2021 IEEE International Symposium on Radio-Frequency Integration Technology (RFIT2021) August 25-27, 2021
Time: 10:00 AM – 10:50 AM, 25 August (Taipei, UTC+8)
Time: 7:00 PM – 7:50 PM, 24 August (SB, UTC-7)

100-300GHz
Spatially Multiplexed Wireless Communications

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SRC® JUMP

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COMMUNICATIONS SENSING TERAHERTZ

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

Acknowledgements

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
digital beamforming


Andreas Molisch
USC
100-300GHz propagation measurements


Danijela Cabric
UCLA
MIMO algorithms (funding via CONIX)

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
140-300GHz SiGe ICs


Muhannad Bakir
Georgia Tech
high-frequency packaging


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


Tim Fisher
UCLA
advanced packaging materials


Andrew Kummel
UCSD
advanced packaging materials

Transistors


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


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


Susanne Stemmer
UC Santa Barbara
transistors in novel materials


Debdeep Jena
Cornell
GaN HEMTs on Si


Srabanti Chowdhury
UC Davis
Diamond cooling for GaN

Massive MIMO demo.

Borivoje Nikolic
UC Berkeley
VLSI design automation
VLSI MIMO processors

Compressive imaging

Amin Arbabian
Stanford
140GHz radar chipsets and arrays

140/210/280GHz arrays for demos.

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

JUMP + nCORE Official Sponsors

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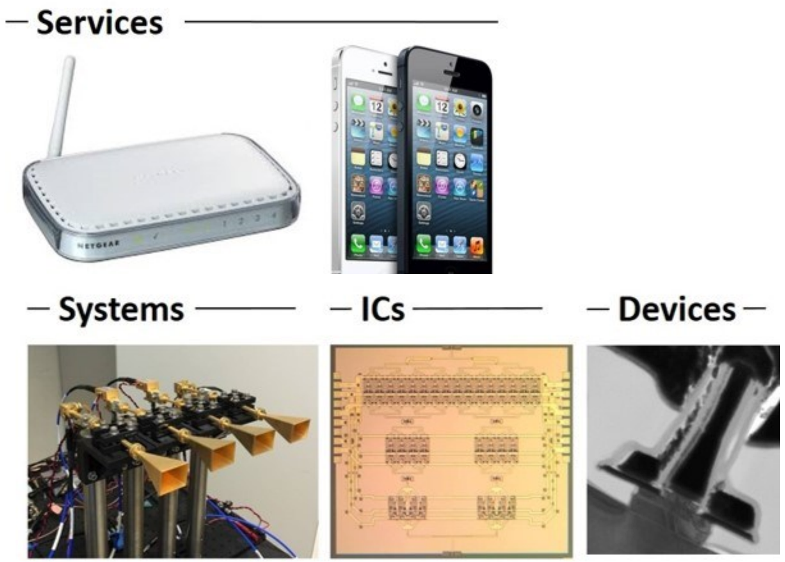
100-300GHz Wireless

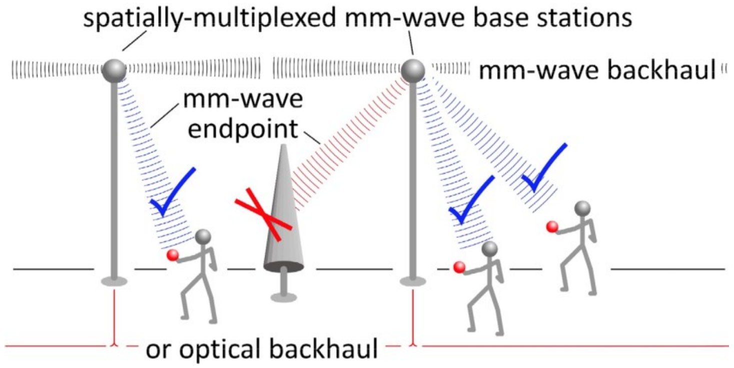
Wireless networks: exploding demand.

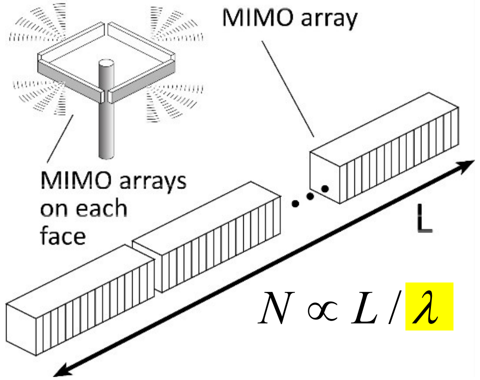
Immediate industry response: 5G.
~10~40 GHz ("5G")
~40~100GHz ("5.5G ?")
increased spectrum, extensive beamforming

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

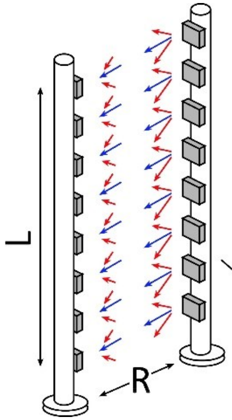


100-300GHz carriers, massive spatial multiplexing
→ Terabit hubs and backhaul links, high-resolution imaging radar

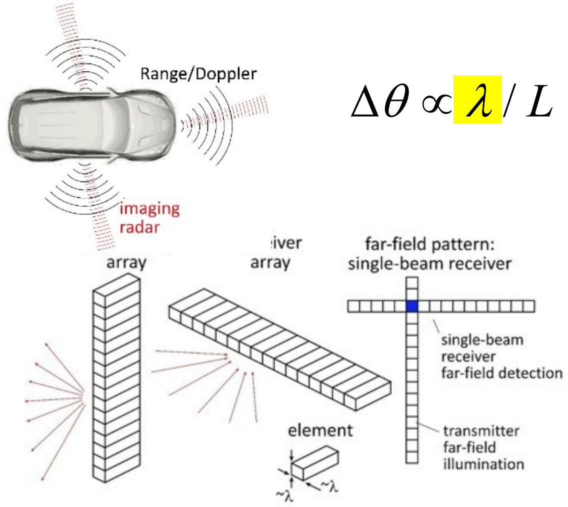




$N \propto L / \lambda$



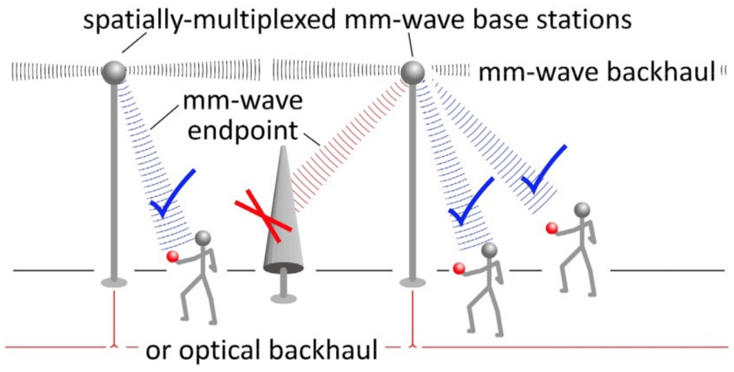
$N \propto L^2 / \lambda R$

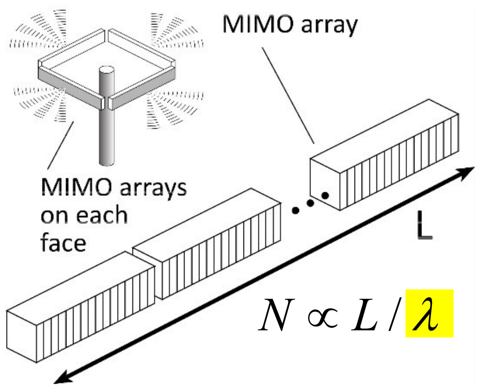


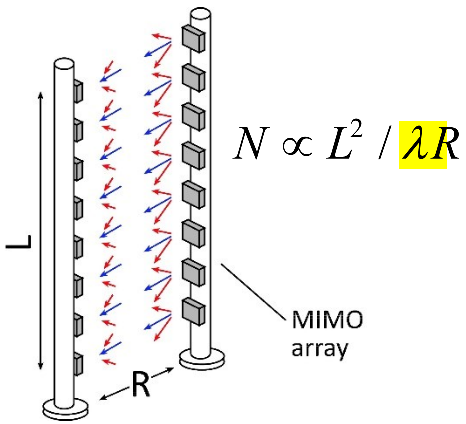
$\Delta\theta \propto \lambda / L$

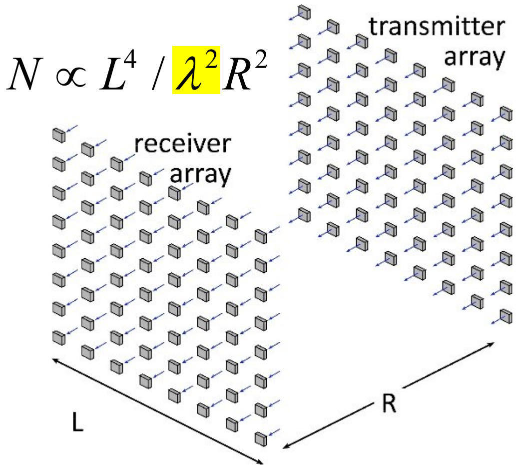
Benefits of Short Wavelengths

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

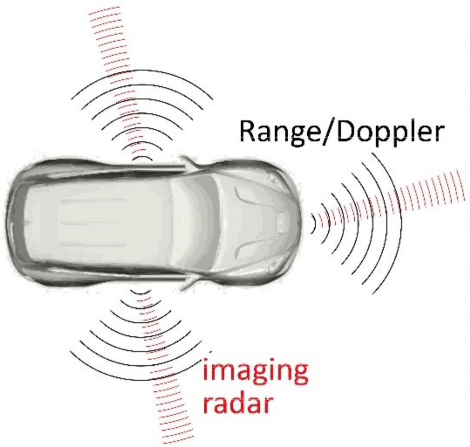


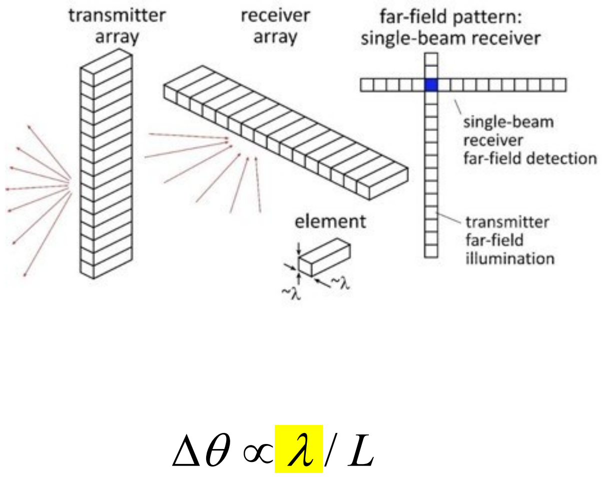






Imaging: very fine angular resolution



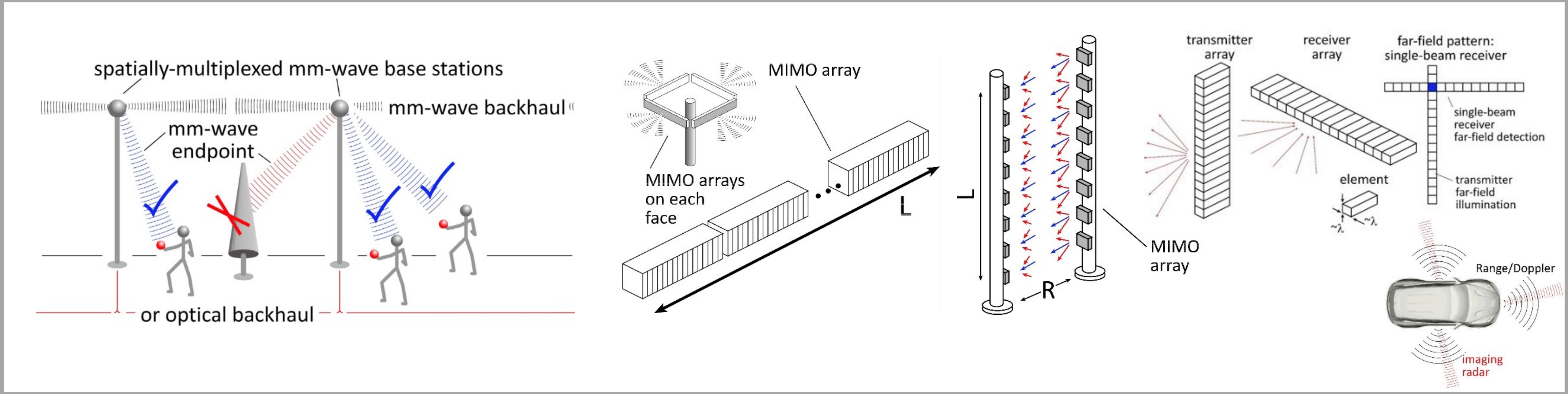


But:

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

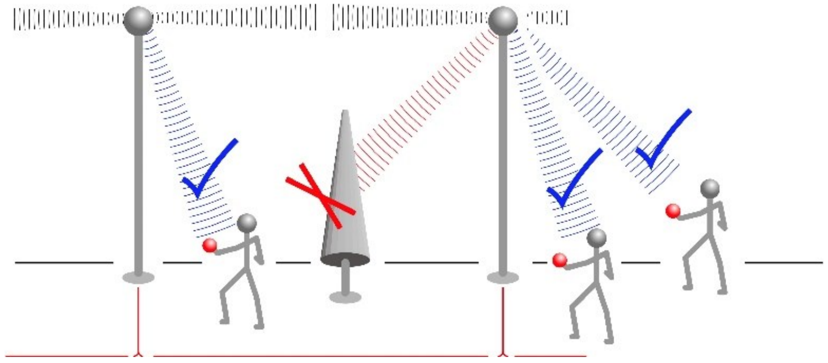
100-340GHz wireless:
terabit capacity,
short range,
highly intermittent

