A 140 GHz Two-Channel CMOS Transmitter using Low-Cost Packaging Technologies

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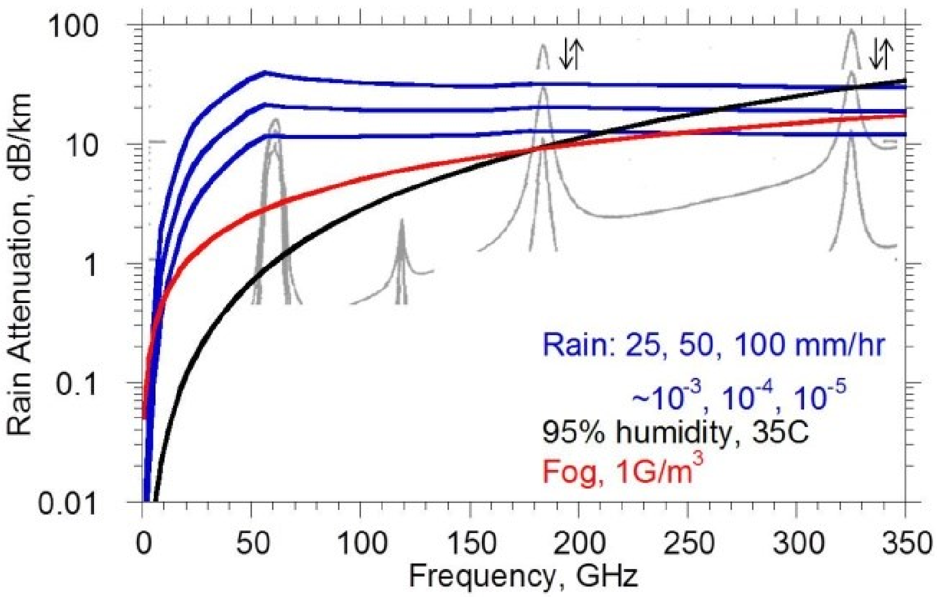
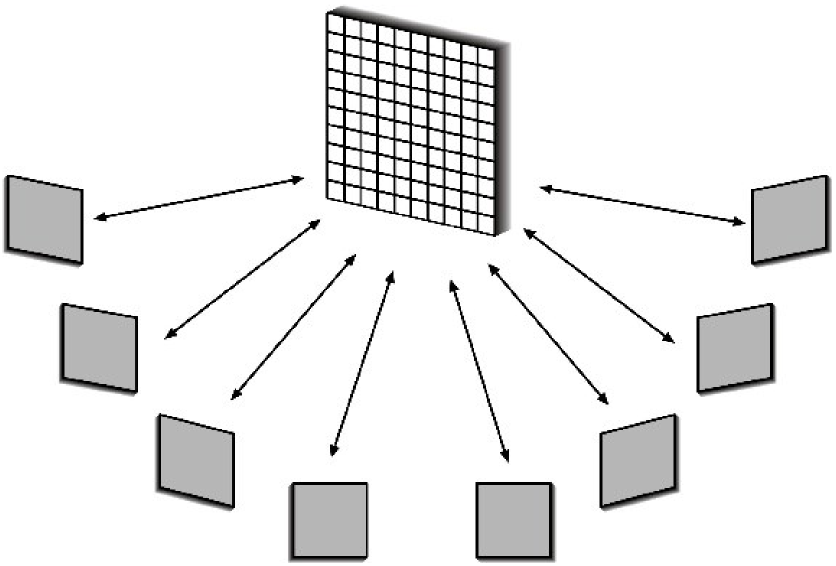
Why 140GHz Wireless ?

Large available spectrum at mm-waves

Shorter wavelength – small IC, antenna arrays

Massive # of parallel channels – multiple independent beams





Low-cost antenna and transition design is critical

IC design above 100 GHz is easier with developments in CMOS and III-V

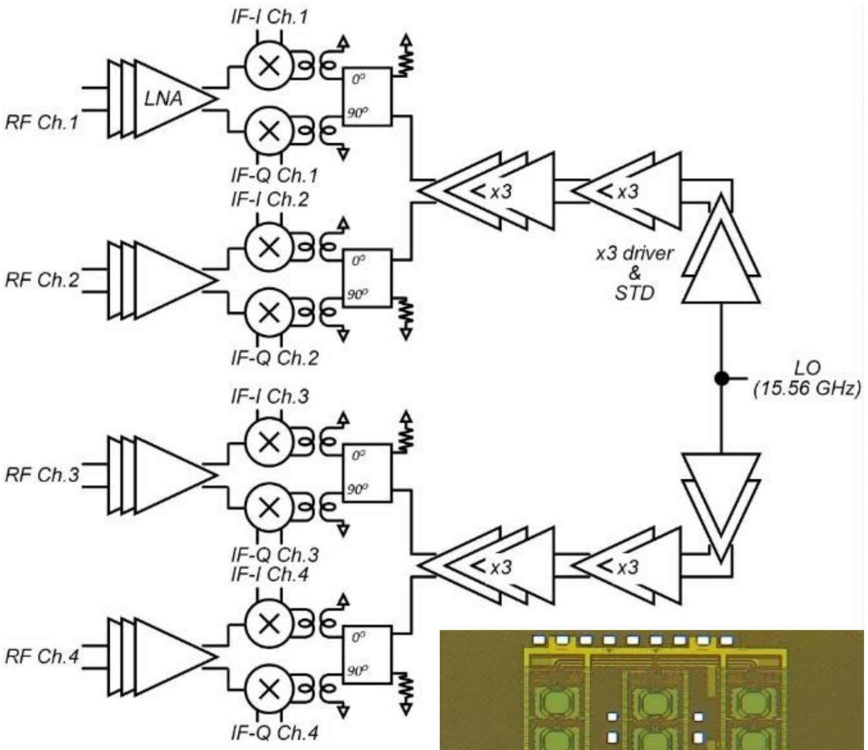
Packaging and antenna design is the challenge

