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Packaging challenges in 100-300 GHz wireless.

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Acknowledgements

Systems


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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

SRC®
JUMP
ComSenTer
COMMUNICATIONS SENSING TERAHERTZ

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

Also:
Kyocera: D. Kim, H. Horikawa, M. Imayoshi.
Samsung: G. Xu, N. Sharma, S. Abu-Surra, W. Choi
Pi-Radio: A. Dhananjay,

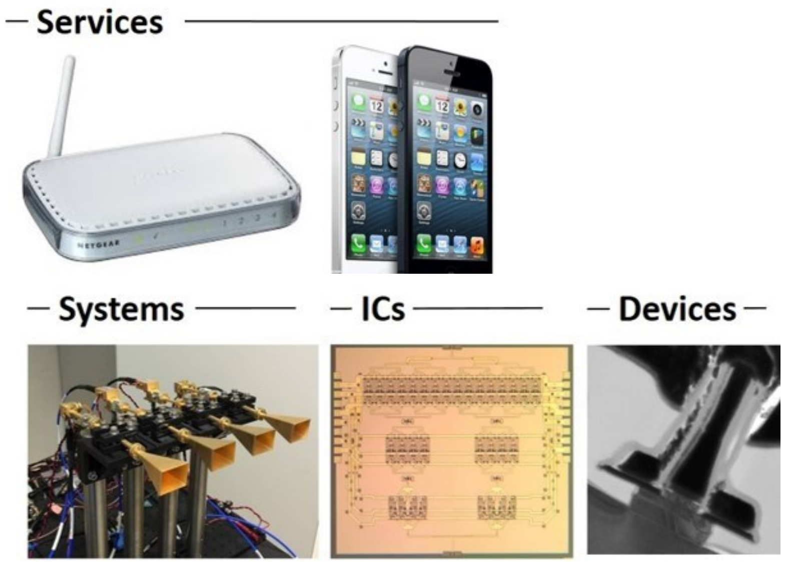
ANALOG DEVICES
IBM
arm
NORTHROP GRUMMAN
NSF
Raytheon Technologies
DARPA
tsmc
EMD Performance Materials
LOCKHEED MARTIN
SAMSUNG
SK hynix
Micron
intel
NIST

100-300GHz Wireless

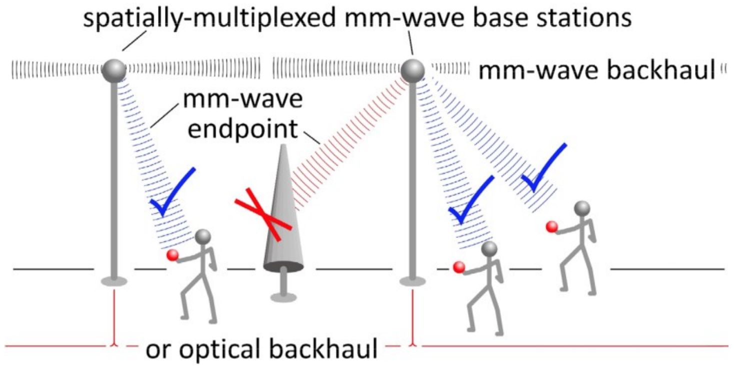
Wireless networks: exploding demand.

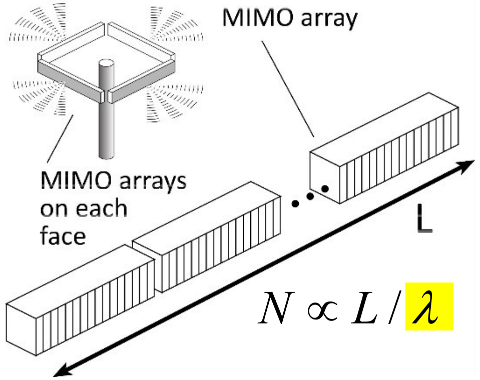
Immediate industry response: 5G.
~1~40 GHz ("5G?")
~40~100GHz ("5.5G ?")
increased spectrum, extensive beamforming

Next generation might be above 100GHz.. (?)
greatly increased spectrum, massive spatial multiplexing



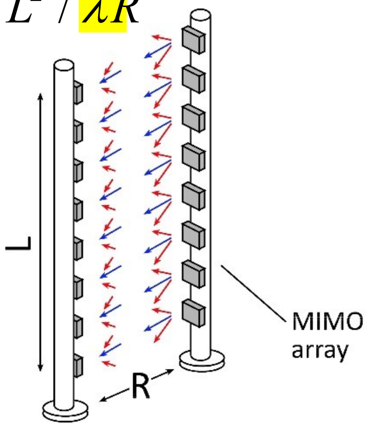
100-300GHz carriers, massive spatial multiplexing
→ **Terabit hubs and backhaul links, high-resolution imaging radar**

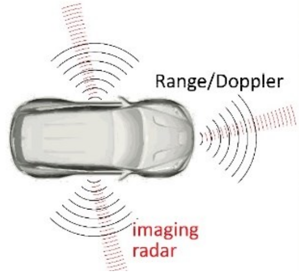




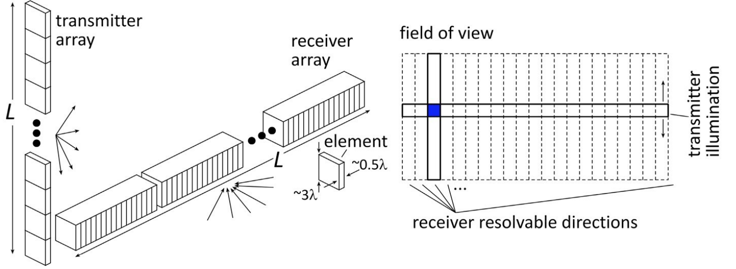
$N \propto L / \lambda$

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



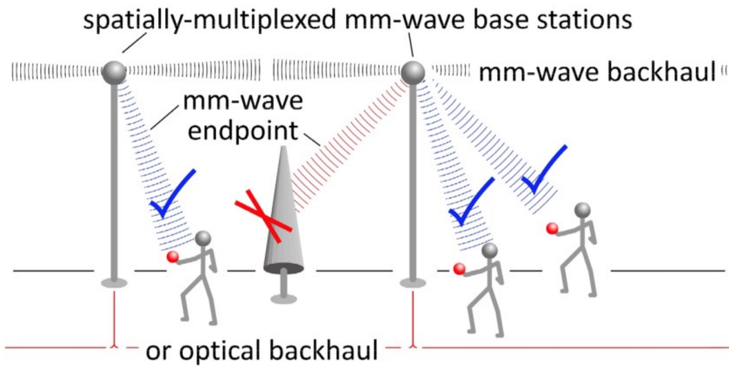


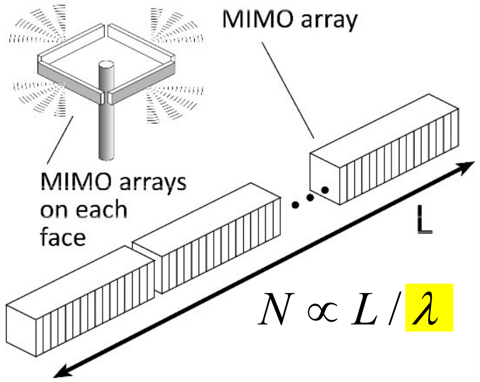
$\Delta\theta \propto \lambda / L$



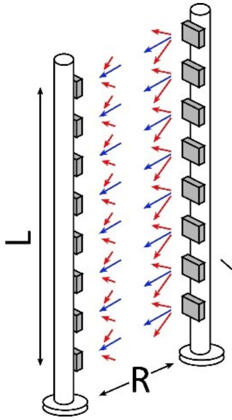
Benefits of Short Wavelengths

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

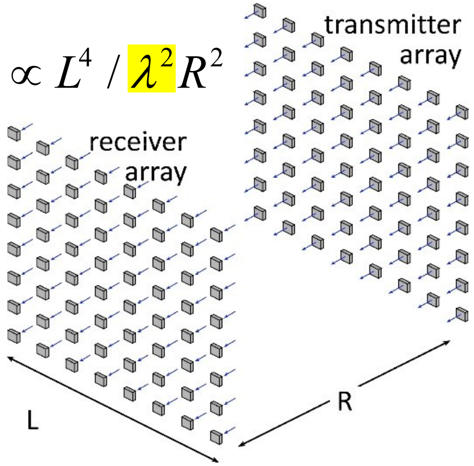




$N \propto L/\lambda$

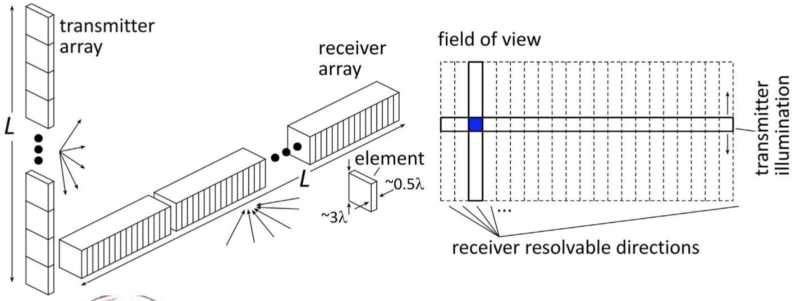


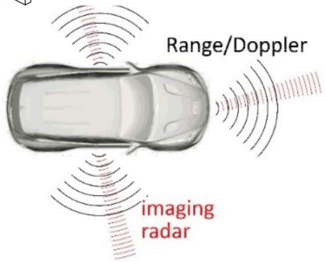
$N \propto L^2/\lambda R$



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

Imaging: very fine angular resolution





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

But:

High losses in foul or humid weather.

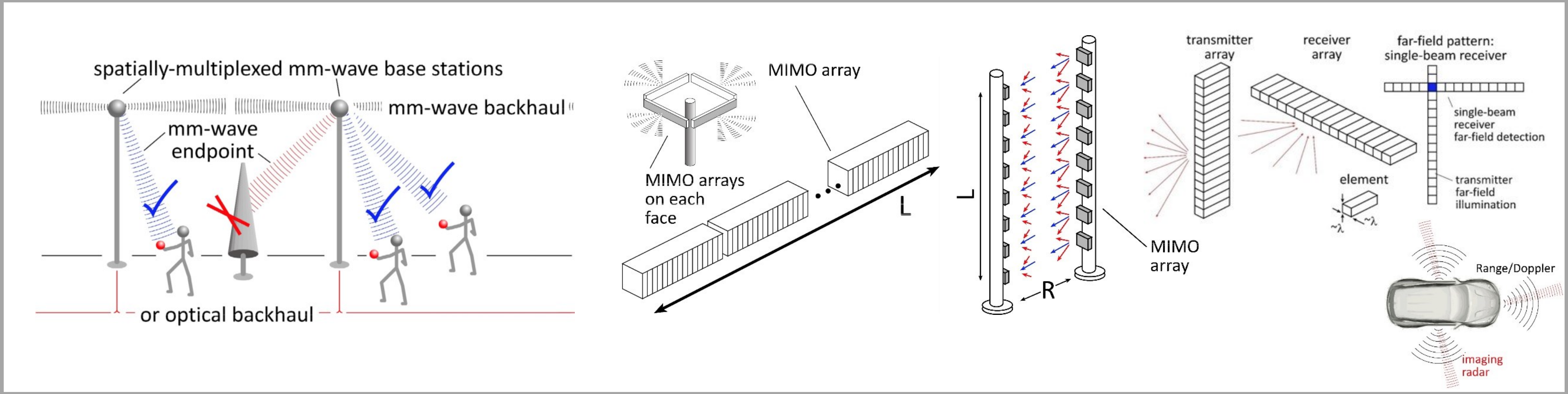
High λ^2/R^2 path losses.

ICs: poorer PAs & LNAs.

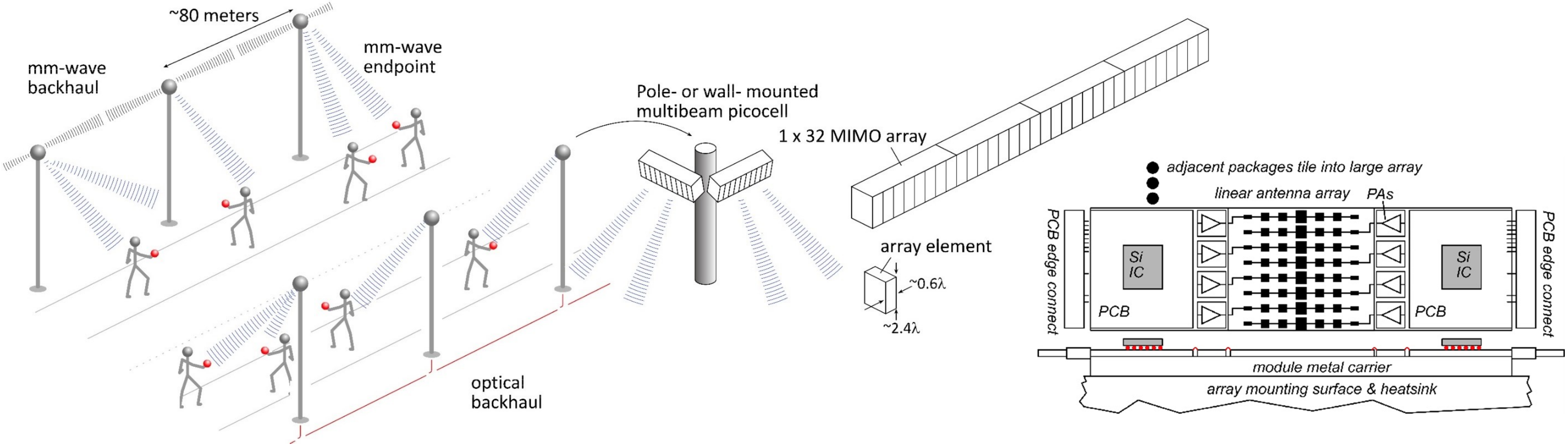
Beams easily blocked.

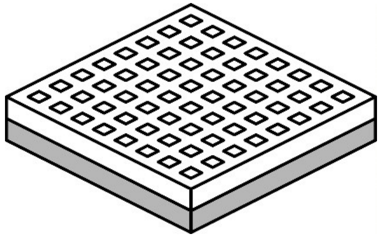
100-340GHz wireless:
terabit capacity,
short range,
highly intermittent

Applications



140 GHz moderate-MIMO hub





Handset:
8 × 8 array
(9×9mm)

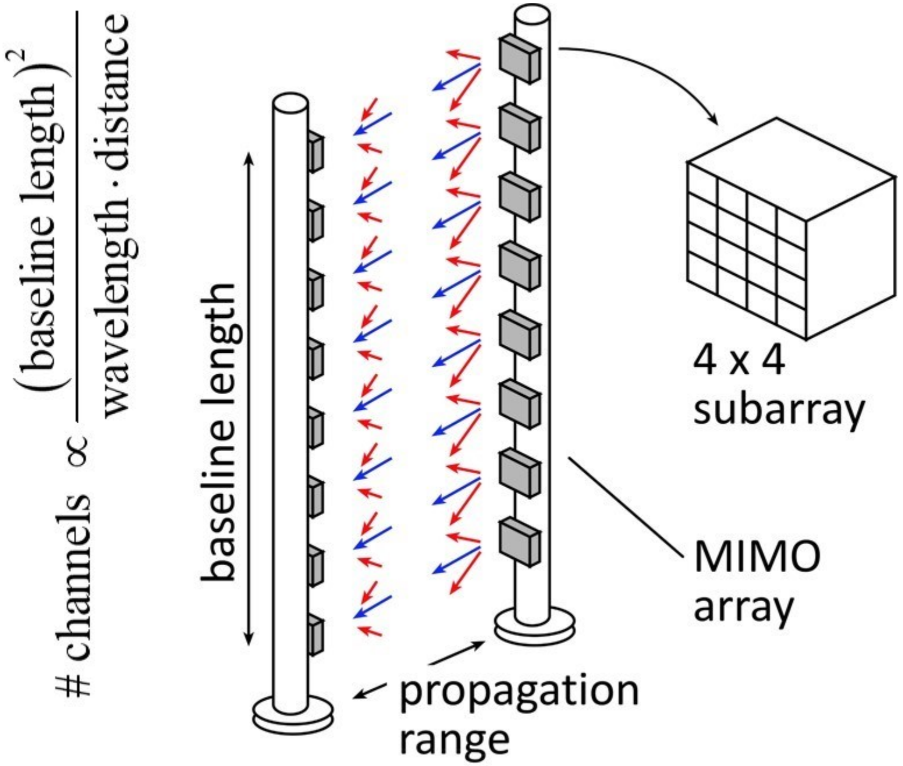
If demo uses 32-element array (four 1×8 modules):

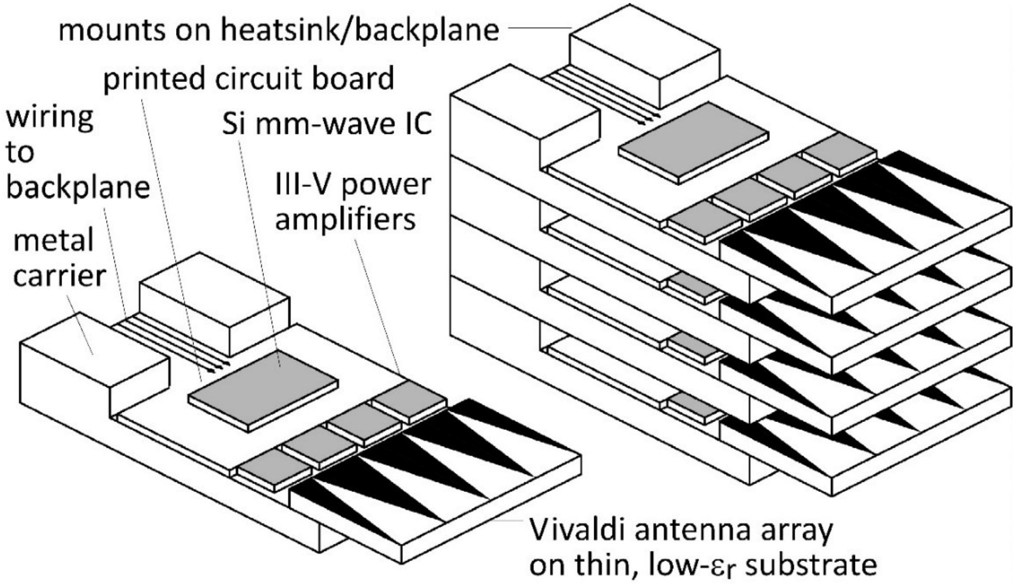
16 users/array. P_{1dB}=21 dB$_m$ PAs, F=8 dB LNAs

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

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

210 GHz, 640 Gb/s MIMO Backhaul





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

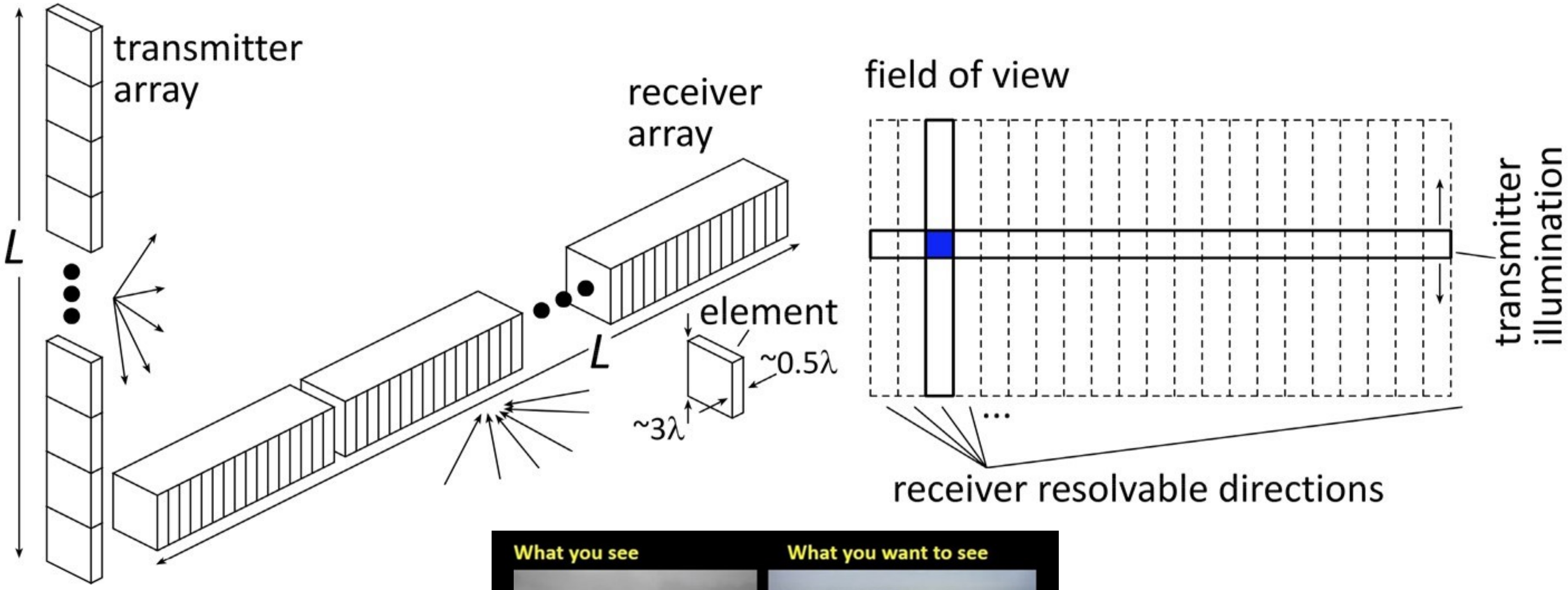
Key link parameters
500 meters range in 50 mm/hr rain; 23 dB/km
20 dB total margins:
packaging loss, obstruction, operating, design, aging
PAs: 18dBm =P_{1dB} (per element)
LNAs: 6dB noise figure

210 GHz FMCW crossed-array imaging car radar

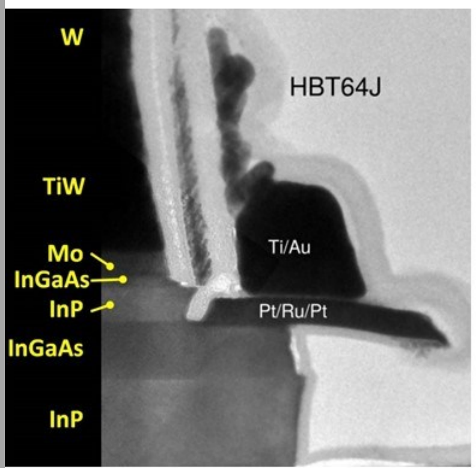
Array:
36×1 transmit,   1×216 receive
36 (v) × 216 (h) image
length: 15cm (6 inches),
beamwidth: 0.27°,
view: 10° (v) ×90° (h).
scan: 40Hz

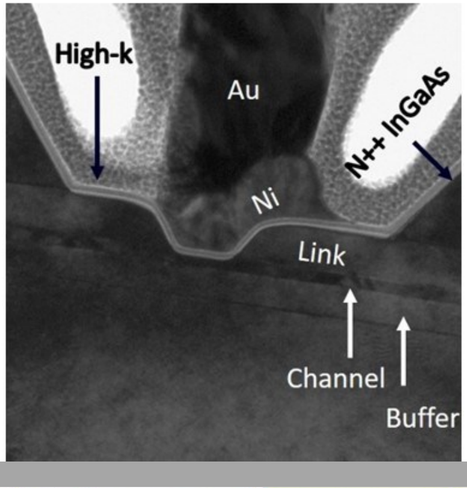
Electronics
transmit power/element: 50mW
receiver noise: 6dB
packaging losses: 2dB TX, 2dB RX

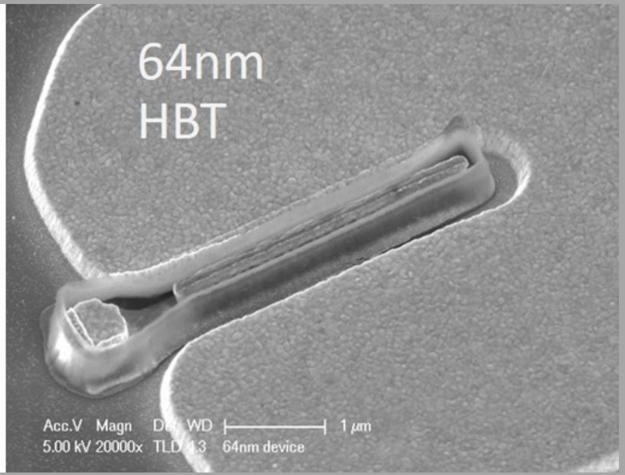
Sees:
22cm diameter target (a soccer ball) @ -10dB reflectivity
200m range,
with 10dB SNR
in heavy fog/rain @ 22dB/km
with 4dB operating margins.

