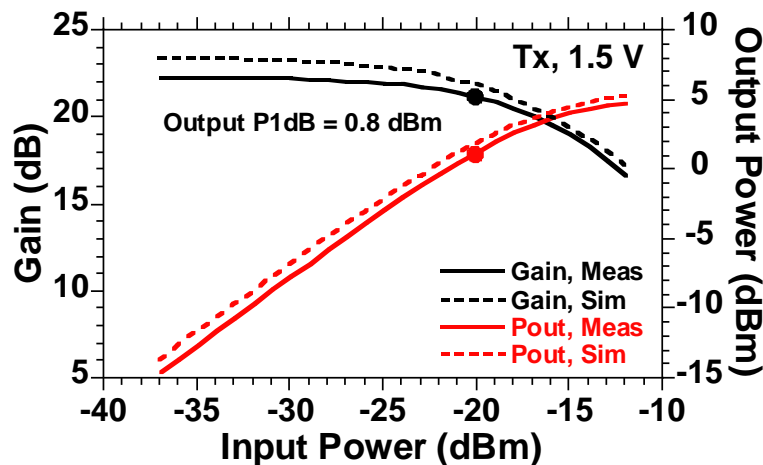
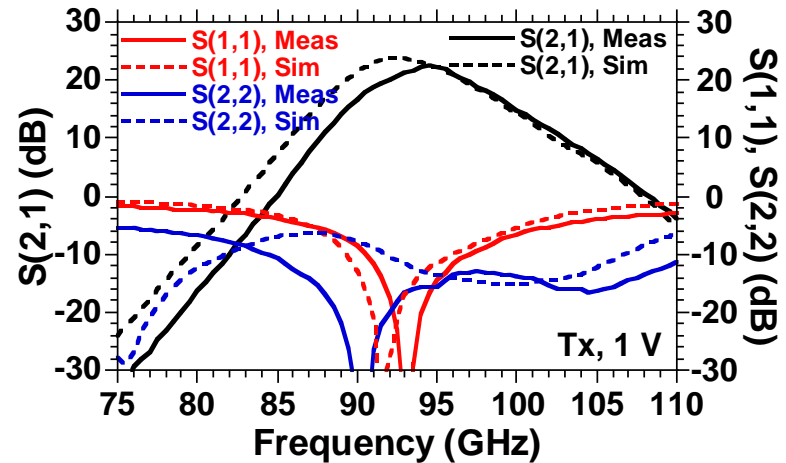
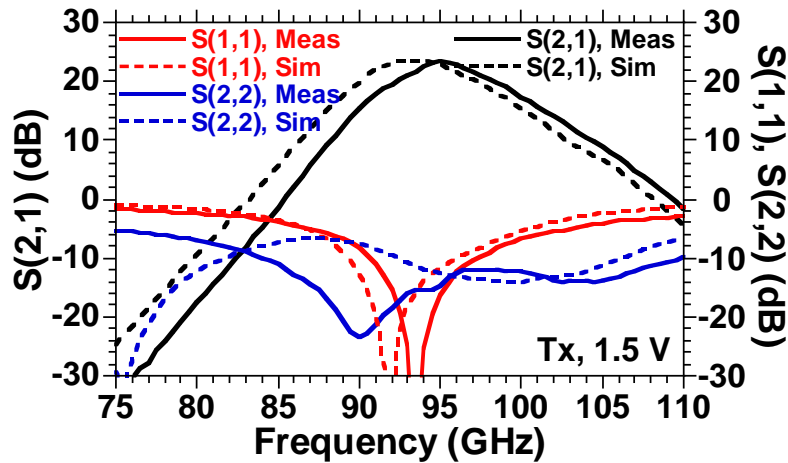


# Transceiver Measurements



Gain difference between V and H < 2 dB

# Transceiver Measurements



## Time-duplexed V and H output

Power consumption: 26.5 mA @ 1.5 V

Gain: 22.2 dB (V)