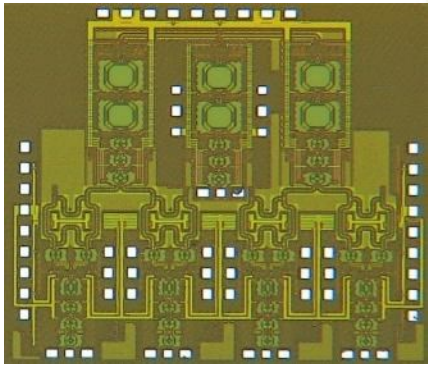
140 GHz 4-Channel Receiver

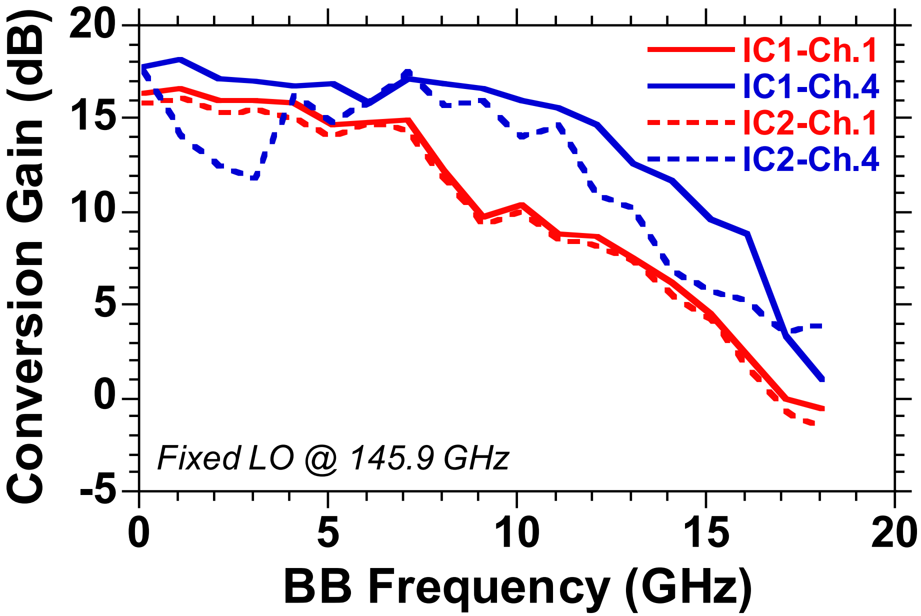
Direct conversion receiver

140 GHz LNA, double balanced passive mixer

LO distribution through two x9 multipliers from common LO port







1.69 mm x 1.76 mm
GlobalFoundries
45nm SOI CMOS

18 dB conversion gain

12 GHz 3-dB BW

495 mA @ 1V

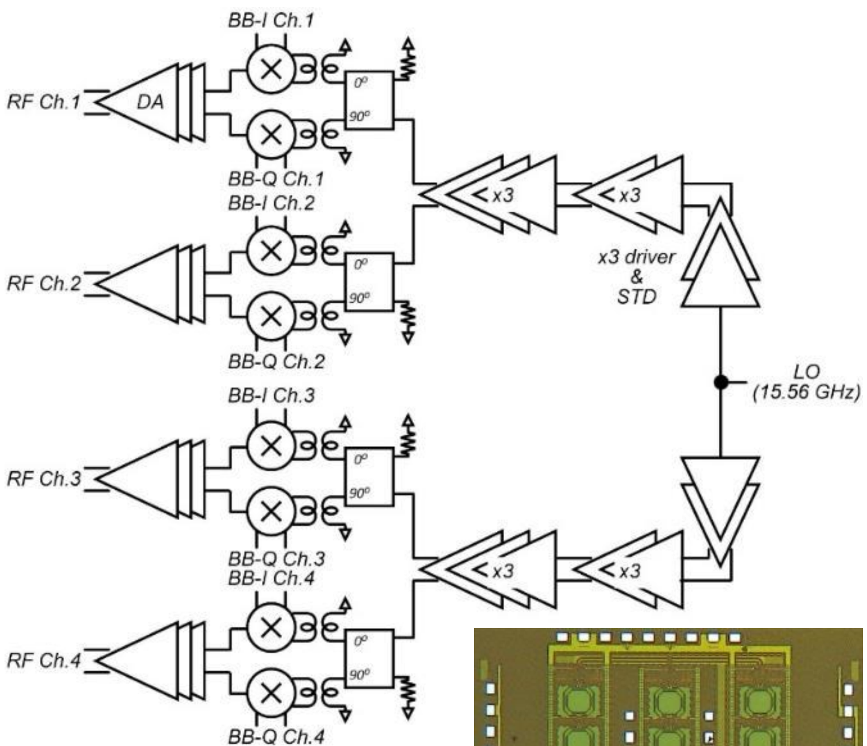
A. Simsek, et al, 2018 IEEE BCICTS,

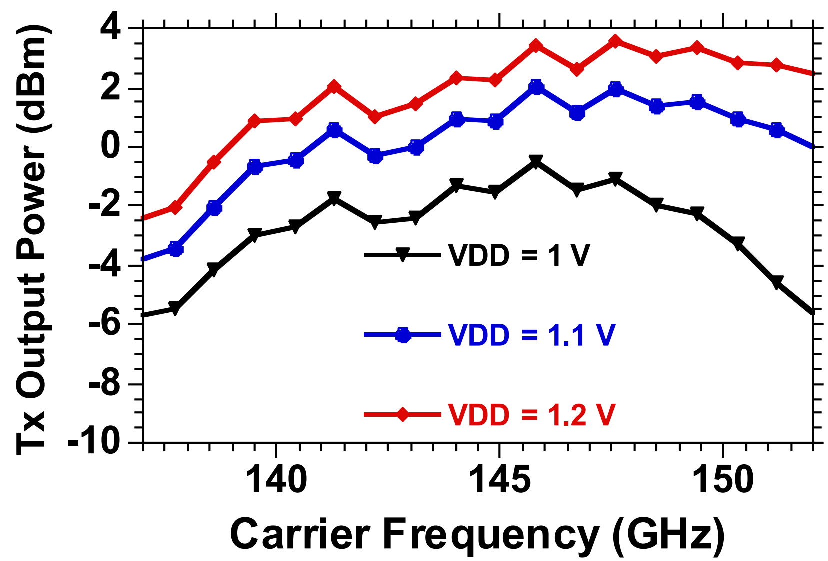
140 GHz 4-Channel Transmitter

Direct conversion transmitter

140 GHz PA (same with LNA), I/Q Gilbert Cell Active Mixer

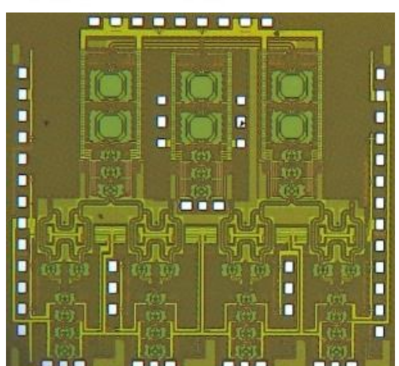
LO distribution thru two x9 multiplier from common LO port





Pout = -2 dBm @ 145 GHz

463 mA @ 1V



1.69 mm x 1.76 mm
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45nm SOI CMOS

A. Simsek, et al, 2018 IEEE BCICTS,

Proposed Low-Cost Package

Multi layer PCBs with

high resolution

large number of vias with < 8 mil diamater

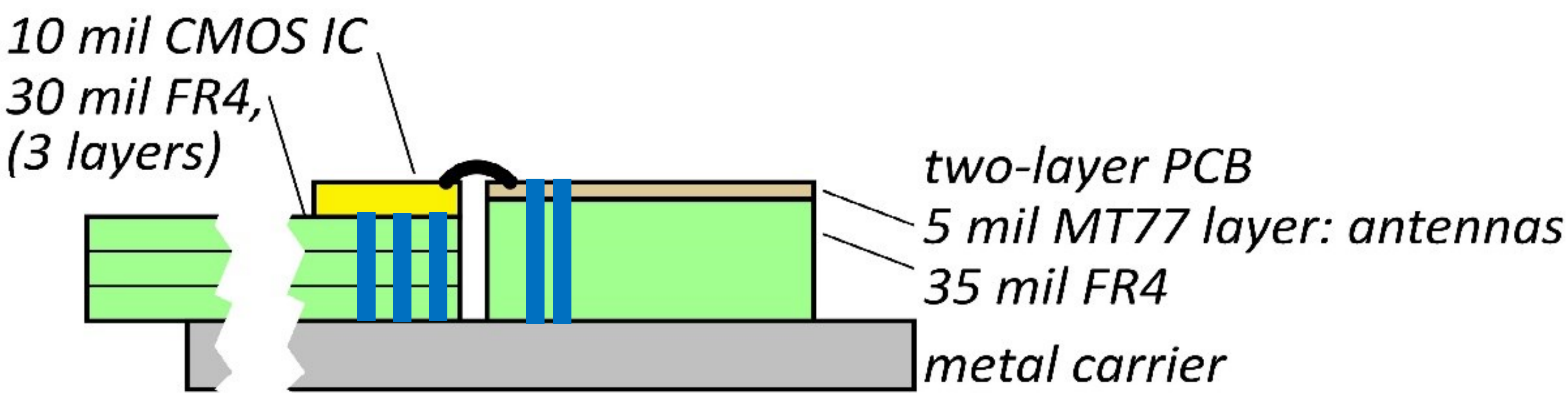
cavity

…are expensive

Can we used 2 separate cheaper PCBs and align the height?

Less number of vias in the antenna board with higher resolution

Carrier PCB with large number of vias and less resolution



Fully Packaged 2-Channel Transmitter

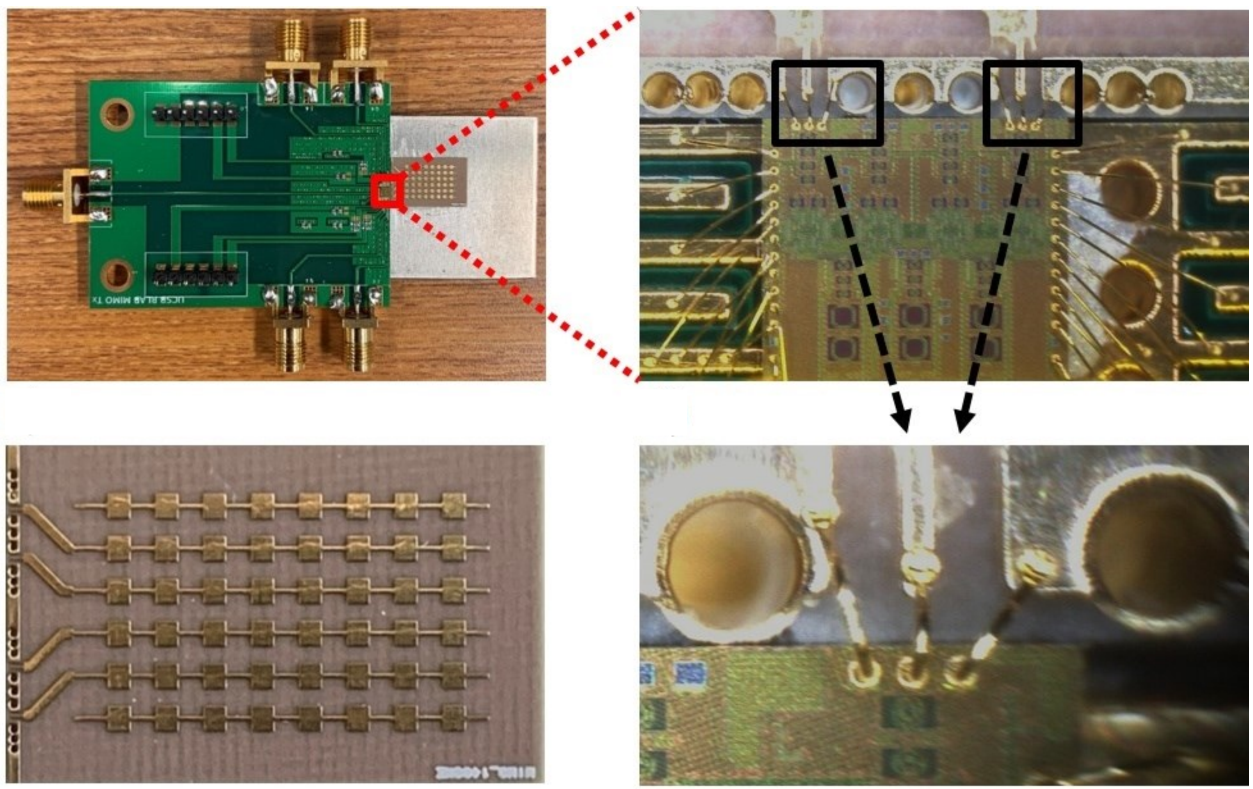
2-channel of one 4-channel CMOS transmitter and

2-channels of the 4-channel series-fed patch antenna array

2 I/Q baseband inputs and single LO input thru SMA connectors

Separation between the carrier and antenna PCB is < 50 um

Wirebond length is < 250-300 um which gives < 250-300 pH @ 140 GHz



Fully Packaged 4-Channel Receiver

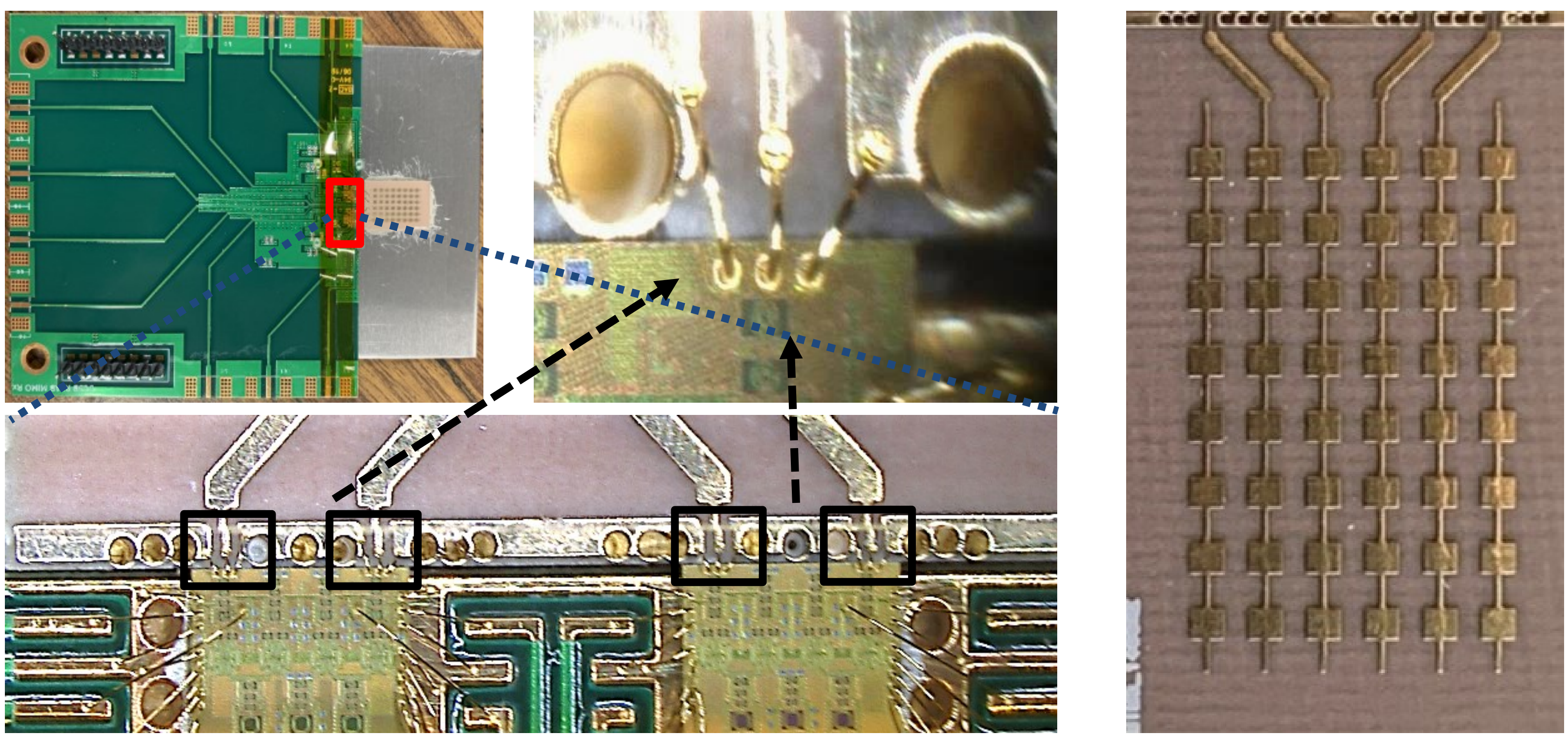
Two 4-channel CMOS receiver ICs used due to wirebond density