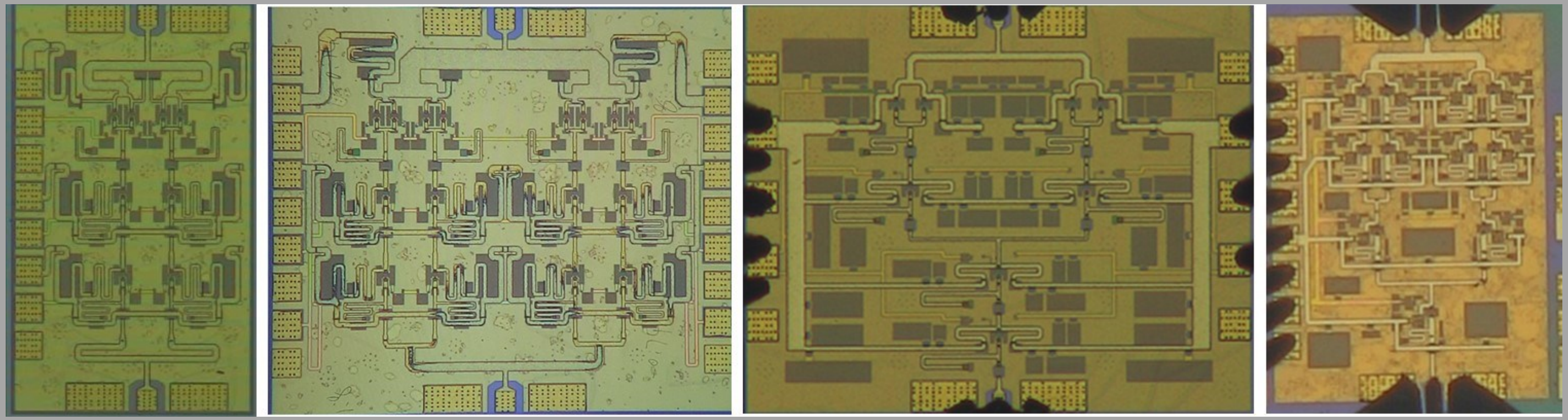


Transistors and ICs









Transistors for 100-300GHz

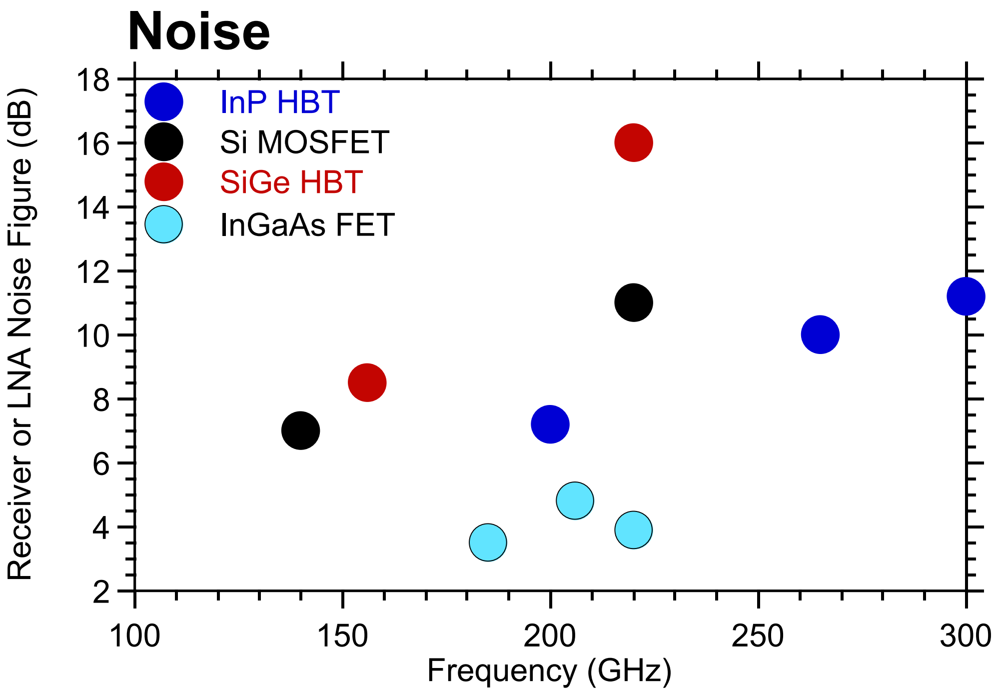
CMOS: good power & noise up to ~150GHz. Not much beyond. 65-32nm nodes are best.

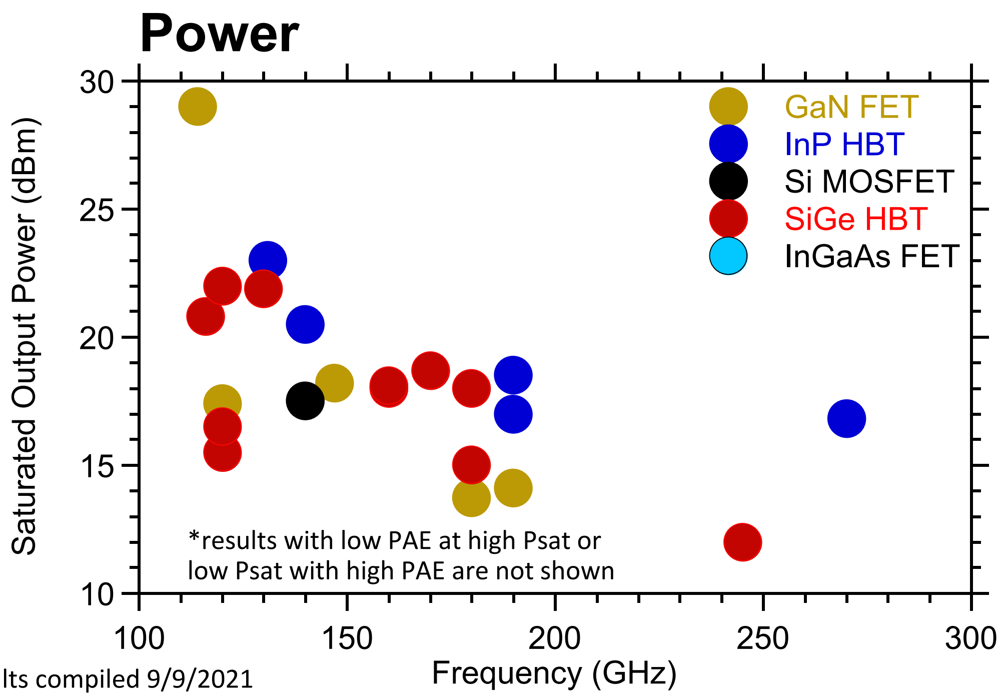
InP HBT: record 100-300GHz PAs

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

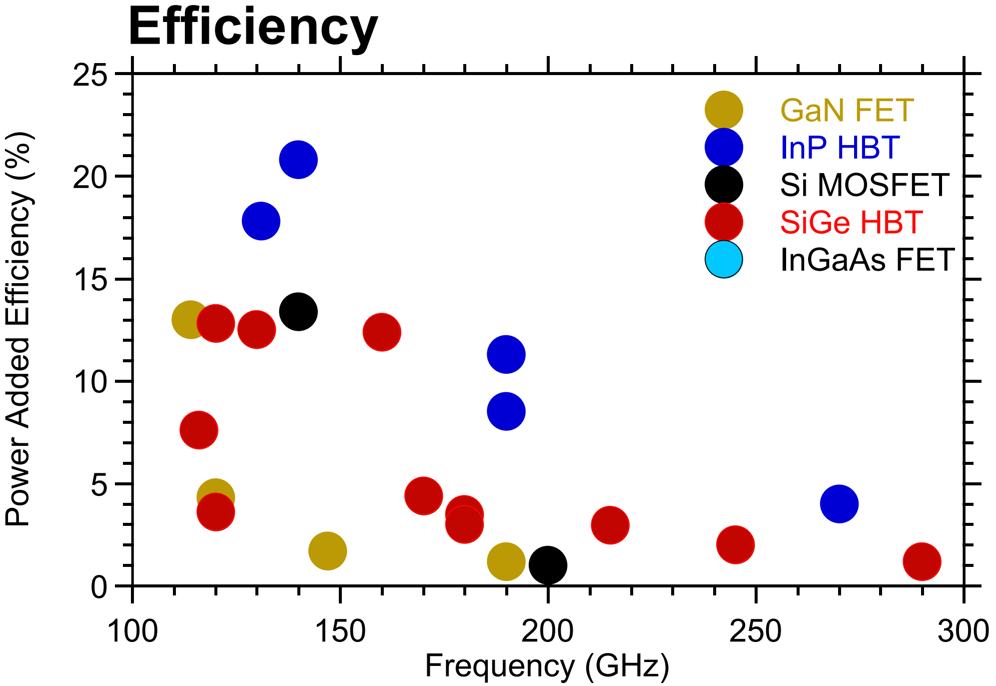
GaN HEMT: record power below 100GHz. Bandwidth improving

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



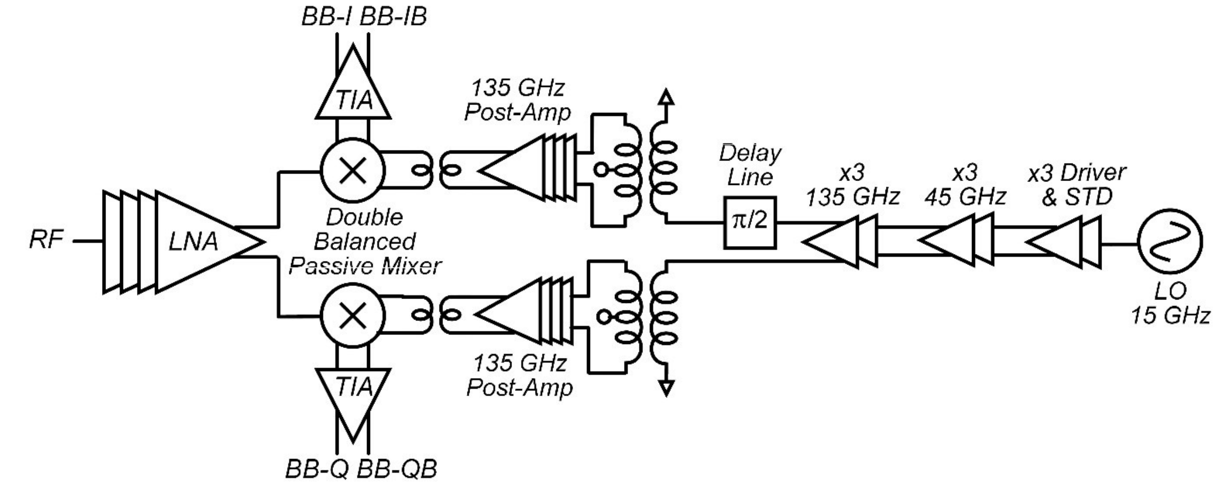


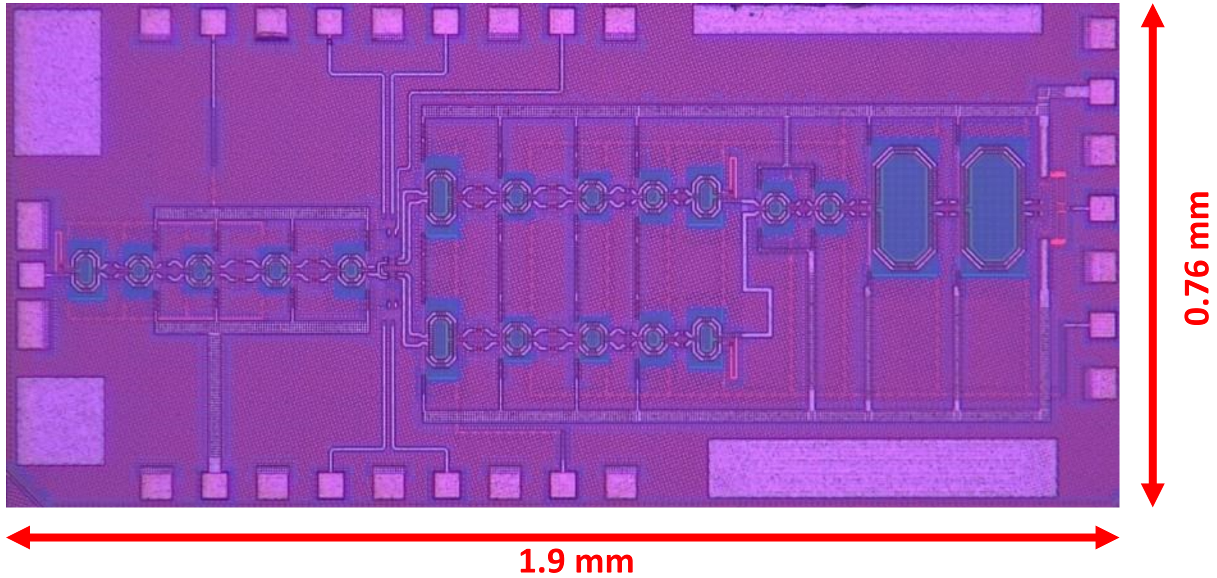
*results with low PAE at high Psat or low Psat with high PAE are not shown

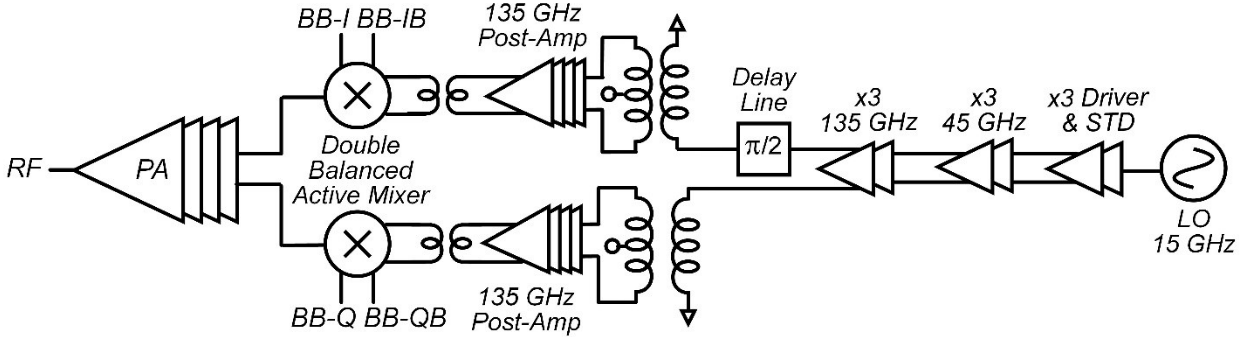


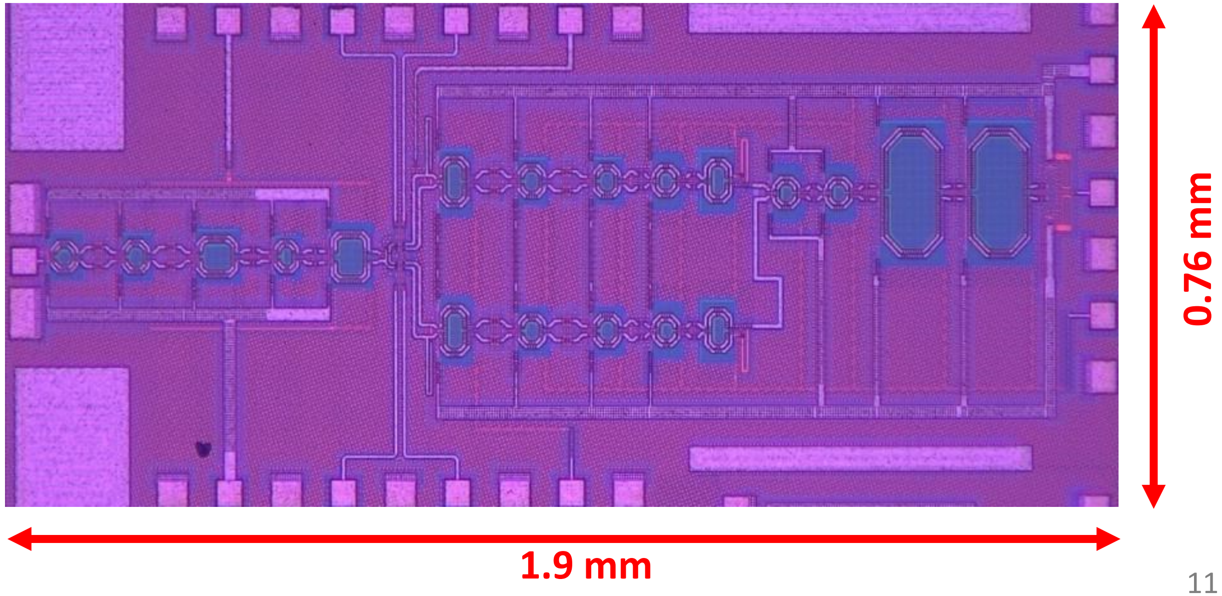
Results compiled 9/9/2021

140GHz Tx/Rx, 22nm SOI CMOS (GlobalFoundries)





