6G Workshop, IEEE RF/Wireless Week, January 2021, online.

100-300GHz Wireless: Transistors, ICs, packages, systems.

Mark Rodwell, UCSB

Harish Krishnaswami: *Columbia University*
Debdeep Jena, Alyosha Molnar, Christoph Studer, Huili Xing*: Cornell University*
Dina Katabi*: MIT*
Sundeep Rangan*: New York University*
Amin Arbabian, Srabanti Chowdhury*: Stanford*
Elad Alon, Ali Niknejad, Borivoje Nikolic, Vladimir Stojanovic*: University of California, Berkeley*
Danijela Cabric*: University of California, Los Angeles*
Gabriel Rebeiz*: University of California, San Diego*
Jim Buckwalter, Upamanyu Madhow, Umesh Mishra, Mark Rodwell, Susanne Stemmer*: University of California, Santa Barbara*
Andreas Molisch, Hossein Hashemi*: University of Southern California*
Kenneth O*: University of Texas, Dallas*

JUMP Team and their roles

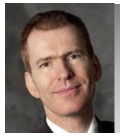
ComSenTer
COMMUNICATIONS SENSING TERAHERTZ

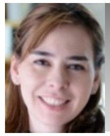
Systems

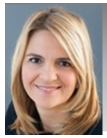

Sundeep Rangan
Networks, Applications, MIMO, Power


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


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


James Buckwalter
UC Santa Barbara
efficient PAs
III-V arrays

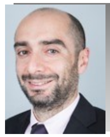

Alyosha Molnar
Cornell
N-path mixers
MIMO ADCs


Kenneth O
UT Dallas
200-300GHz passive CMOS


Elad Alon
UC Berkeley
design automation
equalizers


Harish Krishnaswamy
Columbia
STAR
Novel MIMO


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

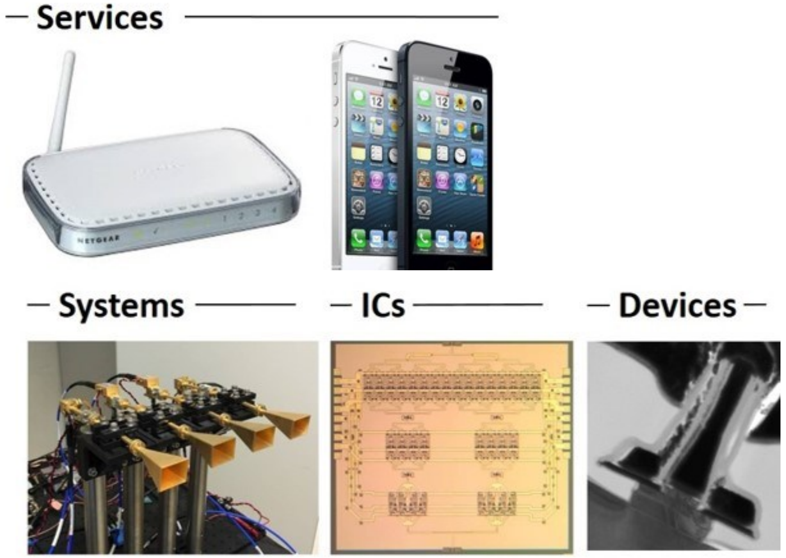
Beyond-5G Wireless

Wireless networks: exploding demand.

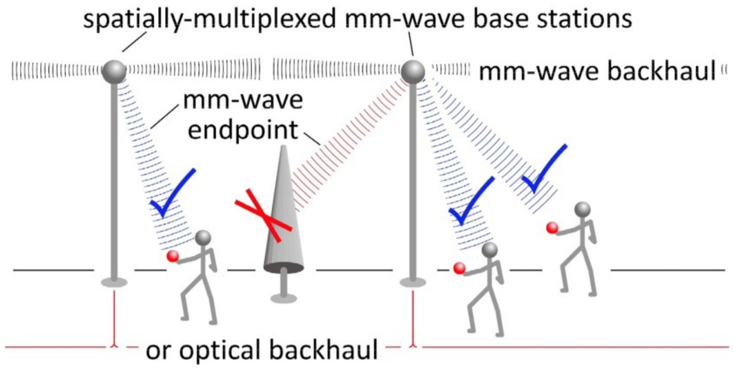
Immediate industry response: 5G.
~10-100GHz carriers.
increased spectrum, extensive beamforming

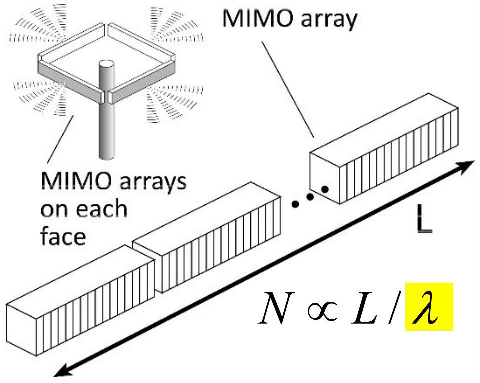
Next generation (6G ??): above 100GHz..
greatly increased spectrum, massive spatial multiplexing

JUMP Centers: research commercialized in 15 years

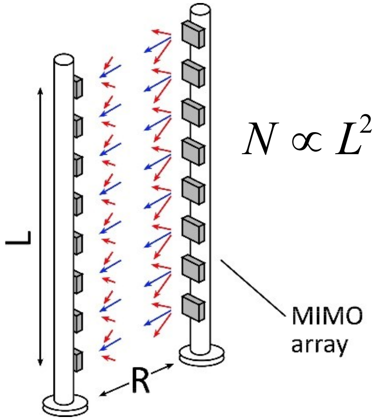


ComSenTer: 100-300GHz carriers, massive spatial multiplexing
→ Terabit hubs and backhaul links, high-resolution imaging radar

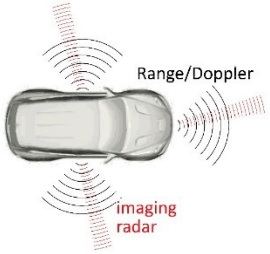




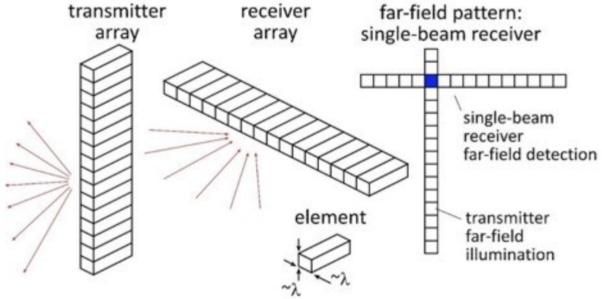
$N \propto L / \lambda$



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

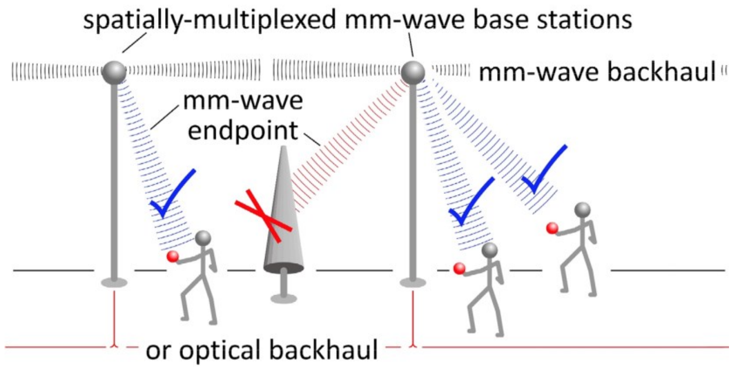


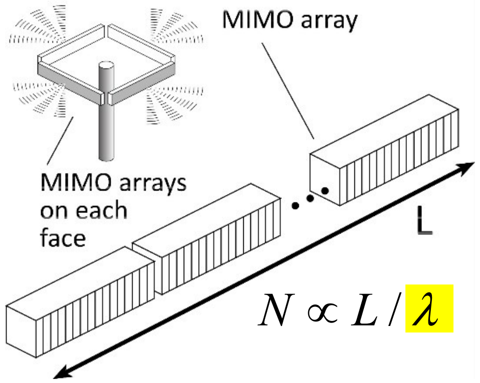
$\Delta\theta \propto \lambda / L$

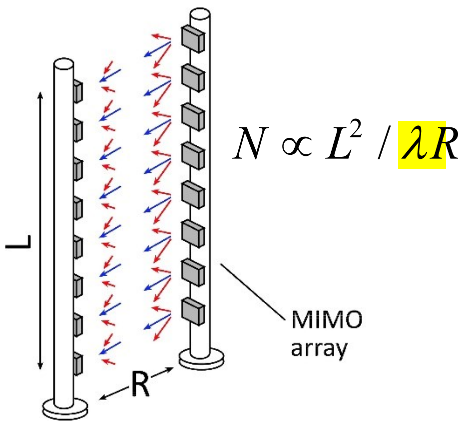


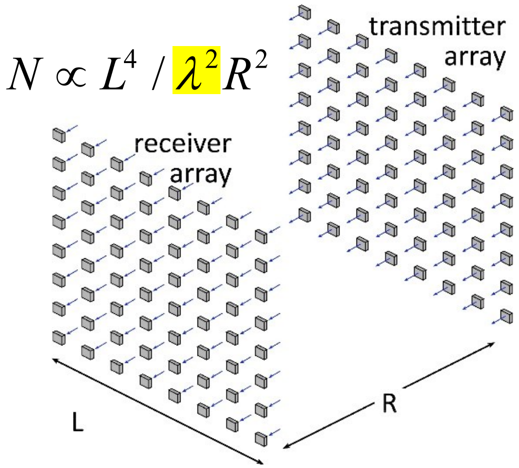
Benefits of Short Wavelengths

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

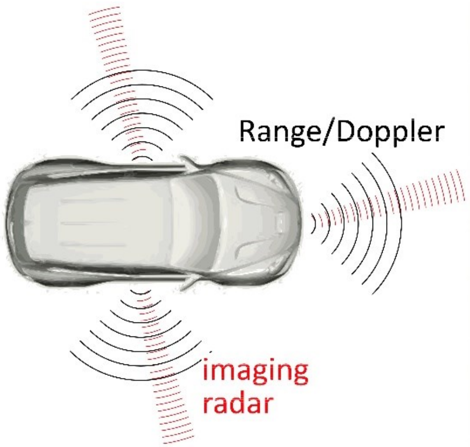


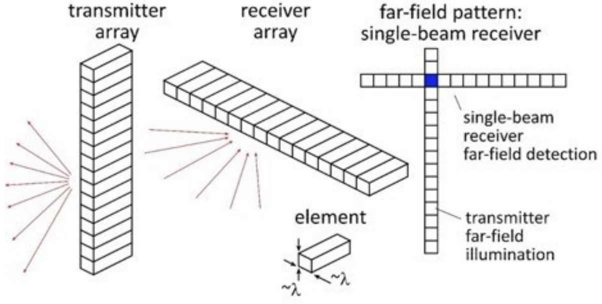






Imaging: very fine angular resolution





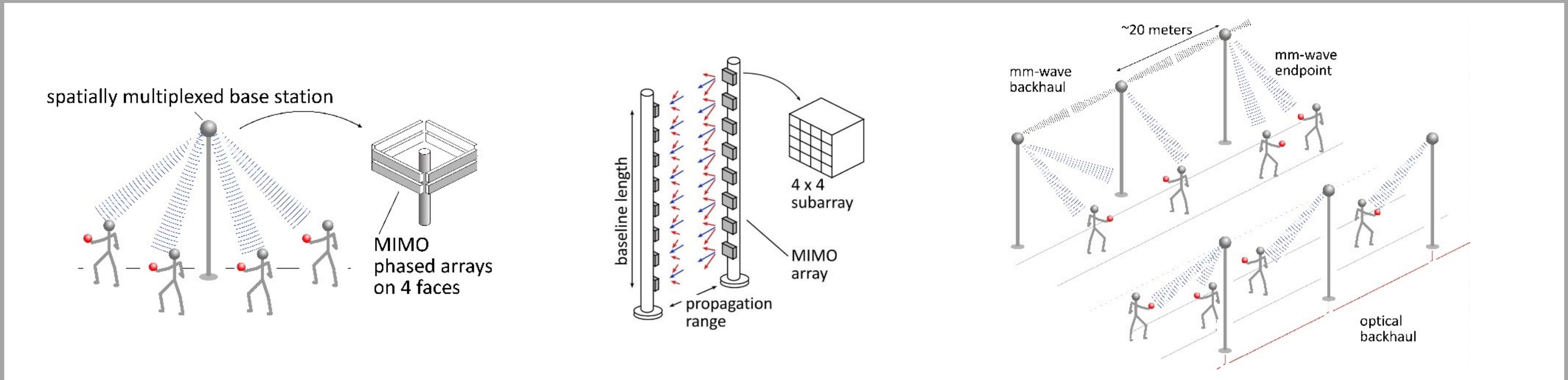
$\Delta\theta \propto \lambda / L$

But:

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

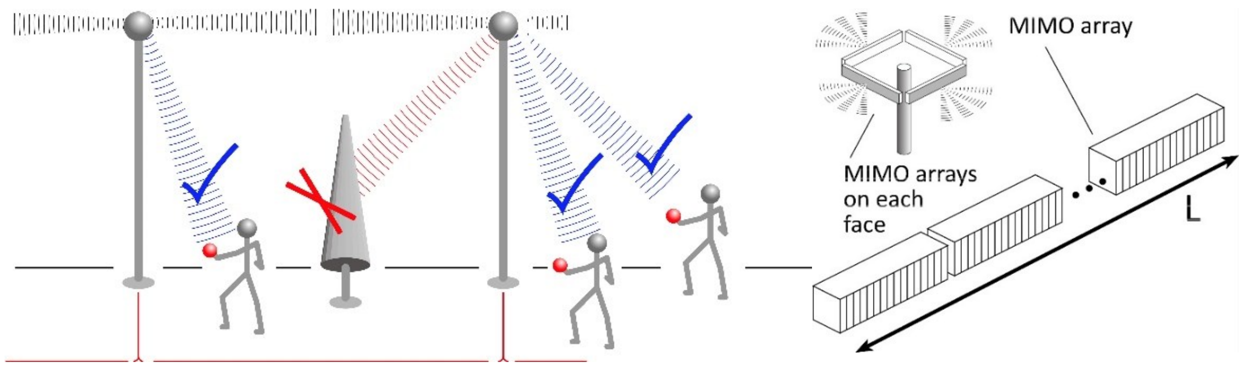
100-340GHz wireless:
terabit capacity,
short range,
highly intermittent

100-300 GHz: Applications

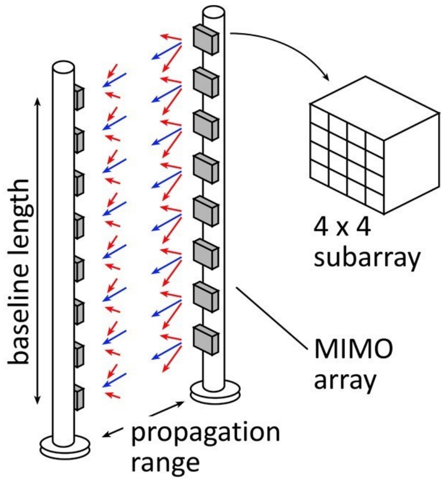


100-300GHz: Demonstration Systems

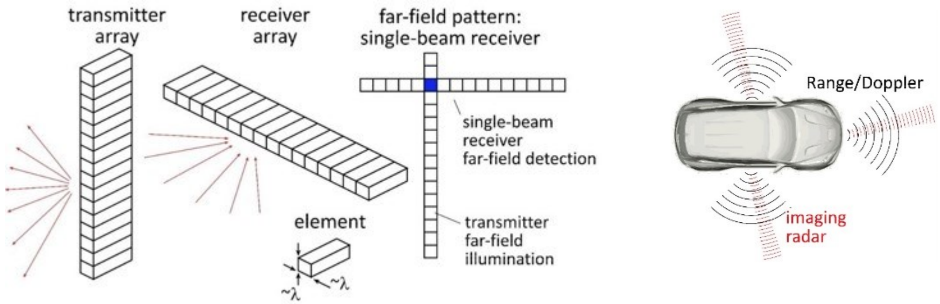
MIMO hub: 140GHz

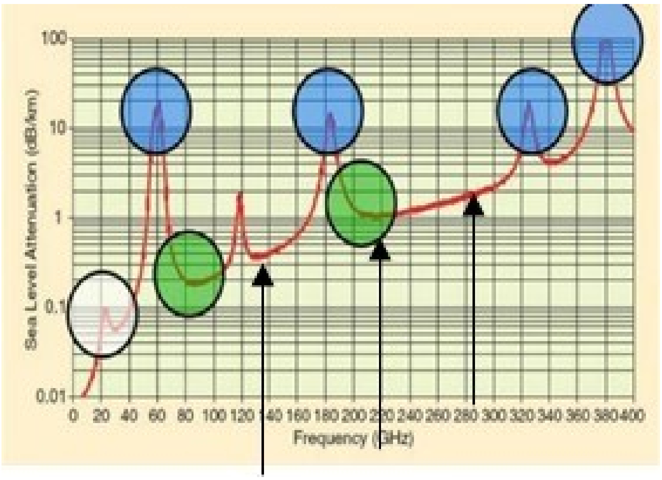


Point-point MIMO: 210, 280GHz



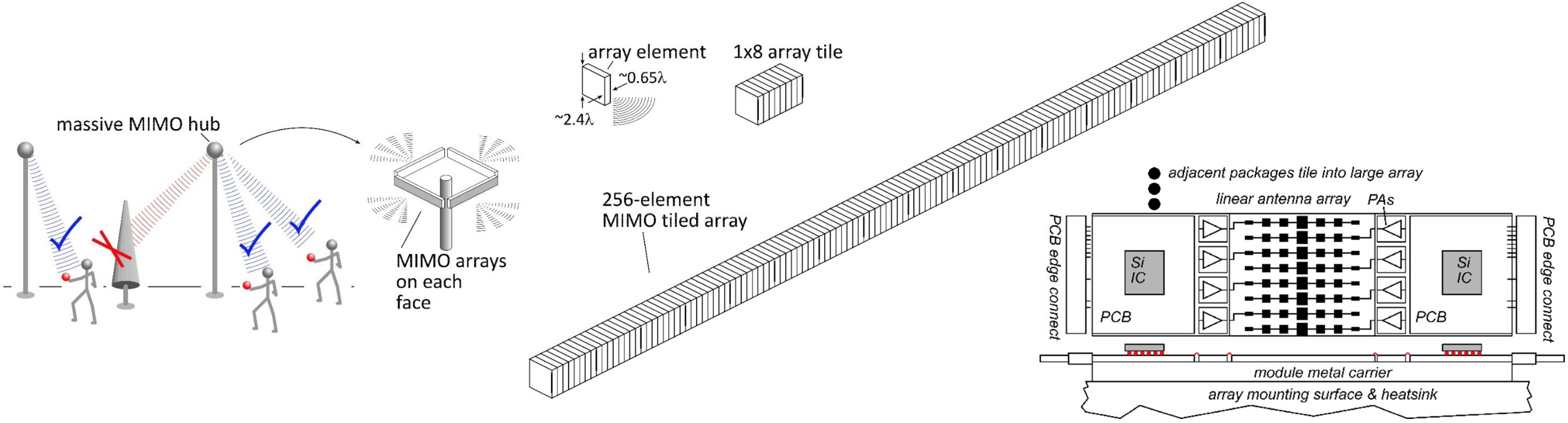
Cross-linear-array imaging: 210, 280GHz

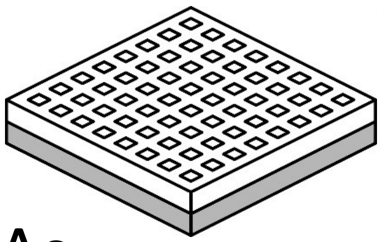




UCSB FCC permit: 137 +/- 15 GHz, 210 +/- 15 GHz, 280 +/- 15 GHz

140GHz massive MIMO hub





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

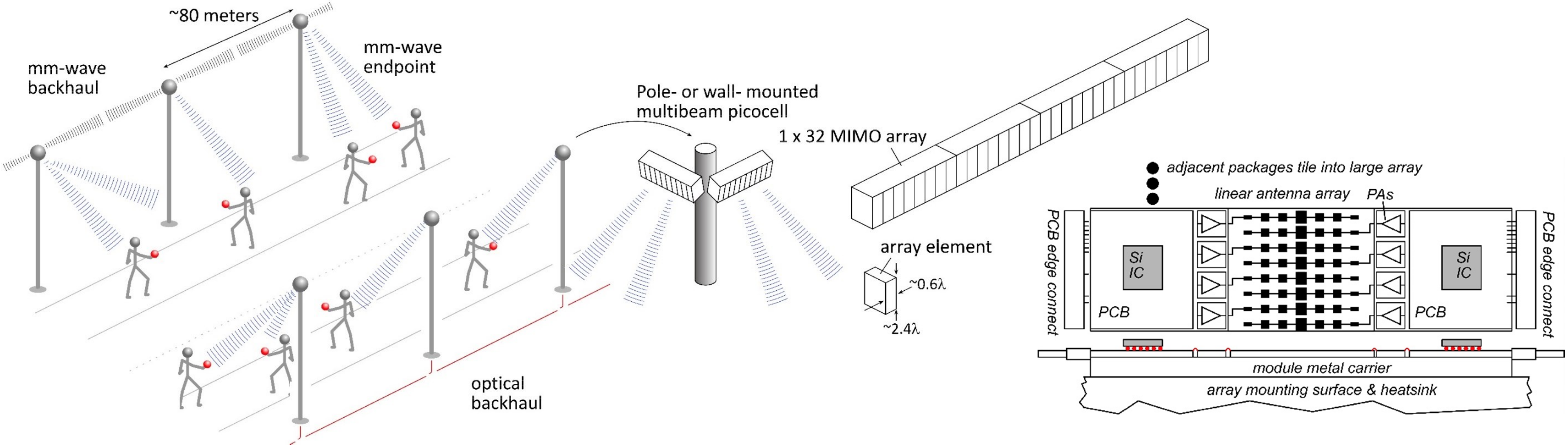
70 GHz spatially multiplexed base station

If we use instead a 70GHz carrier,
the range increases to **168 meters** (vs. **100 meters**)
but the handset becomes 16mm×16mm (vs. 8mm×8mm),
and the hub array becomes 20mm×524mm (vs. 10mm×262mm)

Or, use a 4×4 (8mm×8mm) handset array,
and the range becomes ..**100 meters**.