2-channel of each IC connected to the 4-channel series-fed patch antenna array

4 I/Q baseband outputs and two LO inputs thru SMA connectors

Separation between the carrier and antenna PCB is < 50 um

Wirebond length is < 250-300 um which gives < 250-300 pH @ 140 GHz



Antenna Design and Measurements

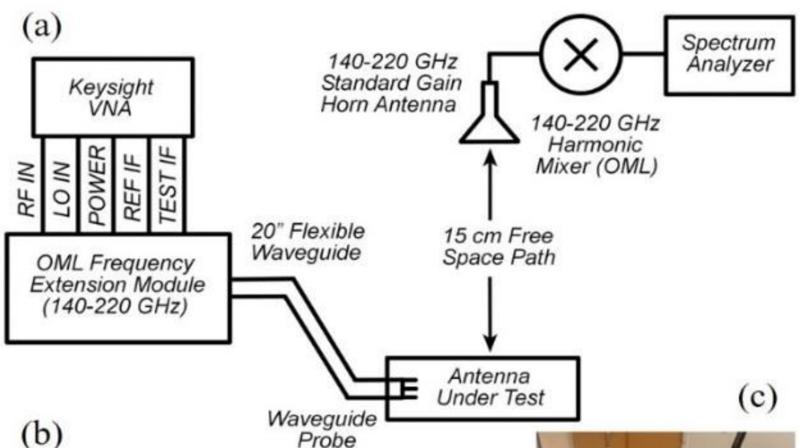
Antennas and transitions designed in **Astra MT77** substrate

5 mil substrate thickness, with Dk = 3, and Df = 0.0017

35 mil FR4 under to match the height with CMOS carrier + CMOS chip height

Test structures with GSG 150 um pitch wafer probe interface

(Single patches and 8-element series-fed patch array)



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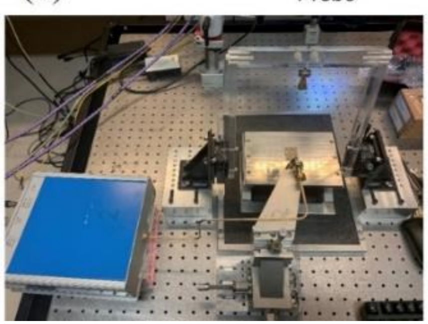
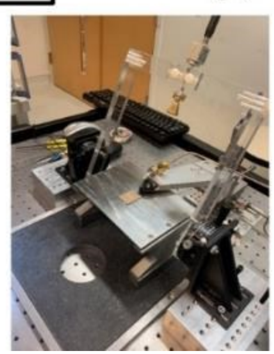
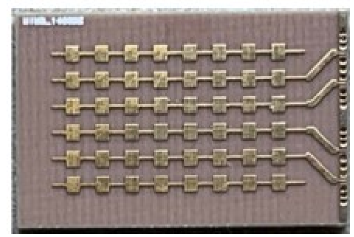
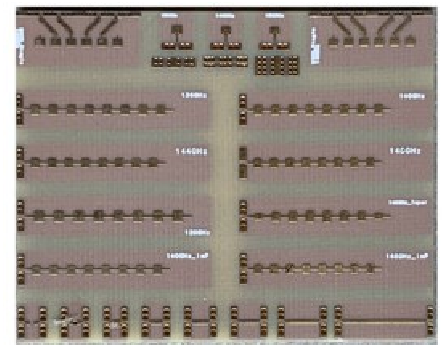
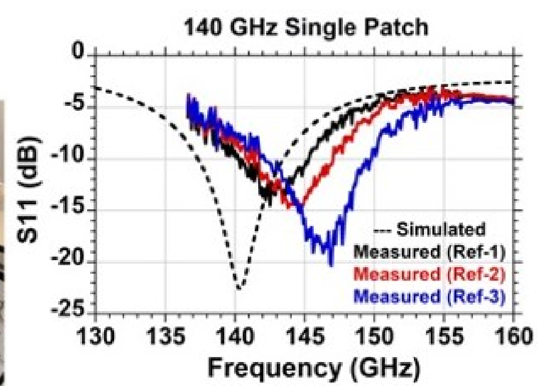


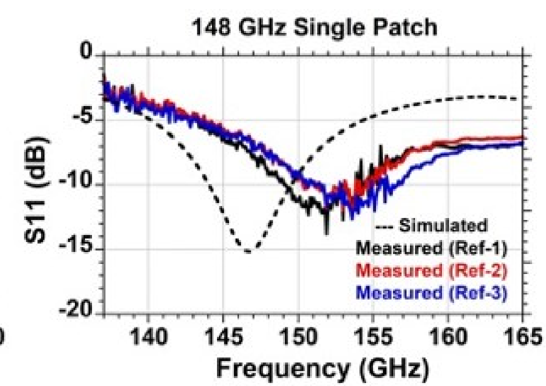
(c)











4-5 GHz frequency shift

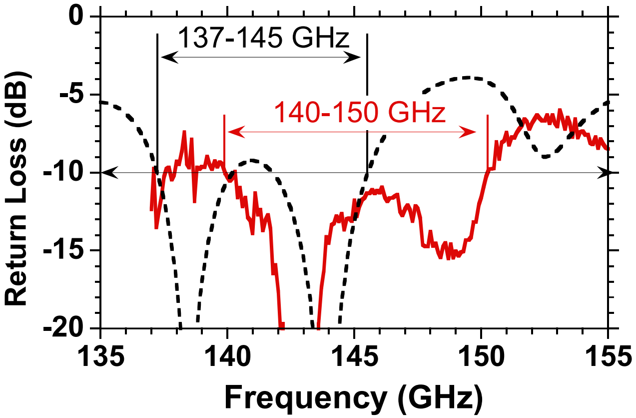
Antenna Design and Measurements

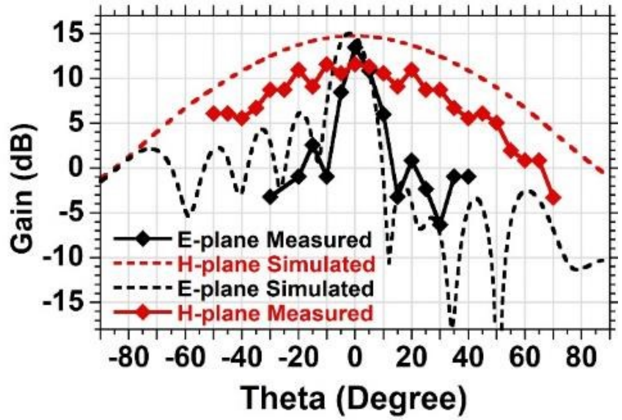
8-element series-fed patch antenna arrays designed in Astra MT77 substrate

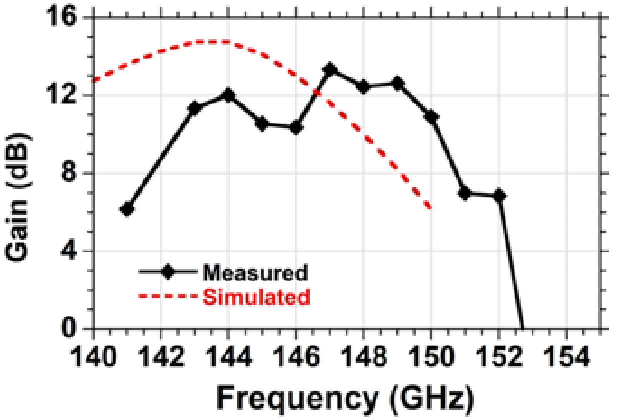
5 mil substrate thickness, with Dk = 3, and Df = 0.0017

Test structure created with GSG 150 um pitch wafer probe interface

136, 140 and 144 GHz series-fed antenna arrays are designed







144 GHz antenna array

Frequency shifted ~ 4-5 GHz

Radiation patterns simulated at 144 GHz, measured at 148 GHz

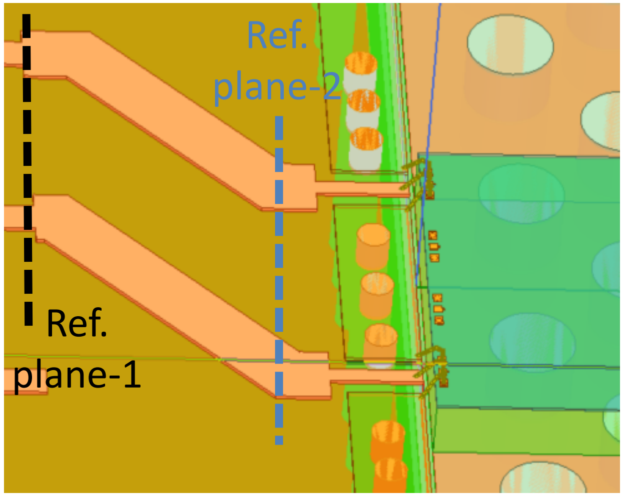
Wirebond Transition Design

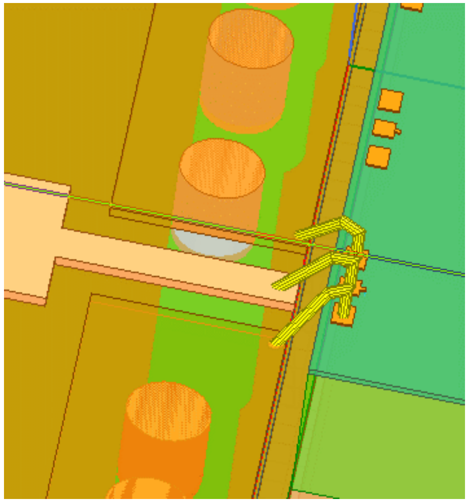
CMOS GSG pads (75 um pitch) to 50 Ohm microstrip line transition