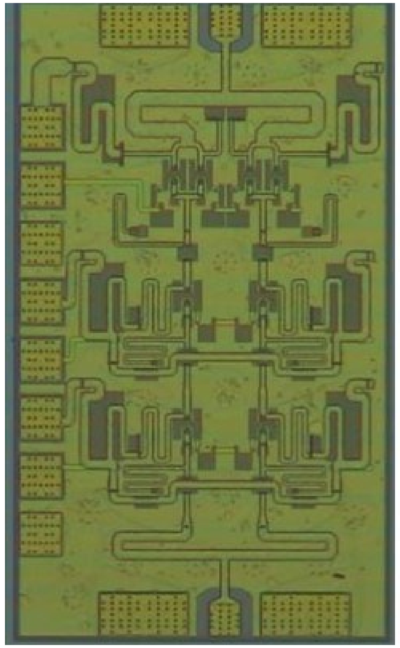




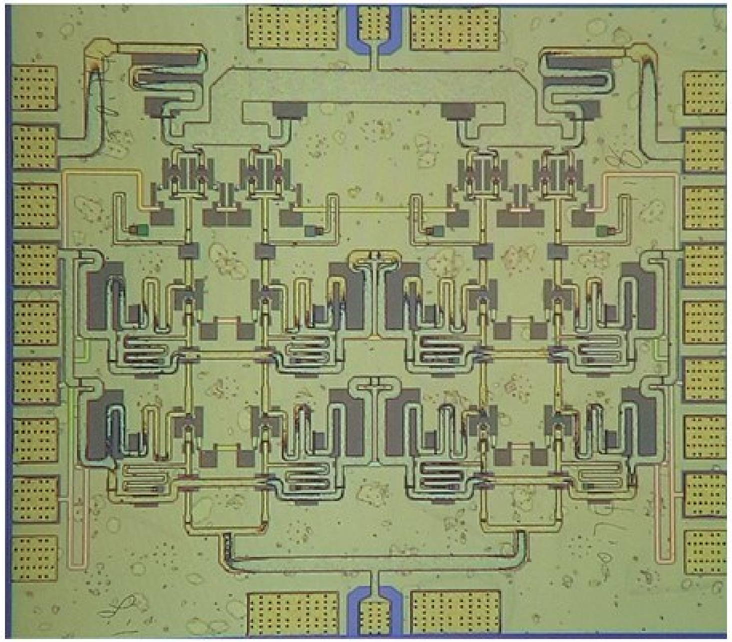
A. Farid UCSB, 2019 RFIC symposium

Power Amplifiers in 250 nm InP HBT

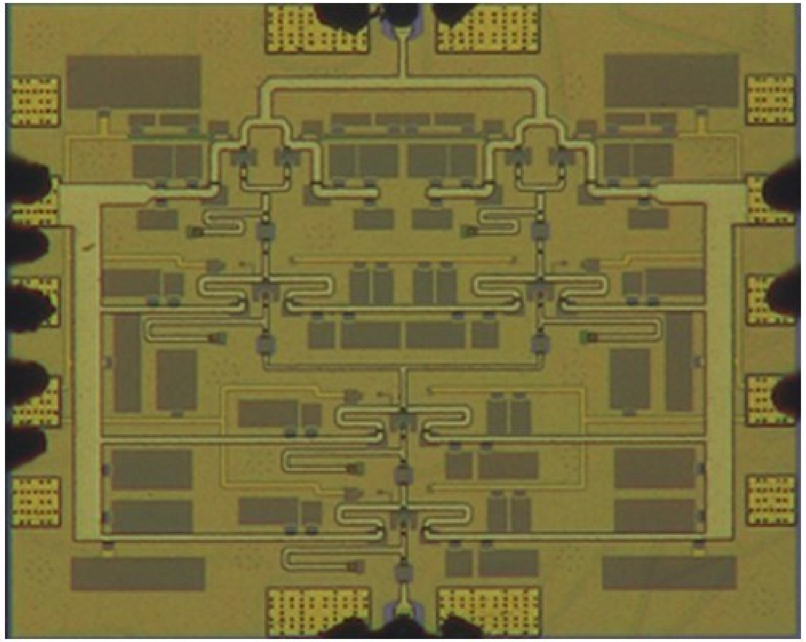
Ahmed et al, 2020 IMS, 2020 EuMIC, 2021 IMS, 2021 RFIC
Teledyne 250nm InP HBT technology



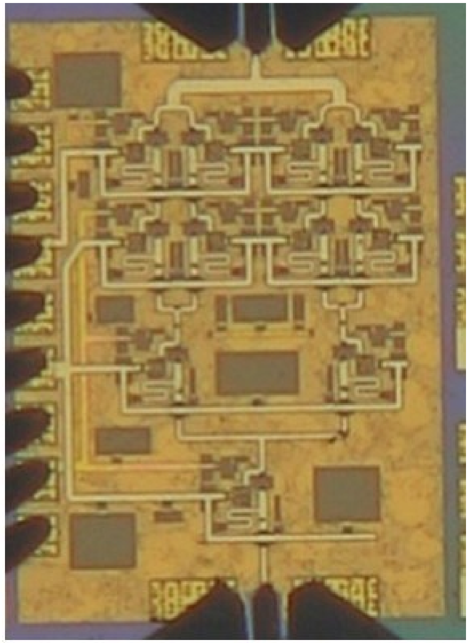
140GHz, 20.5dBm, 20.8% PAE



130GHz, 200mW, 17.8% PAE



194GHz, 17.4dBm, 8.5% PAE



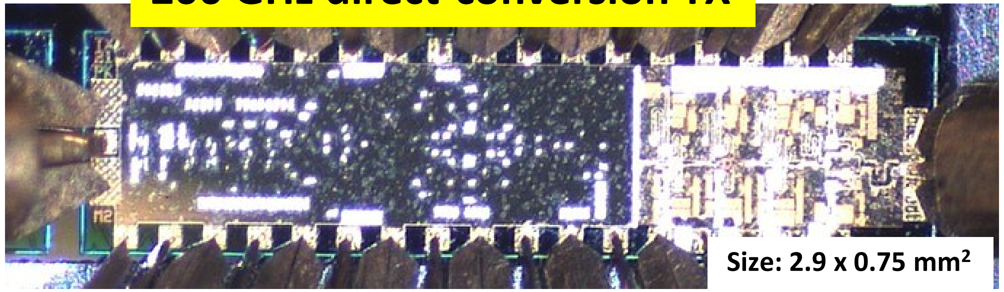
266GHz, 16.8dBm, 4.0% PAE

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

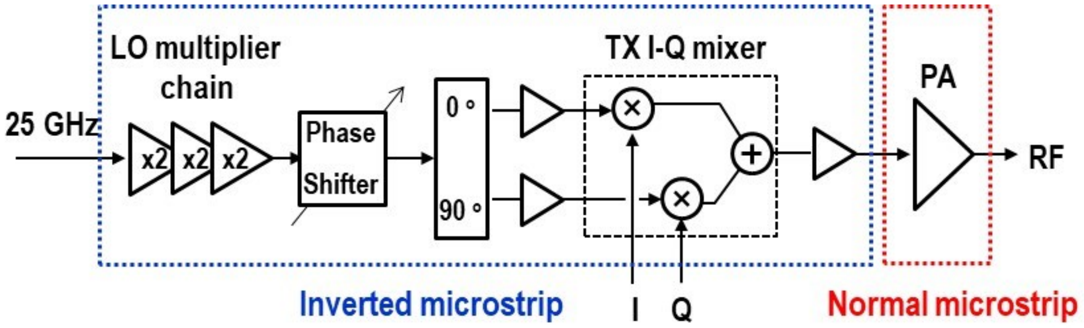
210 GHz Transmitter and Receiver ICs

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

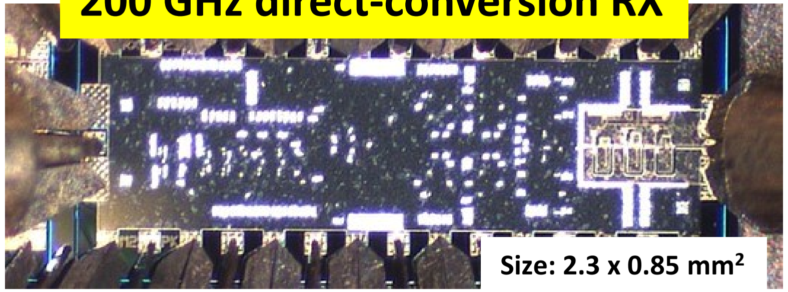
200 GHz direct-conversion TX



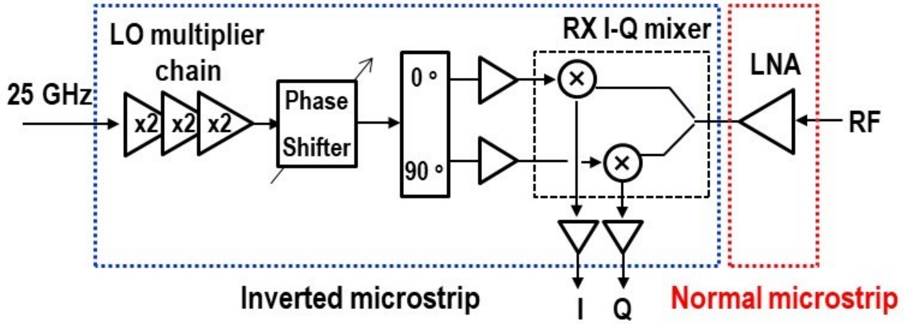
Size: 2.9 x 0.75 mm^2

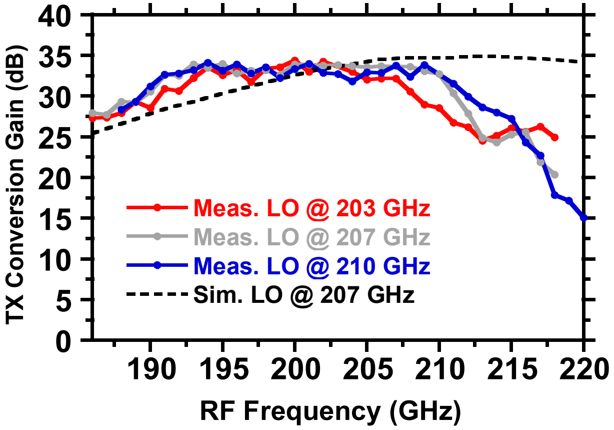


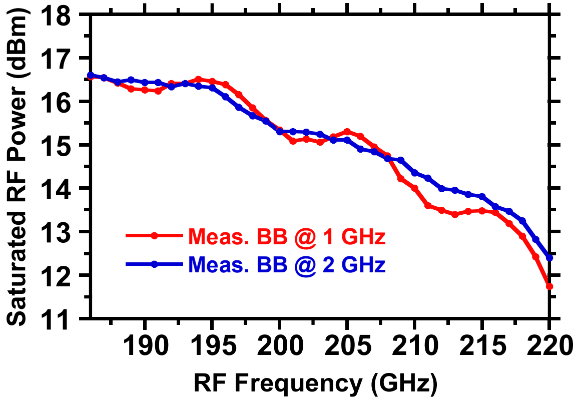
200 GHz direct-conversion RX

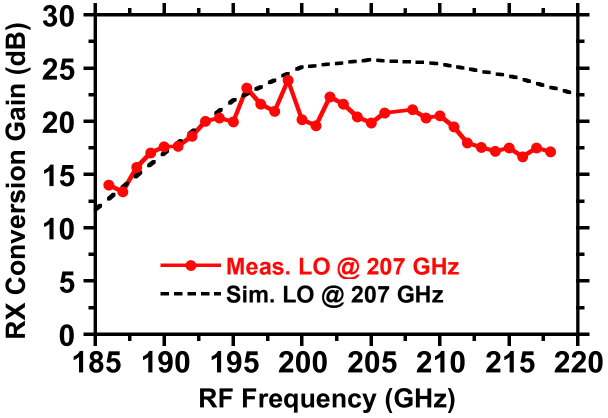


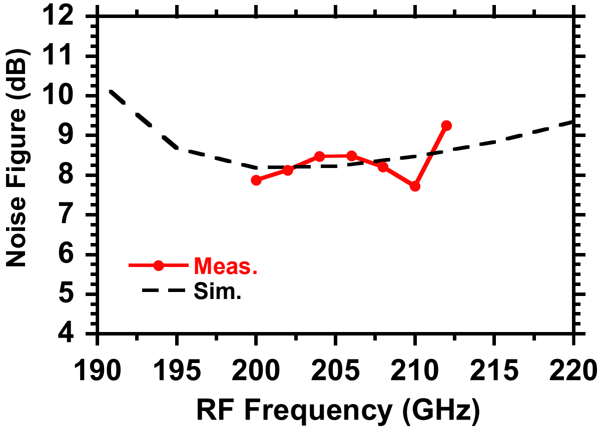
Size: 2.3 x 0.85 mm^2







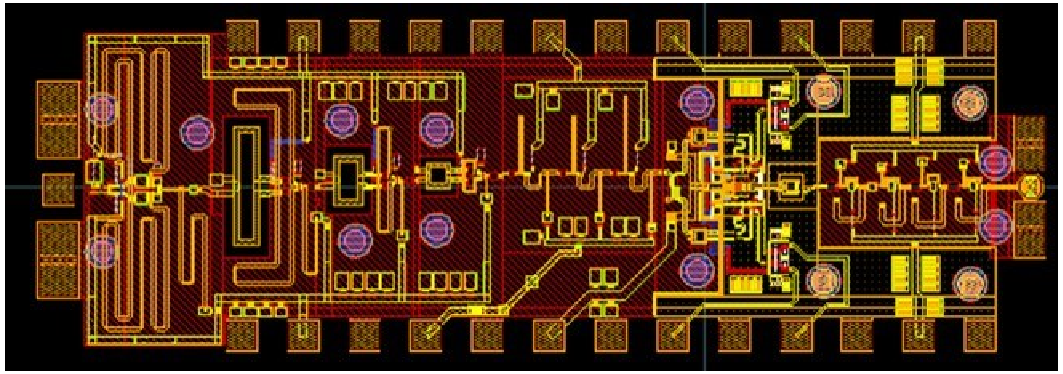




280GHz transmitter and receiver IC designs

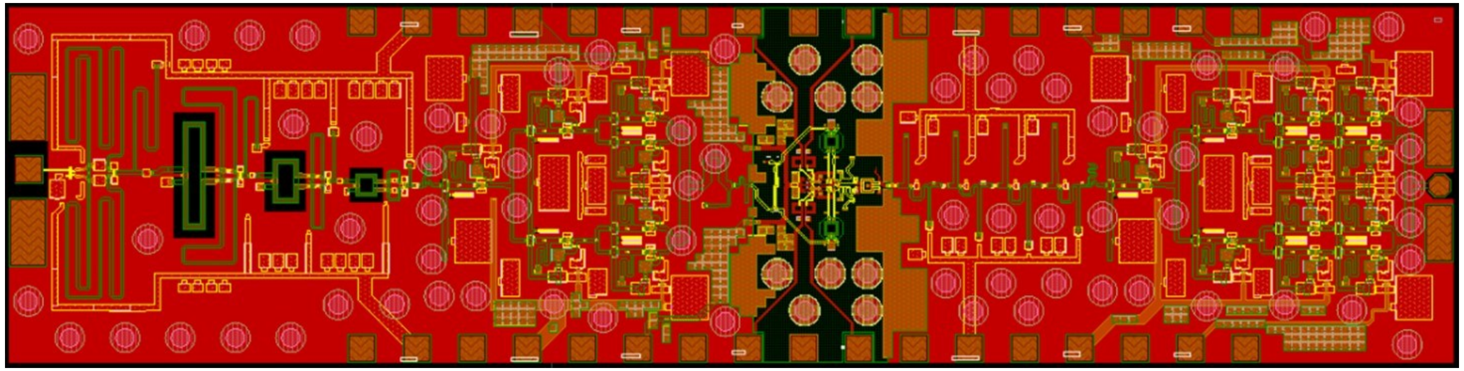
Solyu, Alz, Ahmed, Seo; UCSB/Sungkyunkwan
Teledyne 250nm InP HBT technology

Receiver



simulations: 11dB noise figure, 40GHz bandwidth

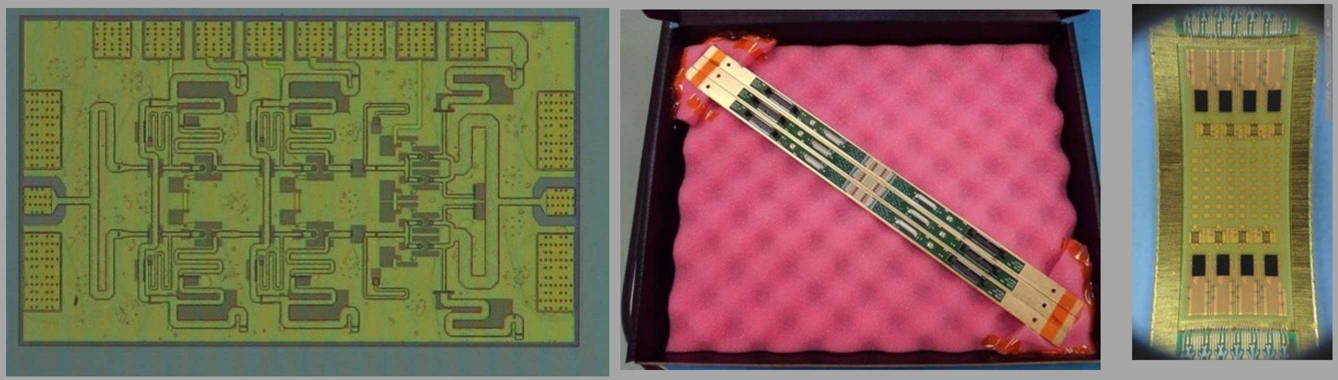
Transmitter



simulations: 17dB saturated output power.

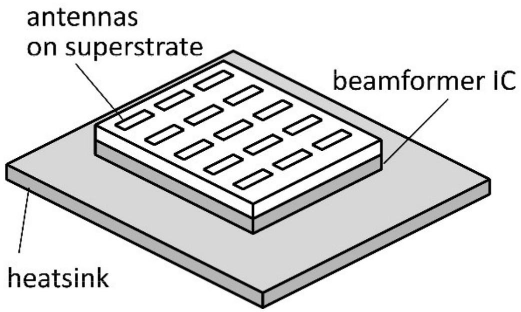
Application: point-point MIMO backhaul links

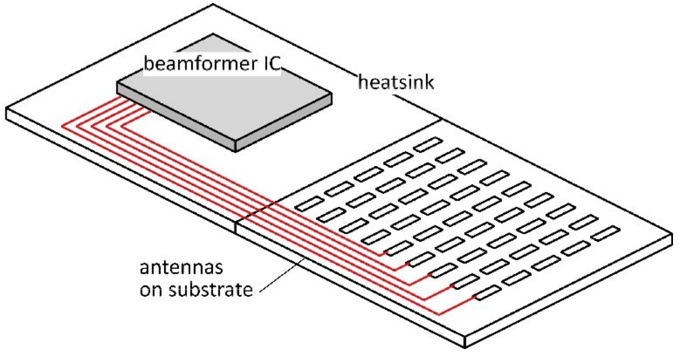
140 GHz
Array Modules



The mm-wave module design problem

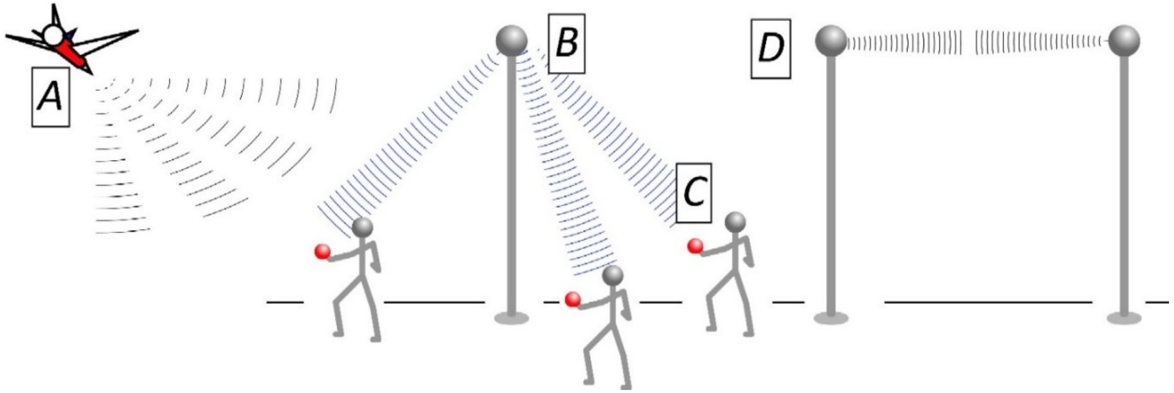
How to make the IC electronics fit ?
How to avoid catastrophic signal losses ?
How to remove the heat ?

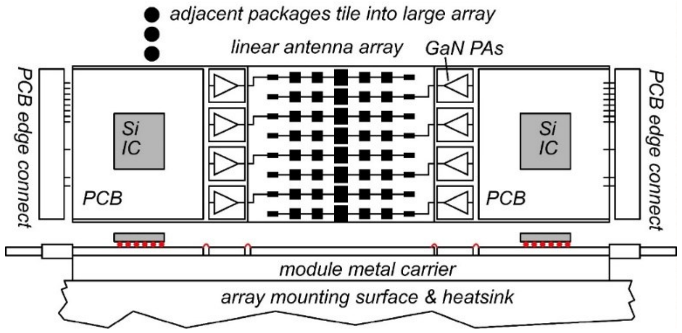


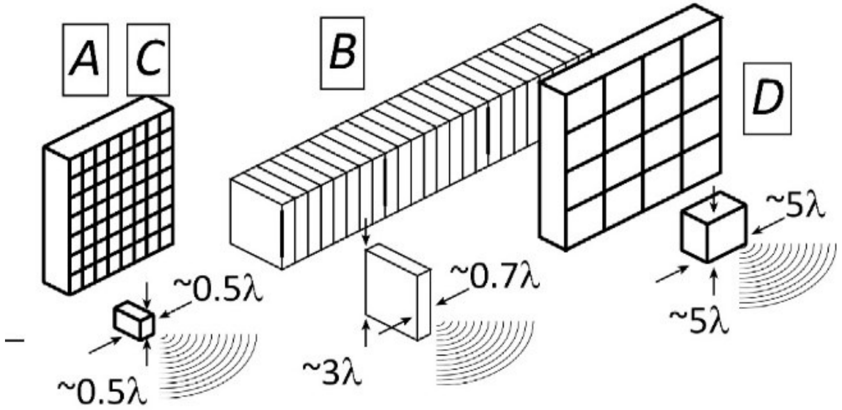


Not all systems steer in two planes...
...some steer in only one.

