2021 IEEE BiCMOS and Compound Semiconductor Integrated Circuits and Technology Symposium (BCICTS): December 6-9

100-300GHz Wireless:
ICs, Arrays, and Systems

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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

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

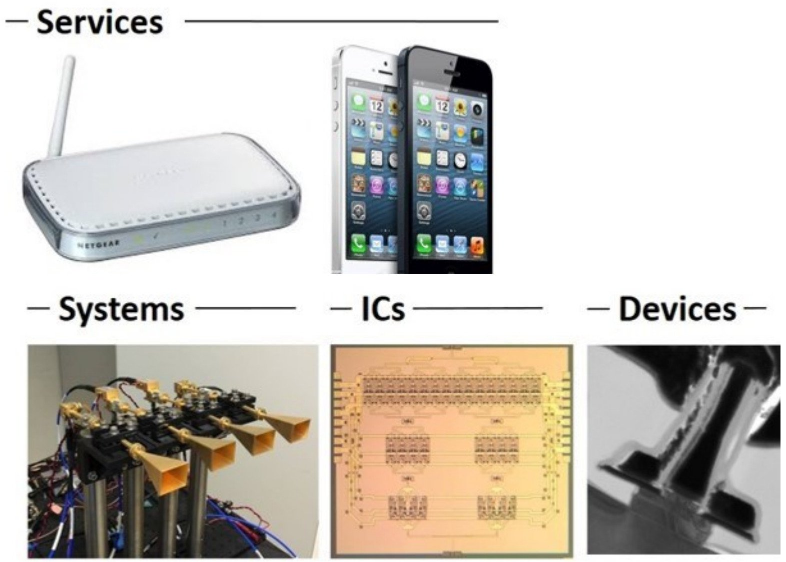
140/210/280GHz arrays for demos.

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

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

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

100-300GHz Wireless

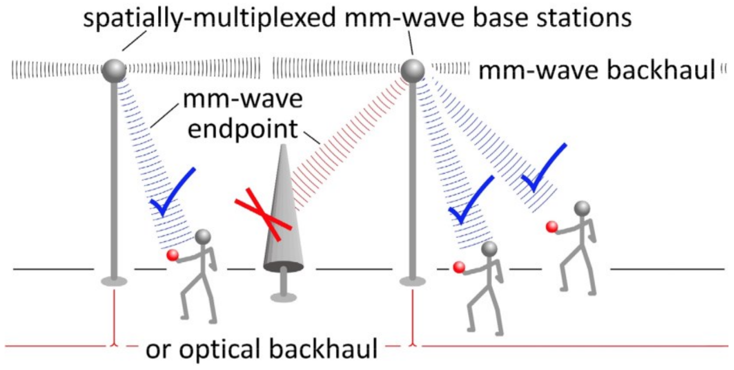


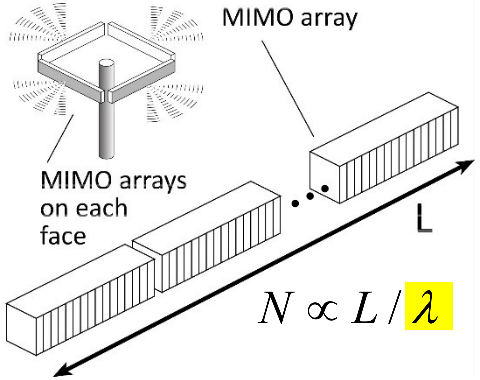
Wireless networks: exploding demand.

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

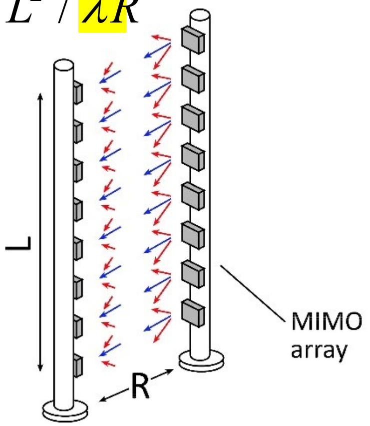
100-300GHz carriers, massive spatial multiplexing
→ Terabit hubs and backhaul links, high-resolution imaging radar