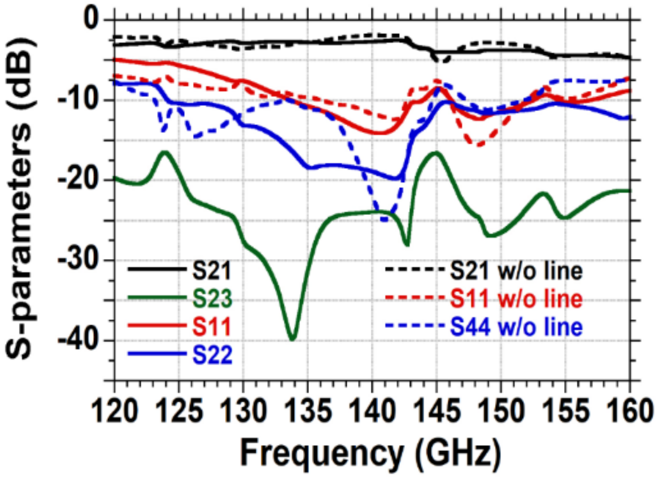
90 Ohm GCPW line as a series tuning element

Fringing capacitance between wide microstrip to ground provides shunt tuning

Ground vias with 6 mil diameter/4 mil edge spacing – adds additional inductance







Insertion loss without the line = ~ 1.8 dB @148 GHz

Insertion loss with the line = ~ 2.5 dB @ 148 GHz

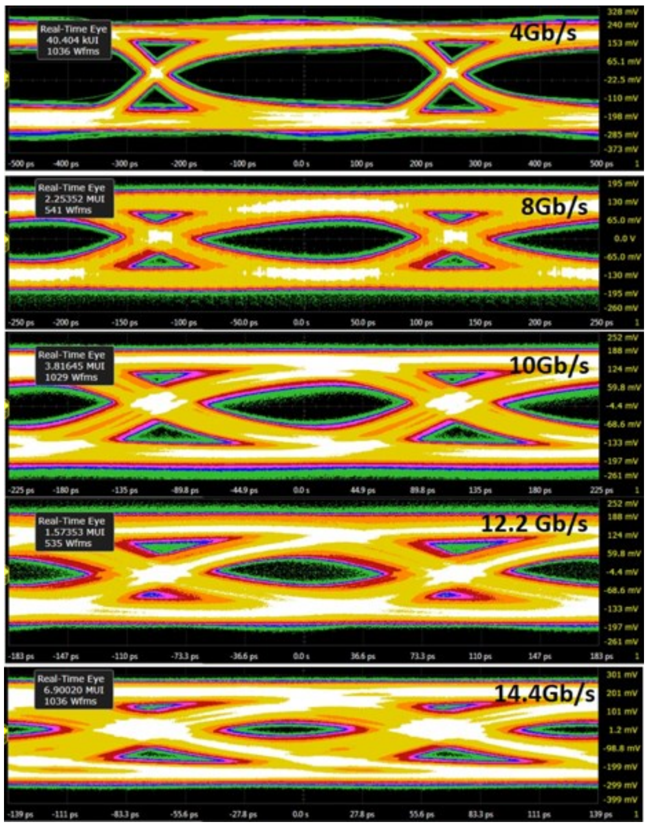
0.7 mil diameter gold wedge bonding with < 250-300 μm length

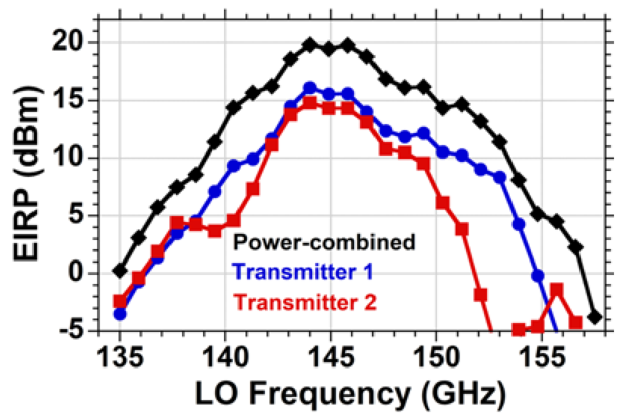
System Experiments

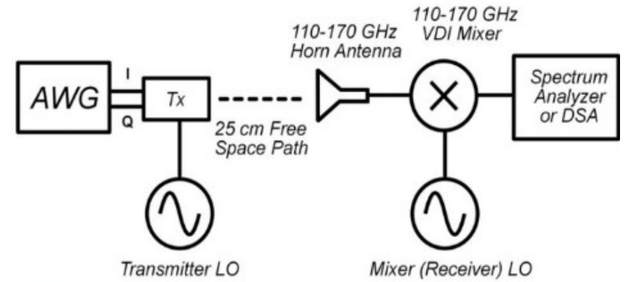
<u>2-channel transmitter board measurements:</u>

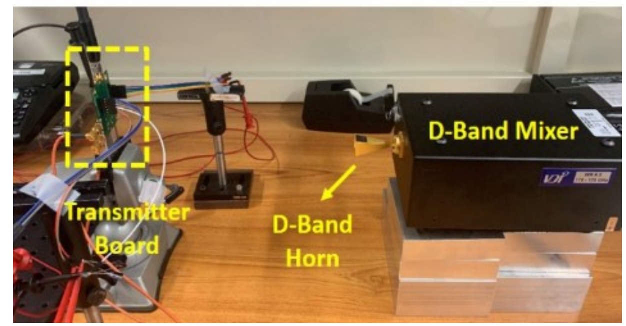
Data transmission and open eyes up to 14.4 Gb/s QPSK using 1-channel

@25 cm wireless distance









Power combining experiment with 2 Tx channels

Tx-1 EIRP ~ 15 dBm

Tx-2 EIRP ~ 15 dBm

Combined EIRP ~ 20 dBm (ideally 6-dB higher)

Alignment and phases are imperfectly

System Experiments

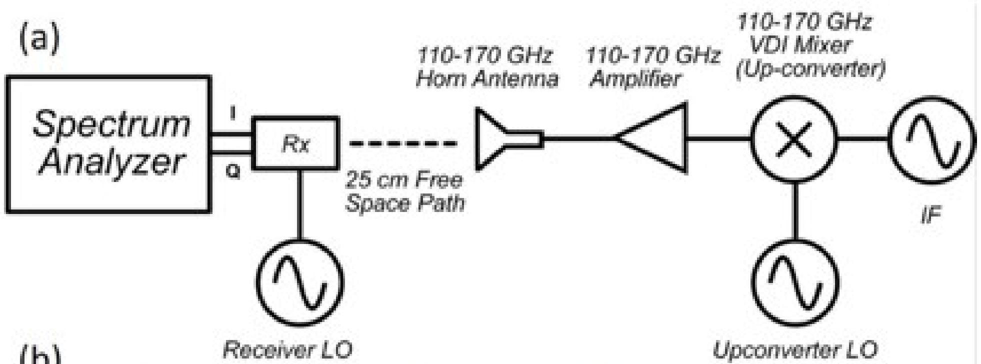
<u>4-channel receiver board measurements:</u>

20-21 dB conversion gain (single ended) with 4-5 GHz 3-dB BW

2 I/Q channels are shown here

I2 channel has a problem in the connector

(a)



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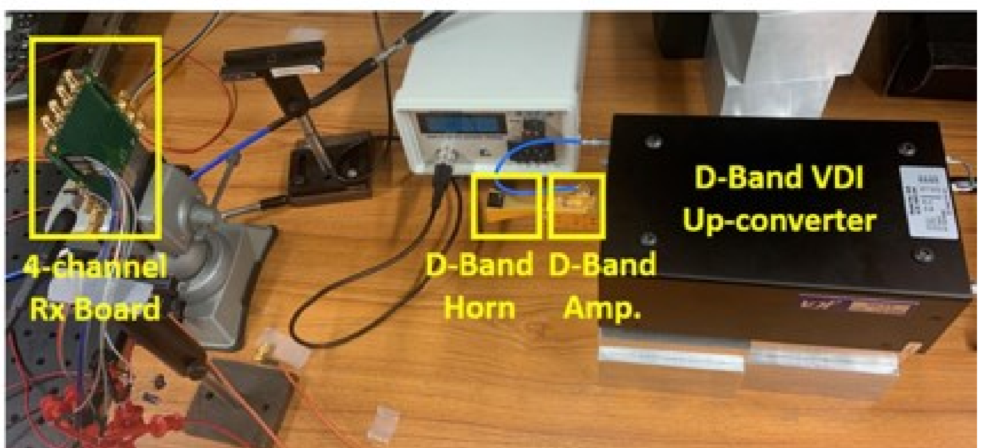
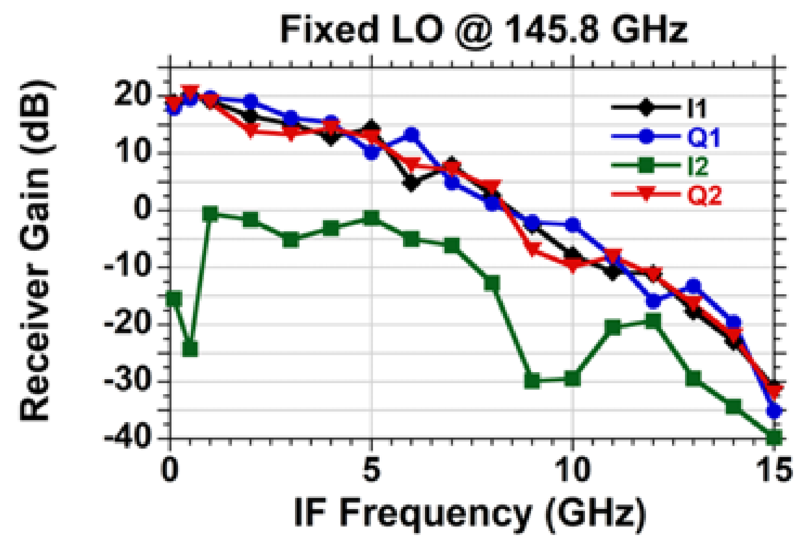
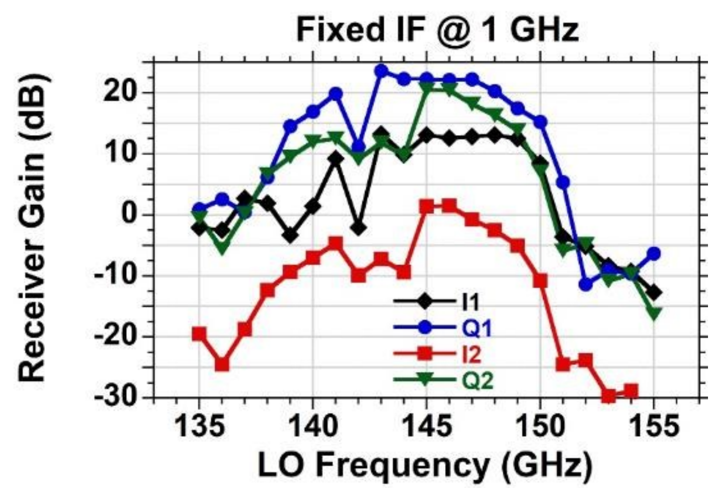