Same handset area (more handset elements)→ same link budget
Easier to obtain license for 140±2.5GHz than 75±2.5GHz

140GHz moderate-MIMO hub

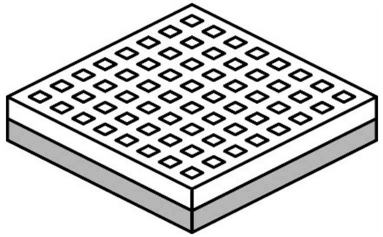


If demo uses 32-element array (four 1×8 modules):

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

140GHz Architecture (Sketch)

75GHz RF front-ends
BWRC

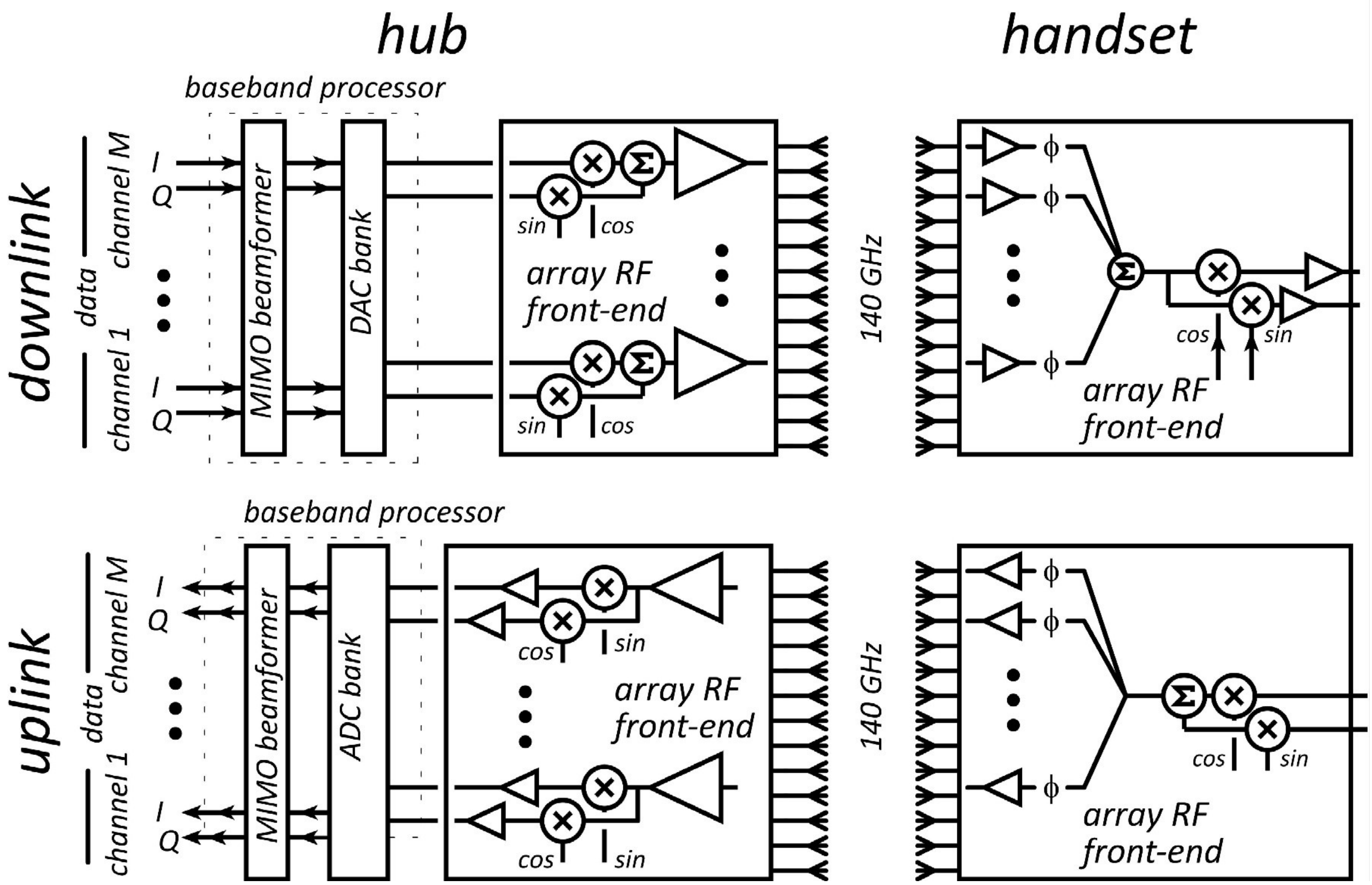
140 GHz hub RF front-ends
UCSB

140GHz handset RF front-ends
UCSD

Beamforming by:

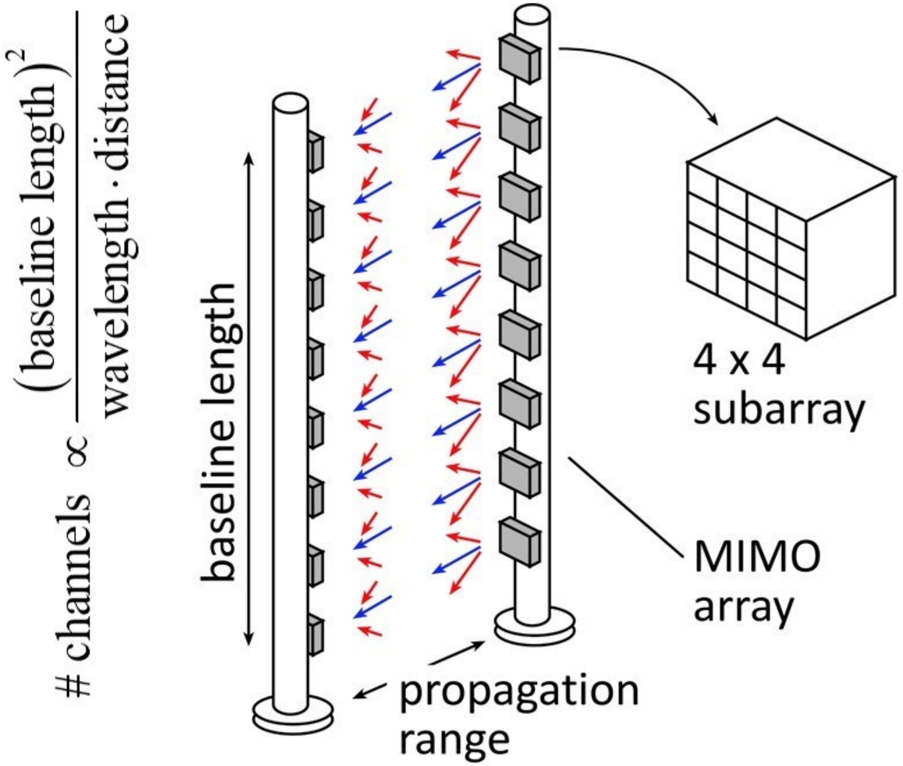
FPGA: demos, algorithms

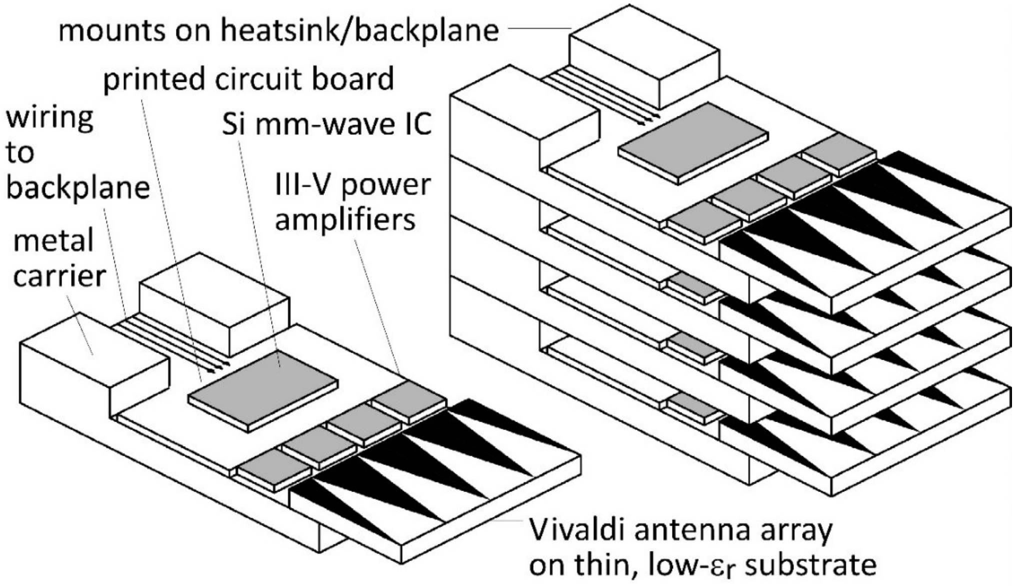
BWRC Hydra: flexible, general



Custom Si VLSI beamformer ICs in development (BWRC, Cornell)

210 GHz, 640 Gb/s MIMO Backhaul





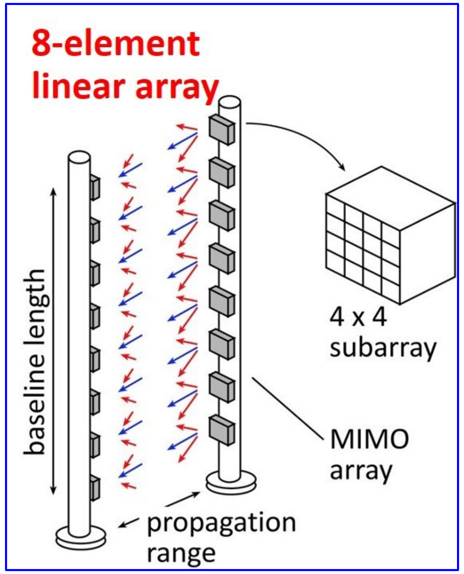
8-element MIMO array
3.1 m baseline.
80Gb/s/subarray→ 640Gb/s total
4 × 4 sub-arrays → 8 degree beamsteering

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

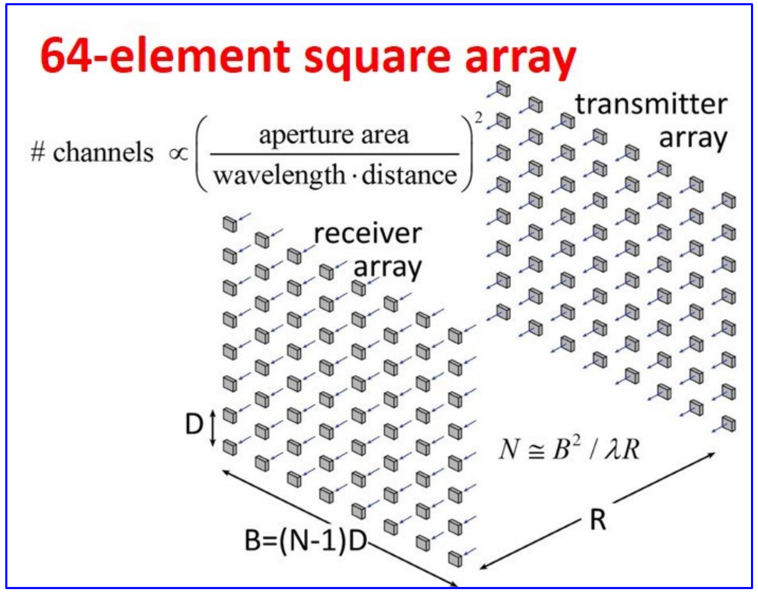
210 GHz, 5.1 Tb/s MIMO backhaul

500m range in 50mm/hr. rain.

8-element 640Gb/s linear array:
requires 14dB$_m$ transmit power/element (P_{out})
....3.2W total output power
requires 2.1m linear array



64-element 5Tb/s square array:
same link assumptions
requires 5dB$_m$ transmit power/element (P_{out})
....3.2W total output power
requires 2.1m square array

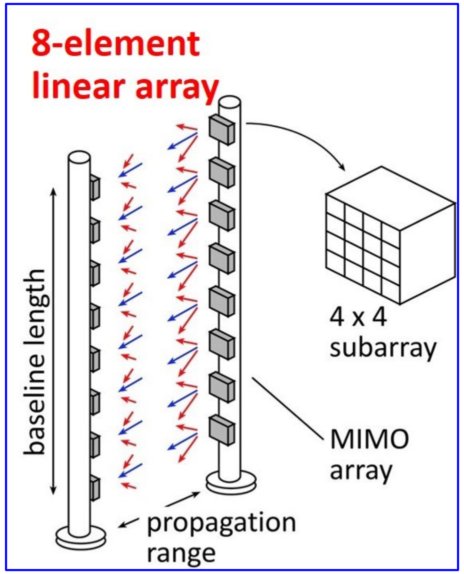


Complex system: can we make it cheaply ?

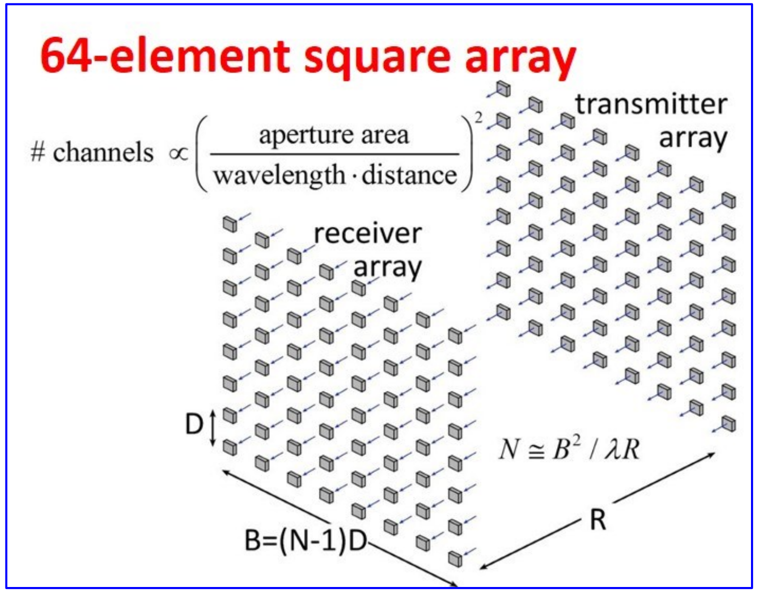
70 GHz, 640 Gb/s MIMO backhaul (16QAM)

Why not use a lower-frequency carrier, e.g. 70 GHz ?

8-element 640Gb/s linear array:
requires 11dB$_m$ transmit power/element (P_{out})
....1.7W total output power
requires 5.5m linear array

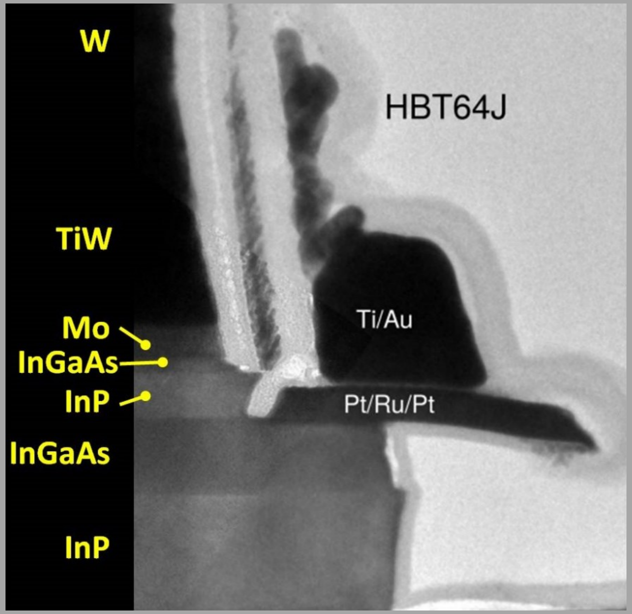


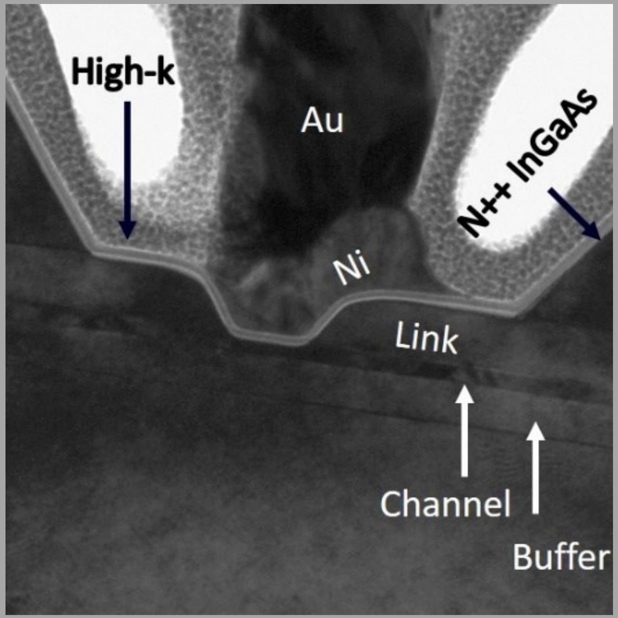
64-element 5Tb/s square array:
same link assumptions
requires 2dB$_m$ transmit power/element (P_{out})
....1.7W total output power
requires 5.5m square array

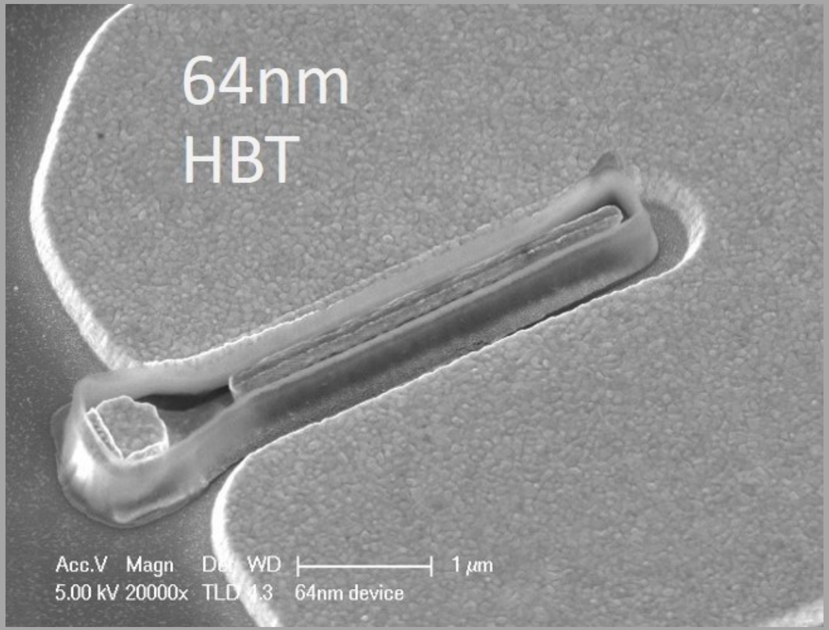


Similar RF power output, physically larger

Transistors







100-1000 GHz Transistors and ICs

	f_{max} GHz	Good ICs to (GHz)	complexity	LNAs	PAS	increased bandwidth ?
CMOS	350	150/200	transceivers	good	weak: 10-30 mW	not easy
Production SiGe	300	200/250	transceivers	ok	OK: 20-100 mW	depends on $$
R&D SiGe	700	300/500	transceivers	good	OK: 20-100 mW	2-3THz
R&D InP HBT	1150	400/650	PA, converters	ok*	good: 100-200 mW	2-3THz
R&D InP HEMT	1500	500/1000	LNA	great	weak: 20-50 mW	2-3THz
R&D GaN	400	120/140	PAs	good	excellent: 0.1-1W	600GHz

ICs with useful performance, hero experiments

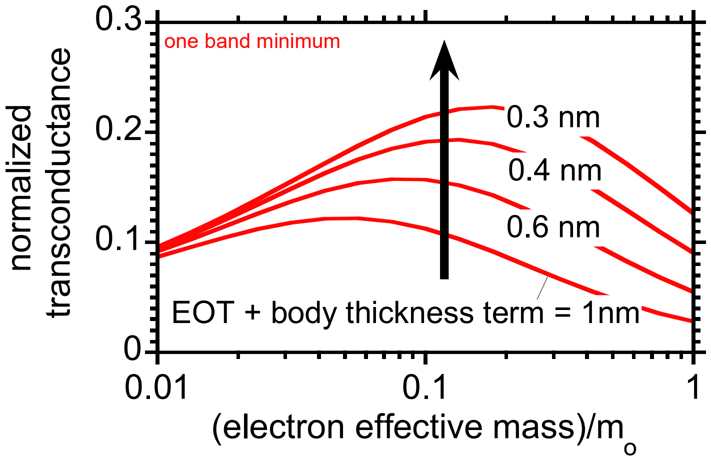
*can be addressed

There are THz transistors today; their bandwidth will increase

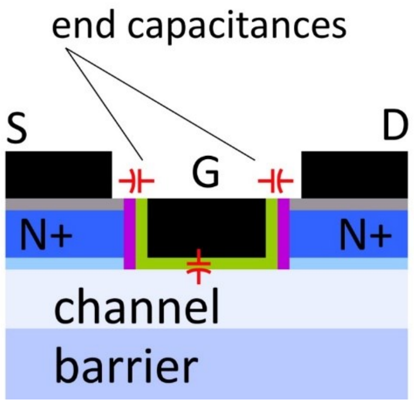
Challenge: reducing costs, increasing market size

mm-Wave CMOS won't scale much further

Gate dielectric can't be thinned
→ on-current, g_m can't increase



Shorter gates give no less capacitance
dominated by ends; ~1fF/μm total

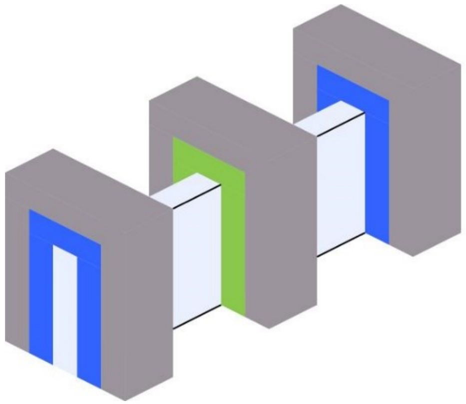


Maximum g_m, minimum C→ upper limit on f_τ.
about 350-400 GHz.