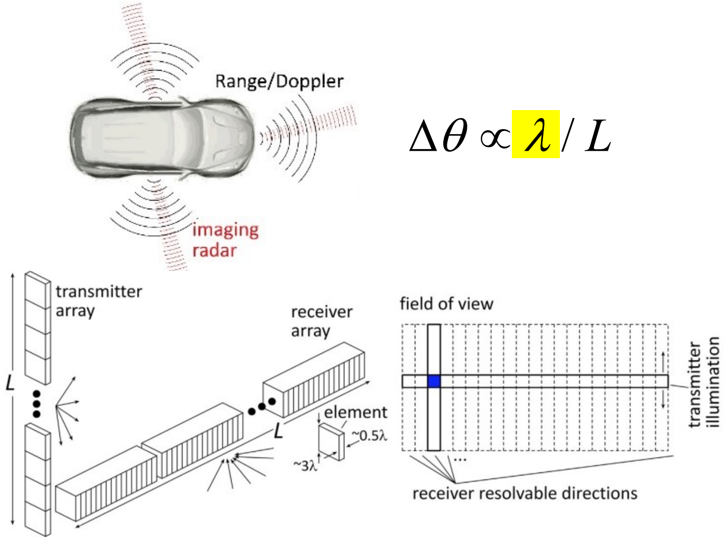




$N \propto L / \lambda$

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

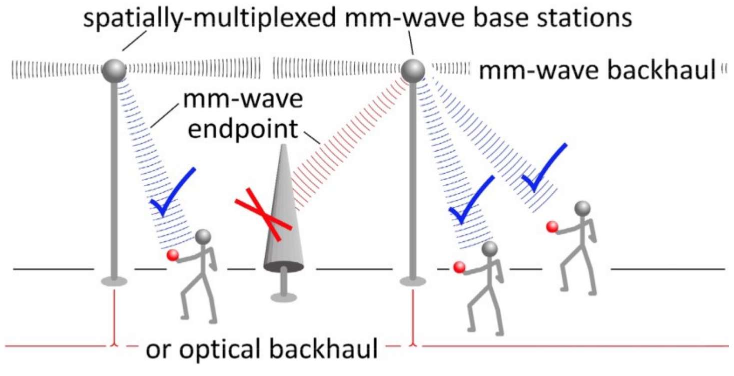


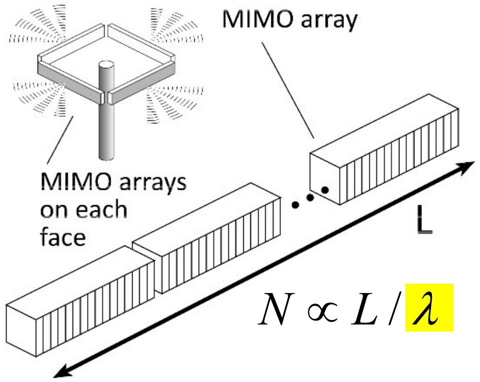


$\Delta\theta \propto \lambda / L$

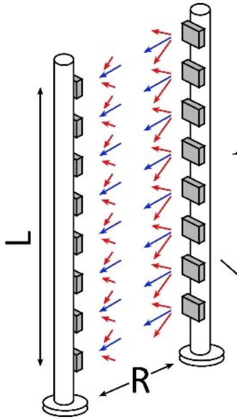
Benefits of Short Wavelengths

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



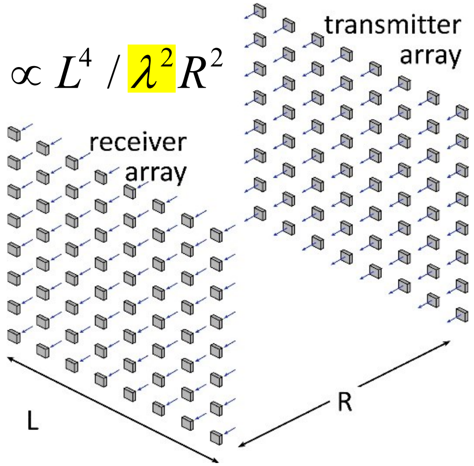


$$N \propto L / \lambda$$

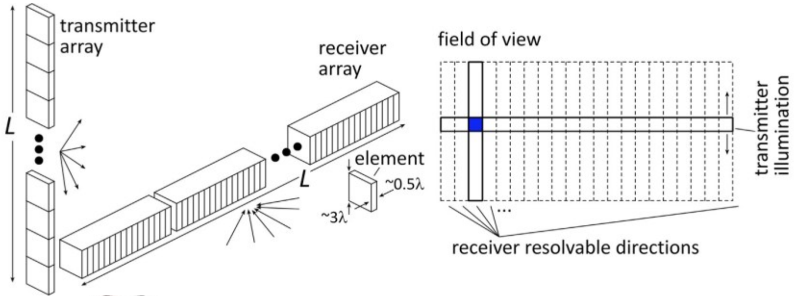


$$N \propto L^2 / \lambda R$$

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



Imaging: very fine angular resolution

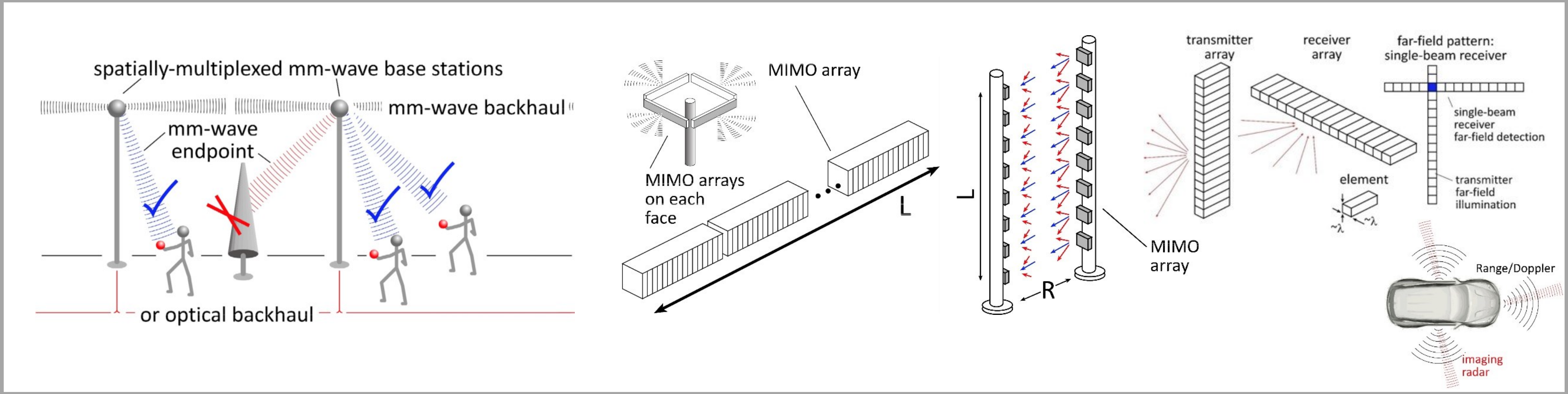


$$\Delta\theta \propto \lambda / L$$

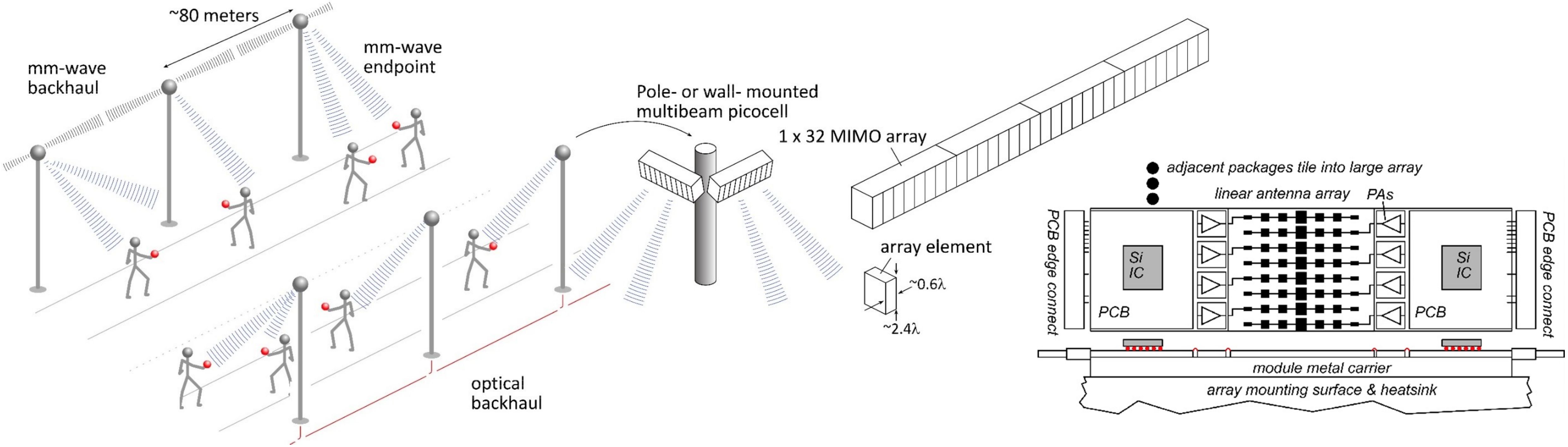
But:
High losses in foul or humid weather.
High λ^2/R^2 path losses.
ICs: poorer PAs & LNAs.
Beams easily blocked.

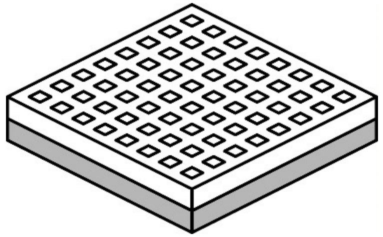
100-340GHz wireless:
terabit capacity,
short range,
highly intermittent

Applications



140GHz 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=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

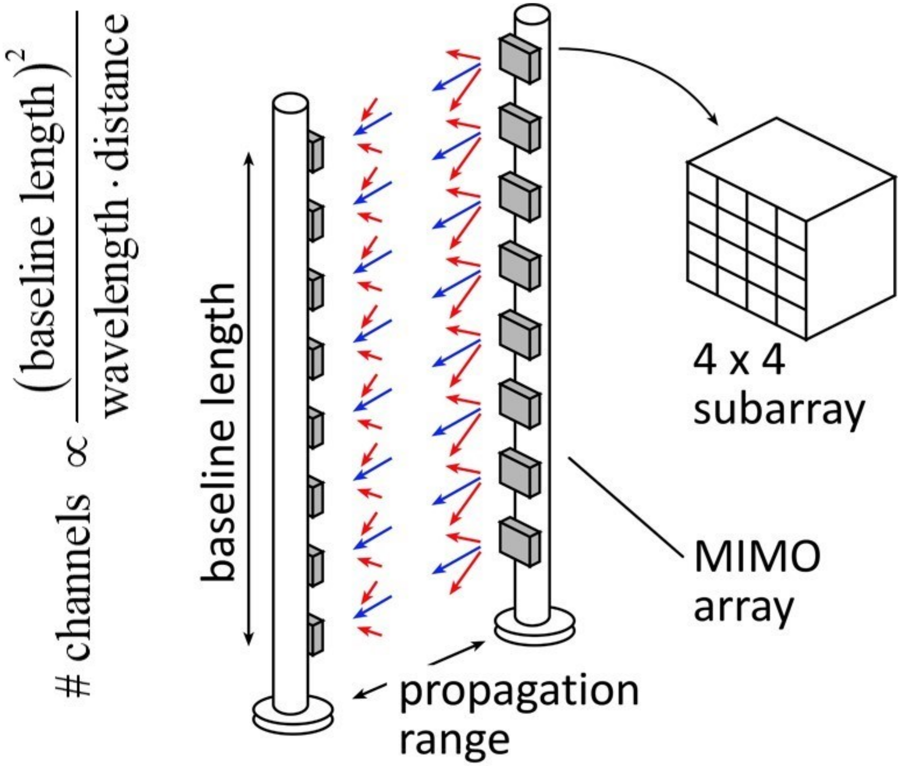
70 GHz spatially multiplexed base station

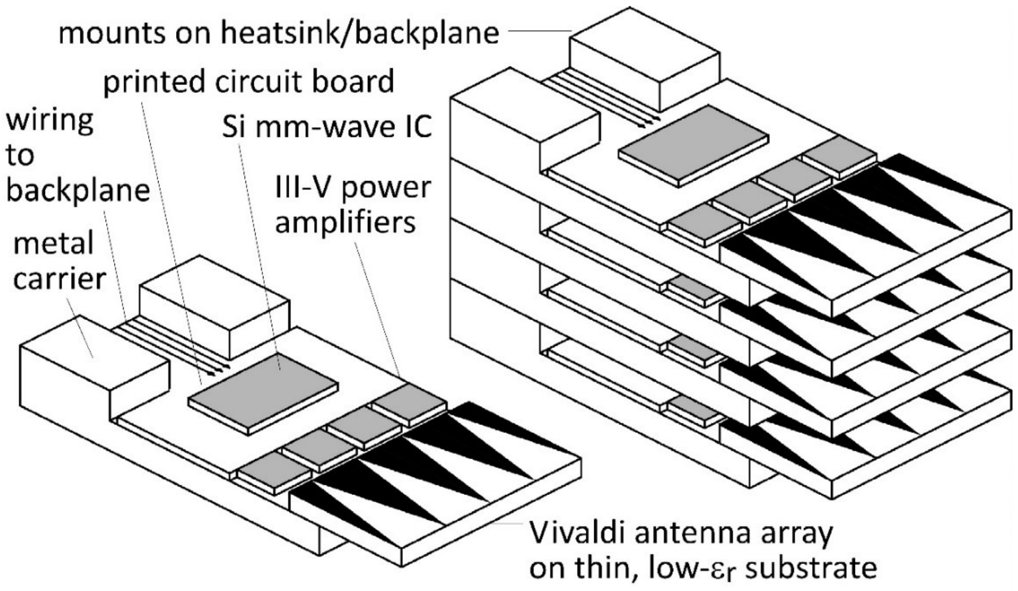
If we use instead a 70GHz carrier,
the range increases to **70 meters** (vs. **40 meters**)
but the handset becomes **16mm×16mm** (vs. 8mm×8mm),
and the hub array becomes 19mm×612mm (vs. 10mm×328mm)

Or, use a 4×4 (**8mm×8mm**) handset array,
and the range becomes ..**about 40 meters**.