Applications

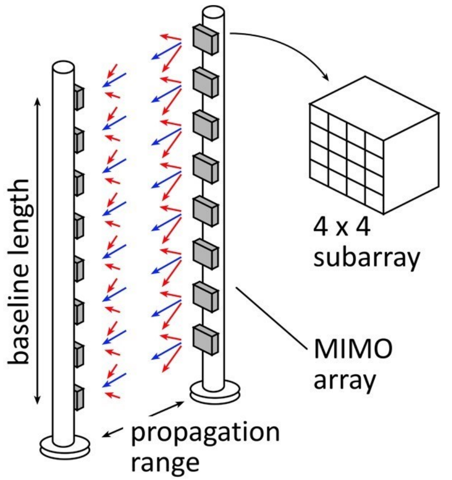


Potential 100-300GHz Systems

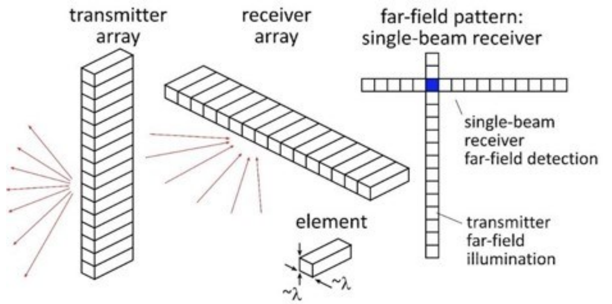
140GHz MIMO Hub

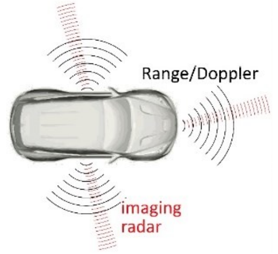


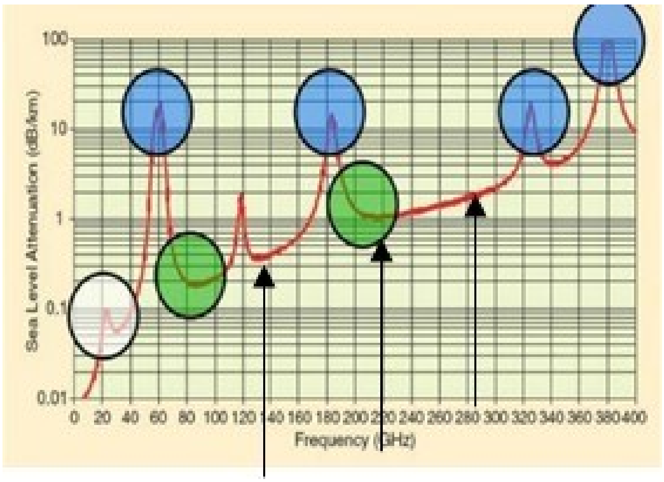
210 or 280GHz MIMO Backhaul



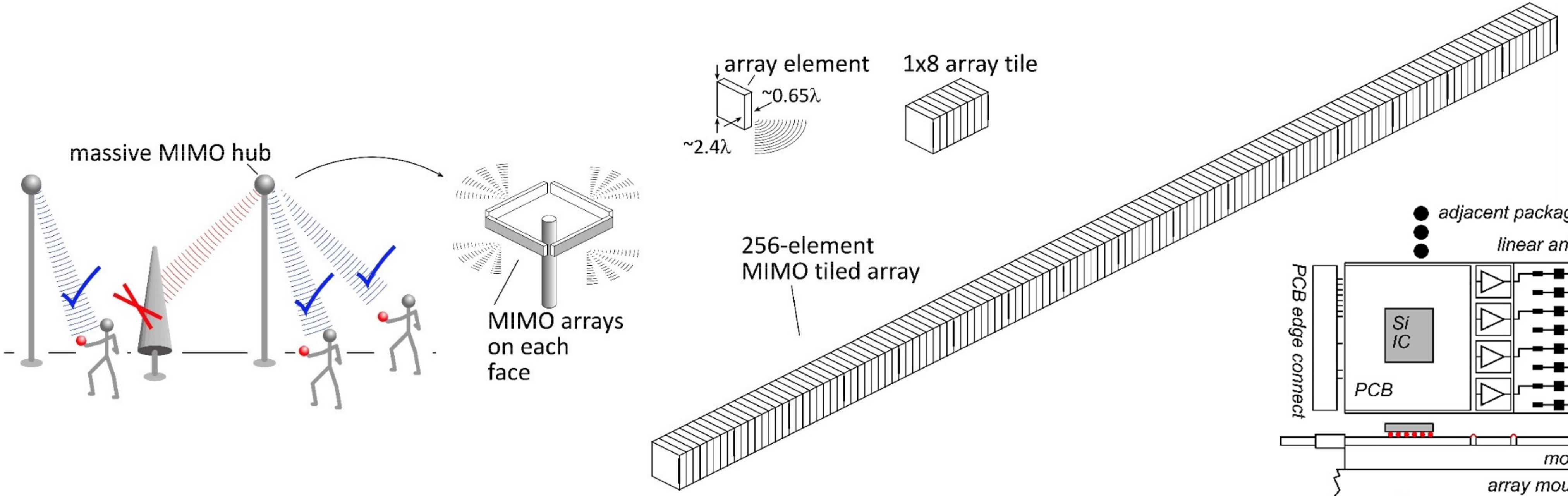
140 or 210GHz Imaging Radar

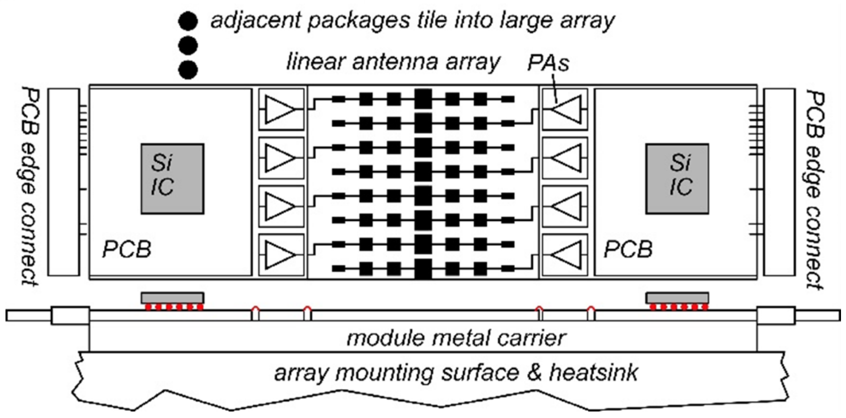


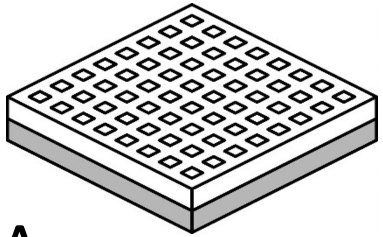




140GHz massive MIMO hub







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

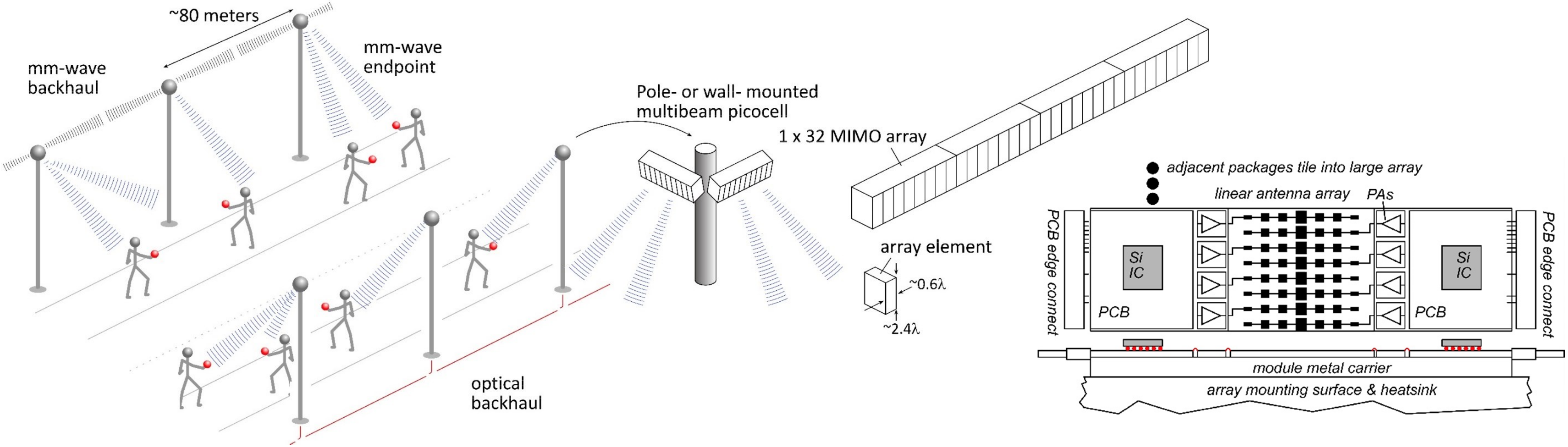
70 GHz spatially multiplexed base station

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,
with 20mm×524mm hub 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

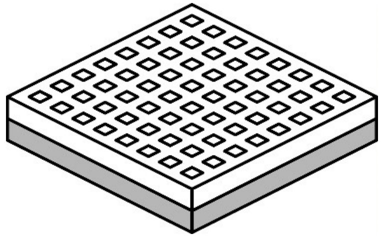


If demo uses 32-element array (four 1×8 modules):

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

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

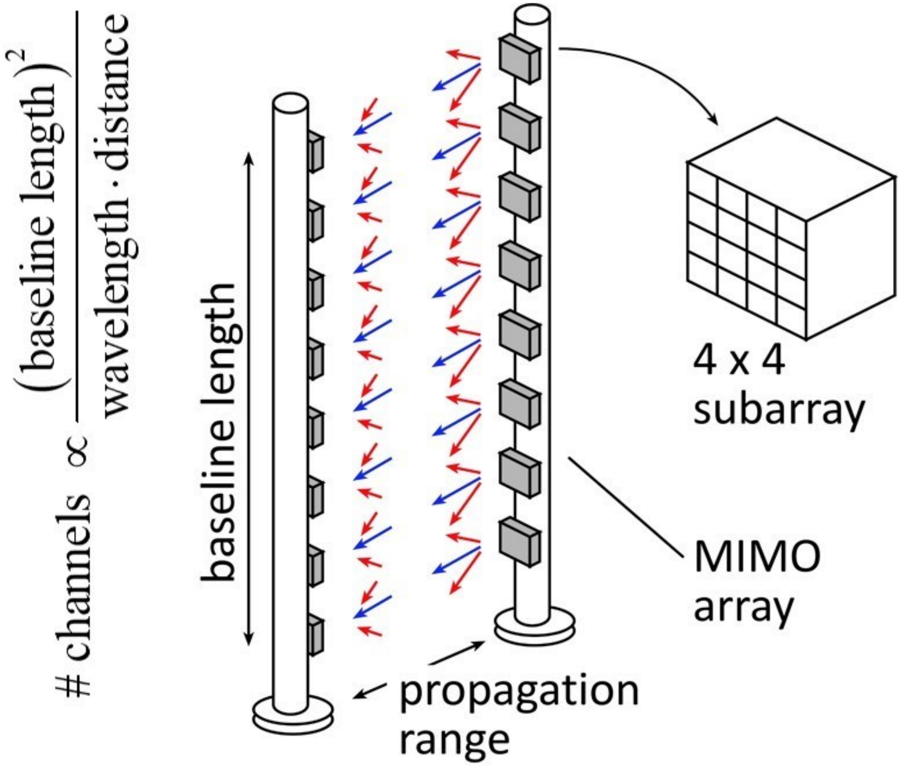
70, 40 m range in 50mm/hr rain with **17**dB total margins

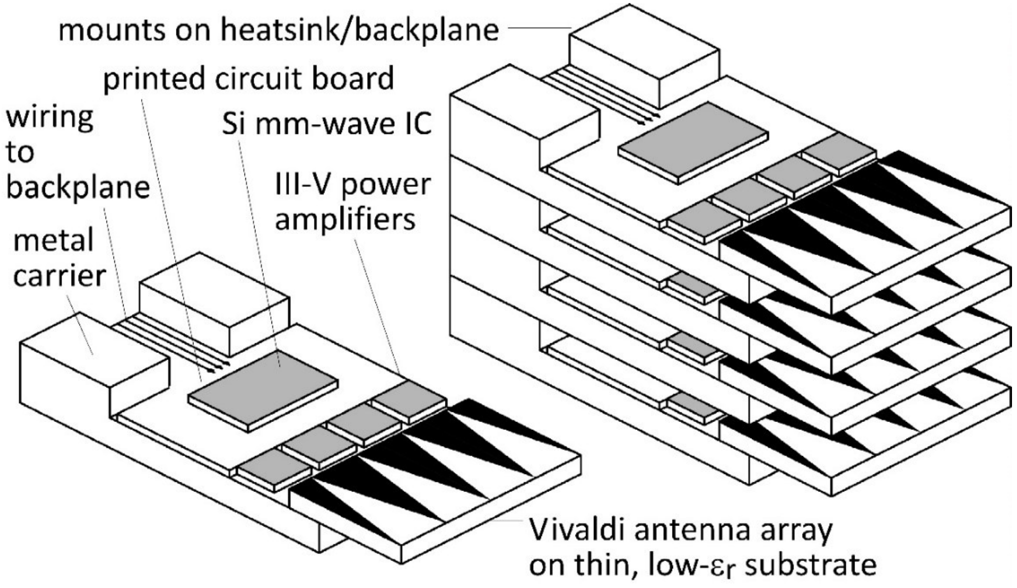


Handset:
8 × 8 array
(9×9mm)

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

210 GHz, 5.1 Tb/s MIMO backhaul

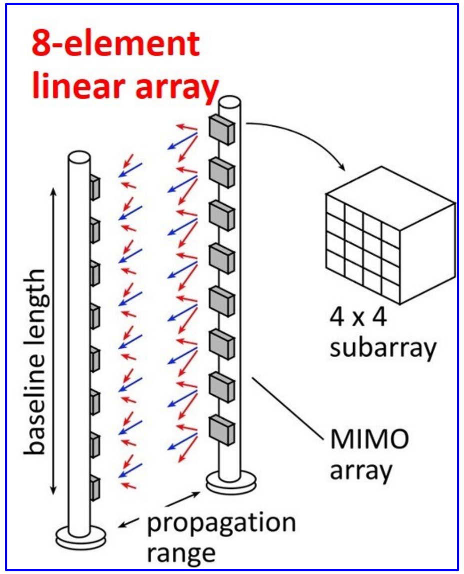
500m range in 50mm/hr. rain.

8-element 640Gb/s linear array:

requires 14dB$_m$ transmit power/element (P_{out})

....3.2W total output power

requires 2.1m linear array



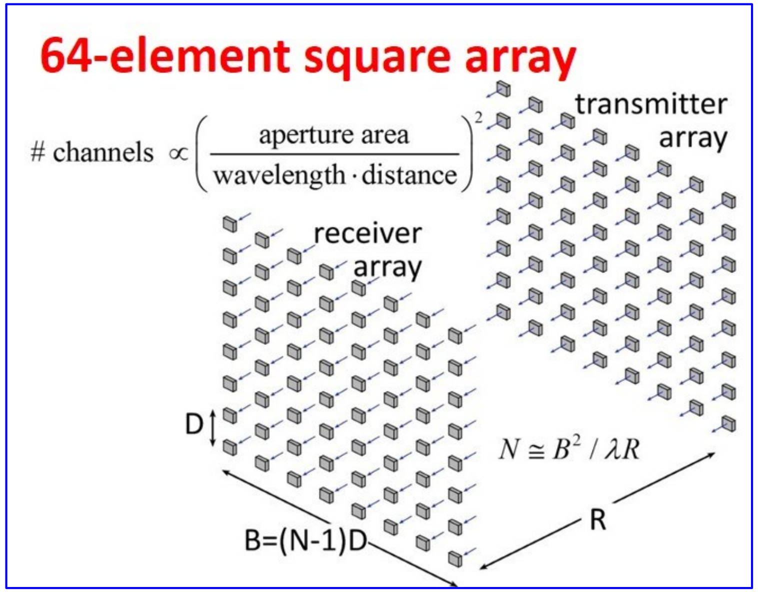
64-element 5Tb/s square array:

same link assumptions

requires 5dB$_m$ transmit power/element (P_{out})

....3.2W total output power

requires 2.1m square array

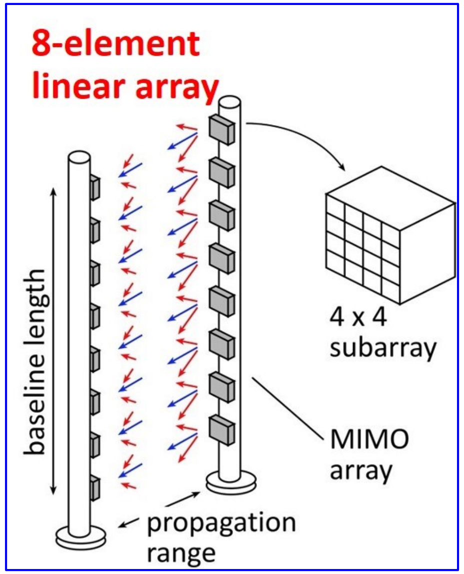


Complex system: can we make it cheaply ?

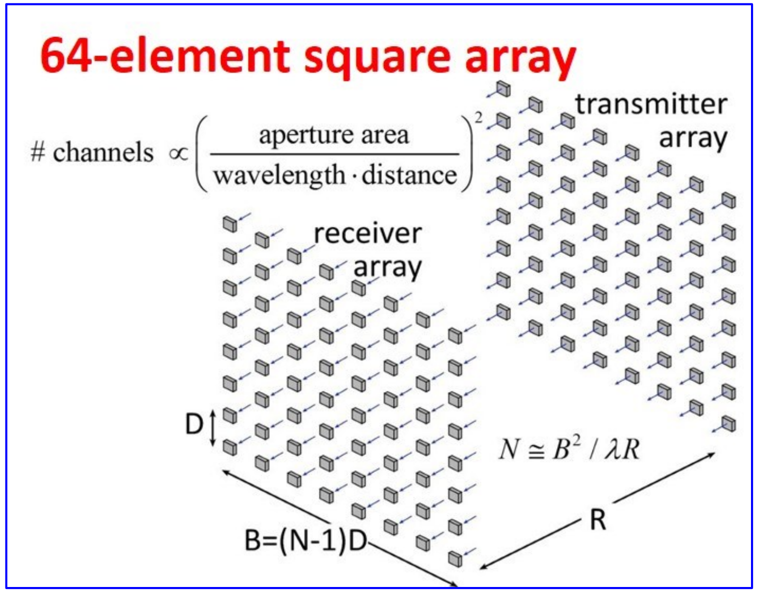
70 GHz, 640 Gb/s MIMO backhaul (16QAM)

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

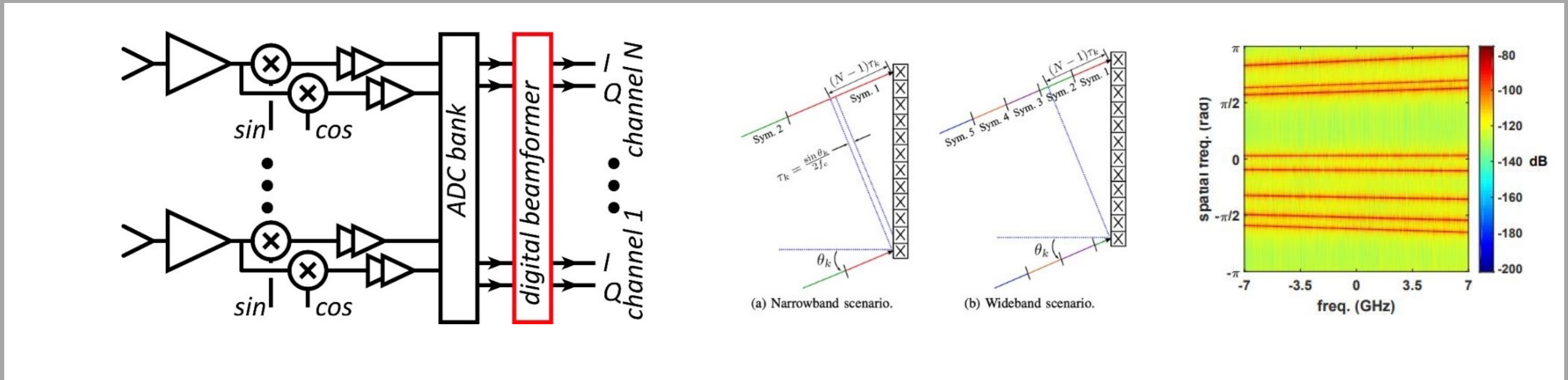


64-element 5Tb/s square array:
same link assumptions
requires 2dB$_m$ transmit power/element (P_{out})
....1.7W total output power
requires 5.5m square array



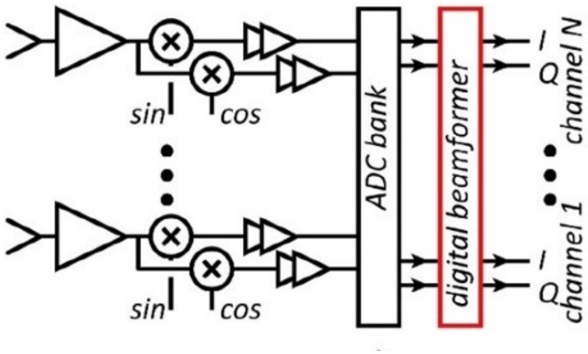
Similar RF power output, physically larger

Systems


sin
cos
ADC bank
digital beamformer
I
Q
channel N
channel 1
Sym. 1
Sym. 2
Sym. 3
Sym. 4
Sym. 5
(a) Narrowband scenario.
(b) Wideband scenario.
spatial freq. (rad)
freq. (GHz)
dB
-80
-100
-120
-140
-160
-180
-200
-7
-3.5
0
3.5
7

System Design

ADCs/DACs: QPSK needs only 3-4 bit ADC/DACs (Madhow, Studer, Rodwell)
N ADC bits, M antennas, K signals: SNR=6N+1.76+10·$\log_{10}(M/K)$
3 bits, (M/K)=2→ SNR=23 dB. QPSK needs 9.8 dB.



