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100-300GHz Wireless Communications: IC and System Design



ComSenTer
COMMUNICATIONS SENSING TERAHERTZ

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Acknowledgements

Systems



Sundeep Rangan
UC Berkeley

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
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Massive
MIMO
demo.



Borivoje Nikolic
UC Berkeley

VLSI design automation
VLSI MIMO processors


Compressive
imaging



Amin Arbabian
Stanford

140GHz radar chipsets
and arrays

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

140/210/280GHz arrays
for demos.



Mark Rodwell
UC Santa Barbara

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

THz HBTs for PAs
THz HEMTs for LNAs

JUMP + nCORE Official Sponsors



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

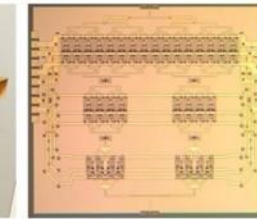
— Services —



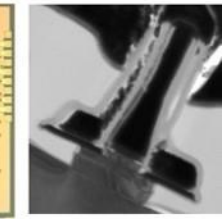
— Systems —



— ICs —

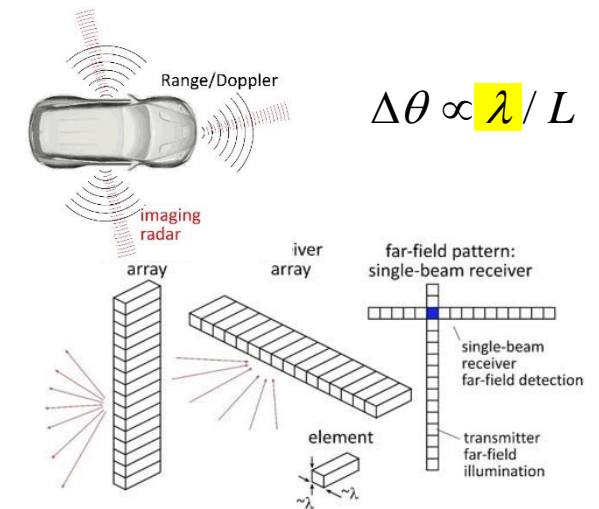
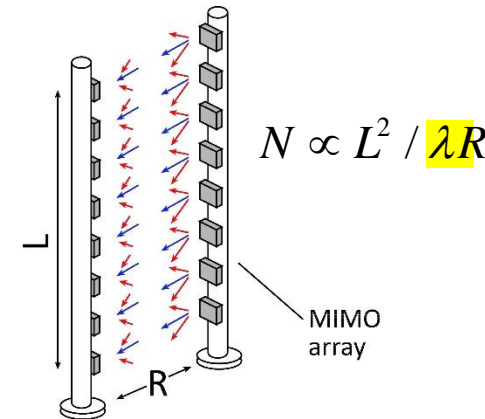
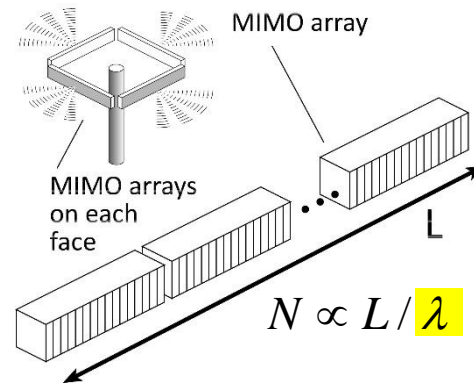
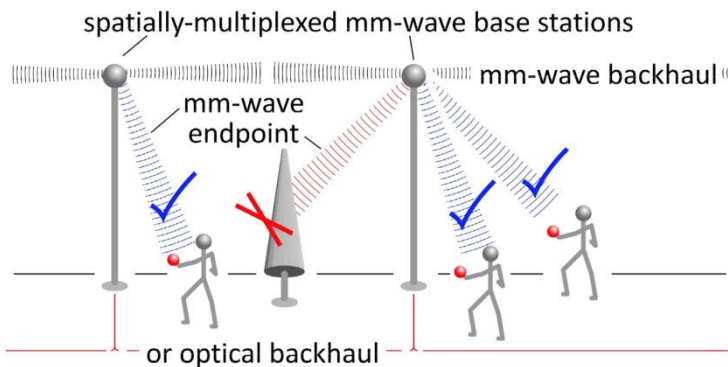


— Devices —



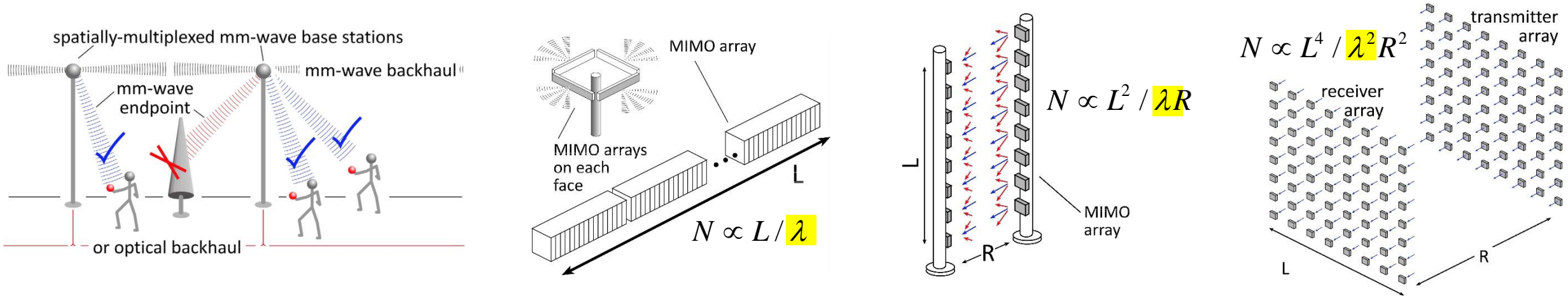
100-300GHz carriers, massive spatial multiplexing

→ **Terabit hubs and backhaul links, high-resolution imaging radar**

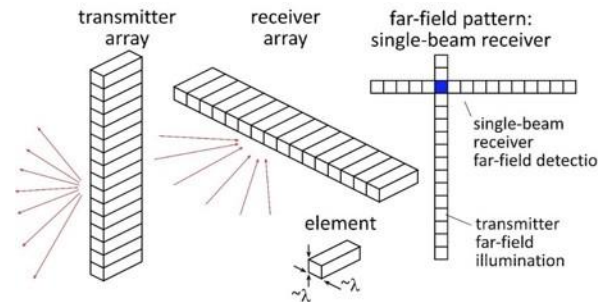
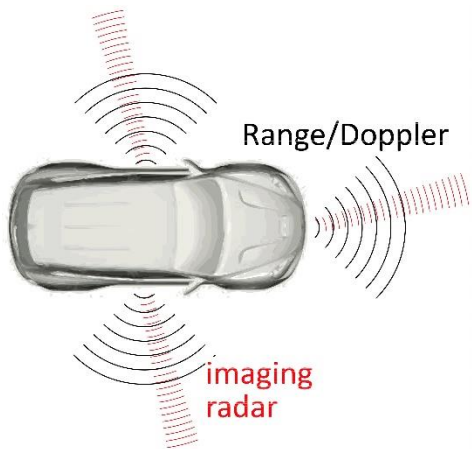


Benefits of Short Wavelengths

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



Imaging: very fine angular resolution



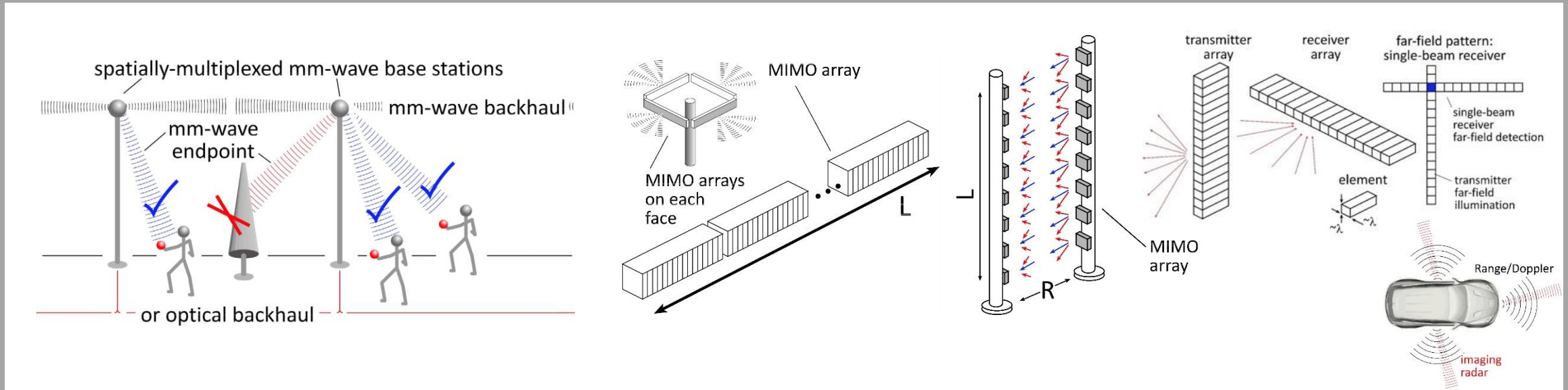
$$\Delta\theta \propto \lambda / L$$

But:

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

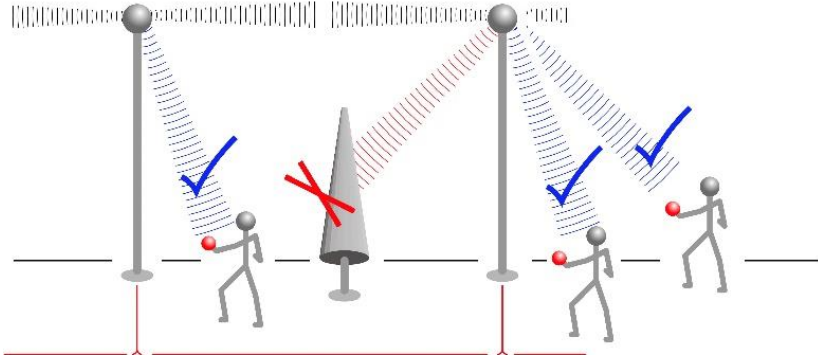
**100-340GHz wireless:
terabit capacity,
short range,
highly intermittent**

Applications

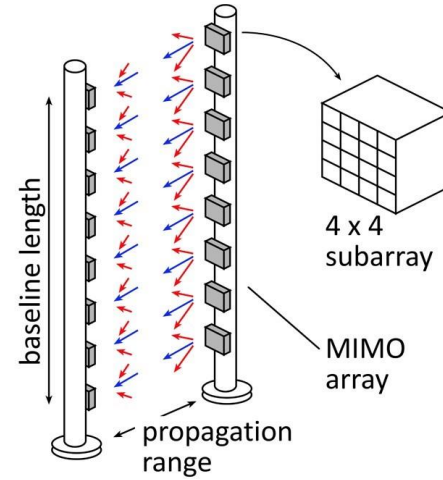


Potential 100-300GHz Systems

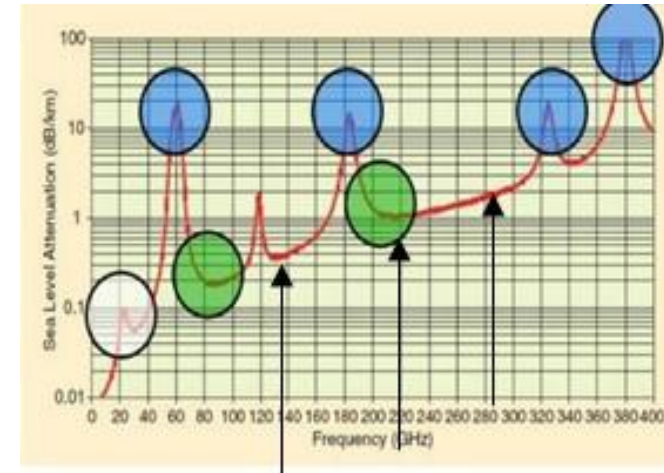
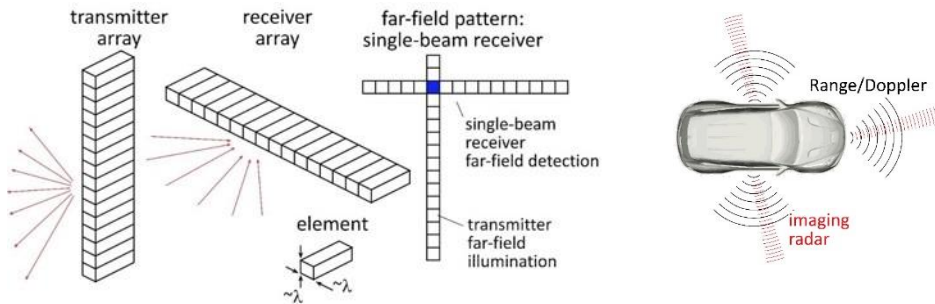
140GHz MIMO Hub



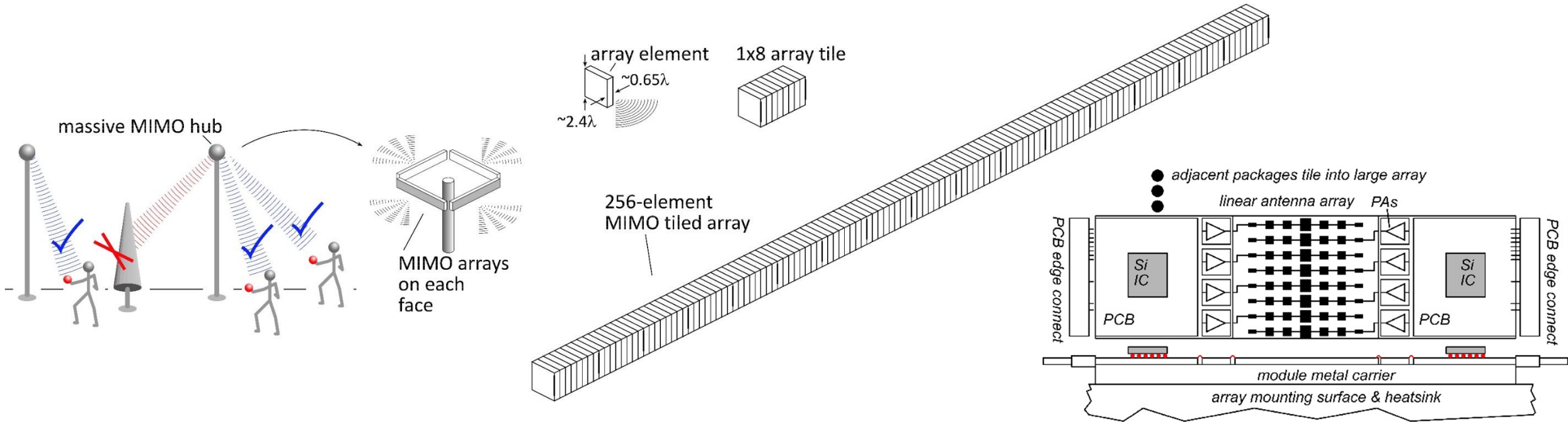
210 or 280GHz MIMO Backhaul



140 or 210GHz Imaging Radar



140GHz massive MIMO hub

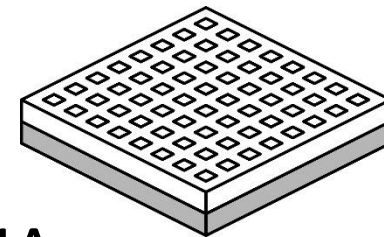


0.5-5 Tb/s spatially-multiplexed 140GHz base station

128 users/face, 4 faces. $P_{1\text{dB}} = 21 \text{ dB}_m$ PAs, $F = 8\text{dB}$ LNAs