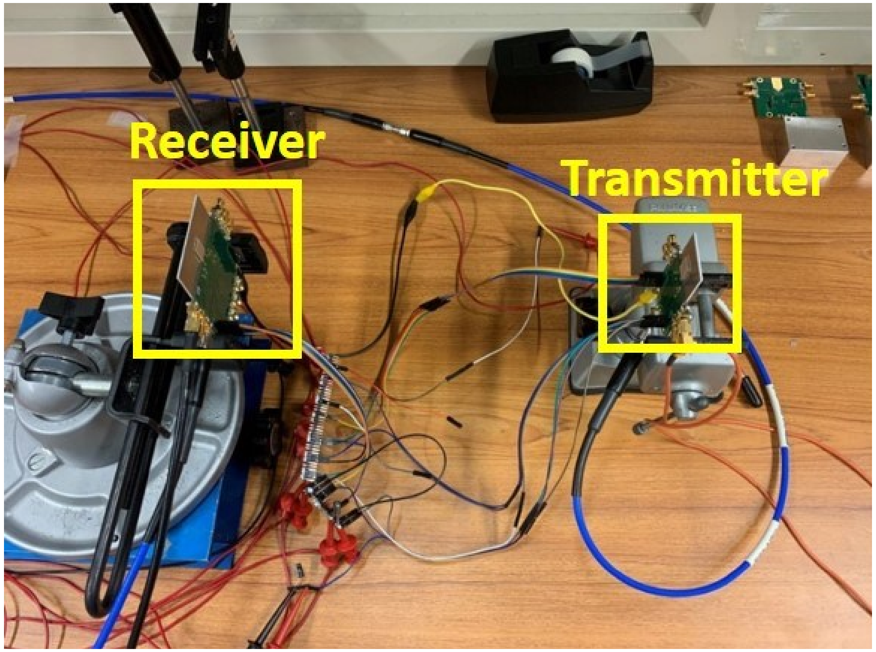
System Experiments

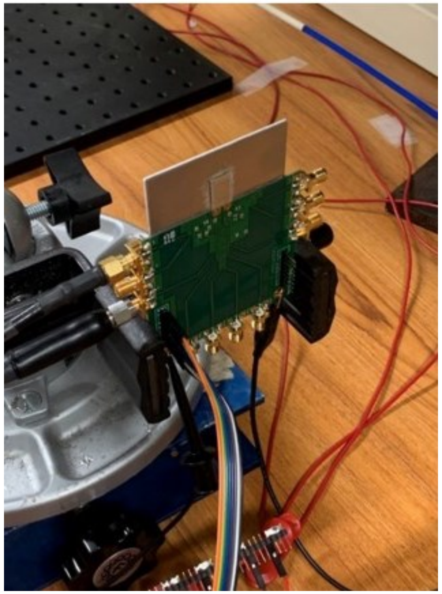
1-channel transceiver measurements:

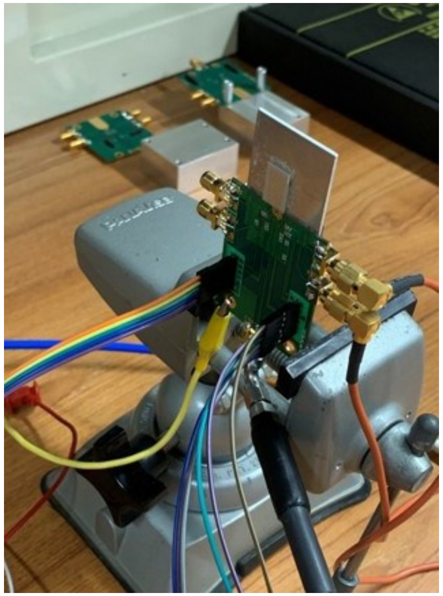
25 cm wireless distance

1-channel transmitter and receiver

All losses de-embedded



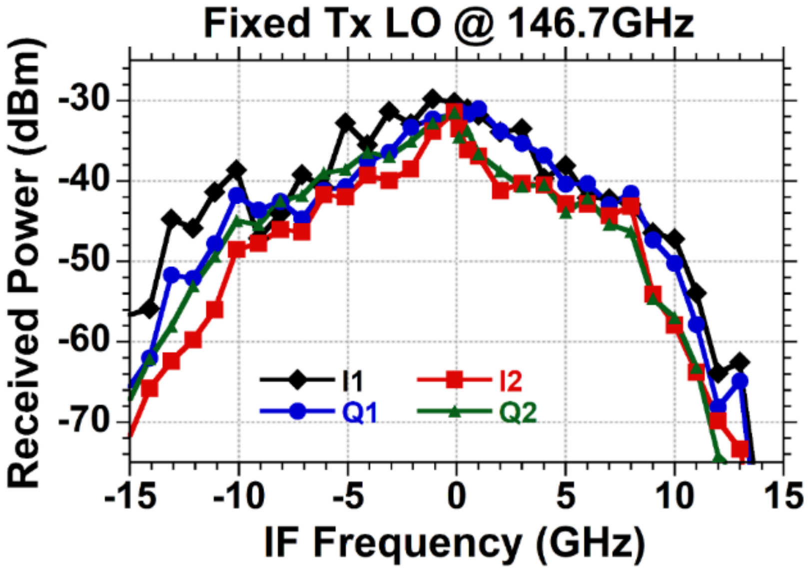




$$P_{sat} + G_{ant,tx} - 2 * WB_{loss} + G_{ant,rx} + G_{Rx} - Loss = P_{rec}$$

$$1 + 13.6 - 2 * WB_{loss} + 13.6 + 12 - 65.3 = -30$$

$$WB_{loss} = 2.45 \text{ dB} \ (1)$$



System Experiments

1-channel transceiver measurements:

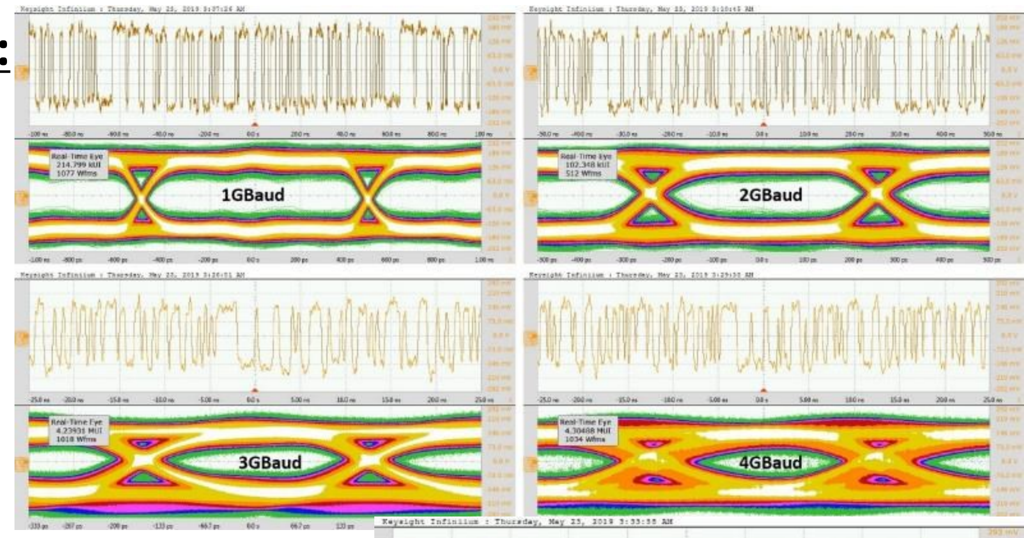
4096 x 400 symbol length from AWG

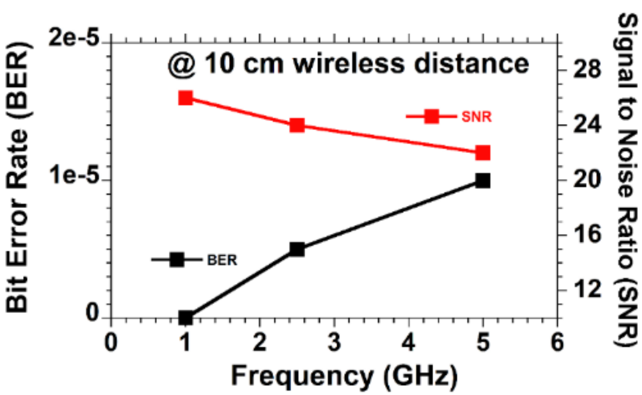
BPSK modulation (same data on I/Q)