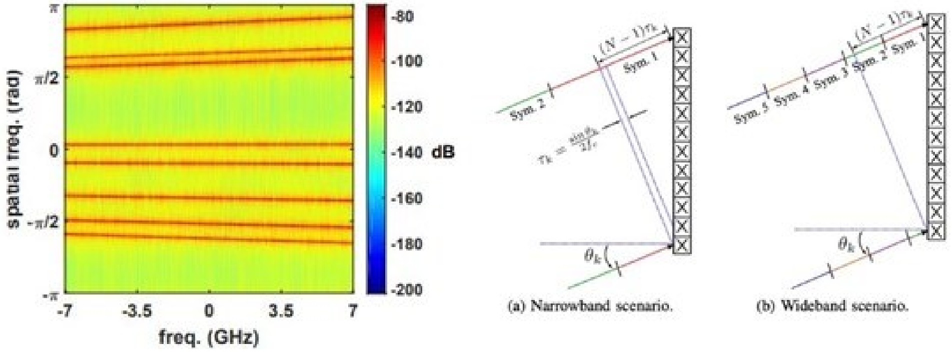
Linearity: Amplifier P_{1dB} need be only 3-4 dB above average power (Madhow).

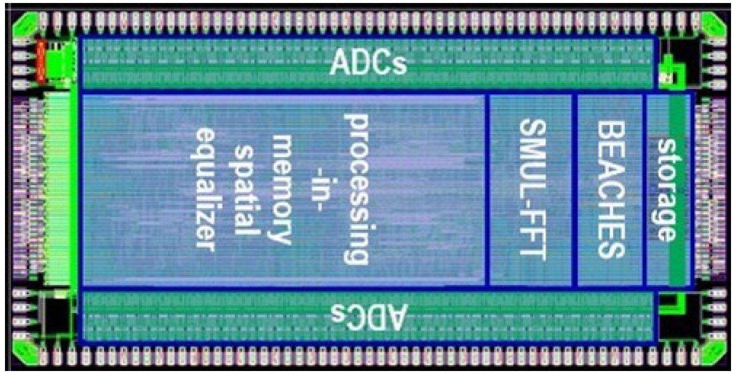
Phase noise: Requirements same as for SISO (Alon, Madhow, Niknejad, Rodwell)

Efficient digital beamforming: beamspace algorithm=complexity ~N× log(N) (Madhow, Studer)

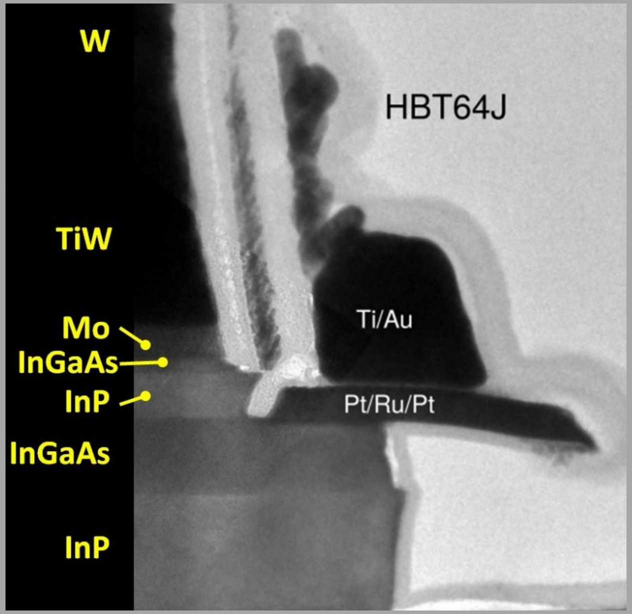
Efficient digital beamforming: low-resolution matrix (Studer: 2021 ESSCIRC, this week)

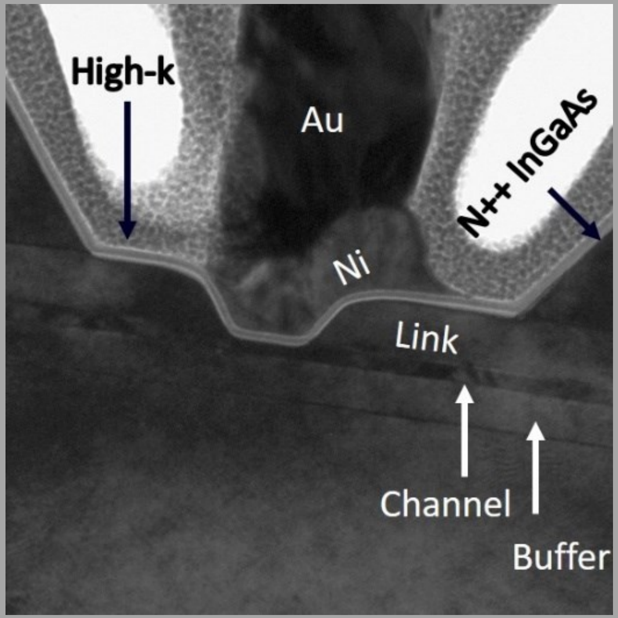
Efficiently addressing true-time-delay problem: "rainbow" FFT algorithm (Madhow, Cabric, Studer)

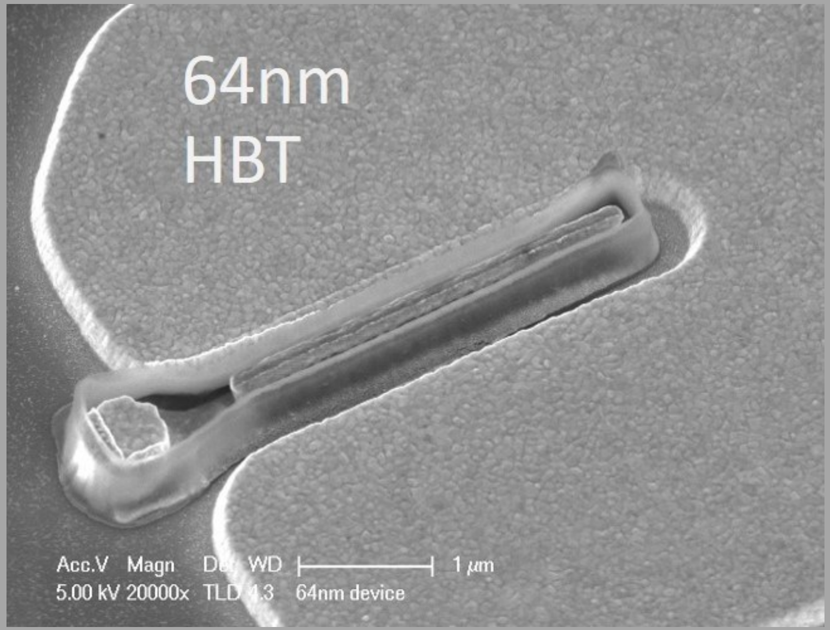




Transistors







Transistors for 100-300GHz

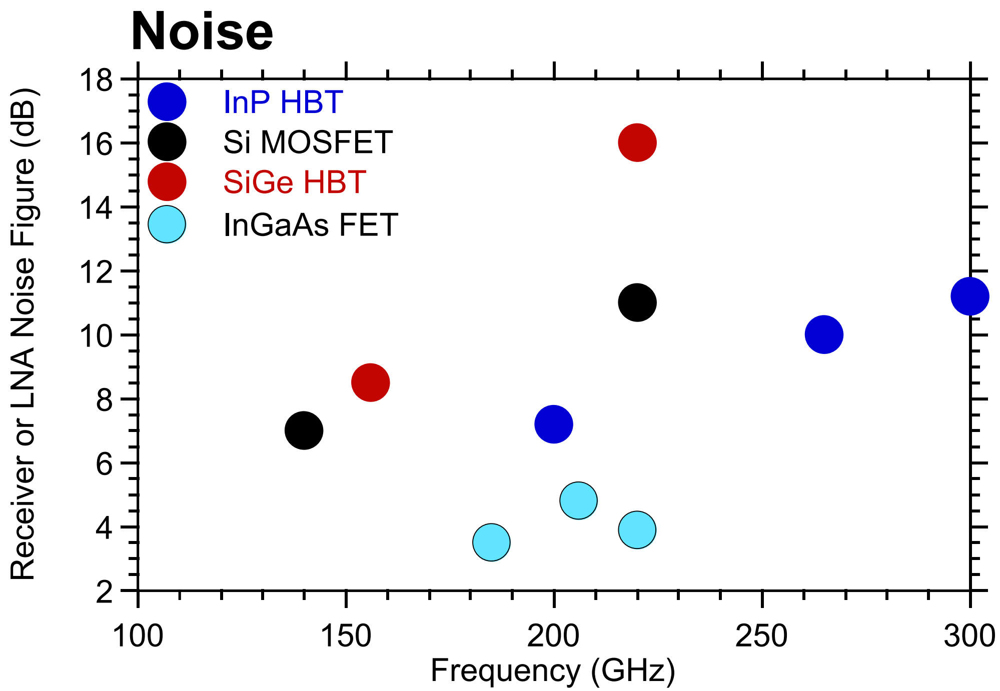
CMOS: good power & noise up to ~150GHz. Not much beyond. 65-32nm nodes are best.

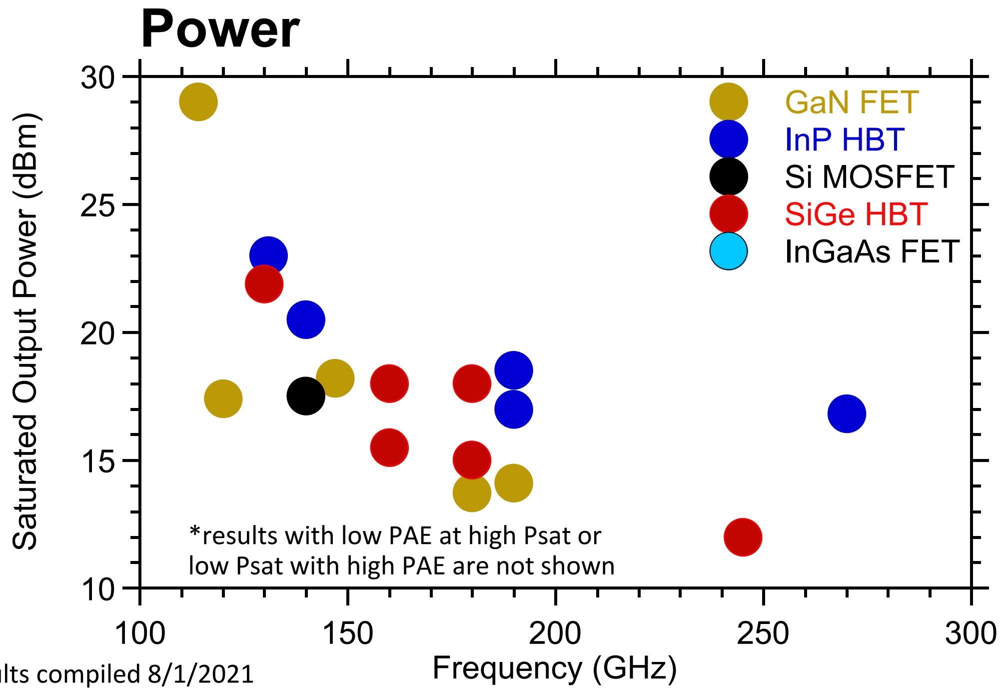
InP HBT: record 100-300GHz PAs

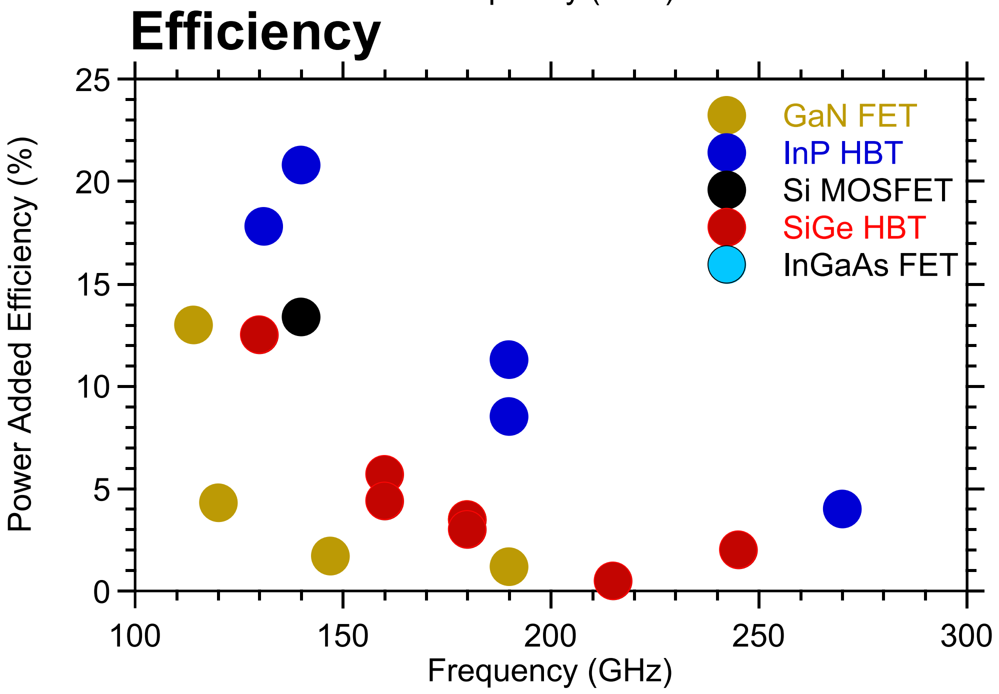
SiGe HBT: power better than CMOS, worse than InP HBT

GaN HEMT: record power below 100GHz. Bandwidth improving

InGaAs-channel HEMT: world's best low-noise amplifiers



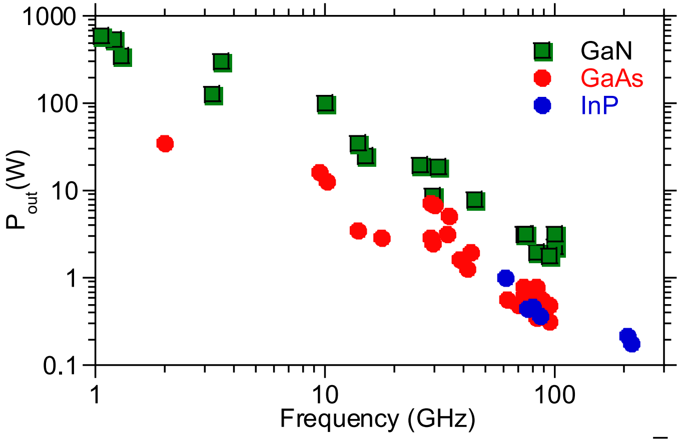


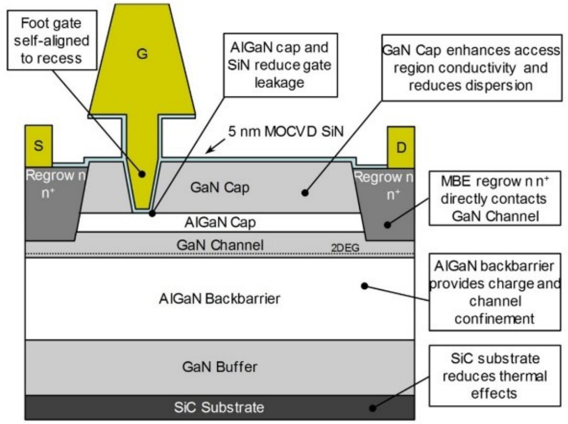


Results compiled 8/1/2021

mm-Wave Transistor Development

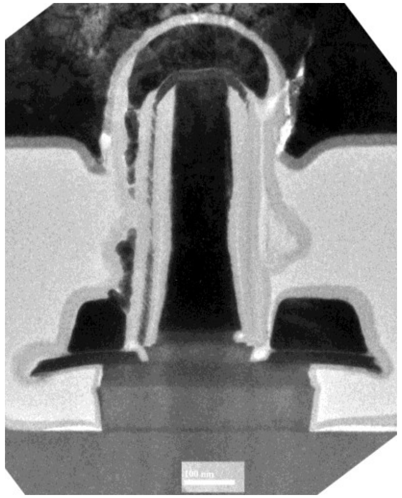
InGaN and GaN HEMTs:
Leading power techology to ~110GHz
Efforts to extend this to 140, 220GHz.