Tungsten via resistances reduce the gain

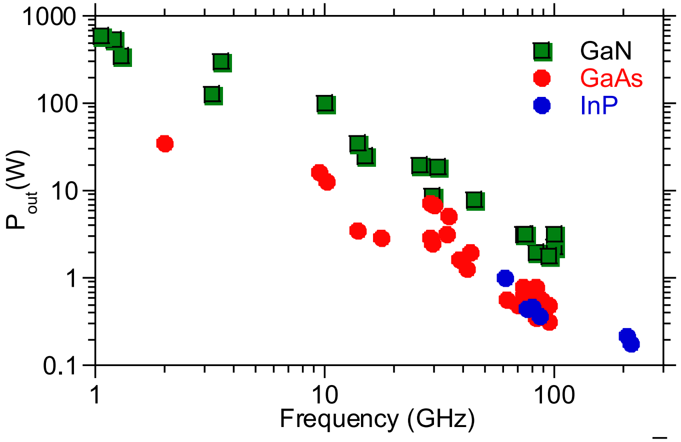
Inac et al, CSICS 2011

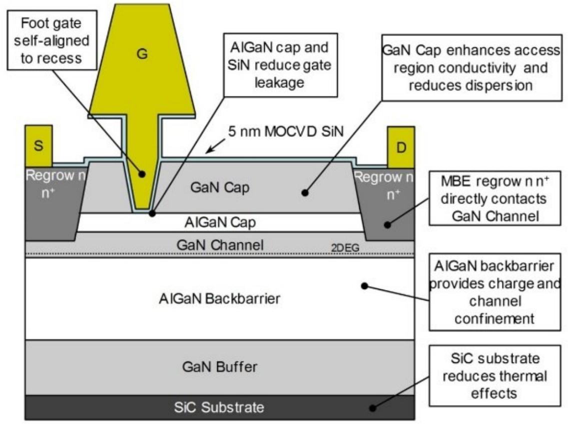
Present finFETs have yet larger end capacitances



mm-Wave Transistor Development

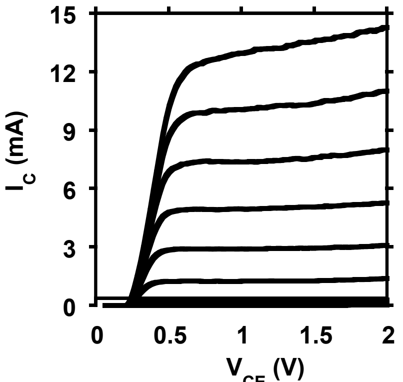
InGaN and GaN HEMTs:
High power from 100-340GHz
GaN: superior power density at all frequencies
UCSB/Mishra: InGaN for increased mobility
Cornell/Xing: AlN/GaN/AlN

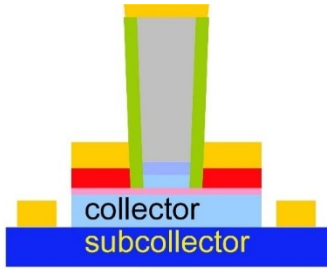




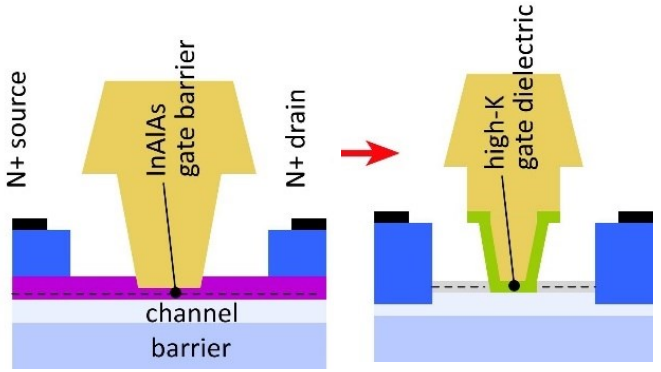
N-polar GaN: Mishra, UCSB

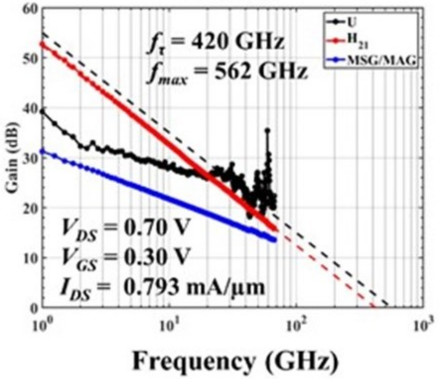
THz InP HBTs:
State-of-art: 1.1THz f_{max} @ 130nm node
Efficient 100-650GHz power
more f_{max}: more efficient, higher frequencies
base regrowth: better contacts→ higher f_{max}.
status: working DC devices; moving to THz



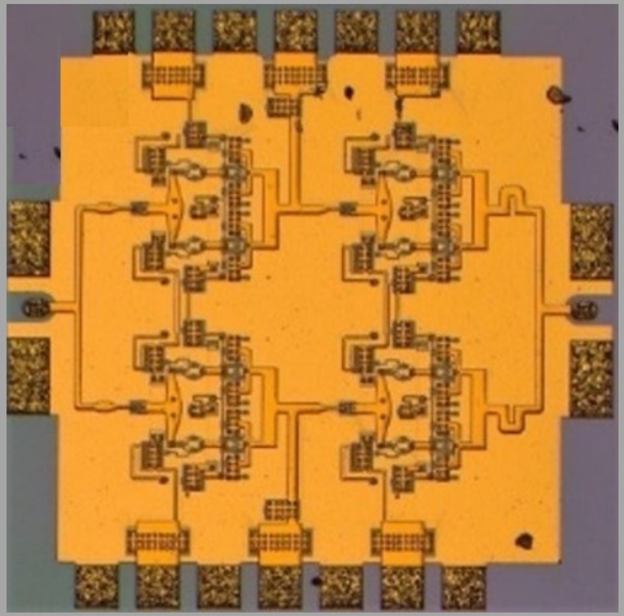


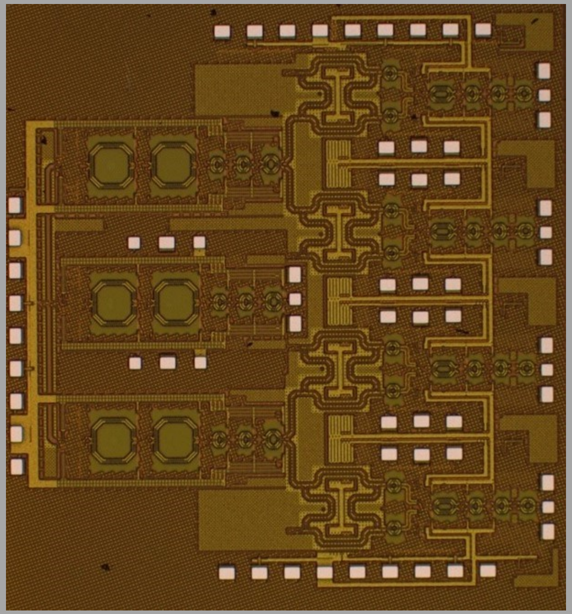
THz InP HEMTs:
State-of-art: 1.5THz f_{max} @ 32nm node
Sensitive 100-650GHz low-noise amplifiers
more f_τ: lower noise, higher frequencies
high-K gate dielectric → higher f_τ, f_{max}

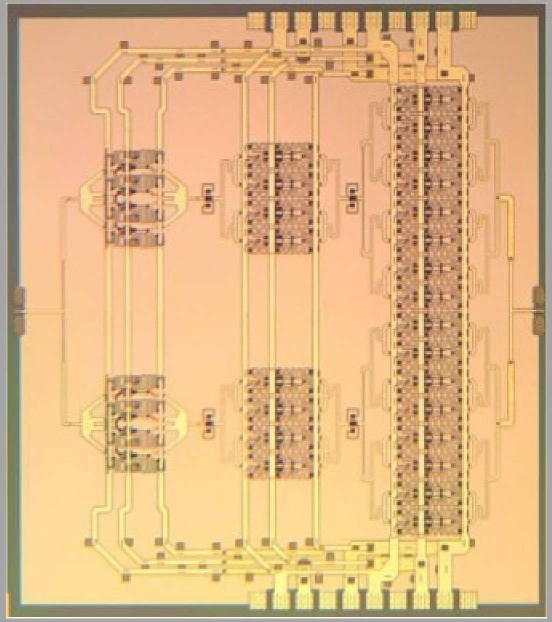




ICs







JUMP ComSenTer Research: ICs

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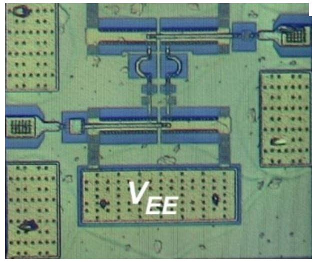
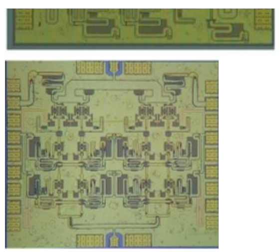
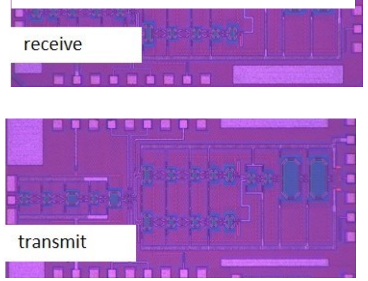
Record-PAE Class B 140GHz PAs Buckwalter



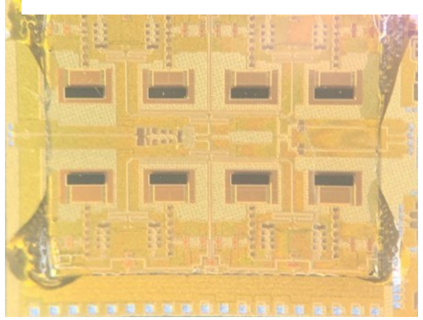
Record-PAE Class A 100-200mW 140GHz PAs Rodwell

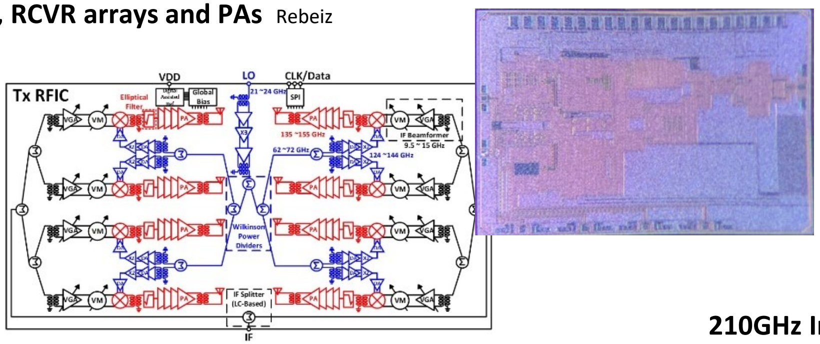


140GHz CMOS handset ICs Rodwell

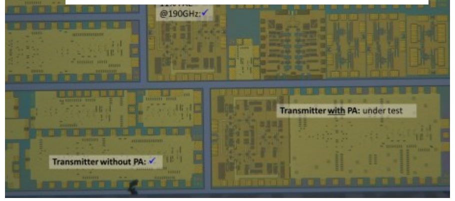


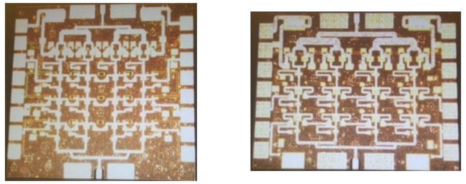
140GHz 8-element handset TRX, RCVR arrays and PAs Rebeiz



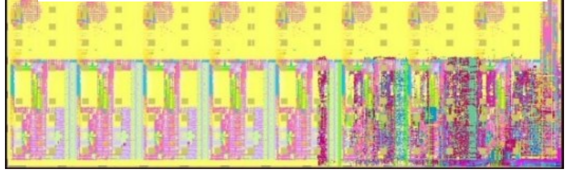


210GHz InP transceivers and arrays, 210, 280GHz PAs Seo/Rodwell

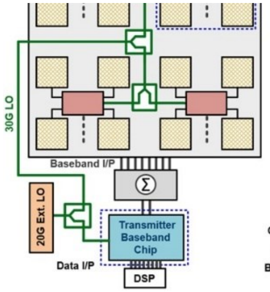


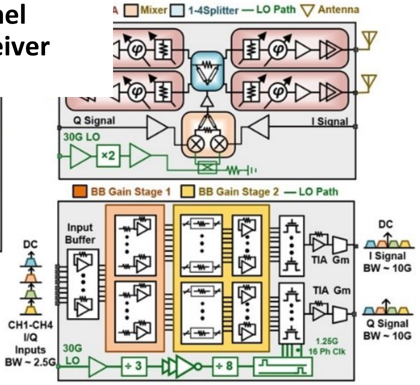


Hydra digital processor (beamformer)
Nikolic

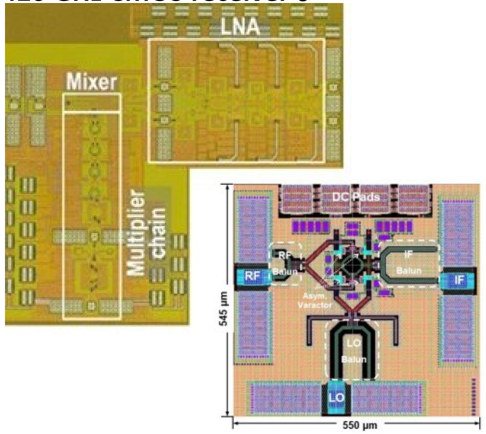


60GHz CMOS channel aggregation transceiver
Krishnaswamy

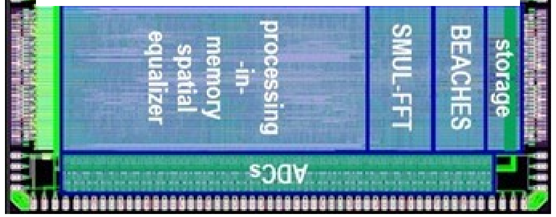




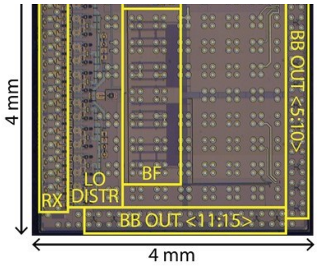
280GHz CMOS upconvert mixers
420 GHz CMOS receiver O



Beamspace digital beamformer
Studer/Molnar



75GHz MIMO front-ends
Niknejad, Alon, Nikolic



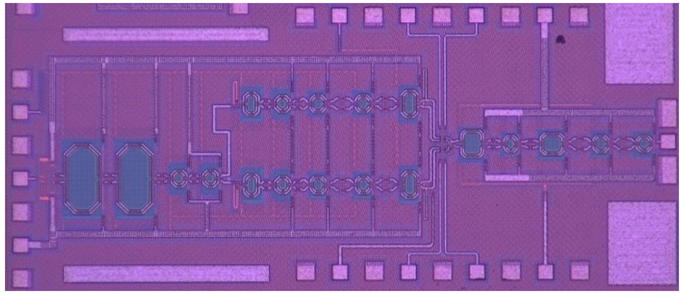
Not shown:

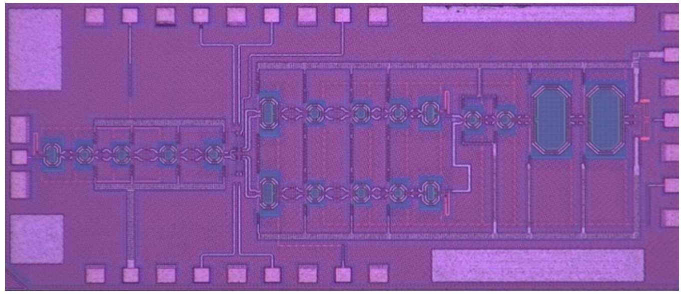
140GHz, 210GHz outphasing transmitters Buckwalter
mm-wave N-path mixers Molnar
GaN active circulators Krishnaswamy
140GHz GaN PAs Buckwalter

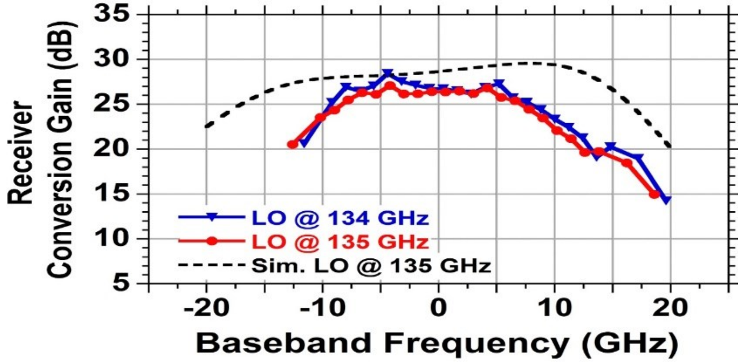
ComSenTer 140GHz CMOS ICs for hub & handset