Saved I/Q output using DSA

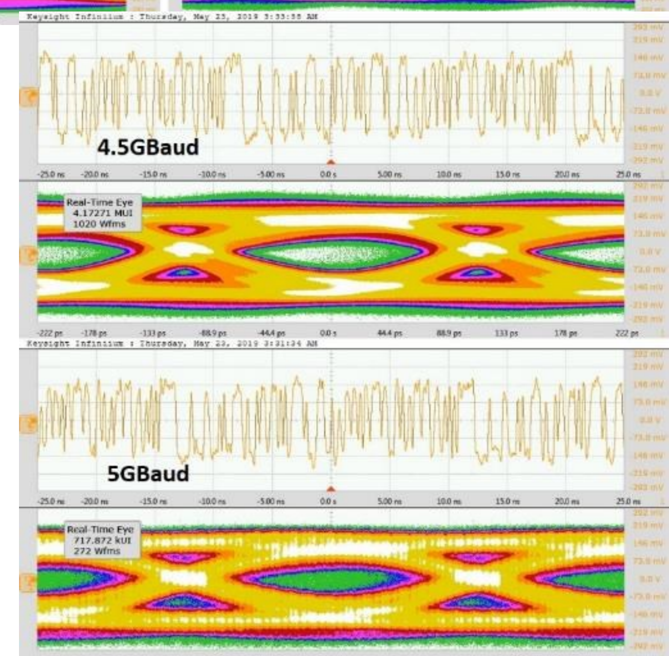
Oversampling ratio of 8/10

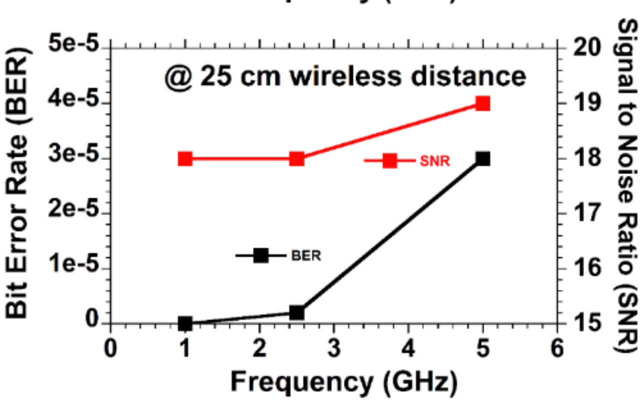
Offline MMSE channel equalization





10 cm wireless data trans.
< 1×10^{-5} BER with
22 dB SNR (5 GBaud)

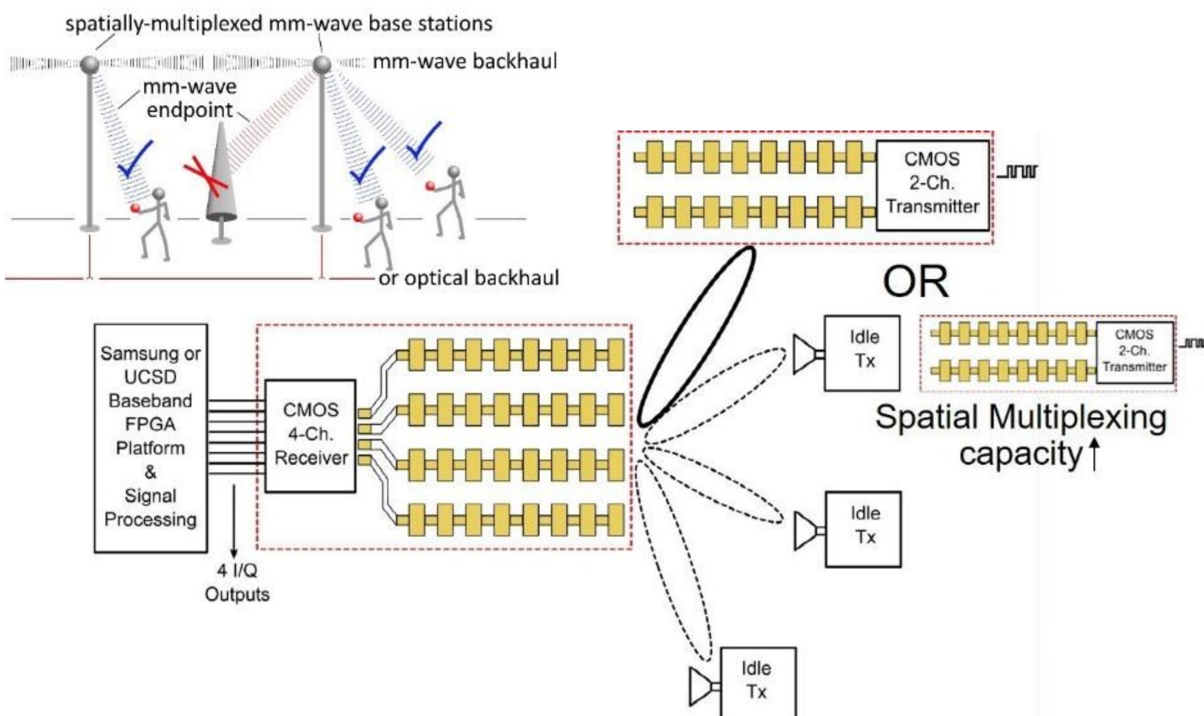




25 cm wireless data trans.
< 3×10^{-5} BER with
19 dB SNR (5 GBaud)

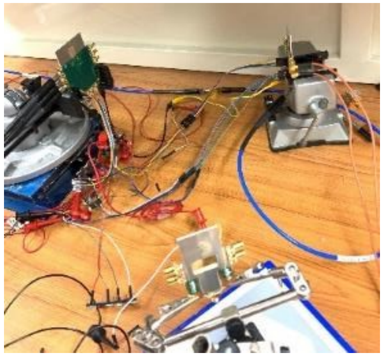
Conclusion and Future Direction

- Low-cost antenna design and measurements at D-Band
- Wirebond transition design with < 2 dB insertion loss above 140 GHz
- Fully packaged, modular 2-channel transmitter and a fully packaged 4-channel receiver
- Beamforming gain demonstrated for a simple 2-channel transmitter
- 1-channel wireless data transmission experiments using these boards:
  - 10 cm wireless data transmission with < 1×10^{-5} BER with 22 dB SNR (5 Gbaud BPSK)
  - 25 cm wireless data transmission with < 3×10^{-5} BER with 19 dB SNR (5 Gbaud BPSK)



What is next?

- Higher order modulation schemes, larger arrays
- Multi-beam communications
- III-V PA integration for higher power



Acknowledgments

- **National Science Foundation (NSF)** GigaNets program, Contract NO. CNS-1518812
- **Global Foundries** for the 45 nm CMOS SOI chip fabrication
- **Advotech** for the assembly
- Navneet Sharma, Hamidreza Memerzadeh, Nikolaus Klammer and Gary Xu at **Samsung Research America** for valuable suggestions and the measurement equipment.
- **Prof. James F. Buckwalter** for valuable comments.

System Experiments

2-channel transmitter board measurements:

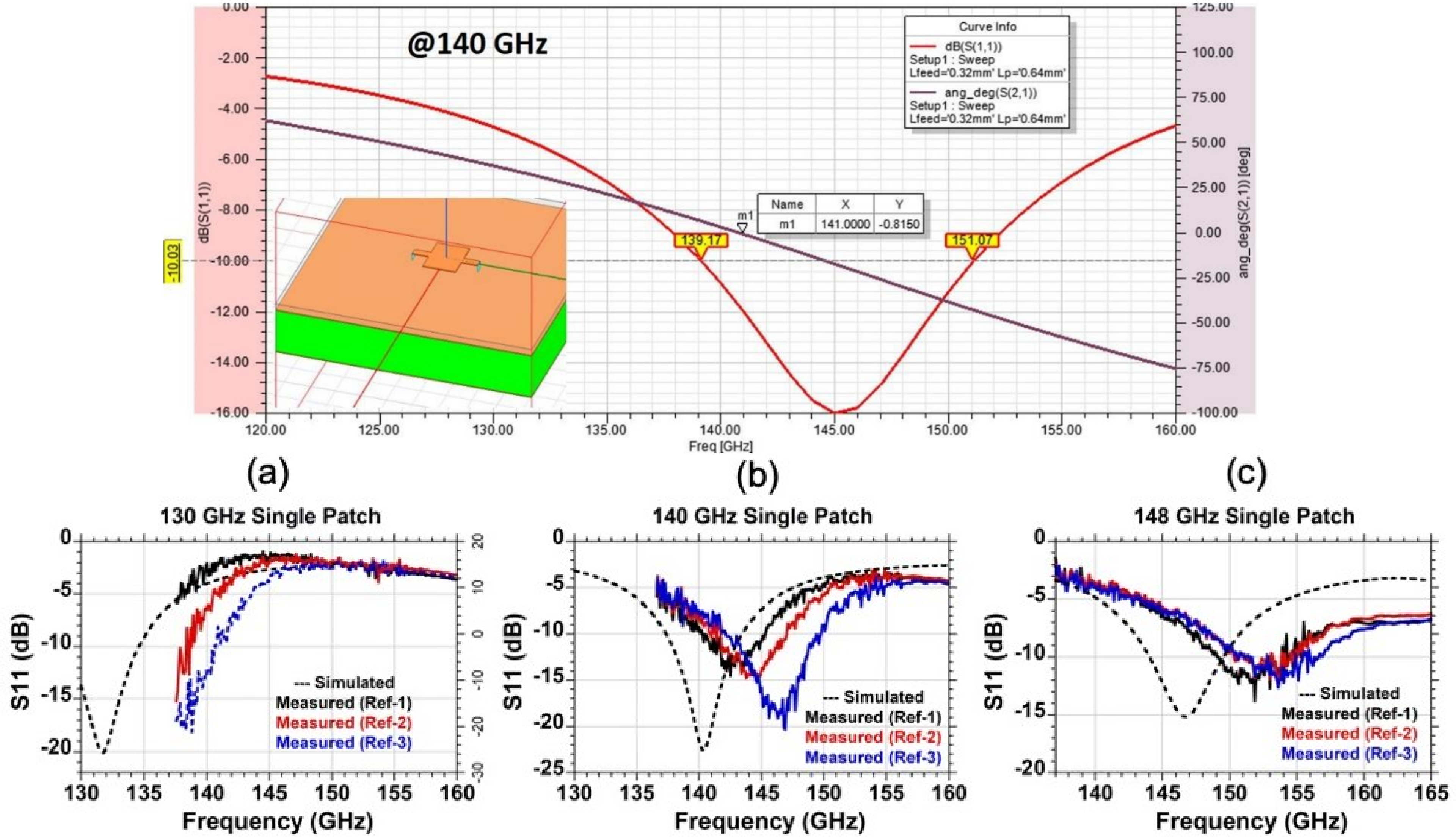
Comparison between state-of-the art designs