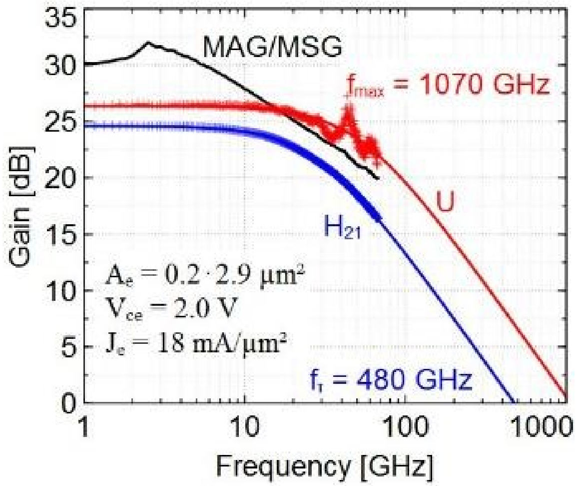




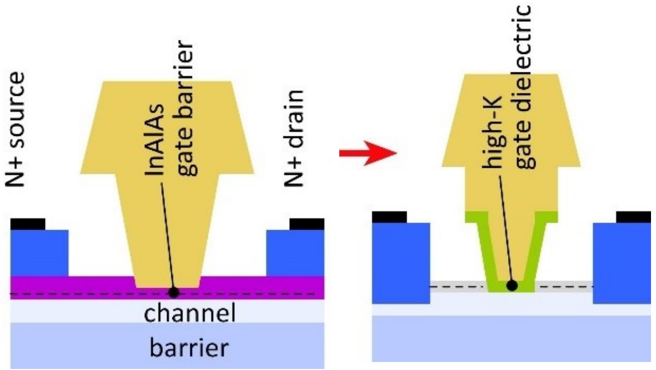
N-polar GaN: Mishra, UCSB

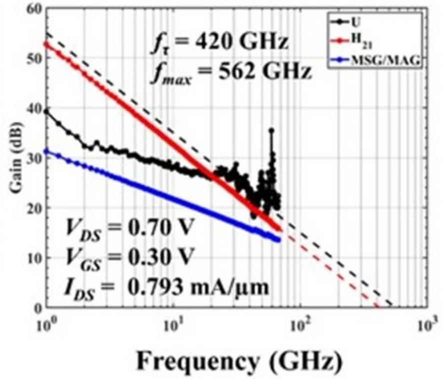
THz InP HBTs:
State-of-art: 1.1THz f_{max} @ 130nm node
Efficient 100-650GHz power



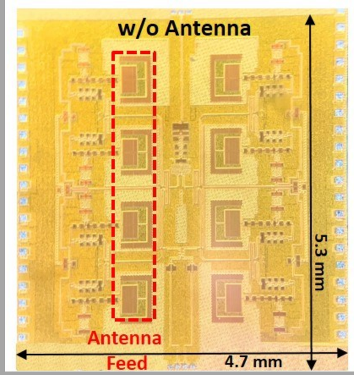


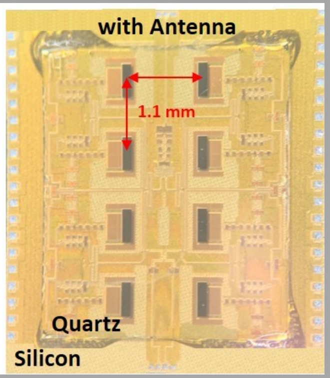
THz InP HEMTs:
State-of-art: 1.5THz f_{max} @ 32nm node
Sensitive 100-650GHz low-noise amplifiers
high-K gate dielectric *might* permit further scaling.

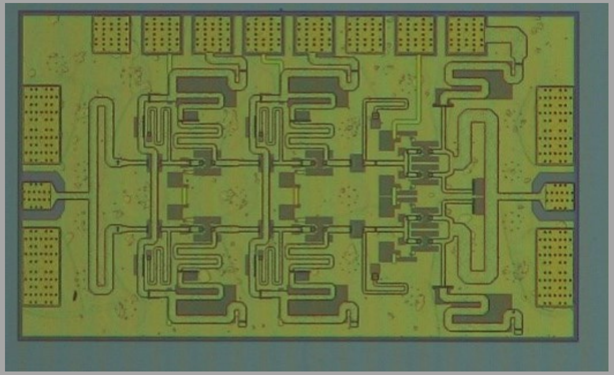


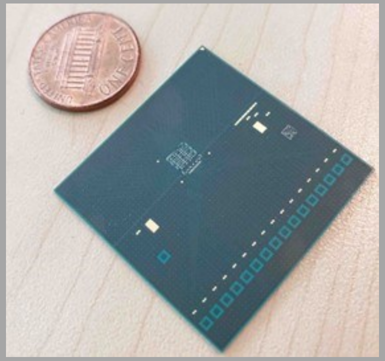


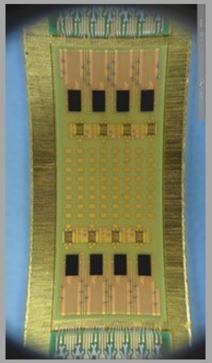
ICs and Packages:
140 GHz





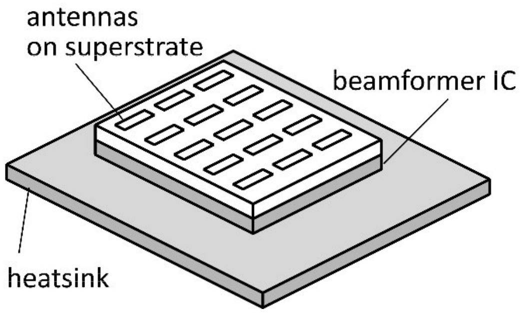


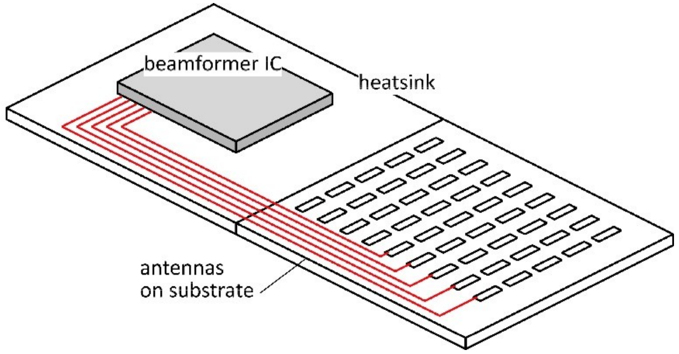




The mm-wave module design problem

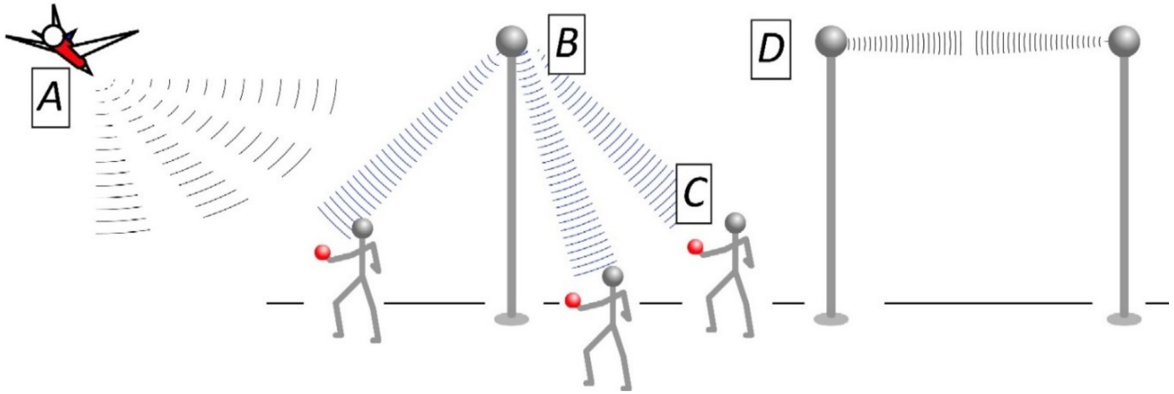
How to make the IC electronics fit ?
How to avoid catastrophic signal losses ?
How to remove the heat ?

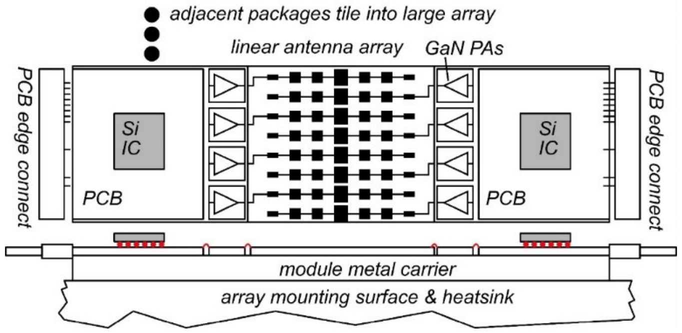


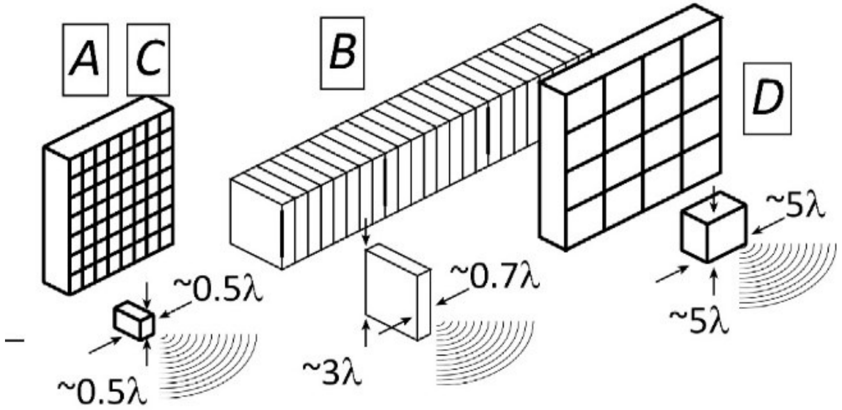


Not all systems steer in two planes...
...some steer in only one.

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





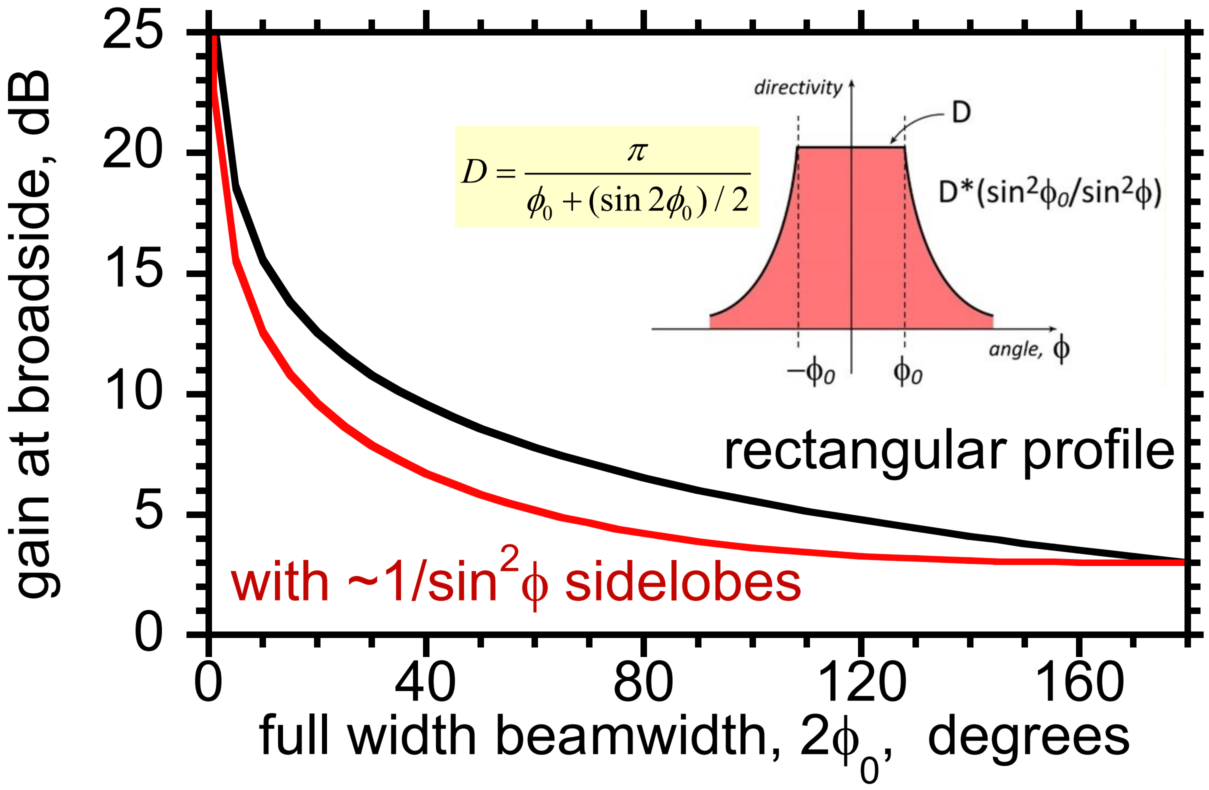


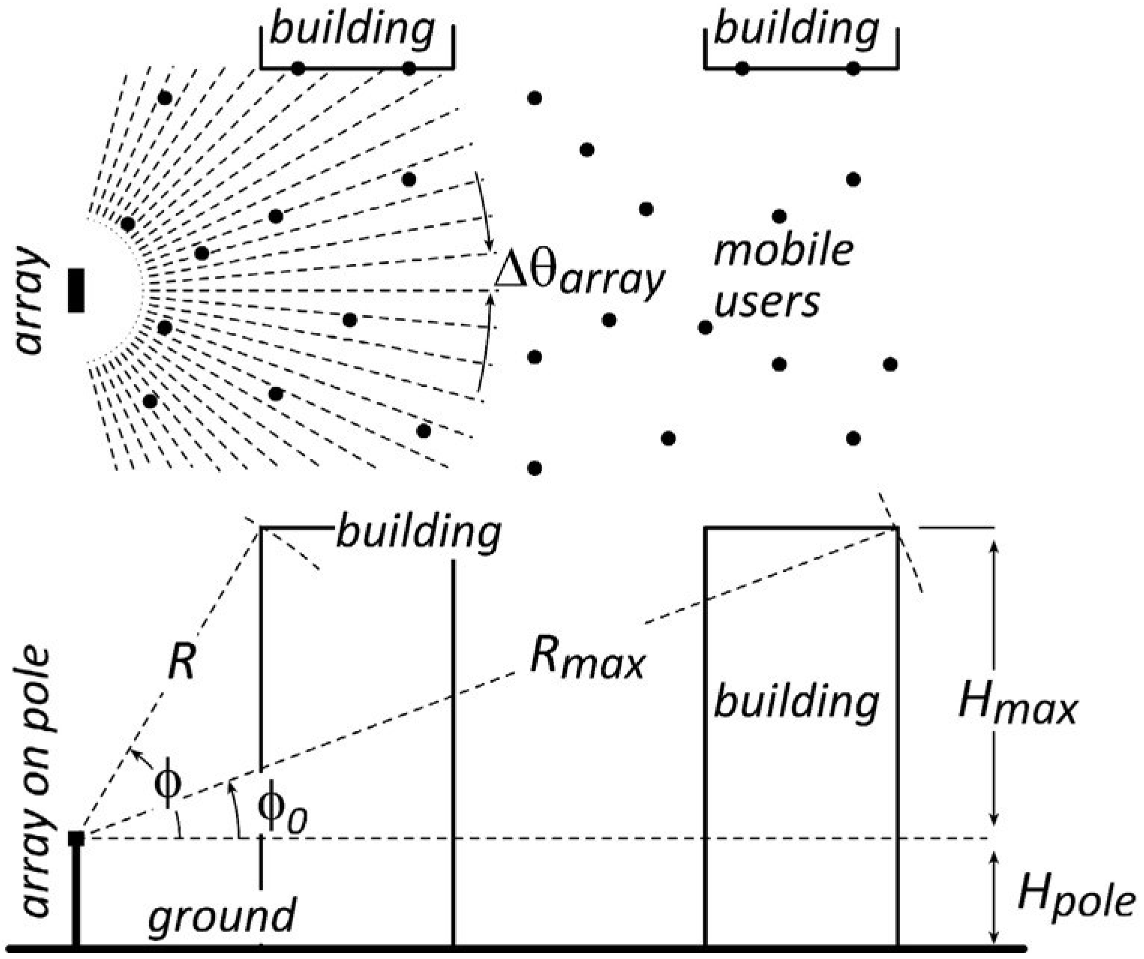
Do we need 2D arrays ? 1D steering might be fine.