Same handset area (more handset elements)→ same link budget
Easier to obtain license for 140±2.5GHz than 70±2.5GHz

210 GHz, 640 Gb/s MIMO Backhaul





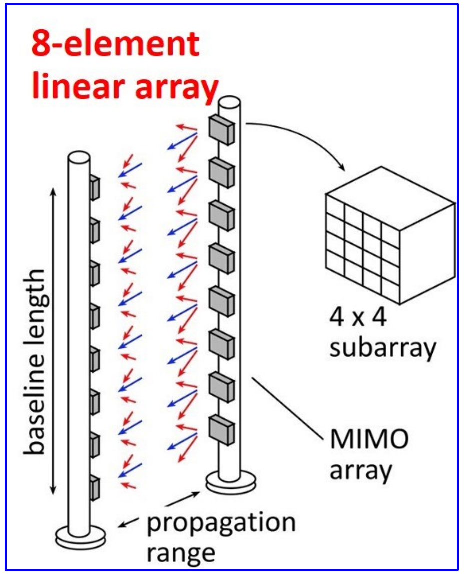
8-element MIMO array
2.1 m baseline.
80Gb/s/subarray→ 640Gb/s total
4 × 4 sub-arrays → 8 degree beamsteering

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

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

Why not use a lower-frequency carrier, e.g. 75 GHz ?

Must use at least 16QAM, given 80Gb/s/channel…



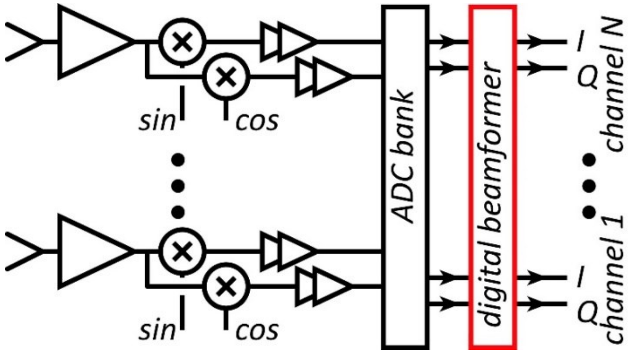
8-element 640Gb/s linear array:

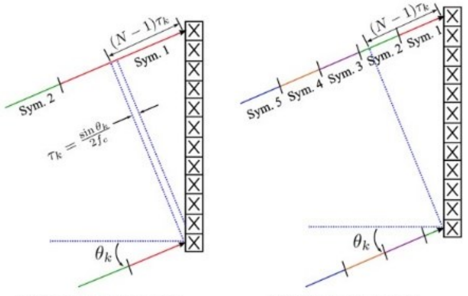
requires 16dB$_m$ transmit power/element (P$_{out}$)

requires 3.5m linear array

Similar RF power output, physically larger

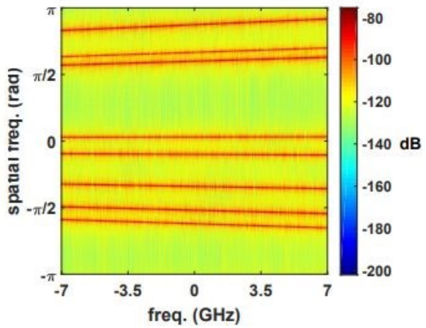
Systems



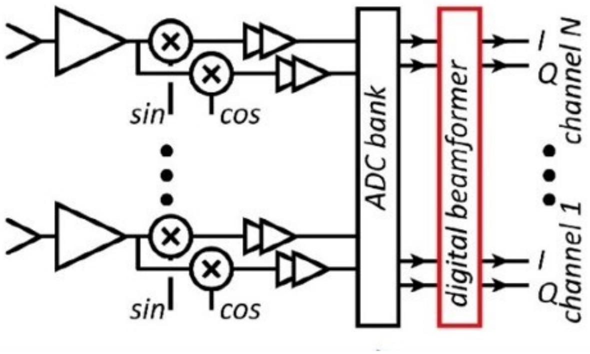


(a) Narrowband scenario.

(b) Wideband scenario.



System Design



ADCs/DACs[1]: QPSK needs only 3-4 bit ADC/DACs

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

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

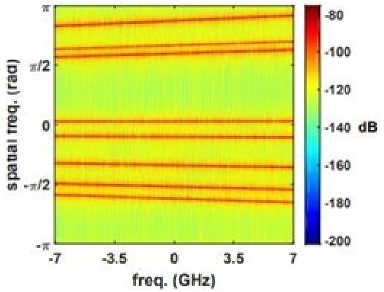
Linearity[1]: Amplifier P_{1dB} need be only 4 dB above average power

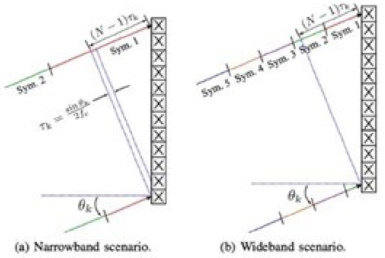
Phase noise[2,3]: Requirements same as for SISO

Efficient digital beamforming[4,5]: beamspace algorithm=complexity ~N× log(N)

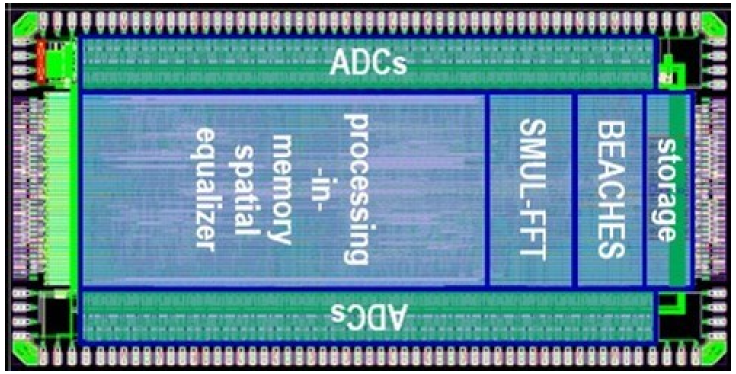
Efficient VLSI digital beamformer implementation[6]: low-resolution matrix

Efficiently beamforming in broadband arrays[7]: combined spatial & temporal FFTs.