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





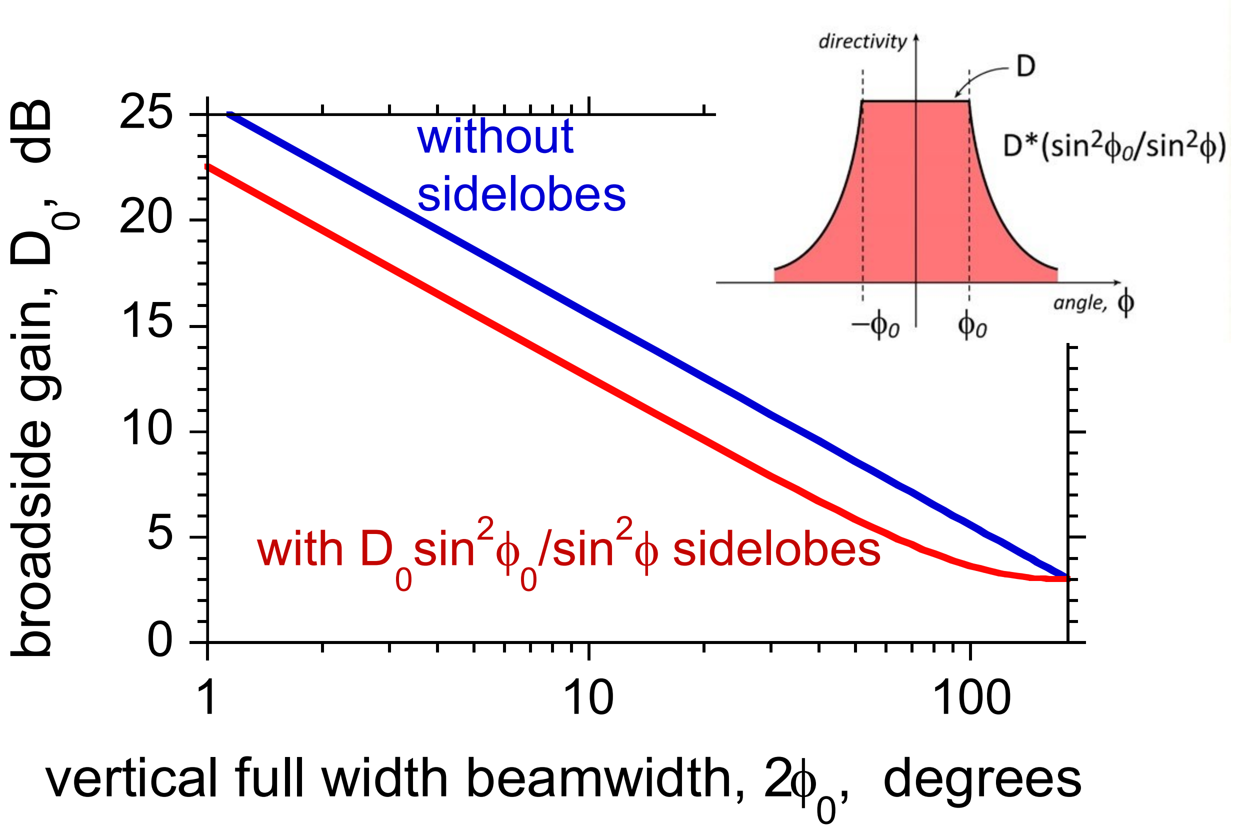


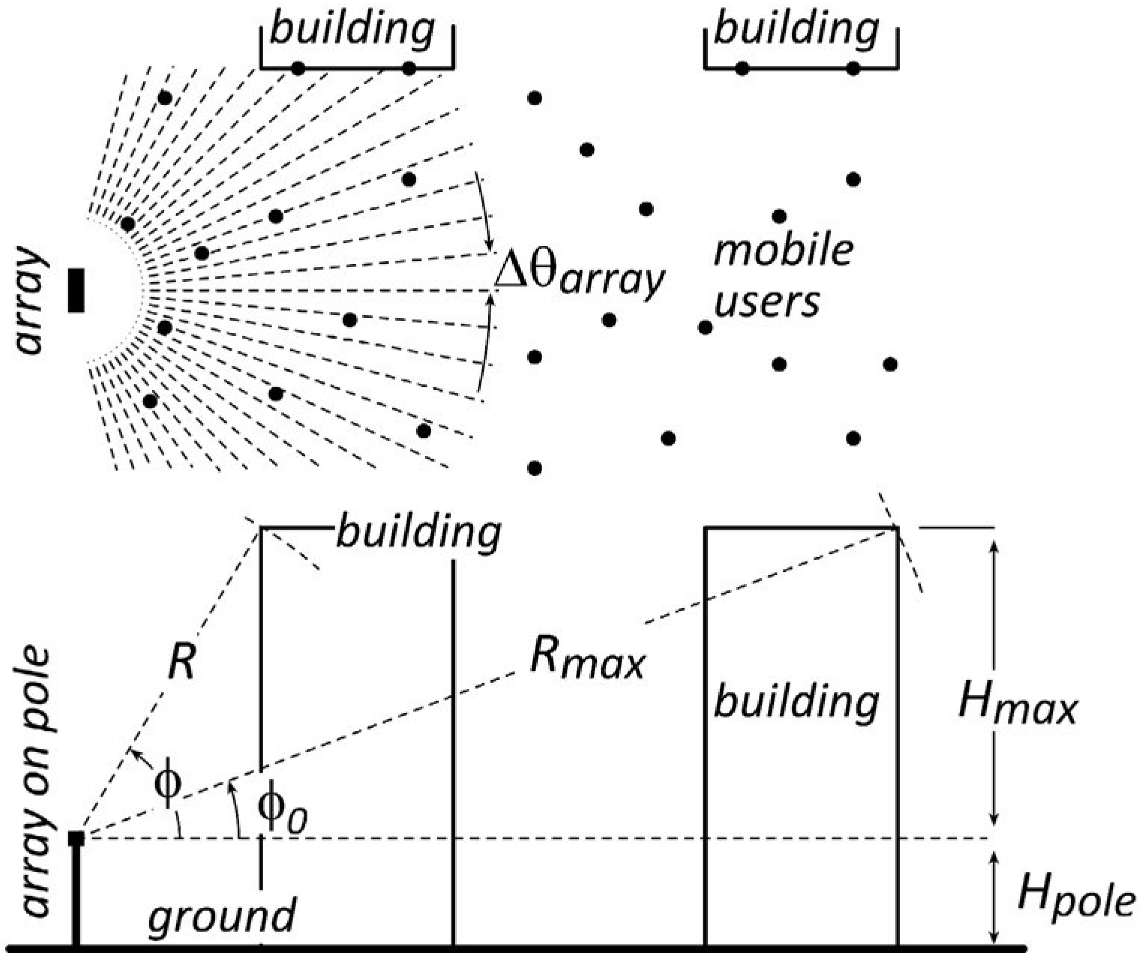
Do we need 2D arrays ? 1D steering might be fine.

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

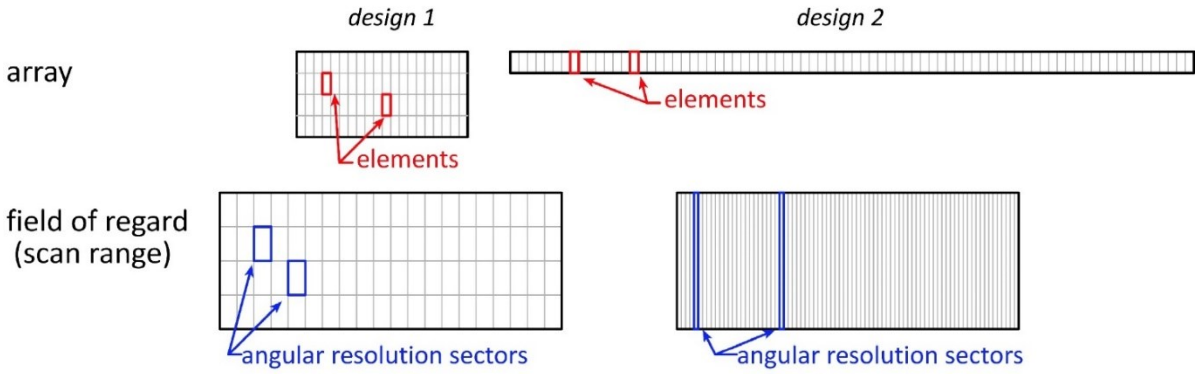
Providing sidelobes reduces broadside gain by less than 3dB.

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





2D vs. 1D: user spatial distribution

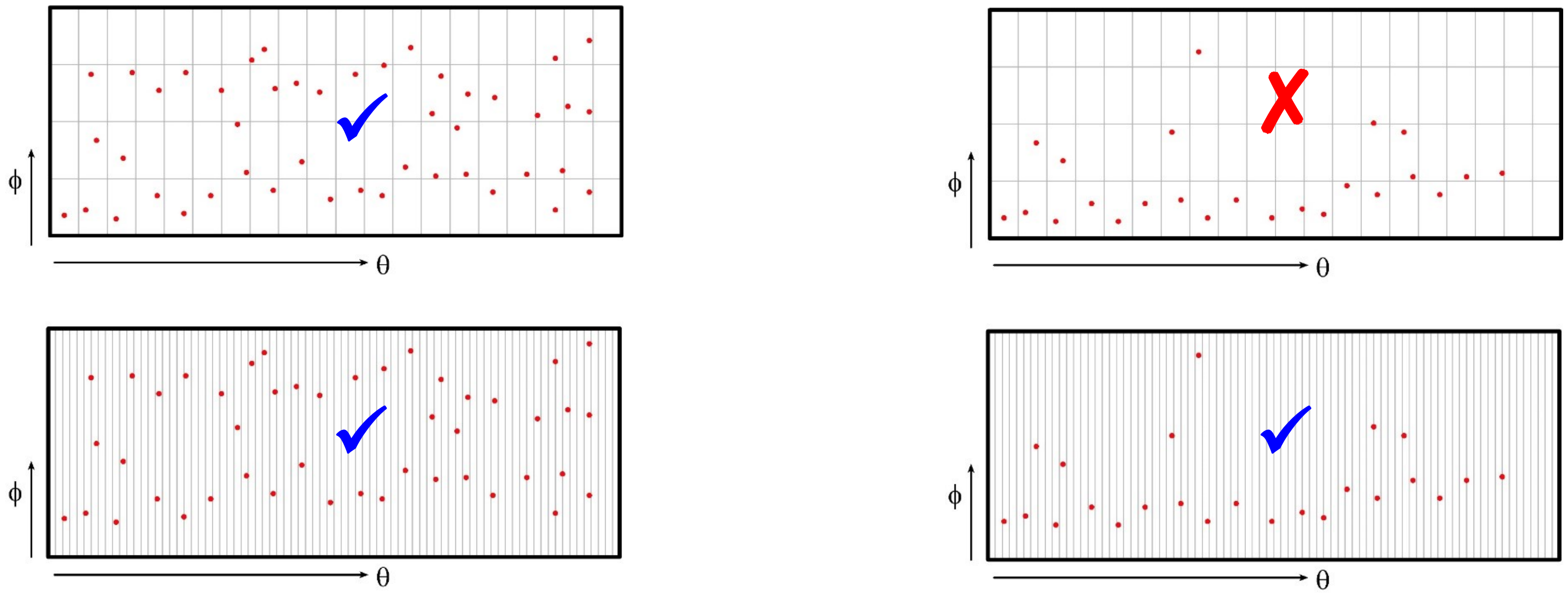


uniform horizontal & vertical user distributions

uniform horizontal, nonuniform vertical

design 1: 2D array

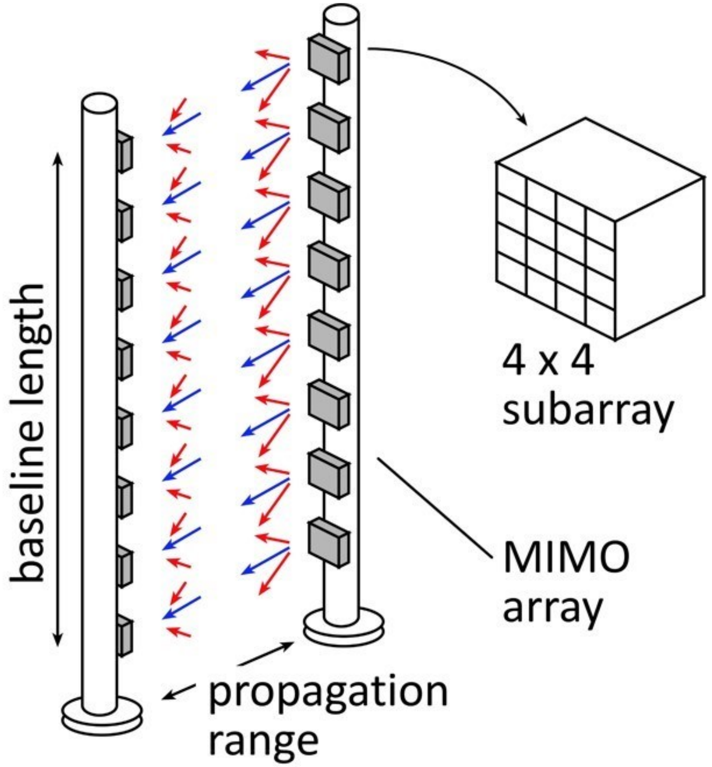
design 2: 1D array

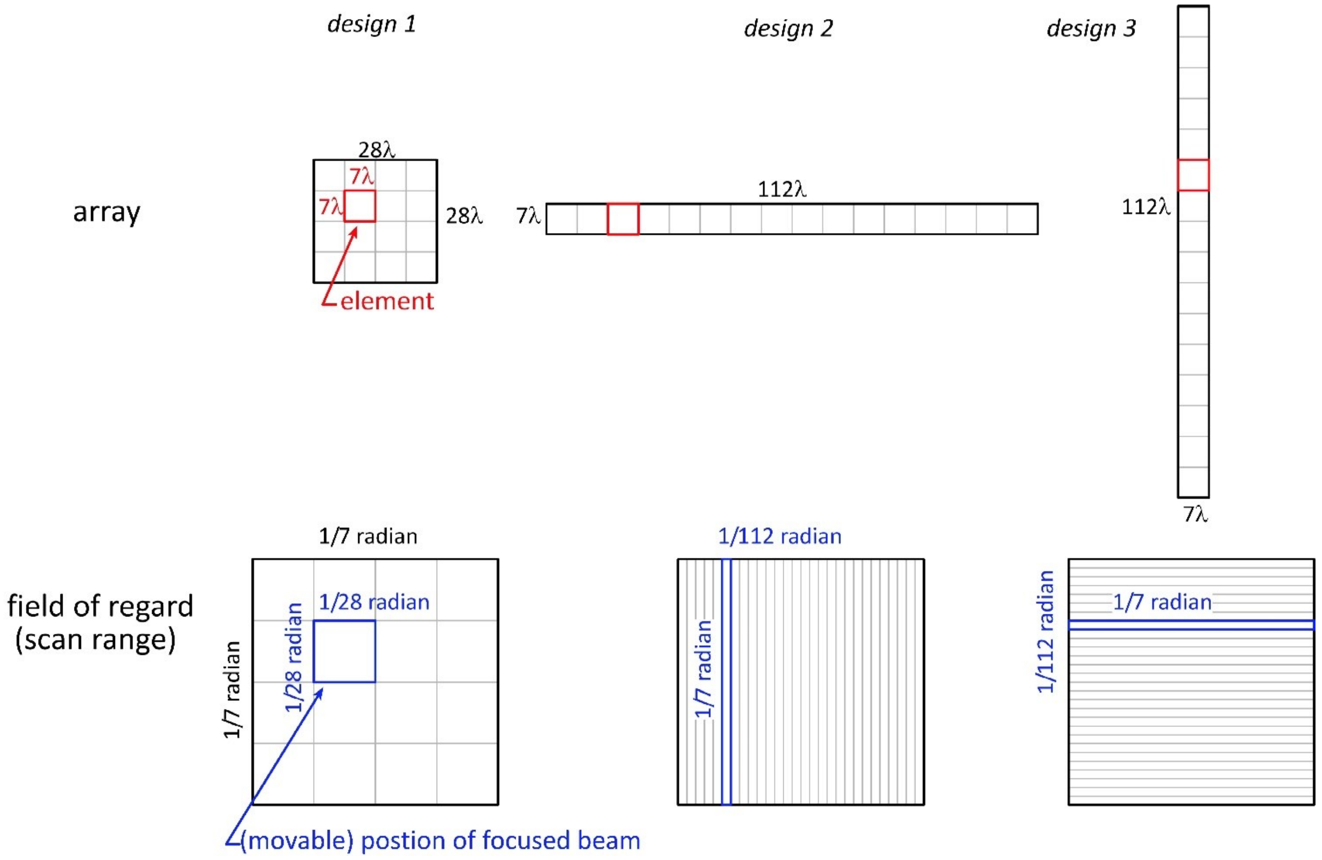


Spatial distribution of users, and of scattering objects, guides choice of array geometry.

1D or 2D subarray for backhaul ?

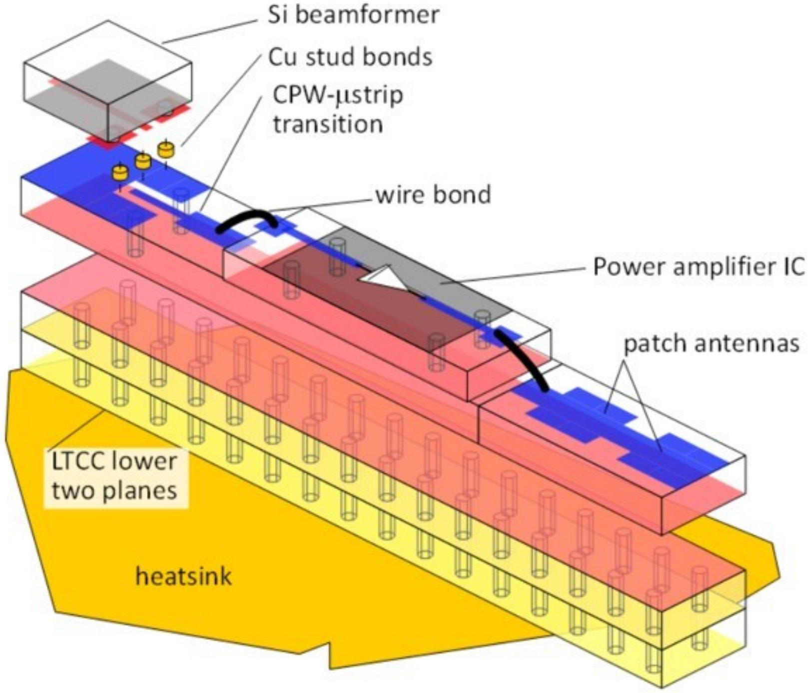
Should we use 4x4 array, 1x16, or 16x1 array ?
All provide same system link budget, same # RF channels, same angular scanning range.



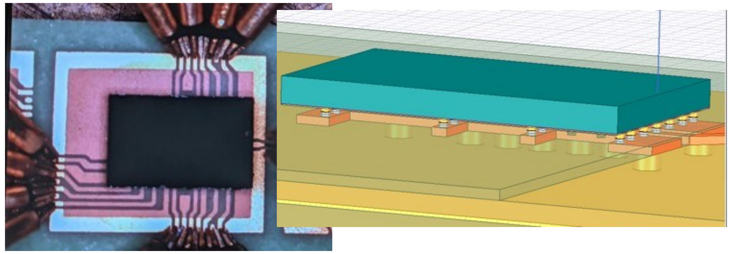


Spatial distribution of users, and of scattering objects, guides choice of array geometry.

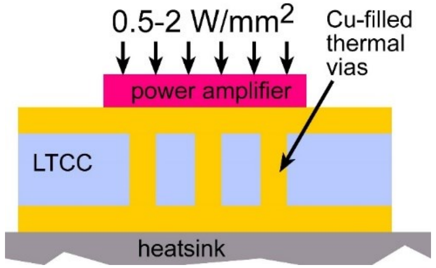
140GHz hub: packaging challenges



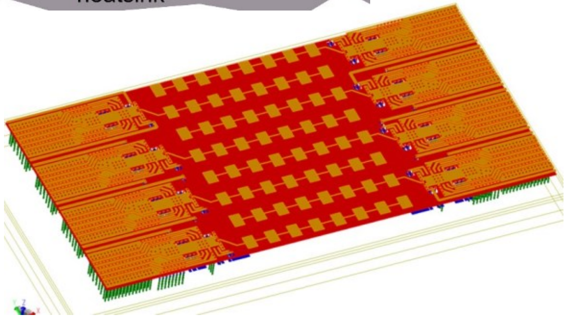
IC-package interconnects
Difficult at > 100 GHz



Removing heat
Thermal vias are marginal

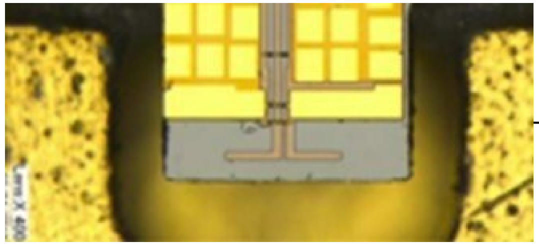


Interconnect density
Dense wiring for DC, LO, IF, control.
Hard to fit these all in.