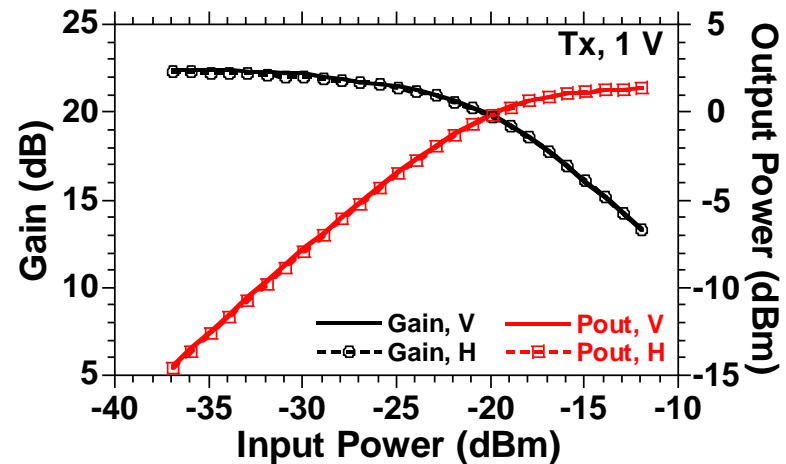
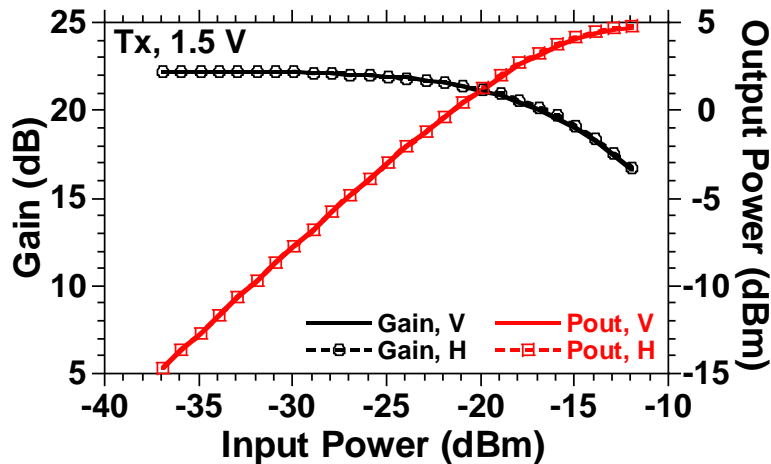
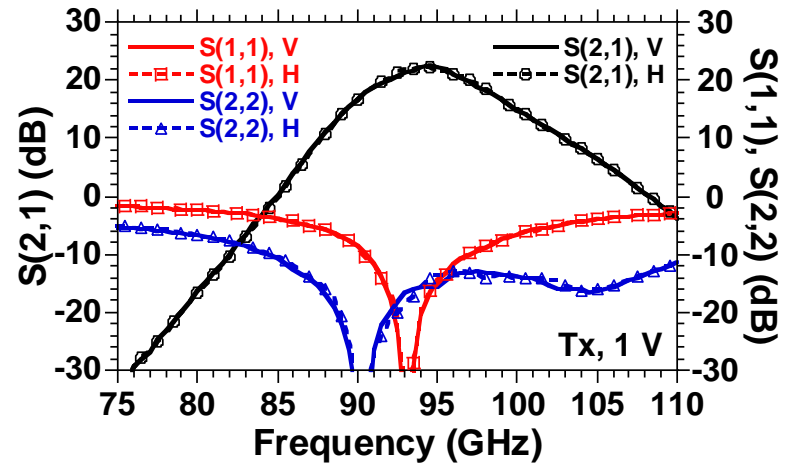
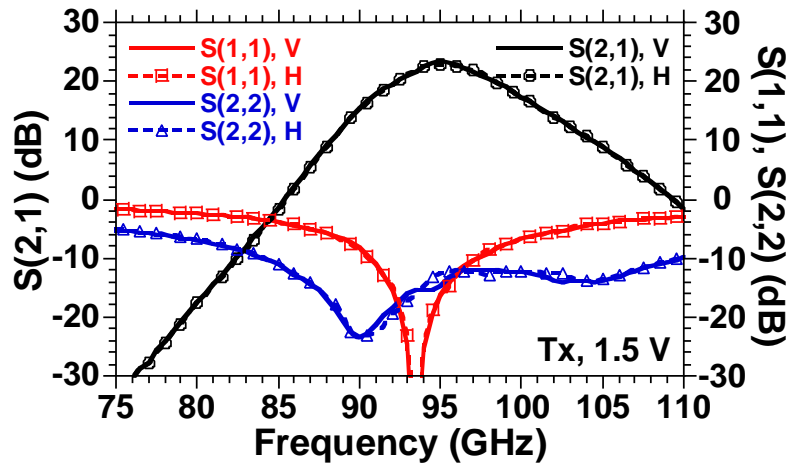
$P_{\text{sat}}$ : 5 dBm (V)