(a) Narrowband scenario.
(b) Wideband scenario.



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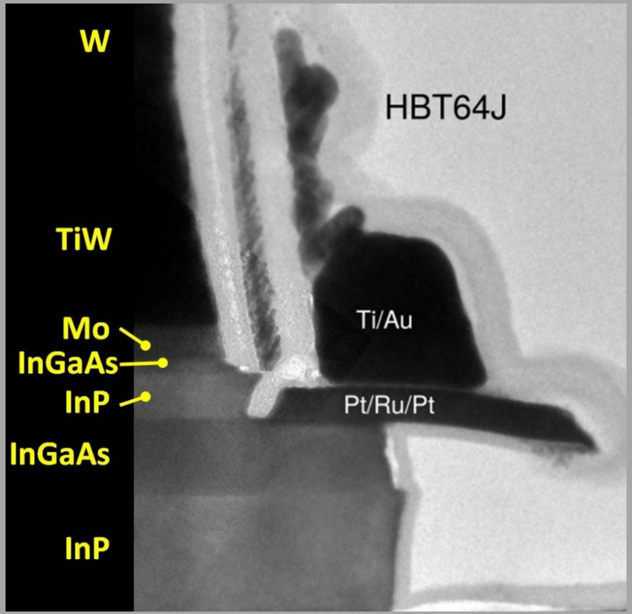
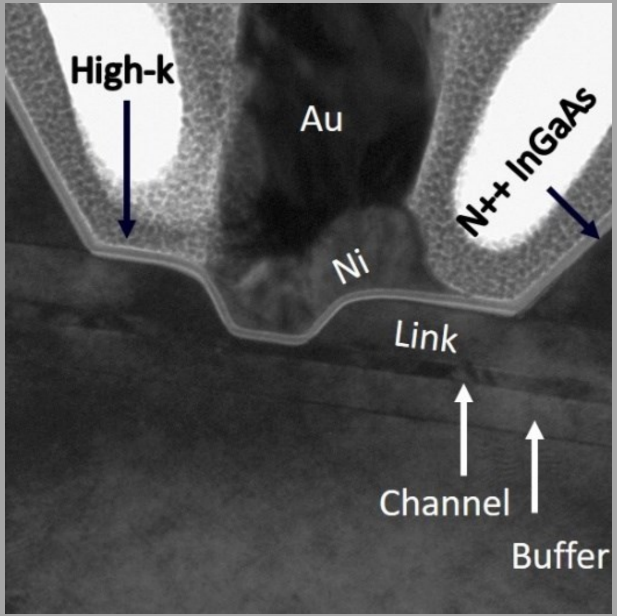
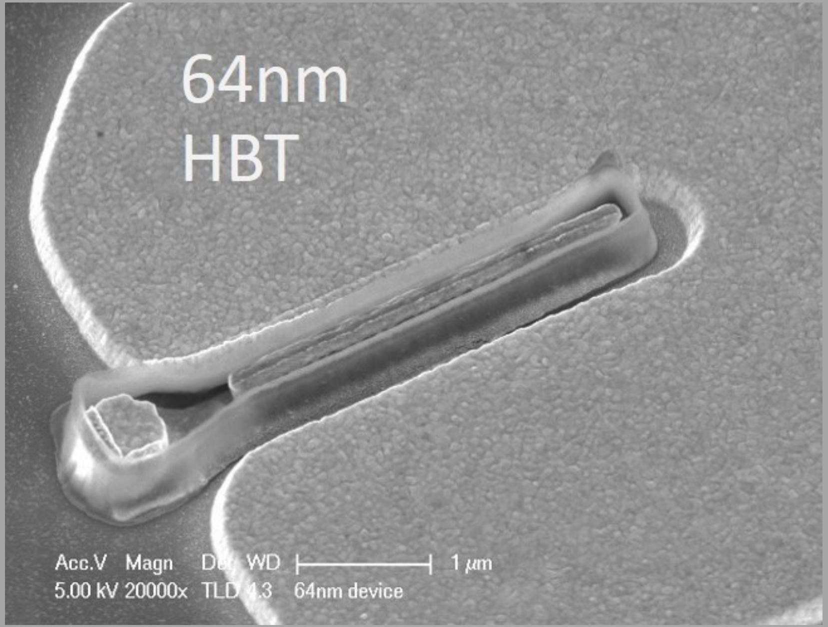
1) M. Abdelghany et al, IEEE Trans. Wireless Comm, Sept. 2021, doi: 10.1109/TWC.2021.3069378.
2) M. E. Rasekh et al, IEEE Trans. Wireless Comm, Oct. 2021, doi: 10.1109/TWC.2021.3074911.
3) A. Puglielli et al, 2016 IEEE ICC, doi: 10.1109/ICC.2016.7511631.
4) M. Abdelghany, et. al, , 2019 IEEE SPAWC: doi: 10.1109/SPAWC.2019.8815585
5) S. H. Mirfarshbafan et al, IEEE Trans CAS 1, 2020, doi: 10.1109/TCSI.2020.3023023
6) O Castañeda Fernández et. al, 2021 ESSCIRC
7) M. Abdelghany et al 2019 IEEE GLOBECOM doi: 10.1109/GLOBECOM38437.2019.9013233.