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

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



Handset:
8 × 8 array
(9×9mm)

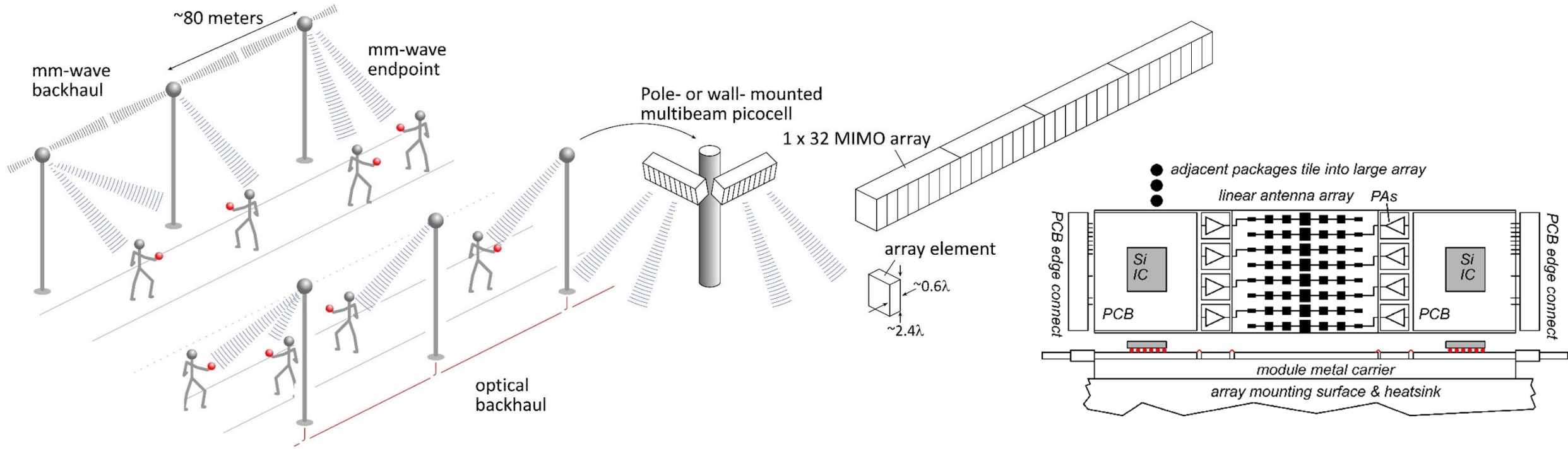
70 GHz spatially multiplexed base station

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

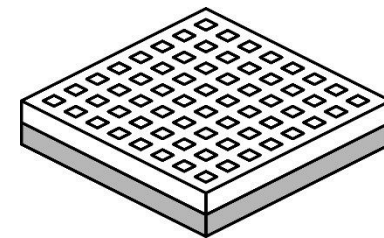


If demo uses 32-element array (four 1×8 modules):

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

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

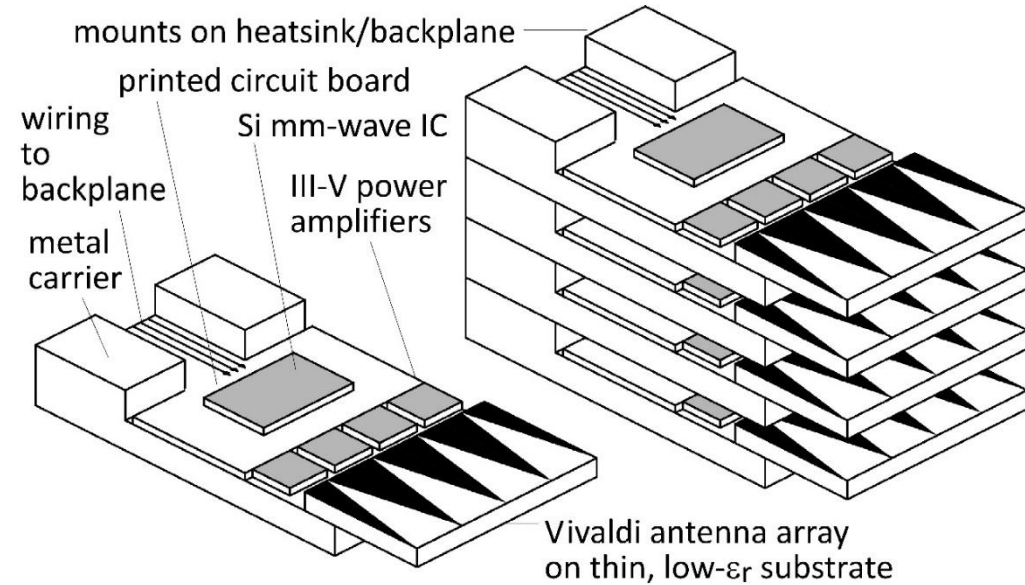
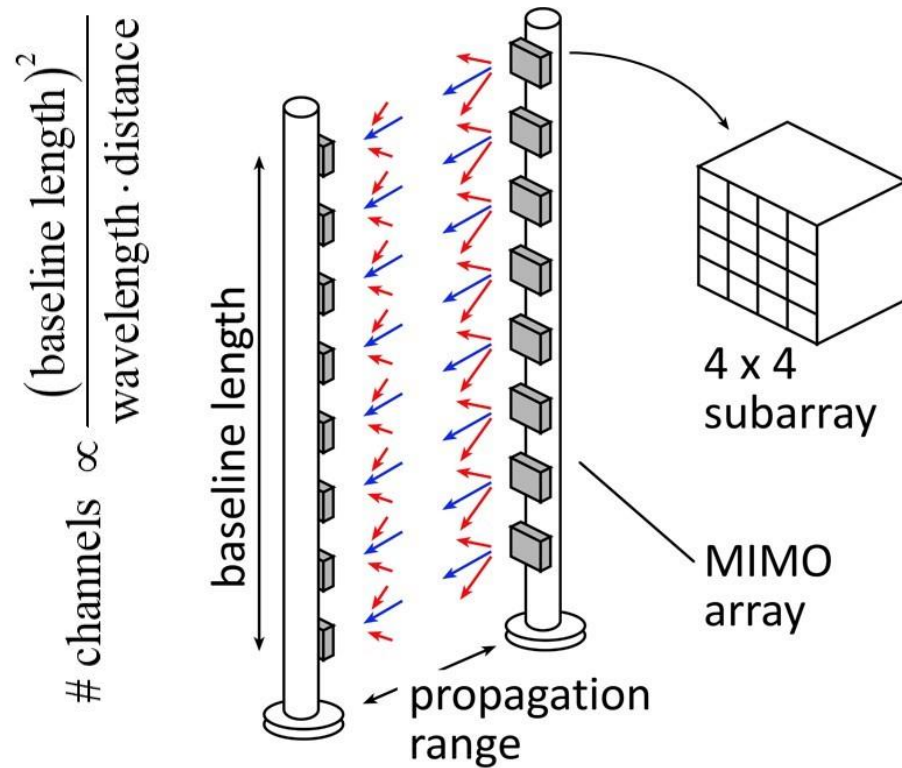
70, 40 m range in 50mm/hr rain with 17dB total margins



Handset:
8 × 8 array
(9×9mm)

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

210 GHz, 640 Gb/s MIMO Backhaul



8-element MIMO array

3.1 m baseline.

80Gb/s/subarray \rightarrow 640Gb/s total

4 x 4 sub-arrays \rightarrow 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 = $P_{1\text{dB}}$ (per element)

LNAs: 6dB noise figure

210 GHz, 5.1 Tb/s MIMO backhaul

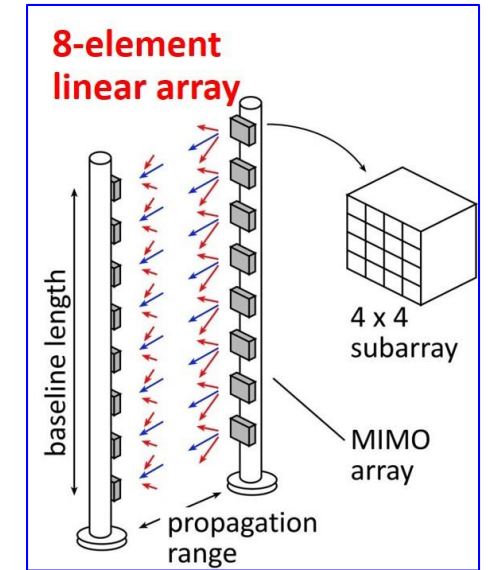
500m range in 50mm/hr. rain.

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:

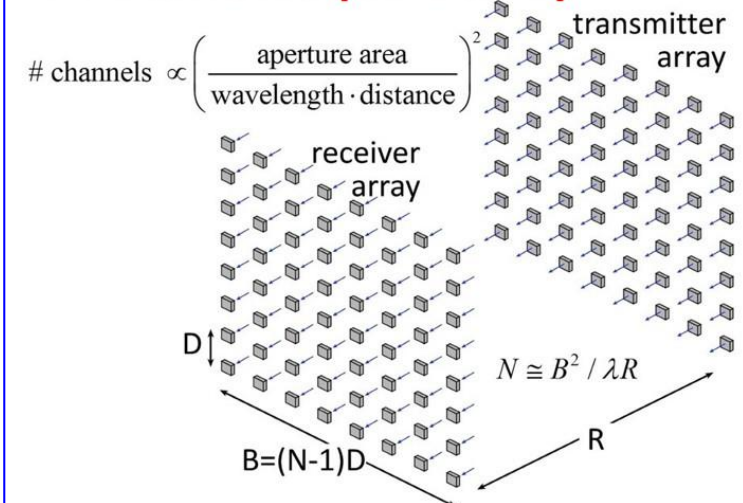
same link assumptions

requires 5dB_m transmit power/element (P_{out})

.... 3.2W total output power

requires 2.1m square array

64-element square array



Complex system: can we make it cheaply ?

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

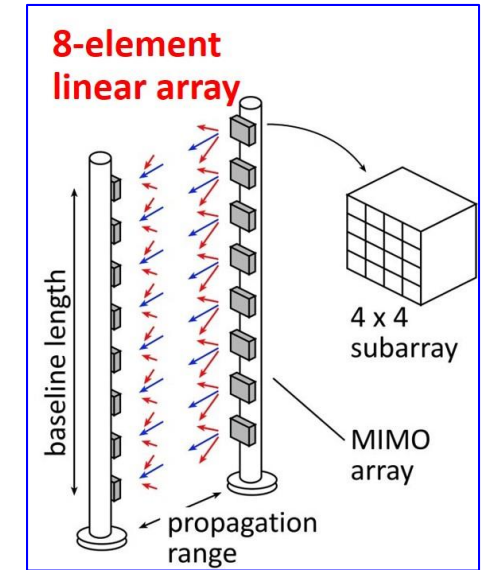
Why not use a lower-frequency carrier, e.g. 70 GHz ?

8-element 640Gb/s linear array:

requires 11dB_m transmit power/element (P_{out})

.... 1.7W total output power

requires 5.5m linear array



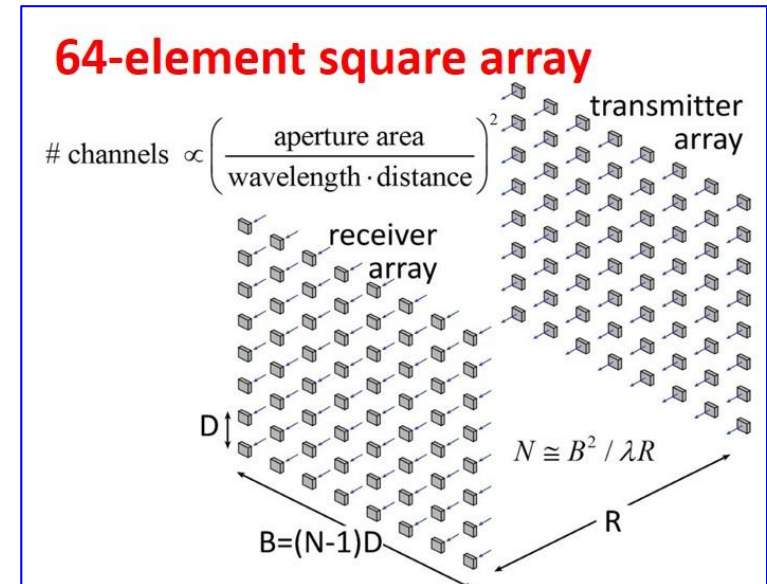
64-element 5Tb/s square array:

same link assumptions

requires 2dB_m transmit power/element (P_{out})

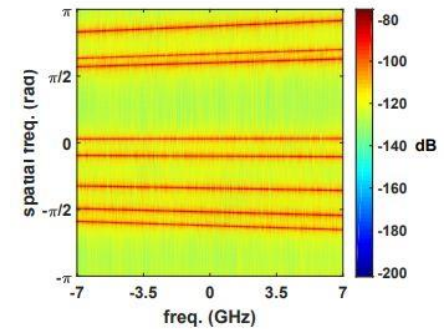
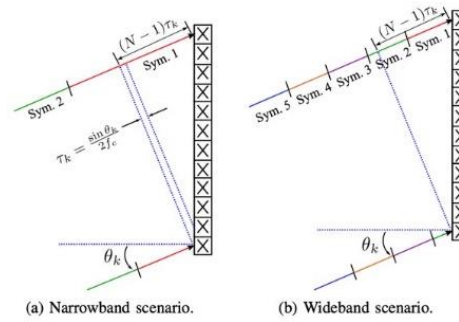
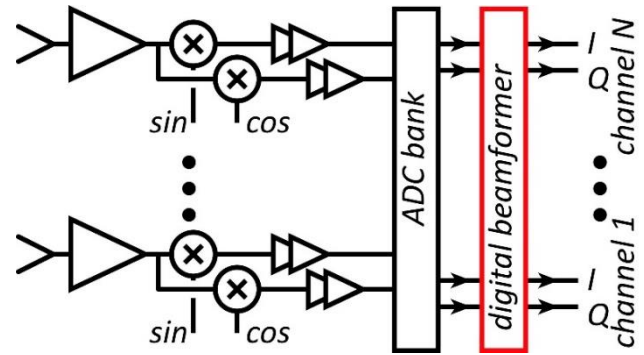
.... 1.7W total output power

requires 5.5m square array



Similar RF power output, physically larger

Systems



System Design

ADCs/DACs: QPSK needs only 3-4 bit ADC/DACs (Madhow, Studer, Rodwell)

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

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

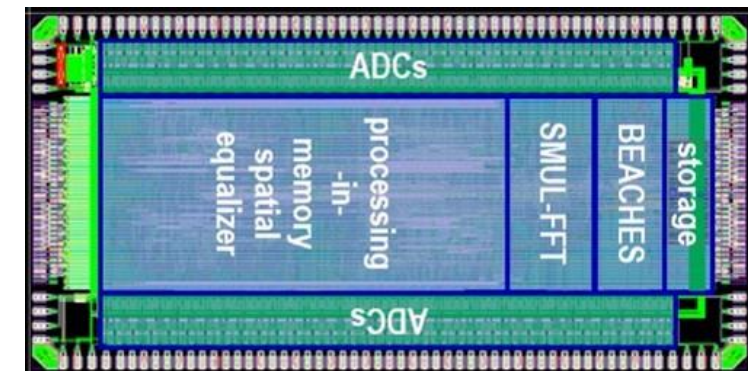
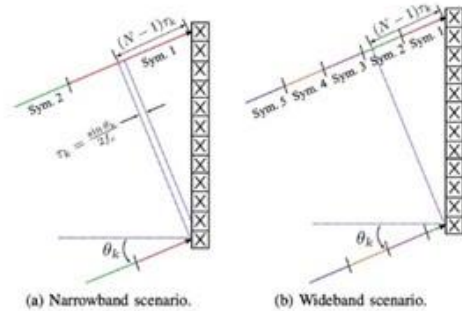
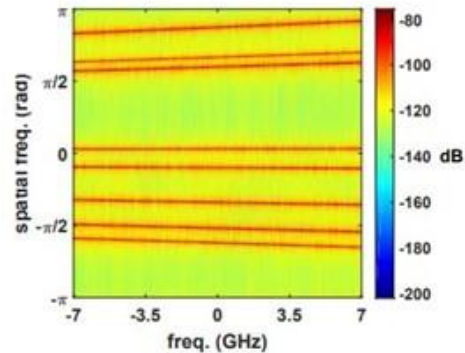
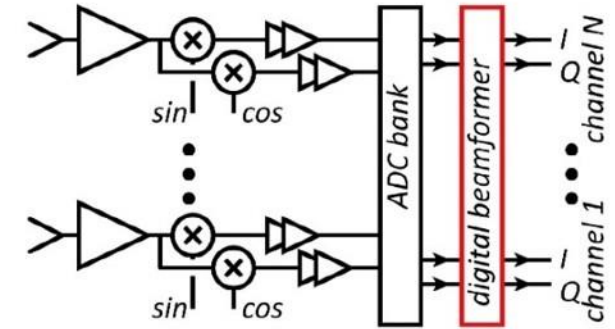
Linearity: Amplifier P_{1dB} need be only 3-4 dB above average power (Madhow).