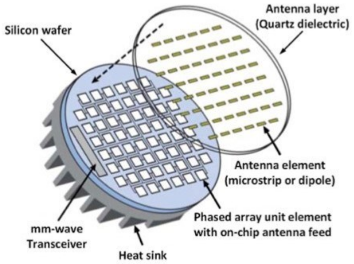


Economies of scale
Advanced packaging standards require sophisticated tools
High-volume orders only
Hard for small-volume orders (research, universities)
Packaging industry is moving offshore

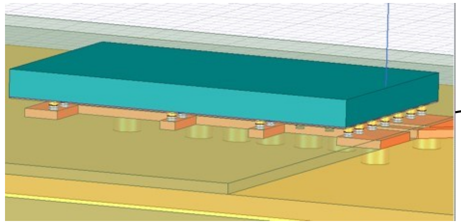
100-300GHz IC-package connections

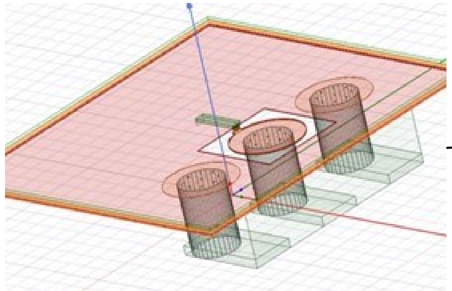


Deal, IEEE Trans THz, Sept 2011



G. Rebeiz

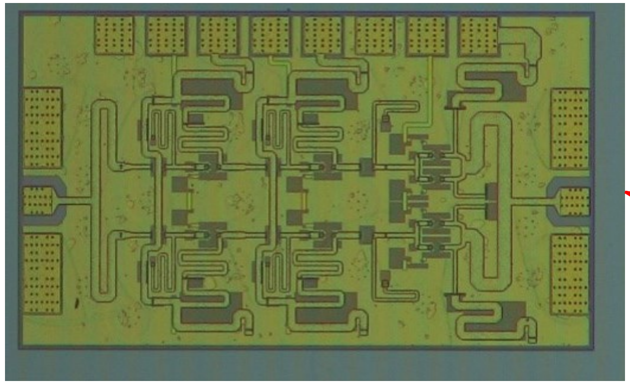




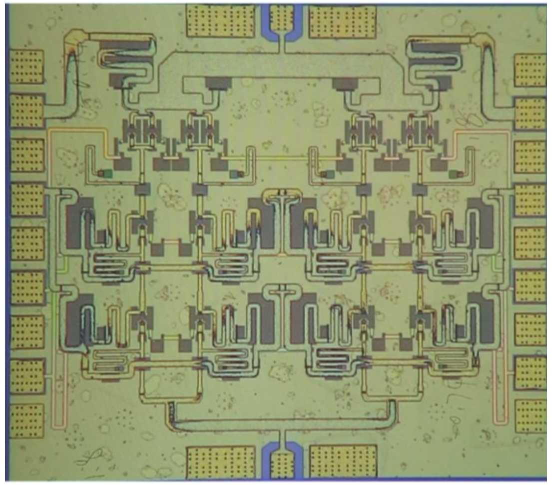
type	Frequency	technology	cost	heatsinking
micromachined waveguide interface	1000 GHz	Research. Cheap one day ?	**high** ✗	good
ribbon, mesh bond	200 GHz	Handcrafted.	**high** ✗	good
patch antennas on superstrate	1000 GHz	Straightforward	low	good
Cu stud flip-chip	>200 GHz	Industry standard	low	ok, **marginal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

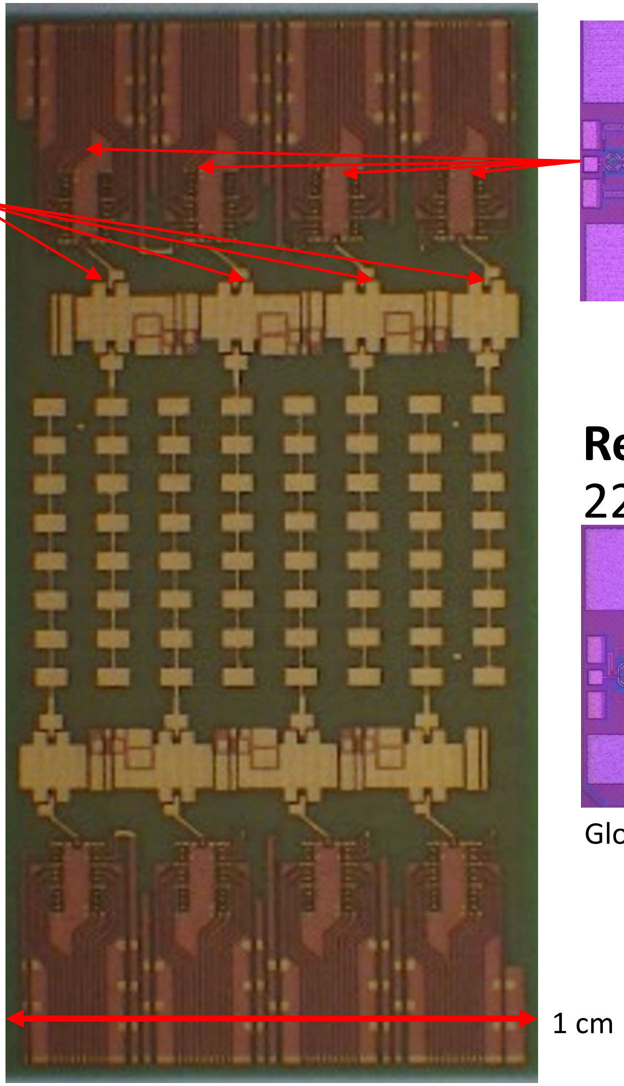


190mW InP Power Amplifier
16.7% PAE



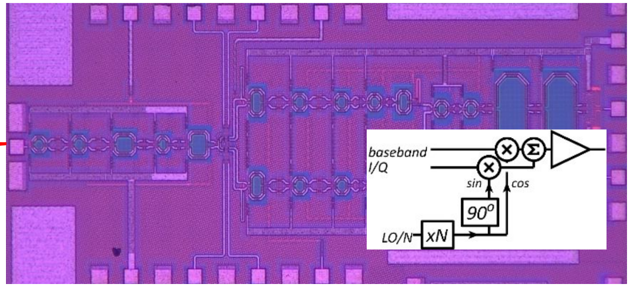
Teledyne InP HBT

LTCC Array module

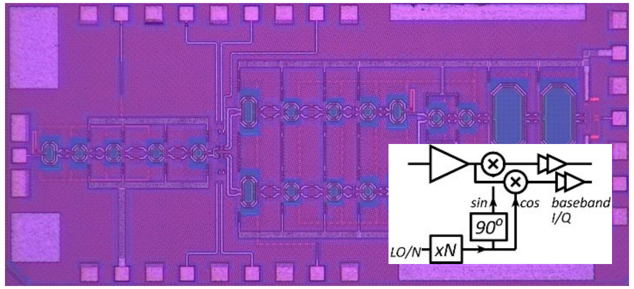


Kyocera

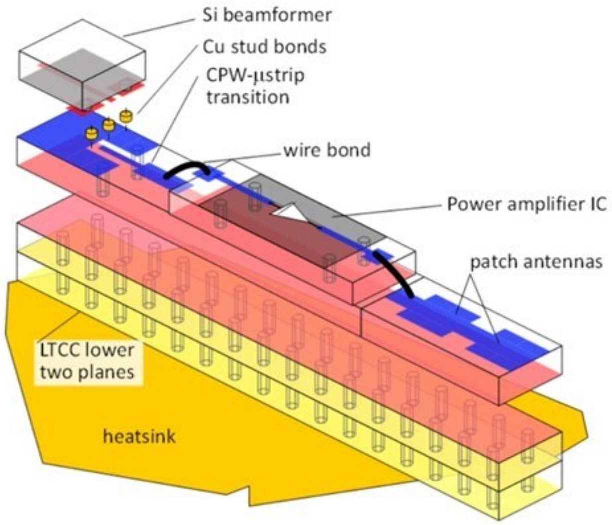
CMOS Transmitter IC
22nm SOI CMOS.



Receiver IC
22nm SOI CMOS.



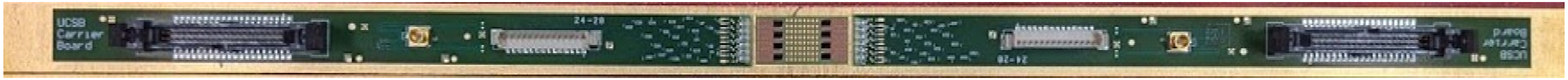
GlobalFoundries 22nm SOI CMOS

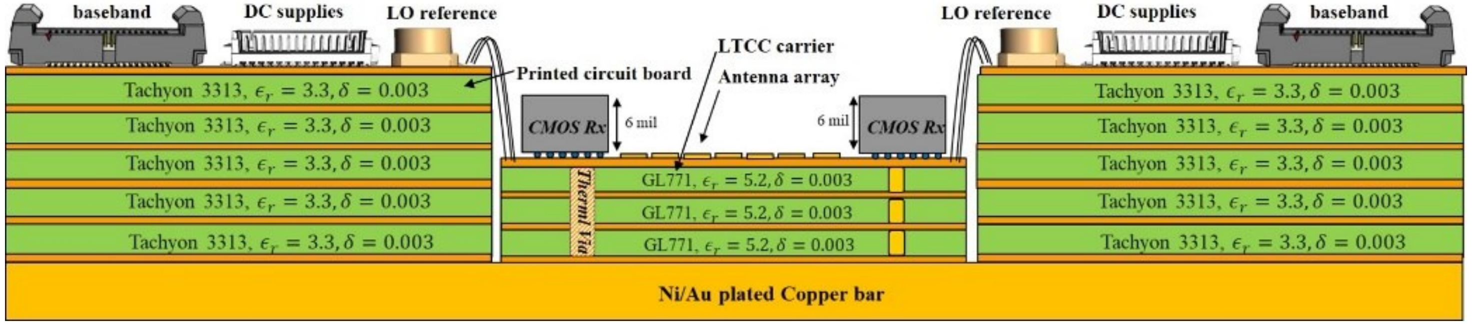


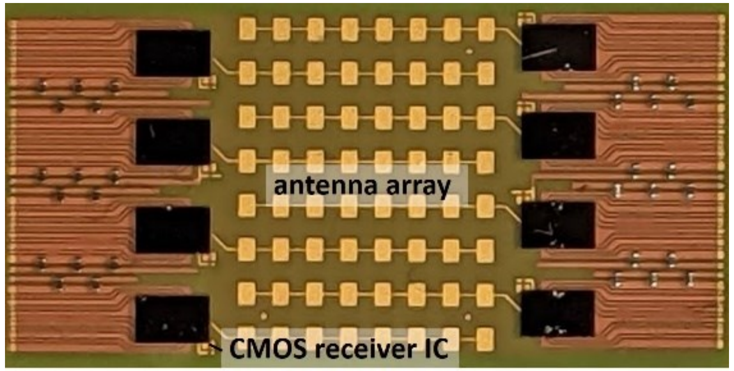
Farid, Ahmed, Rodwell, UCSB; Flynn, Dunn, Niknejad, Nikolic, BWRC; Rebeiz, UCSD

135GHz 8-channel MIMO hub array tile modules

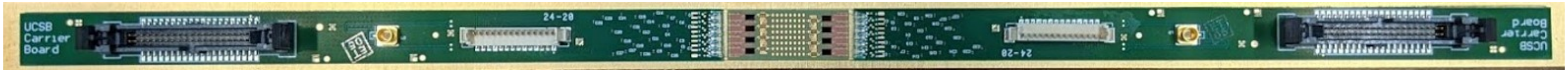
Receiver: A. Farid et. al, 2021 IEEE BCICTS Symposium

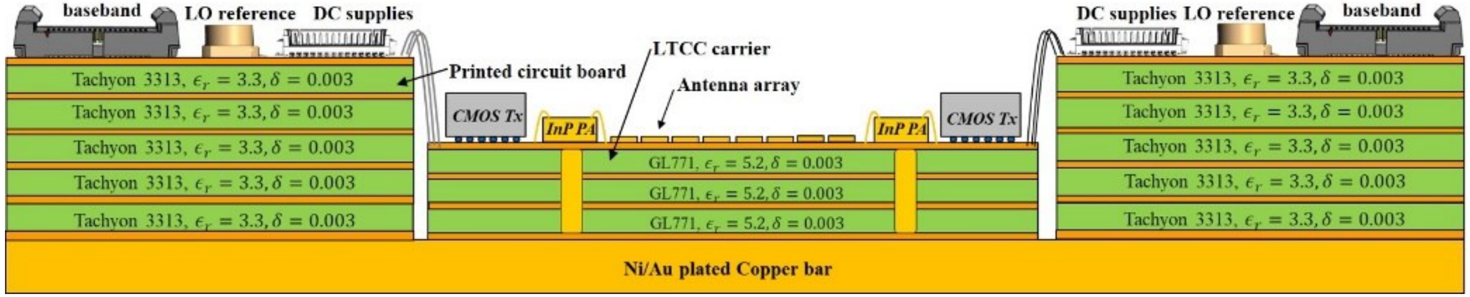


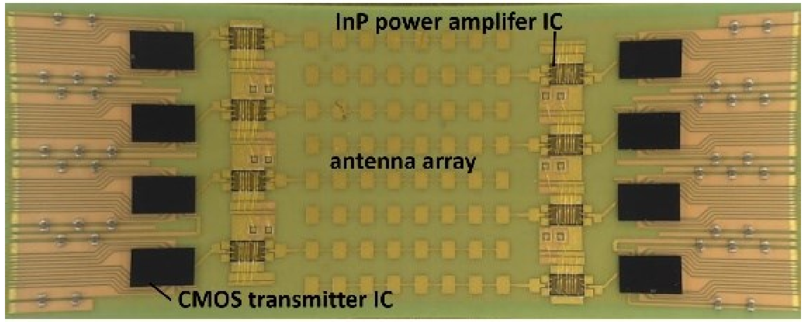




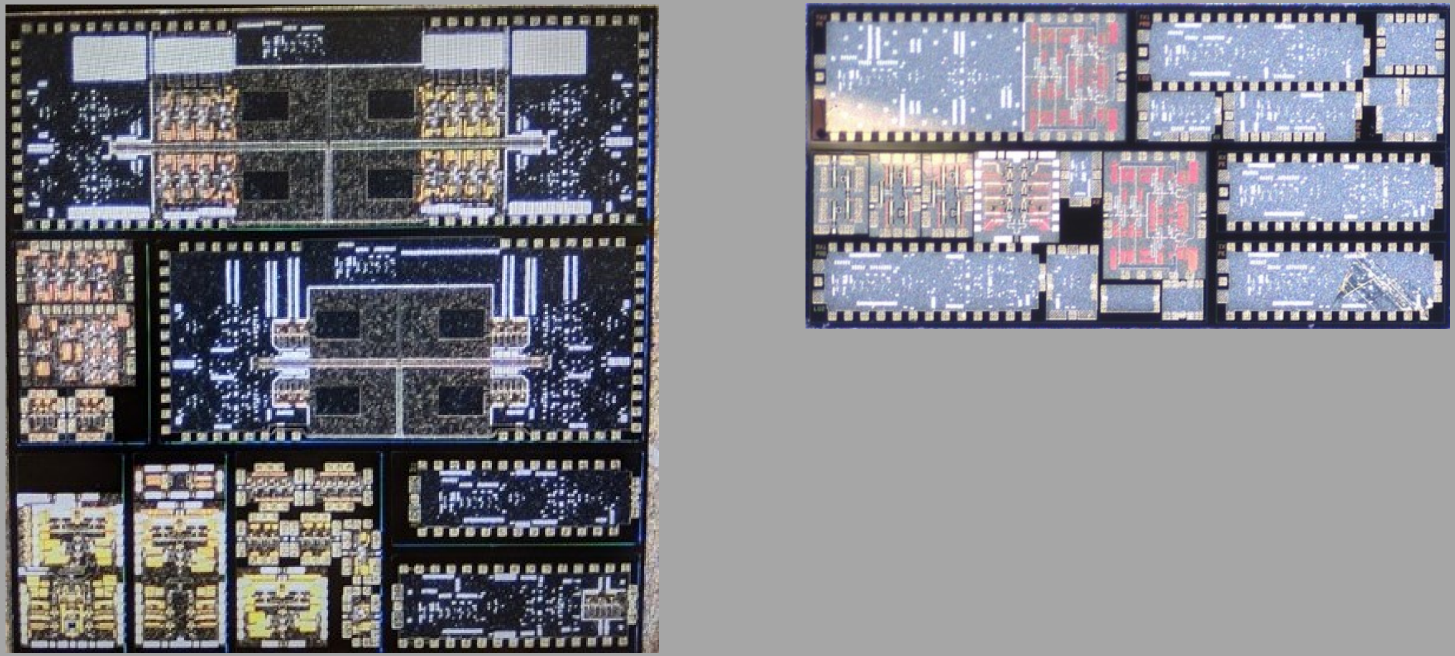
Transmitter: Results to be submitted



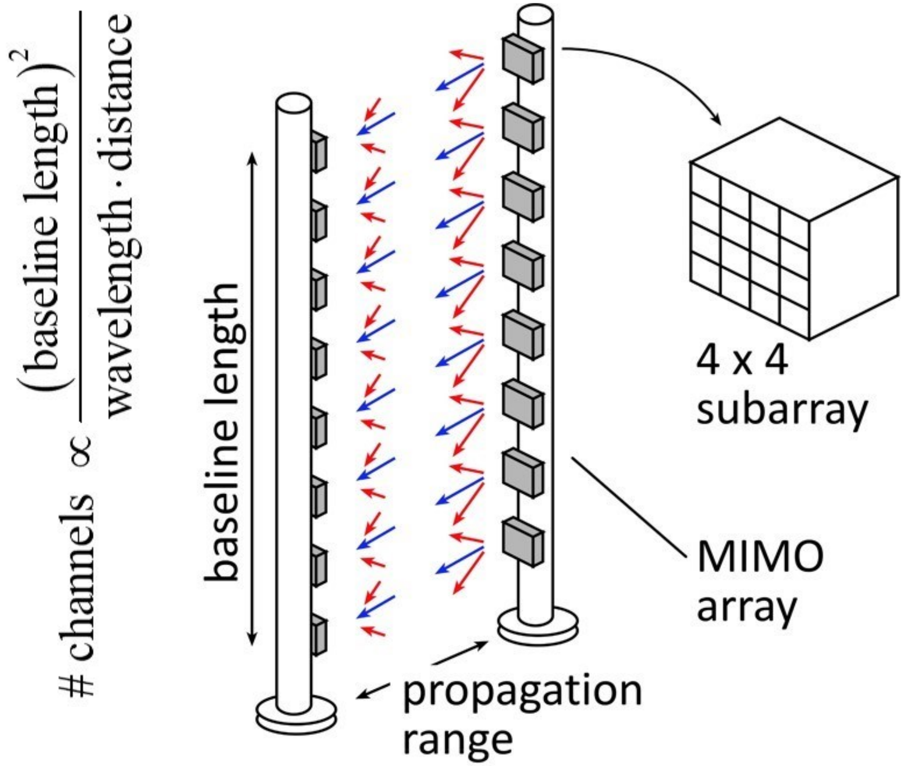


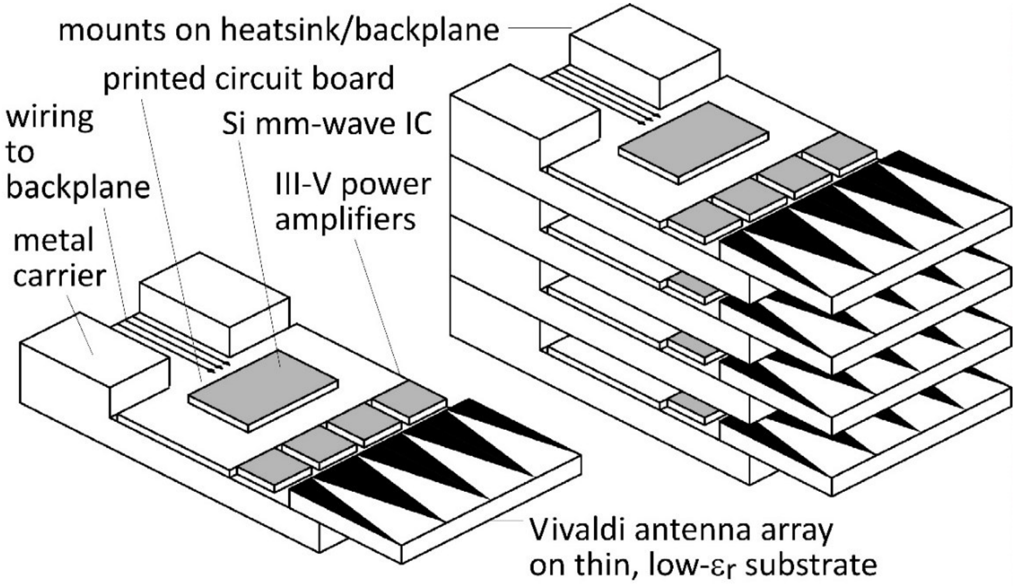


210 GHz and 280 GHz Array Modules



210 GHz MIMO backhaul demo

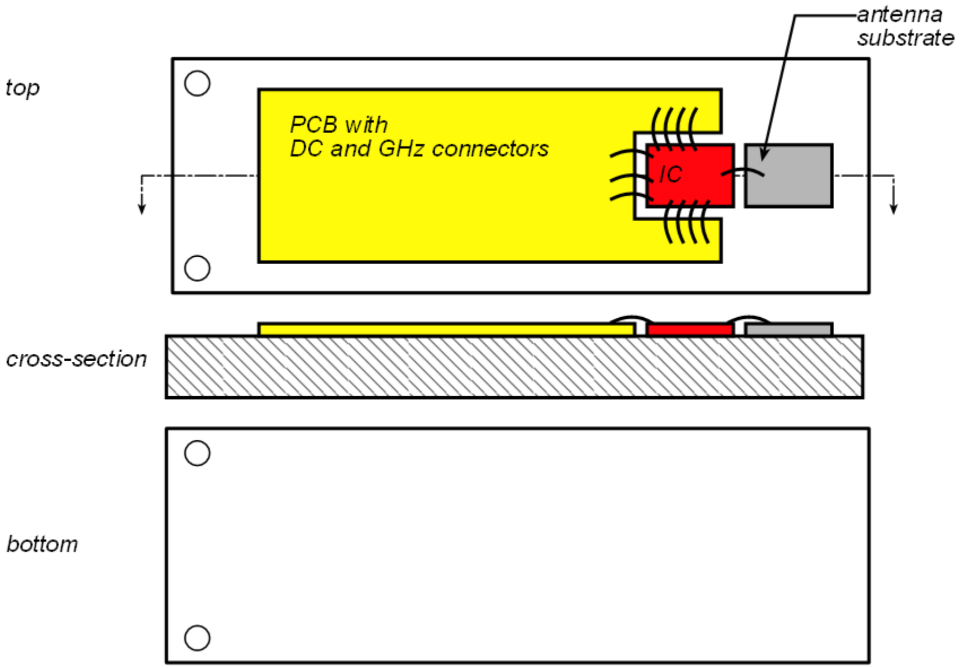


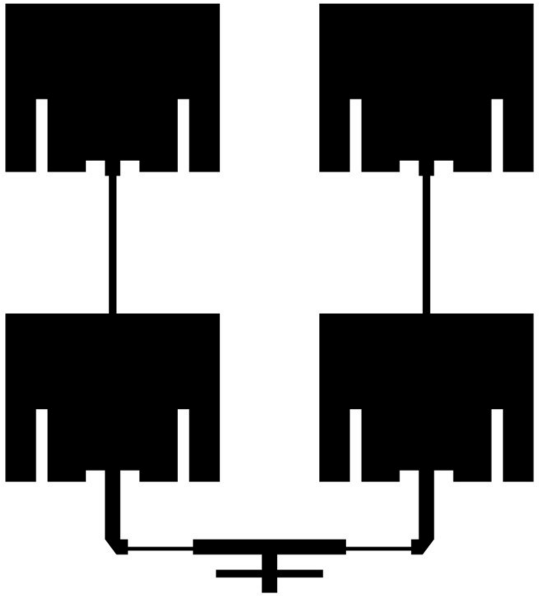


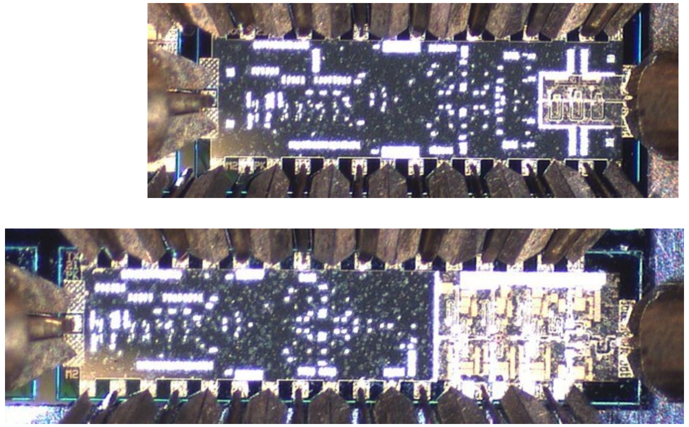
8-element MIMO array
3.1 m baseline for 500m link.
80Gb/s/subarray→ 640Gb/s total
4 × 4 sub-arrays → 8 degree beamsteering