Transistors







Transistors for 100-300GHz

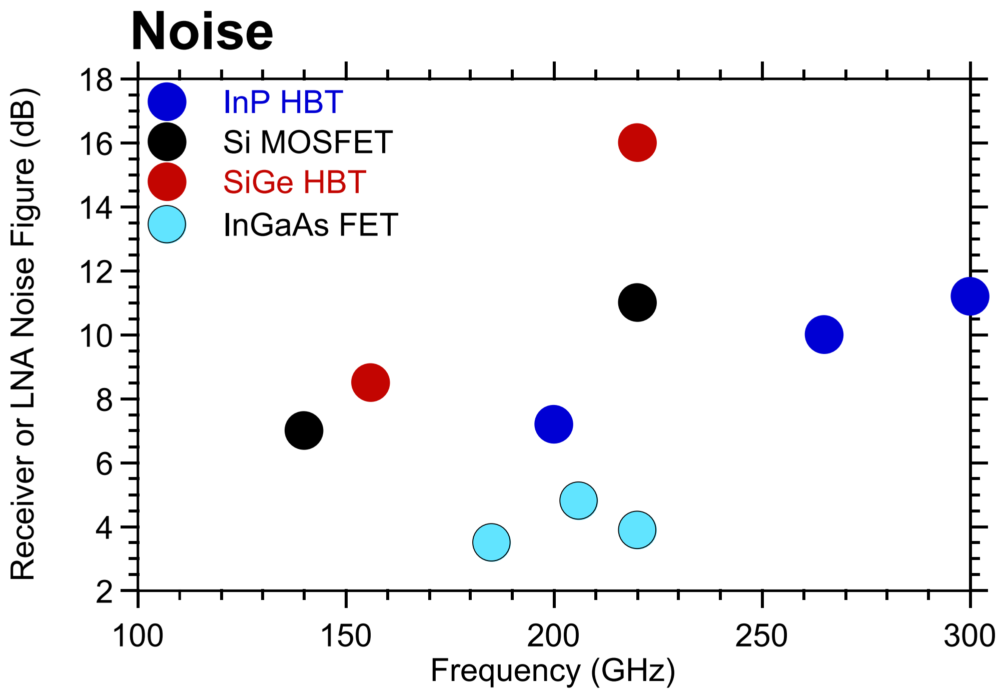
CMOS: good power & noise up to ~150GHz. Not much beyond. 65-32nm nodes are best.

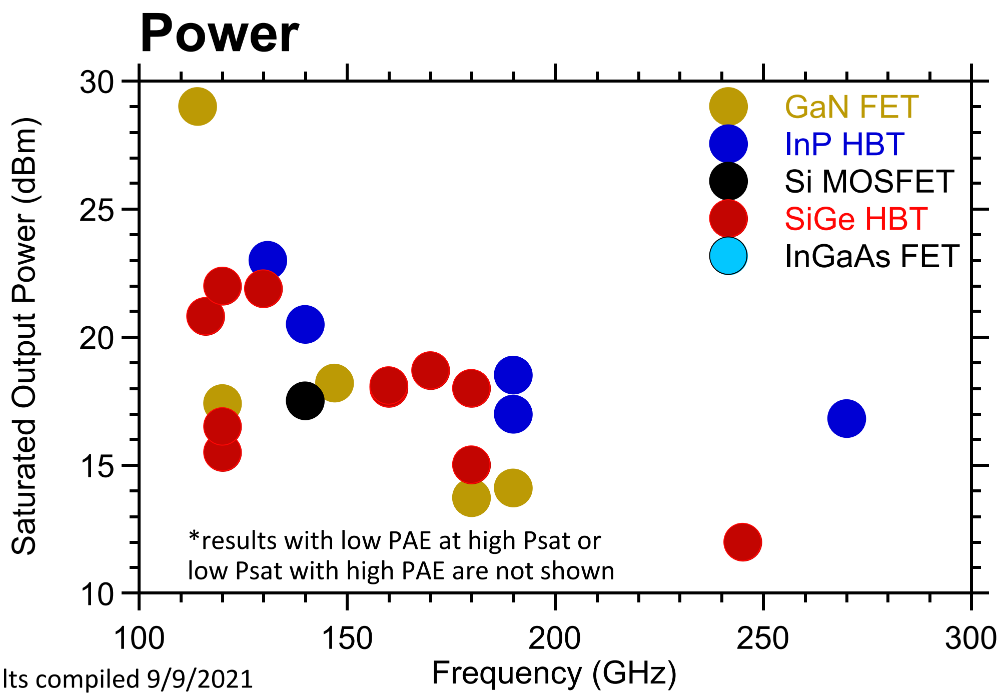
InP HBT: record 100-300GHz PAs

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

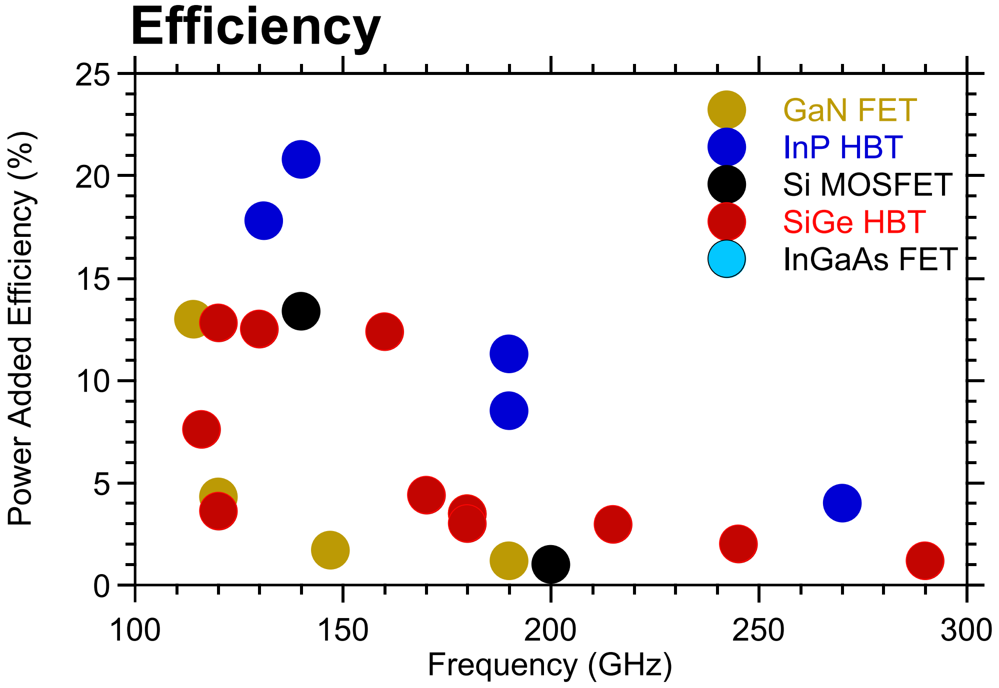
GaN HEMT: record power below 100GHz. Bandwidth improving

