Silicon Monolithic Integrated Circuits in RF Systems (SiRF2021), San Diego, CA, 21 January 2021

IC, Package, and System Technologies for 140GHz MIMO hubs and 210/280GHz MIMO backhaul links

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University of California, Santa Barbara
Munkyo Seo
Sungkyunkwan University (on sabbatical at UCSB)

This work was supported in part by the Semiconductor Research Corporation (SRC) and DARPA.

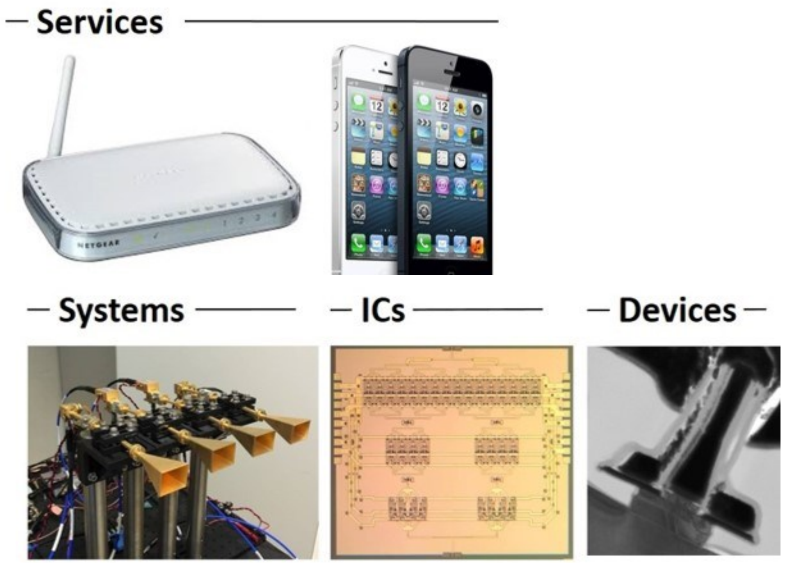
Beyond-5G Wireless

Wireless networks: exploding demand.

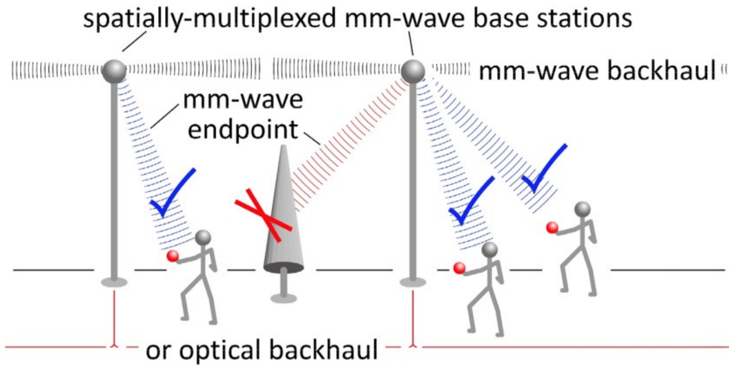
Immediate industry response: 5G.
~10-100GHz carriers.
increased spectrum, extensive beamforming

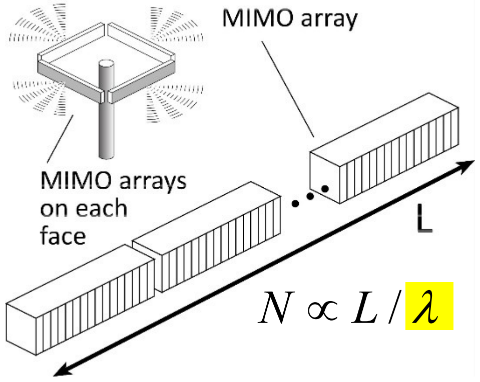
Next generation (6G ??): above 100GHz..
greatly increased spectrum, massive spatial multiplexing

JUMP Centers: research commercialized in 15 years

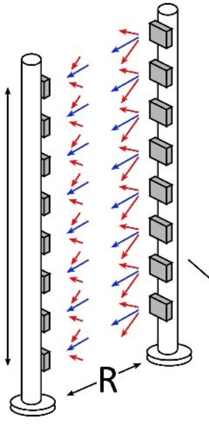


ComSenTer: 100-300GHz carriers, massive spatial multiplexing
→ Terabit hubs and backhaul links, high-resolution imaging radar

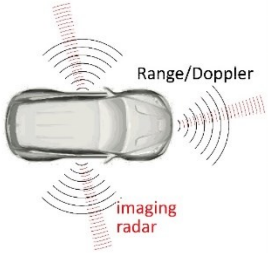




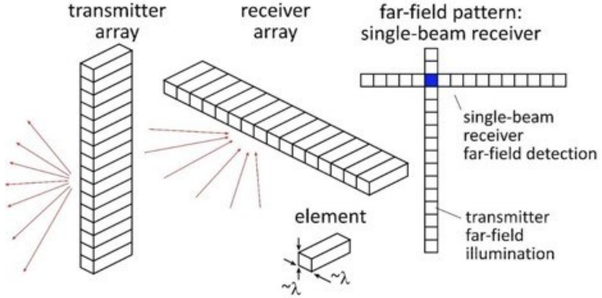
$N \propto L / \lambda$



$N \propto L^2 / \lambda R$

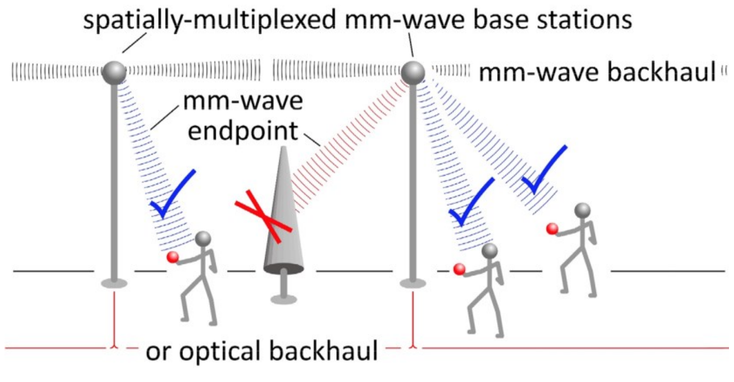


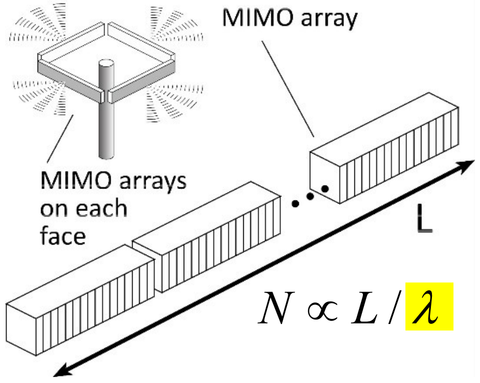
$\Delta\theta \propto \lambda / L$



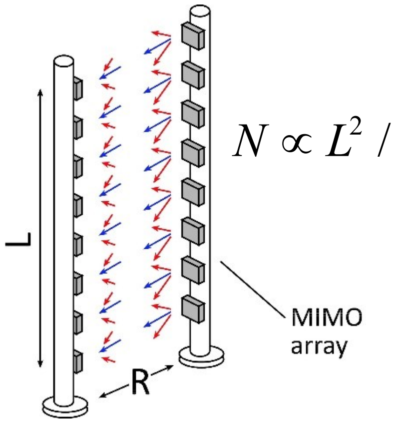
Benefits of Short Wavelengths

Communications: Massive spatial multiplexing, massive # of parallel channels. Also, more spectrum!



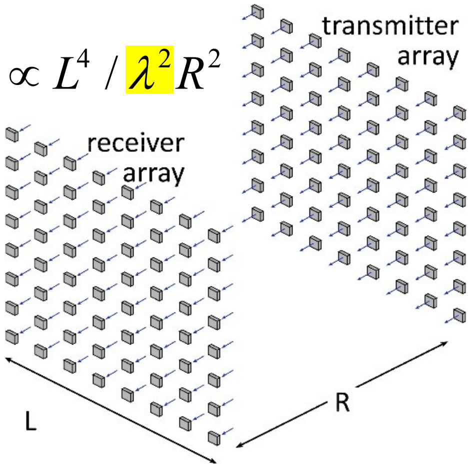


$N \propto L/\lambda$

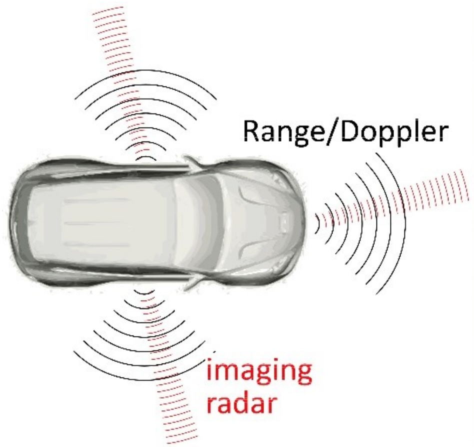


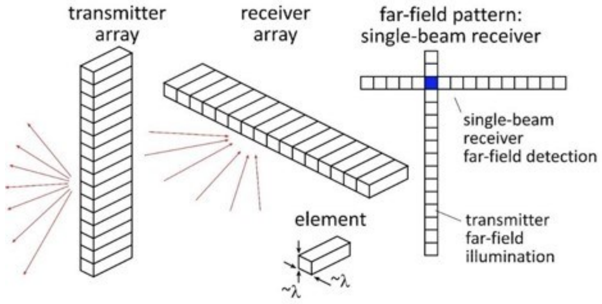
$N \propto L^2/\lambda R$

$N \propto L^4/\lambda^2 R^2$



Imaging: very fine angular resolution





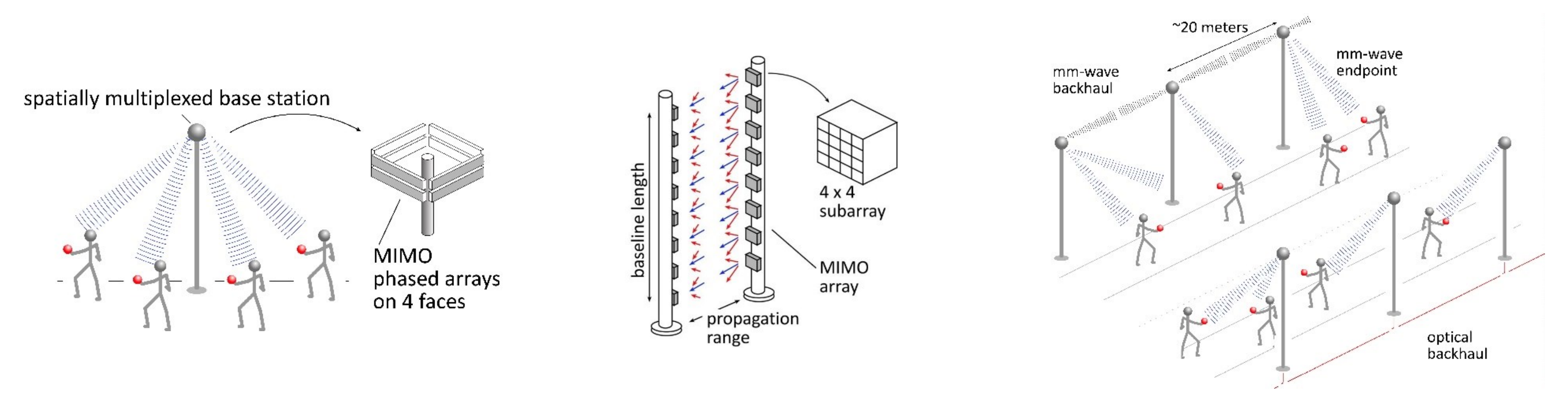
$\Delta\theta \propto \lambda/L$

But:

High losses in foul or humid weather.
High λ^2/R^2 path losses.
ICs: poorer PAs & LNAs.
Beams easily blocked.

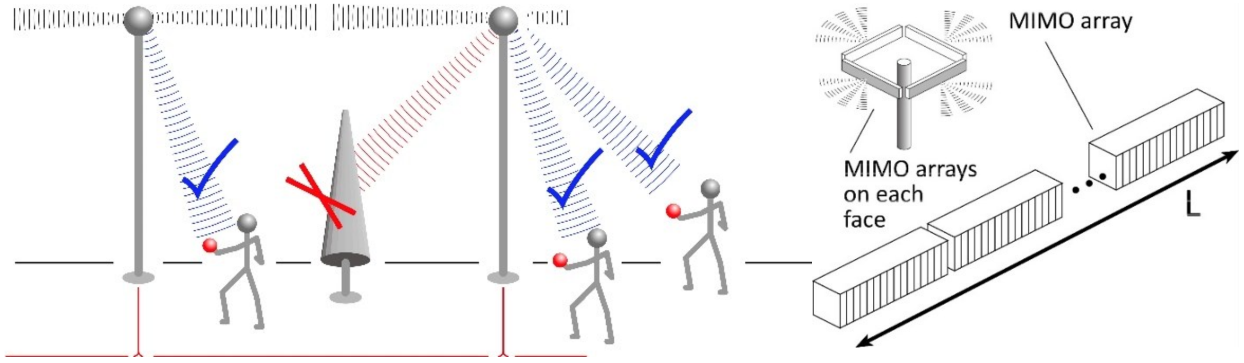
100-340GHz wireless:
terabit capacity,
short range,
highly intermittent

100-300 GHz: Applications

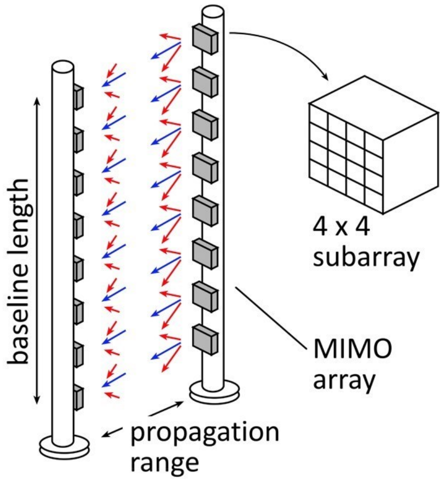


100-300GHz: Demonstration Systems

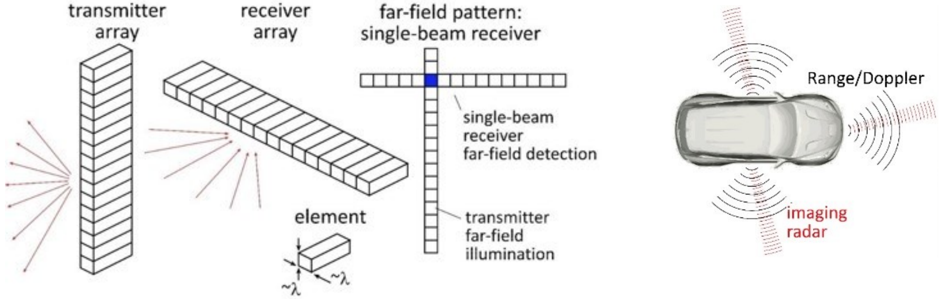
MIMO hub: 140GHz

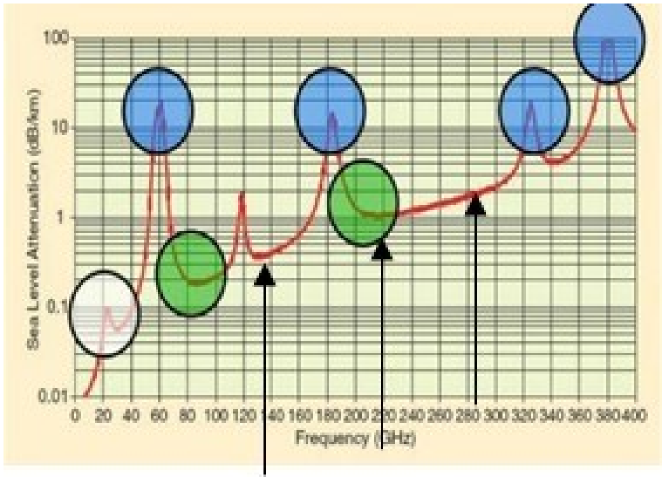


Point-point MIMO: 210, 280GHz



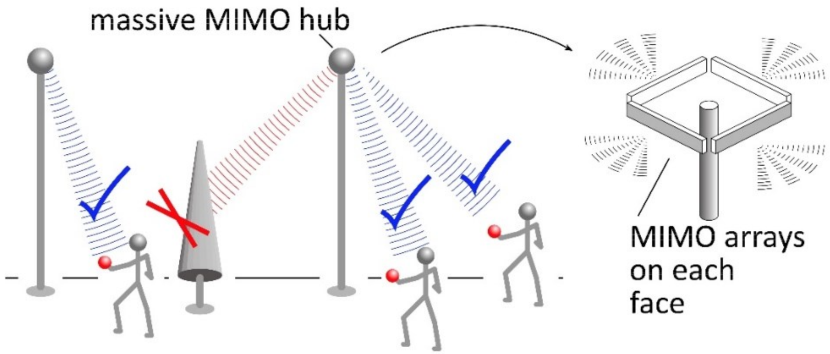
Cross-linear-array imaging: 210, 280GHz

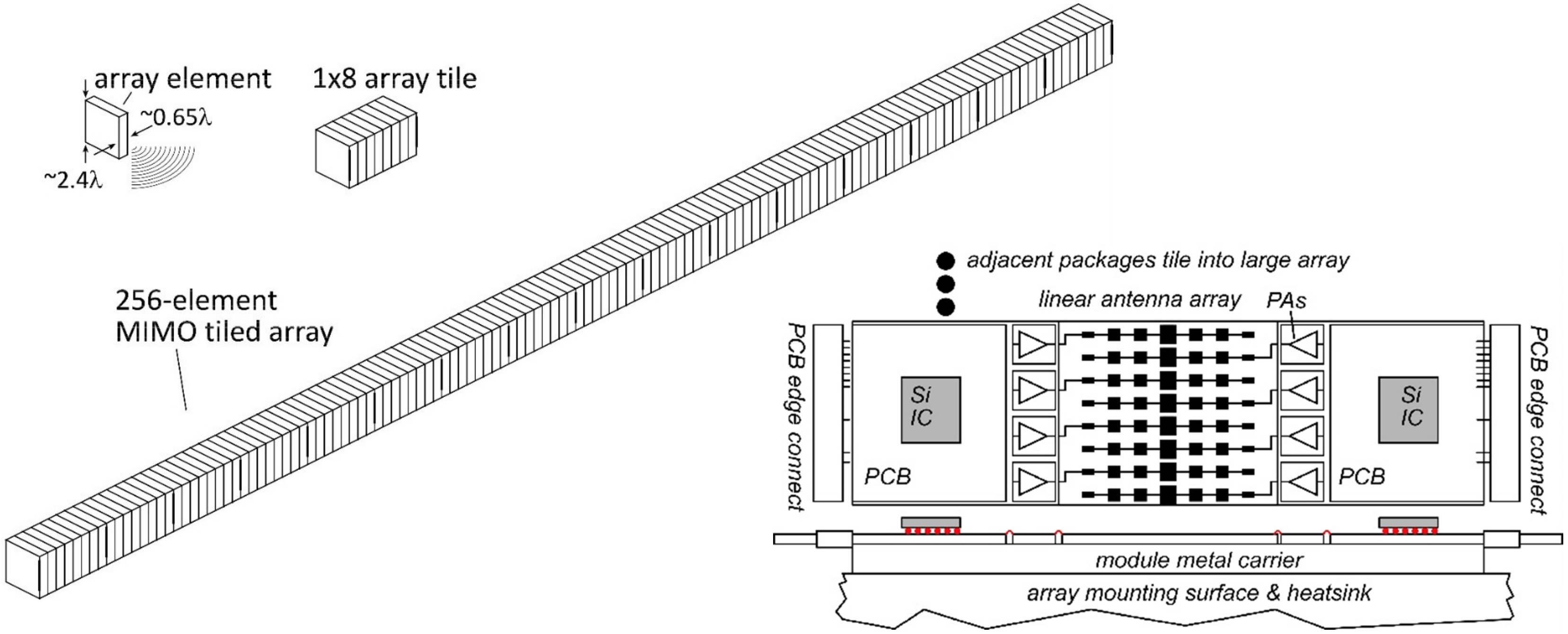


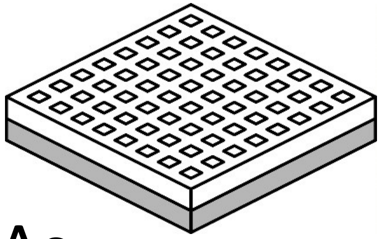


UCSB FCC permit: 137 +/- 15 GHz, 210 +/- 15 GHz, 280 +/- 15 GHz

140GHz massive MIMO hub







Handset:
8 × 8 array
(9×9mm)