1st-generation hub ICs: UCSB

Farid et al, RFIC 2019

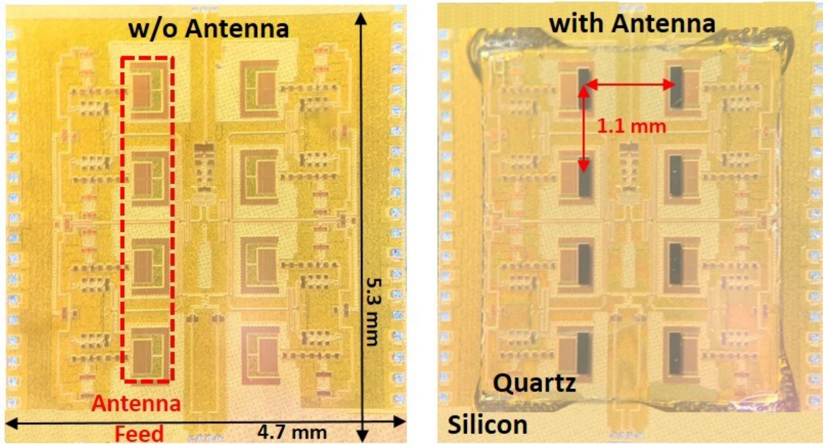




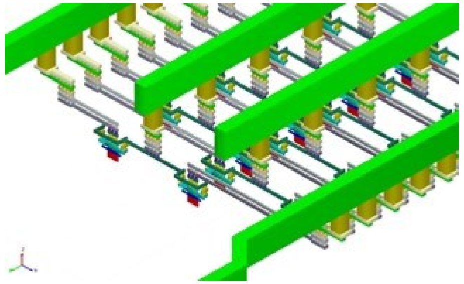


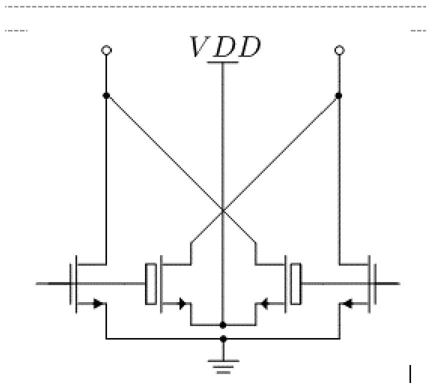
Handset array ICs: UCSD

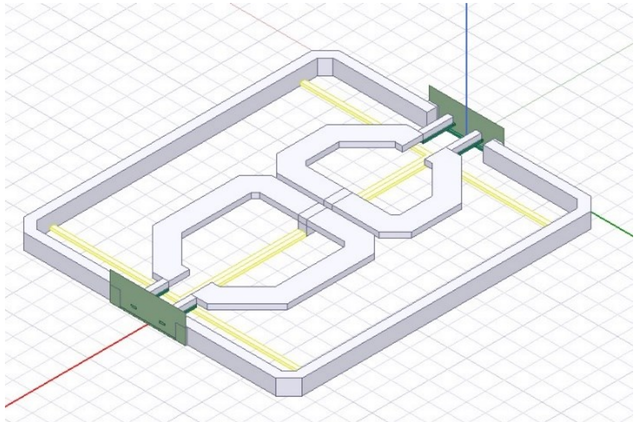
Rebeiz group



2nd-generation hub ICs: UC Berkeley

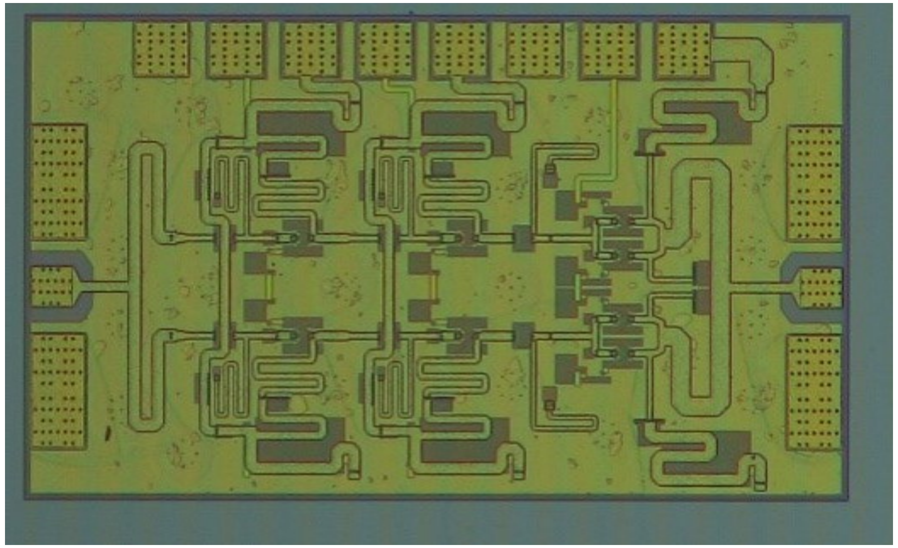




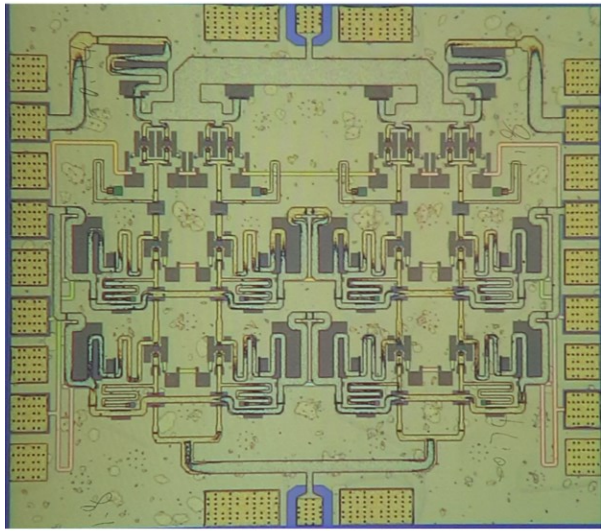


ComSenTer 140GHz InP ICs for hub

110mW power amplifier, 20.8% PAE
A. Ahmed, IMS 2020



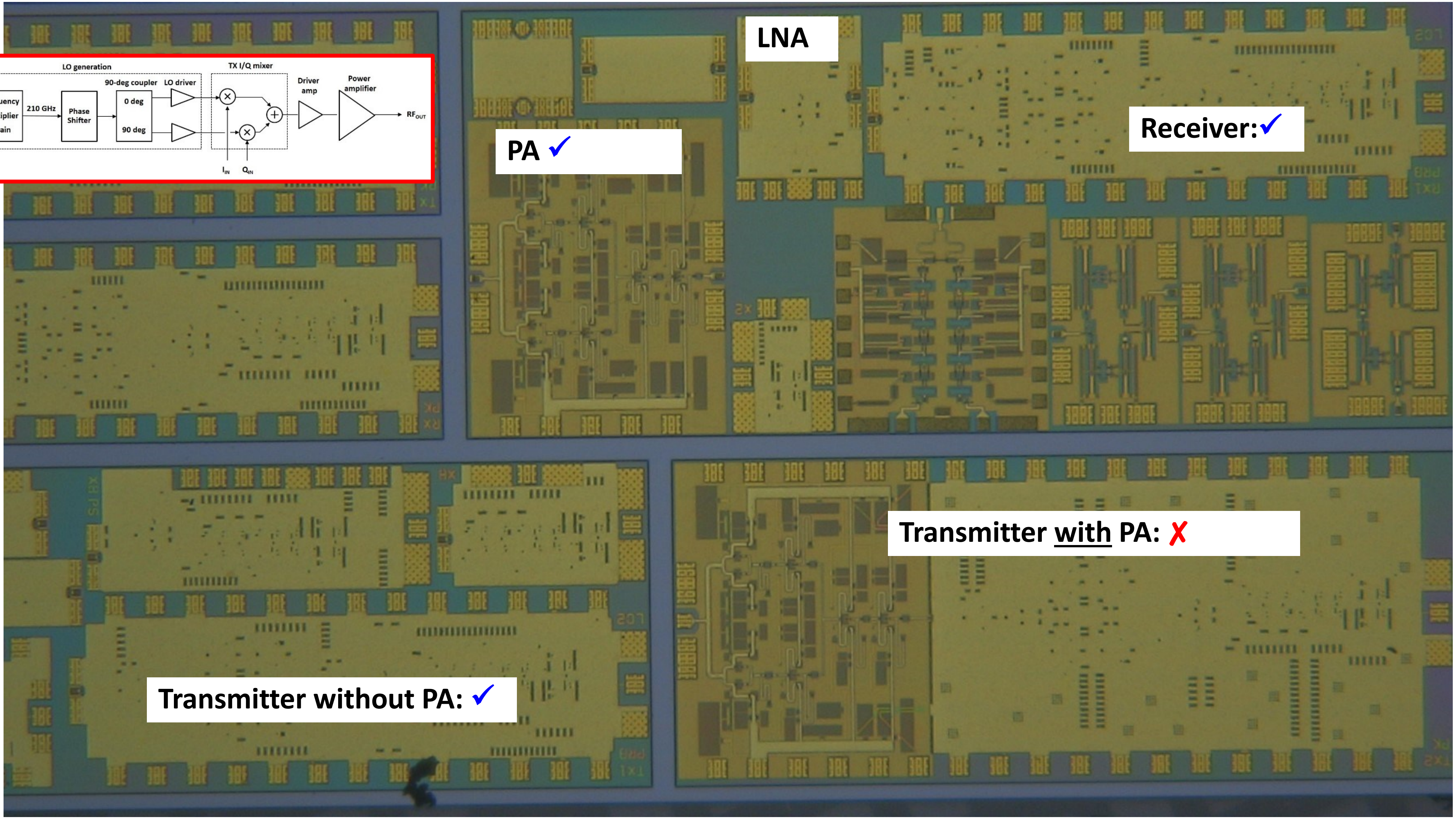
190mW power amplifier, 16.7% PAE
A. Ahmed, EuMIC 2020.



Also: **"A 130-GHz Power Amplifier in a 250-nm InP Process with 32% PAE"**
Kang Ning (Buckwalter group) 2020 RFIC symposium

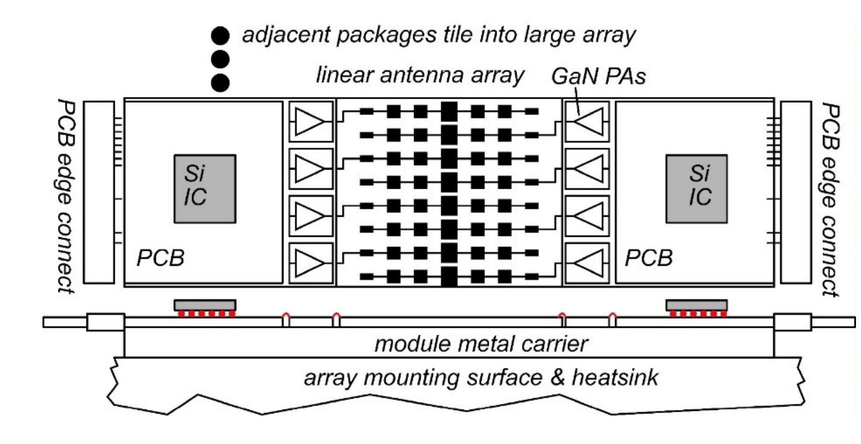
210 GHz MIMO backhaul: ICs

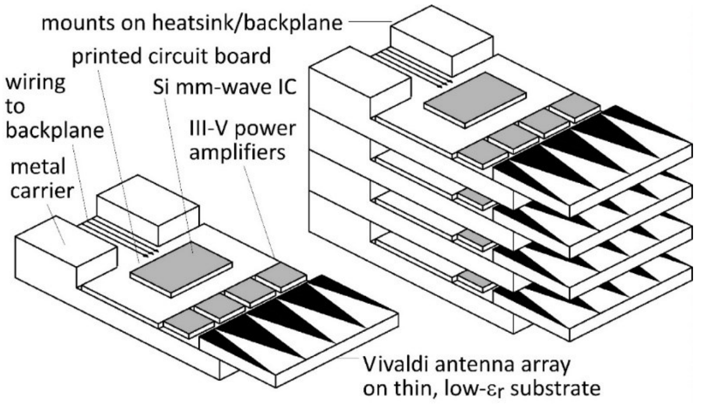
M. Seo Sungkyunkwan/UCSB
A. Ahmed, U. Solyu, M. Rodwell UCSB



Teledyne 250nm (650GHz) InP HBT.

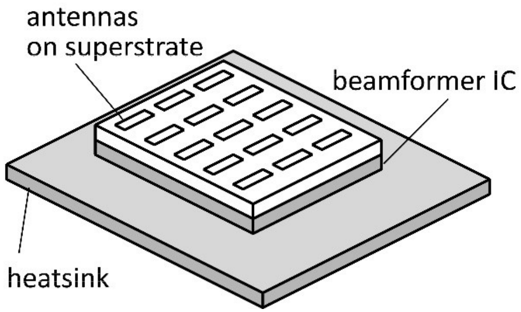
Packages / array modules

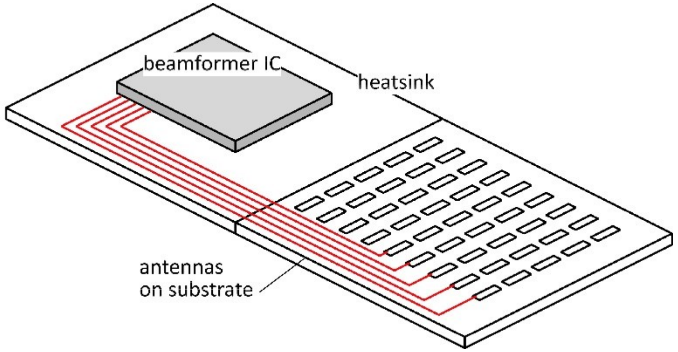




The mm-wave module design problem

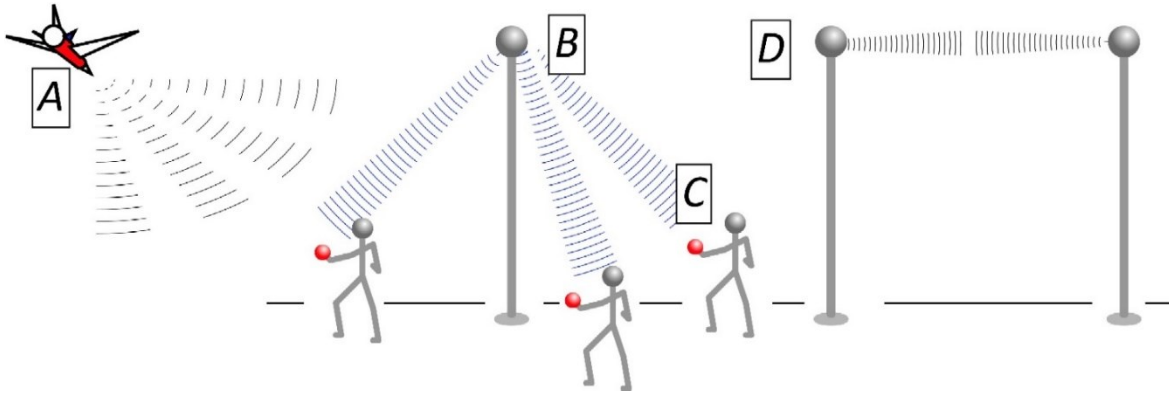
How to make the IC electronics fit ?
How to avoid catastrophic signal losses ?
How to remove the heat ?

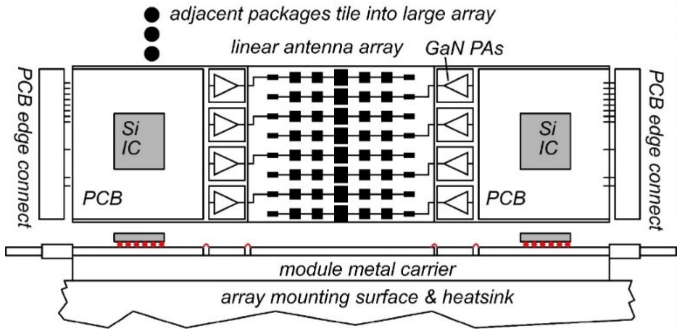


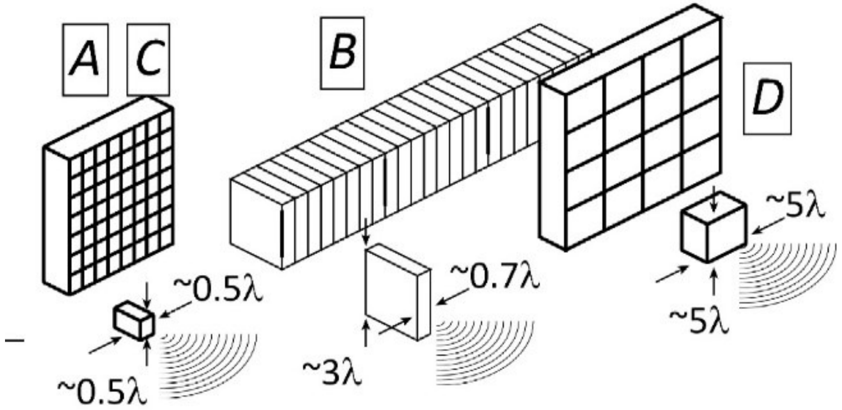


Not all systems steer in two planes...
...some steer in only one.

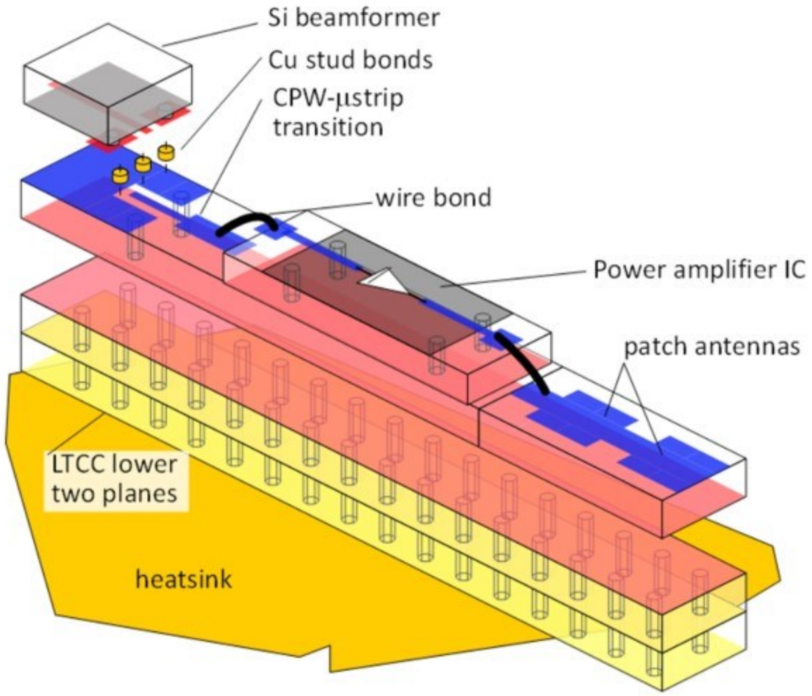
Not all systems steer over 180 degrees...
...some steer a smaller angular range



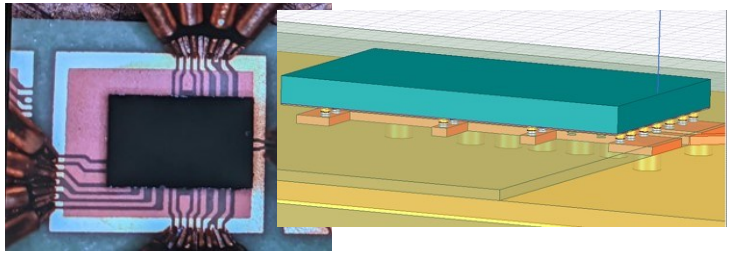




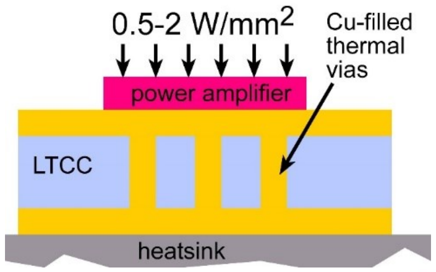
140GHz hub: packaging challenges



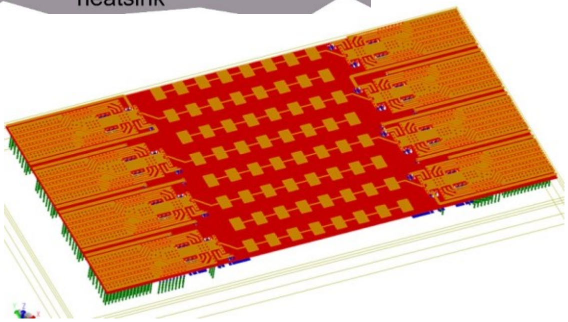
IC-package interconnects
Difficult at > 100 GHz



Removing heat
Thermal vias are marginal

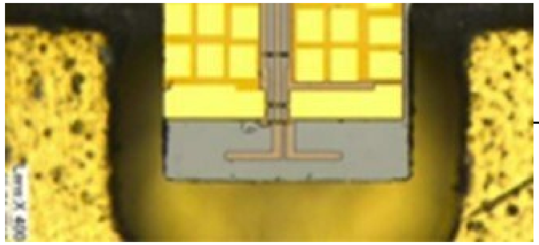


Interconnect density
Dense wiring for DC, LO, IF, control.
Hard to fit these all in.