	Farid et al.	Visweswaran et al.	Carpenter et al.	Sawaby et al.	**This Work**
Technology	22nm FDSOI CMOS	28nm CMOS	250nm InP	55nm SiGe HBT	45nm CMOS
Freq. [GHz]	125-145	138-151	110-170	110-150	140-150
Pout (dBm)	2.8	7	9	2.5	2
EIRP (dBm)	**-**	**11.5**	**-**	**-**	**20 (2-Ch)**
Data Rate (Gb/s)	-	-	44 (QPSK)	36 (QPSK)	14.4 (QPSK)
Pdc [mW]	198 (Rx) 196 (Tx)	500 (3 TRx)	357 (1 TRx)	220 (1 Tx)	500 (4 Tx)
Area [mm^2]	1.44 (Tx) 1.44 (Rx)	6.5 (3 TRx)	2.34 (1 TRx)	90 (package)	2.94 (4 Tx)
Integration	No Antenna	On-Chip Antenna	Wafer Probing	Off-Chip Antenna	Off-Chip Antenna

Back-up Slides

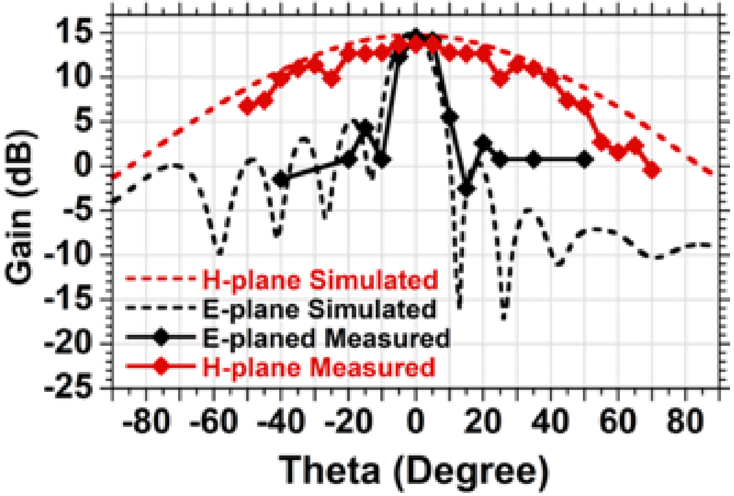
Antenna Design and Measurements

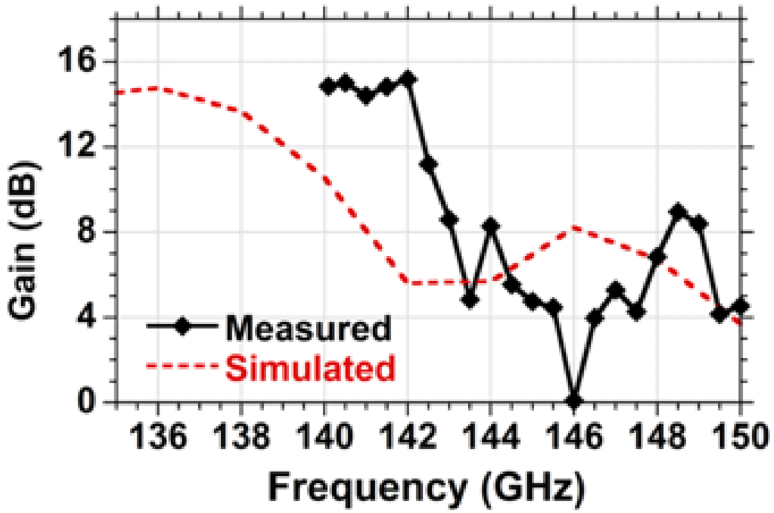
Unit cell design and patch results



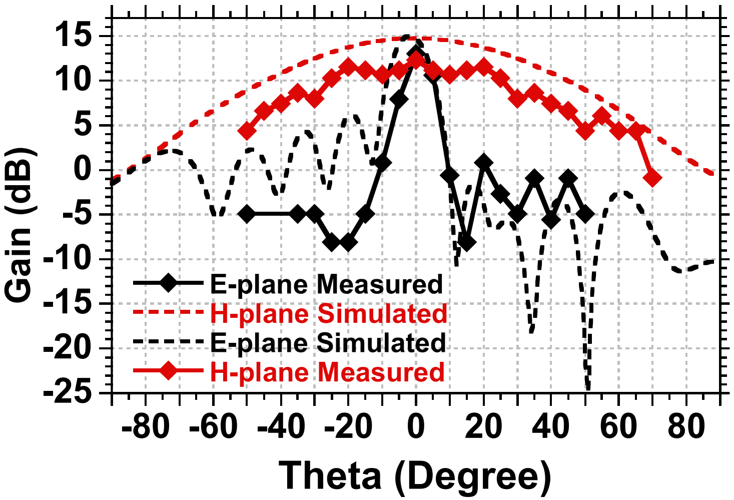
Antenna Design and Measurements

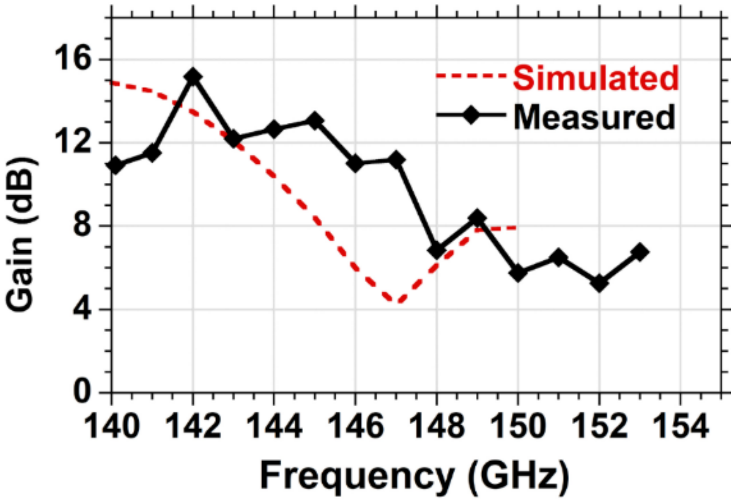
136 GHz (measured @140 GHz, return loss is not available)