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





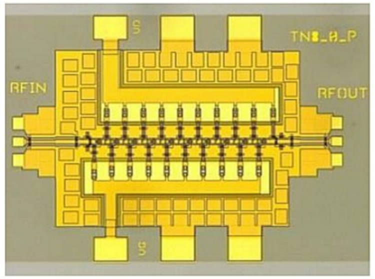
Results compiled 9/9/2021

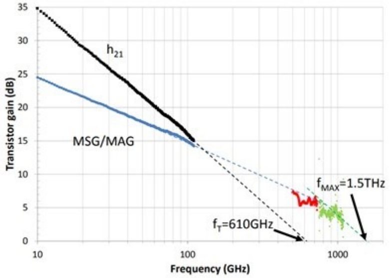


InP Transistors and ICs

InP HEMTs: 1.5THz f_{max}, 1.0THz amplifiers

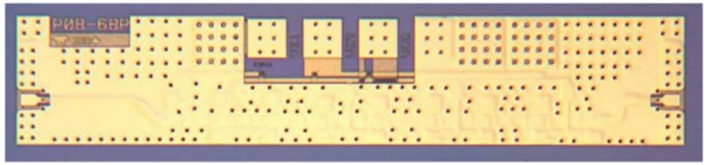
W. Deal et al, 2016 IEDM (Northrop-Grumman)

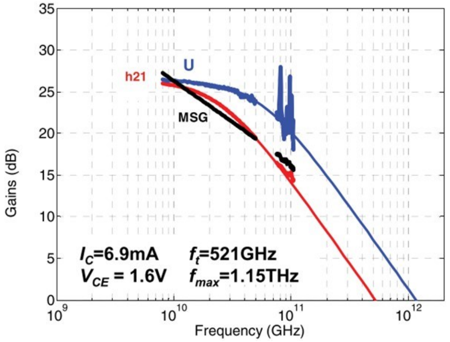


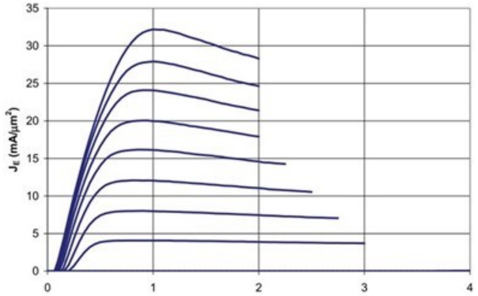


130nm InP HBTs: 1.1THz f_{max}, 3.5V. 670 GHz amplifiers

M. Urteaga, et al, IEEE Proceedings June 2017 (Teledyne)



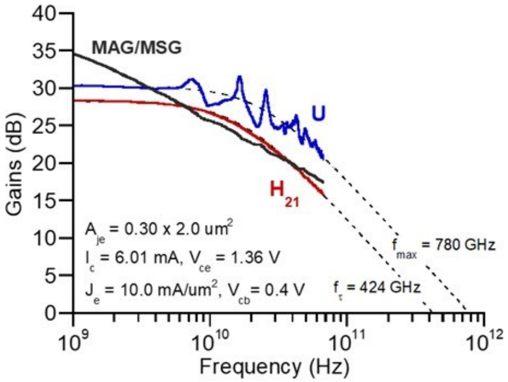


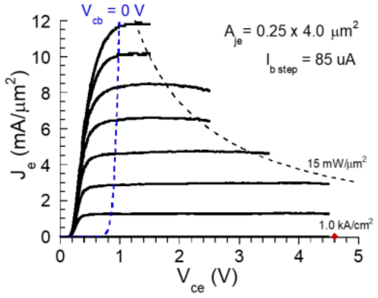


250nm InP HBTs: 650GHz f_{max}, 4.5V.

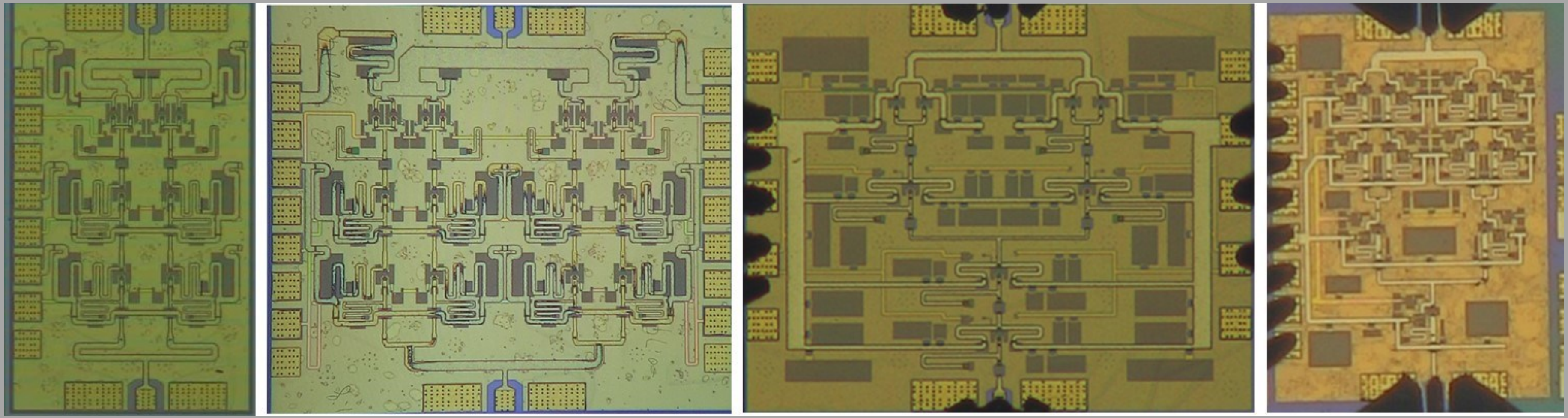
Z. Griffith et al, 2007 IPRM conference (UCSB)

M. Urteaga, et al, IEEE Proceedings June 2017 (Teledyne)



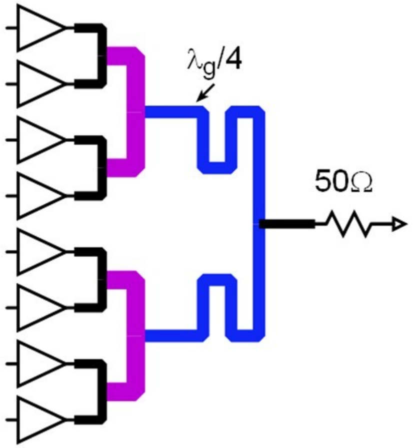


Power Amplifiers



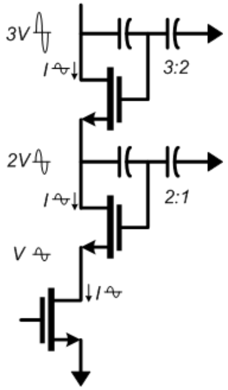
100-300GHz Power combining: what is best ?