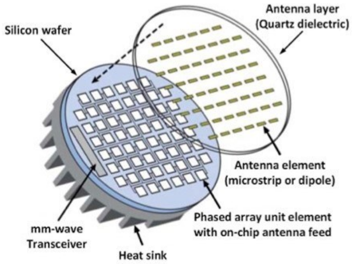


Economies of scale
Advanced packaging standards require sophisticated tools
High-volume orders only
Hard for small-volume orders (research, universities)
Packaging industry is moving offshore

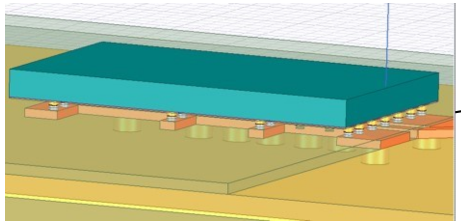
100-300GHz IC-package connections

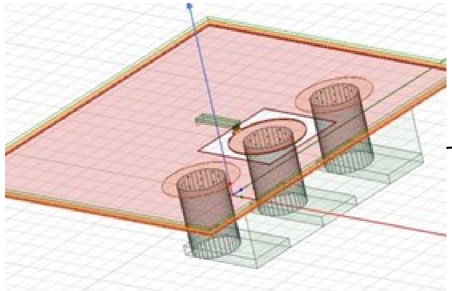


Deal, IEEE Trans THz, Sept 2011



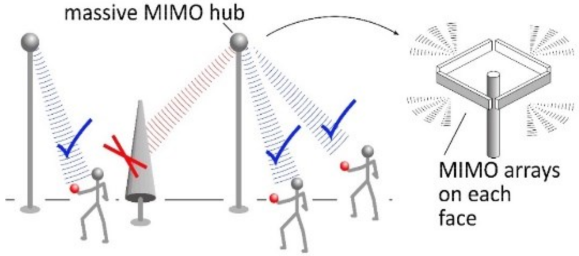
G. Rebeiz

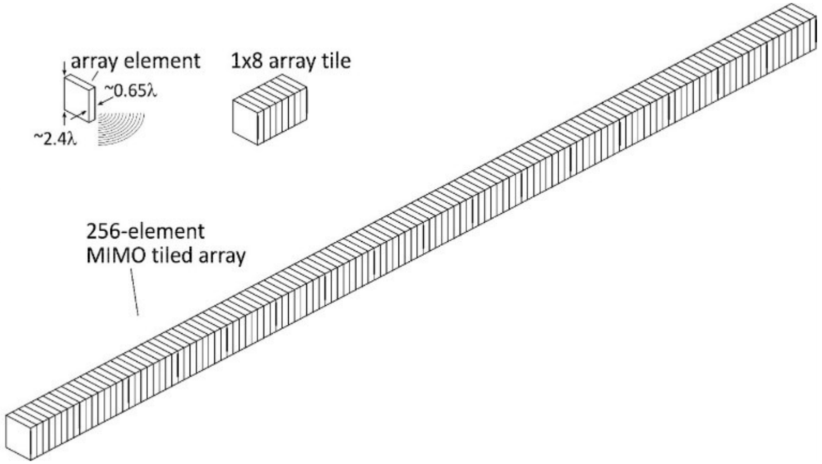




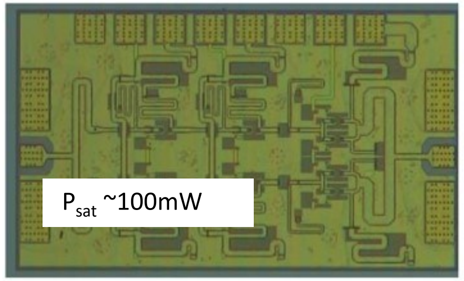
type	Frequency	technology	cost	heatsinking
micromachined waveguide interface	1000 GHz	Research. Cheap one day ?	**high** ✗	good
ribbon, mesh bond	200 GHz	Handcrafted.	**high** ✗	good
patch antennas on superstrate	1000 GHz	Straightforward	low	good
Cu stud flip-chip	>200 GHz	Industry standard	low	ok, **marginal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

140GHz massive MIMO hub modules

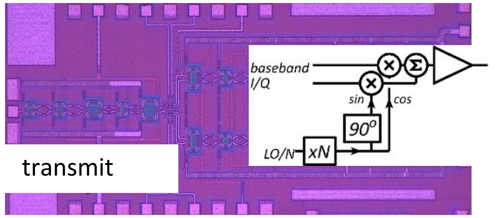


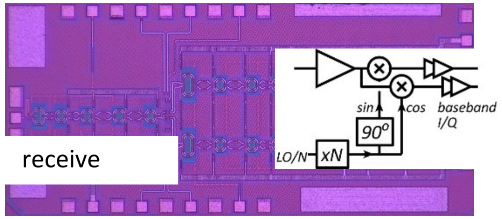


140GHz InP PAs



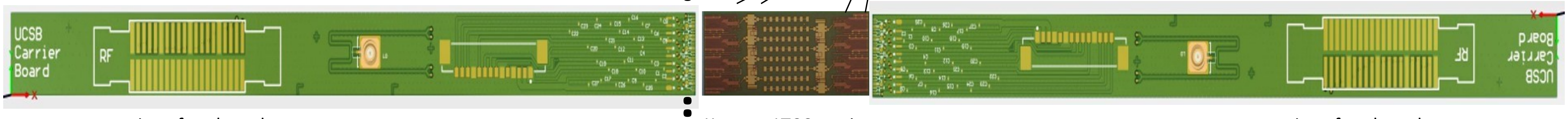
140GHz CMOS ICs





8 CMOS ICs, 8 InP PAs

LTCC-based array tile



connector interface board

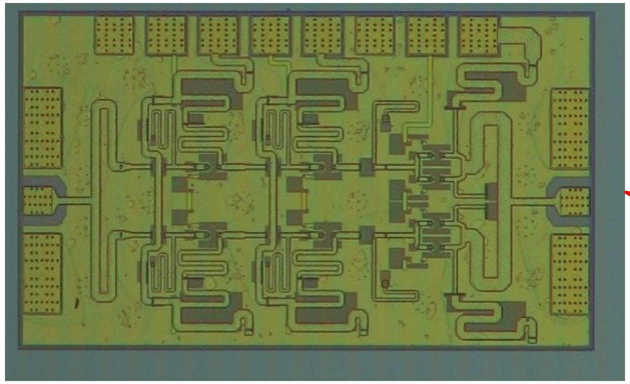
Kyocera LTCC carrier

connector interface board

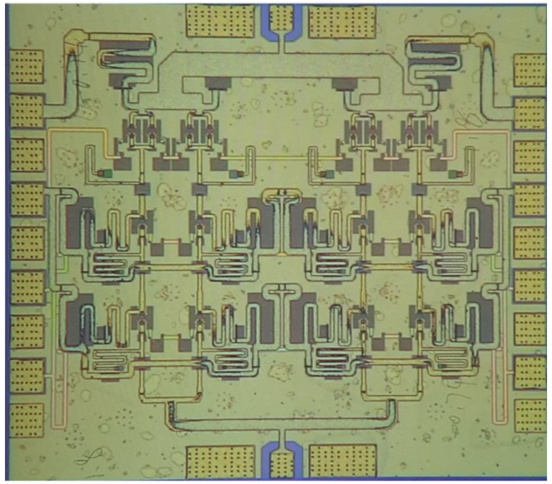
Farid, Ahmed, Rodwell, UCSB; Flynn, Dunn, Niknejad, Nikolic, BWRC; Rebeiz, UCSD

140GHz hub: ICs & Antennas

110mW InP Power Amplifier
20.8% PAE

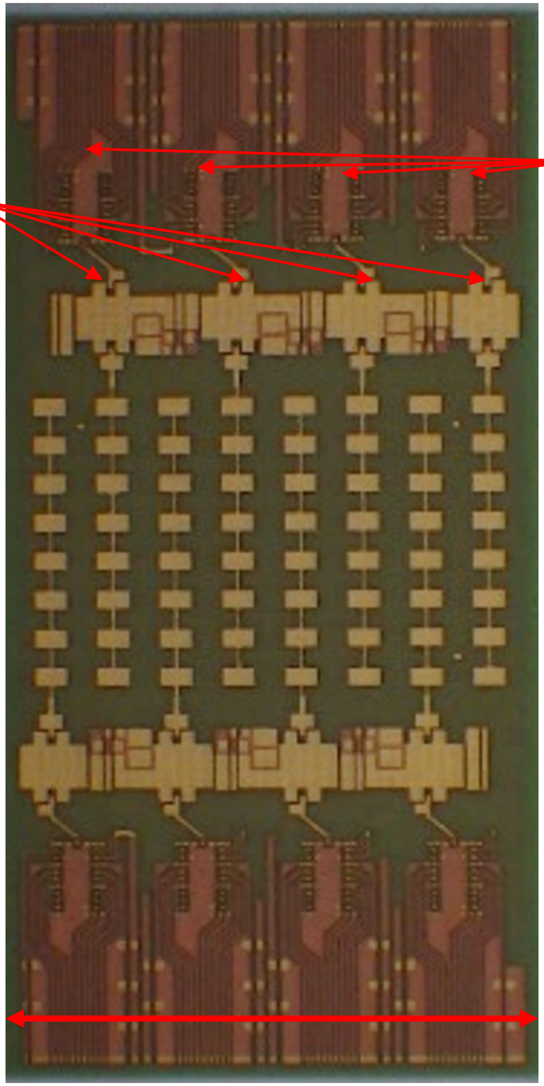


190mW InP Power Amplifier
16.7% PAE



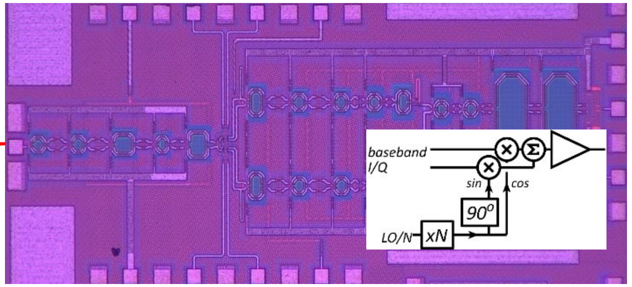
Teledyne InP HBT

LTCC Array module

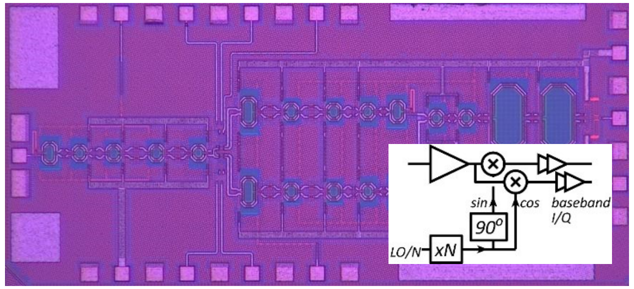


Kyocera

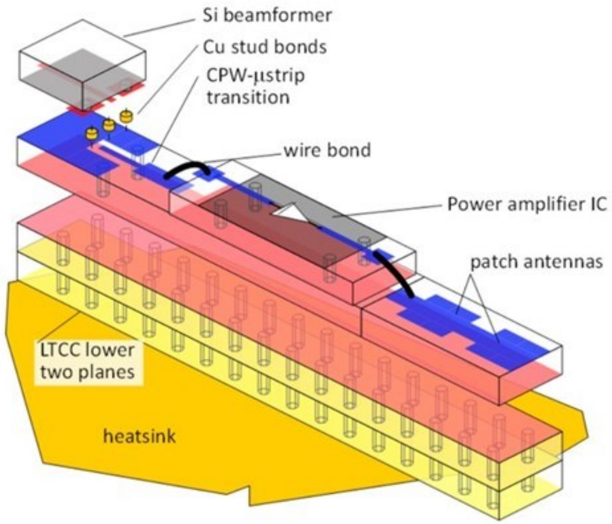
CMOS Transmitter IC
22nm SOI CMOS.



Receiver IC
22nm SOI CMOS.



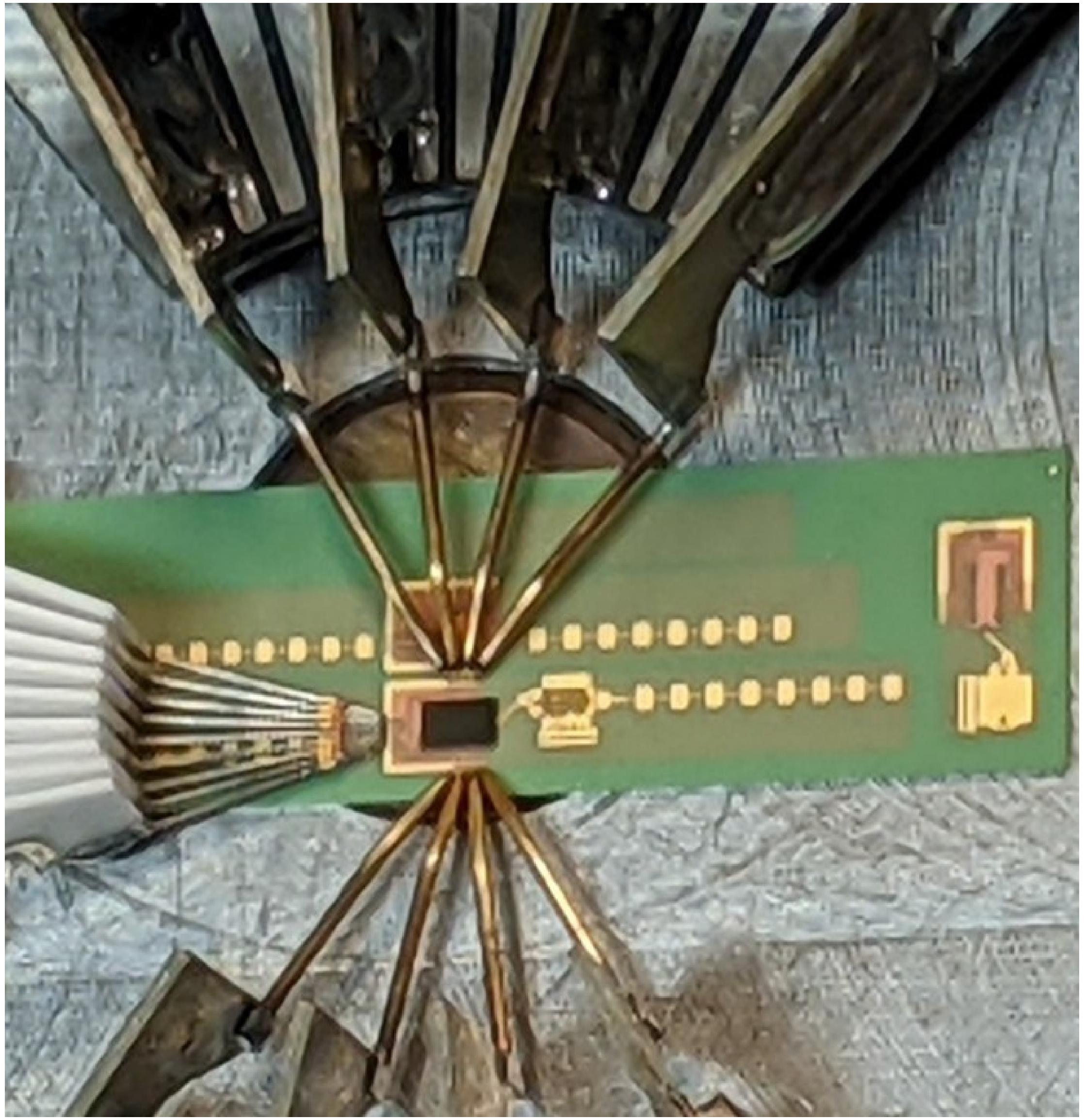
GlobalFoundries 22nm SOI CMOS

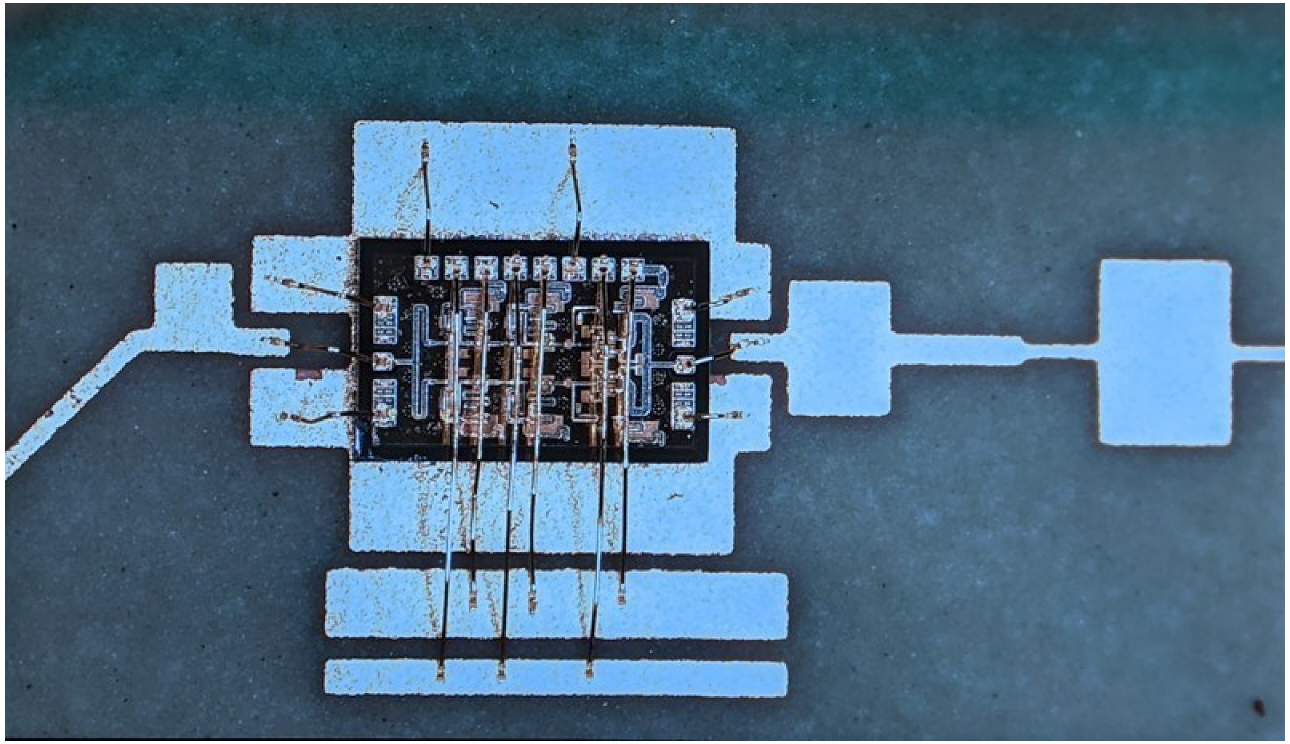


Farid, Ahmed, Rodwell, UCSB; Flynn, Dunn, Niknejad, Nikolic, BWRC; Rebeiz, UCSD

140GHz Single-Channel CMOS+InP Transmitter

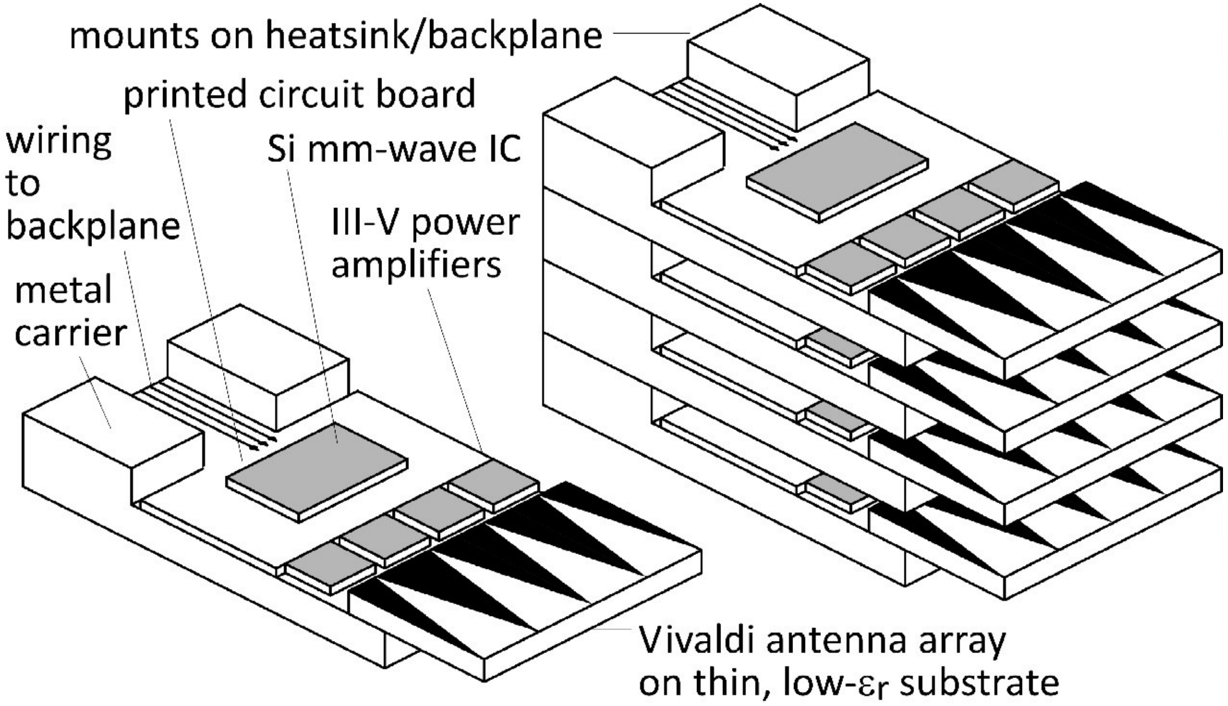
A. Farid, A. S. Ahmed, UCSB, modules being tested