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

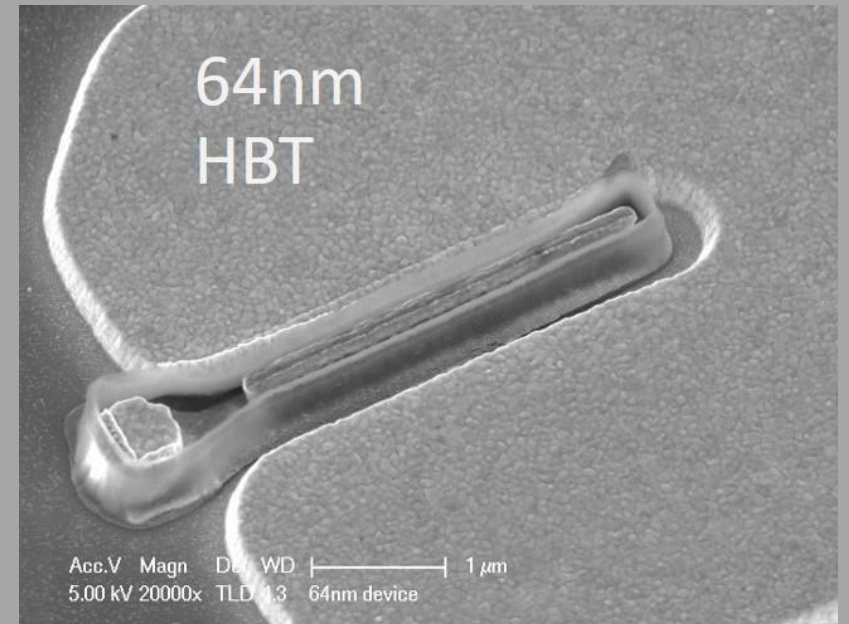
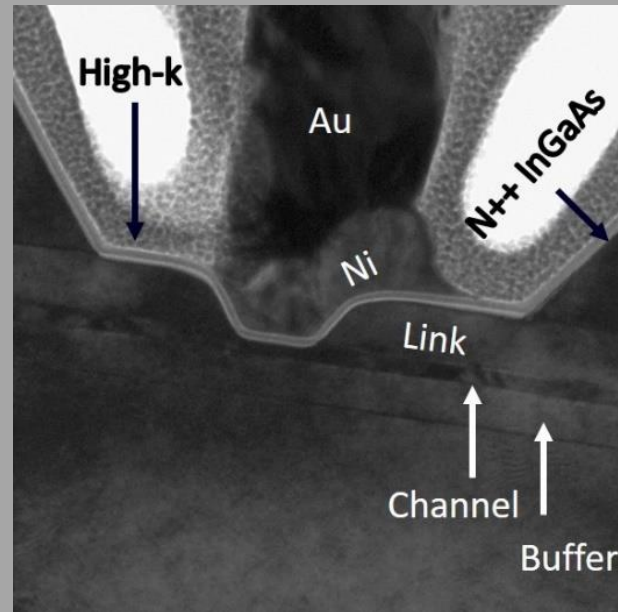
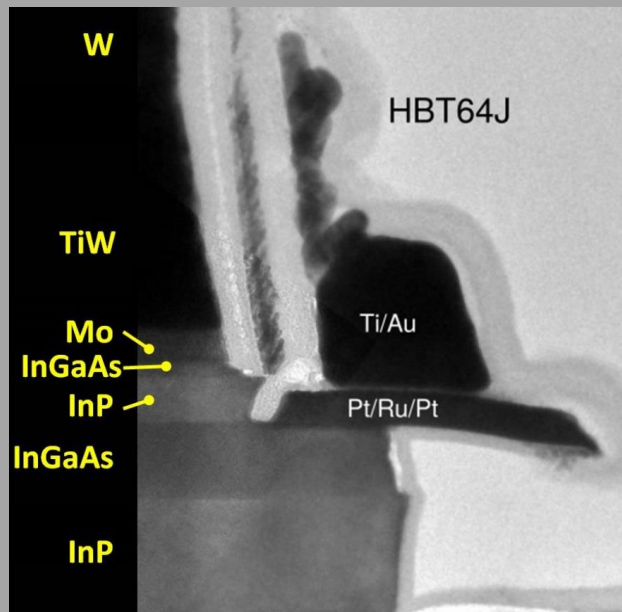
Efficient digital beamforming: beamspace algorithm=complexity $\sim N \times \log(N)$ (Madhow, Studer)

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

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



Transistors



100-300GHz ICs

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

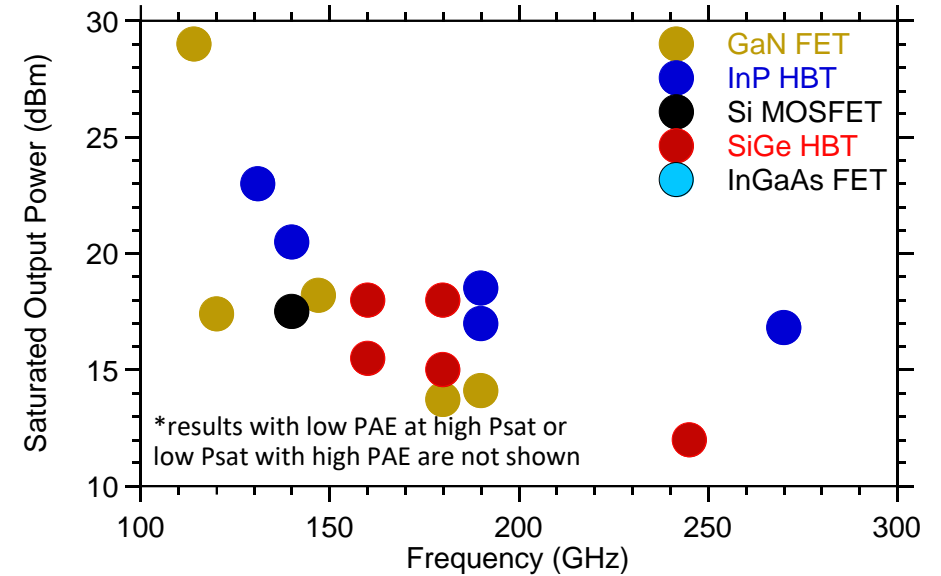
InP HBT: record 100-300GHz PAs

SiGe HBT: out-performs CMOS above 200GHz

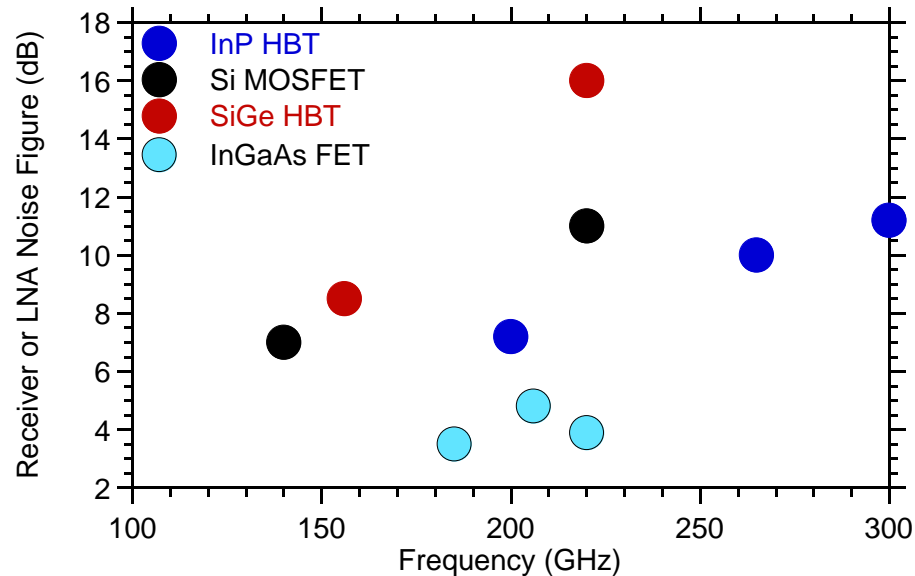
GaN HEMT: record power below 100GHz. Bandwidth improving

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

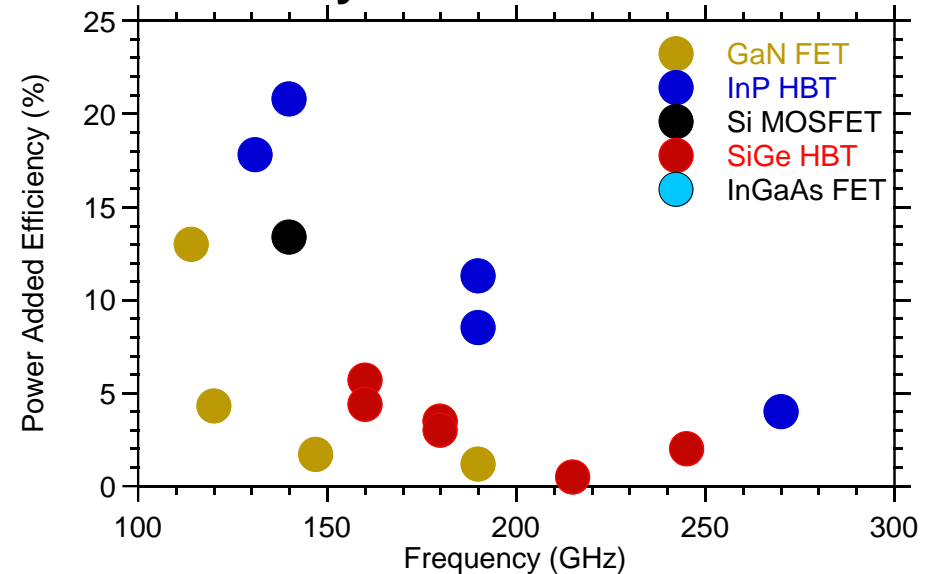
Power



Noise



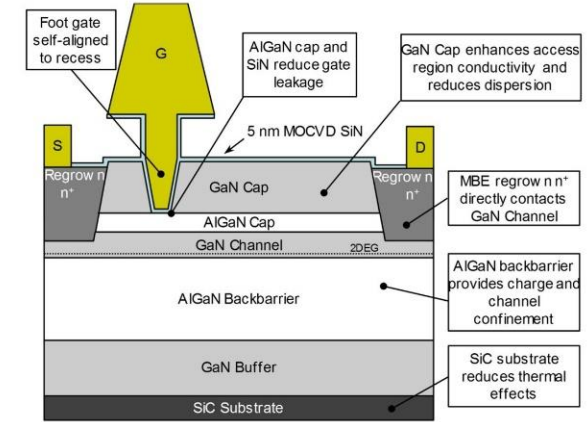
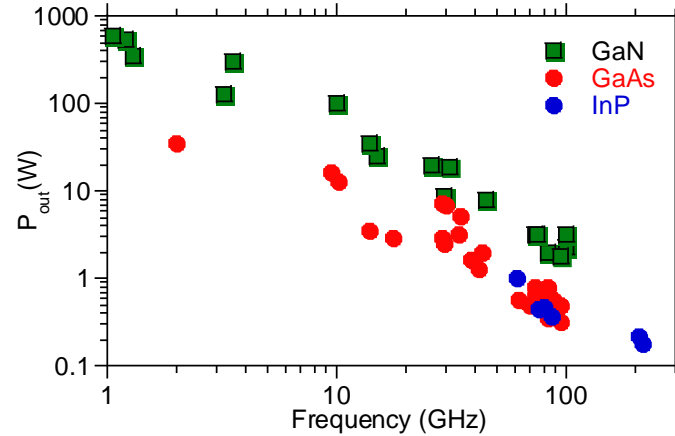
Efficiency



mm-Wave Transistor Development

InGaN and GaN HEMTs:

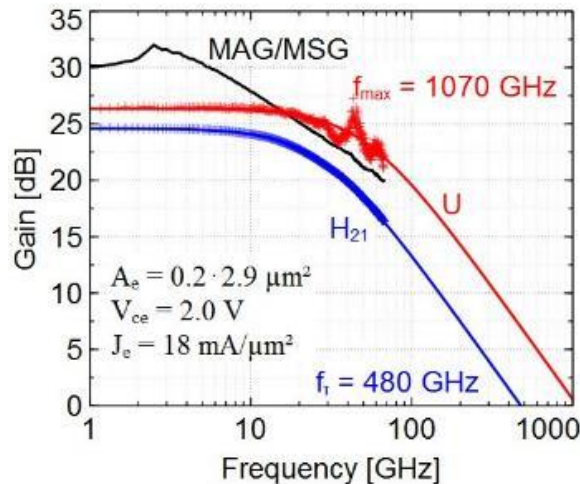
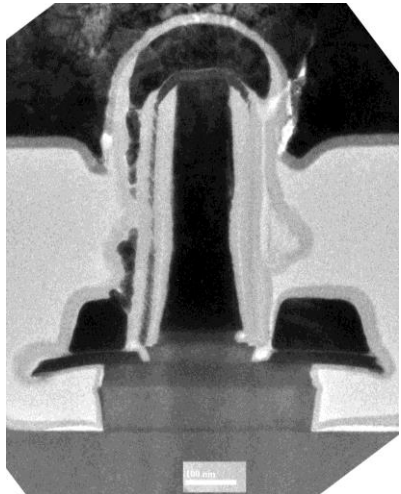
Leading power technology to ~110GHz
Efforts to extend this to 140, 220GHz.