$1/\sin^2\phi$ sidelobes provide strong signals to tall buildlings.

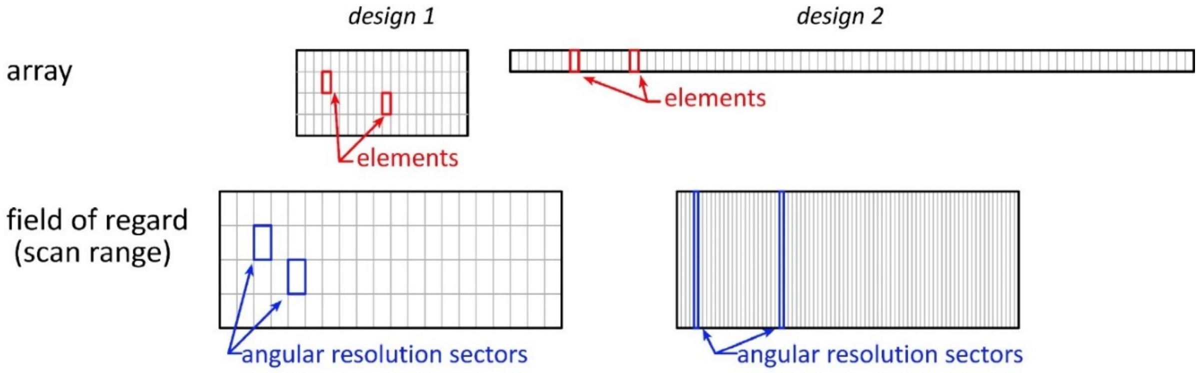
Providing sidelobes reduces broadside gain by less than 3dB.

→ Don't need 2D arrays to serve tall buildings





2D vs. 1D: user spatial distribution

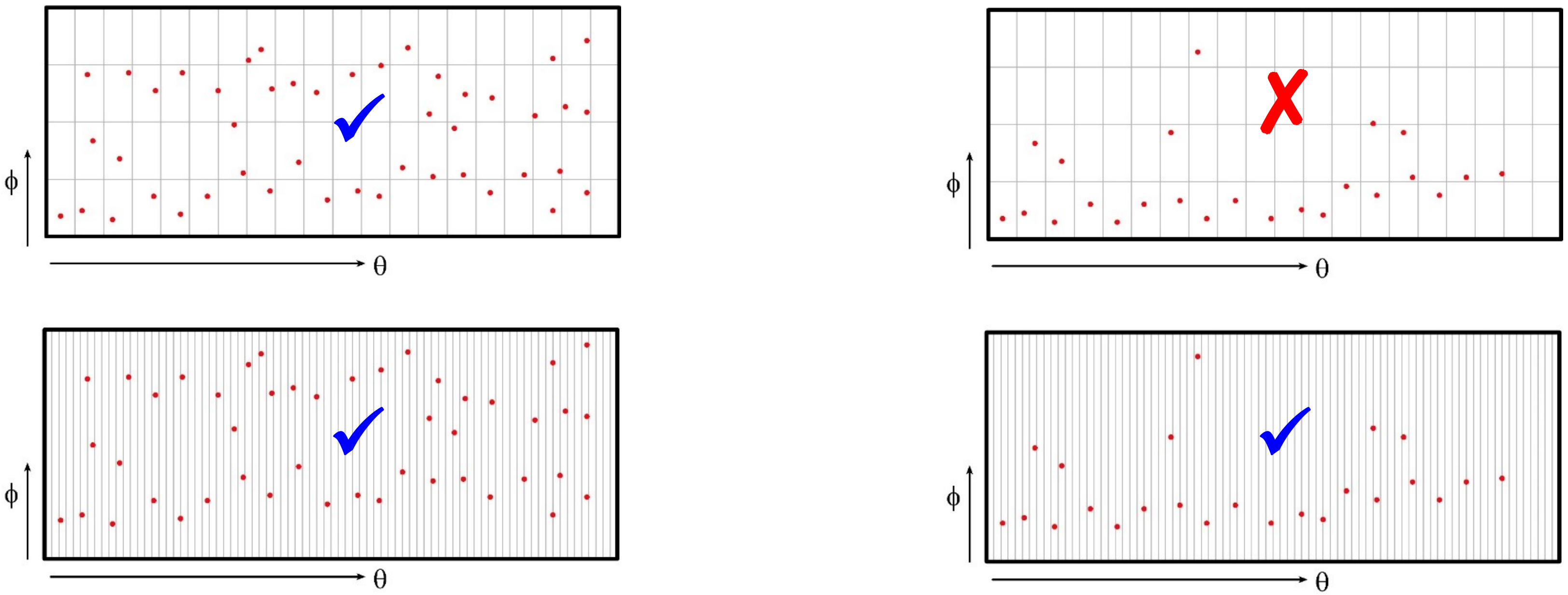


uniform horizontal & vertical user distributions

uniform horizontal, nonuniform vertical

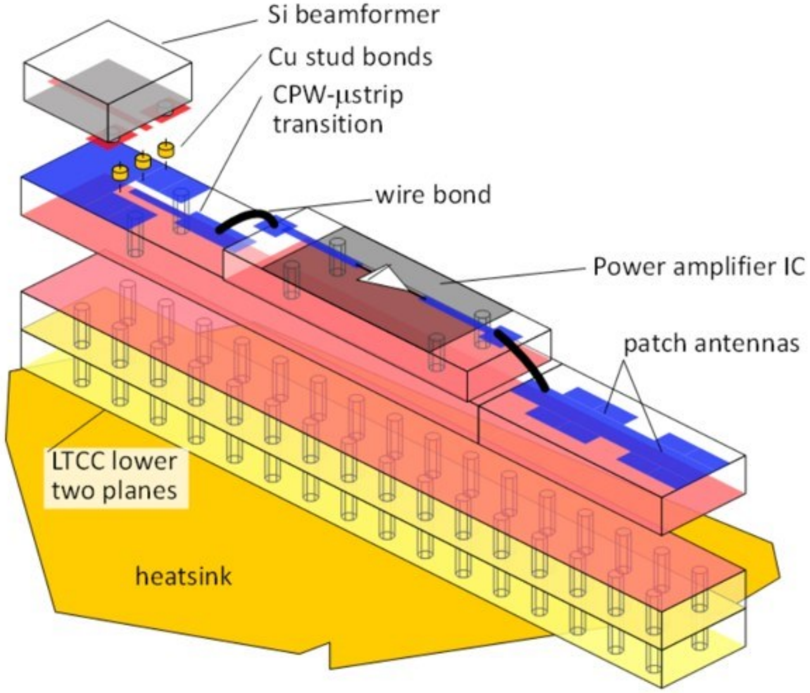
design 1: 2D array

design 2: 1D array

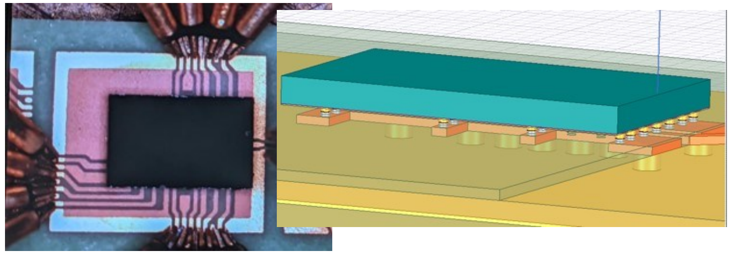


Spatial distribution of users, and of scattering objects, guides choice of array geometry.

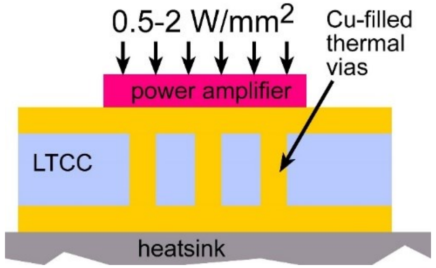
140GHz hub: packaging challenges



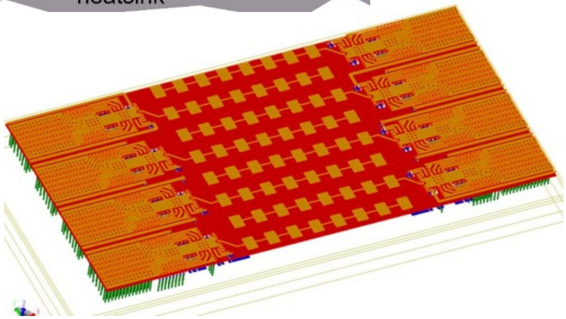
IC-package interconnects
Difficult at > 100 GHz



Removing heat
Thermal vias are marginal



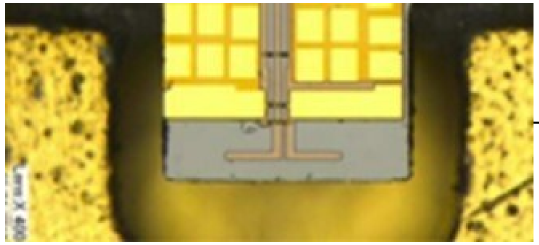
Interconnect density
Dense wiring for DC, LO, IF, control.
Hard to fit these all in.



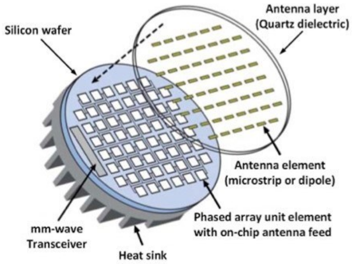
Economies of scale
Advanced packaging standards require sophisticated tools
High-volume orders only
Hard for small-volume orders (research, universities)
Packaging industry is moving offshore

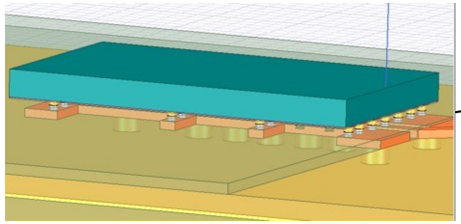
100-300GHz IC-package connections

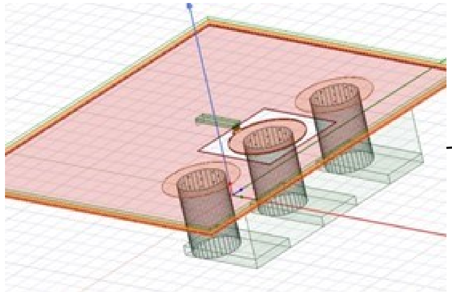
Deal, IEEE Trans THz, Sept 2011



G. Rebeiz



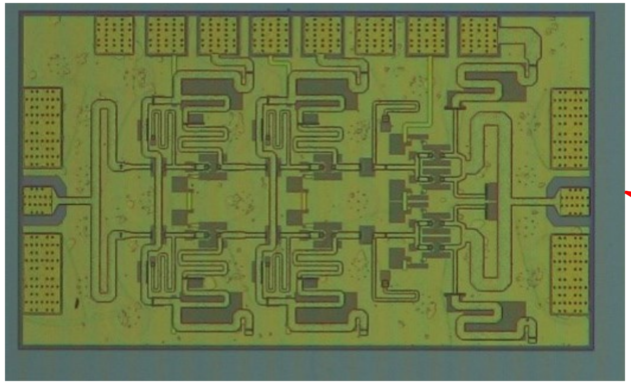




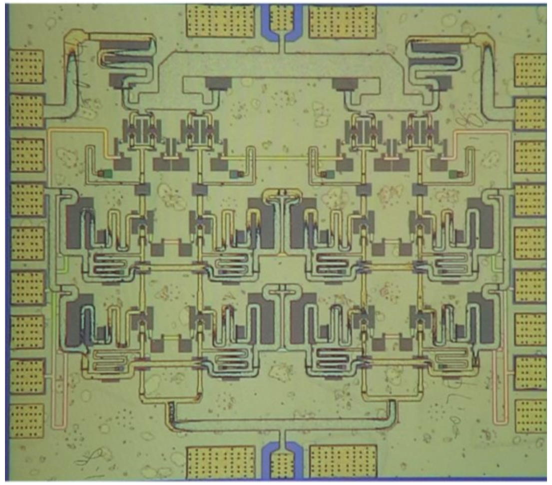
type	Frequency	technology	cost	heatsinking
micromachined waveguide interface	1000 GHz	Research. Cheap one day ?	**high** ✗	good
ribbon, mesh bond	200 GHz	Handcrafted.	**high** ✗	good
patch antennas on superstrate	1000 GHz	Straightforward	low	good
Cu stud flip-chip	>200 GHz	Industry standard	low	ok, **marginal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

140GHz hub: ICs & Antennas

110mW InP Power Amplifier
20.8% PAE

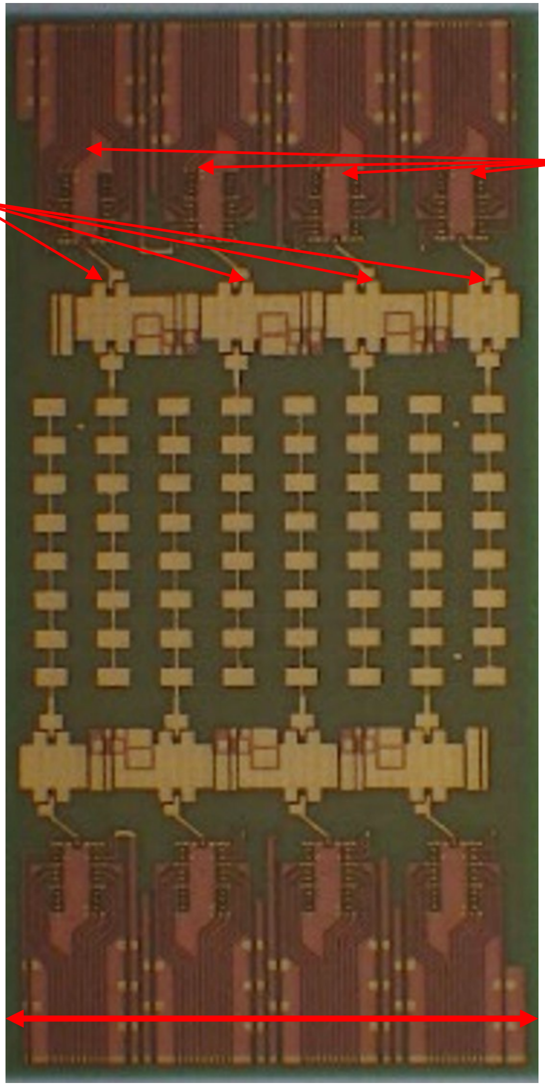


190mW InP Power Amplifier
16.7% PAE



Teledyne InP HBT

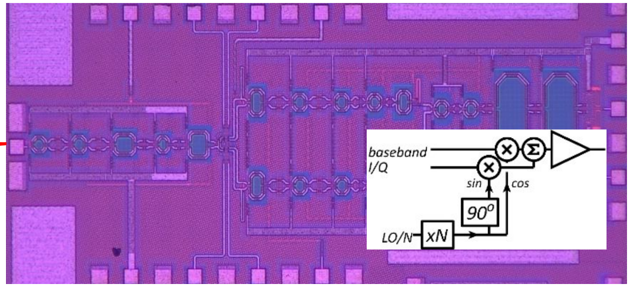
LTCC Array module



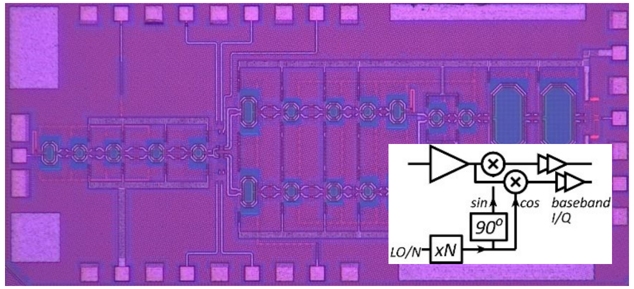
1 cm

Kyocera

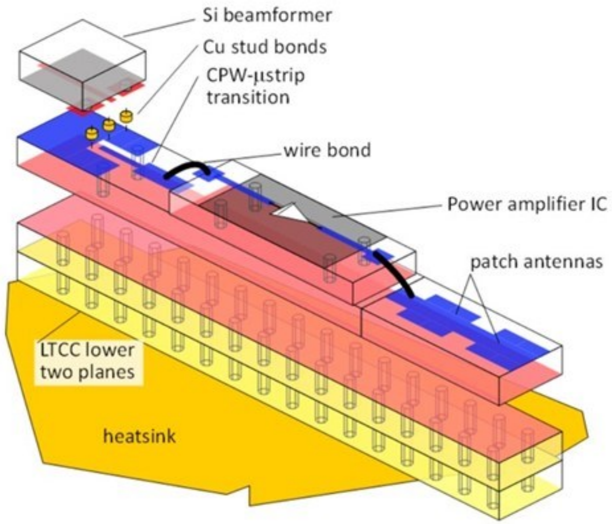
CMOS Transmitter IC
22nm SOI CMOS.



Receiver IC
22nm SOI CMOS.