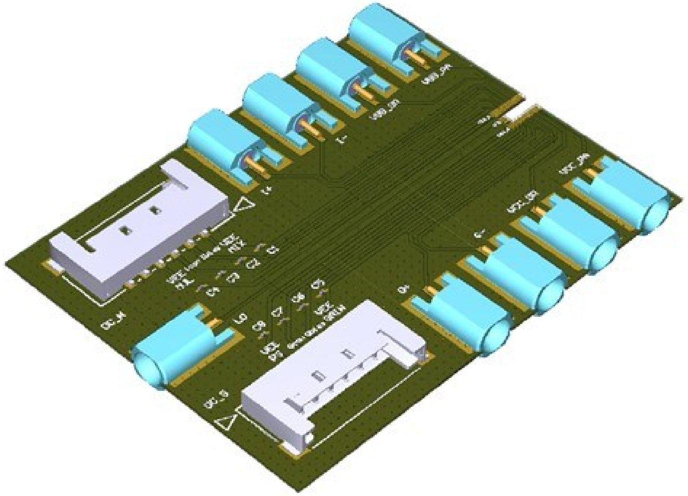
Key link parameters
500 meters range in 50 mm/hr rain; 23 dB/km
20 dB total margins:
packaging loss, obstruction, operating, design, aging
PAs: 63mW =P_{1dB} (per element)
LNAs: 6dB noise figure

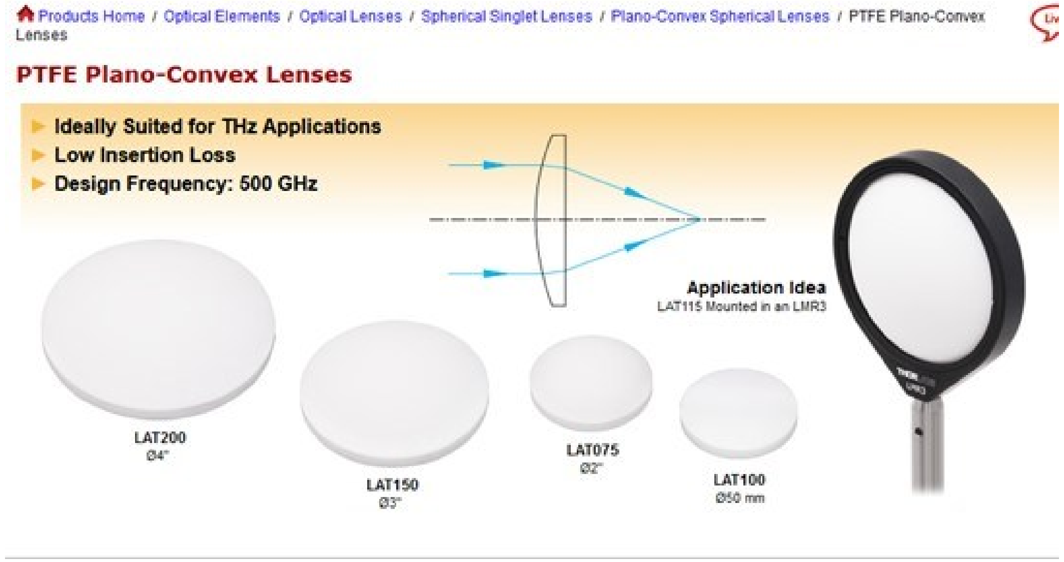
210GHz Module: Single-Channel Backup Plan











Products Home / Optical Elements / Optical Lenses / Spherical Singlet Lenses / Plano-Convex Spherical Lenses / PTFE Plano-Convex Lenses

PTFE Plano-Convex Lenses

- Ideally Suited for THz Applications
- Low Insertion Loss
- Design Frequency: 500 GHz

Application Idea
LAT115 Mounted in an LMR3

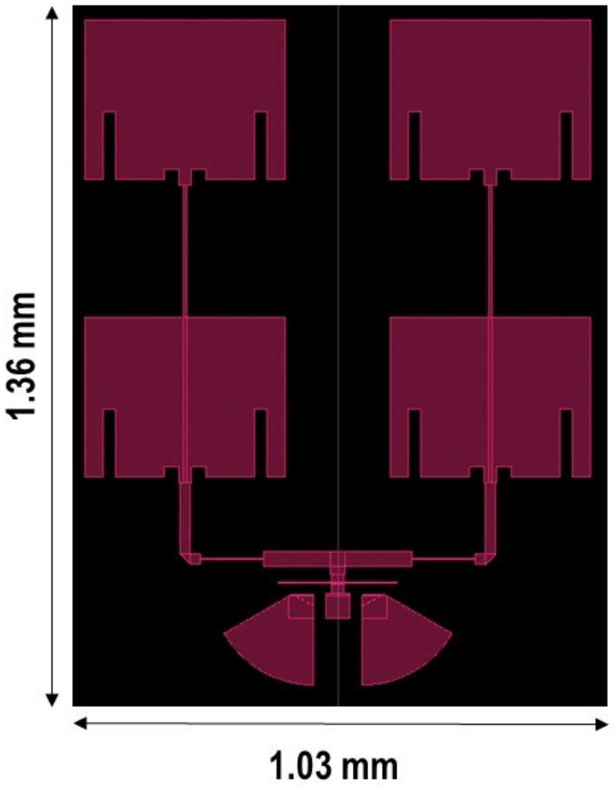
LAT200
Ø4"

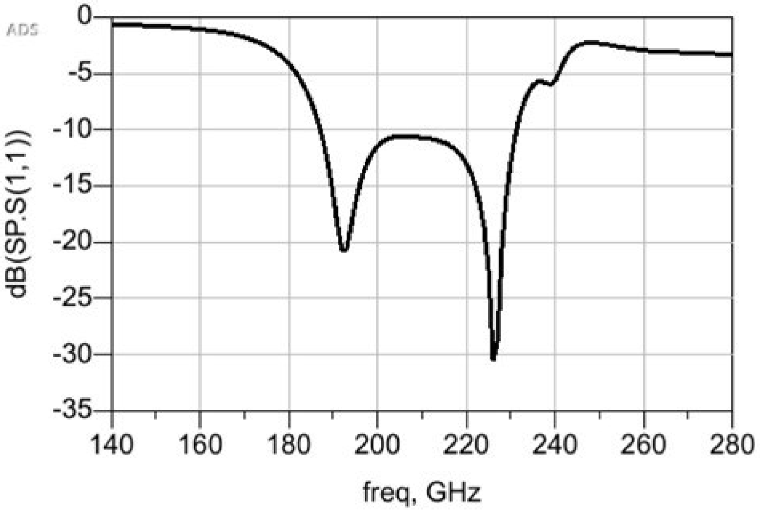
LAT150
Ø3"

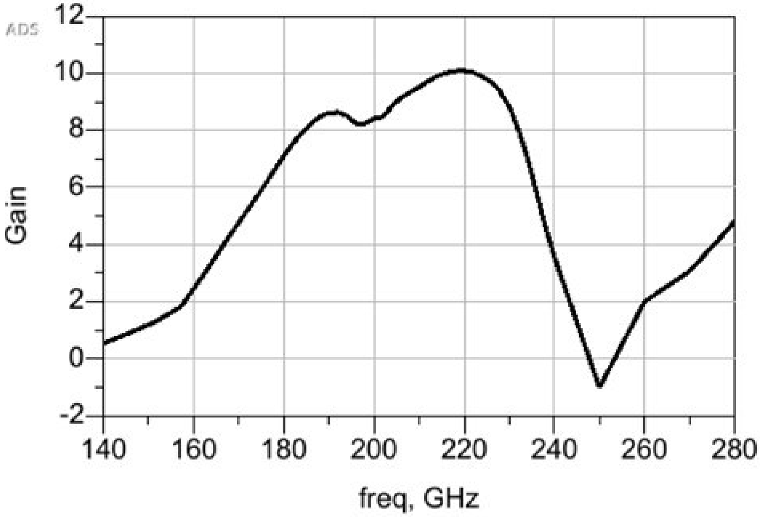
LAT075
Ø2"

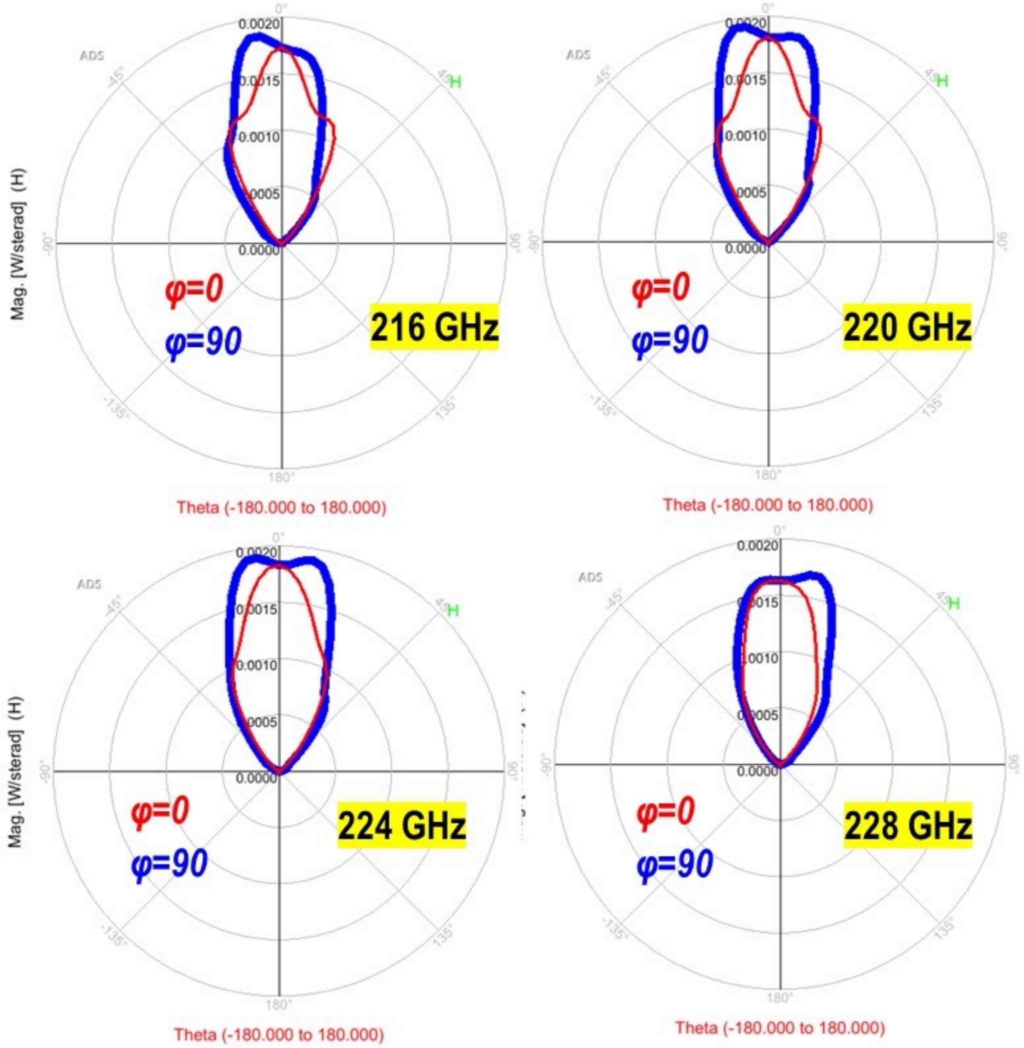
LAT100
Ø50 mm

210GHz Series Feed Antenna on 50 μm Fused Silica

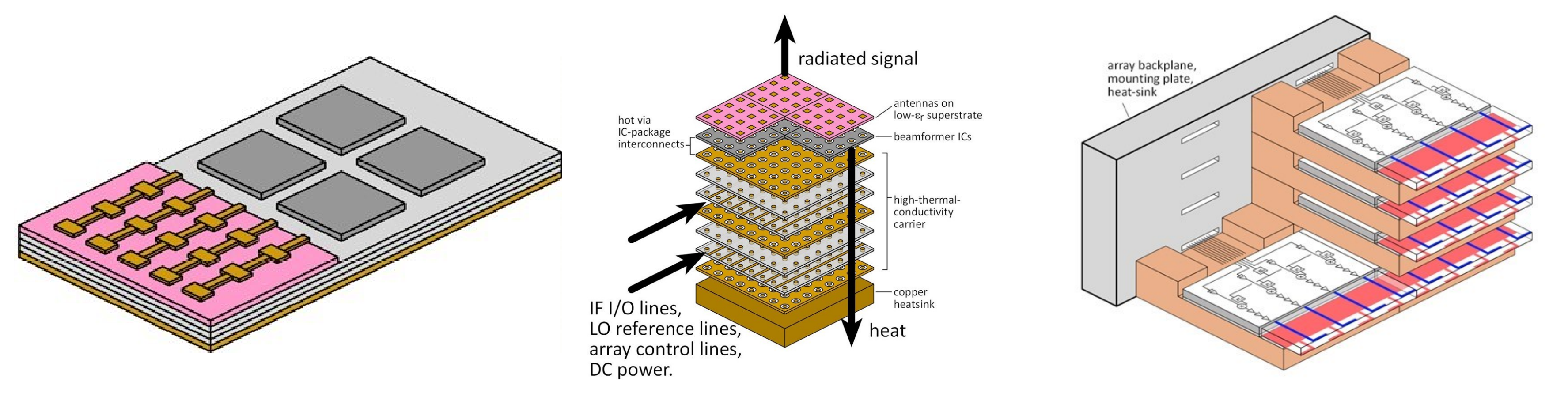






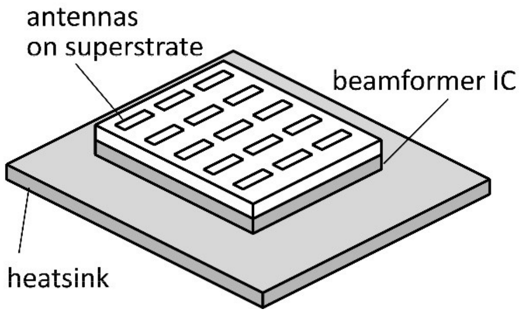


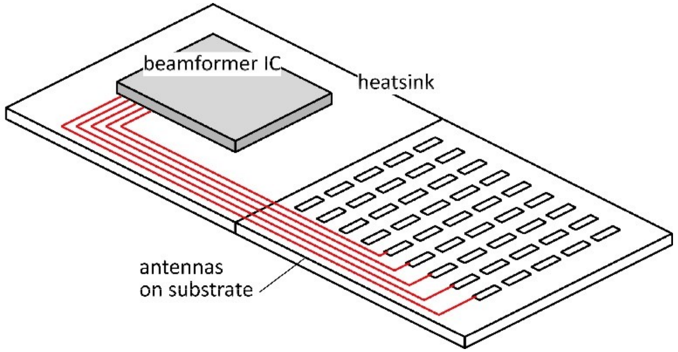
Advanced Packages



The mm-wave module design problem

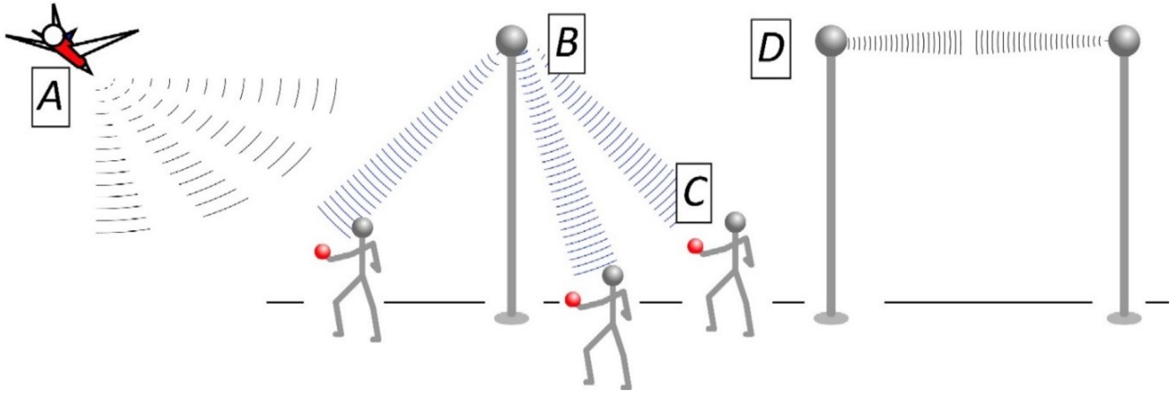
How to make the IC electronics fit ?
How to avoid catastrophic signal losses ?
How to remove the heat ?

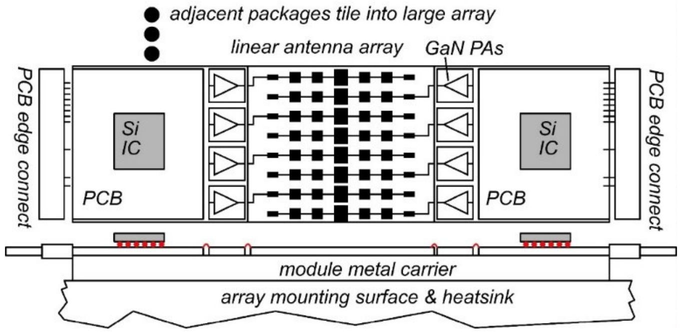


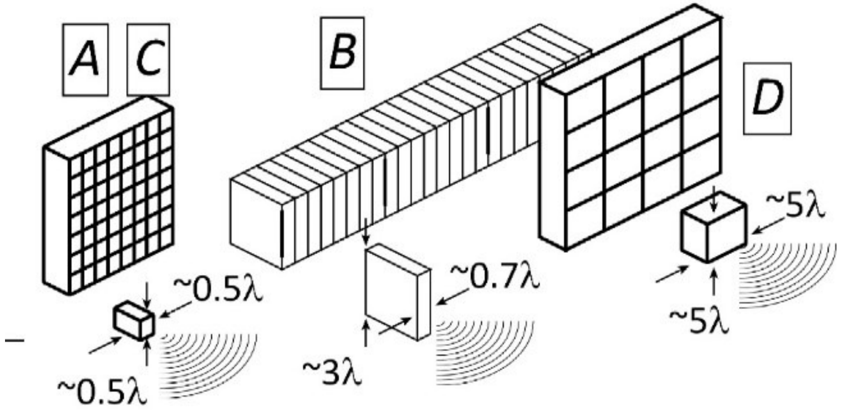


Not all systems steer in two planes...
...some steer in only one.