N-polar GaN: Mishra, UCSB

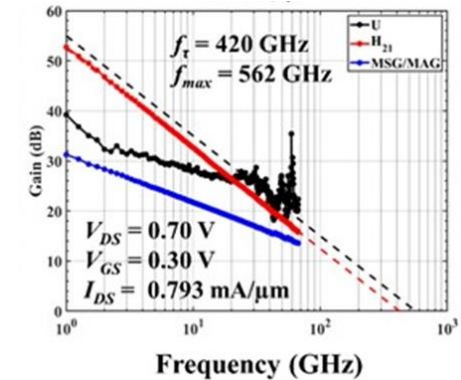
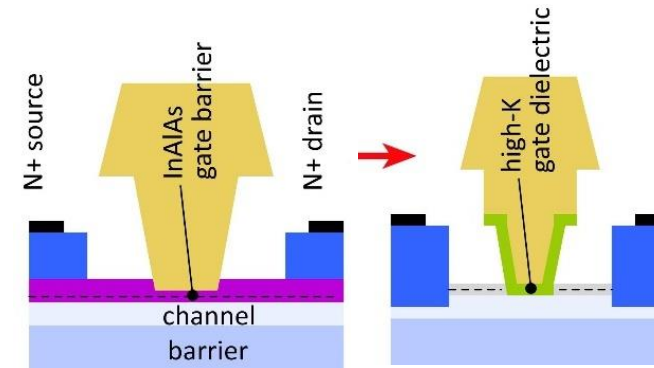
THz InP HBTs:

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

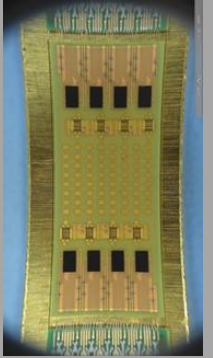
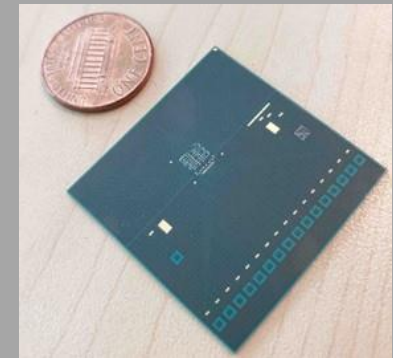
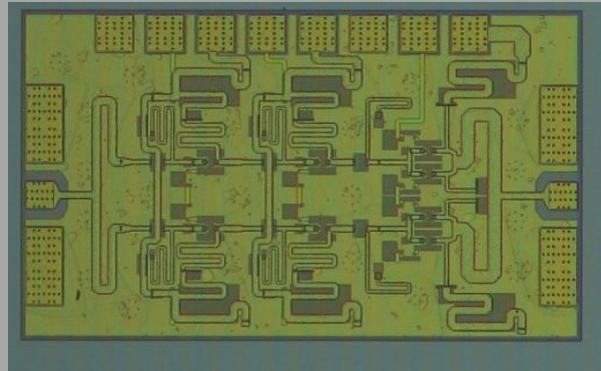
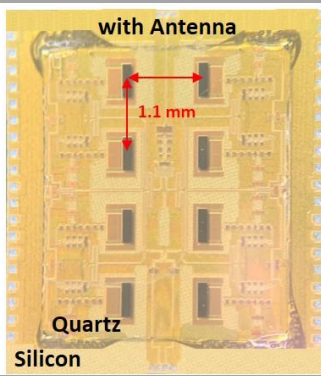
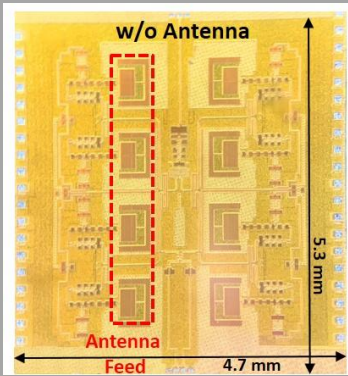


THz InP HEMTs:

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

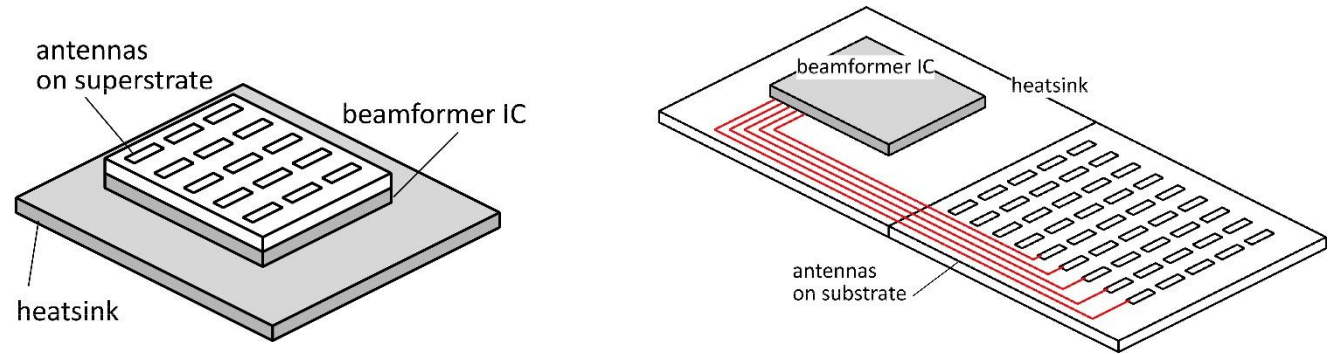


ICs and Packages: 140 GHz



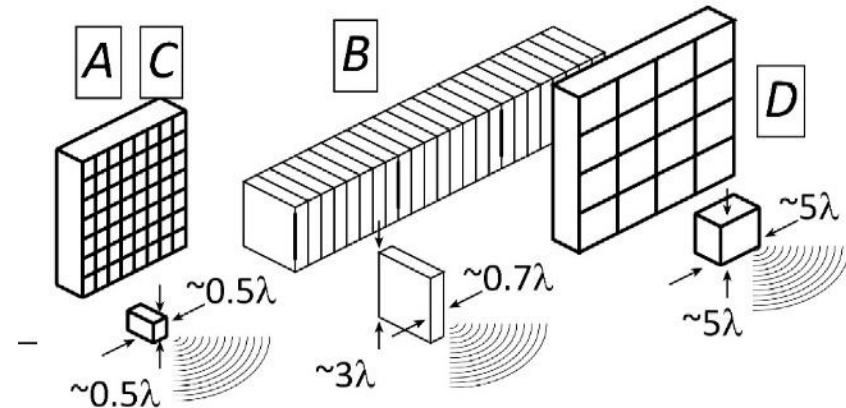
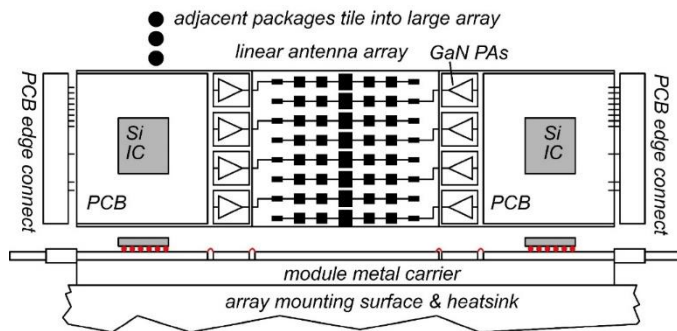
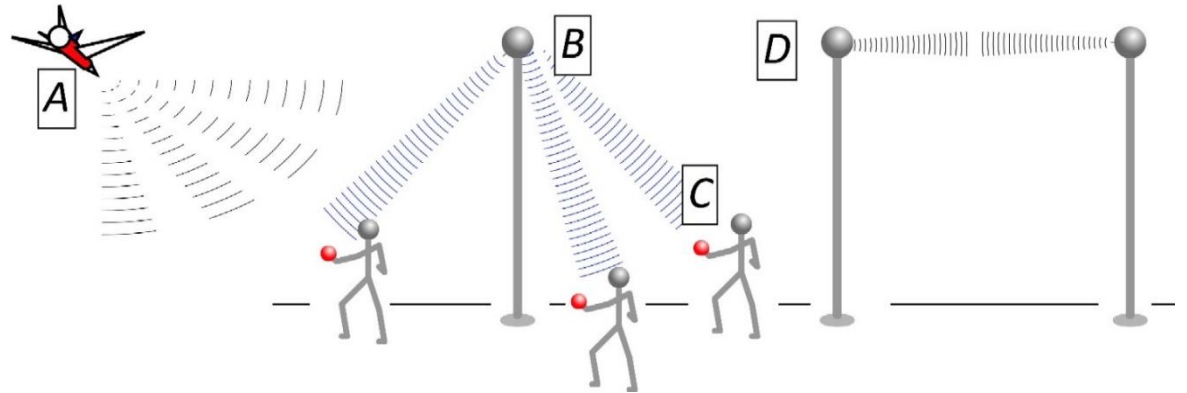
The mm-wave module design problem

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

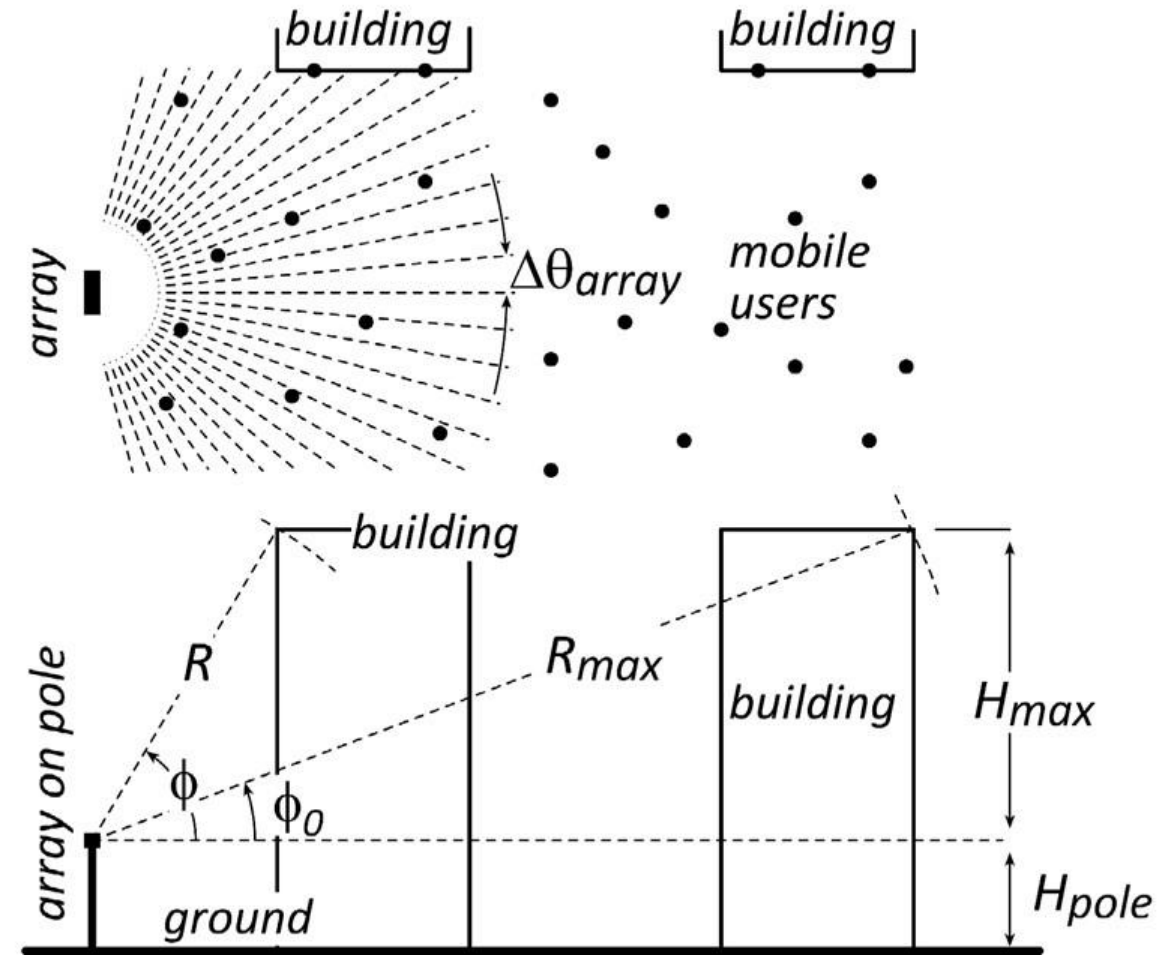
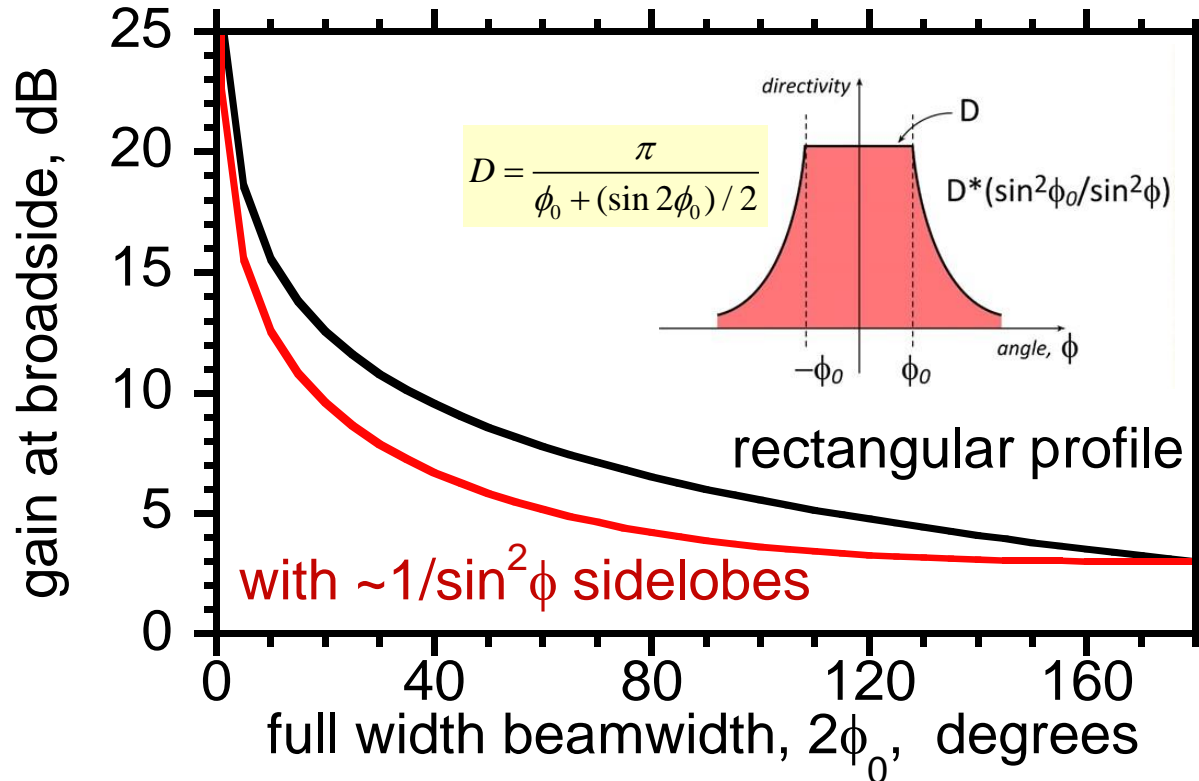


Do we need 2D arrays ? 1D steering might be fine.

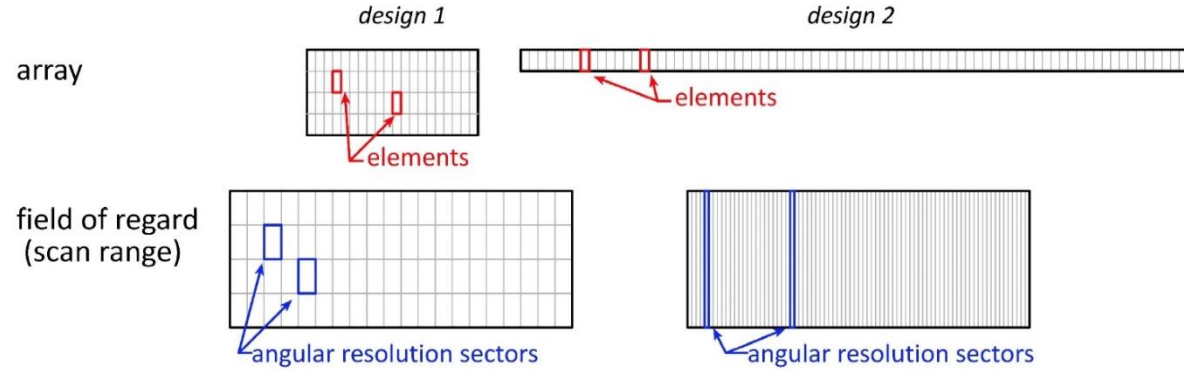
$1/\sin^2\phi$ sidelobes provide strong signals to tall buildings.