GlobalFoundries 22nm SOI CMOS

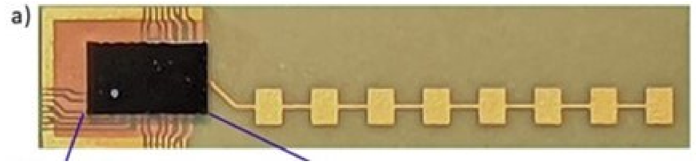


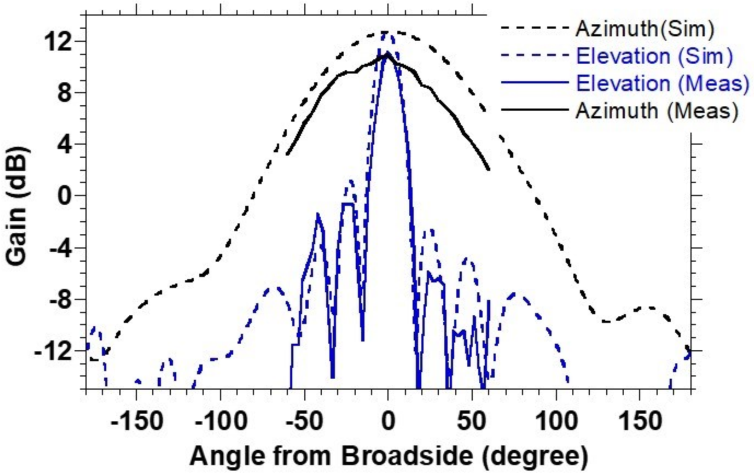
Farid, Ahmed, Rodwell, UCSB; Flynn, Dunn, Niknejad, Nikolic, BWRC; Rebeiz, UCSD

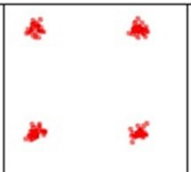
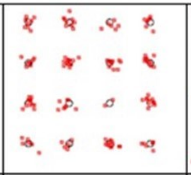
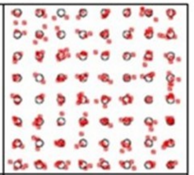
140GHz transmitter channel

Farid, 2021 IMS, RFIC

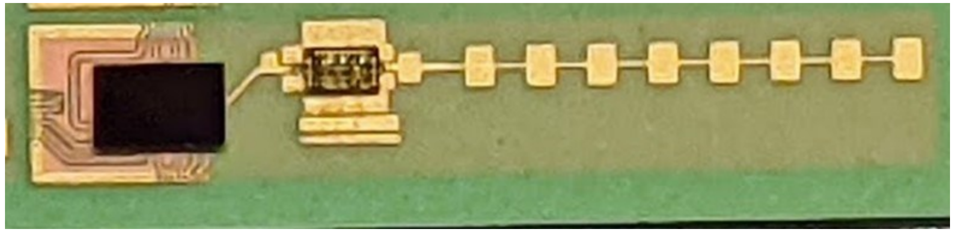
CMOS-only TX channel

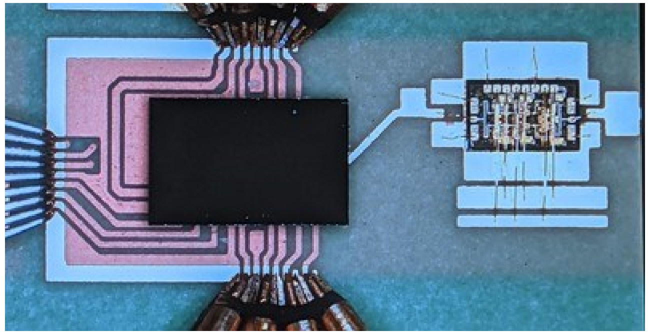


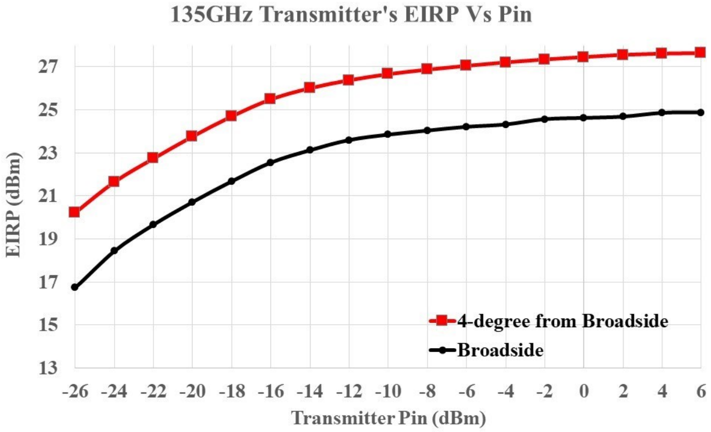


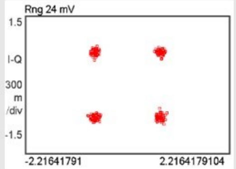
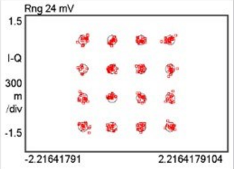
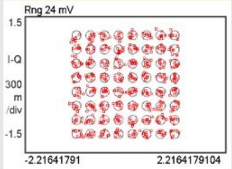
			
rate	4 Gbaud	4 Gbaud	2 Gbaud
power	3dB backoff	6dB backoff	8dB backoff
EVM (RMS)	7.9%	9.2%	7.4%

CMOS+InP TX channel

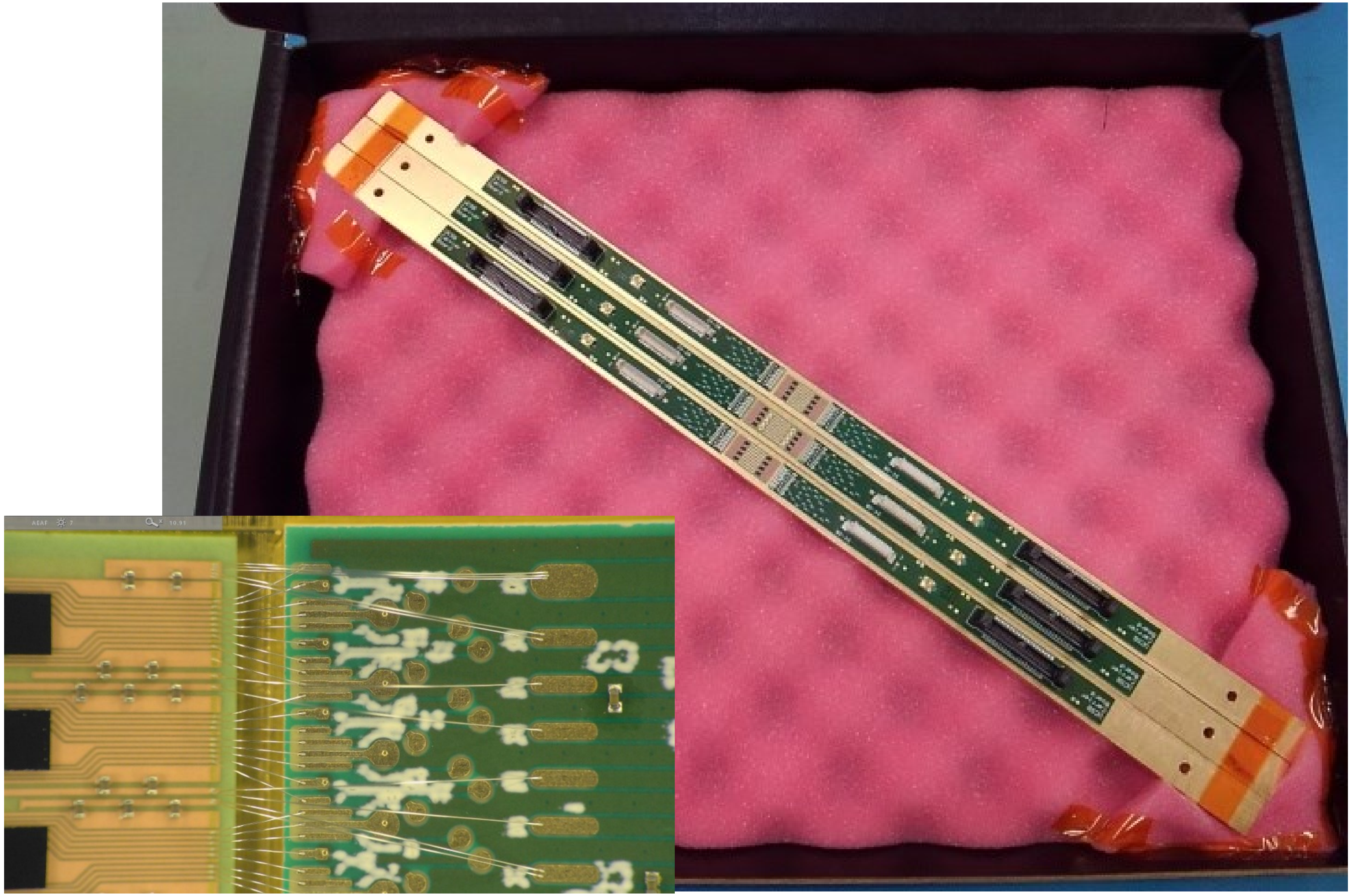


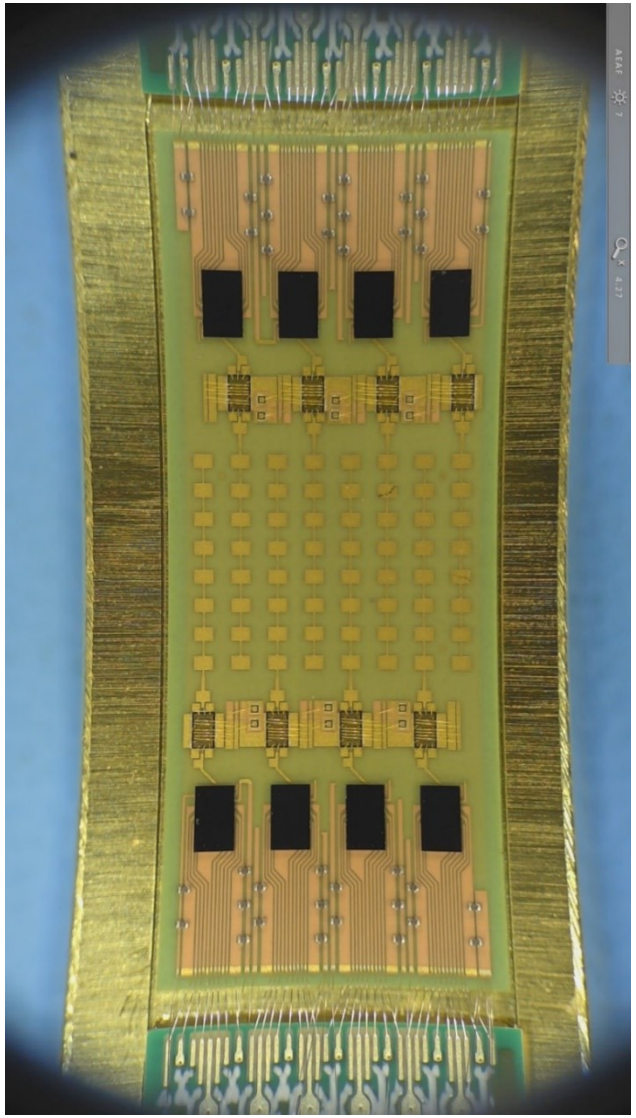




EIRP =19dBm/ 6dB-BO from Psat		
QPSK (5G Baud)	16QAM (5G Baud)	64QAM (5G Baud)
		
7.69% (RMS)	8.4% (RMS)	8.5% (RMS)

8-Channel 140GHz MIMO hub modules

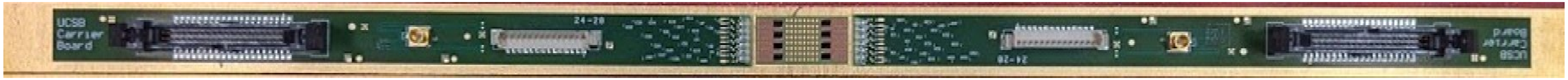


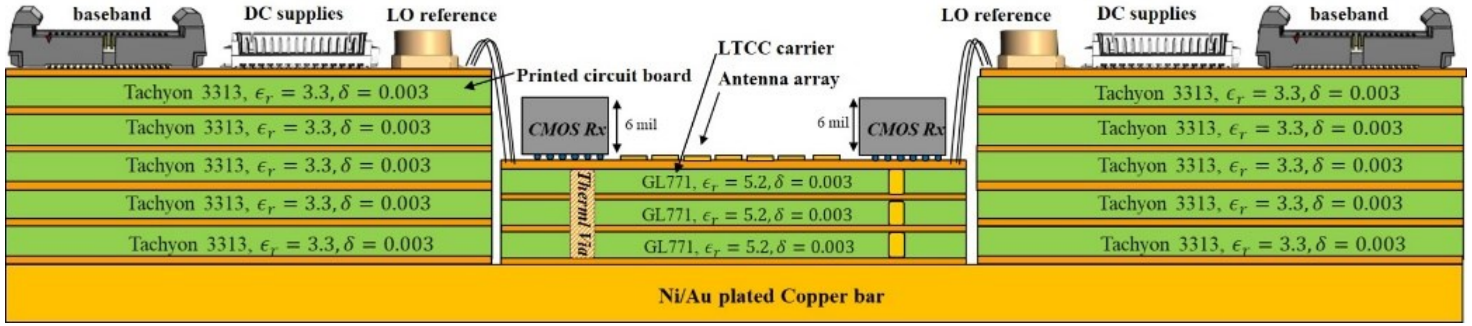


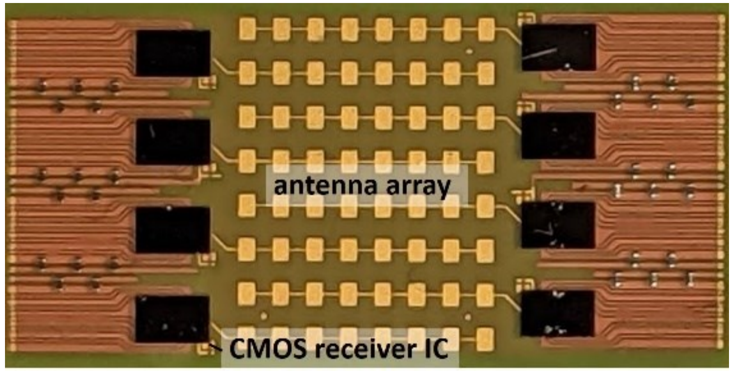
135GHz 8-channel MIMO hub array tile modules