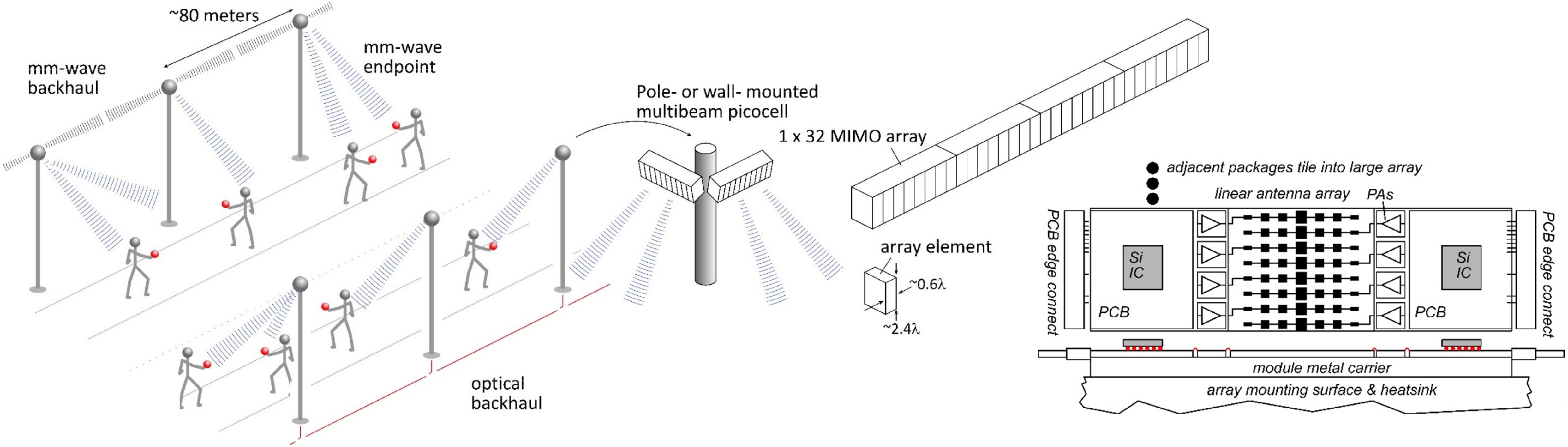
0.5-5 Tb/s spatially-multiplexed 140GHz base station

128 users/face, 4 faces. P_{1dB}=21 dB_m PAs, F=8dB LNAs

512 total users @ 1 user/beam, 1,10 Gb/s/beam;

230, 100 m range in 50mm/hr rain with **17**dB total margins

140GHz moderate-MIMO hub

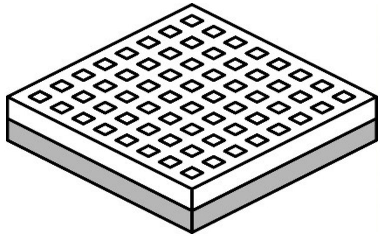


If demo uses 32-element array (four 1×8 modules):

16 users/array. P_{1dB}=21 dB_m PAs, F=8dB LNAs

1,10 Gb/s/beam→ 16, 160 Gb/s total capacity

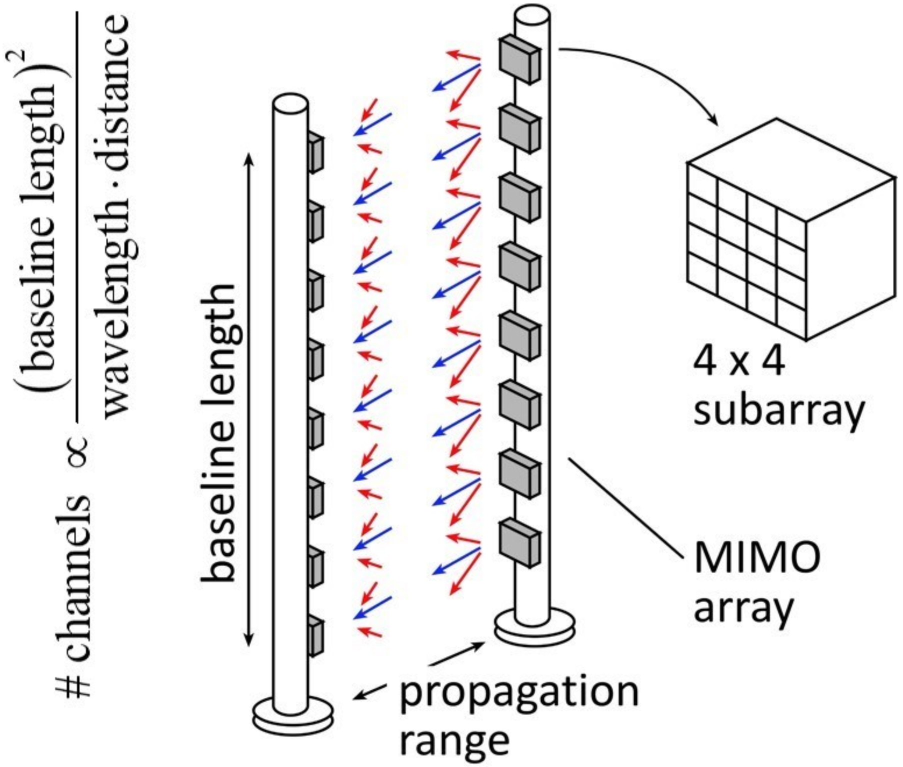
40, 70 m range in 50mm/hr rain with **17**dB total margins

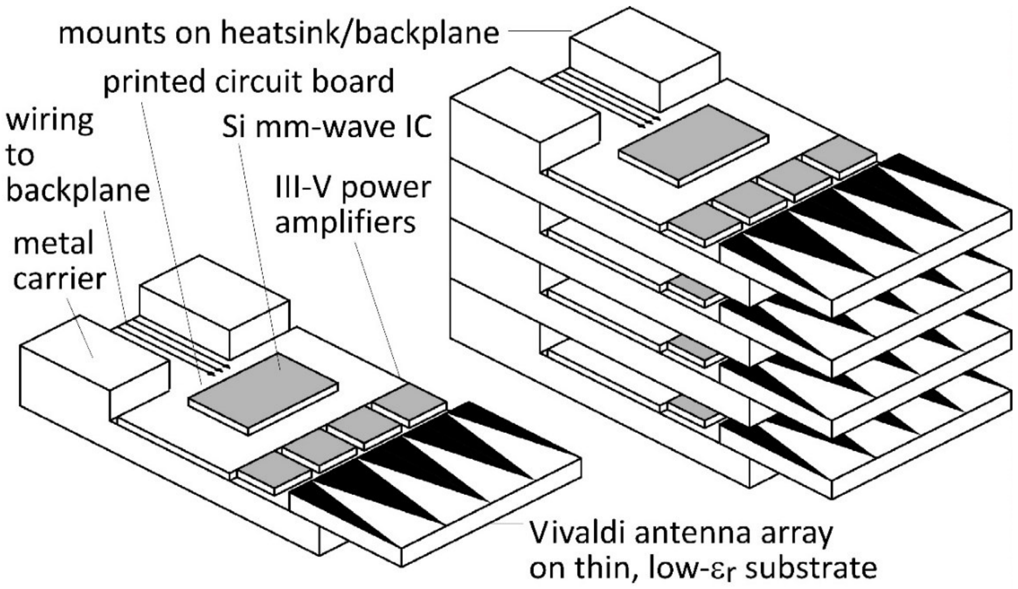


Handset:
8 × 8 array
(9×9mm)

Range varies as (# hub elements)$^{0.5}$ → (Service area/element) is constant

210 GHz, 640 Gb/s MIMO Backhaul

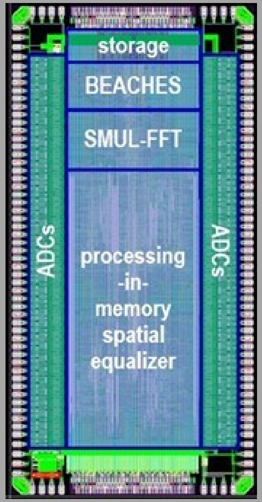


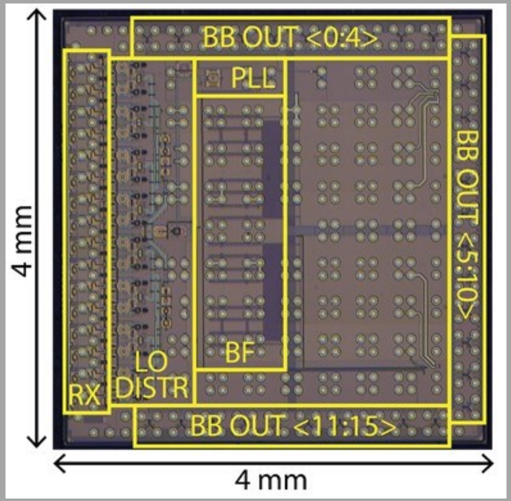


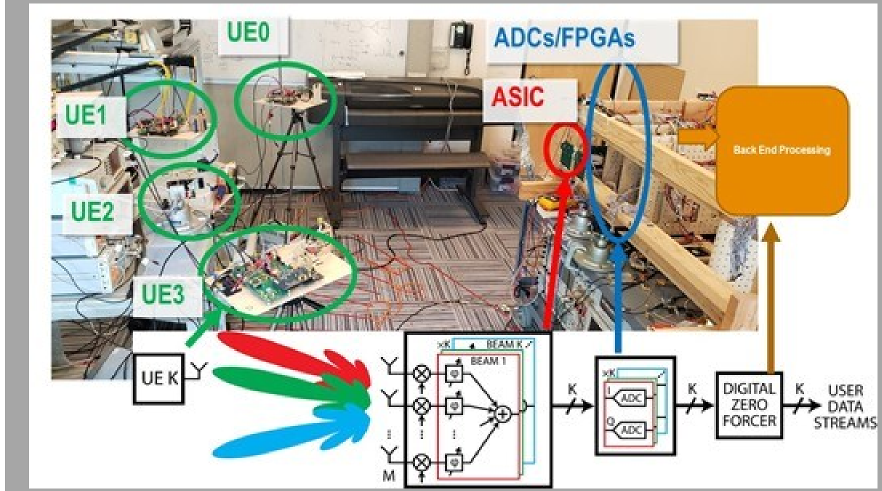
8-element MIMO array
3.1 m baseline.
80Gb/s/subarray→ 640Gb/s total
4 × 4 sub-arrays → 8 degree beamsteering

Key link parameters
500 meters range in 50 mm/hr rain; 23 dB/km
20 dB total margins:
    packaging loss, obstruction, operating, design, aging
PAs: 18dBm $=P_{1dB}$ (per element)
LNAs: 6dB noise figure

Overall ComSenTer Research







SRC JUMP

ComSenTer: Wireless Research

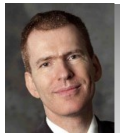
ComSenTer
COMMUNICATIONS SENSING TERAHERTZ

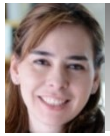
Systems

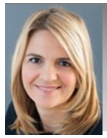

Sundeep Rangan
Networks, Applications, MIMO, Power


Upamanyu Madhow
UC Santa Barbara
MIMO algorithms
Imaging algorithms
Compressive imaging


Christoph Studer
Cornell
MIMO algorithms
VLSI MIMO processors


Andreas Molisch
USC
100-300GHz propagation measurements


Dina Katabi
MIT
Applications: VR, cars, …


Danijela Cabric
UCLA
MIMO algorithms

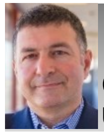
ICs


Ali Niknejad
UC Berkeley
mm-wave CMOS: hub
mm-wave arrays
mm-wave MIMO


James Buckwalter
UC Santa Barbara
efficient PAs
III-V arrays


Kenneth O
UT Dallas
200-300GHz passive CMOS

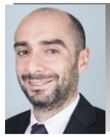

Harish Krishnaswamy
Columbia
STAR
Novel MIMO


Gabriel Rebeiz
UC San Diego
mm-wave CMOS: handset
mm-wave arrays


Alyosha Molnar
Cornell
N-path mixers
MIMO ADCs


Elad Alon
UC Berkeley
design automation
equalizers


Vladimir Stojanovic
UC Berkeley
photonic links


Hossein Hashemi
USC
acoustic filters

Massive MIMO demo.


Borivoje Nikolic
UC Berkeley
VLSI design automation
VLSI MIMO processors

Compressive imaging


Amin Arbabian
Stanford
140GHz radar chipsets and arrays

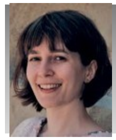
Transistors


Umesh Mishra
UC Santa Barbara
N-polar GaN HEMTs for 140, 210GHz

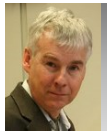

Huili (Grace) Xing
Cornell
AlN/GaN HEMTs for 140, 210GHz


Debdeep Jena
Cornell
GaN HEMTs on Si


Srabanti Chowdhury
UC Davis
Diamond cooling for GaN

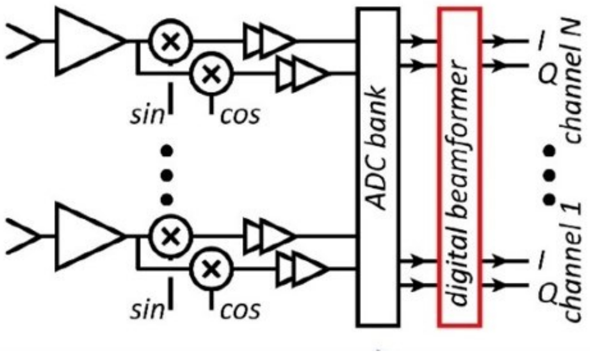

Susanne Stemmer
UC Santa Barbara
transistors in novel materials

140/210/290GHz arrays for demos.

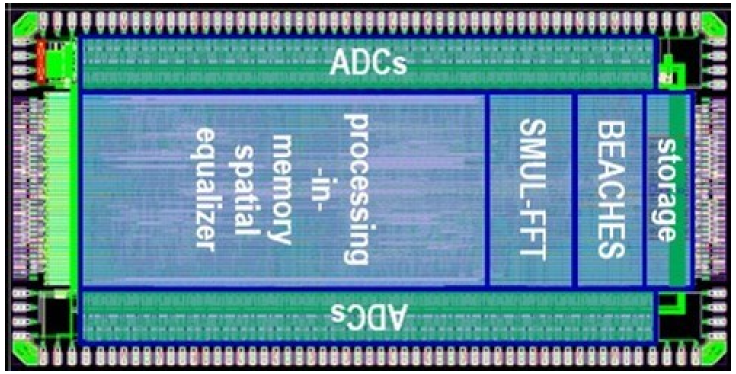

Mark Rodwell
UC Santa Barbara
THz HBTs for PAs
THz HEMTs for LNAs

ComSenTer Research: Systems

Digital beamforming:



- **ADCs/DACs**: only 3-4 bit ADC/DACs required (Madhow, Studer)
- **Linearity**: Amplifier P_{1dB} need be only 3dB above average power (Madhow).
- **Phase noise**: Requirements same as for SISO (Alon, Madhow, Niknejad, Rodwell)
- **Efficient digital beamforming**: beamspace algorithm=complexity ~N× log(N) (Madhow, Studer)
- **Efficient digital beamforming**: low-resolution matrix (Studer, Molnar)
- **Efficient channel estimation** : fast beamspace algorithm (Studer)
- **Efficiently addressing true-time-delay problem**: "rainbow" FFT algorithm (Madhow, Cabric)



Other issues:

- **Propagation models and measurements**
- **Blockage probability, mesh networks, network protocols**

JUMP ComSenTer Research: ICs

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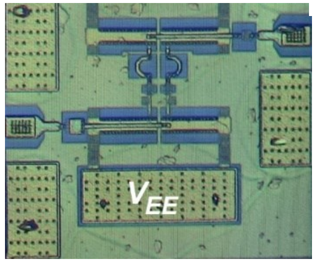
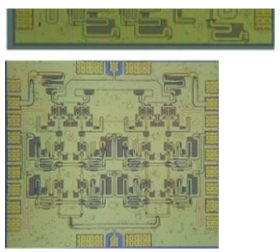
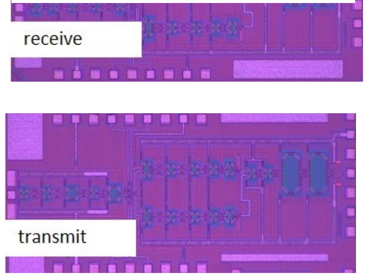
Record-PAE Class B 140GHz PAs Buckwalter



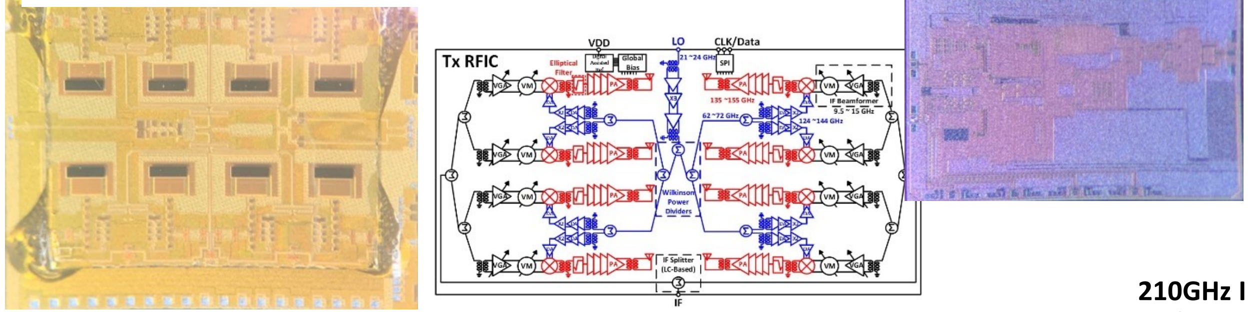
Record-PAE Class A 100-200mW 140GHz PAs Rodwell