Power consumption: 28.7 mA @ 1 V

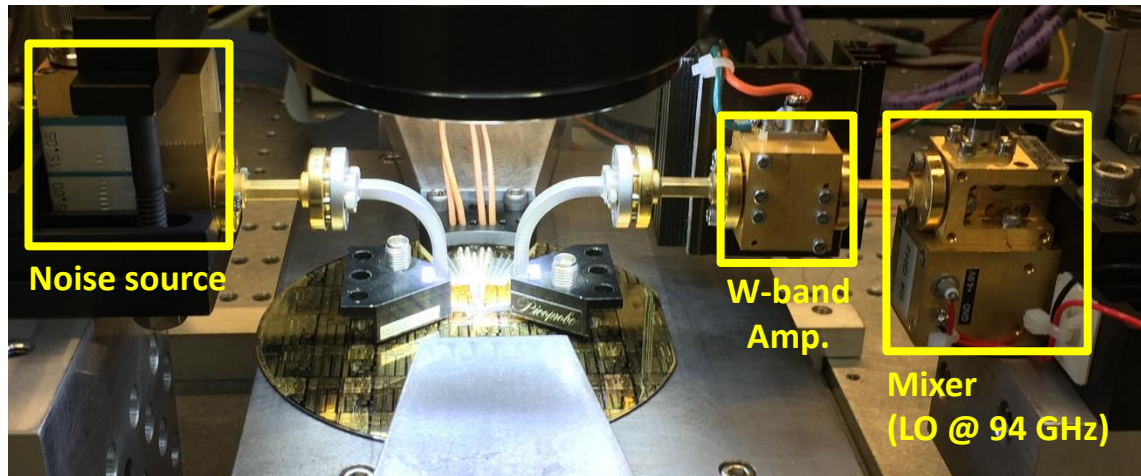
Gain: 22.4 dB (V)

$P_{\text{sat}}$ : 1.4 dBm (V)

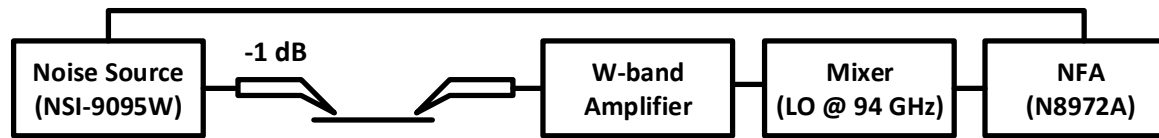
# Transceiver Measurements



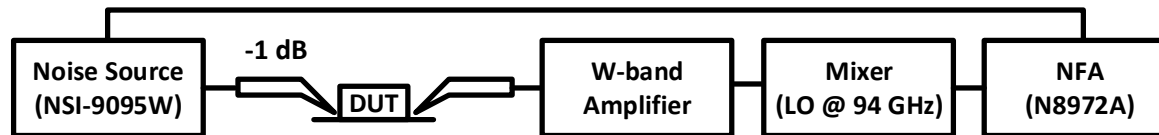
# NF Measurement Setup



## Calibration



## Measurement



Loss before the DUT: compensated using the NFA's internal function therefore, measured gain should be subtracted by -1 dB