Providing sidelobes reduces broadside gain by less than 3dB.

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

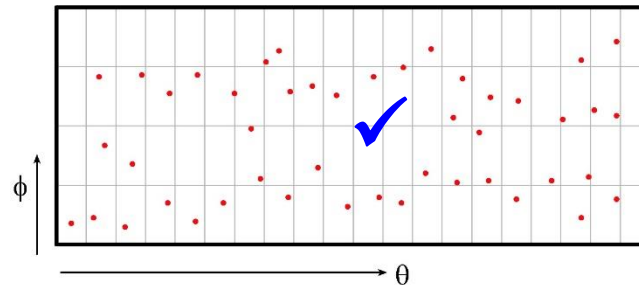


2D vs. 1D: user spatial distribution

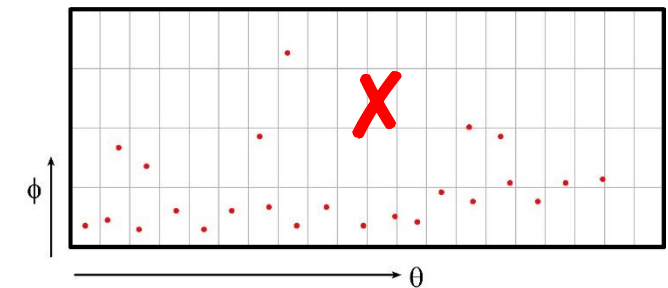


uniform horizontal & vertical user distributions

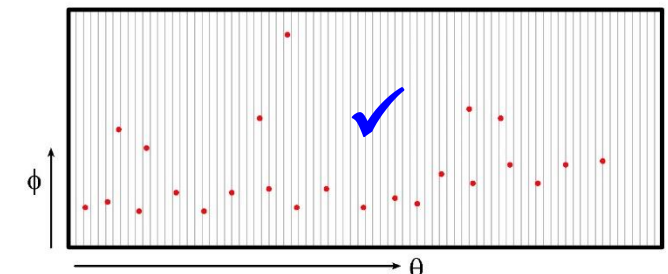
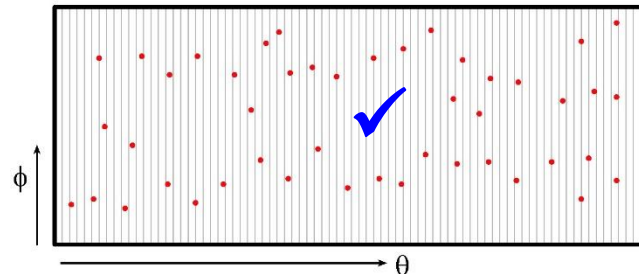
design 1: 2D array



uniform horizontal, nonuniform vertical

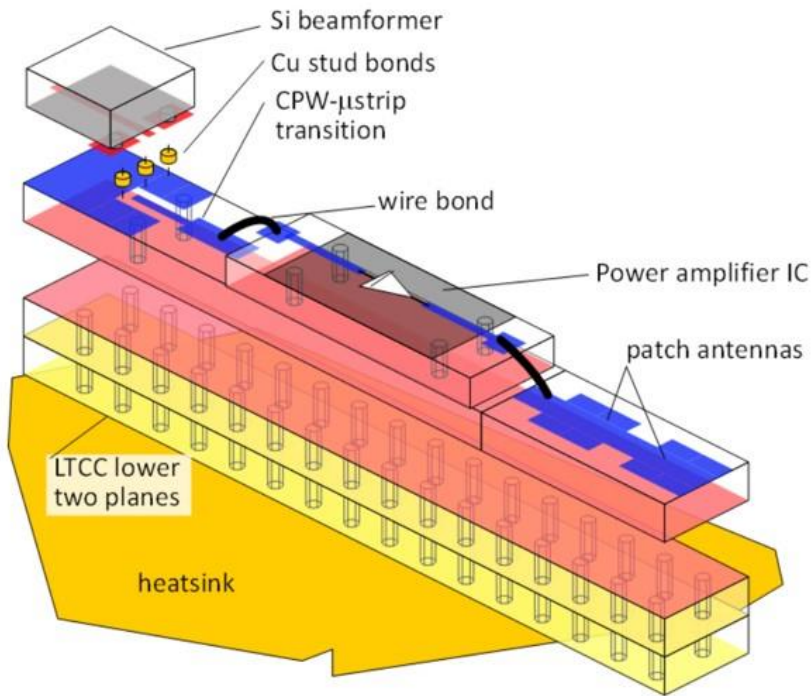


design 2: 1D array



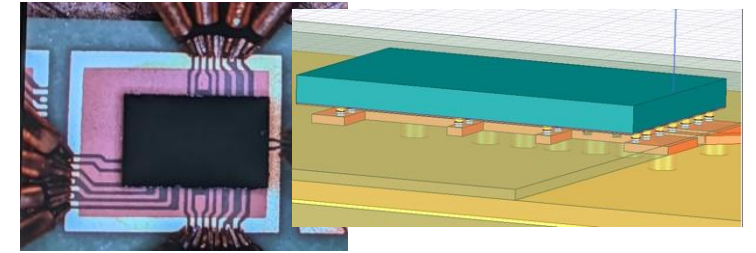
Spatial distribution of users, and of scattering objects, guides choice of array geometry.

140GHz hub: packaging challenges



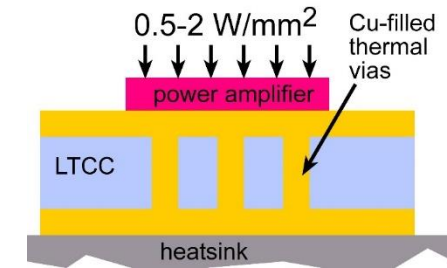
IC-package interconnects

Difficult at > 100 GHz



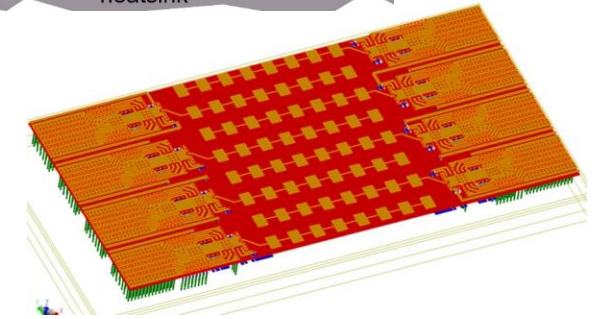
Removing heat

Thermal vias are marginal



Interconnect density

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

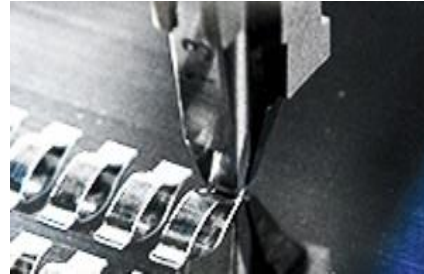
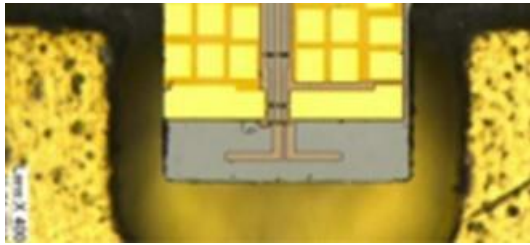


Economies of scale

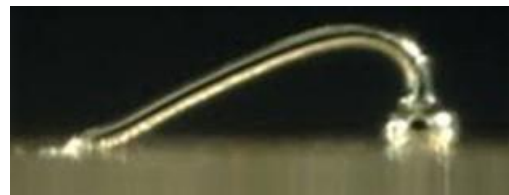
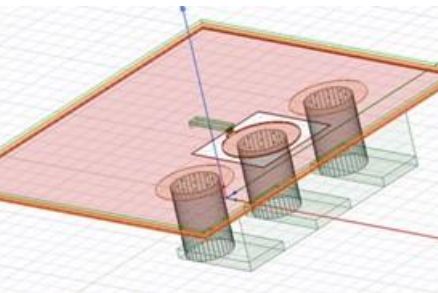
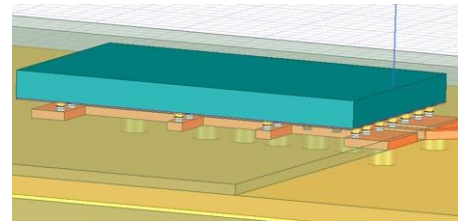
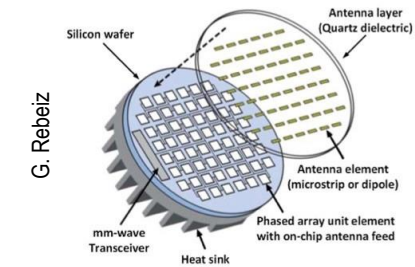
Advanced packaging standards require sophisticated tools
High-volume orders only
Hard for small-volume orders (research, universities)
Packaging industry is moving offshore

100-300GHz IC-package connections

Deal, IEEE Trans THz, Sept 2011

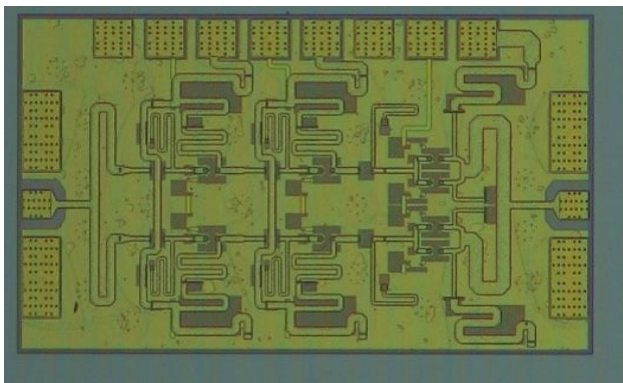


type	Frequency	technology	cost	heatsinking
micromachined waveguide interface	1000 GHz	Research. Cheap one day ?	high X	good
ribbon, mesh bond	200 GHz	Handcrafted.	high X	good
patch antennas on superstrate	1000 GHz	Straightforward	low	good
Cu stud flip-chip	>200 GHz	Industry standard	low	ok, marginal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

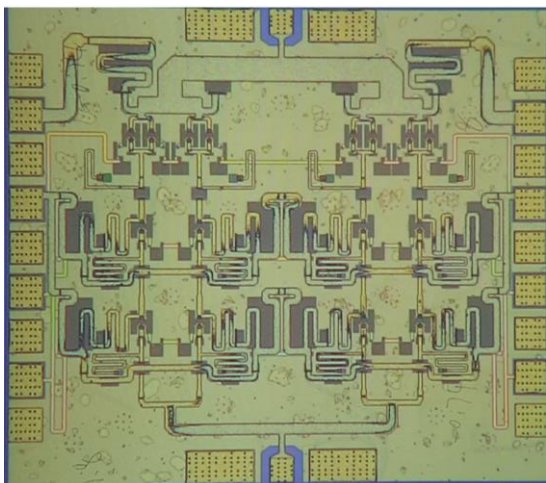


140GHz hub: ICs & Antennas

110mW InP Power Amplifier
20.8% PAE

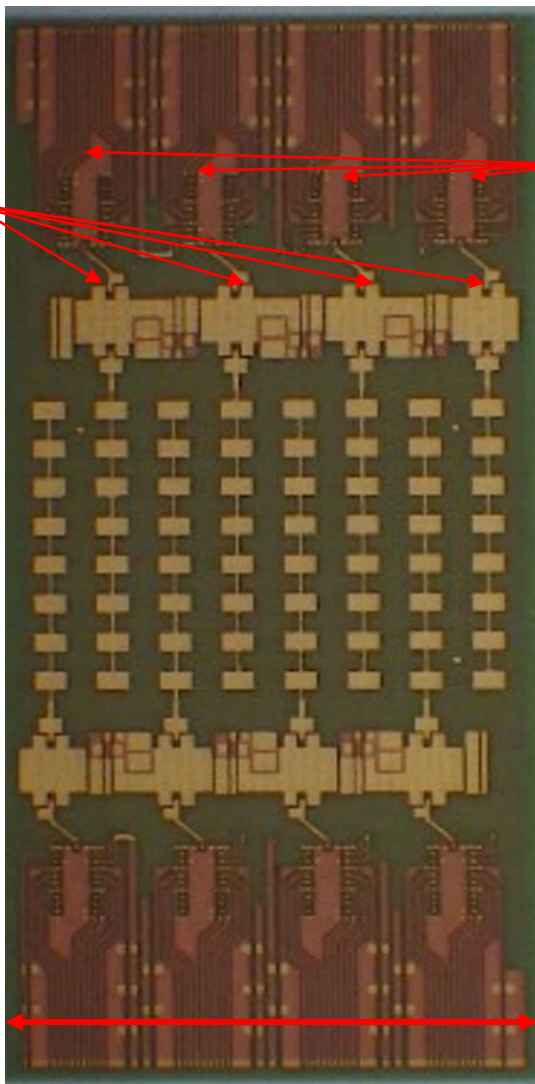


190mW InP Power Amplifier
16.7% PAE



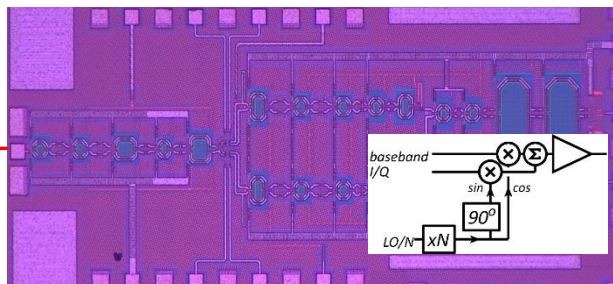
Teledyne InP HBT

LTCC Array module

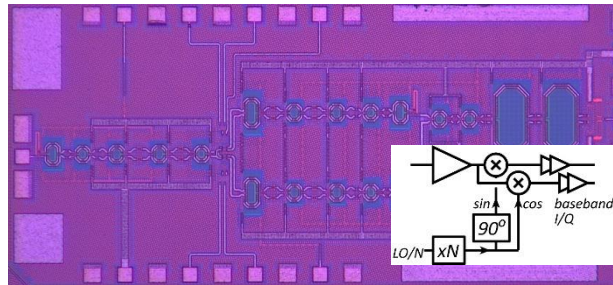


Kyocera

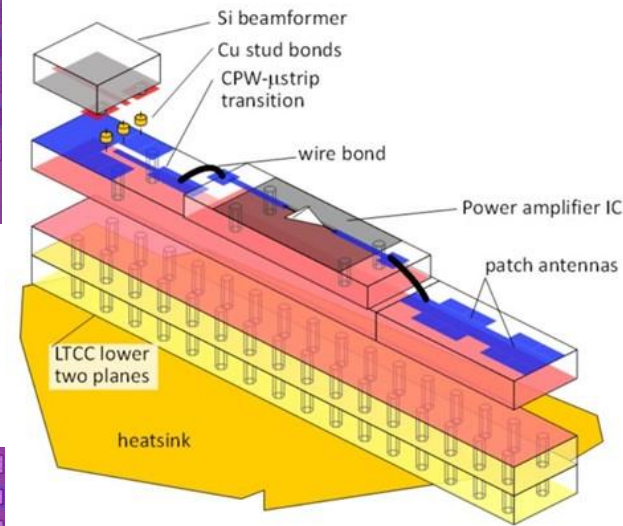
CMOS Transmitter IC
22nm SOI CMOS.