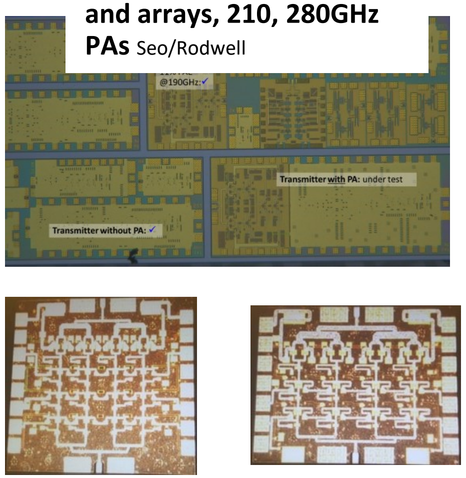
140GHz CMOS handset ICs Rodwell



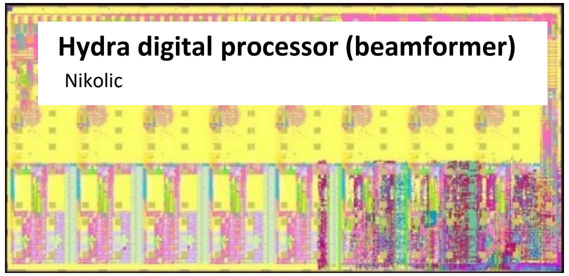
140GHz 8-element handset TRX, RCVR arrays and PAs Rebeiz



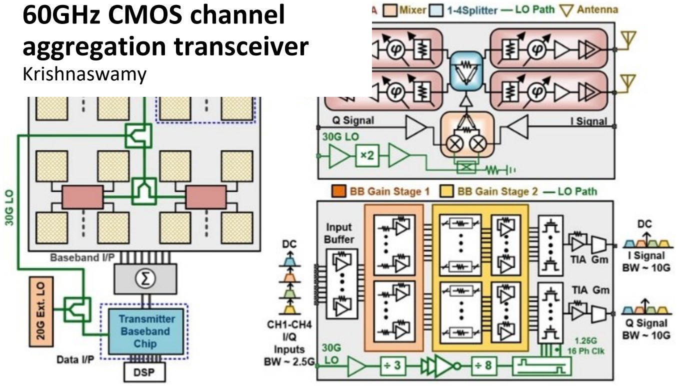
210GHz InP transceivers and arrays, 210, 280GHz PAs Seo/Rodwell



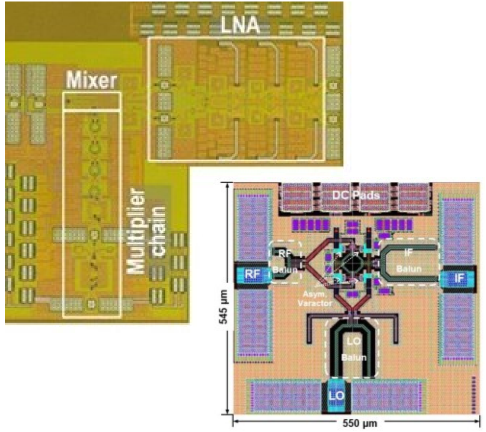
Hydra digital processor (beamformer)
Nikolic



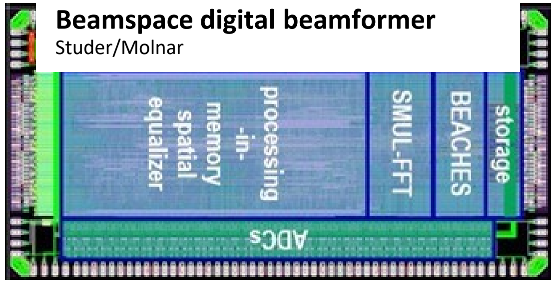
60GHz CMOS channel aggregation transceiver
Krishnaswamy



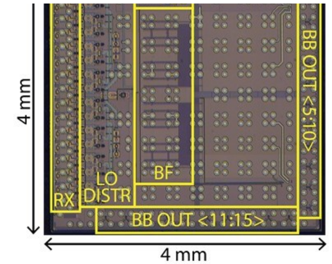
280GHz CMOS upconvert mixers
420 GHz CMOS receiver o



Beamspace digital beamformer
Studer/Molnar



75GHz MIMO front-ends
Niknejad, Alon, Nikolic



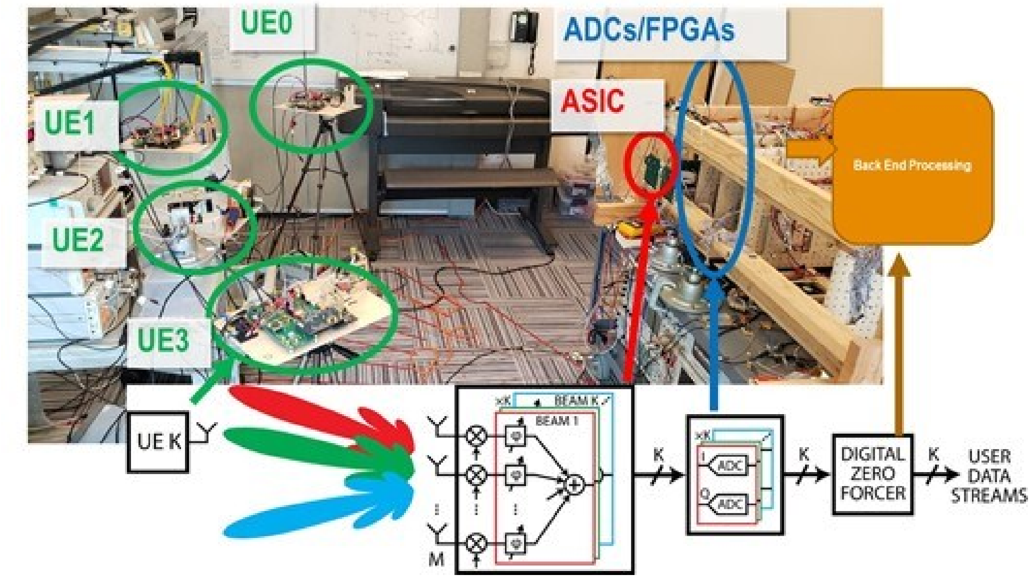
Not shown:
140GHz, 210GHz outphasing transmitters Buckwalter
mm-wave N-path mixers Molnar
GaN active circulators Krishnaswamy
140GHz GaN PAs Buckwalter

ComSenTer Research: Demos

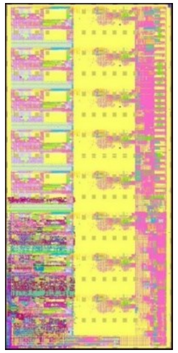
BWRC Testbed:

RF: 75GHz BWRC & 140GHz UCSB

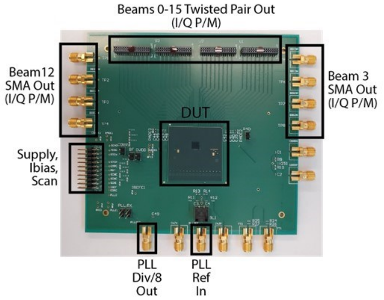
Digital: FPGA, COTS Hydra, ASIC Hydra



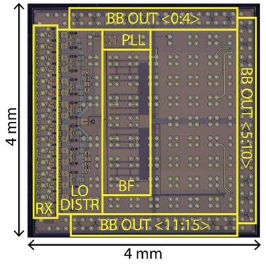
Hydra digital processor
Nikolic



75GHz MIMO Module
Niknejad



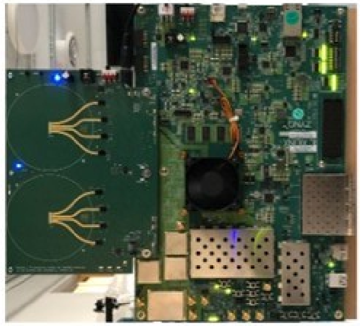
75GHz MIMO IC
Niknejad



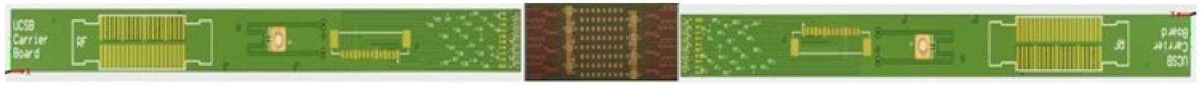
NYU Testbed:

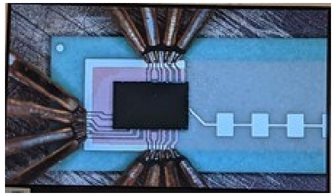
RF: 60GHz SDR (NYU) & 140GHz UCSB

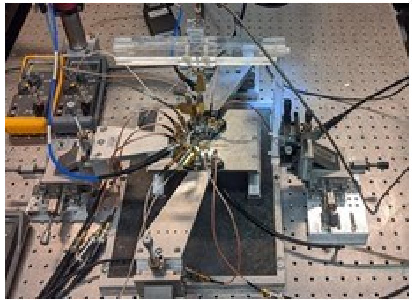
Digital: FPGA



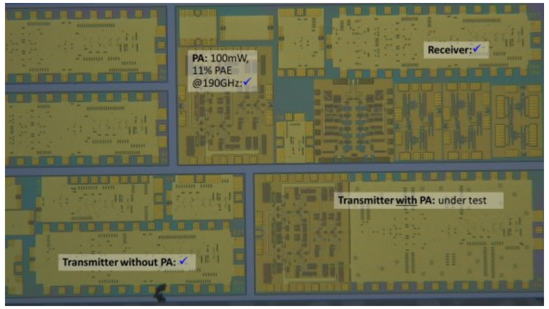
140GHz MIMO hub modules UCSB





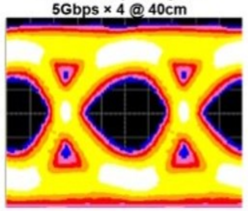


ICs for 210GHz Demo
Rodwell

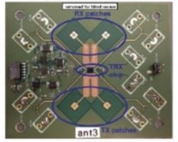


120GHz MIMO link
Niknejad

Measured Eye Diagram
5Gbps × 4 @ 40cm

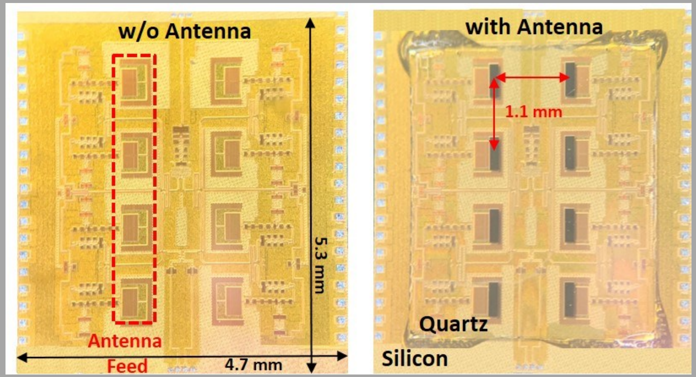


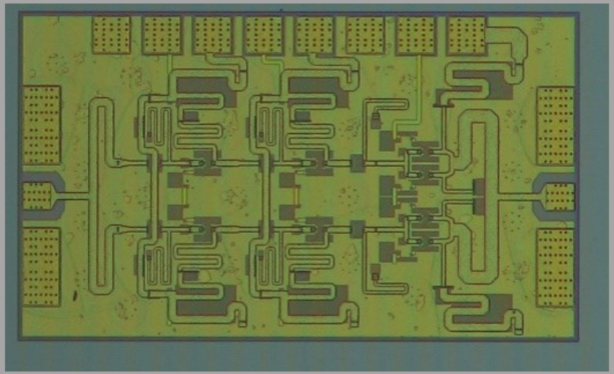
Chip assembled onto test PCB

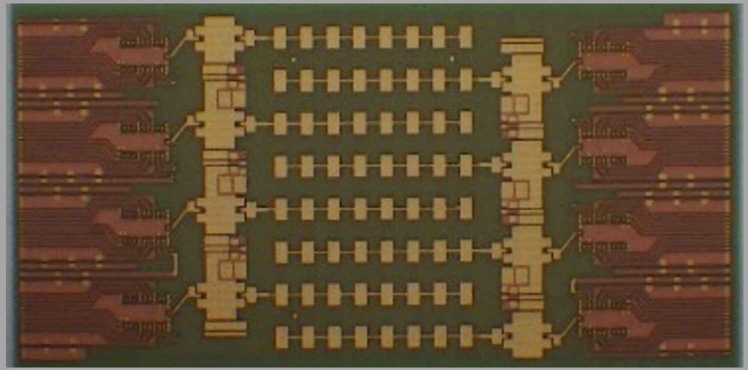


130GHz MIMO link
Arabian

140GHz ICs and Modules

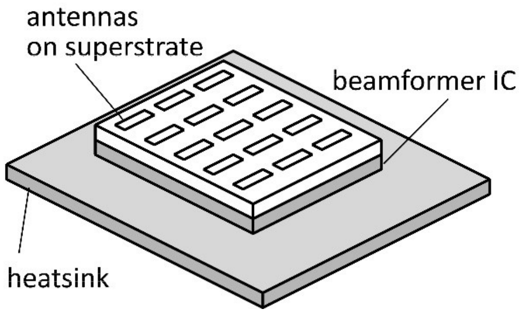


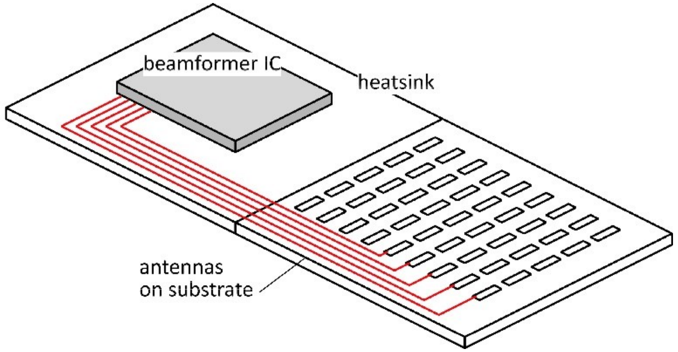




The mm-wave module design problem

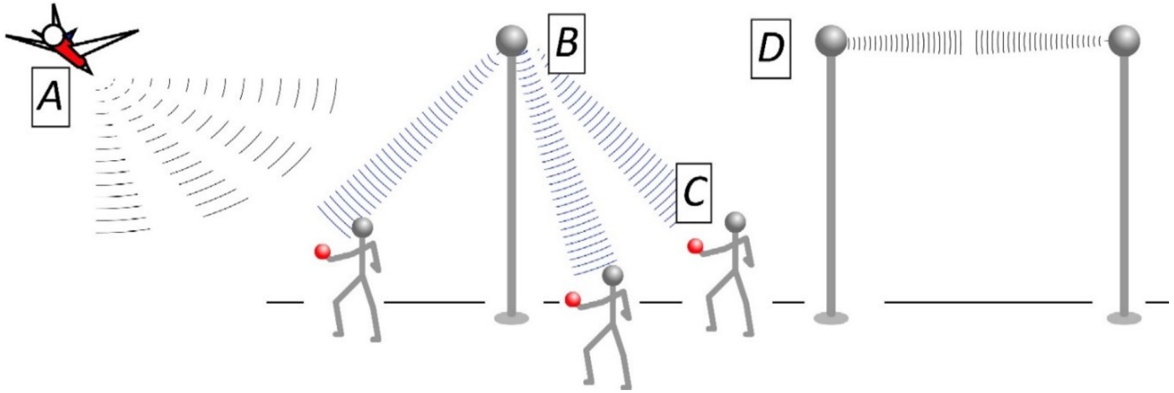
How to make the IC electronics fit ?
How to avoid catastrophic signal losses ?
How to remove the heat ?

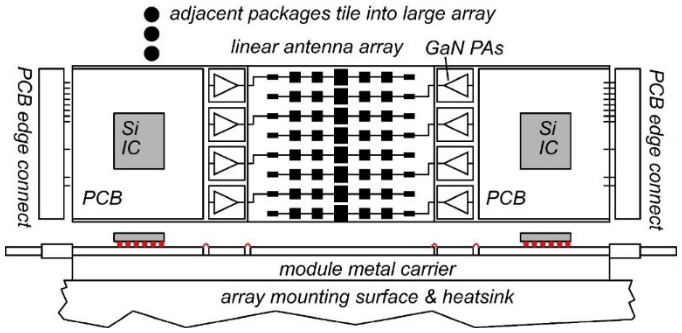


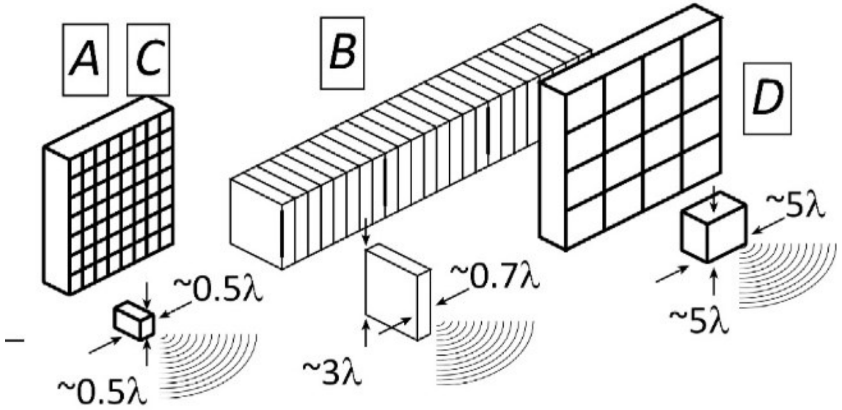


Not all systems steer in two planes...
    ...some steer in only one.