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





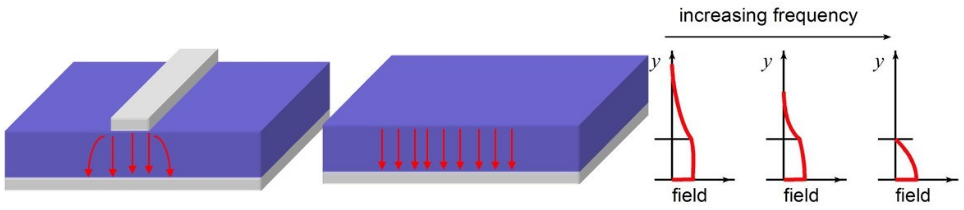


Materials for 100-300GHz Packages

Coupling loss into dielectric slab modes:

→ layers must be thinner than $\sim\lambda_o / 20\varepsilon_r^{1/2}$

→ thin, low-ε_r layers



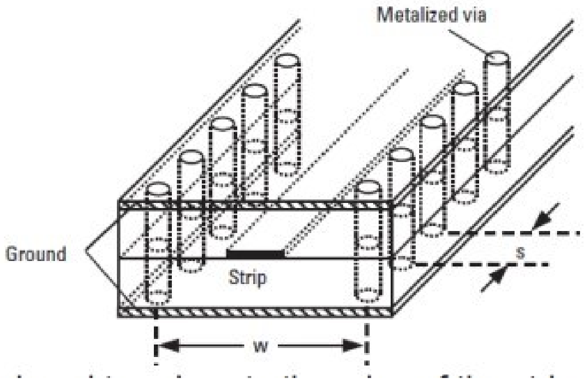
Skin loss:

→ loss (dB/mm) $\propto f^{1/2}\varepsilon_r^{1/2} / (\text{thickness})^{1/2}$

→ thick, low-ε_r layers

Stripline can't radiate

→ width, height $< \lambda_o / 2\varepsilon_r^{1/2}$



Packages for medium-to-high-power 1D arrays

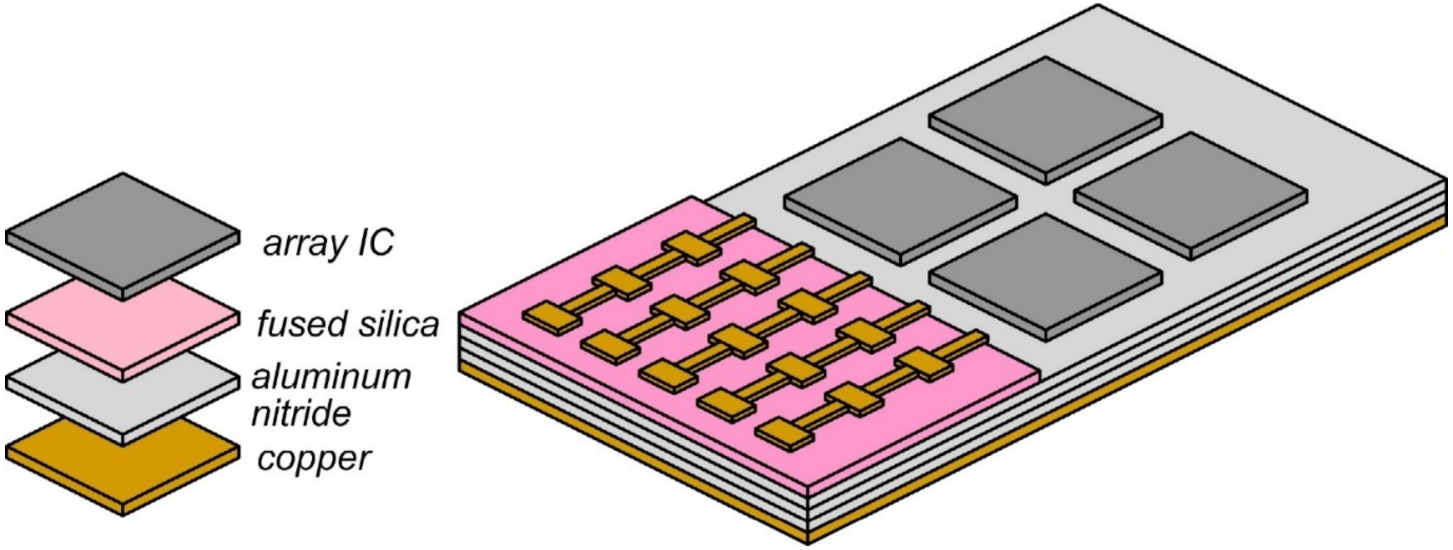
PA heatsinking: good-high thermal conductivity under ICs

Even 1D arrays are dense:

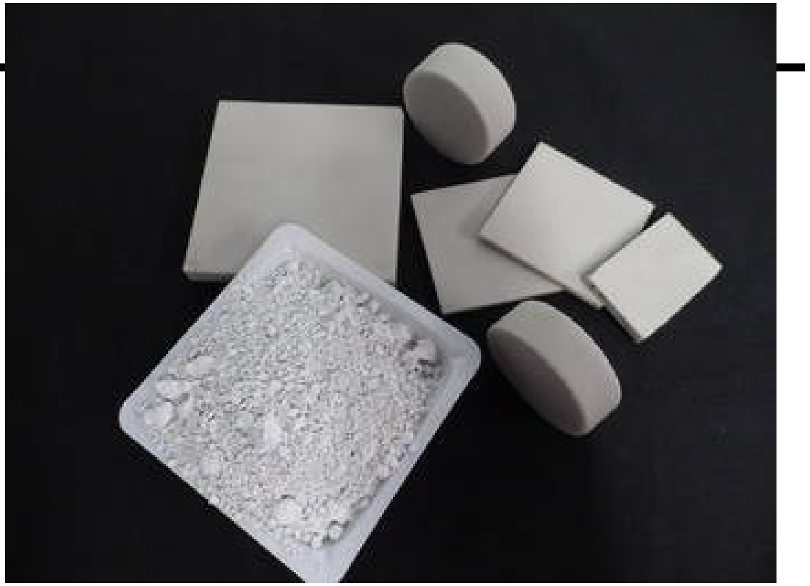
IF, power, control, LO/N lines must run under IC
need OK line losses @ DC~30GHz
→ moderate dielectric constant, high thermal K.
ceramic AlN or SiC ? (~200W/K/M)

Need high-quality 100-300GHz antennas

one thin and low-ε_r insulator plane required.
fused silica or similar.
for high-performance antennas
for 100-300GHz routing, if needed

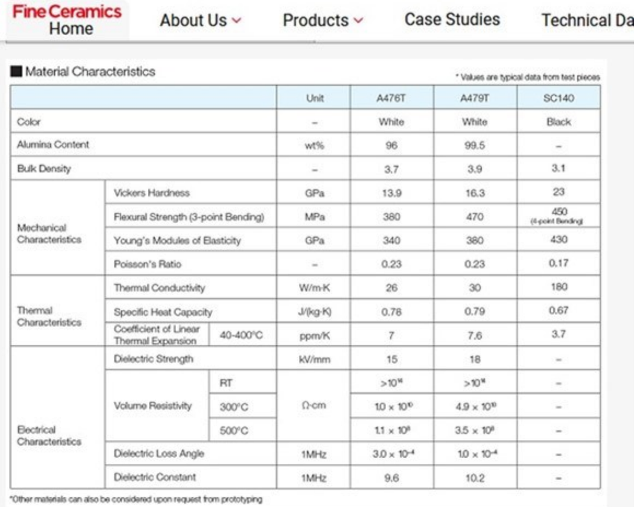


Ceramic AlN and SiC



Crystalline AlN and SiC are expensive.
Ok for high-performance DOD packages
need cheaper package material for industry, consumers

Ceramic AlN and SiC can be substantially less expensive
lower thermal conductivity
can be formed into thick layers
ceramic AlN apparently has K_{th}~100W/K/m
ceramic SiC apparently has K_{th}~180W/K/m
excellent for many packages

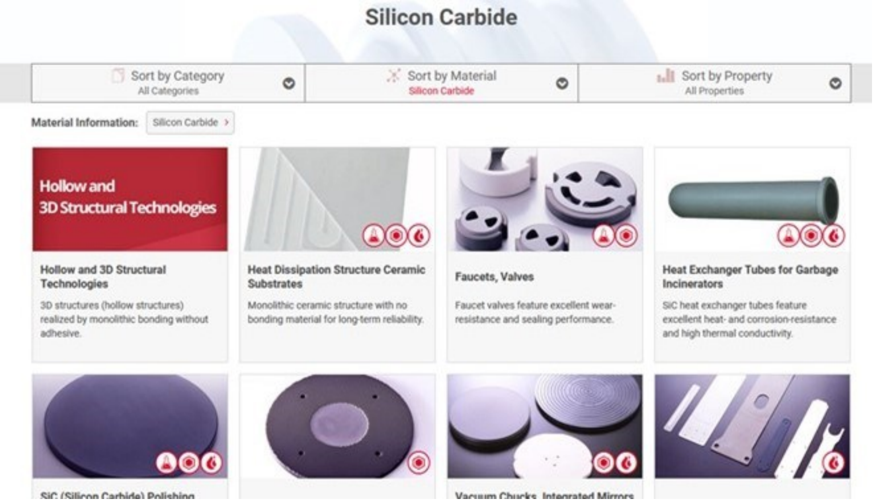


Material Characteristics

* Values are typical data from test pieces

			Unit	A476T	A479T	SC140
Color			–	White	White	Black
Alumina Content			wt%	96	99.5	–
Bulk Density			–	3.7	3.9	3.1
Mechanical Characteristics	Vickers Hardness		GPa	13.9	16.3	23
	Flexural Strength (3-point Bending)		MPa	380	470	450 (4-point Bending)
	Young's Modules of Elasticity		GPa	340	380	430
	Poisson's Ratio		–	0.23	0.23	0.17
Thermal Characteristics	Thermal Conductivity		W/m·K	26	30	180
	Specific Heat Capacity		J/(kg·K)	0.78	0.79	0.67
	Coefficient of Linear Thermal Expansion	40-400°C	ppm/K	7	7.6	3.7
Electrical Characteristics	Dielectric Strength		kV/mm	15	18	–
	Volume Resistivity	RT	Ω·cm	$>10^{14}$	$>10^{14}$	–
		300°C		1.0×10^{10}	4.9×10^{10}	–
		500°C		1.1×10^{8}	3.5×10^{8}	–
	Dielectric Loss Angle		1MHz	3.0×10^{-4}	1.0×10^{-4}	–
	Dielectric Constant		1MHz	9.6	10.2	–

*Other materials can also be considered upon request from prototyping



Hollow and 3D Structural Technologies
3D structures (hollow structures) realized by monolithic bonding without adhesive.

Heat Dissipation Structure Ceramic Substrates
Monolithic ceramic structure with no bonding material for long-term reliability.

Faucets, Valves
Faucet valves feature excellent wear-resistance and sealing performance.

Heat Exchanger Tubes for Garbage Incinerators
SiC heat exchanger tubes feature excellent heat- and corrosion-resistance and high thermal conductivity.

SiC (Silicon Carbide) Polishing

Vacuum Chucks, Integrated Mirrors

https://www.ortechceramics.com/products/uncategorized/aluminum-nitride-substrate/

http://www.surmet.com/technology/aln/index.php

https://precision-ceramics.com/materials/aluminum-nitride/

https://www.accuratus.com/alumni.html

https://global.kyocera.com/prdct/fc/product/category/life/life011.html

https://global.kyocera.com/prdct/fc/list/material/silicon_carbide/index.html?gclid=CjwKCAjwvuGJBhB1EiwACU1AiftisyIcz-7Zw1pUJ2FXYrgWSHwIq1sCKNcSA6dtuBwhc6aw_cmEzBoC54EQAvD_BwE

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**

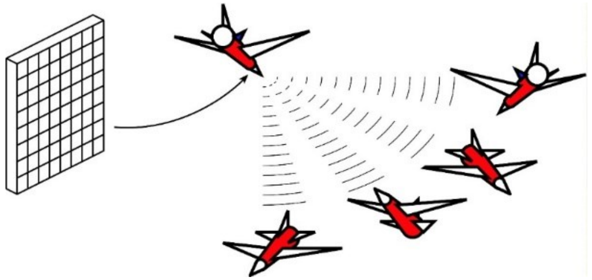
Arrays must be vast: 100-1,000-10,000 elements

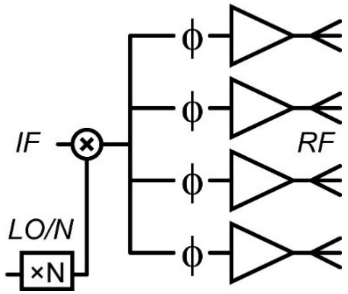
Arrays must be dense: packaging challenges

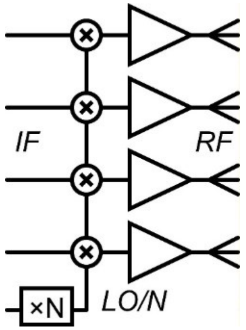
Many DC/IF/LO lines, plus antenna interface.

Fitting IC functions into available area.

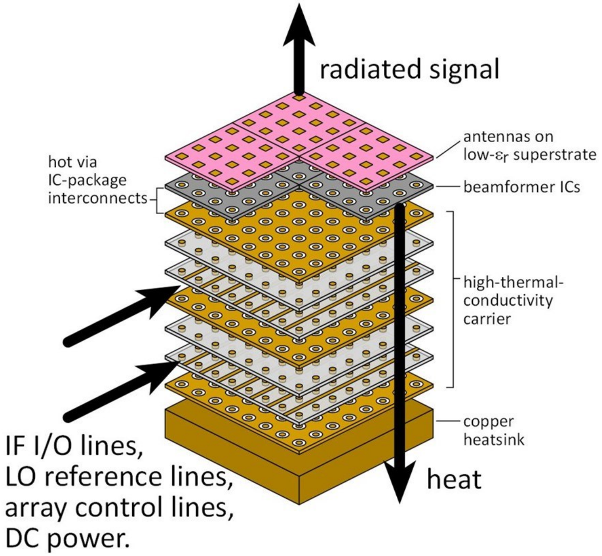
Removing the heat.

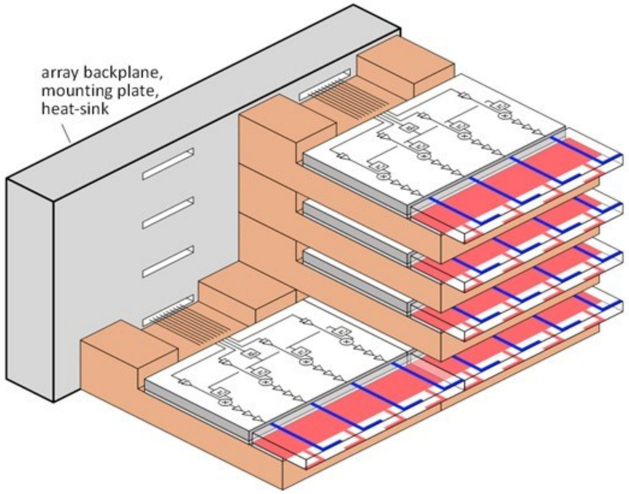






f	100	150	200	250	300	GHz
λ	3	2	1.5	1.2	1	mm
$\lambda/2$	1.5	1	0.75	0.6	0.5	mm
0.6λ	1.8	1.2	0.9	0.72	0.6	mm

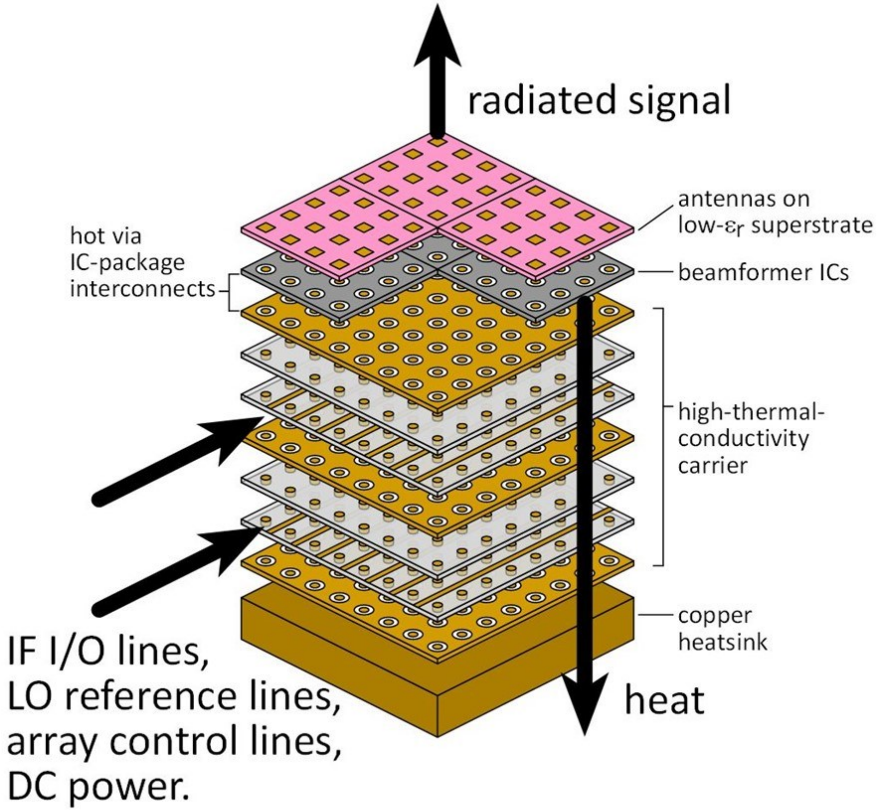


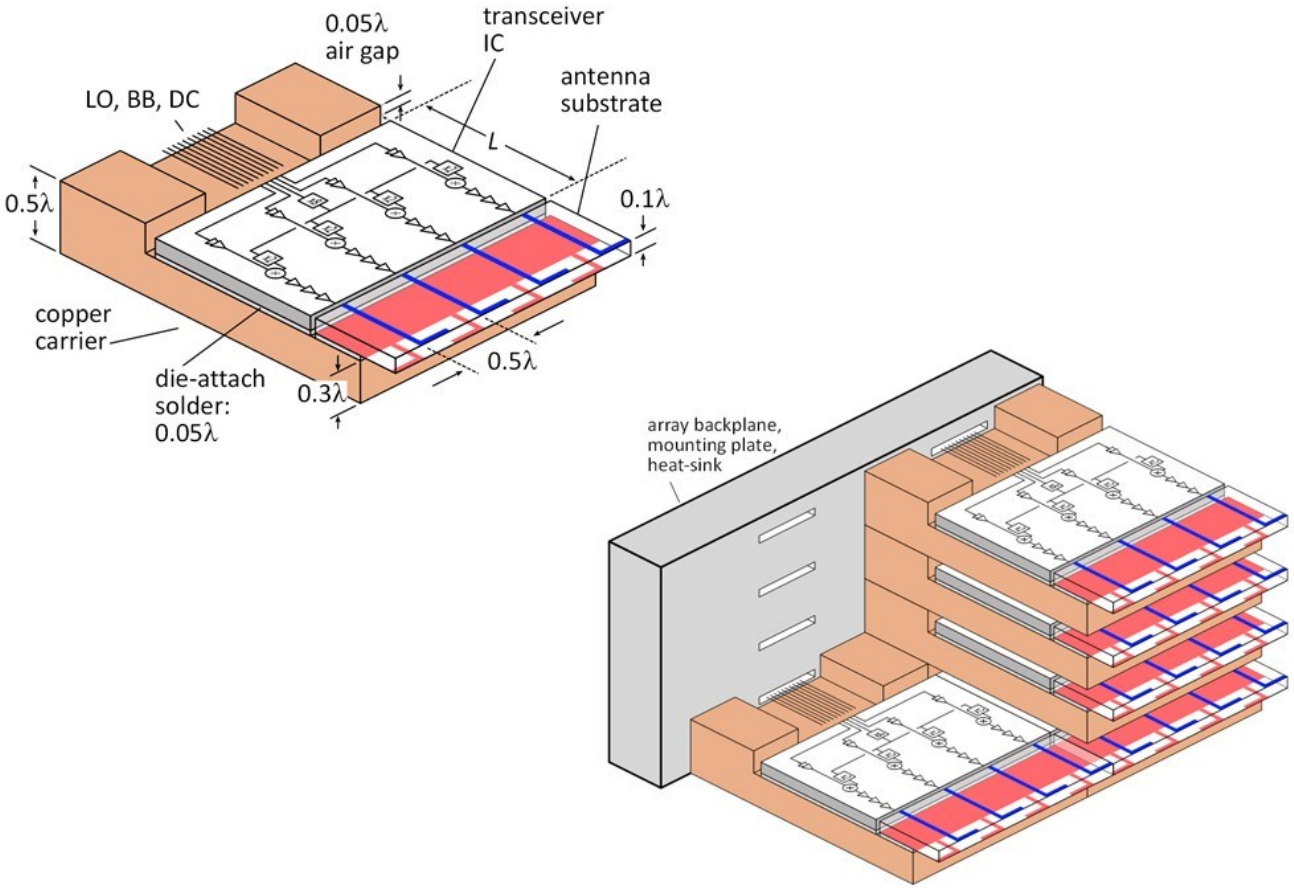


The 100-300GHz 2D Arrays: tiles vs. trays

Tiles:
thinner, cheaper, lighter
less space to fit the electronics: ~0.6λ × 0.6λ
more difficult to remove the heat

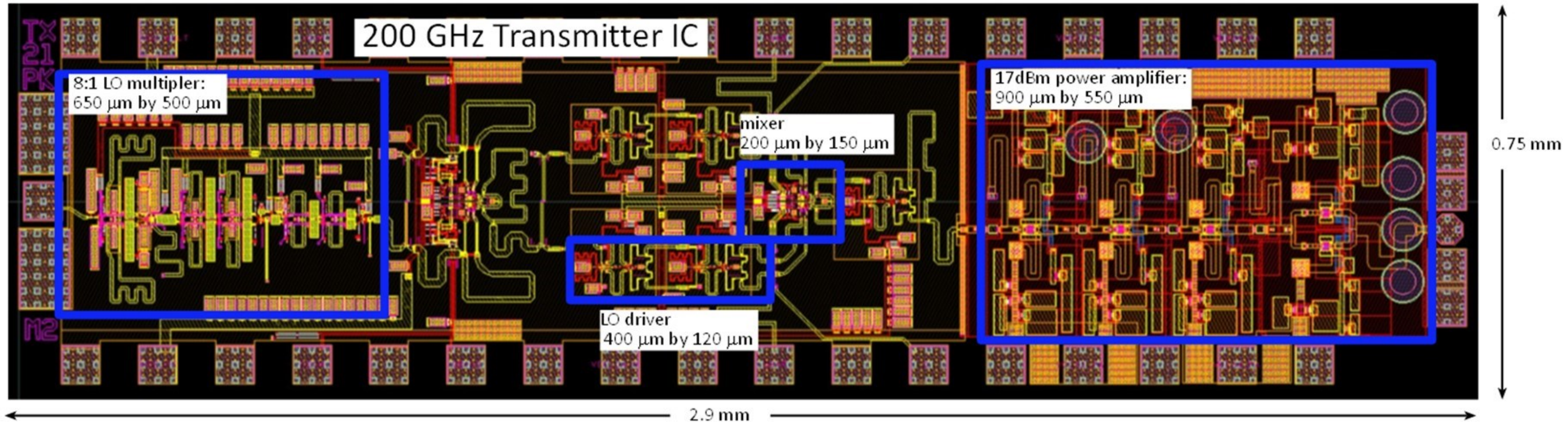
Trays (Slats):
thicker, more expensive, heavier
more space to fit the electronics: ~ L × 0.6λ
easier to remove the heat