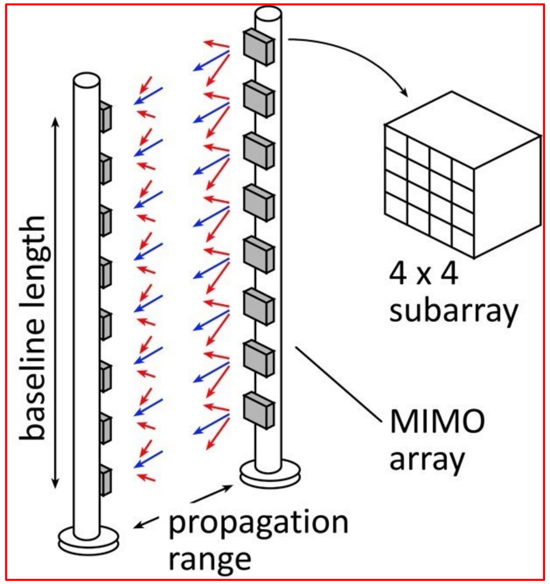




Farid, Ahmed, Rodwell, UCSB; Flynn, Dunn, Niknejad, Nikolic, BWRC; Rebeiz, UCSD

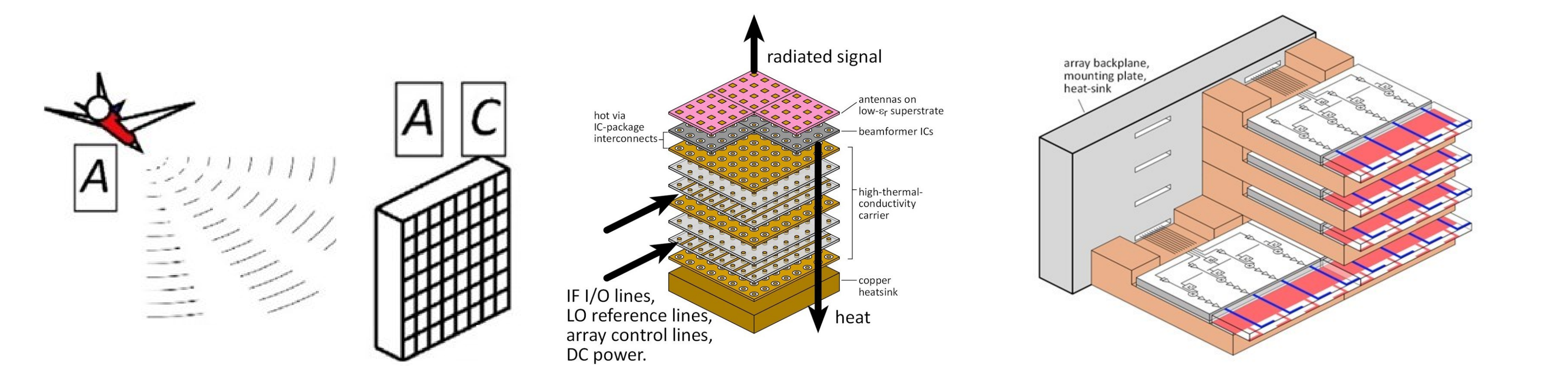
Concept: module for small angular scanning





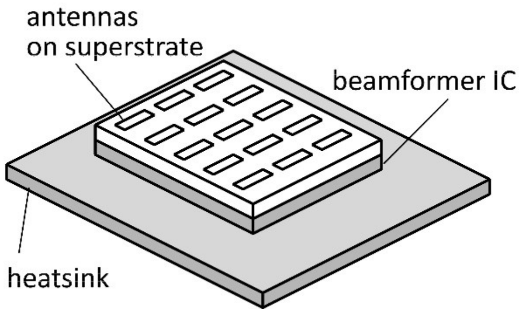
Terrestrial system: horizontal + vertical steering → rectangular array.
Limited angular steering range (installation)→ spacing >> $\lambda/2$
Endfire / edge-card geometry: room for III-V PAs, LNAs.
Mounting directly on metal carrier→ heatsinking.

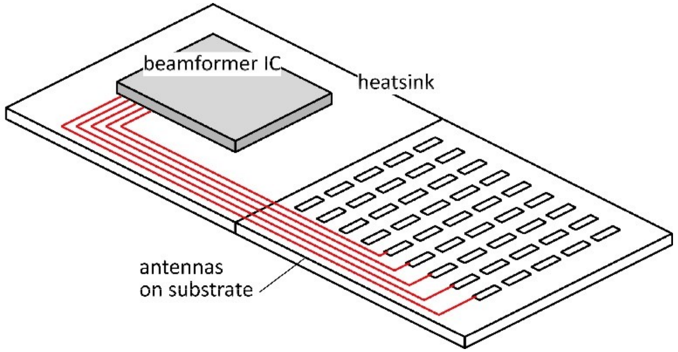
2D arrays


A
A
C
radiated signal
hot via
IC-package
interconnects
antennas on
low-εr superstrate
beamformer ICs
high-thermal-
conductivity
carrier
copper
heatsink
IF I/O lines,
LO reference lines,
array control lines,
DC power.
heat
array backplane,
mounting plate,
heat-sink

The mm-wave module design problem

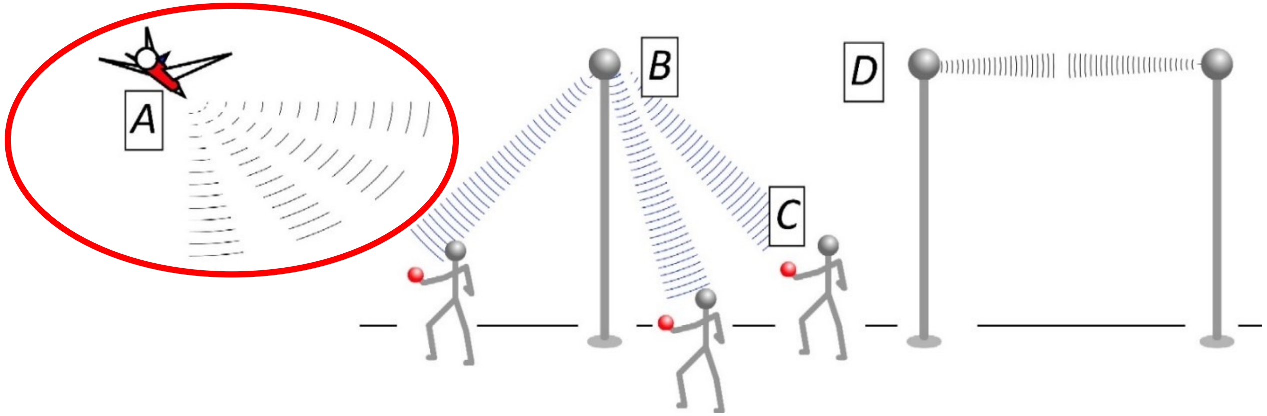
How to make the IC electronics fit ?
How to avoid catastrophic signal losses ?
How to remove the heat ?

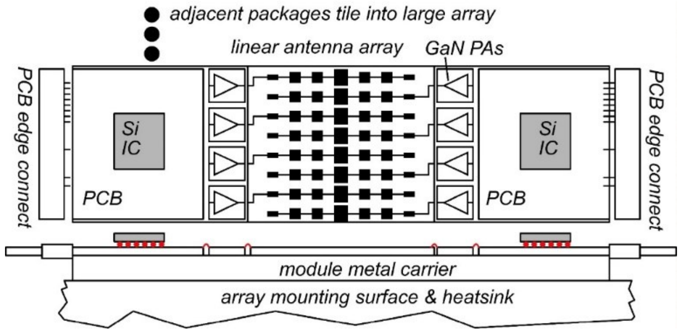


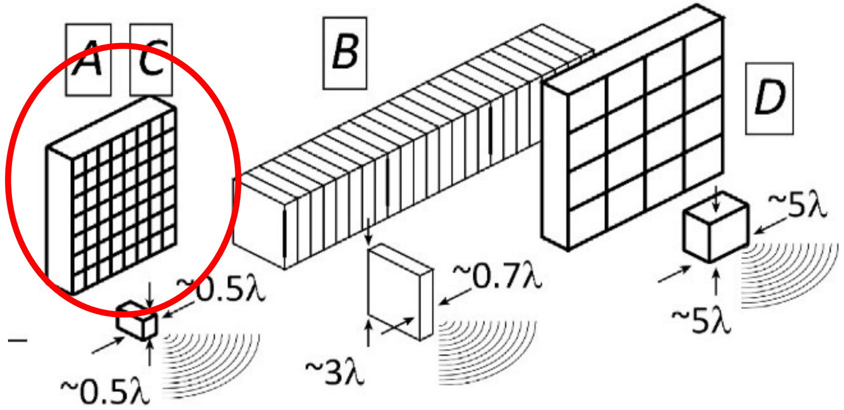


Not all systems steer in two planes...
...some steer in only one.

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

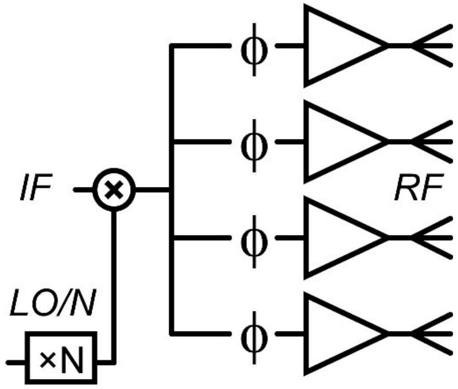




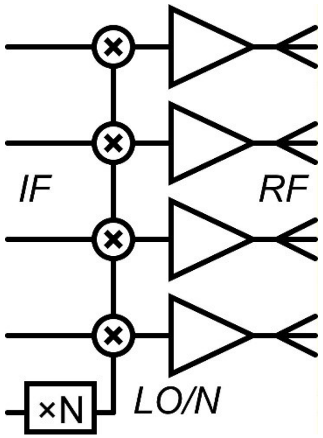


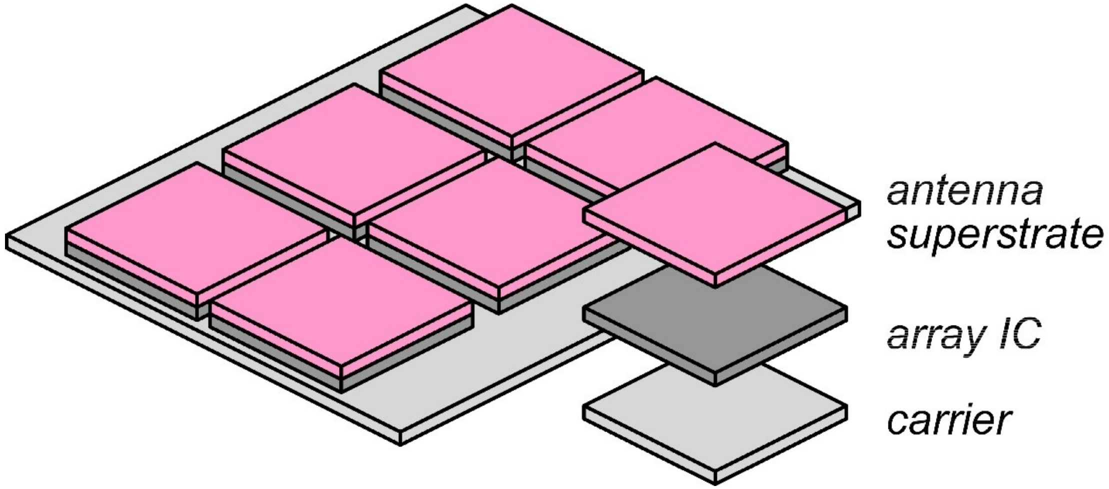
100-300GHz: 2D arrays

Single-beam array:
1 PA, one phase-shifter in ~$0.36\lambda^2$

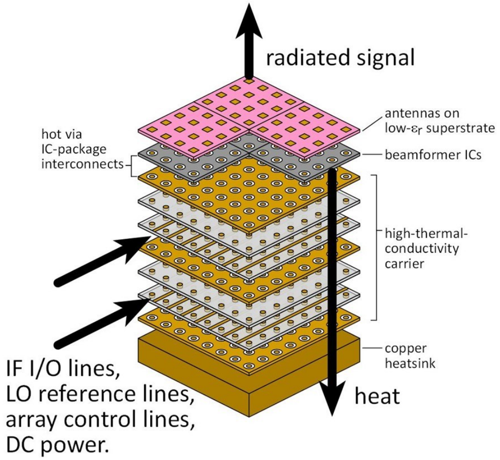


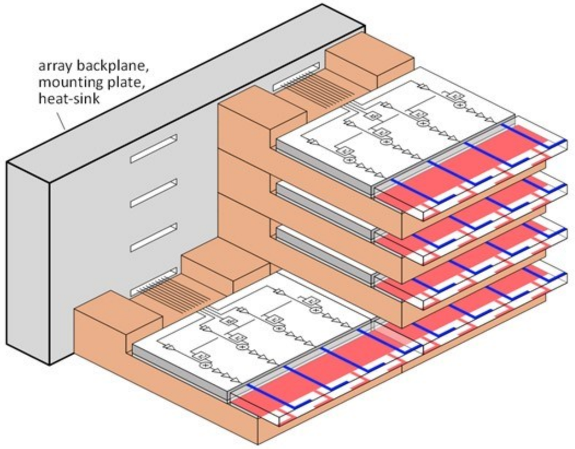
Multi-beam array:
1 PA, one mixer in ~$0.36\lambda^2$





f	100	150	200	250	300	GHz
λ	3	2	1.5	1.2	1	mm
λ/2	1.5	1	0.75	0.6	0.5	mm
0.6λ	1.8	1.2	0.9	0.72	0.6	mm



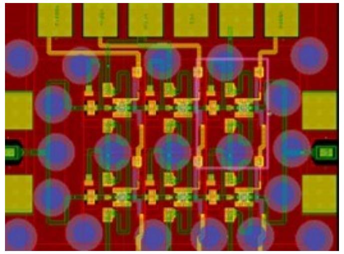


100-300GHz, 2D arrays: ICs can fit

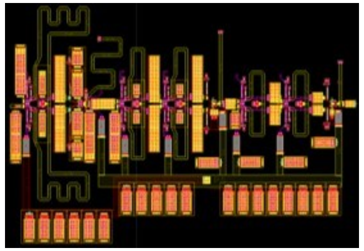
200GHz array cell
0.9 mm x 0.9 mm

0.6λ x 0.6λ

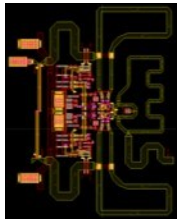
200GHz 40mW PA
0.56 mm x 0.78 mm



LO frequency multiplier
0.58 mm x 0.4 mm



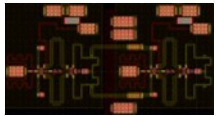
Phase shifter
0.3 mm x 0.4 mm



TX I/Q mixer
0.16mm x 0.08 mm

RX mixer (I or Q)
0.16 mm x 0.11 mm

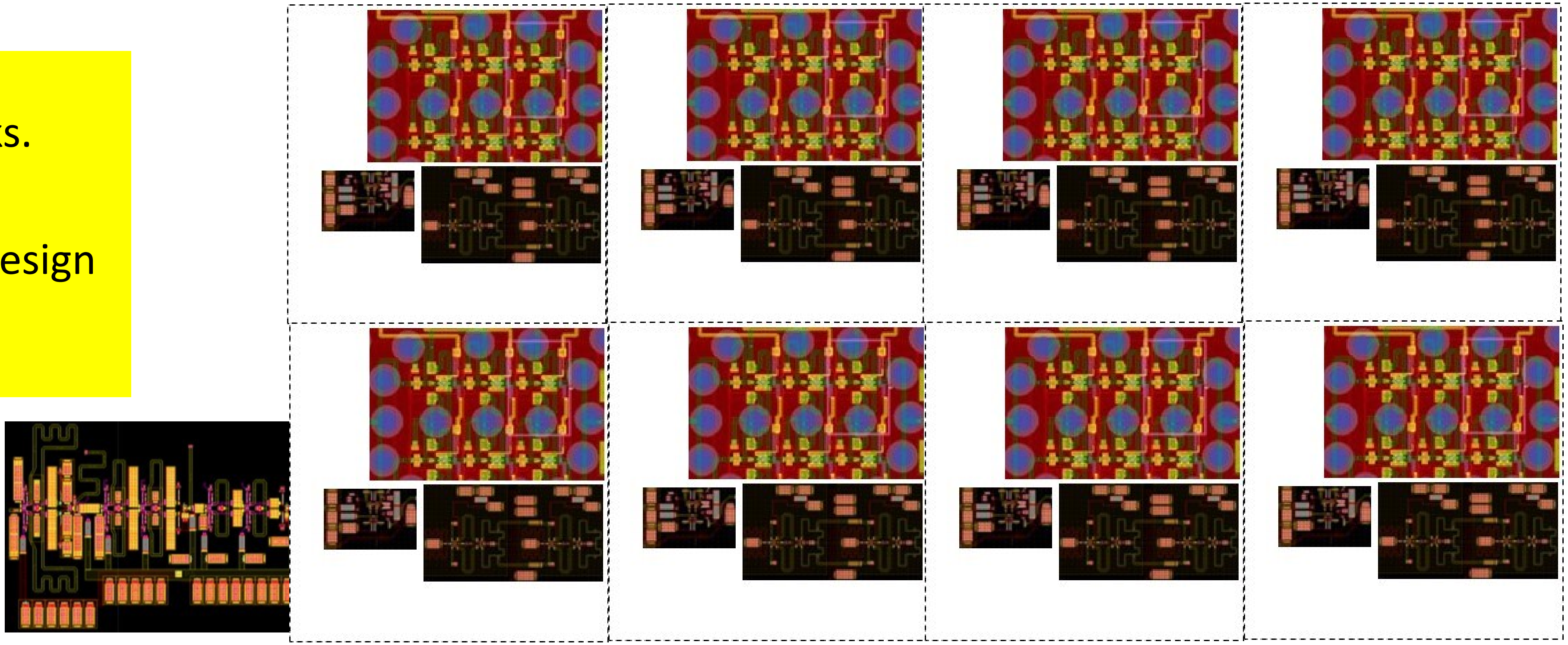
LO buffer amp.
0.34 mm x 0.18 mm



(layouts are roughly in proportion; may not be in exact scale)

200GHz 2D arrays:
~feasible with present IC blocks.

300GHz 2D arrays:
layout compaction: better IC design
smaller power amplifiers
better wiring



How should we scale array design at high frequencies ?

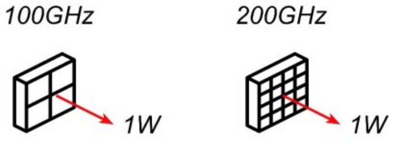
$$P_{received} = \frac{A_t A_r}{\lambda^2 R^2} e^{-\alpha R} \cdot P_{trans} \longrightarrow \#\text{beams} \cdot (\text{bit rate per beam}) \cdot kTF \cdot \text{SNR} = \frac{A_t A_r}{\lambda^2 R^2} e^{-\alpha R} \cdot P_{trans}$$

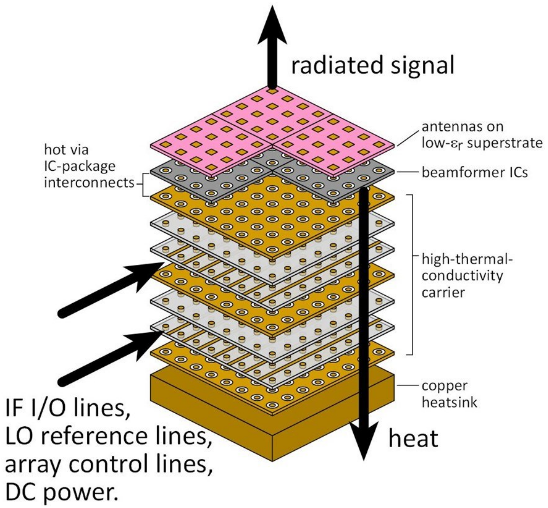
(Worst-case atmospheric loss: ~constant over 50-300GHz)

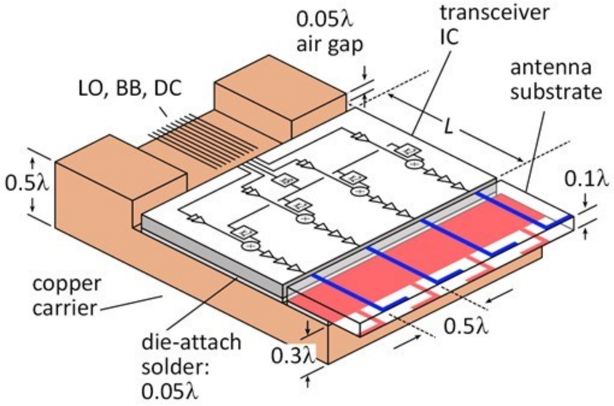
Proposed scaling law	change
carrier frequency	increase 2:1
aperture area	keep constant
total transmit power	keep constant

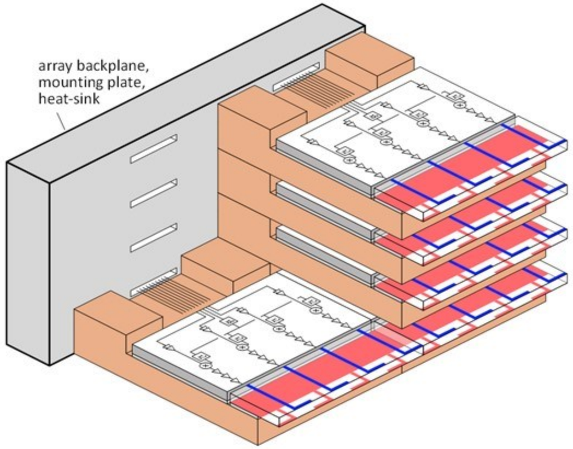
→

Implication	change
capacity (# beams·bit rate per beam)	increases 4:1
number elements	increases 4:1
RF power per cm^2 aperture area	stays constant
RF power per element	decreases 4:1
IC area/element (tiled array)	decreases 4:1
IC area/element (trayed array)	decreases 2:1
IC power/area (tiled array)	stays constant
IC power/area (trayed array)	decreases 2:1