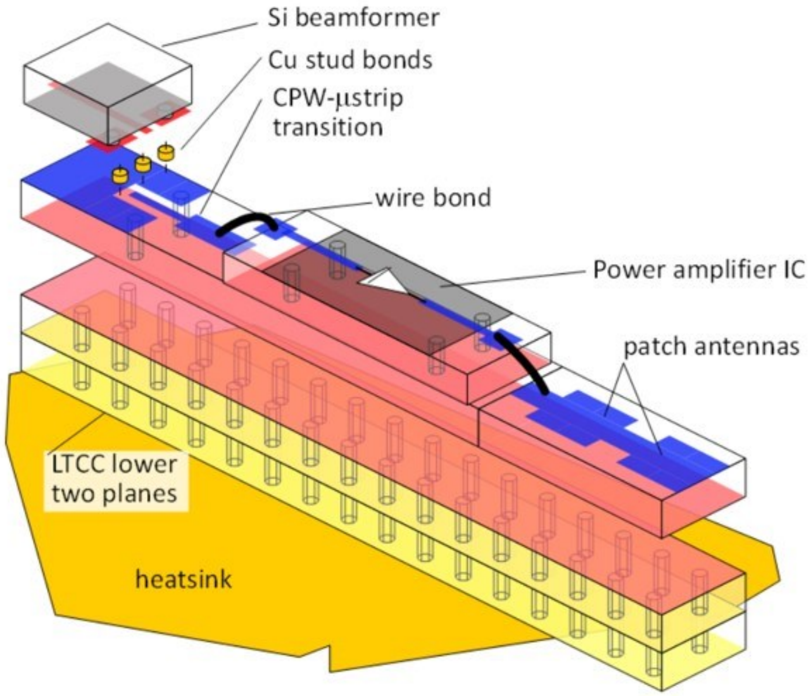
Not all systems steer over 180 degrees...
    ...some steer a smaller angular range



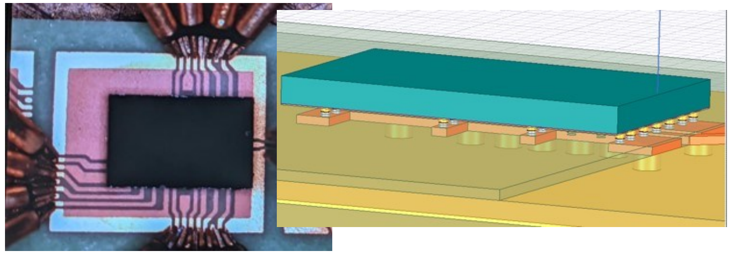




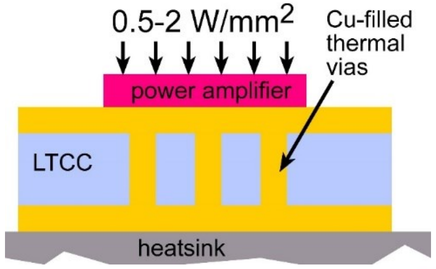
140GHz hub: packaging challenges



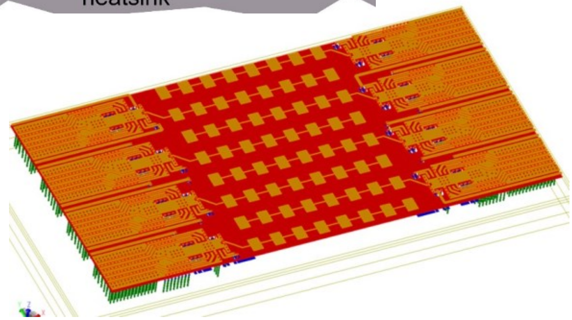
IC-package interconnects
Difficult at > 100 GHz



Removing heat
Thermal vias are marginal

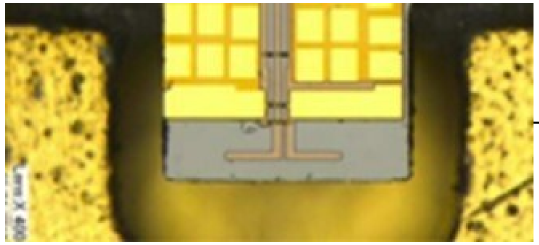


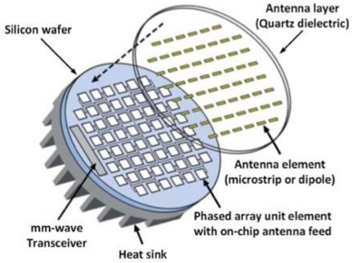
Interconnect density
Dense wiring for DC, LO, IF, control.
Hard to fit these all in.



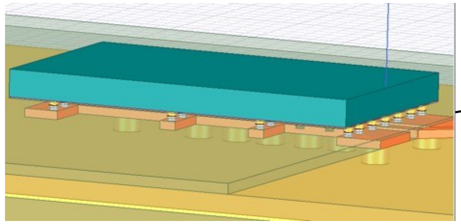
Economies of scale
Advanced packaging standards require sophisticated tools
High-volume orders only
Hard for small-volume orders (research, universities)
Packaging industry is moving offshore

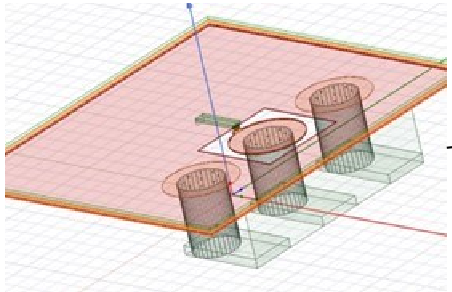
100-300GHz IC-package connections


Deal, IEEE Trans THz, Sept 2011



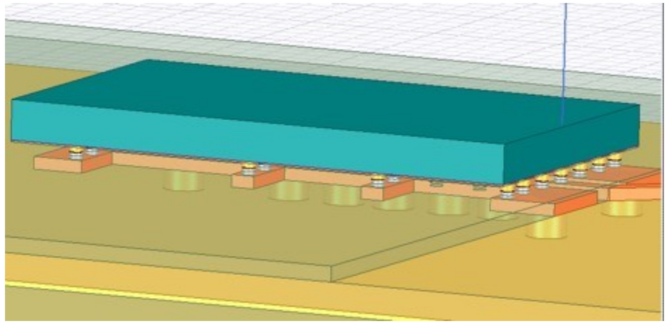
G. Rebeiz





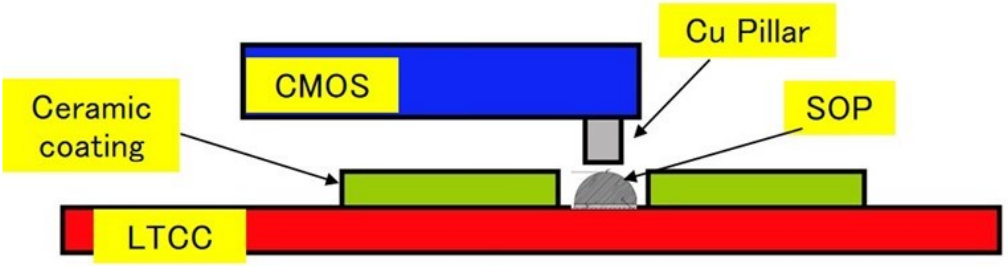
type	Frequency	technology	cost	heatsinking
micromachined waveguide interface	1000 GHz	Research. Cheap one day ?	**high** ✗	good
ribbon, mesh bond	200 GHz	Handcrafted.	**high** ✗	good
patch antennas on superstrate	1000 GHz	Straightforward	low	good
Cu stud flip-chip	>200 GHz	Industry standard	low	ok, **marginal for PA** ✗
hot vias	200 GHz	Development	low ?	good
(ball) wirebonds	**100 GHz** ✗	Industry standard	low	good

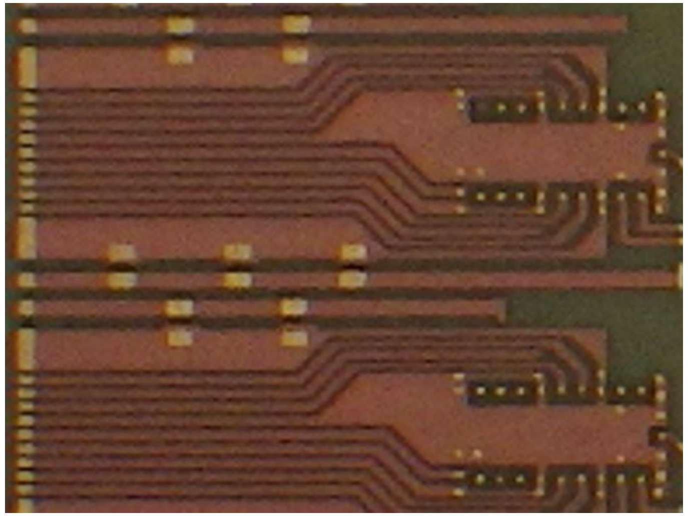
Cu Pillars vs. C4 Solder-bonds



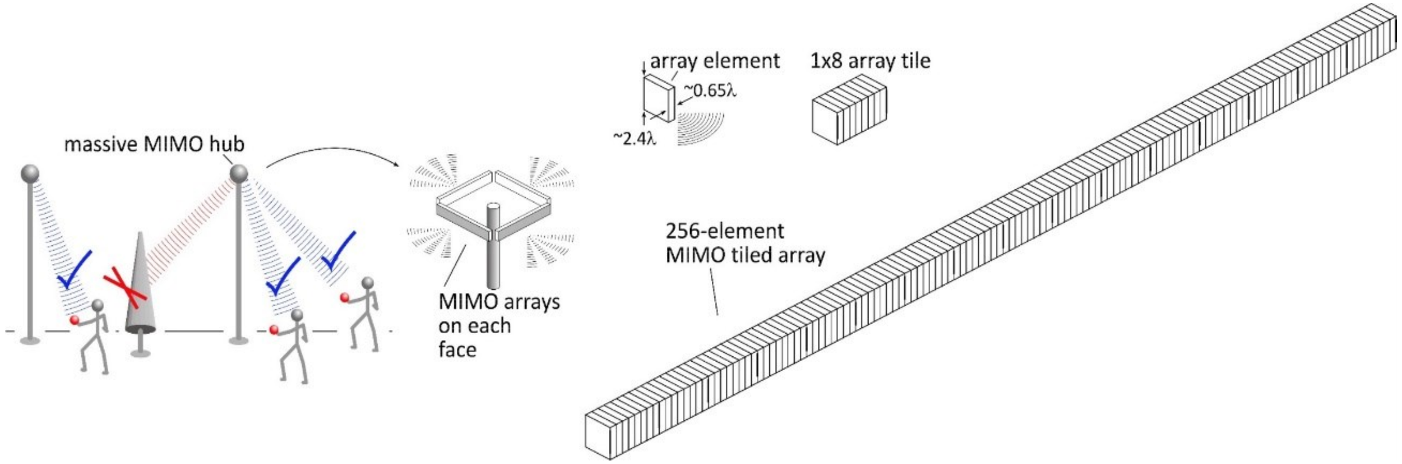
Cu pillars:
Small geometry: 50 μm diameter
Excellent 140GHz characteristics: ~0.7dB loss without tuning.
Requires solder mask with very small openings (<75 μm).
Requires tight lithographic resolution on interposer.

C4 bonds:
Readily handled by LTCC and PCB board and assembly firms.
140GHz parasitics require impedance-tuning on LTCC carriers.
0.5dB loss feasible after tuning

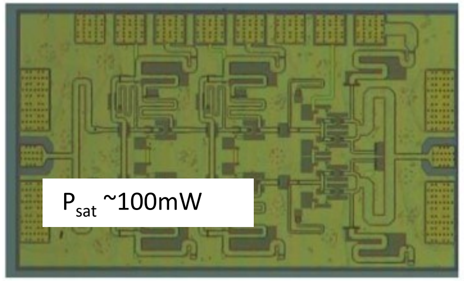




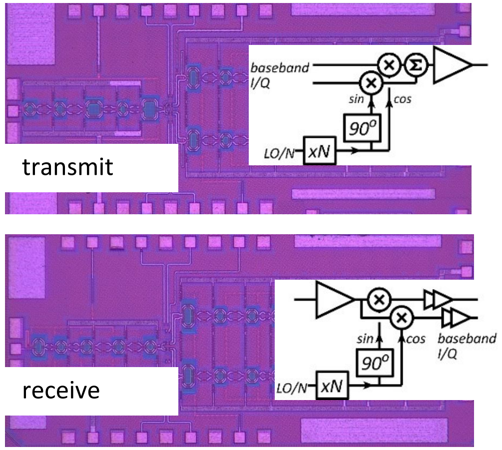
140GHz massive MIMO hub modules



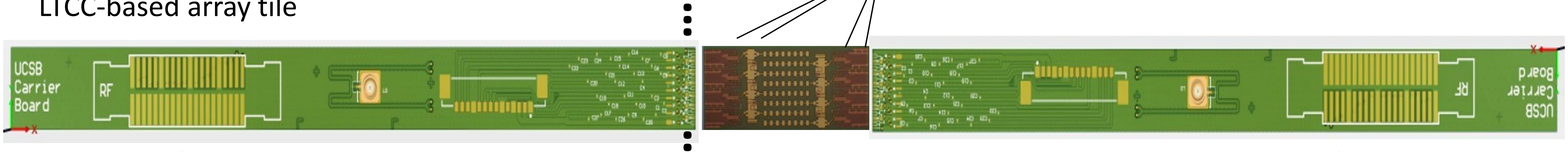
140GHz InP PAs



140GHz CMOS ICs



LTCC-based array tile



connector interface board

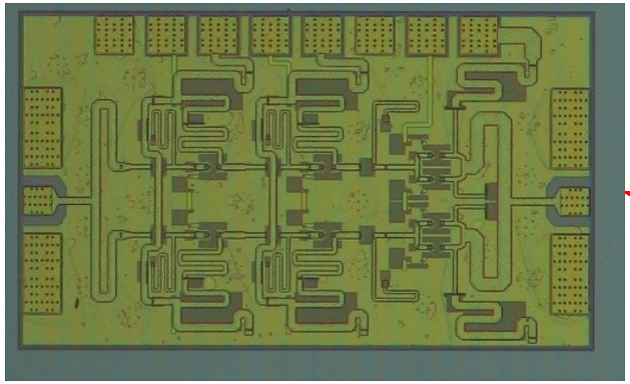
Kyocera LTCC carrier

connector interface board

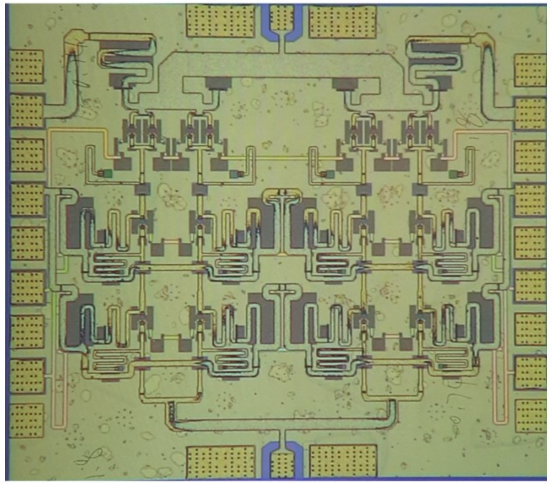
Farid, Ahmed, Rodwell, UCSB; Flynn, Dunn, Niknejad, Nikolic, BWRC; Rebeiz, UCSD

140GHz hub: ICs & Antennas

110mW InP Power Amplifier
20.8% PAE

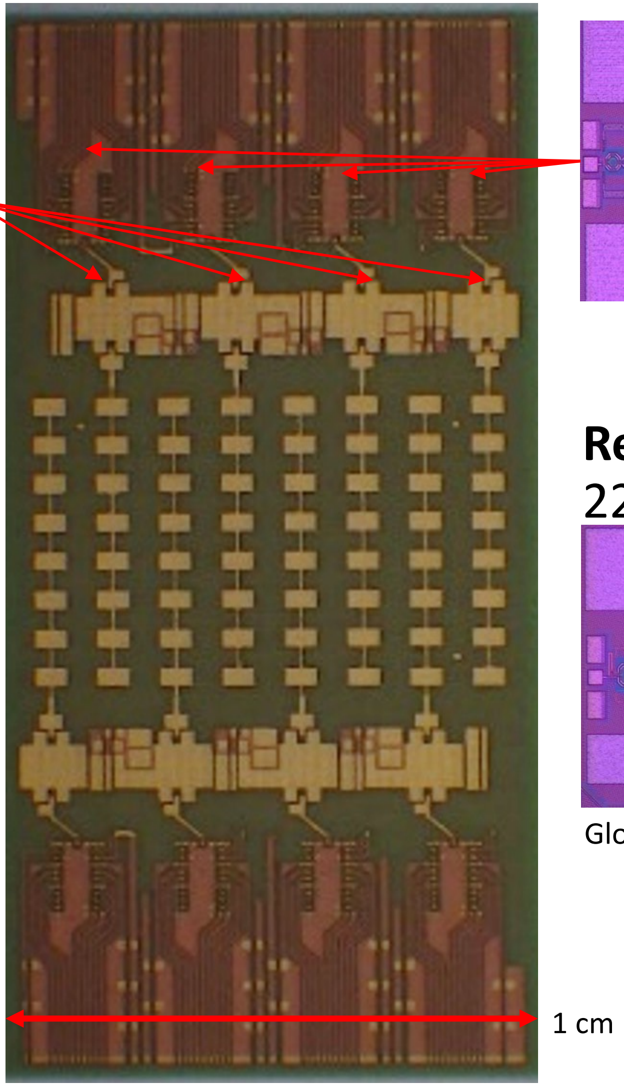


190mW InP Power Amplifier
16.7% PAE



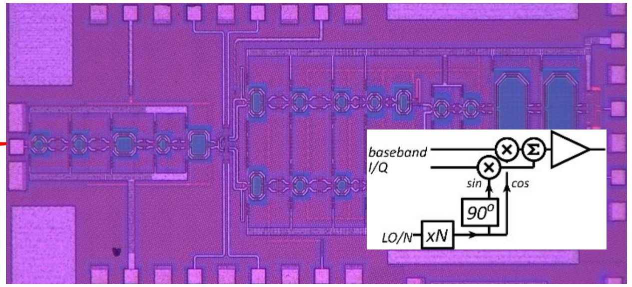
Teledyne InP HBT

LTCC Array module

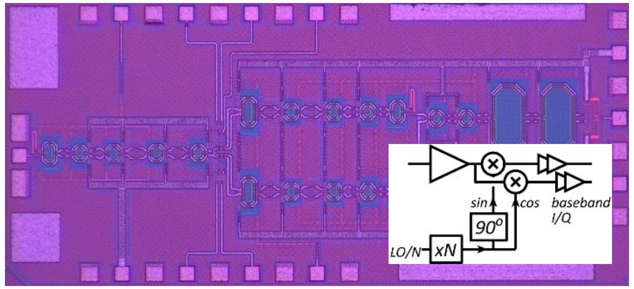


Kyocera

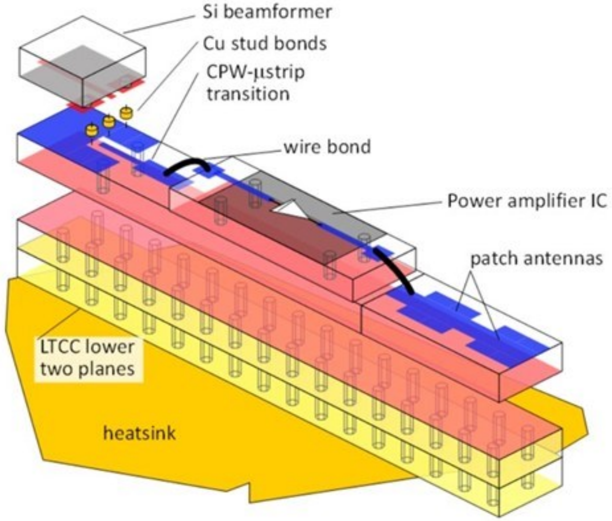
CMOS Transmitter IC
22nm SOI CMOS.



Receiver IC
22nm SOI CMOS.