Receiver IC
22nm SOI CMOS.



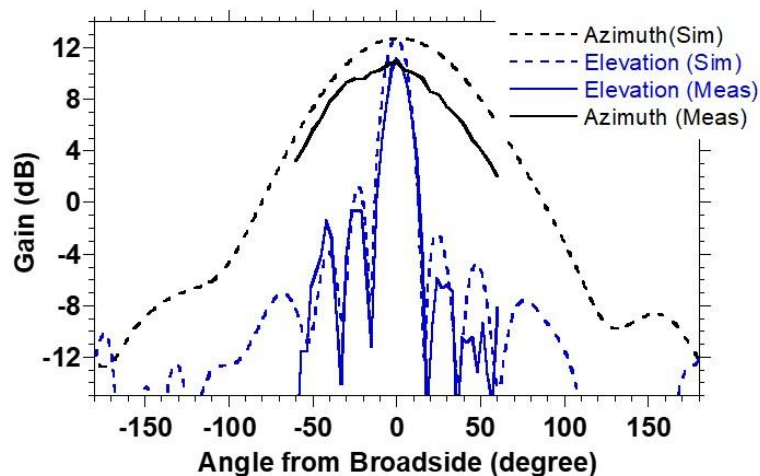
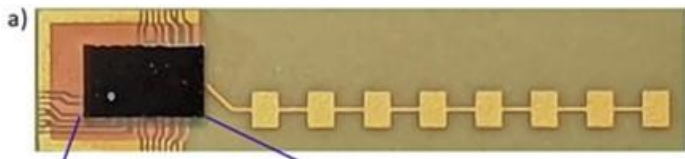
GlobalFoundries 22nm SOI CMOS



140GHz transmitter channel

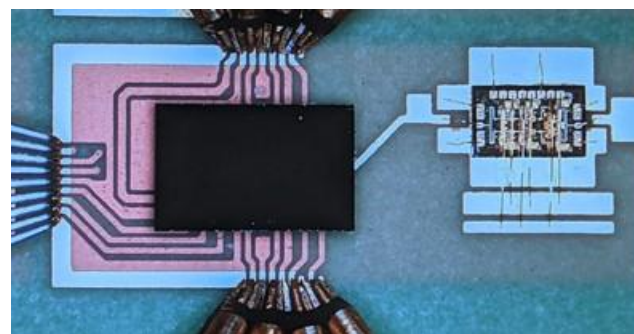
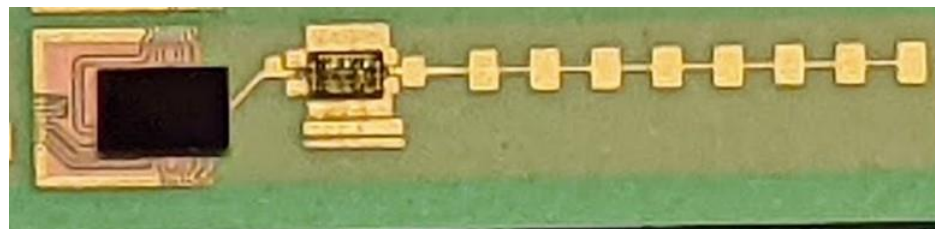
Farid, 2021 IMS, RFIC

CMOS-only TX channel

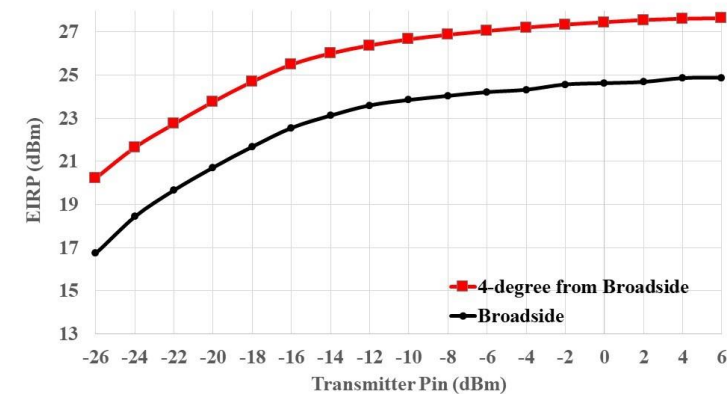


rate	4 Gbaud	4 Gbaud	2 Gbaud
power	3dB backoff	6dB backoff	8dB backoff
EVM (RMS)	7.9%	9.2%	7.4%

CMOS+InP TX channel

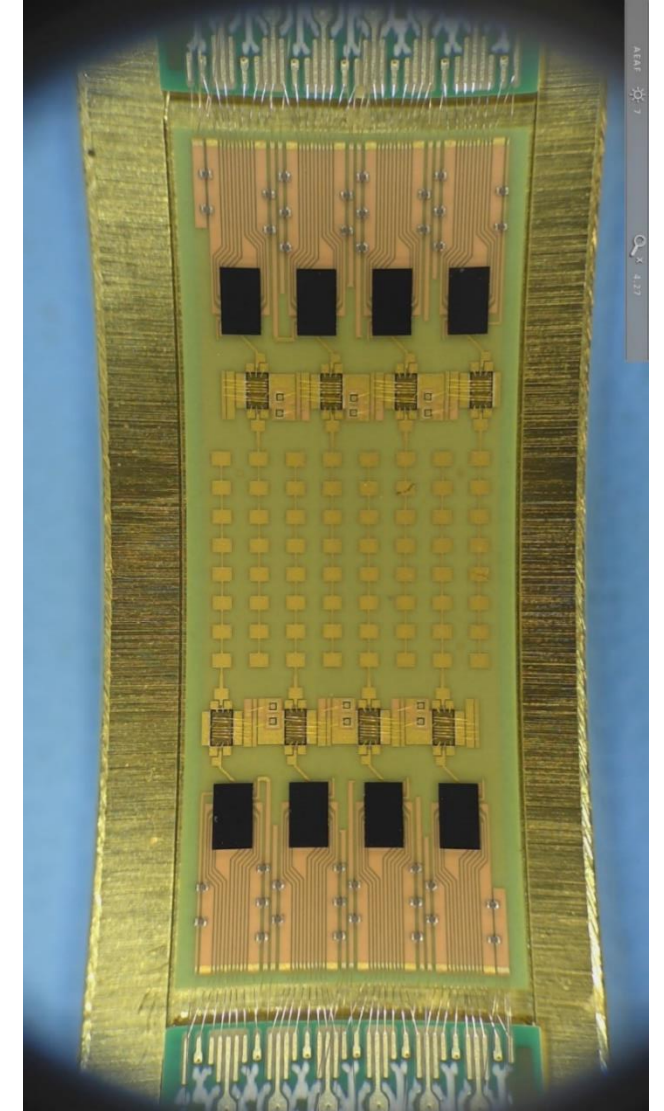
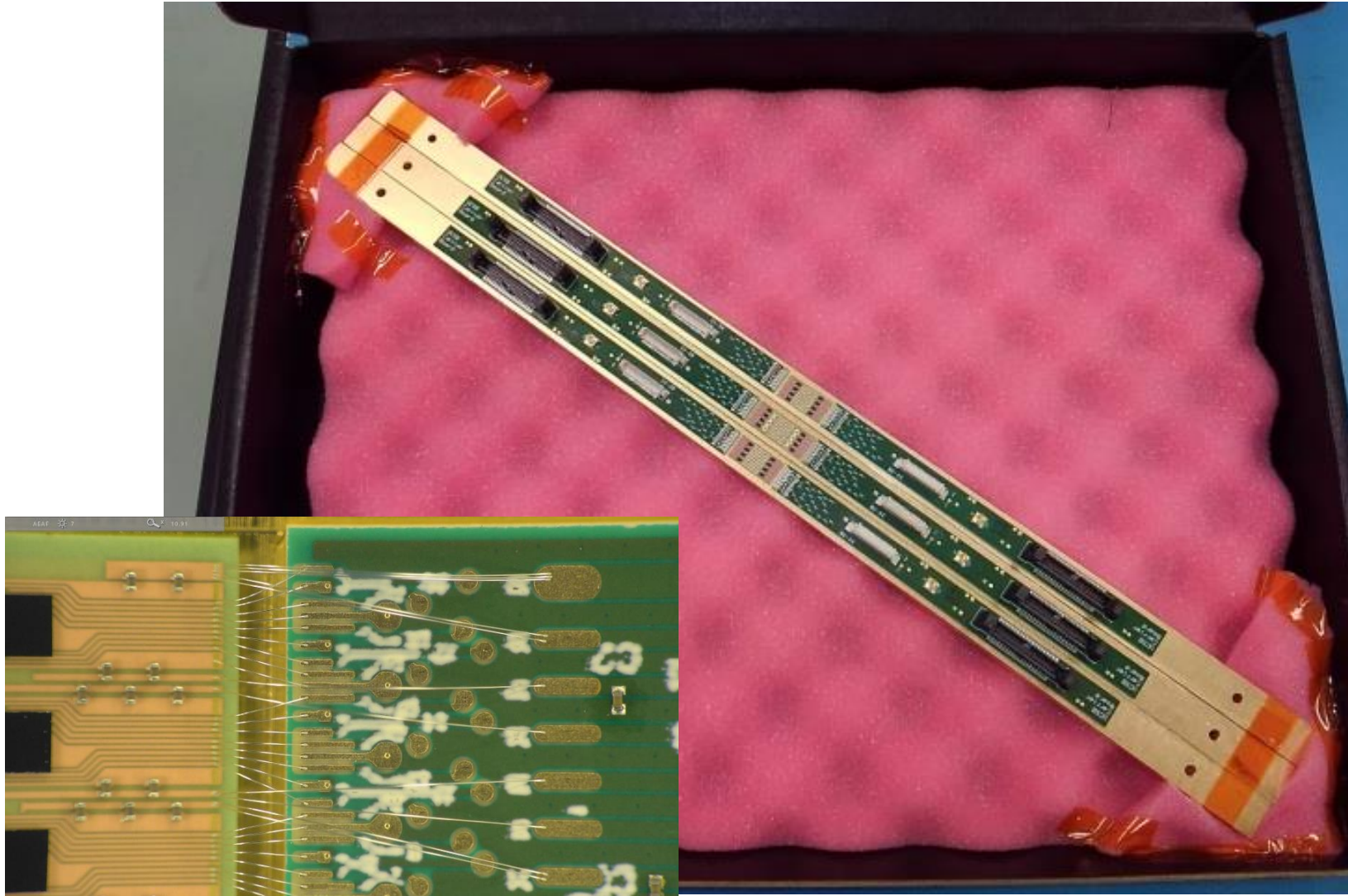


135GHz Transmitter's EIRP Vs Pin



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

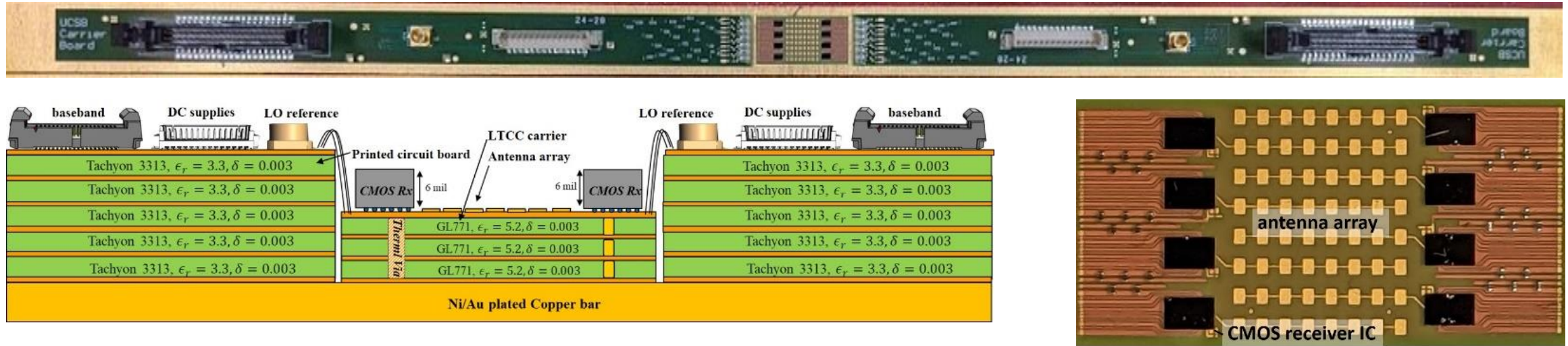
8-Channel 140GHz MIMO hub modules



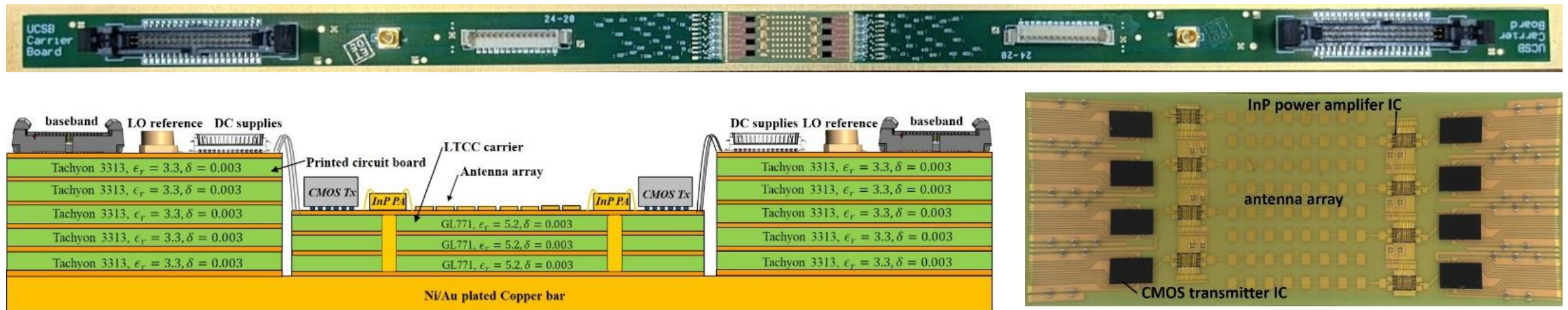
135GHz 8-channel MIMO hub array tile modules

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

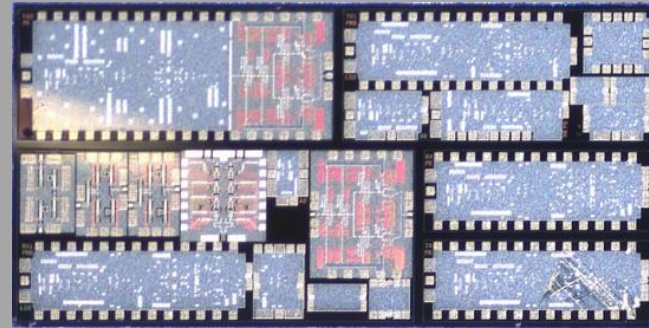
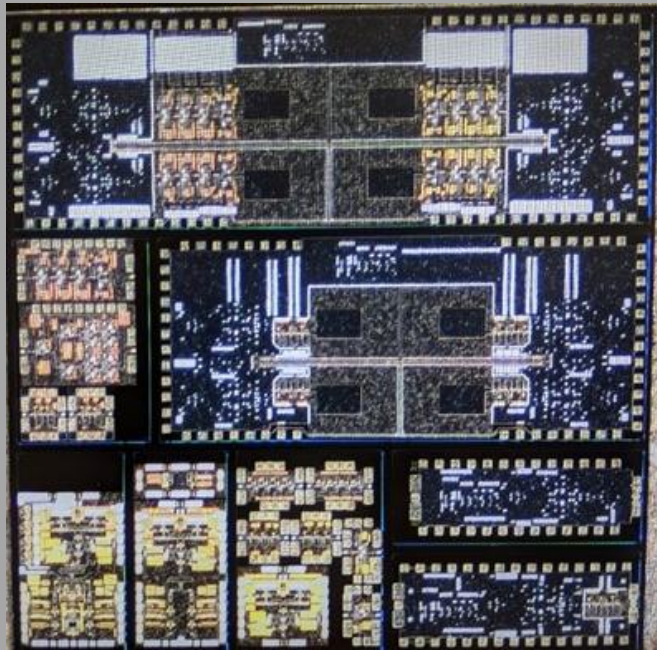
Receiver