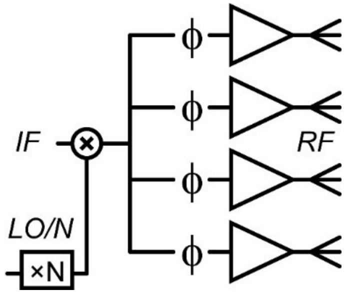




A simple 200GHz, 0.6λ×0.6λ array can just fit

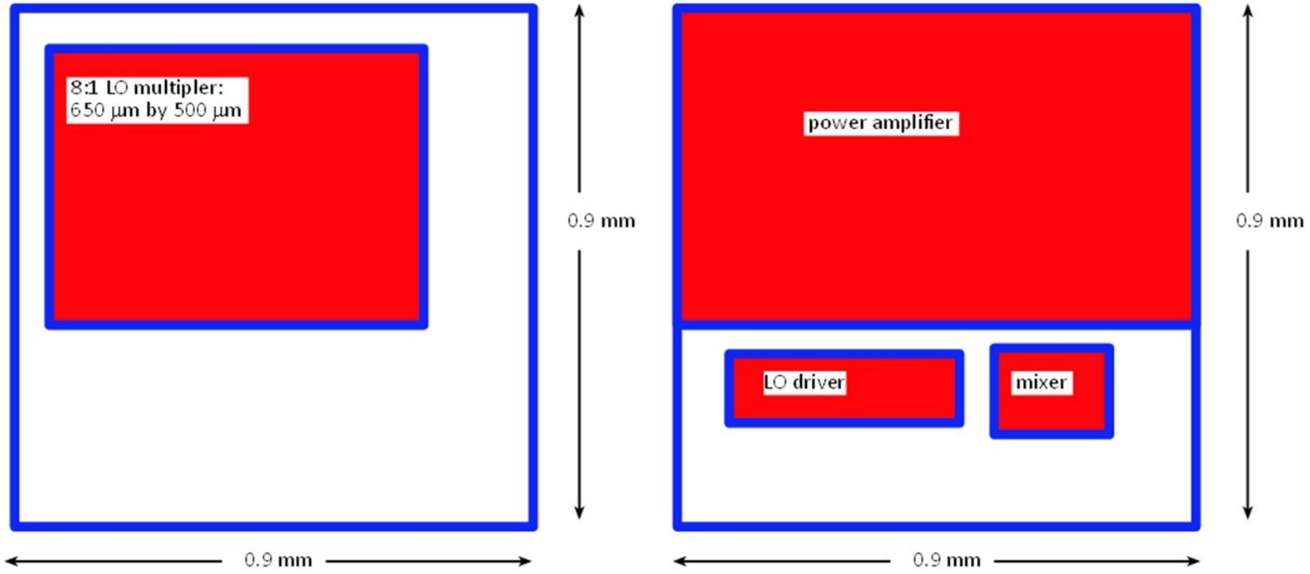
Seo et al, 2021 IMS

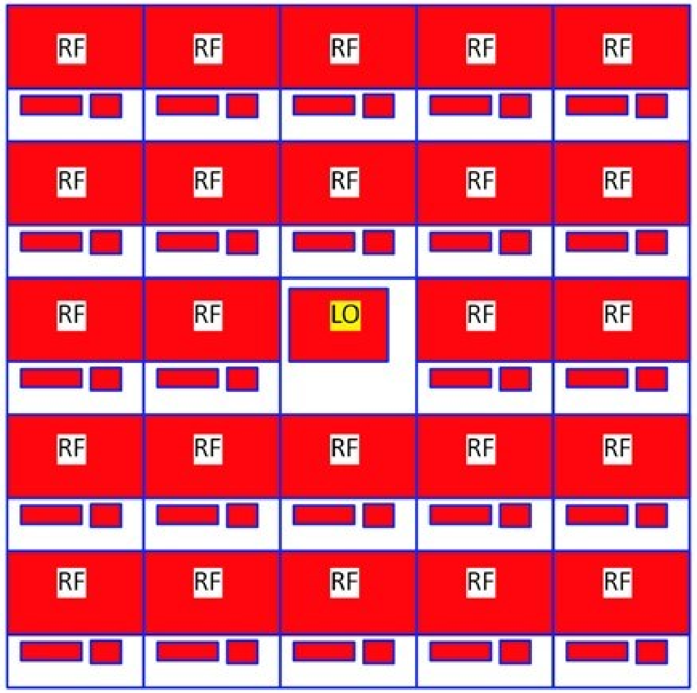




24-element array

4.5mm × 4.5mm



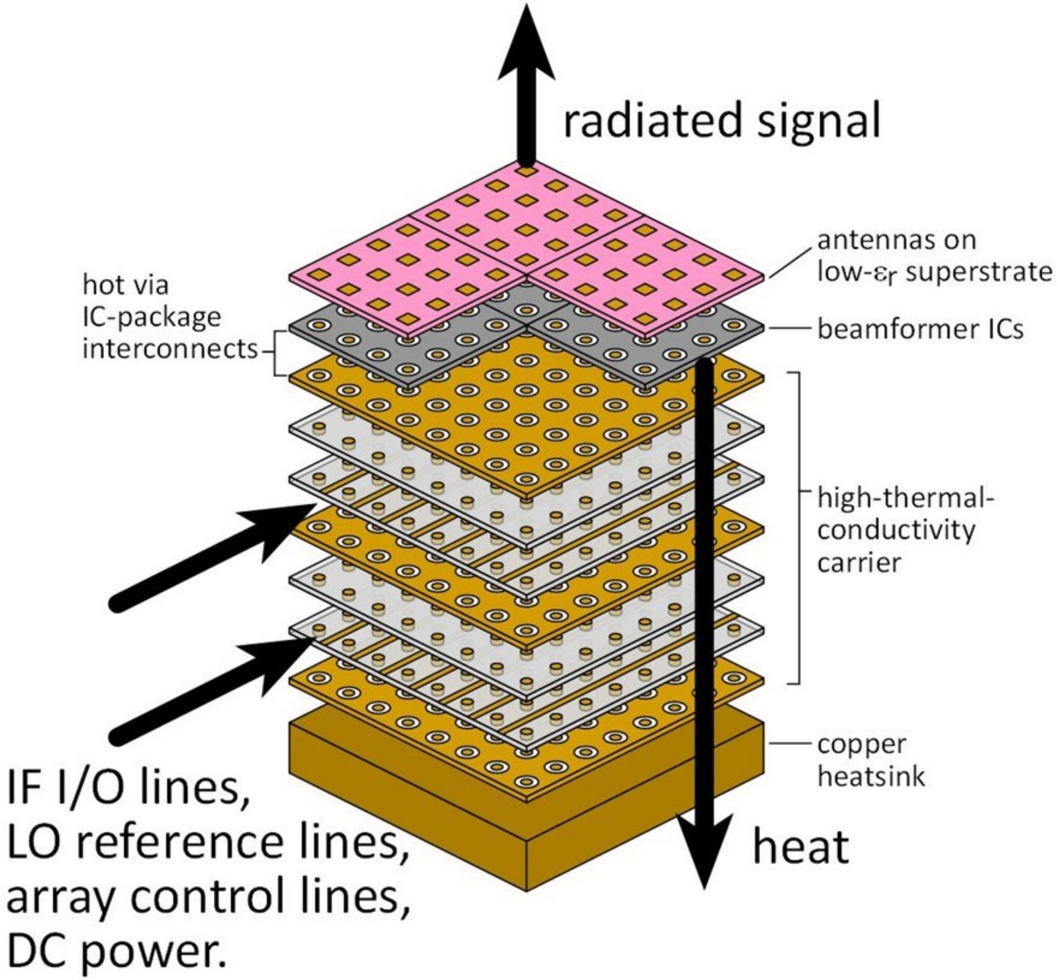


Packages for medium-to-high-power 2D arrays

PA heatsinking:
good-high thermal conductivity material under ICs

2D arrays are very dense:
IF, power, control, LO reference lines must run under IC
need OK line losses @ DC~30GHz
→ moderate dielectric constant, high thermal K.
ceramic AlN or SiC (~200W/K/M)
possibly LTCC; need better thermal vias, better density.

Need high-quality 100-300GHz antennas *above ICs*.
need thin low-ε_r insulator plane above IC.
fused silica superstrate.



100-300GHz array frequency scaling

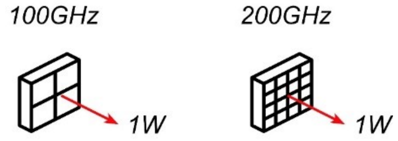
$$P_{received} = \frac{A_t A_r}{\lambda^2 R^2} e^{-\alpha R} \cdot P_{trans} \longrightarrow \#\text{beams} \cdot (\text{bit rate per beam}) \cdot kTF \cdot \text{SNR} = \frac{A_t A_r}{\lambda^2 R^2} e^{-\alpha R} \cdot P_{trans}$$

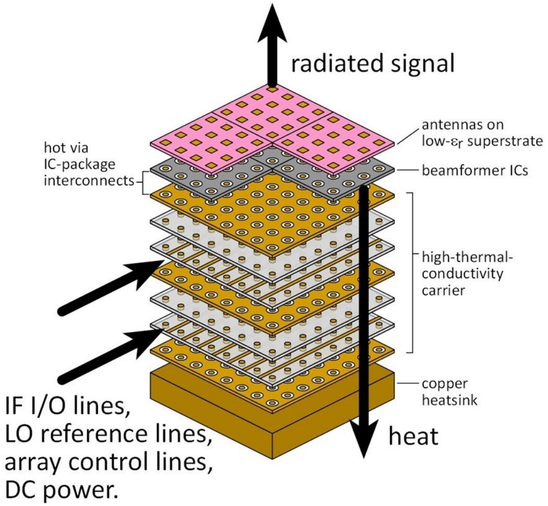
(Worst-case atmospheric loss: ~constant over 50-300GHz)

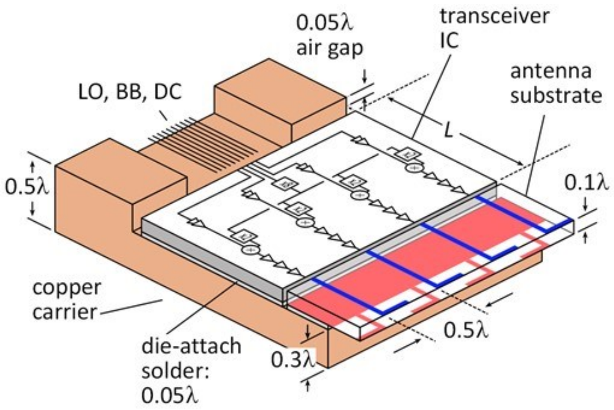
Proposed scaling law	change
carrier frequency	increase 2:1
aperture area	keep constant
total transmit power	keep constant

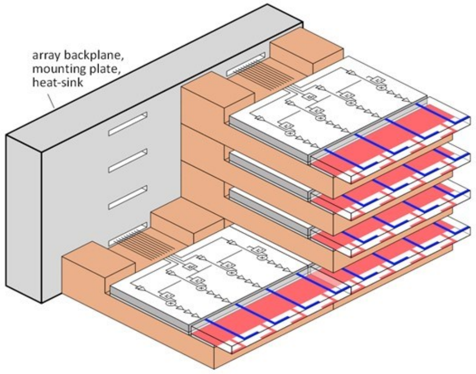
→

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









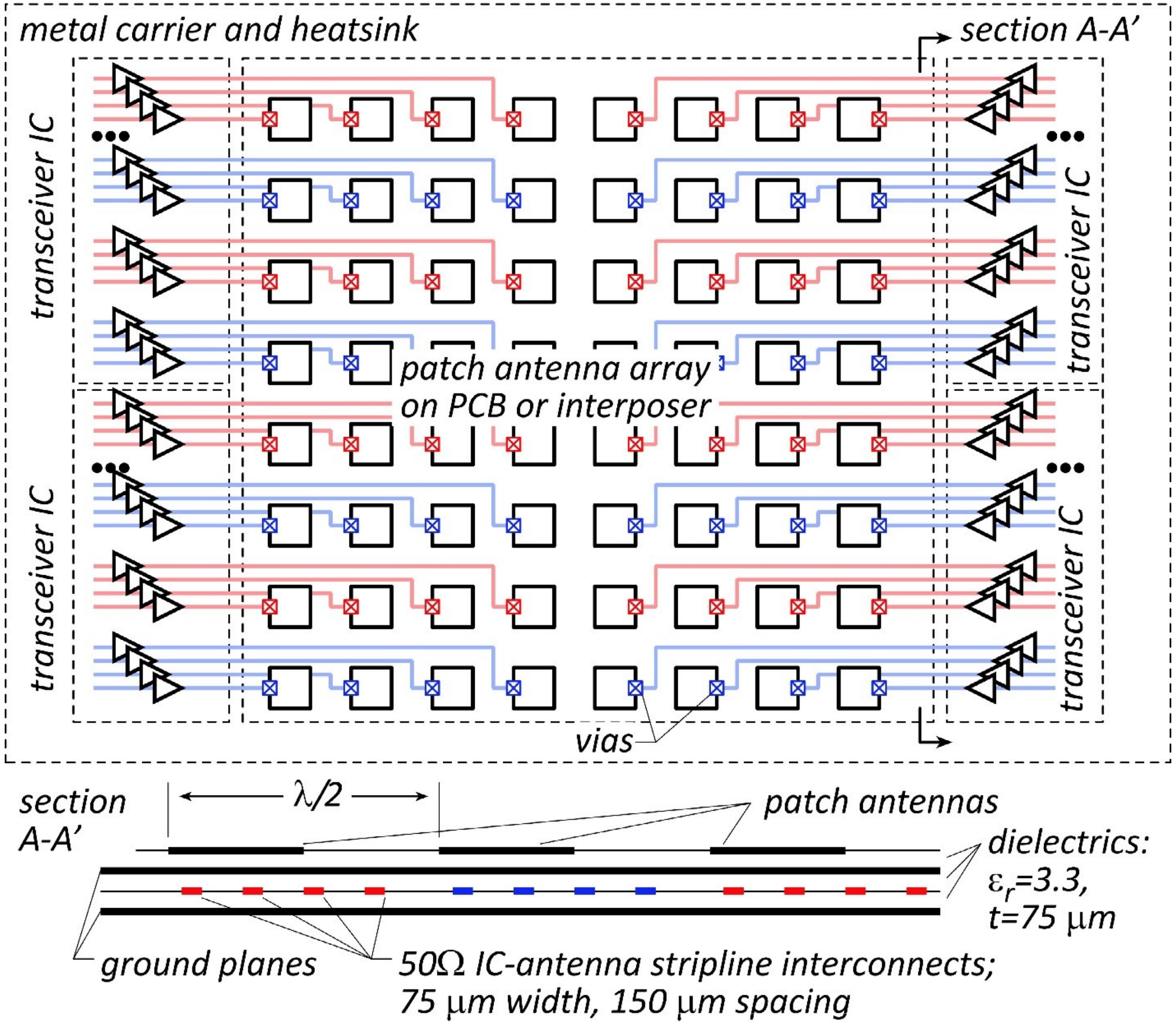
2D arrays with ICs *beside* antennas

Concept:
N × N 2D array array
RF ICs placed at sides
50Ω striplines between ICs and antennas

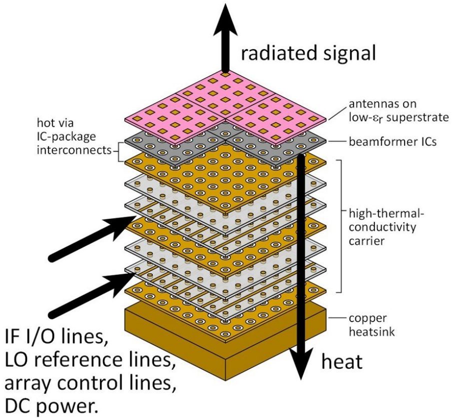
Interconnect losses are acceptable
line lengths are <Nλ/4: low loss

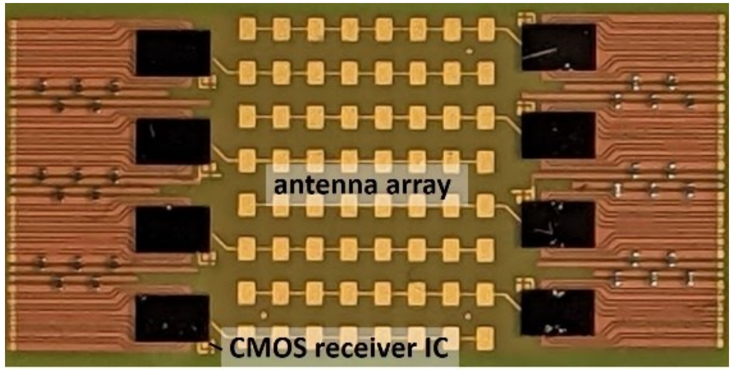
Interconnect density limits array size:
Assume: 4-layer LCP interposer (75 μm layers, ε_r~3.3),
50Ω striplines are 75 μm wide
minimal line coupling: 150 μm line spacings
→ 4 interconnects in λ/2 pitch of 140GHz array.
→ 8×8 maximum array tile size at 140GHz
→ 16×16 maximum array tile size at 75GHz

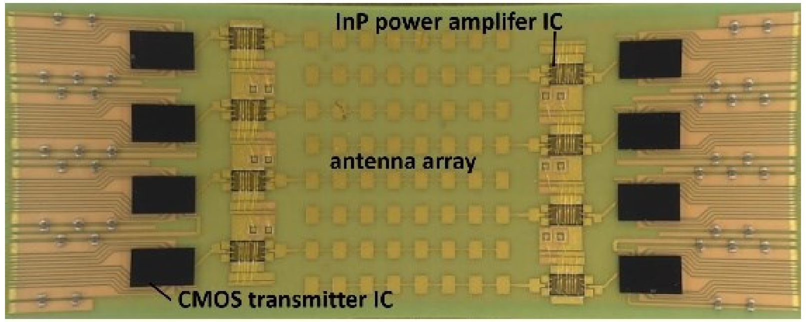
IC channel density limits array size:
λ/2 antenna pitch, N × N antenna array fed from both sides
→ IC channel pitch = λ/N.
Assume 250 μm channel pitch:
→ 8×8 maximum array tile size at 140GHz
→ 16×16 maximum array tile size at 75GHz



Packaging for 100-300GHz Wireless



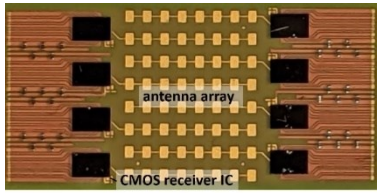


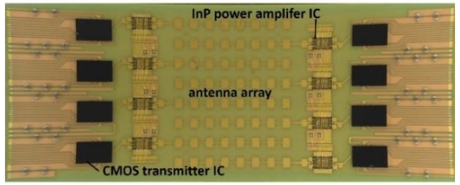


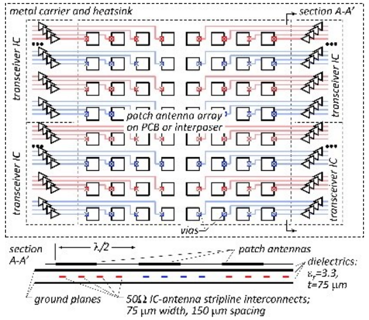
Packaging for 100-300GHz wireless

Overall Challenges:
100-300GHz antenna-IC connections
removing heat.
Interconnect density
Supply chain (domestic, R&D small-volume)

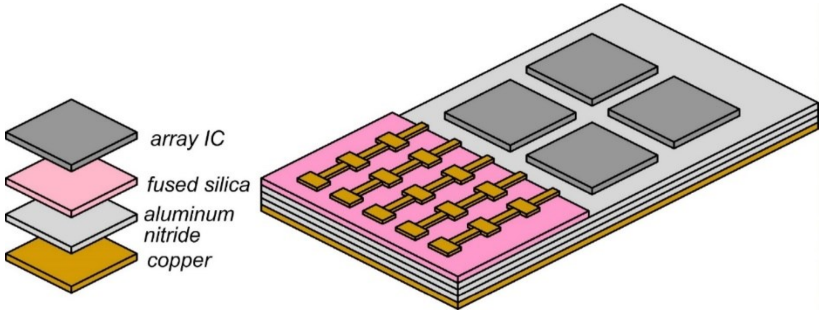
Established technologies:
effective for 1D arrays and smaller 2D arrays.
Low-ε_r (LCP, organic, LTCC) interposers: good antennas
Cu stud flip-chip bonding: good connections
thermal challenges: thermal via performance and density

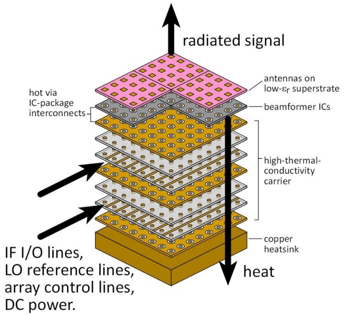


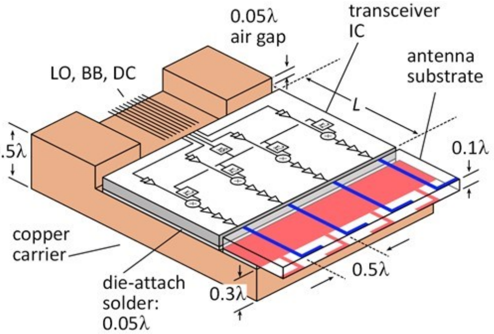


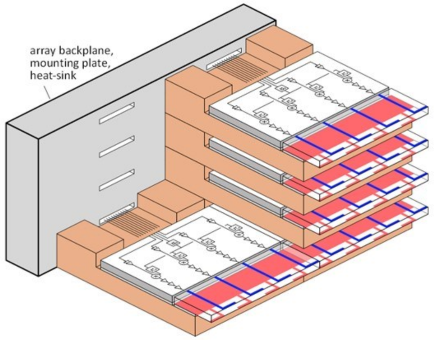


Advanced technologies
High-power 1D arrays: package laminates with both low-ε_r and high-K_{th} layers
Medium-power 2D tiled arrays: low-ε_r antenna superstrate, high-K_{th} interconnect substrate
Medium-power 2D trayed arrays: assembly cost, high-K_{th} trays









(backup files follow)