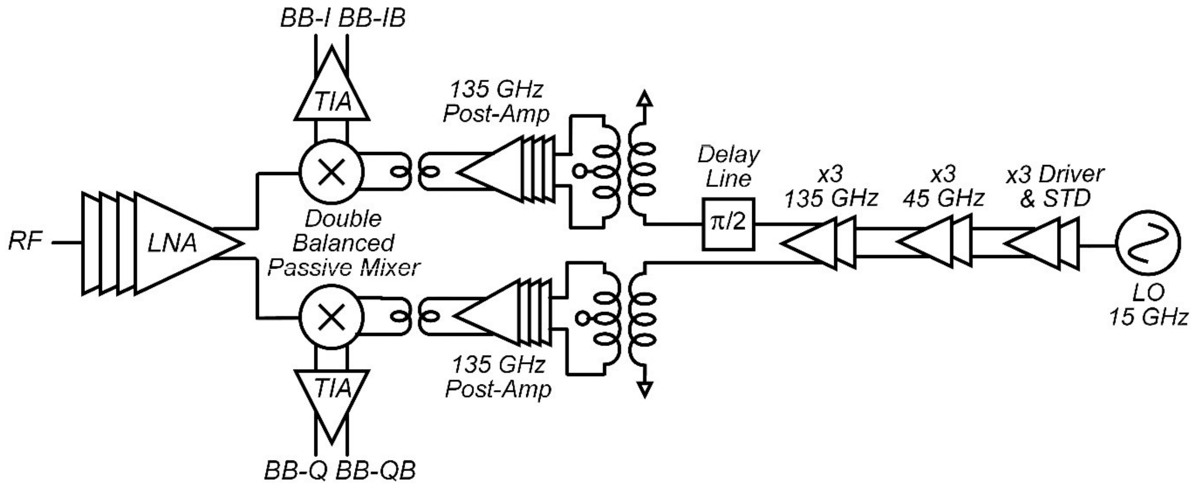
GlobalFoundries 22nm SOI CMOS

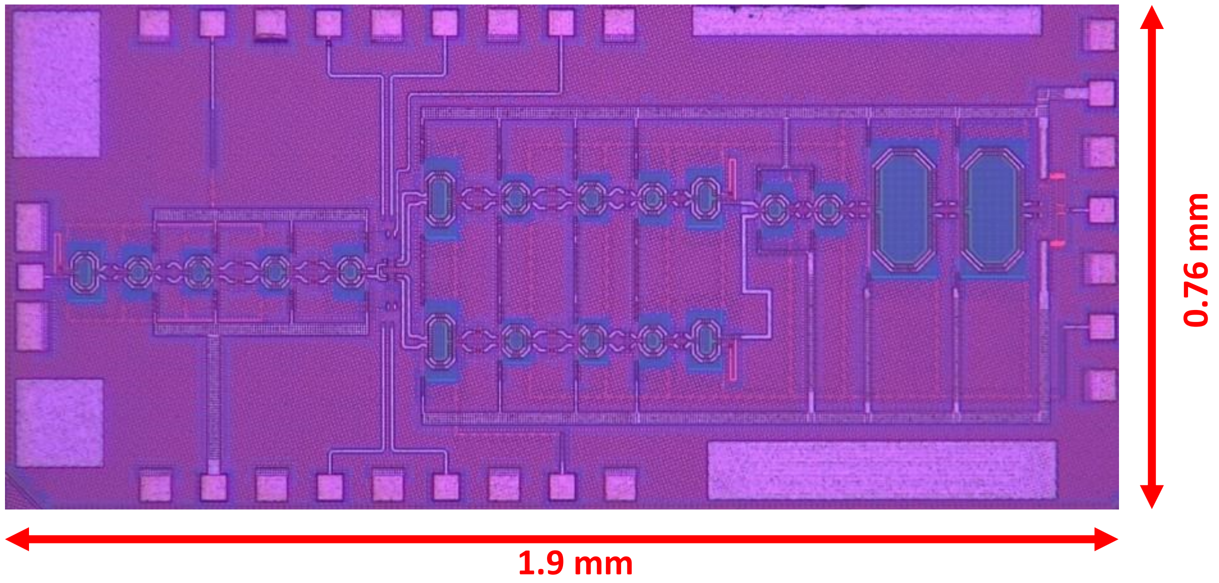


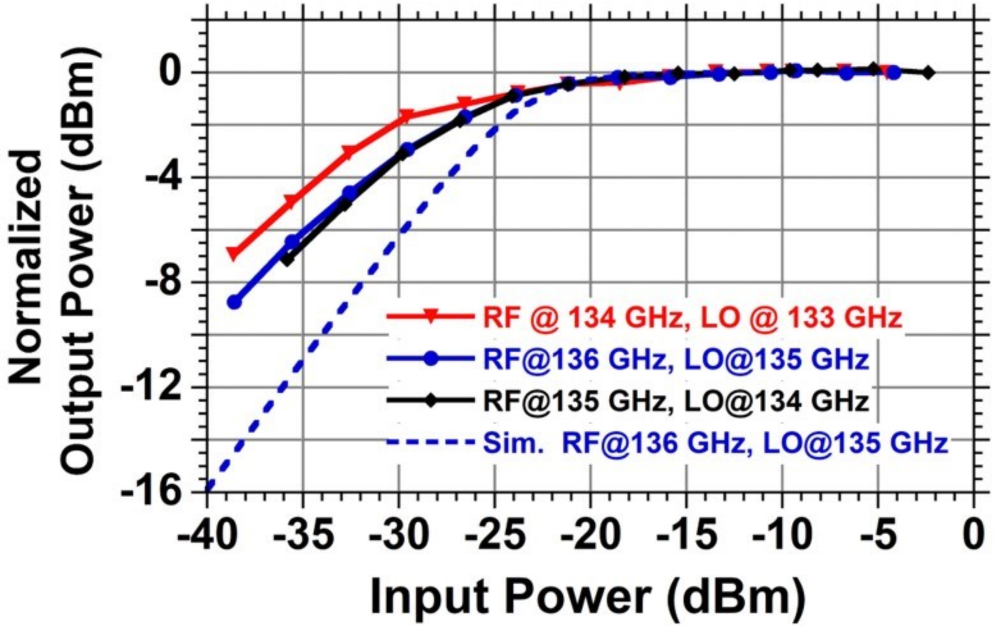
140GHz Receiver, GlobalFoundries 22nm SOI CMOS

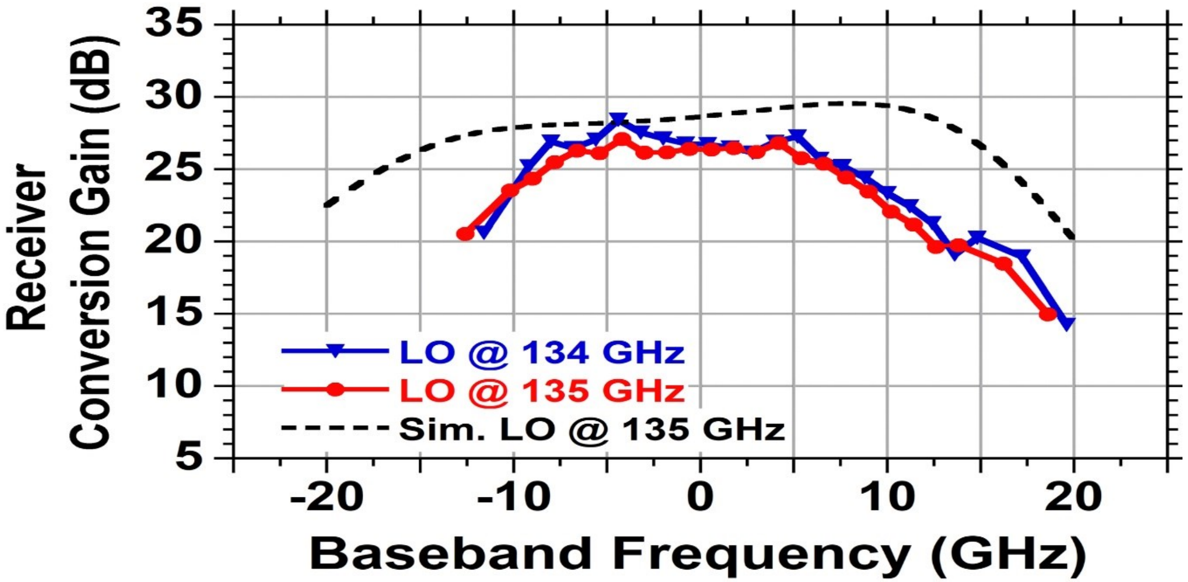
~15GHz bandwidth,
~8dB Noise Figure

A. Farid UCSB, 2019 RFIC symposium





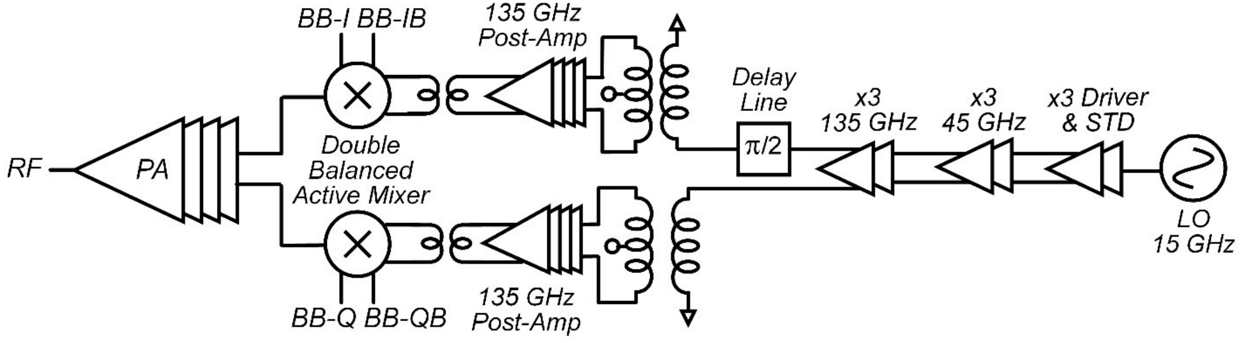


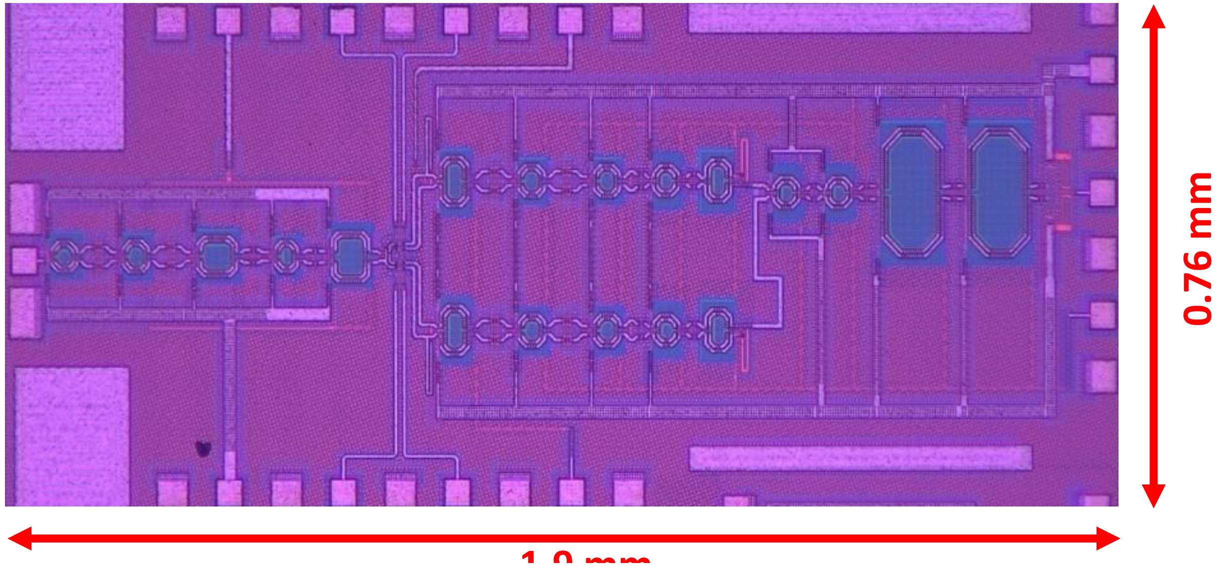


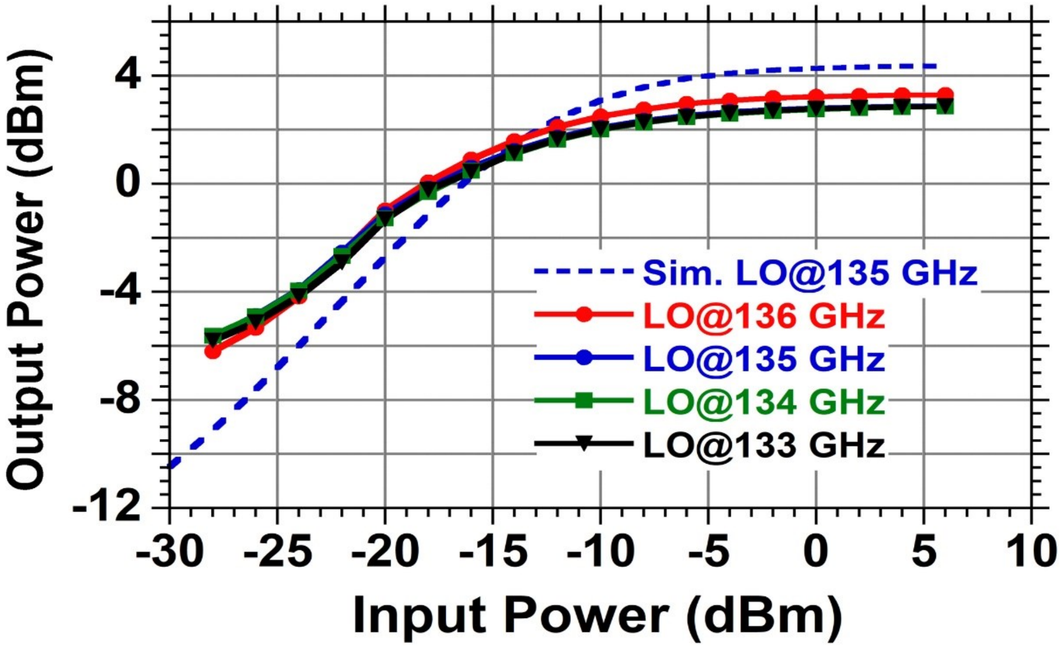
140GHz Transmitter, GlobalFoundries 22nm SOI CMOS

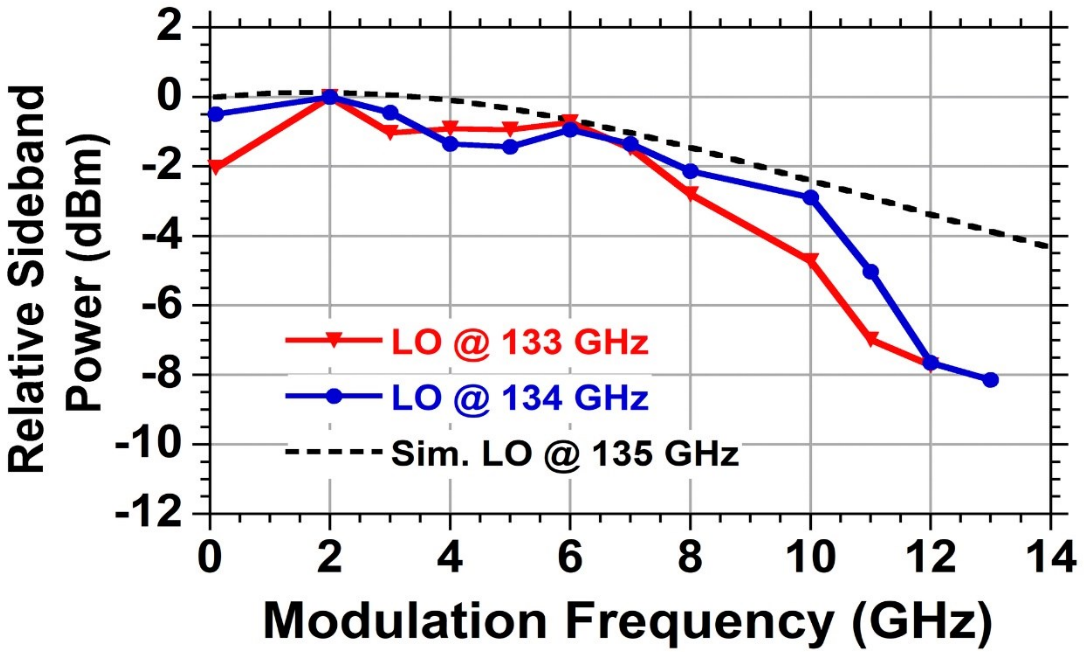
~10GHz bandwidth,
~2dBm output power

A. Farid UCSB, 2019 RFIC symposium





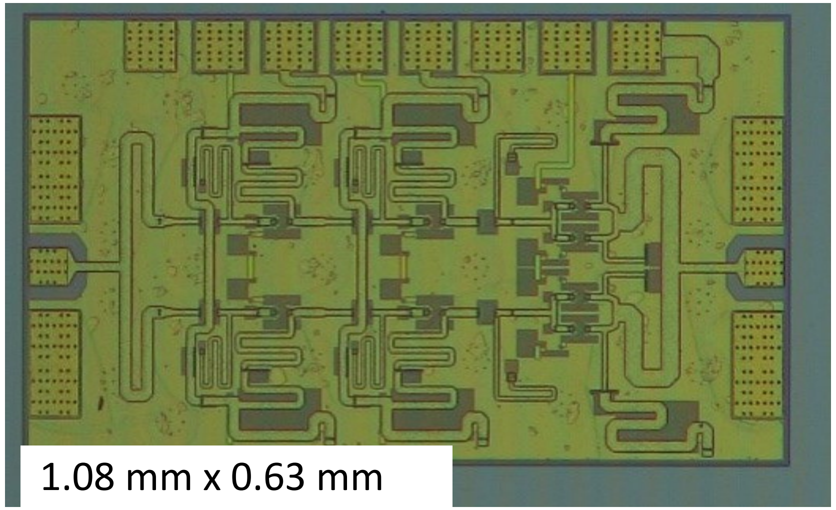


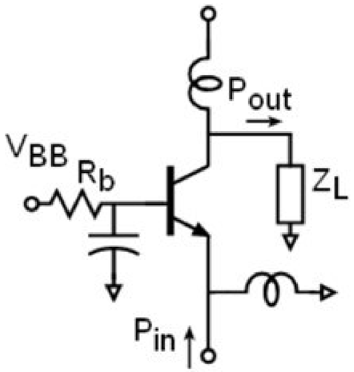


140GHz InP PA: 20.5dBm, 20.8% PAE

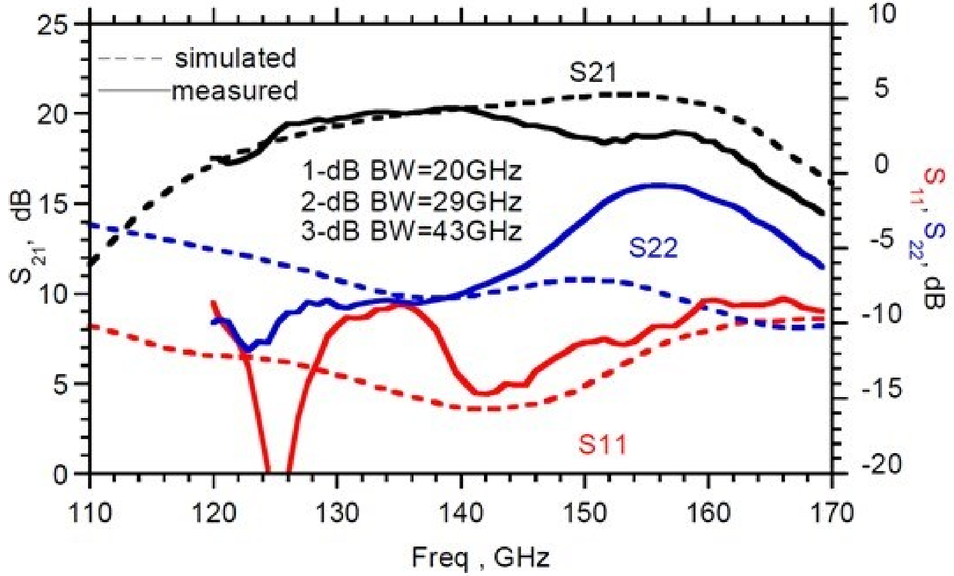
17dBm, 9.7% PAE @ P_{1dB}

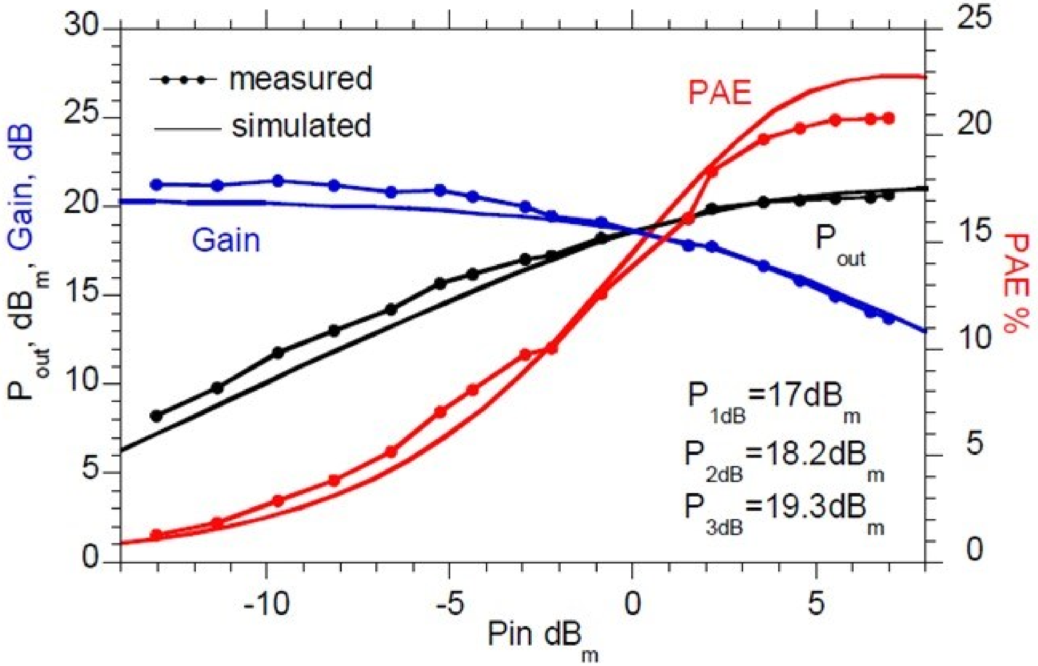
A. S. Ahmed UCSB, 2020 IMS   Teledyne 250nm InP HBT