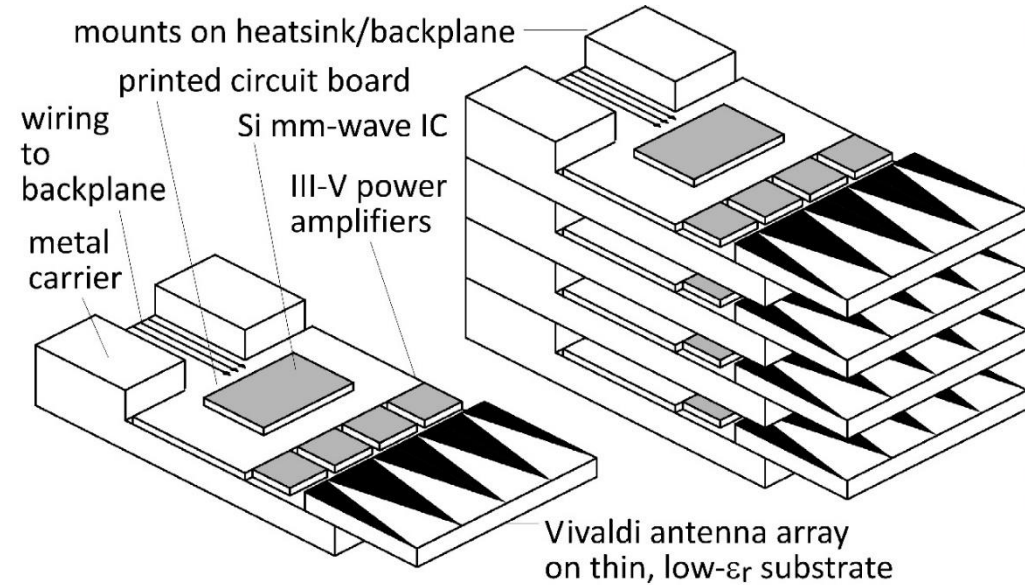
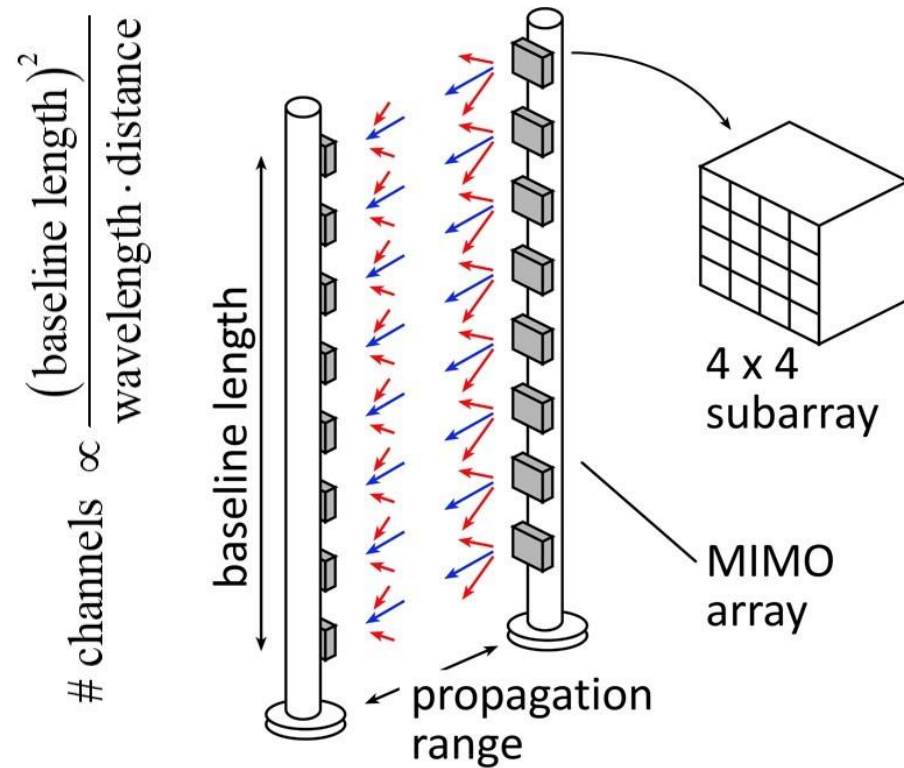
Transmitter



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 \rightarrow 640Gb/s total

4 x 4 sub-arrays \rightarrow 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

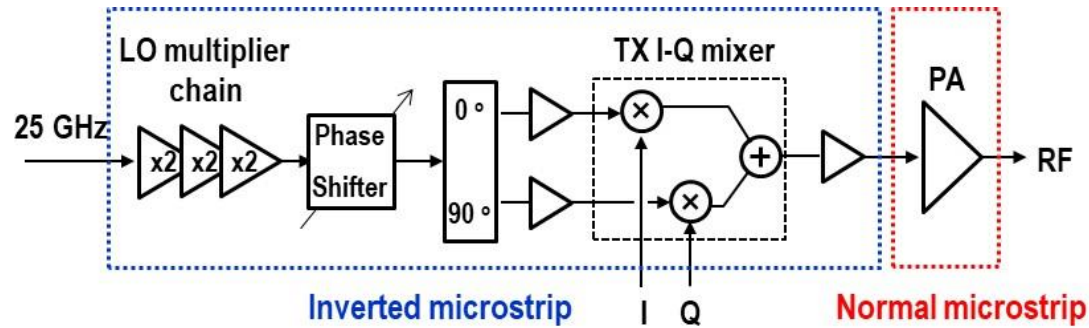
PAs: 63mW = $P_{1\text{dB}}$ (per element)

LNAs: 6dB noise figure

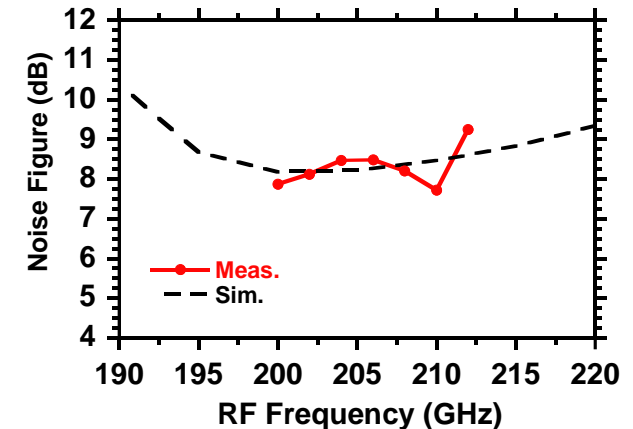
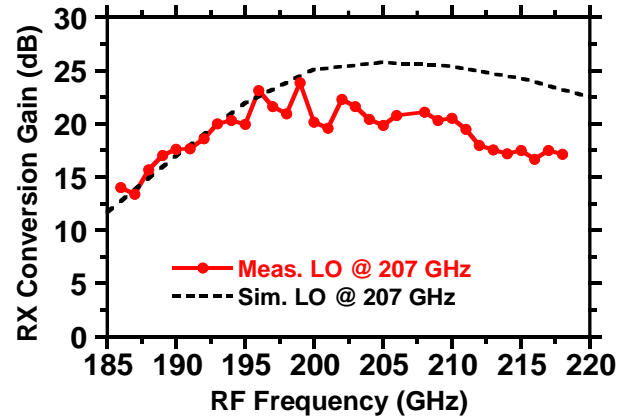
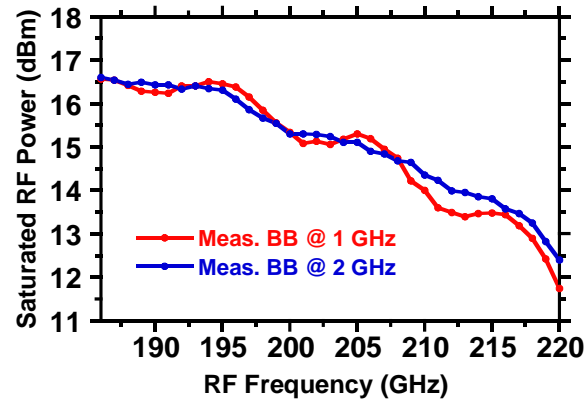
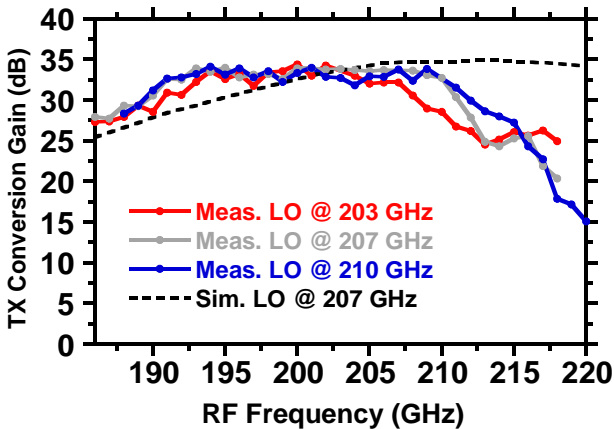
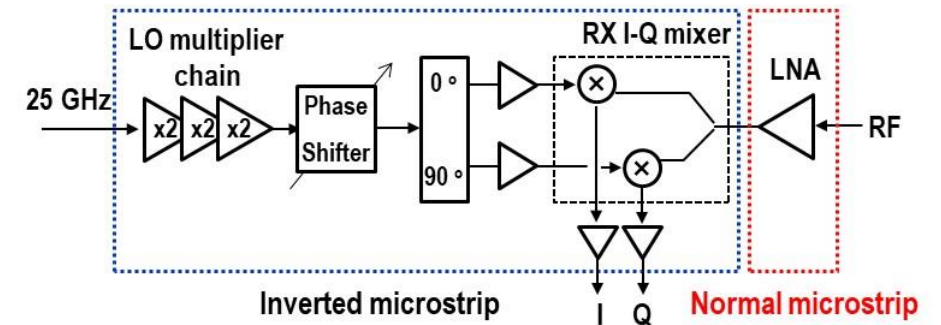
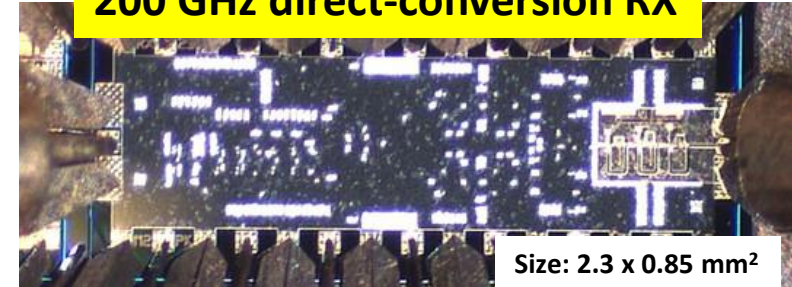
210 GHz Transmitter and Receiver ICs

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

200 GHz direct-conversion TX

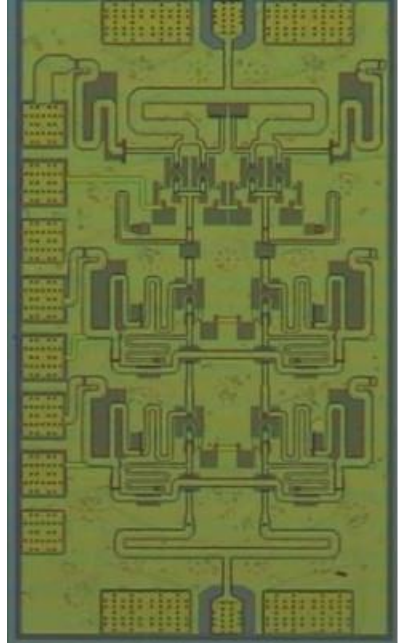


200 GHz direct-conversion RX

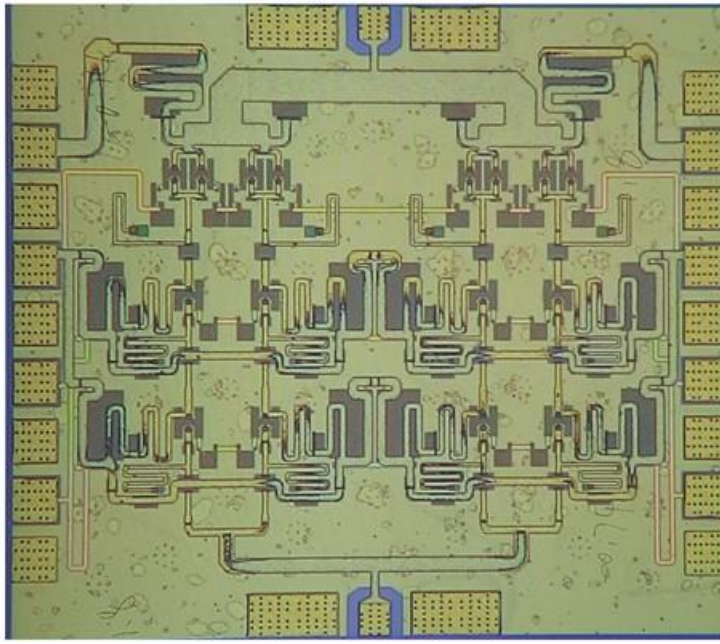


Power Amplifiers in 250nm InP HBT

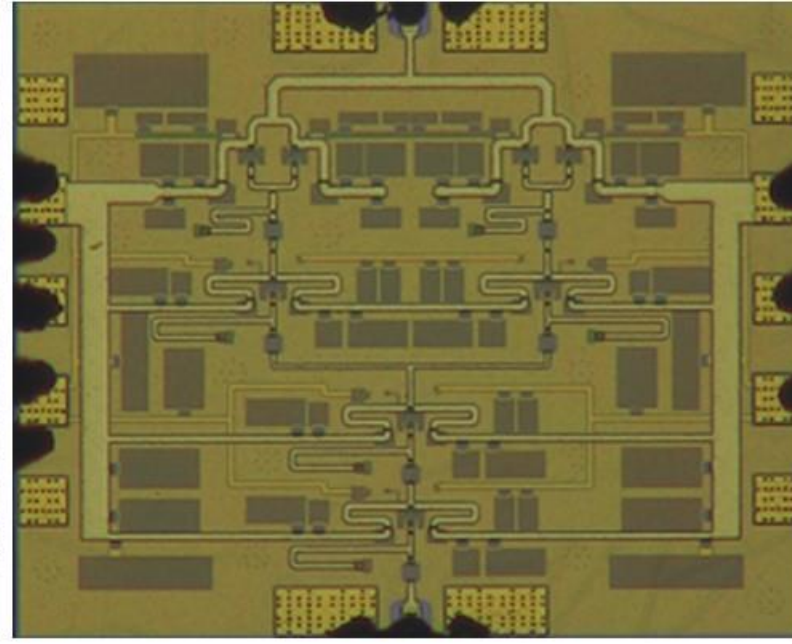
Ahmed et al, 2020 IMS, 2020 EuMIC, 2021 IMS, 2021 RFIC
Teledyne 250nm InP HBT technology