A. Farid et. al, submitted to the 2021 IEEE BCICTS Symposium

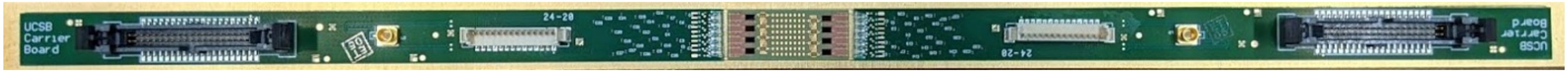
Receiver

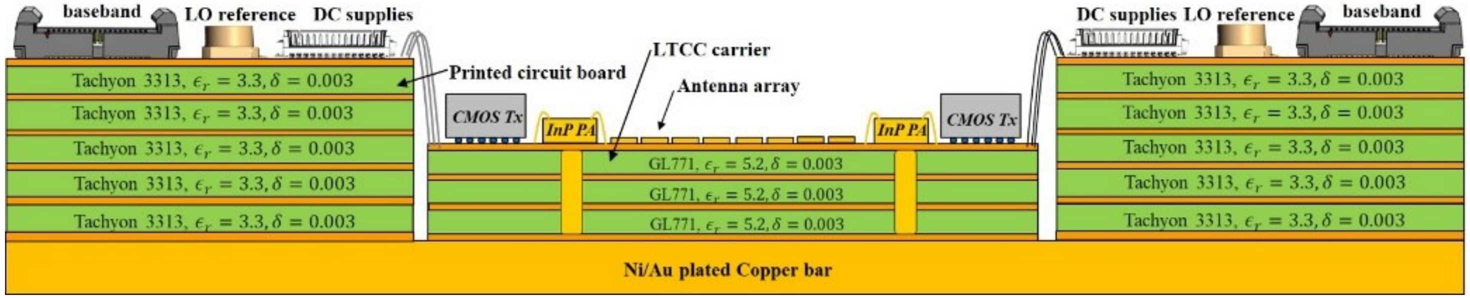


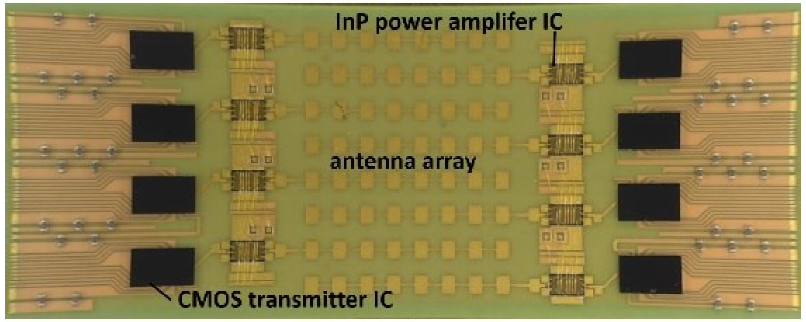




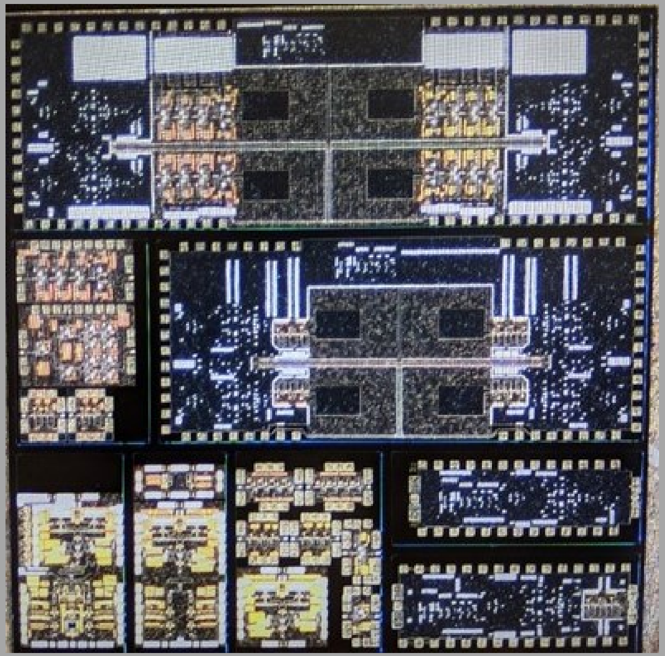
Transmitter

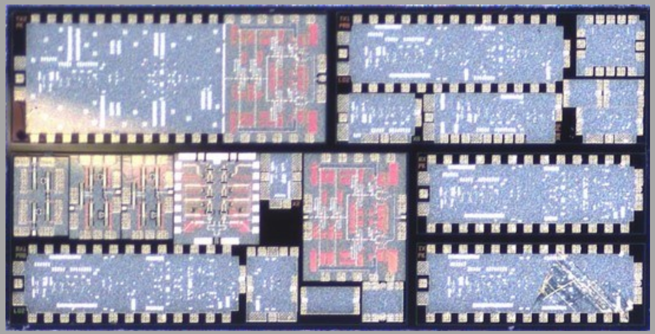




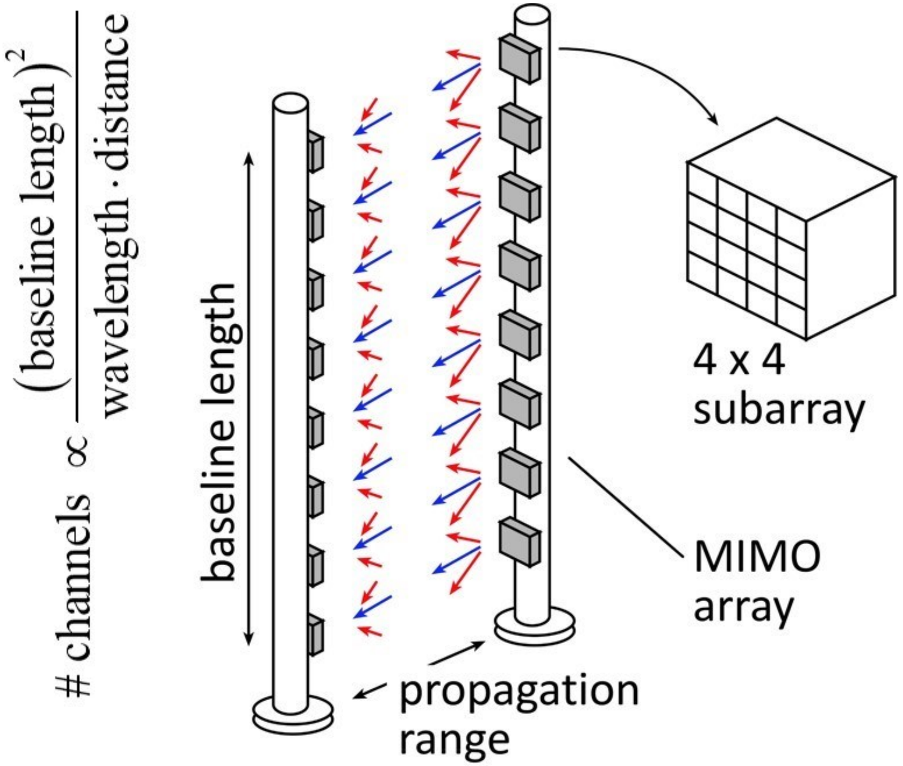


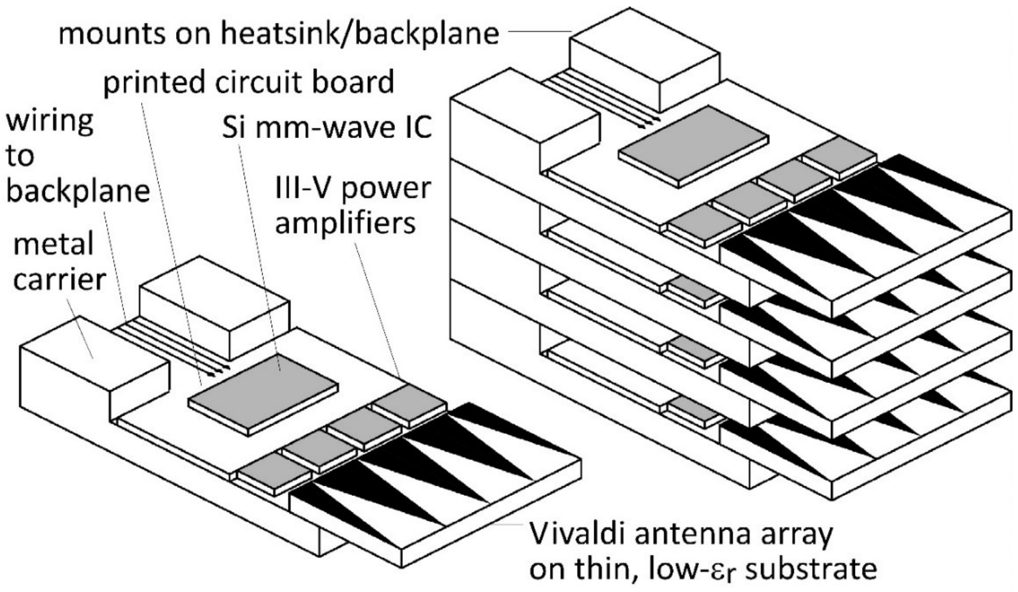
ICs and Packages: 210 & 280 GHz





210 GHz MIMO backhaul demo





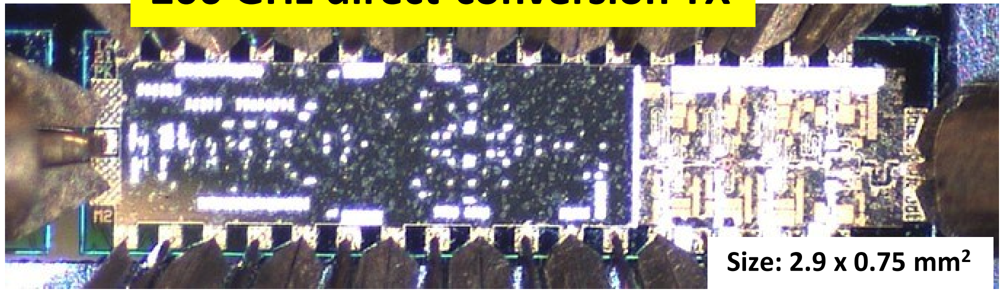
8-element MIMO array
3.1 m baseline for 500m link.
80Gb/s/subarray→ 640Gb/s total
4 × 4 sub-arrays → 8 degree beamsteering

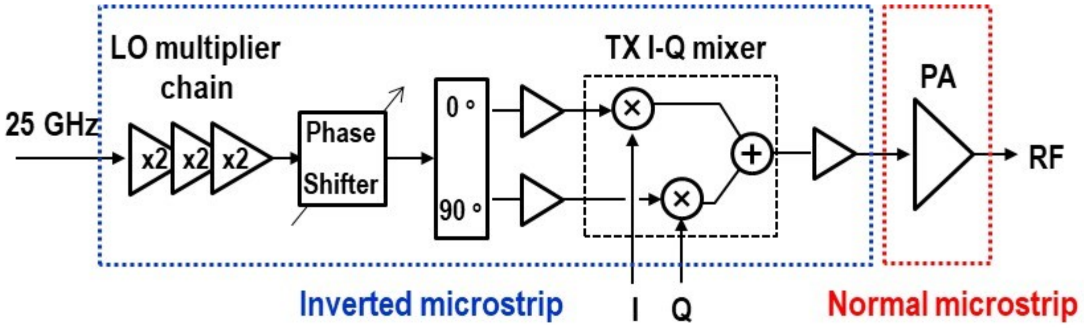
Key link parameters
500 meters range in 50 mm/hr rain; 23 dB/km
20 dB total margins:
packaging loss, obstruction, operating, design, aging
PAs: 63mW $=P_{1dB}$ (per element)
LNAs: 6dB noise figure

210 GHz Transmitter and Receiver ICs

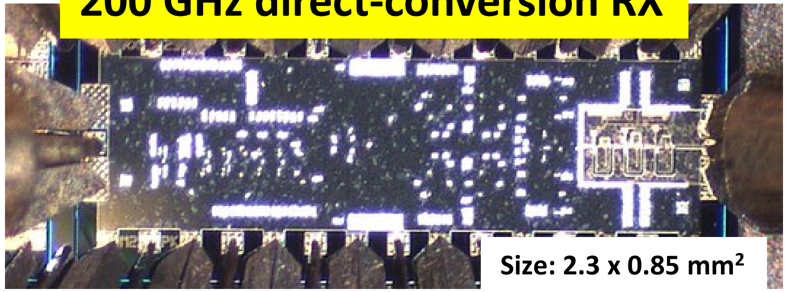
M. Seo et al, 2021 IMS; Teledyne 250nm InP HBT

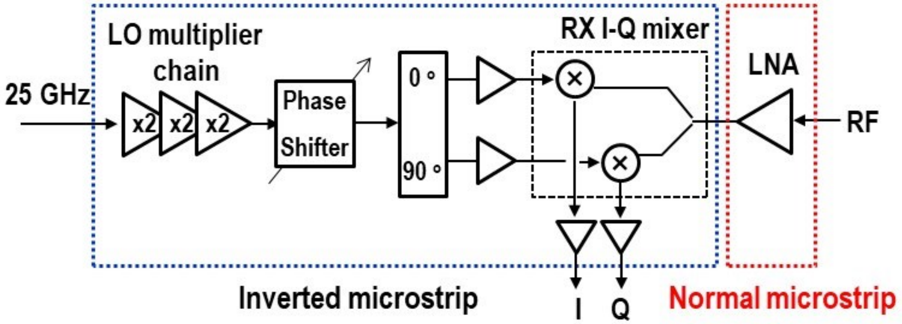
200 GHz direct-conversion TX

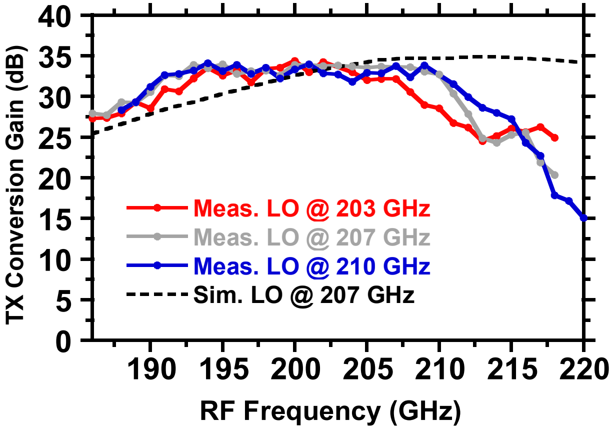


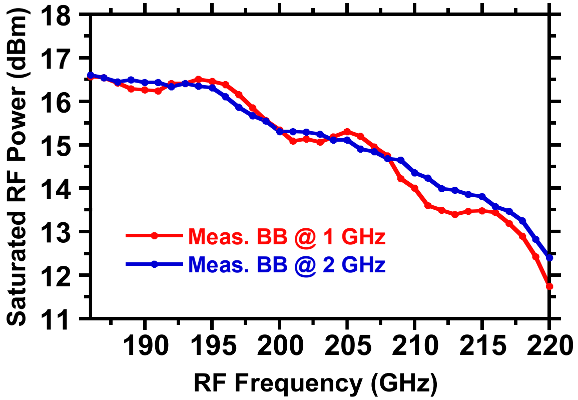


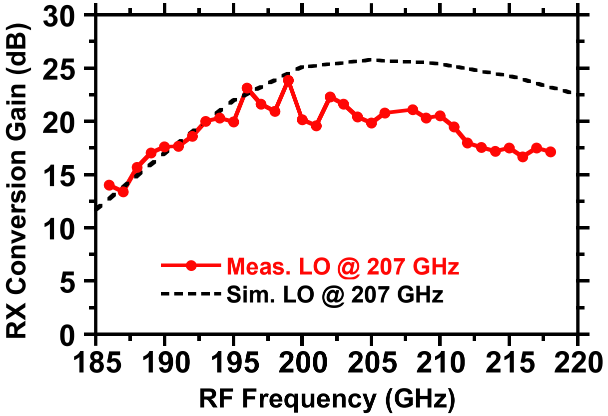
200 GHz direct-conversion RX

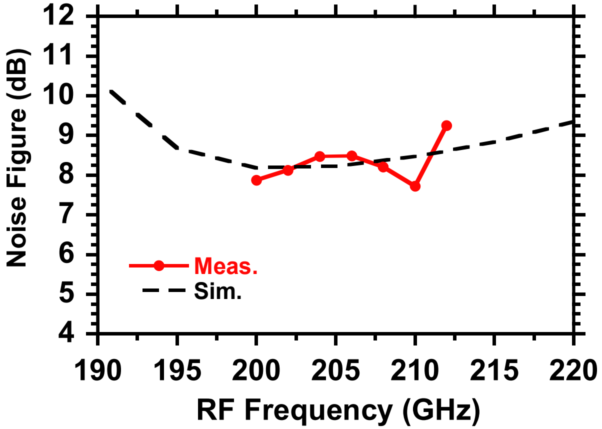






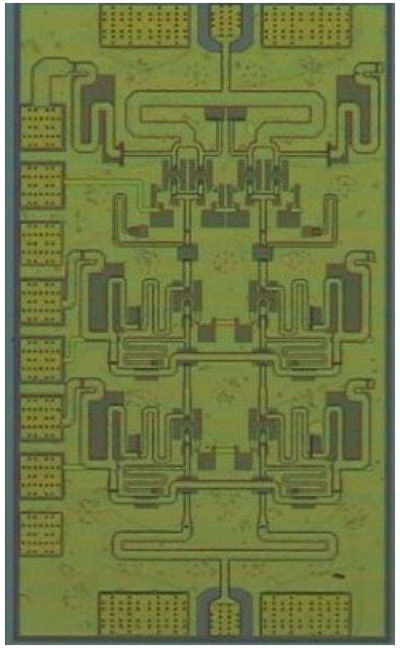




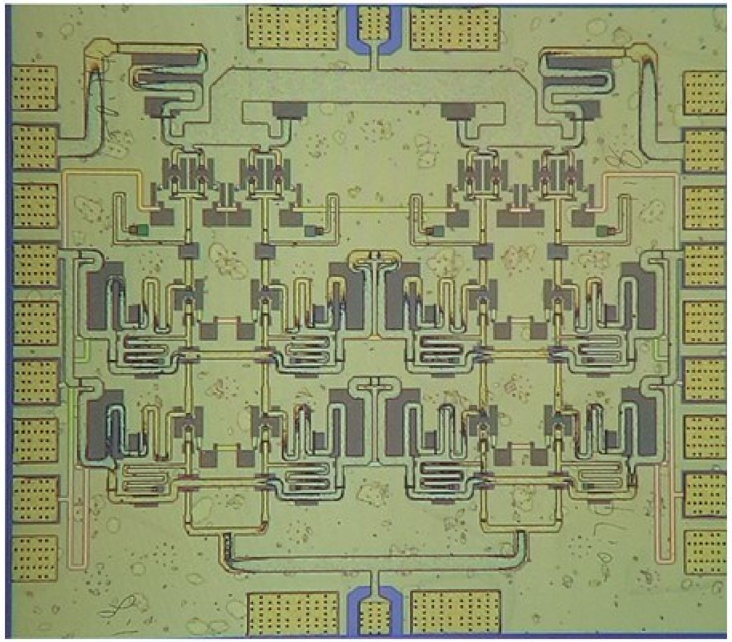


Power Amplifiers in 250nm InP HBT

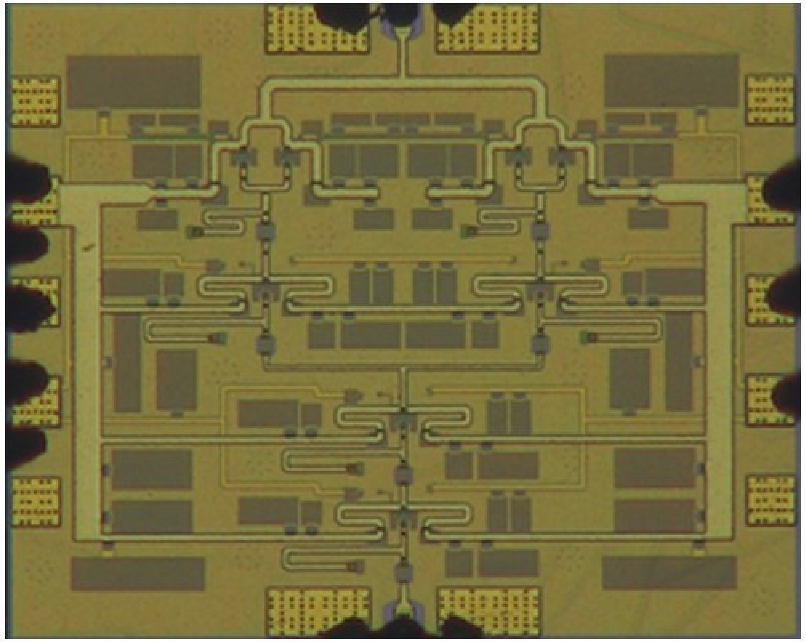
Ahmed et al, 2020 IMS, 2020 EuMIC, 2021 IMS, 2021 RFIC
Teledyne 250nm InP HBT technology