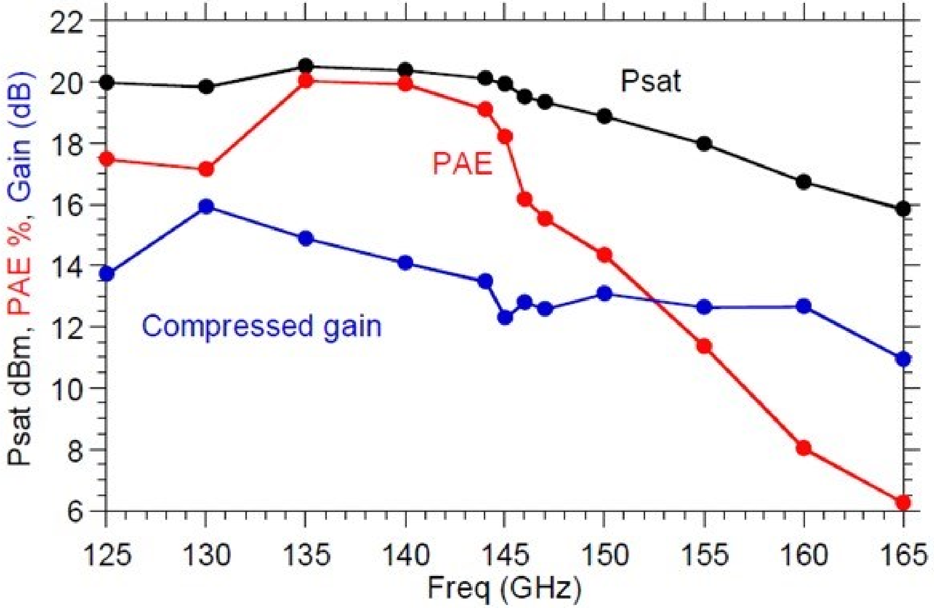




Capacitively-degenerated common-base stages



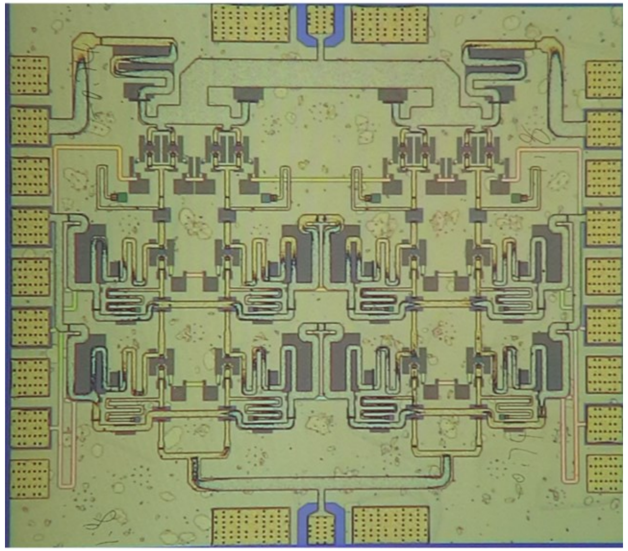




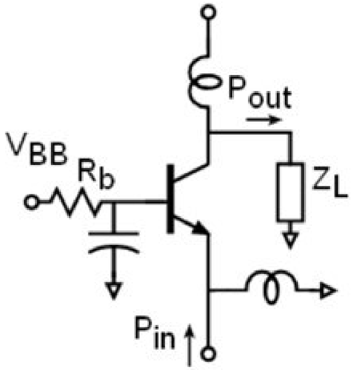
140GHz InP PA: 23dBm, 17.8% PAE

20.2dBm, 9.4% PAE @ P_{1dB}

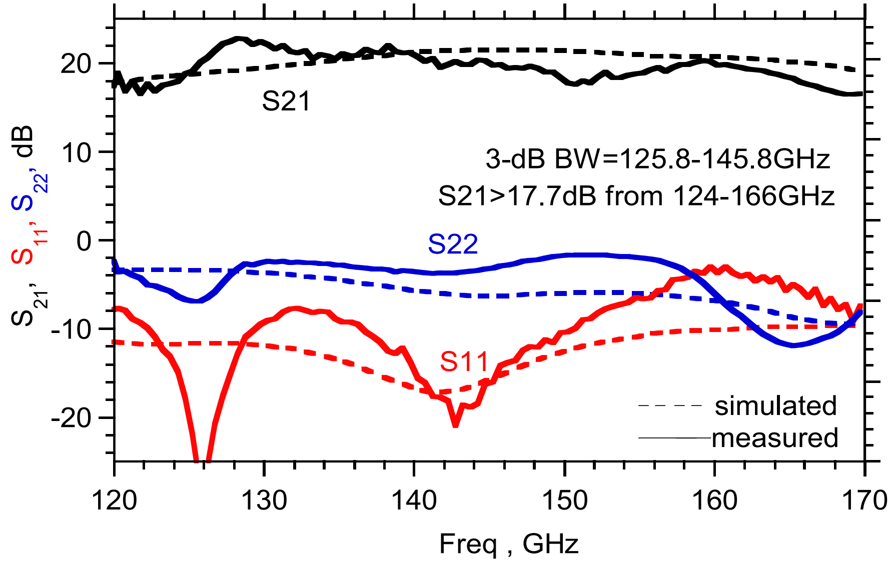
A. S. Ahmed UCSB, 2020 EuMiC   Teledyne 250nm InP HBT

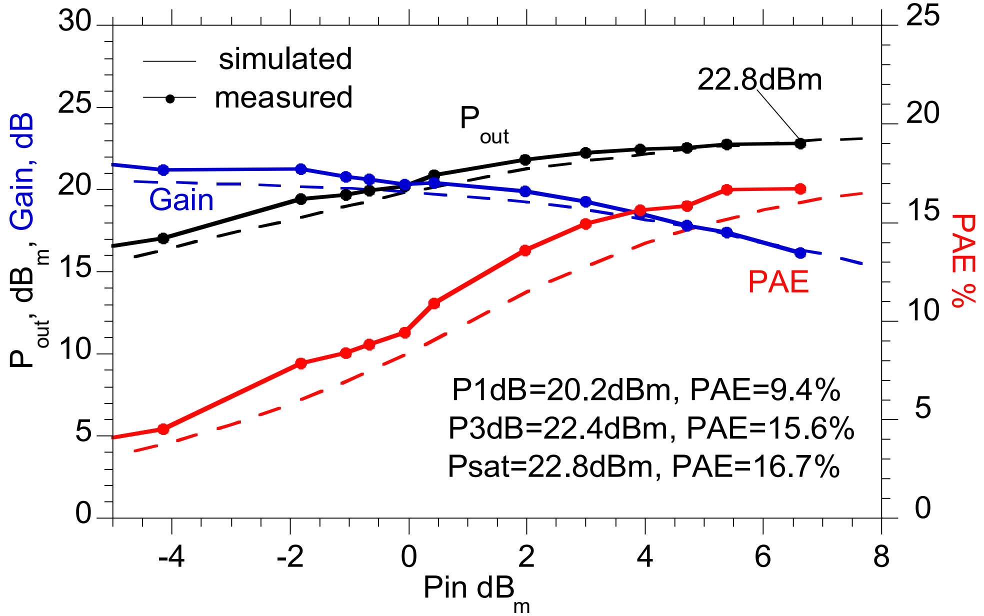


1.23 mm x 1.09 mm

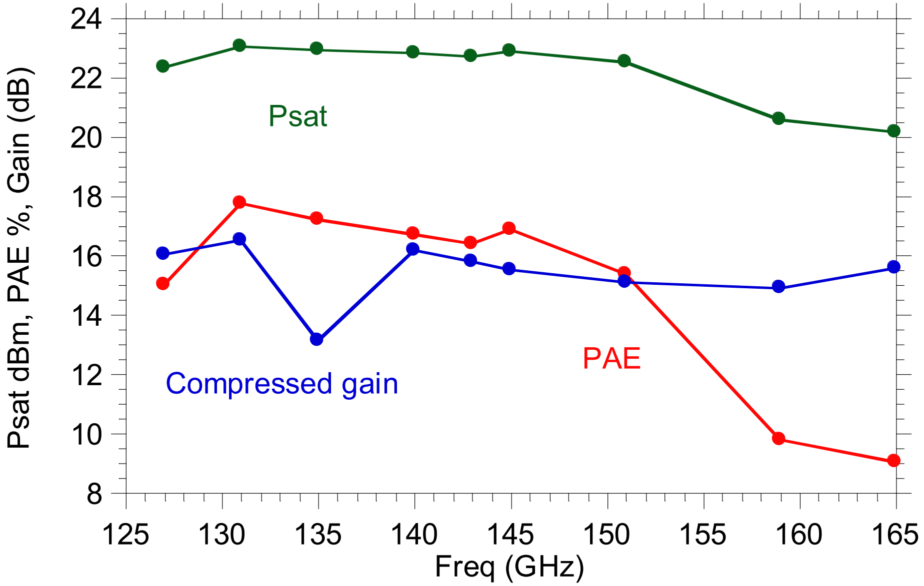


Capacitively-degenerated common-base stages



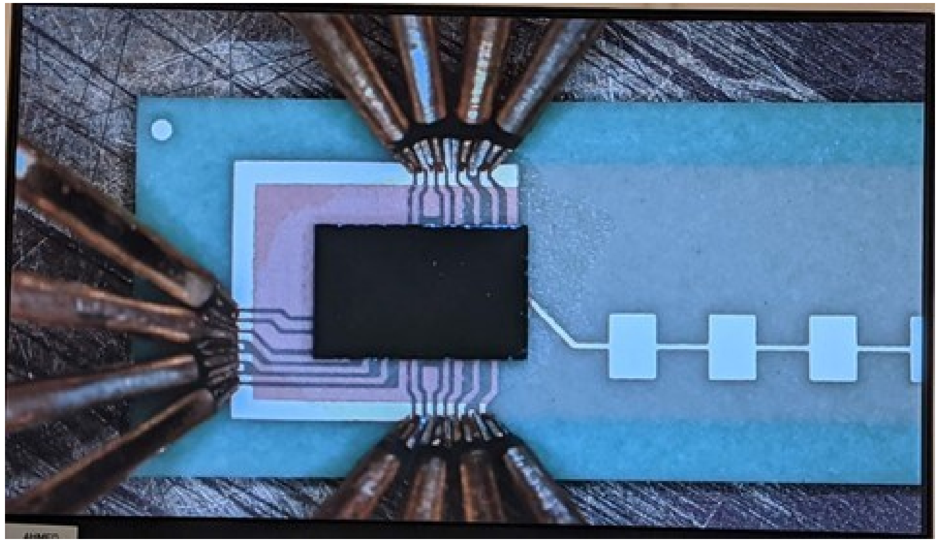


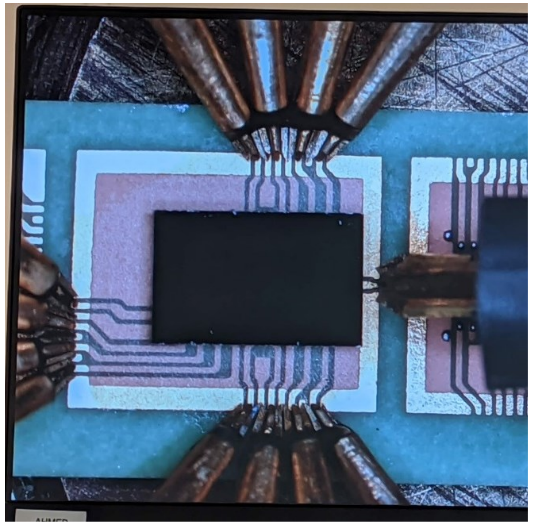
P1dB=20.2dBm, PAE=9.4%
P3dB=22.4dBm, PAE=15.6%
Psat=22.8dBm, PAE=16.7%