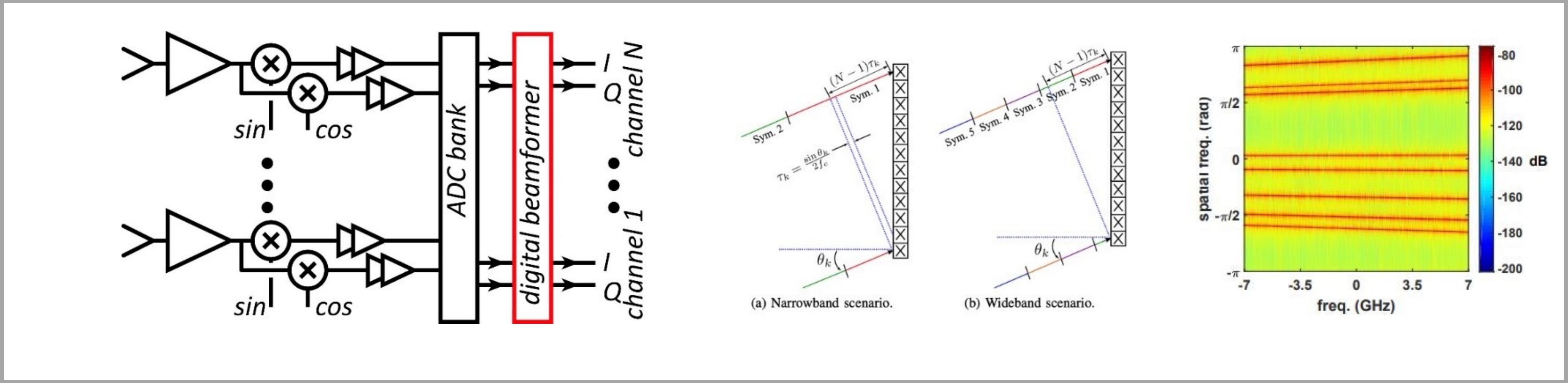




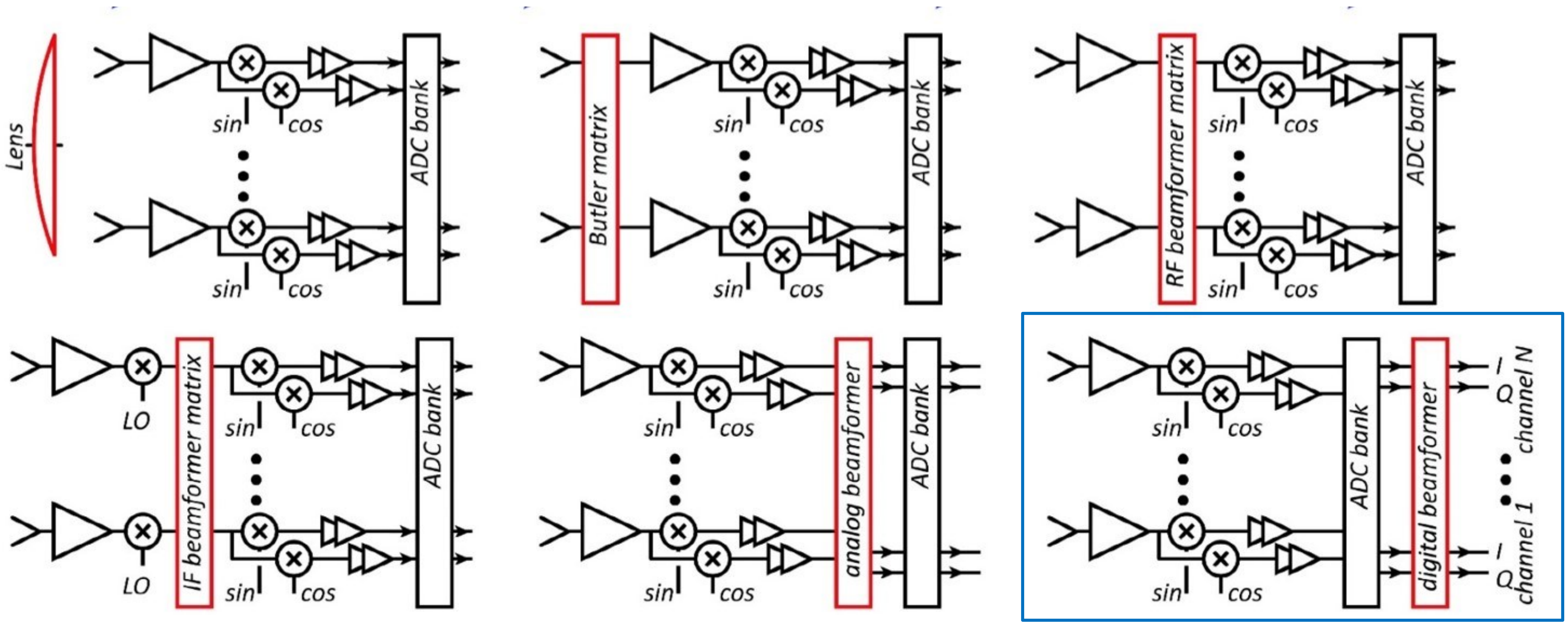




Systems


sin
cos
sin
cos
ADC bank
digital beamformer
I
Q
channel N
I
Q
channel 1
$(N-1)\tau_k$
Sym. 1
Sym. 2
$\tau_k = \frac{\sin\theta_k}{2f_c}$
θ_k
(a) Narrowband scenario.
$(N-1)\tau_k$
Sym. 5
Sym. 4
Sym. 3
Sym. 2
Sym. 1
θ_k
(b) Wideband scenario.
spatial freq. (rad)
π
π/2
0
-π/2
-π
-7
-3.5
0
3.5
7
freq. (GHz)
-80
-100
-120
-140
-160
-180
-200
dB

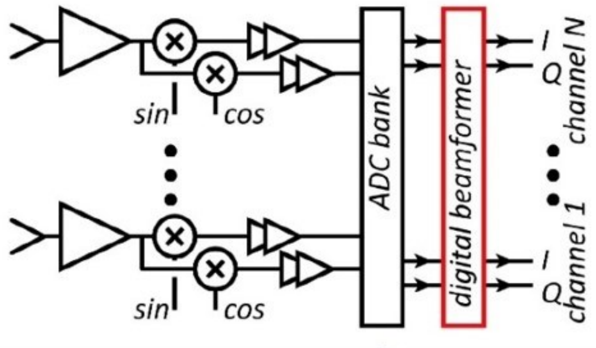
Beamforming for massive spatial multiplexing



Pure digital beamforming:
dynamic range & phase noise requirements: appear to be manageable ✓✓✓
Digital back-end processing requirements (die area, DC power): being investigated ?

Analog, hybrid beamforming:
Do not appear to significantly improve dynamic range in massive MIMO.

Progress in System Design



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 (spatial FFT, sparsity) (Madhow, Studer)

Efficient digital beamforming: low-resolution matrix (Studer, Molnar)

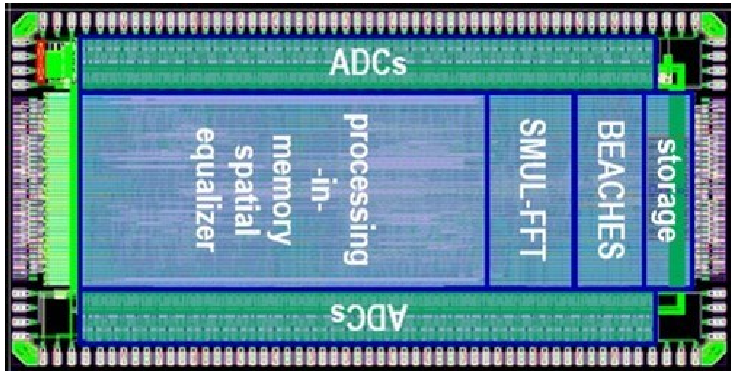
Efficient channel estimation : fast beamspace algorithm (Studer)

Efficiently addressing true-time-delay problem: "rainbow" FFT algorithm (Madhow, Cabric)

Other issues:

Propagation models and measurements

Blockage probability, mesh networks, network protocols

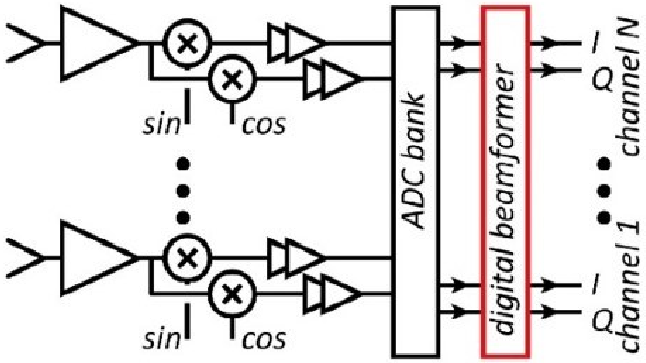


Progress in System Design

ADC resolution:

N ADC bits, M antennas, K signals: $\text{SNR}=6N+1.76+10\cdot\log_{10}(M/K)$

3 bits, $(M/K)=2 \rightarrow$ SNR=23 dB.   QPSK needs 9.8 dB.



Jammer tolerance:

Increase ADC resolution by 1 bit$\rightarrow$ $P_{\text{jammer,max}} = K\cdot P_{\text{signal}}$

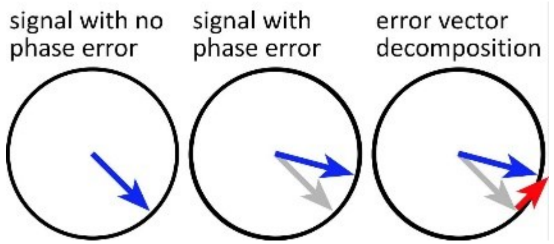
Maximum jammer power = sum of all user's power.

Phase noise:

Phase error σ_ϕ : $\text{SNR}= -20\cdot\log_{10}(\sigma_\phi)+10\cdot\log_{10}(M/K)$, where

$$\sigma_\phi^2 = \int_{f_{low}}^{f_{symbol}/2} L(f)df.$$

MIMO and SISO require similar $L(f)$.

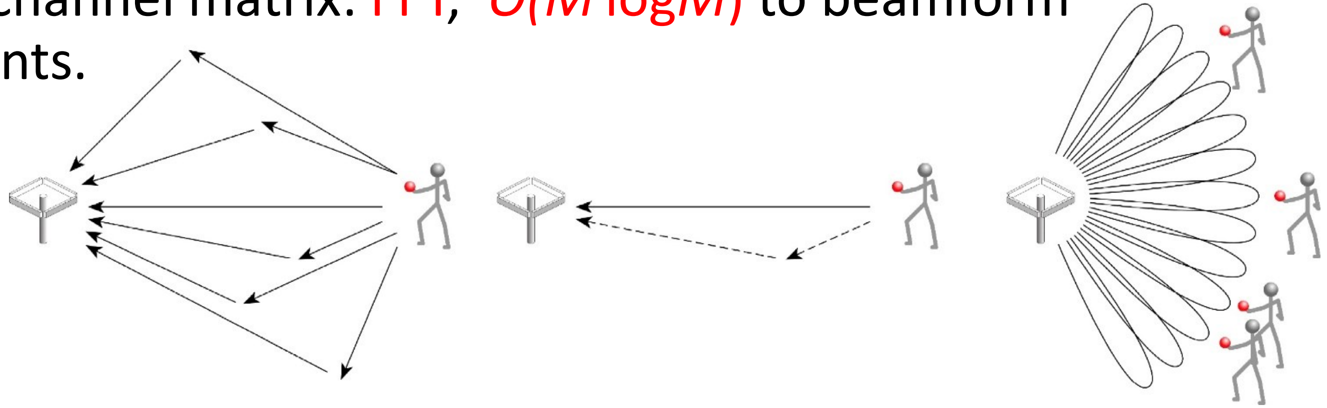


Beamspace:

lower frequencies, many NLOS paths, complicated channel matrix: $O(M^3)$ to beamform

higher frequencies, few NLOS paths, simpler channel matrix: FFT, $O(M\cdot\log M)$ to beamform

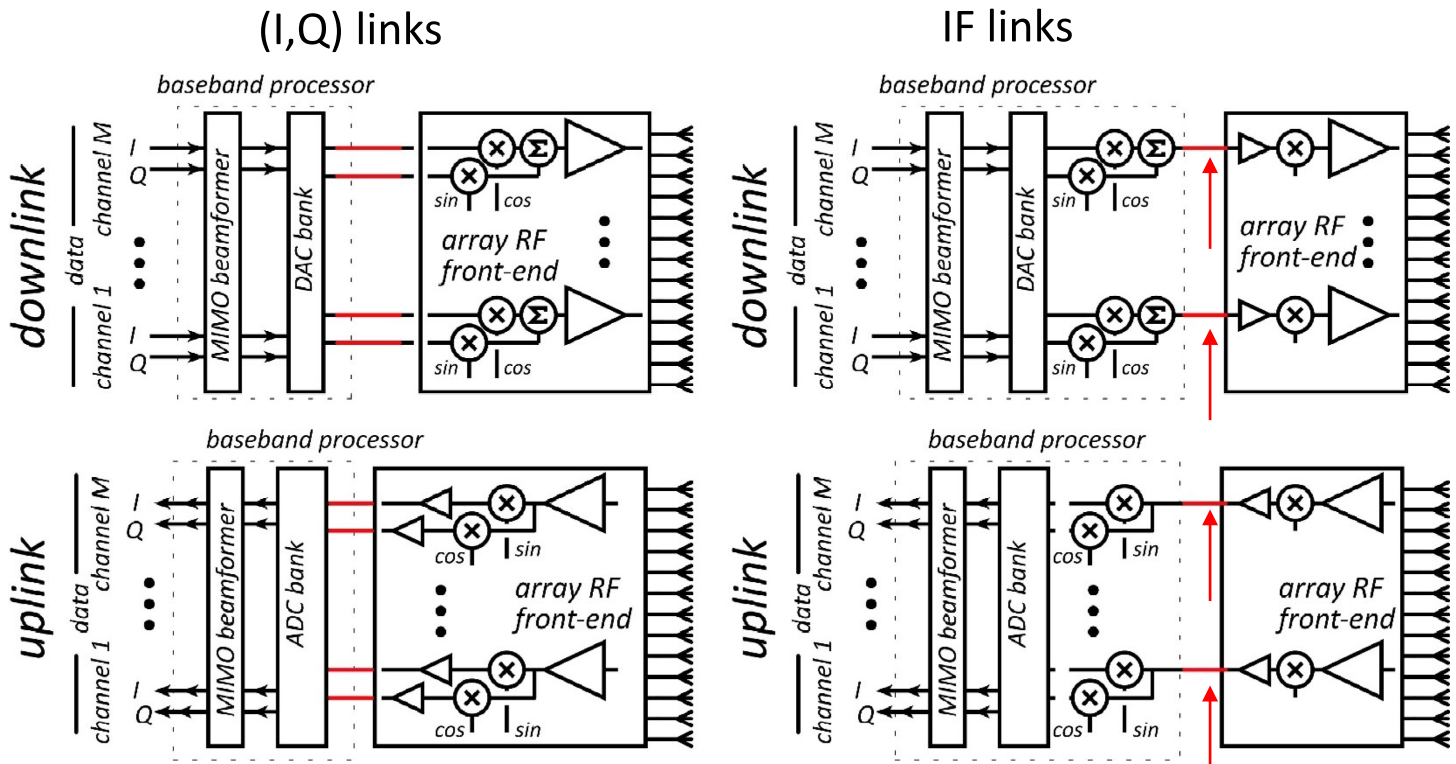
fewer bits in signal; fewer bits in FFT coefficients.



Array-beamformer interconnects

(I,Q) links
needs 4 (differential IQ) lines/antenna
physically large modules.
OK DC power/line (few mW)

IF links
as in emerging 5G systems
needs one IF line/antenna
physically much smaller modules
small required DC power/line



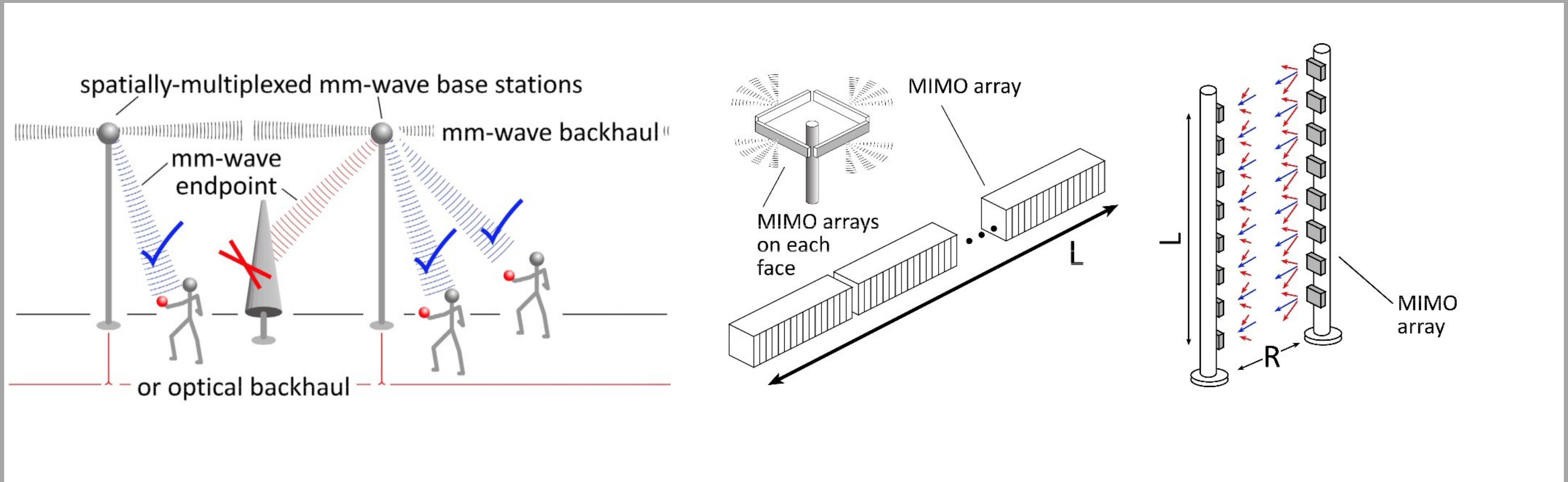
$$P_{\text{total signal,IF}} = kTFB \cdot (\text{SNR}) \cdot (\text{safety margin}) \cdot (\#\text{signals}/\#\text{antennas})$$

$$= -174\ \text{dBm} + 10\ \text{dB} + 10 \cdot \log_{10}\left(\frac{10\text{GHz}}{1\text{Hz}}\right) + 9.8\text{dB} + 30\text{dB} + 10 \cdot \log_{10}\left(\frac{1}{2}\right)$$

$$\cong -174\ \text{dBm} + 10\ \text{dB} + 100\ \text{dB} + 10\text{dB} + 30\text{dB} - 3\text{dB} = -27\ \text{dBm} \approx 2\mu\text{W}$$

Required IF signal interface power is very small; low required DC power for line driver.

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.