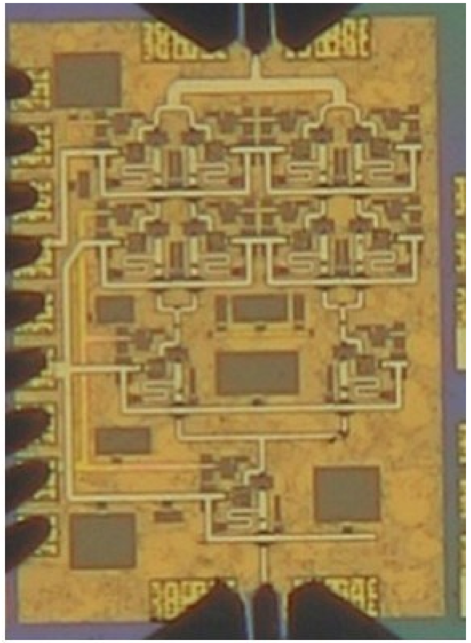
140GHz, 20.5dBm, 20.8% PAE



130GHz, 200mW, 17.8% PAE



194GHz, 17.4dBm, 8.5% PAE



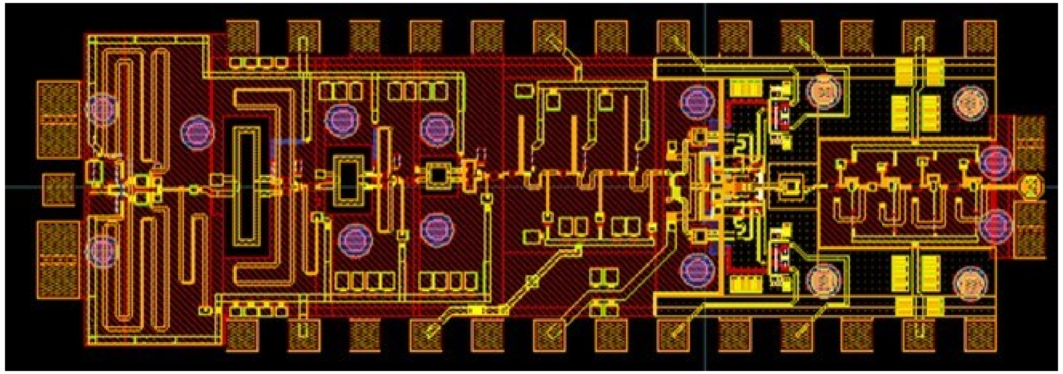
266GHz, 16.8dBm, 4.0% PAE

Record-setting efficiency for 100-300GHz power amplifiers.

280GHz transmitter and receiver IC designs

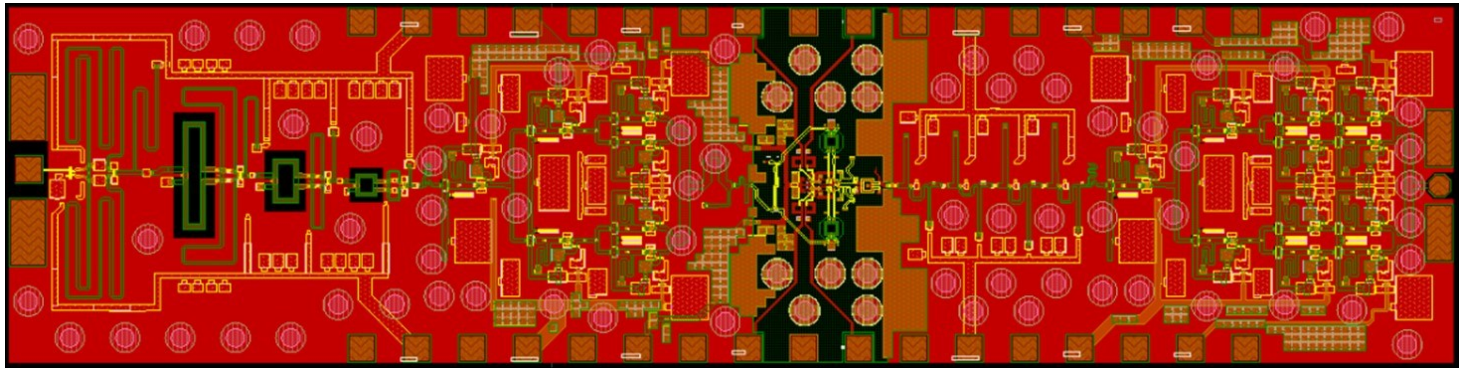
Solyu, Alz, Ahmed, Seo; UCSB/Sungkyunkwan
Teledyne 250nm InP HBT technology

Receiver



simulations: 11dB noise figure, 40GHz bandwidth

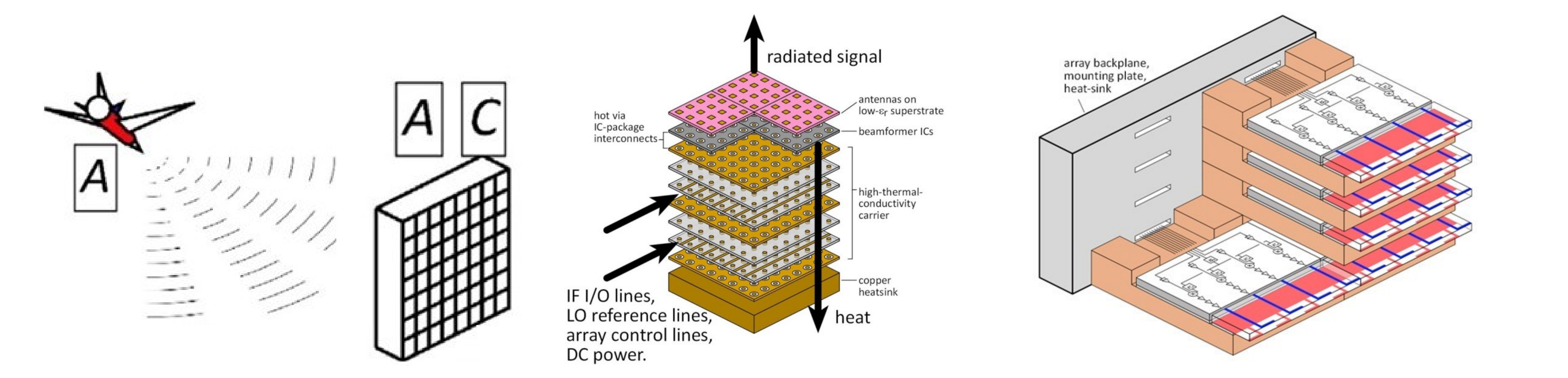
Transmitter



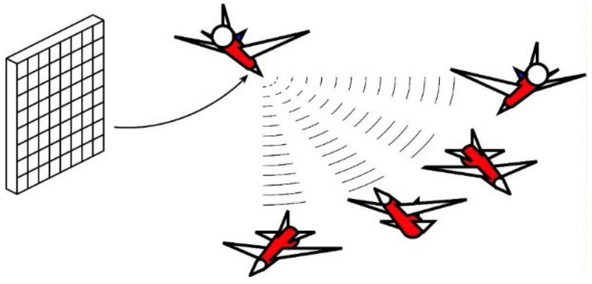
simulations: 17dB saturated output power.

Application: point-point MIMO backhaul links

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
heat
IF I/O lines,
LO reference lines,
array control lines,
DC power.
array backplane,
mounting plate,
heat-sink

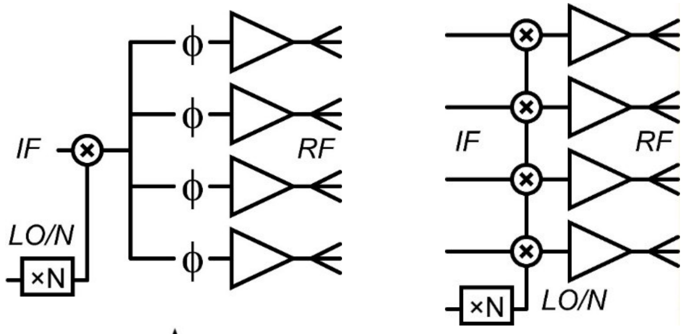
The 100-300GHz 2D Array Challenge



System architecture:

Single-beam: simpler RF front-end, simpler baseband

MIMO: complex digital baseband, flexible, many beams



Arrays can be made from either **tiles** or **trays**

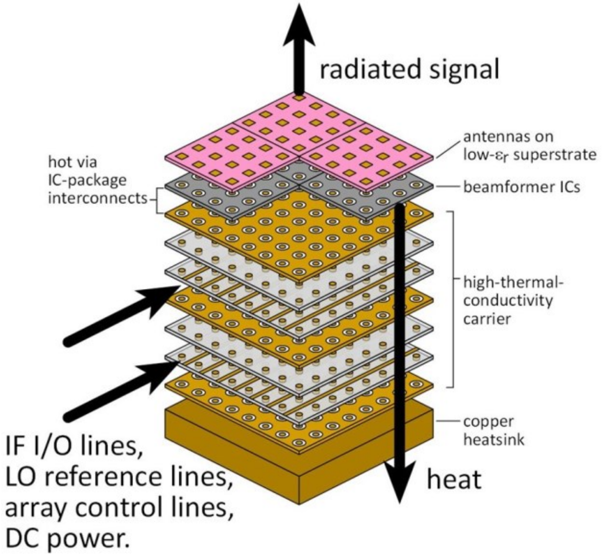
Arrays must be vast: 100-1,000-10,000 elements

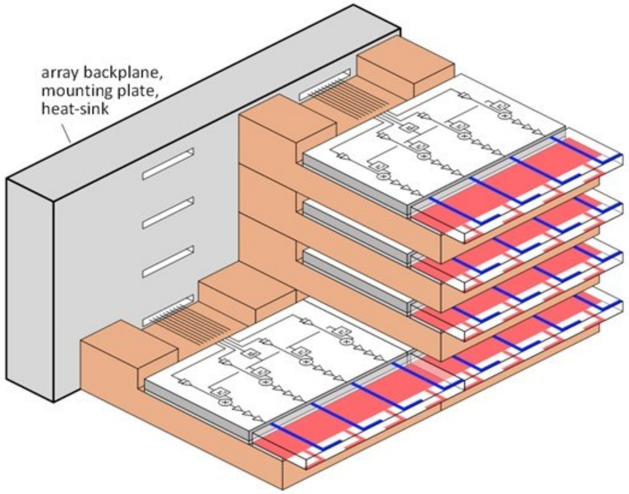
Arrays must be dense: packaging challenges

Many DC/IF/LO lines, plus antenna interface.

Fitting IC functions into available area.

Removing the heat.





f	100	150	200	250	300	GHz
λ	3	2	1.5	1.2	1	mm
$\lambda/2$	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 array frequency scaling

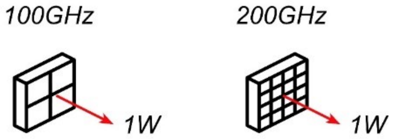
$$P_{received} = \frac{A_t A_r}{\lambda^2 R^2} e^{-\alpha R} \cdot P_{trans} \longrightarrow \#\text{beams} \cdot (\text{bit rate per beam}) \cdot kTF \cdot \text{SNR} = \frac{A_t A_r}{\lambda^2 R^2} e^{-\alpha R} \cdot P_{trans}$$

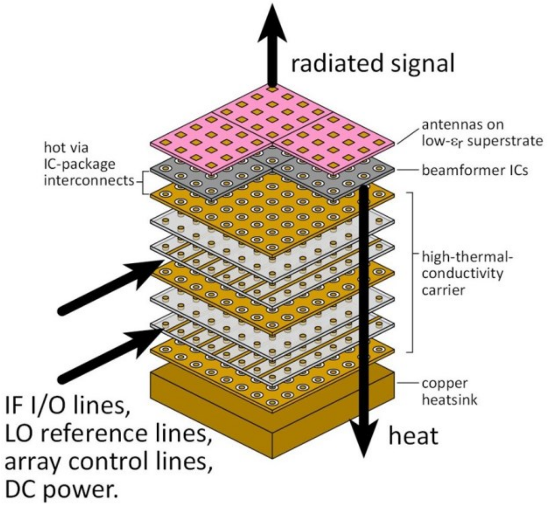
(Worst-case atmospheric loss: ~constant over 50-300GHz)

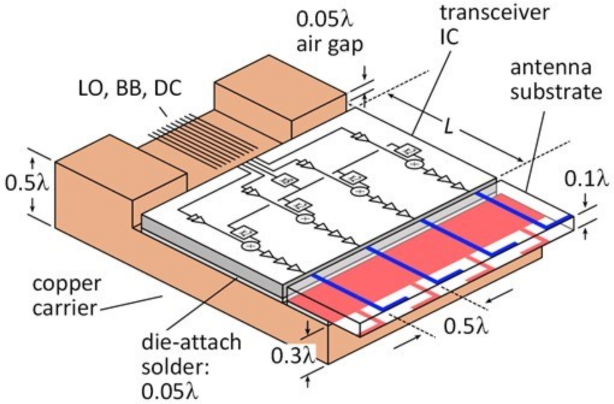
Proposed scaling law	change
carrier frequency	increase 2:1
aperture area	keep constant
total transmit power	keep constant

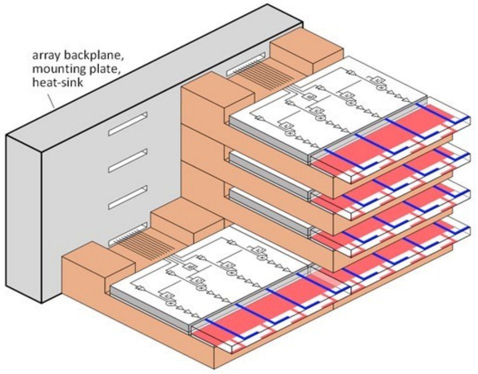
→

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

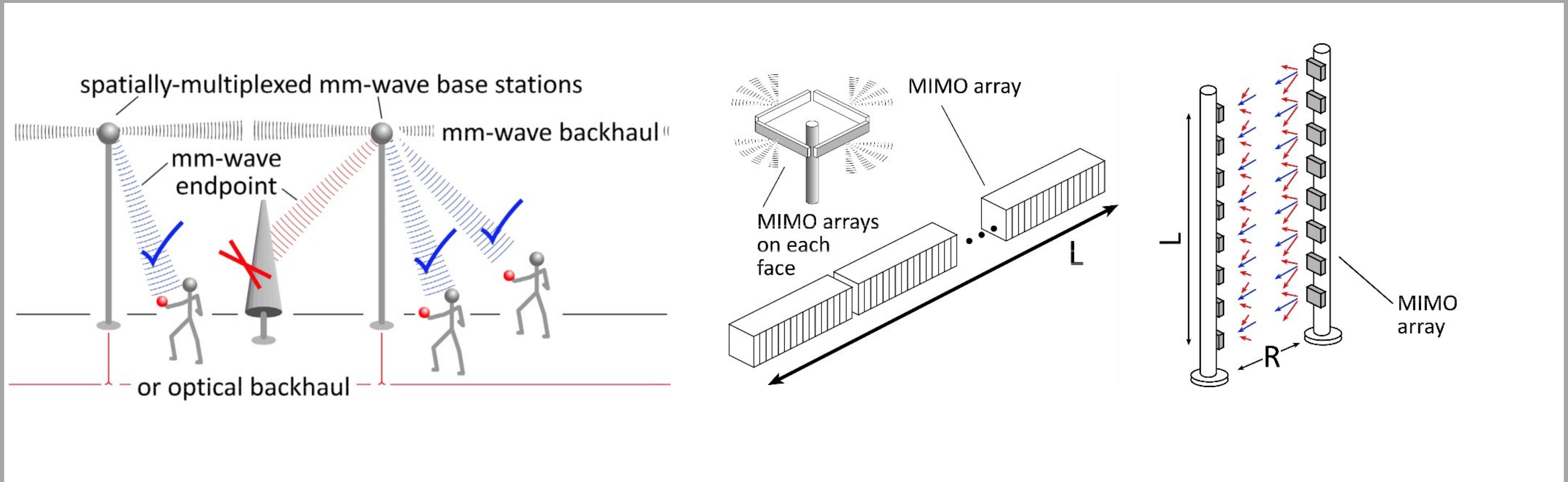








100-300GHz Wireless



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-silicon for short ranges below 200 GHz.
III-V LNAs and PAs for longer-range links. Just like cell phones today
III-V frequency extenders for 340GHz and beyond

The challenges
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)