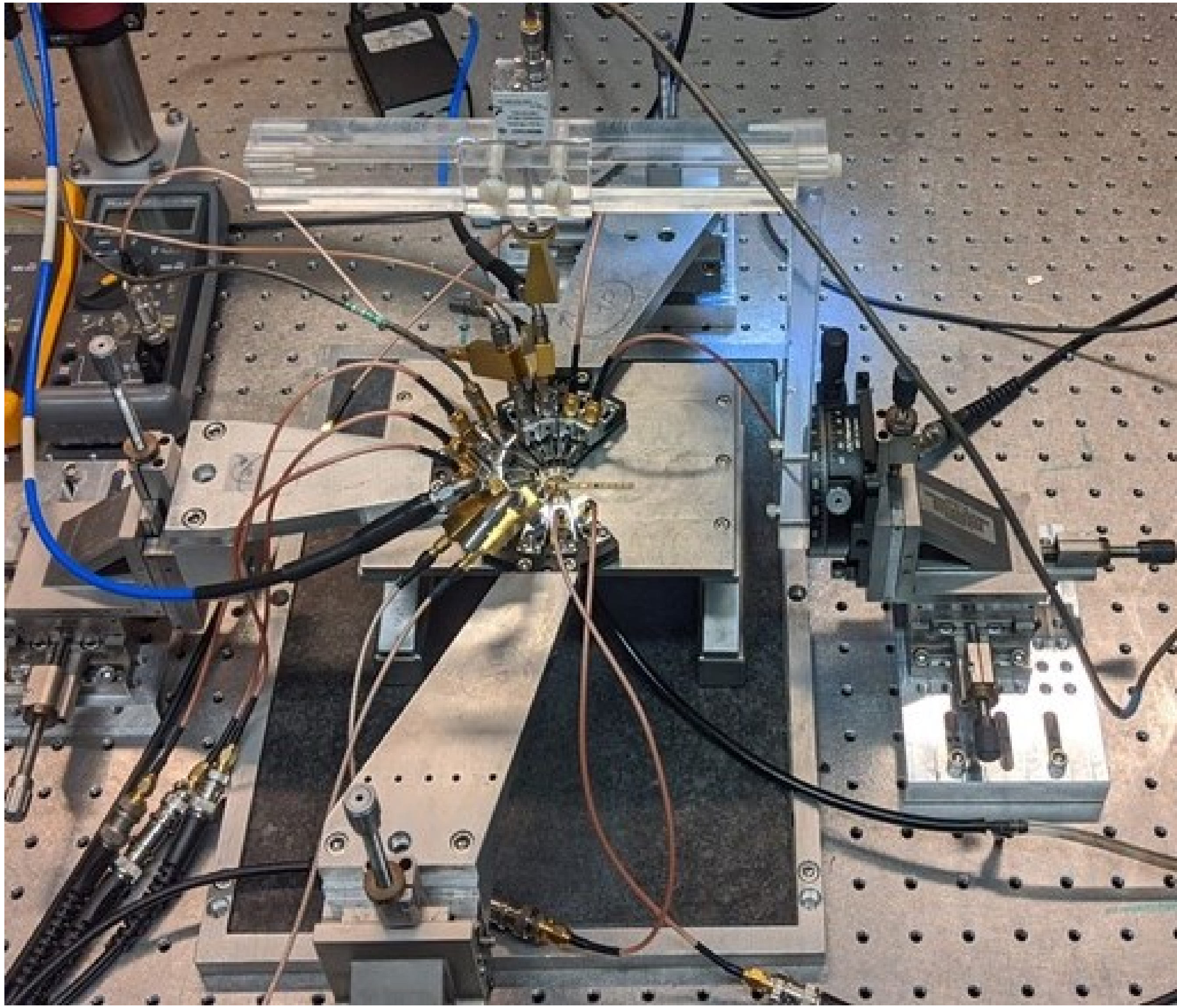


140GHz Single-Channel CMOS-Only Transmitter

A. Farid, A. S. Ahmed, UCSB, results in review

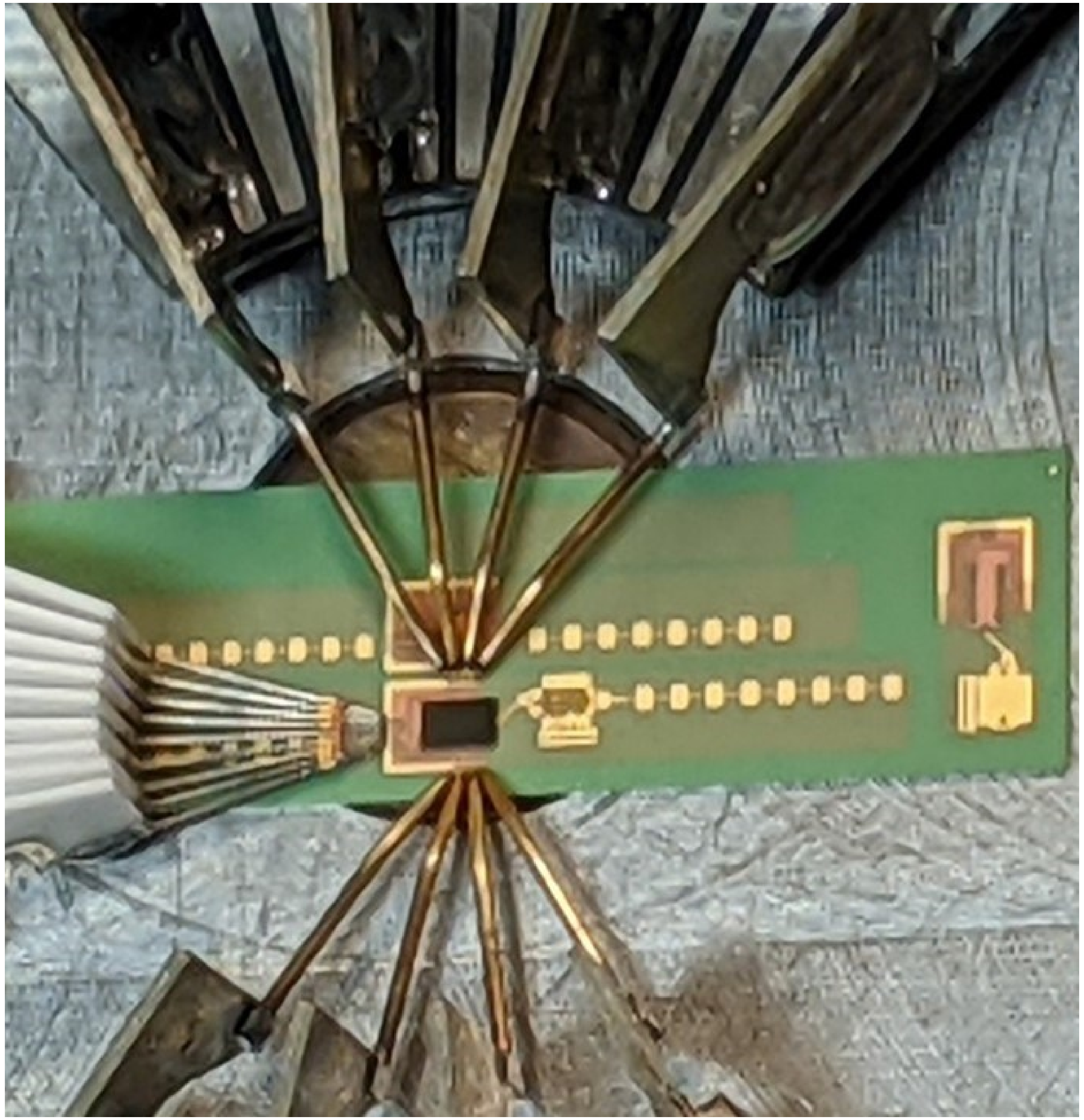


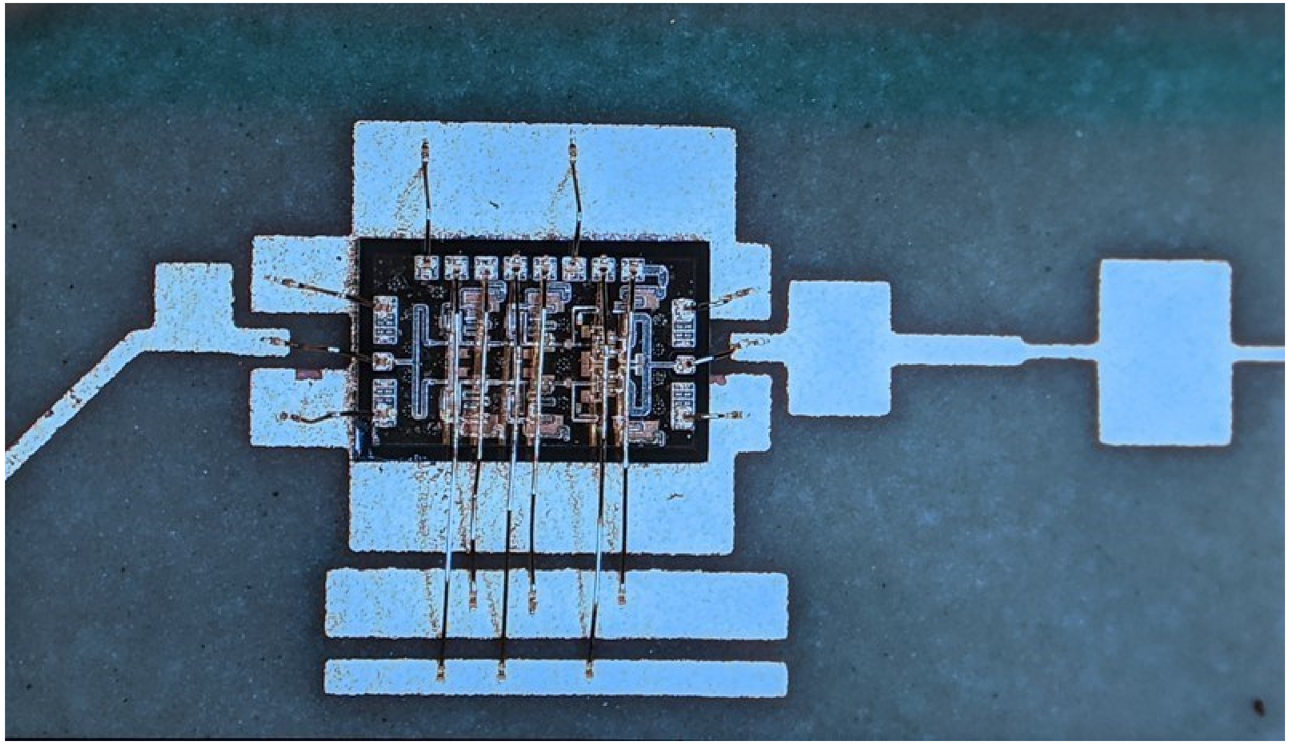




140GHz Single-Channel CMOS+InP Transmitter

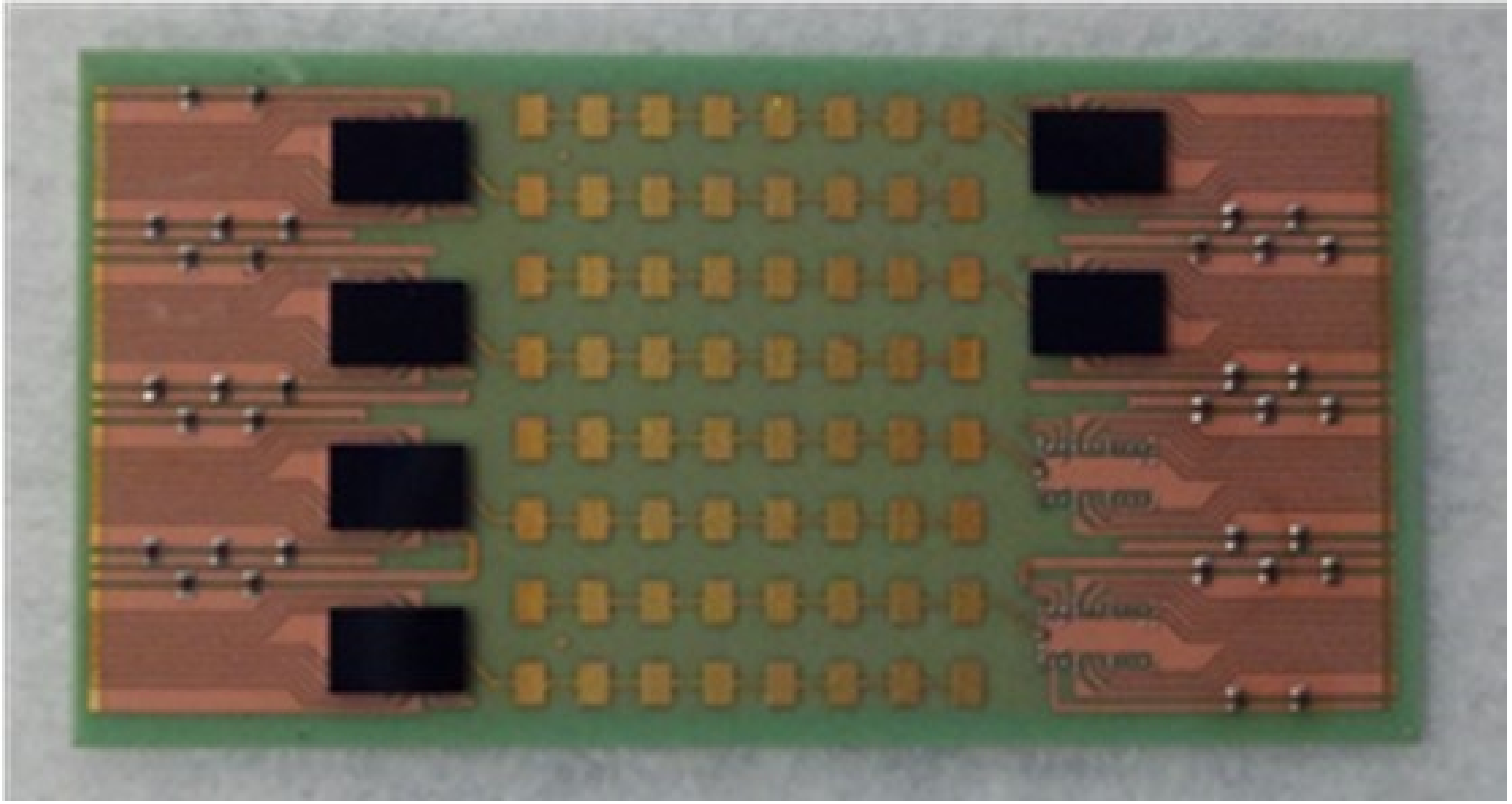
A. Farid, A. S. Ahmed, UCSB, modules being tested



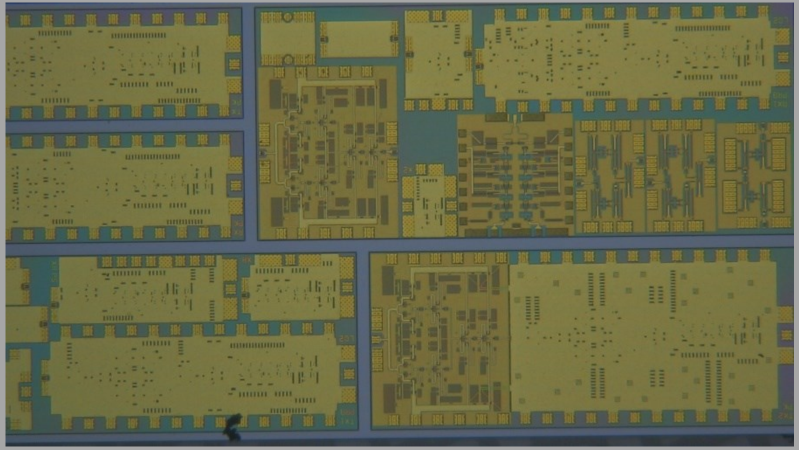


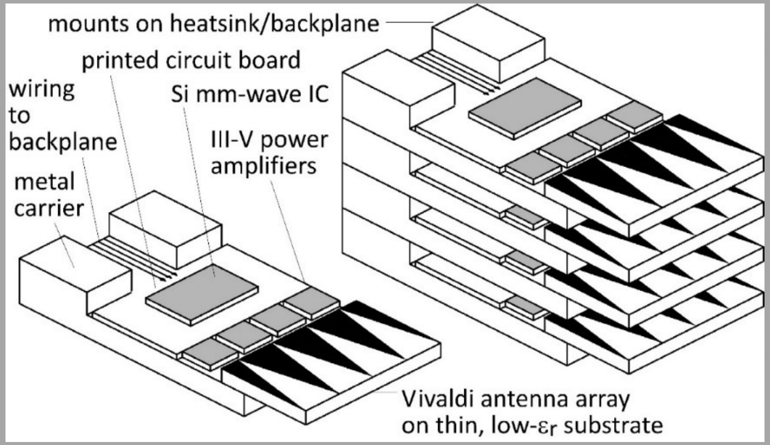
140GHz 8-Channel All-CMOS Transmitter Array

Presently learning how to assemble complex modules…

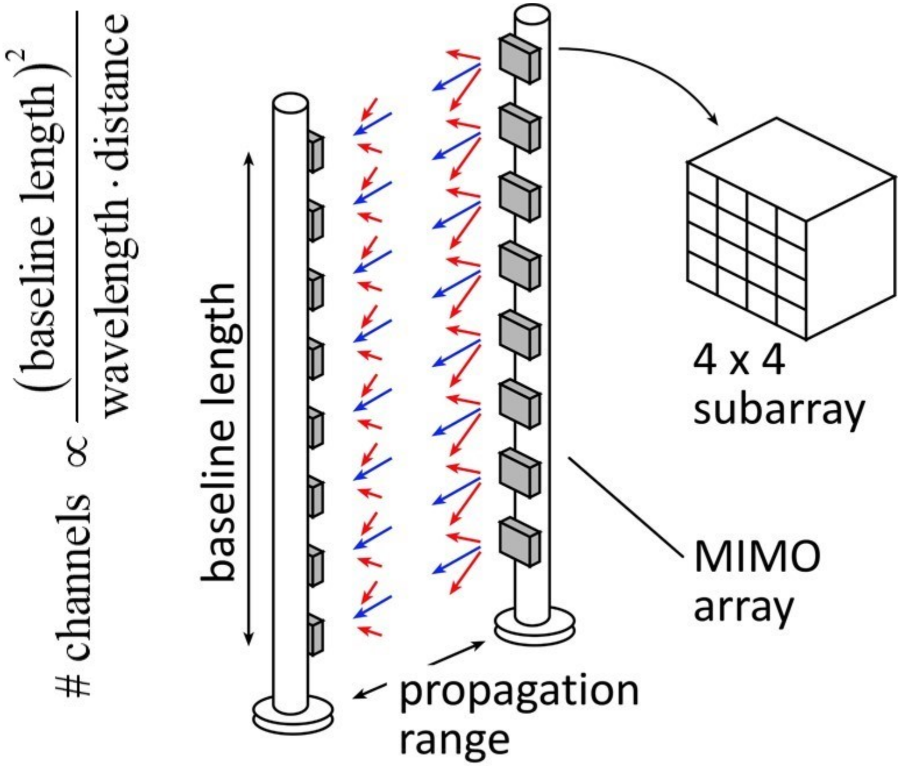


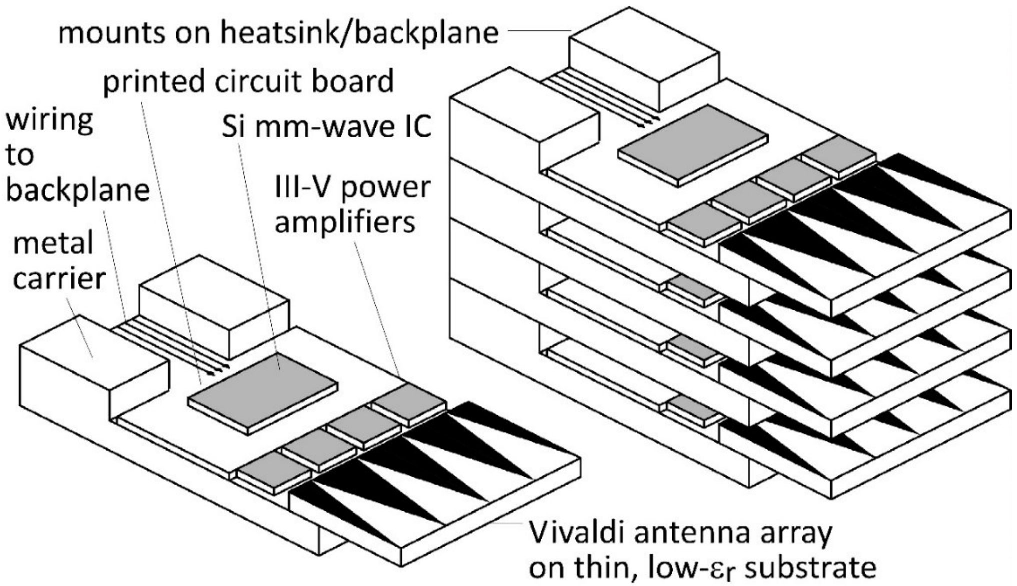
210GHz ICs and Modules





210 GHz MIMO backhaul demo





8-element MIMO array
3.1 m baseline for 500m link.
80Gb/s/subarray→ 640Gb/s total
4 × 4 sub-arrays → 8 degree beamsteering

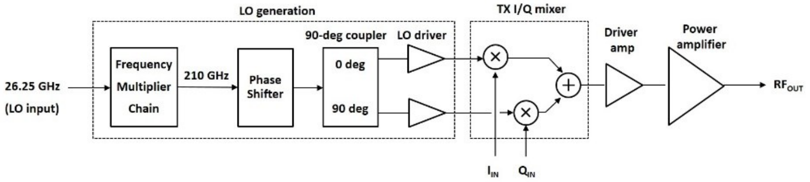
Key link parameters
500 meters range in 50 mm/hr rain; 23 dB/km
20 dB total margins:
packaging loss, obstruction, operating, design, aging
PAs: 63mW =P_{1dB} (per element)
LNAs: 6dB noise figure

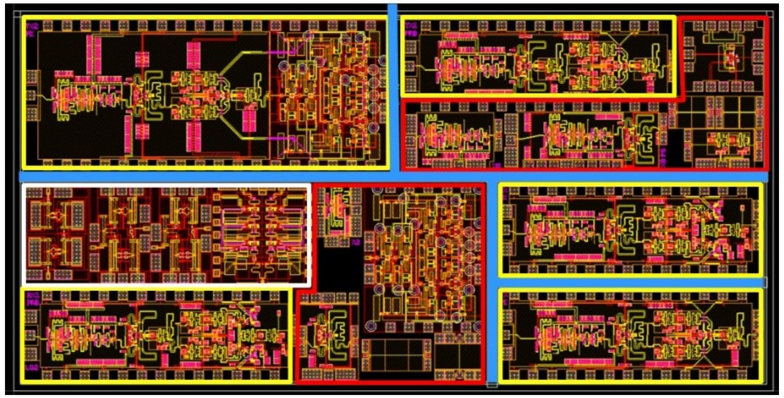
InP ICs for 210GHz Point-Point MIMO

Transceivers & Arrays for 210GHz MIMO links

2/2020 tapeout:
- 210 GHz TX front-end w/ +20 dBm Psat
- 210 GHz TX front-end w/ +2 dBm Psat
- 210 GHz RX front-end
- 280GHz PAs and LNAs

5/2020 tapeout:
- Improved 210, 280GHz LNAs and PAs
- 210 GHz transmitters, receivers using these
- 2x2 transmitter array with superstrate antenna
- 2x2 receiver array with superstrate antenna

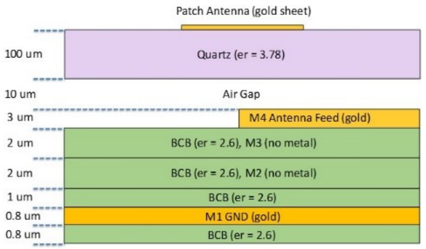


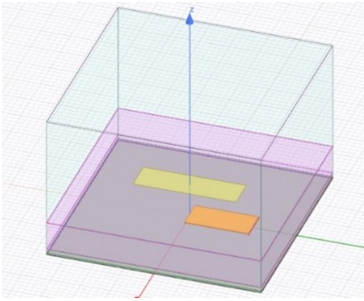


Planned packaging approaches

InP IC bonding to patch antenna arrays on quartz.
plan: ribbon bonds using wedge bonder

2x2 array with UCSD SiO_2 antenna superstrate
simple, expensive in die area
limits array size to 2x2 (or 2x4).