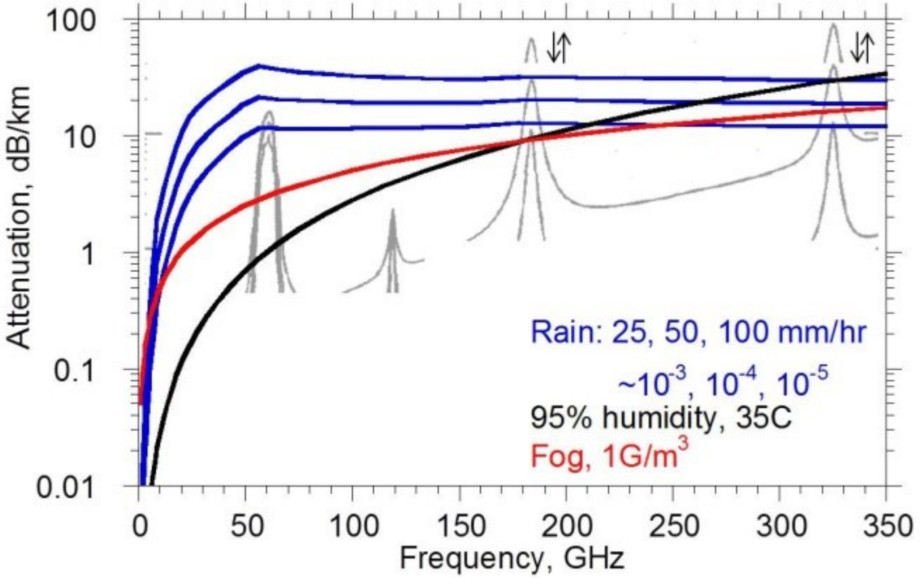
IC Technology
All-CMOS for short ranges below 200 GHz.
SiGe, GaN, or III-V LNAs and PAs for longer-range links. Just like cell phones today
SiGe or III-V frequency extenders for 220GHz and beyond

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)

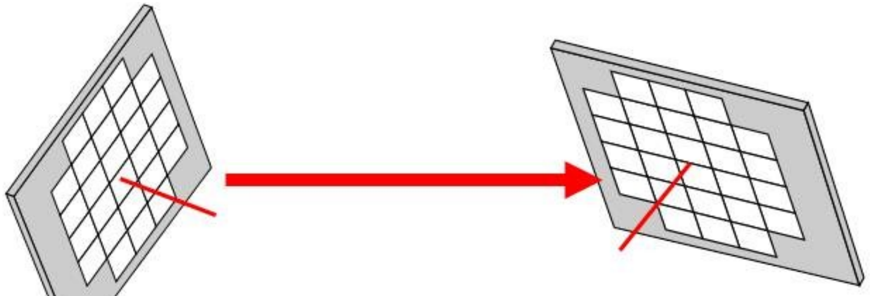
100-300 GHz: challenges & solutions

High attenuation in foul or humid weather

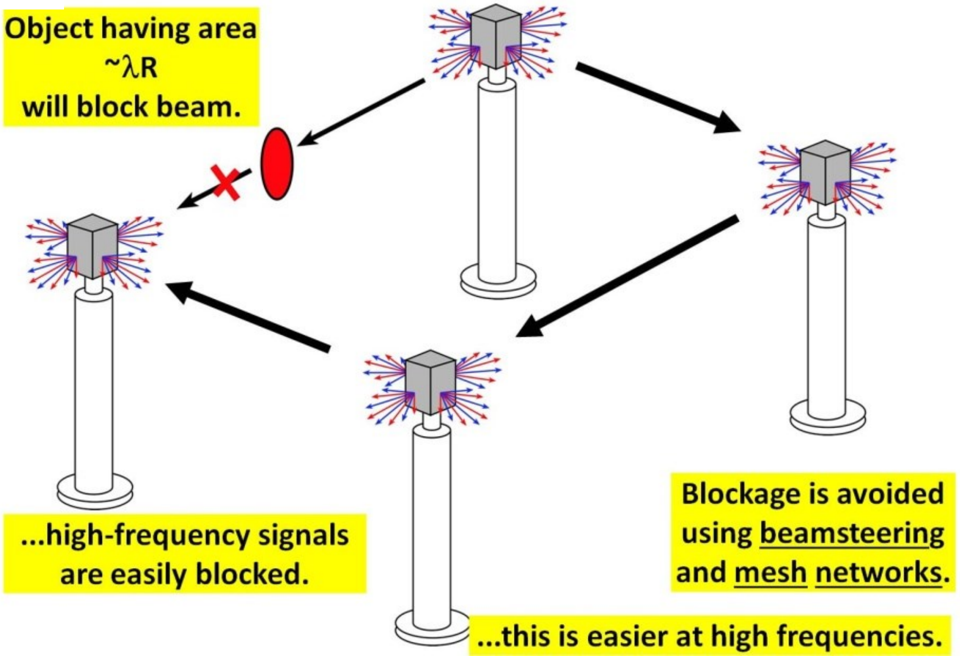


Need mesh networks

Need large arrays



$$\frac{P_{received}}{P_{transmit}} \propto N_{receive} N_{transmit} \frac{\lambda^2}{R^2} e^{-\alpha R}$$



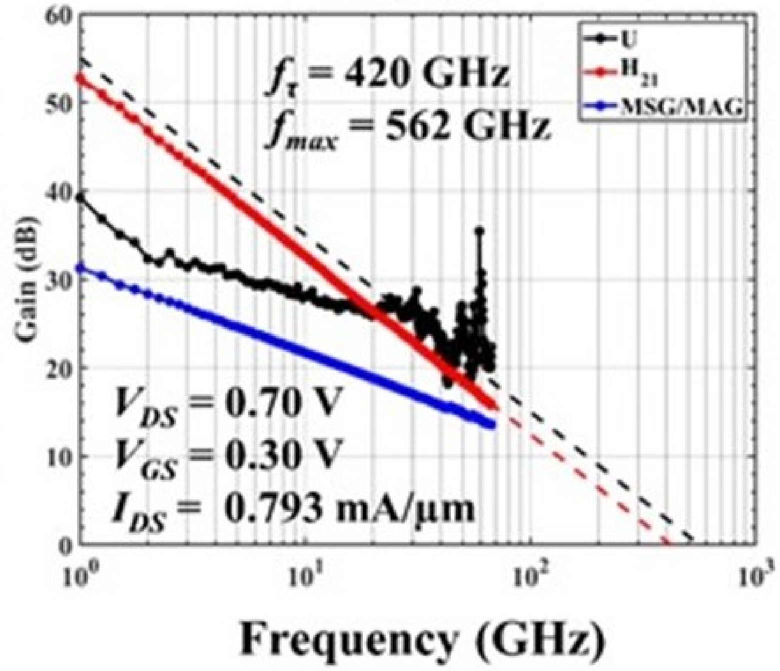
Towards faster HEMTs: InAs MOS-HEMTs

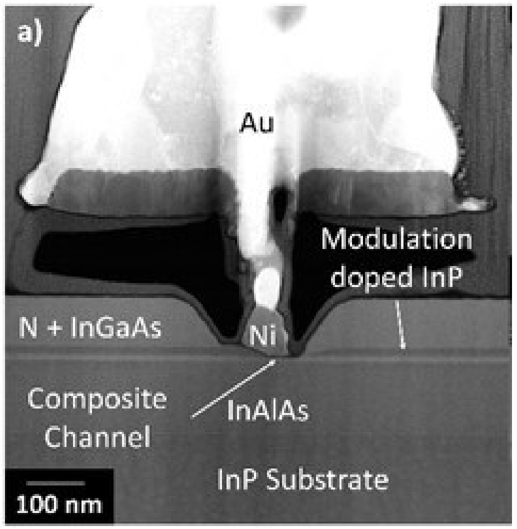
Goal: Higher f_τ for lower noise, sensitive receivers
1200 vs. 600GHz f_τ : 1.5dB better F_{min} @ 300GHz.
Increased bandwidth by scaling.

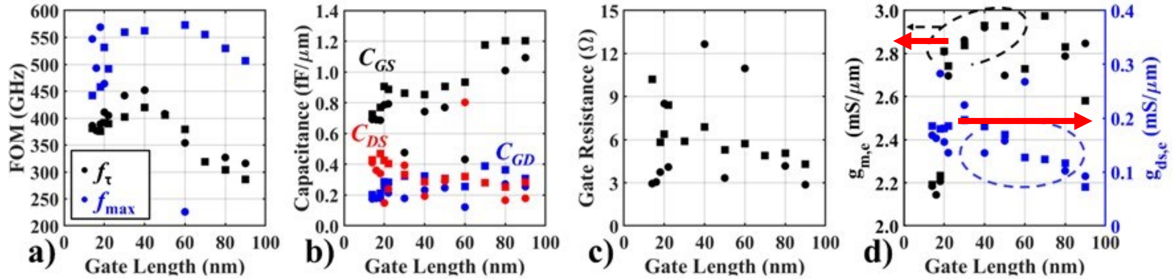
Scaling limit: gate insulator thickness
InAlAs barrier with high-K dielectric

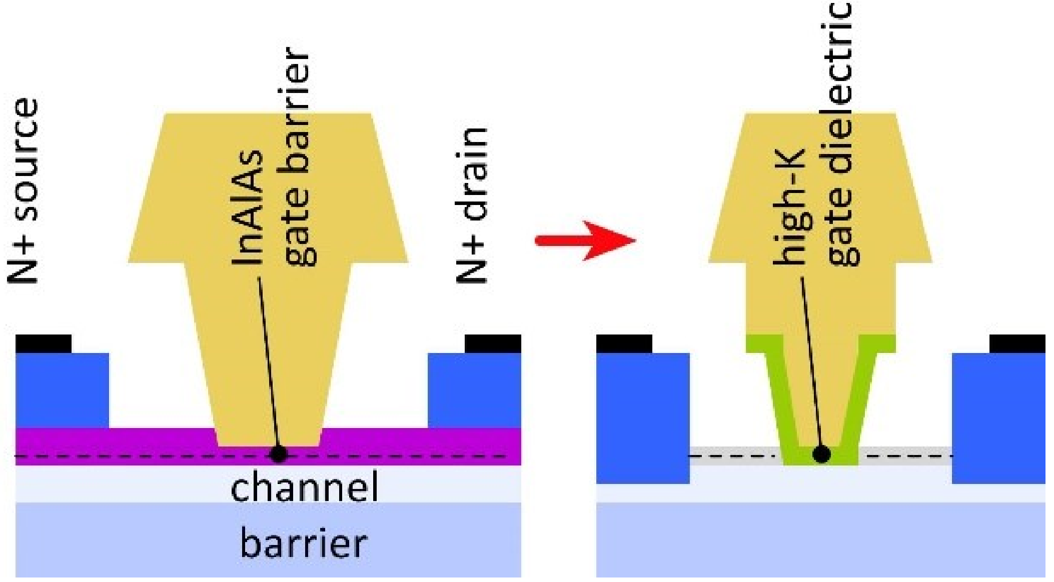
Scaling limit: source access resistance
by regrowth, place N+ layer <u>on</u> InAs channel

Also:
thinner channel, higher barriers, larger electron sup









Present devices: 420GHz f_τ, 560GHz f_{max} @ ~20nm L_g
Bandwidth limited by gate misalignment
Next step: self-aligned process

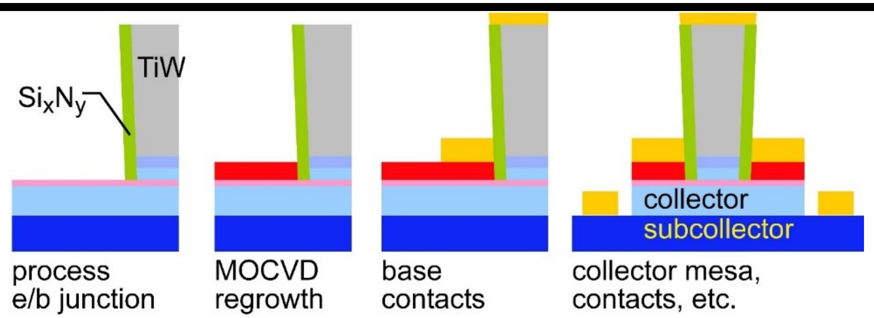
Base Regrowth for THz HBTs

Why regrowth ?

good contacts: need high base doping under contacts

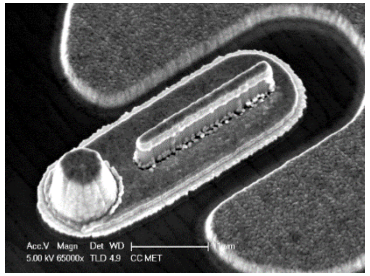
good DC gain : need lower base doping under emitter

solution: heavily-doped regrown extrinsic base



Initial ComSenTer HBT work: nm scaling.

HBTs with 90nm emitter width.

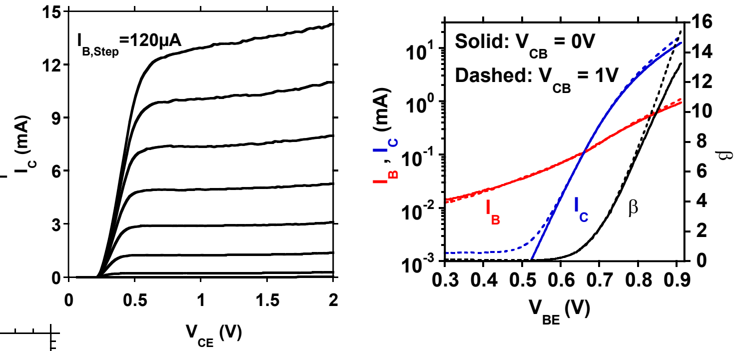


First regrown-base results: InGaAs base

InGaAs intrinsic base. Regrown GaAs extrinsic base

Excellent DC characteristics. ✓

But: hydrogen passivation of InGaAs base during regrowth ✗

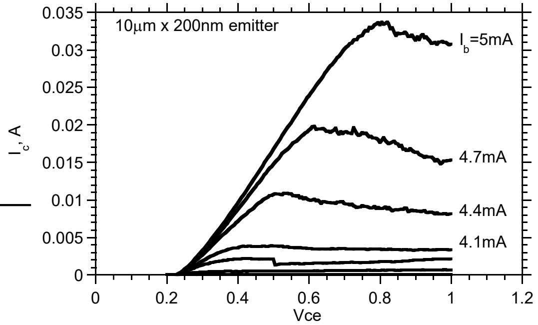


Second regrown-base results: GaAsSb base

GaAsSb: resistance to hydrogen passivation

DC results in winter: good DC characteristics

Next step: scaled THz device run.



100-300GHz tile array

How to make everything fit ?

radiated signal: up

intense thermal flux: down

DC/control/LO/IF lines: laterally

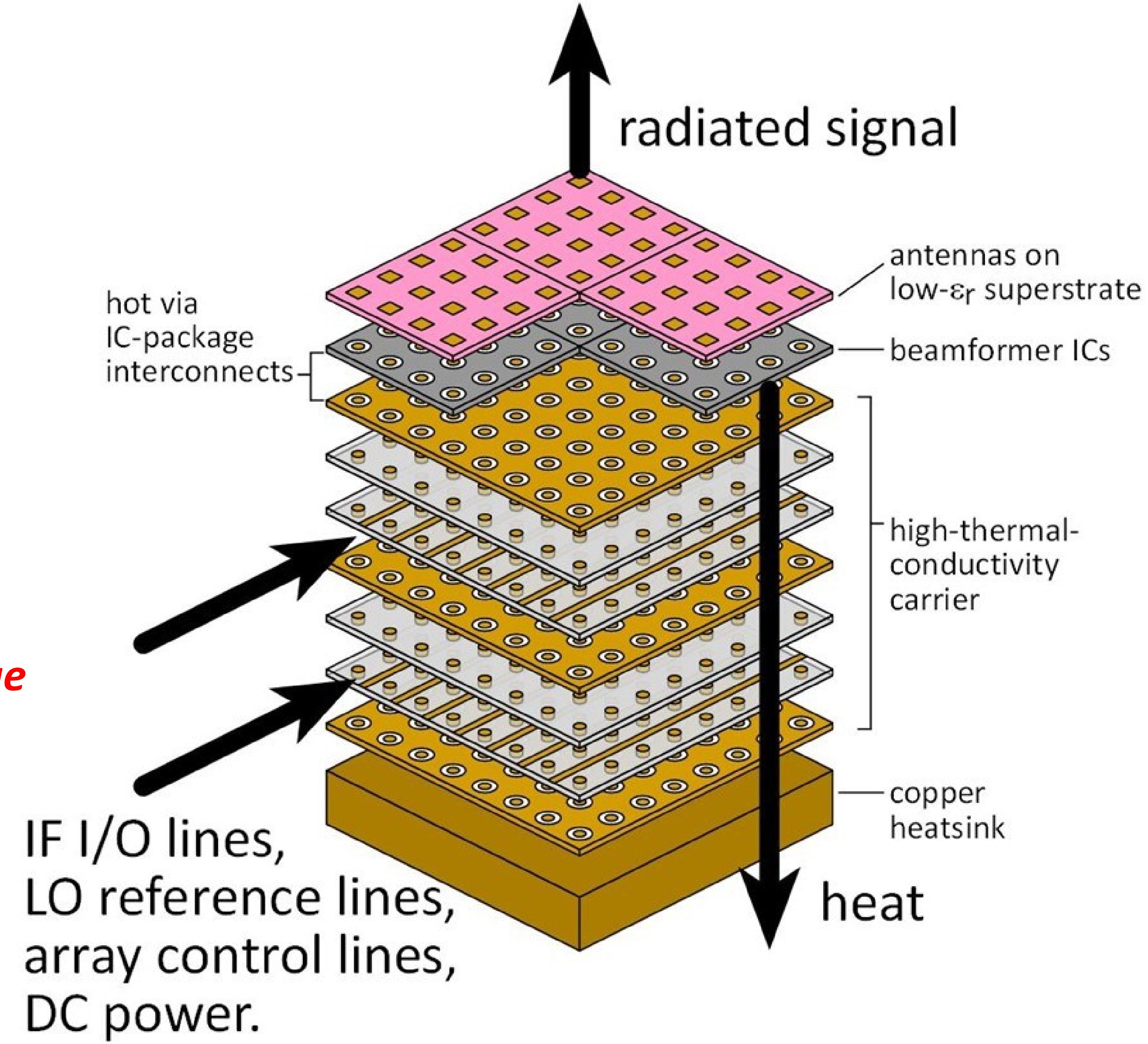
Need dense I/O and heat removal directly under IC

→ Crystalline SiC or AlN carrier ($$$)

→ Ceramic SiC or AlN carrier ($$)

→ LTCC with diamond/silver-filled thermal vias ($)

If RF power density is independent of wavelength, then so will be the temperature rise across the package

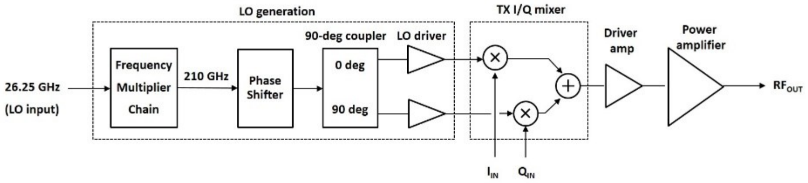


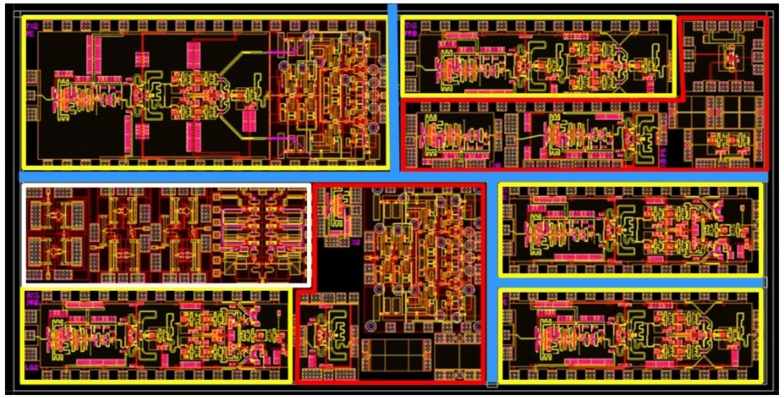
InP ICs for 210GHz Point-Point MIMO

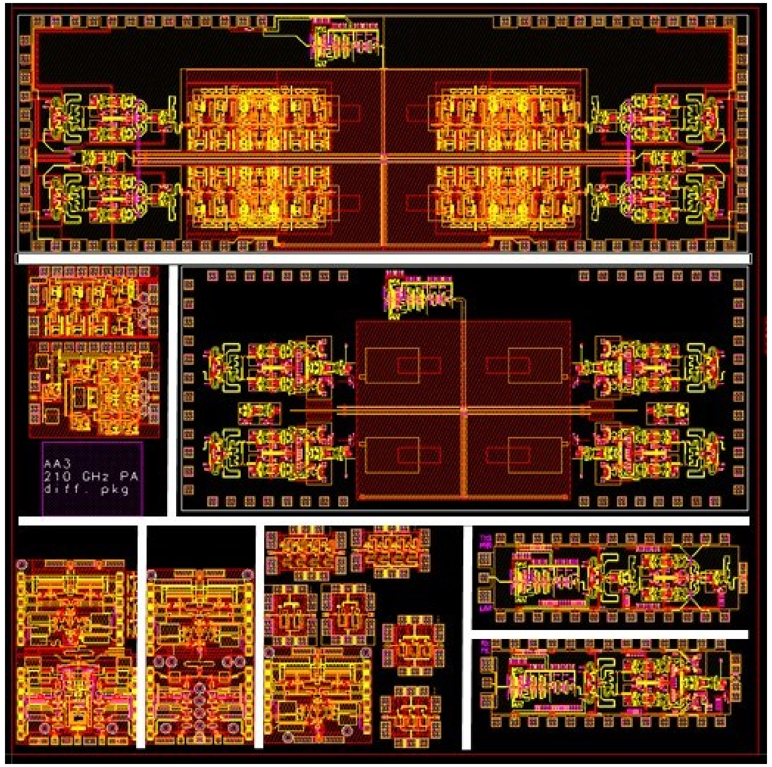
Transceivers & Arrays for 210GHz MIMO links

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



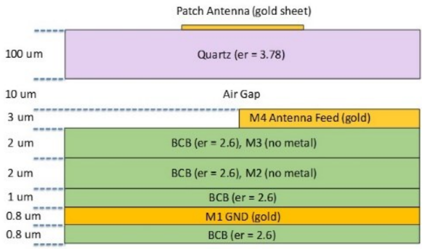


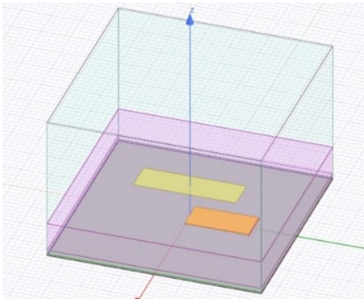


Planned packaging approaches

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