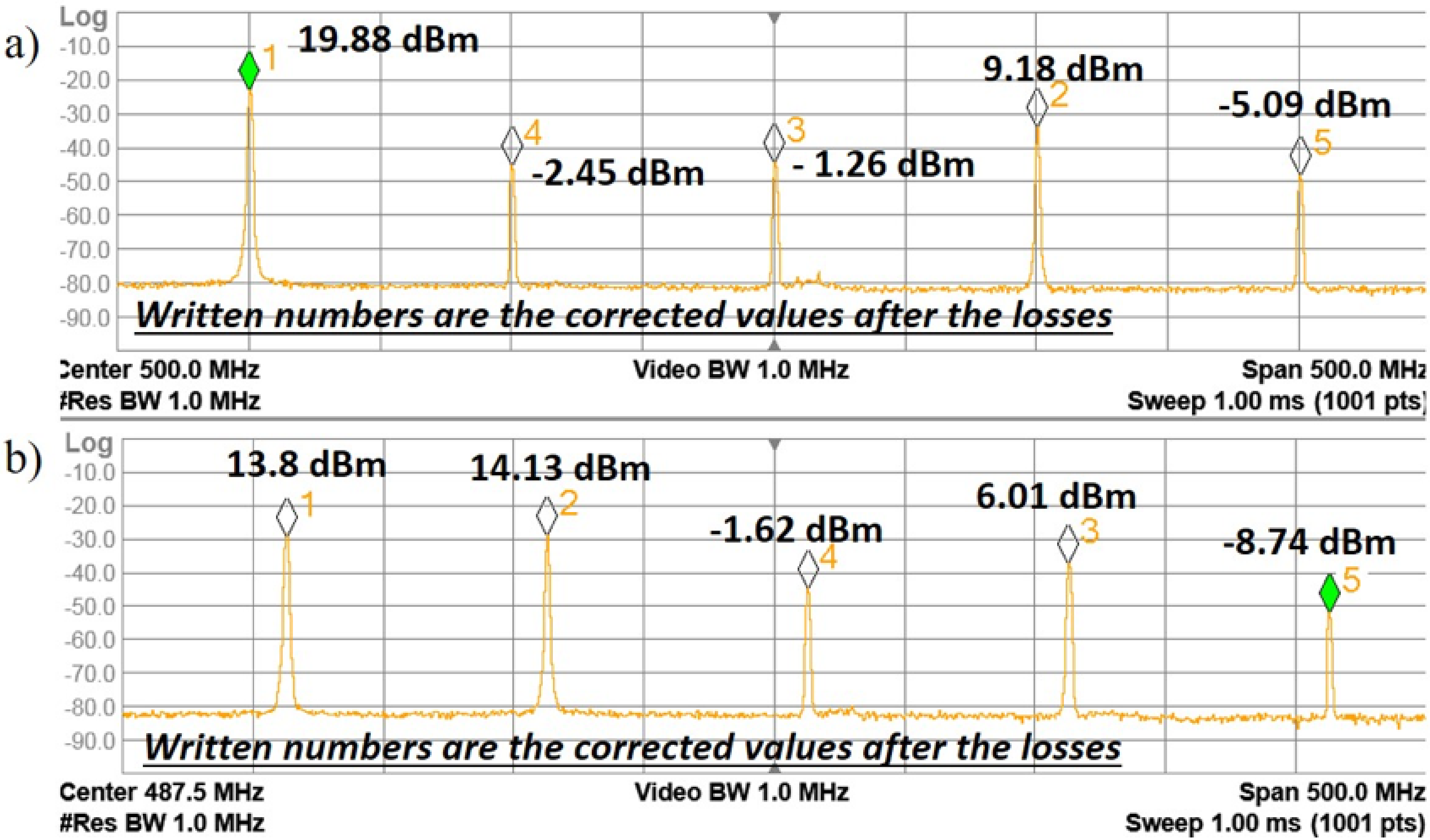


140 GHz (measured @144 GHz)

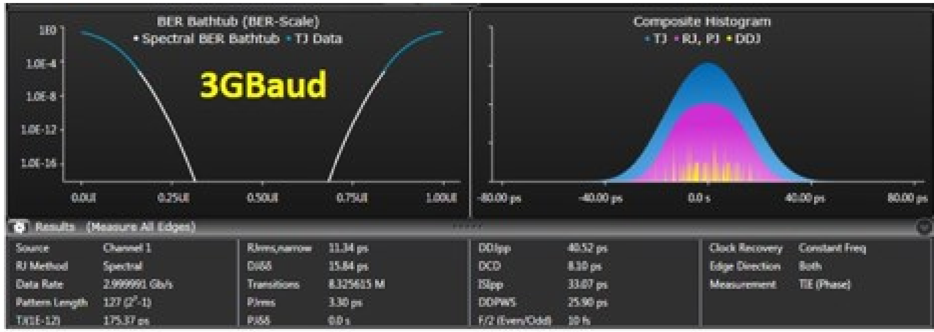


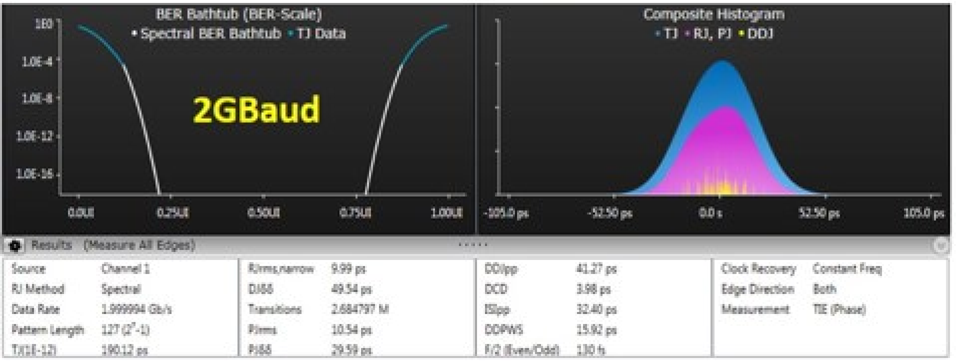


Transmitter Beamforming Gain



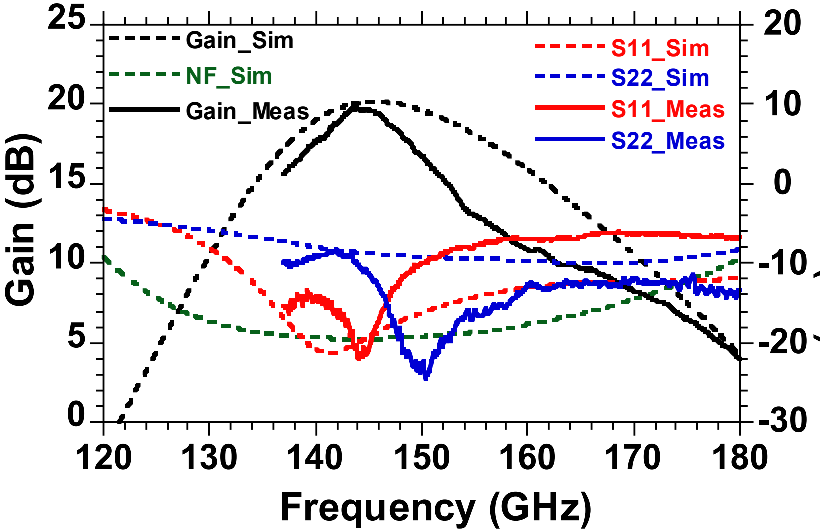
Transceiver (Bathtub)





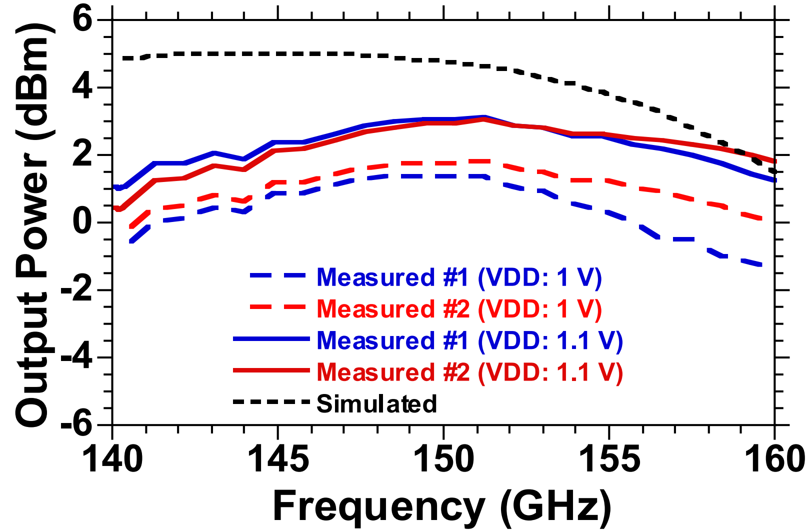
Measurements – Circuit Blocks

LNA



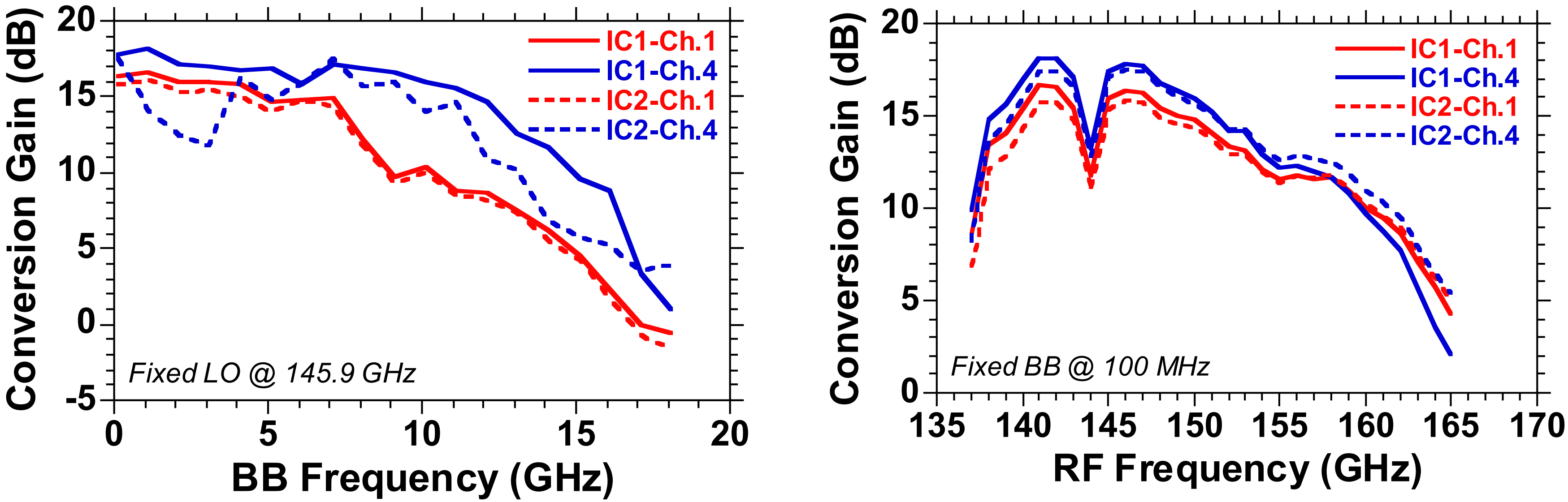
41 mA @ 1V
Peak Gain = 19.9 dB @ 145 GHz
3-dB BW = 10GHz

x9 LO Multiplier



98 mA @ 1V
Peak output power = 1.5 dBm
@ 148 GHz

Measurements – Receiver Channel



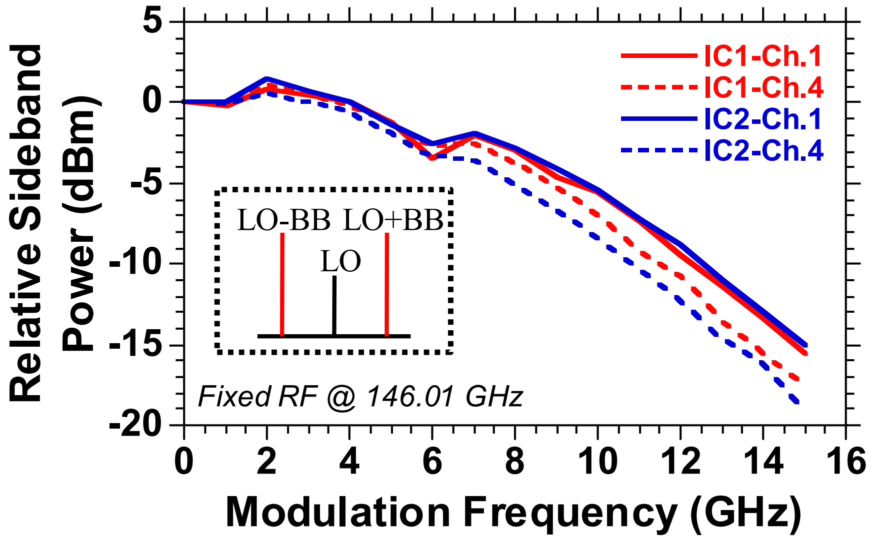
18 dB conversion gain

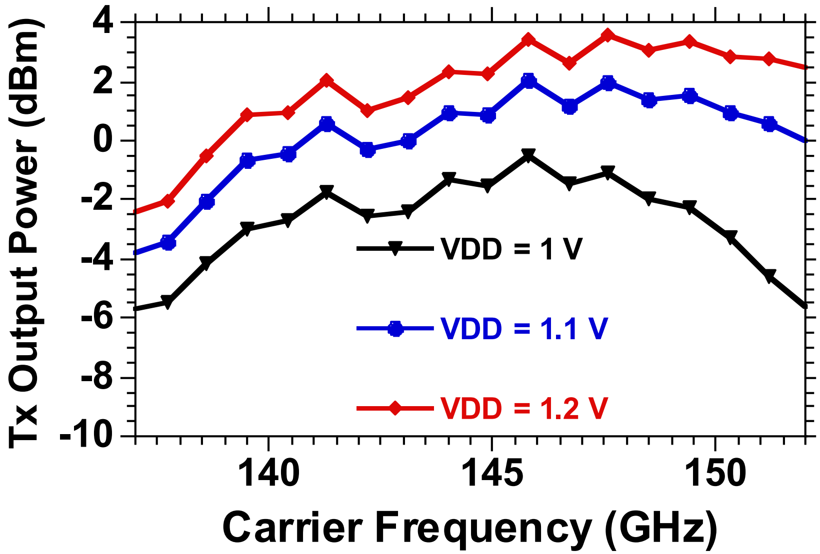
12 GHz 3-dB BW

Narrow-band notch in RF response - limits the data rate

163 mA + 109 mA + 223 mA = **495 mA @ 1V**

Measurements – Transmitter Channel





3-dB modulation bandwidth ~ 6 - 8 GHz

Total transmitter output power: -2 dBm with 1 V supply,

3 dBm with 1.2 V supply **@ 145 GHz**

161 mA + 94 mA + 208 mA = **463 mA @ 1V**

Outline

- Motivation
- 140 GHz Transceiver in 45 nm CMOS SOI
- Proposed Low-Cost Package
  - 2-Channel Transmitter
  - 4-Channel Receiver
- Wirebond Transition Design
- 140 GHz Antenna Design and Measurements
- System Experiments and Results
- Conclusion and Future Direction