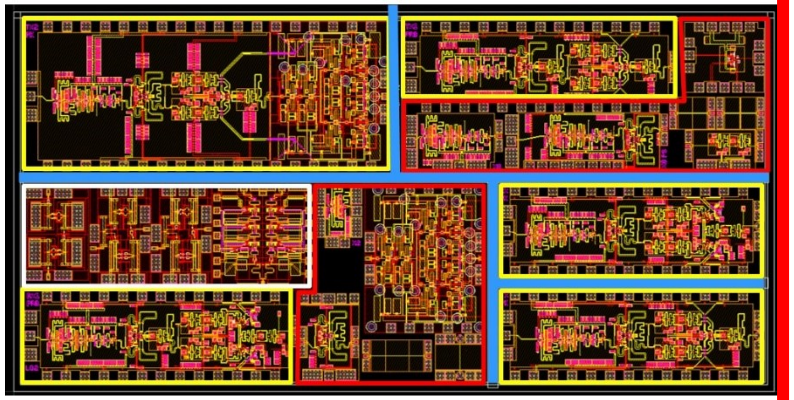


Seo, UCSB & Sungkyunkwan Univ.; Ahmed, Solyu, Rodwell, UCSB; Li, Zhang, Rebeiz, UCSD

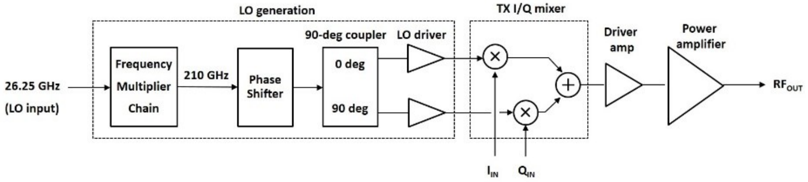
InP ICs for 210GHz Point-Point MIMO

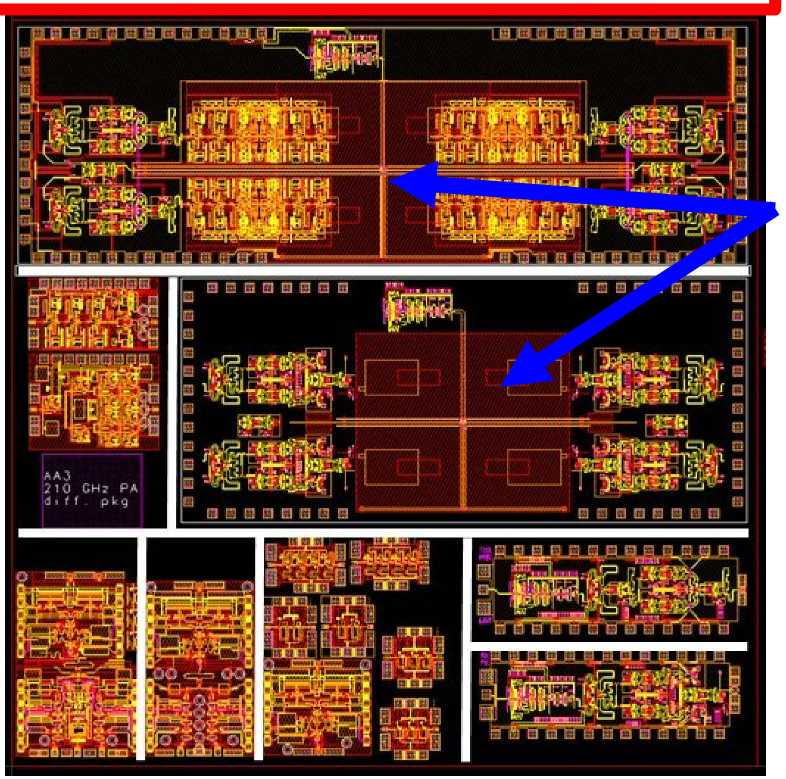
Transceivers & Arrays for 210GHz MIMO links

2/2020 tapeout:
- 210 GHz TX front-end w/ +20 dBm Psat
- 210 GHz TX front-end w/ +2 dBm Psat
- 210 GHz RX front-end
- 280GHz PAs and LNAs



5/2020 tapeout:
- Improved 210, 280GHz LNAs and PAs
- 210 GHz transmitters, receivers using these
- 2x2 transmitter array with superstrate antenna
- 2x2 receiver array with superstrate antenna

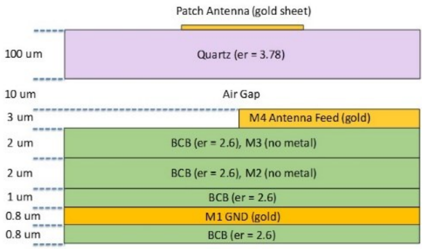


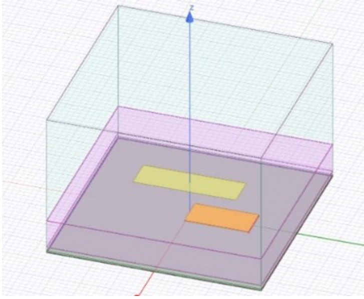


Planned packaging approaches

InP IC bonding to patch antenna arrays on quartz.
plan: ribbon bonds using wedge bonder

2x2 array with UCSD SiO_2 antenna superstrate
simple, expensive in die area
limits array size to 2x2 (or 2x4).





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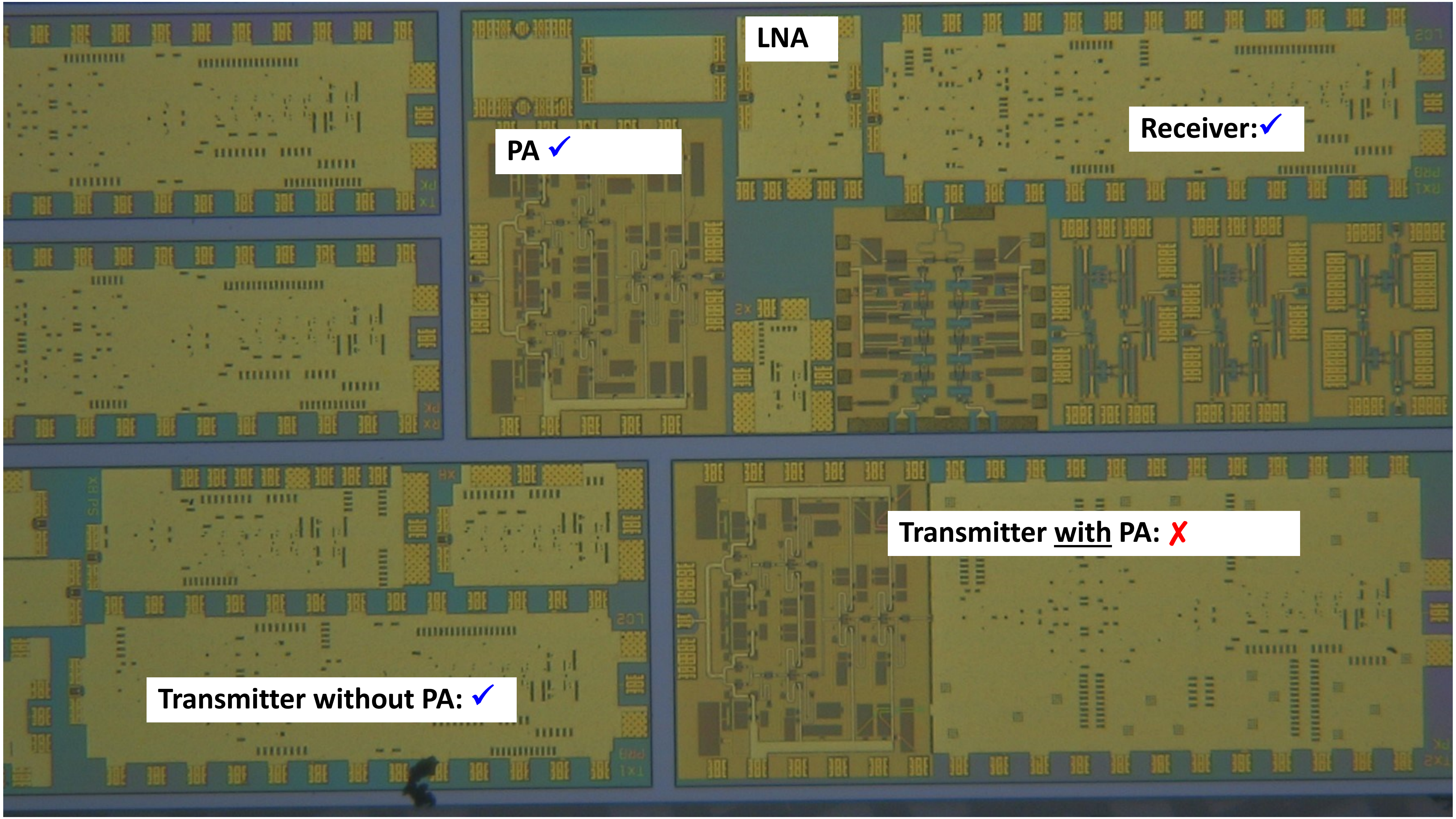
210 GHz MIMO backhaul: ICs

ICs being tested;
some to be submitted, others need re-design.

Teledyne 250nm (650GHz) InP HBT.



LNA

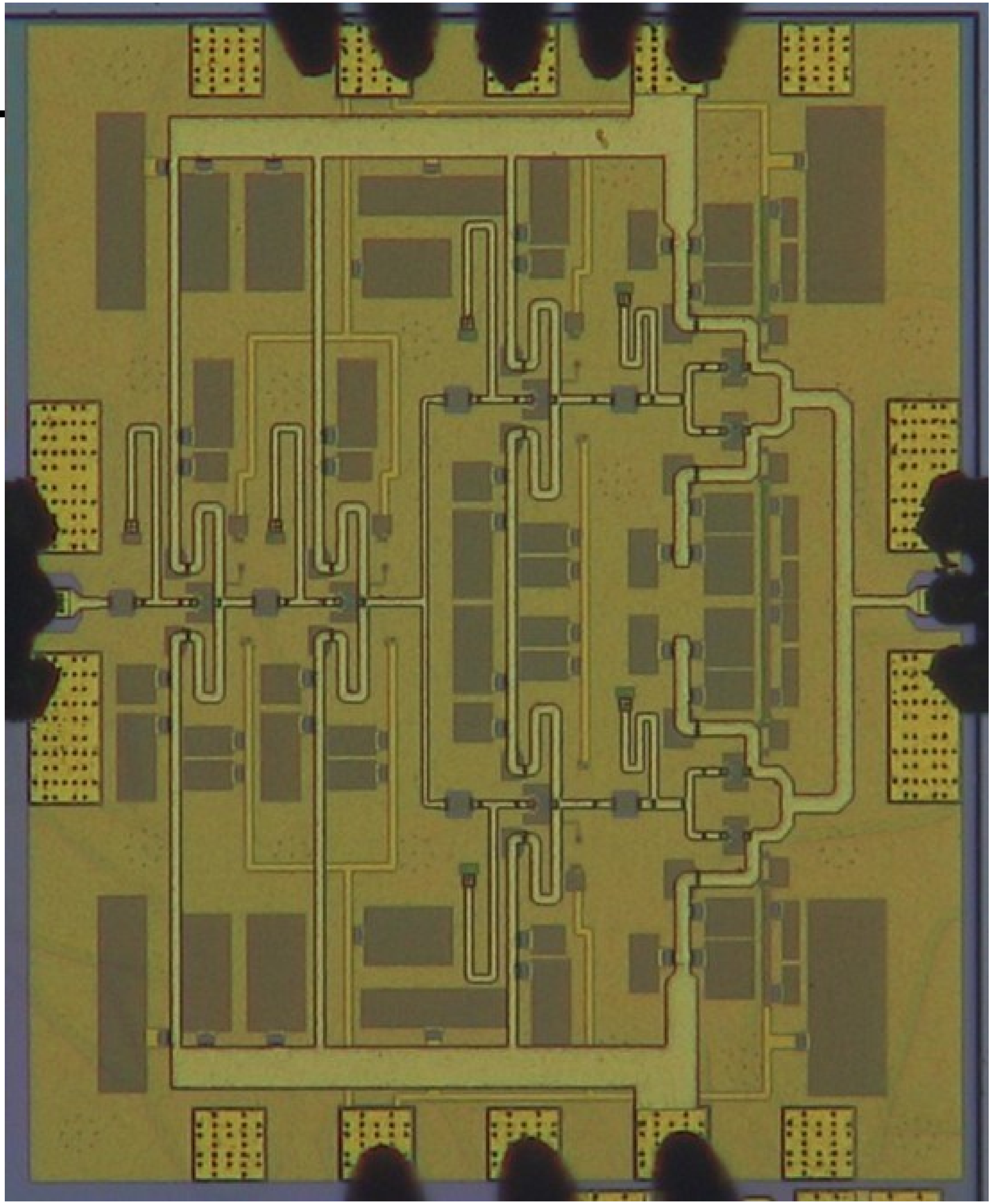
PA ✓

Receiver: ✓

Transmitter with PA: ✗

Transmitter without PA: ✓

210GHz Power Amplifier

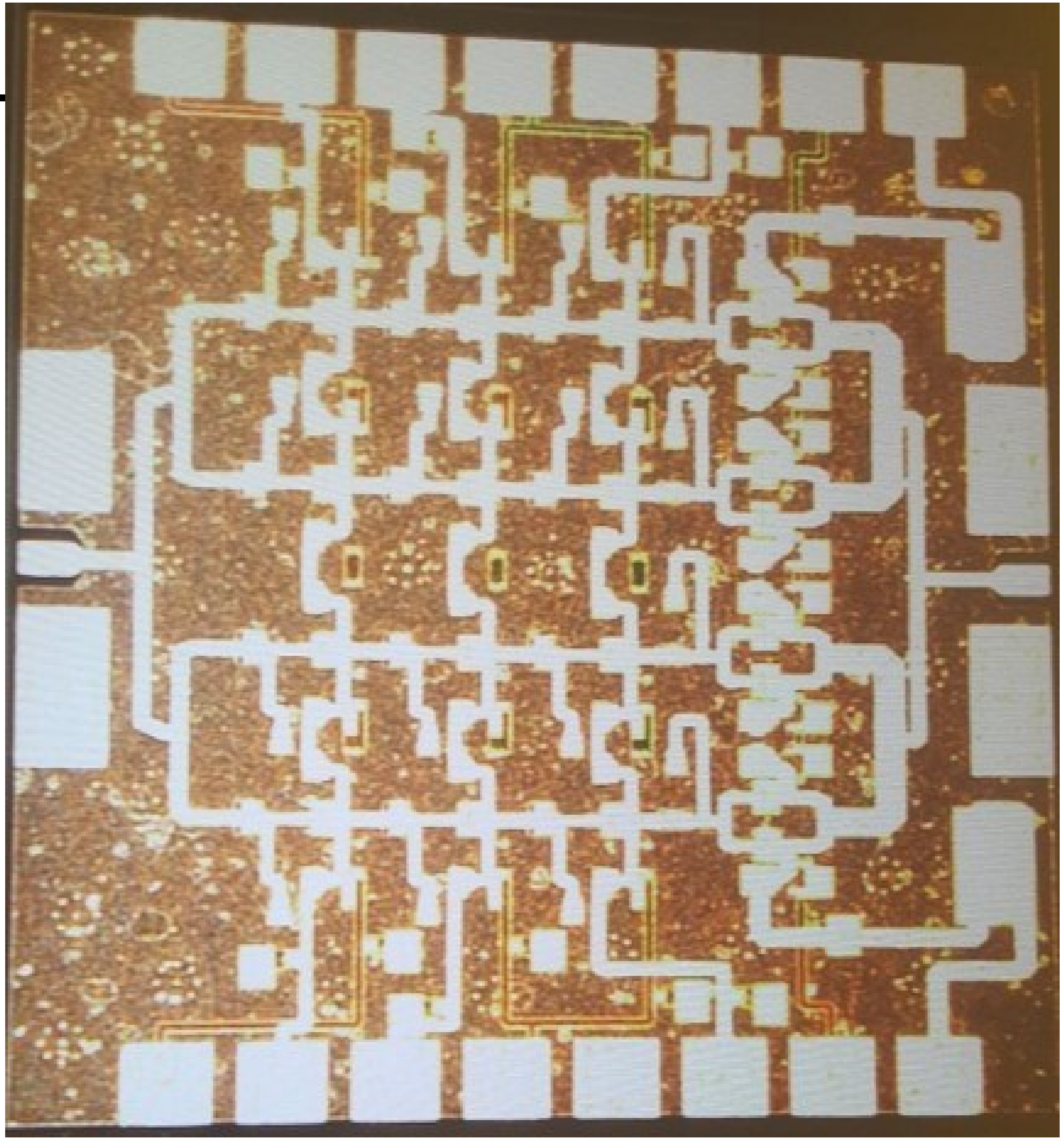


Design goal: high PAE @ 1dB gain compression

Teledyne 250nm InP HBT

A. S. Ahmed, UCSB, results in review

300GHz Power Amplifier



Design goal: high PAE @ 1dB gain compression

Teledyne 250nm InP HBT

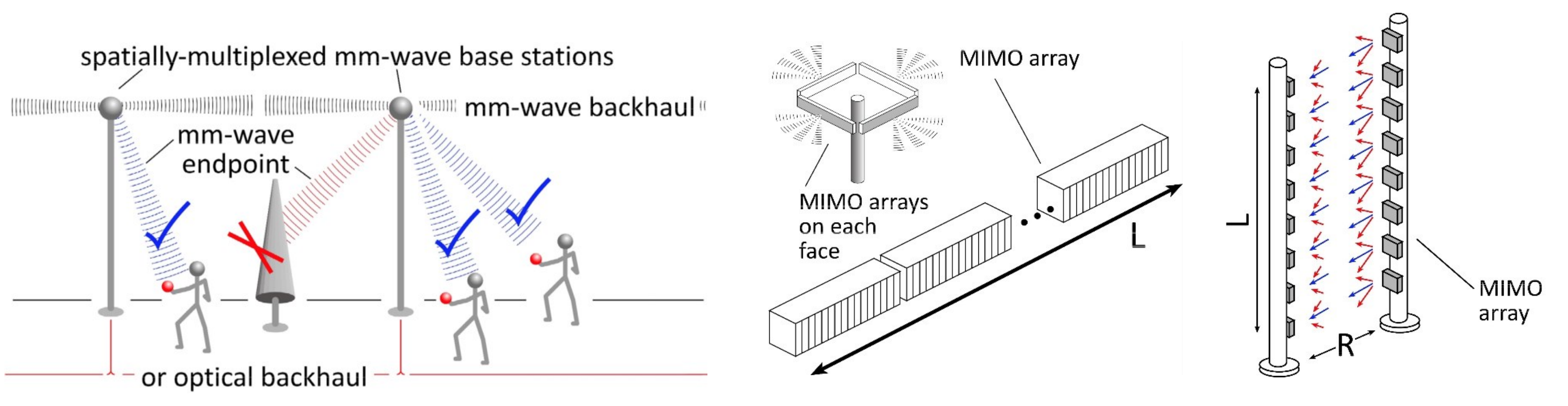
Measured S-parameters on target

Large-signal (power) data pending.

280GHz design also being tested.

A. S. Ahmed, UCSB

100-300GHz Wireless



Wireless above 100 GHz

Massive capacities
large available bandwidths
massive spatial multiplexing in base stations and point-point links

Very short range: few 100 meters
short wavelength, high atmospheric losses. Easily-blocked beams.

IC Technology
All-CMOS for short ranges below 200 GHz.
SiGe, GaN, or III-V LNAs and PAs for longer-range links. Just like cell phones today
SiGe or III-V frequency extenders for 220GHz and beyond

The challenges
digital beamformer computational complexity
packaging: fitting signal channels in very small areas
mesh networking to accommodate beam blockage
driving the technologies to low cost

(backup files follow)