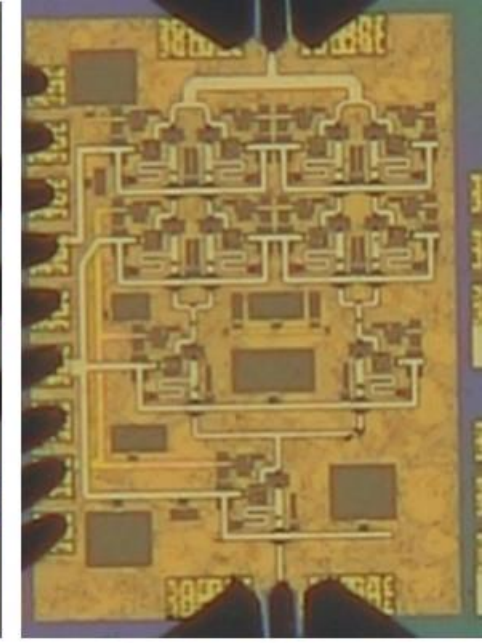
140GHz, 20.5dBm, 20.8% PAE



130GHz, 200mW, 17.8% PAE



194GHz, 17.4dBm, 8.5% PAE



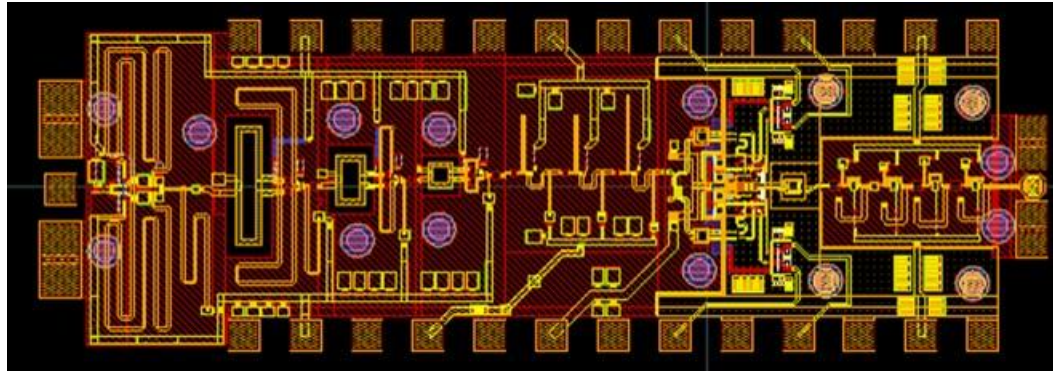
266GHz, 16.8dBm, 4.0% PAE

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

280GHz transmitter and receiver IC designs

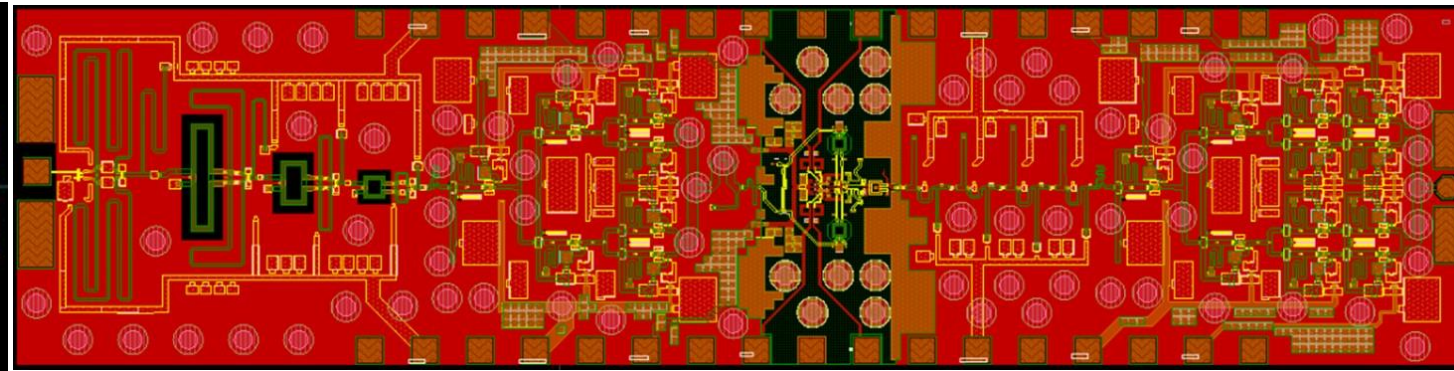
Solyu, Alz, Ahmed, Seo; UCSB/Sungkyunkwan
Teledyne 250nm InP HBT technology

Receiver



simulations: 11dB noise figure, 40GHz bandwidth

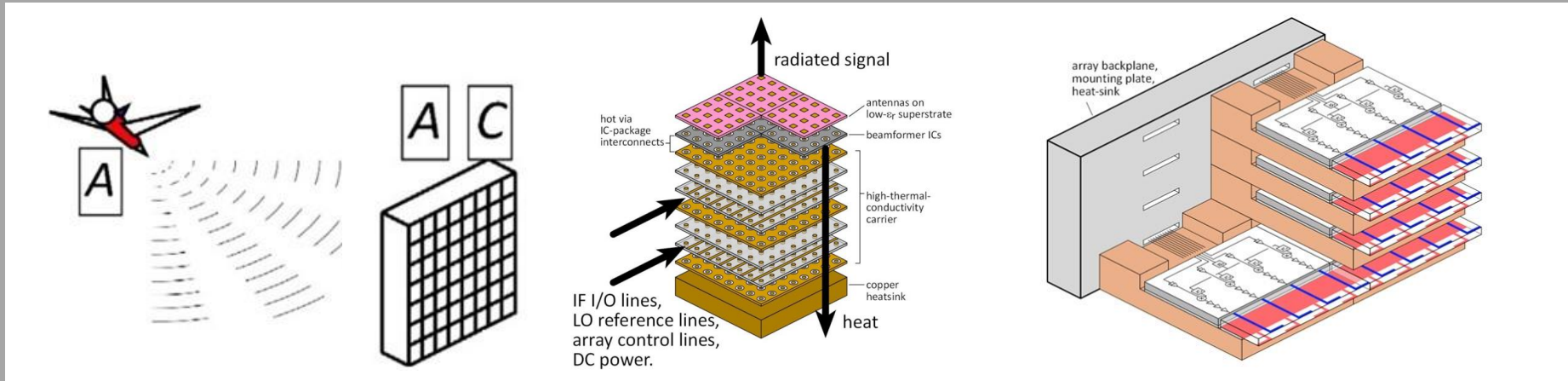
Transmitter



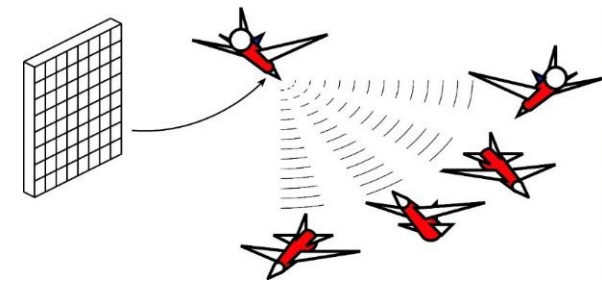
simulations: 17dB saturated output power.

Application: point-point MIMO backhaul links

2D arrays



The 100-300GHz 2D Array Challenge



System architecture:

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

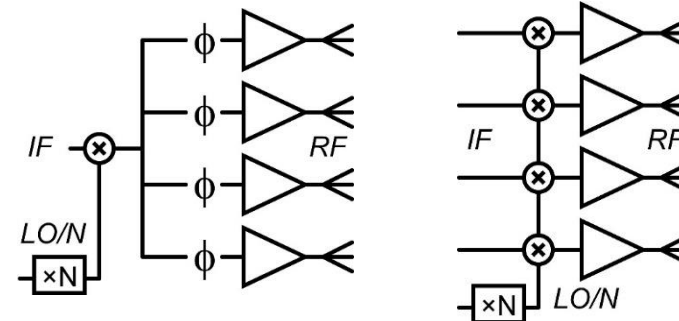
MIMO: complex digital baseband, flexible, many beams

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

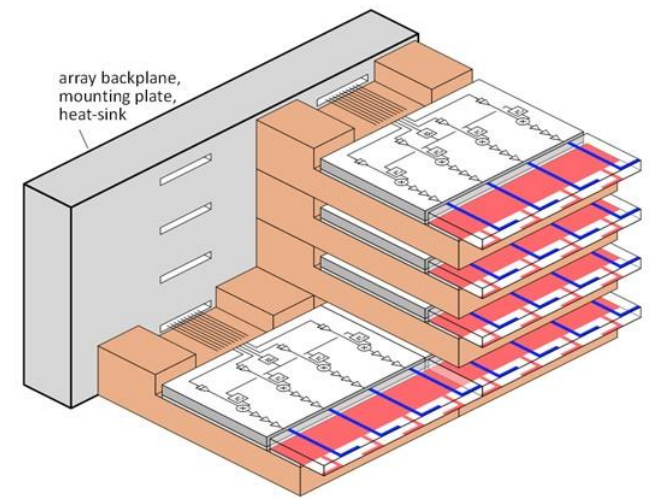
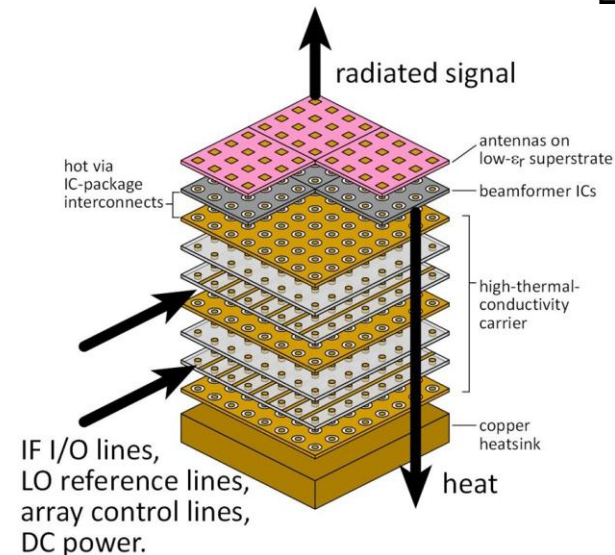
Arrays must be vast: 100-1,000-10,000 elements

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

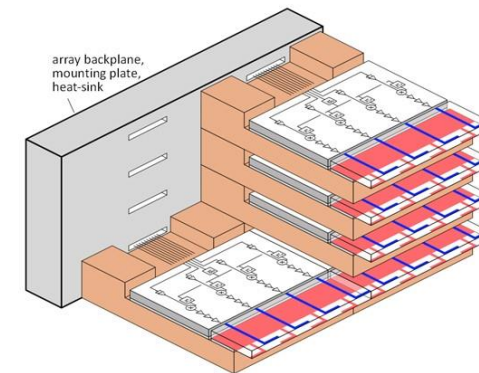
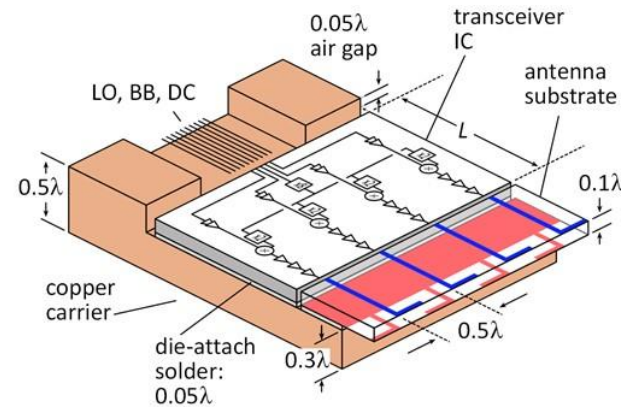
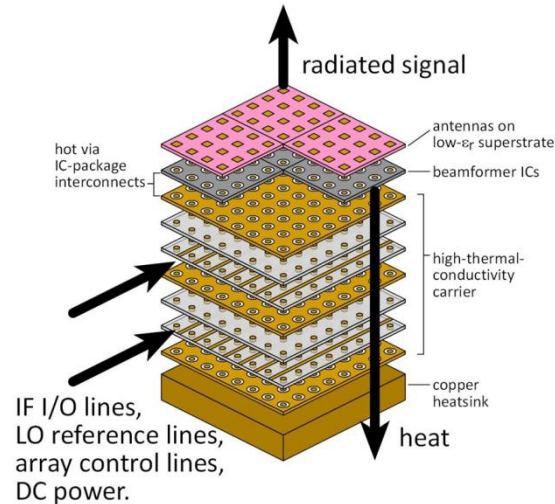
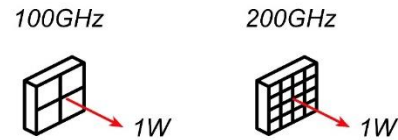


100-300GHz array frequency scaling

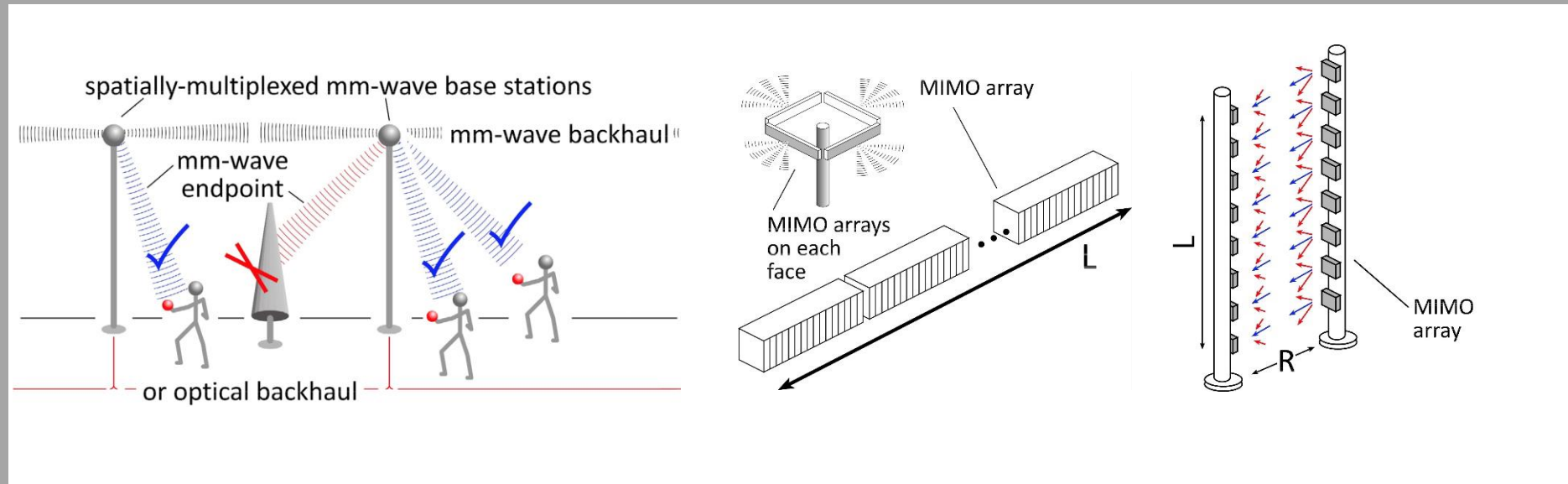
$$P_{received} = \frac{A_t A_r}{\lambda^2 R^2} e^{-\alpha R} \cdot P_{trans} \longrightarrow \# \text{beams} \cdot (\text{bit rate per beam}) \cdot kTF \cdot \text{SNR} = \frac{A_t A_r}{\lambda^2 R^2} e^{-\alpha R} \cdot P_{trans}$$

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

Proposed scaling law	change	Implication	change
carrier frequency	increase 2:1	capacity (# beams · bit rate per beam)	increases 4:1
aperture area	keep constant	number elements	increases 4:1
total transmit power	keep constant	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.

SiGe or 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)

Updated tech comparsion
slide

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