Corporate T-line



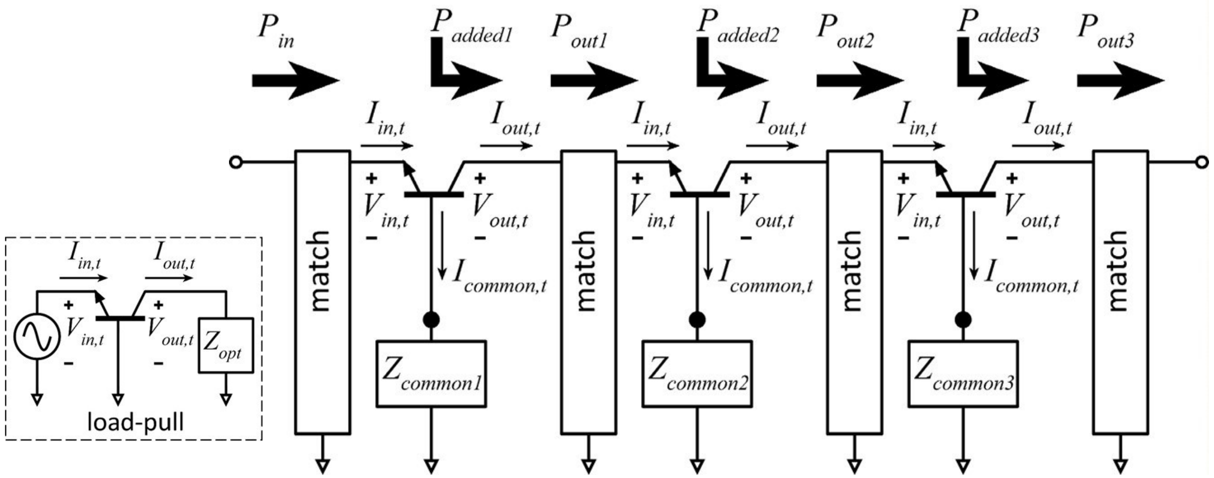
Direct series-connected

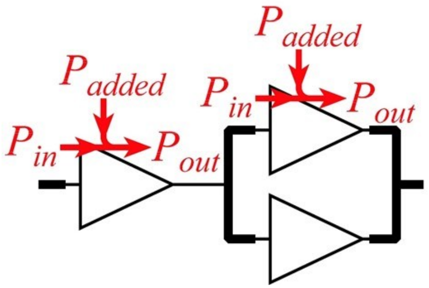
M. Shifrin: 1992 IEEE μWave/mmWave Monolithic Circuits Symp. **(Raytheon)**



Cascaded combining

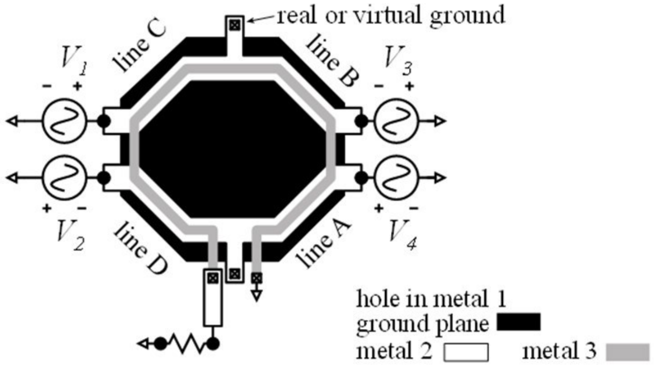
A. Ahmed 2018 EuMIC, 2021 RFIC **(UCSB)**





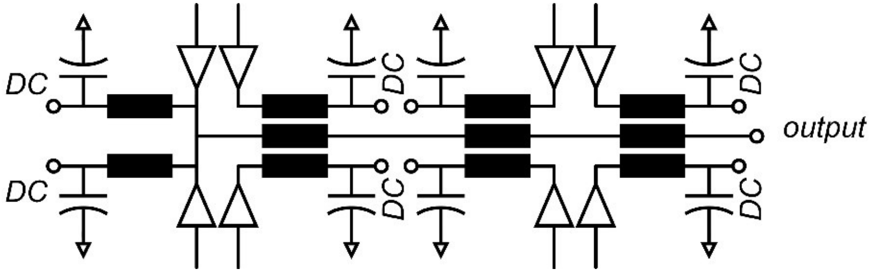
Distributed Active Transformer

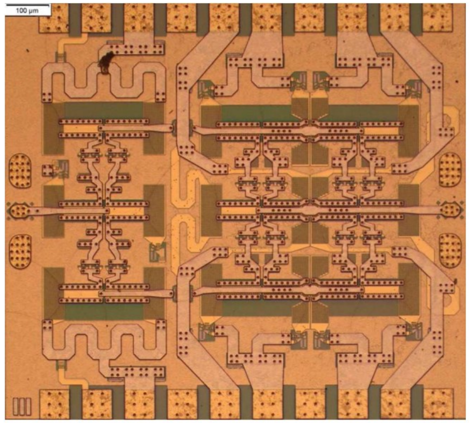
I. Aoki, IEEE Trans MTT, Jan. 2002 **(CalTech)**



Sub-λ/4-coupler series-connected

H. Park, et al, IEEE JSSC, Oct. 2014 **(UCSB)**

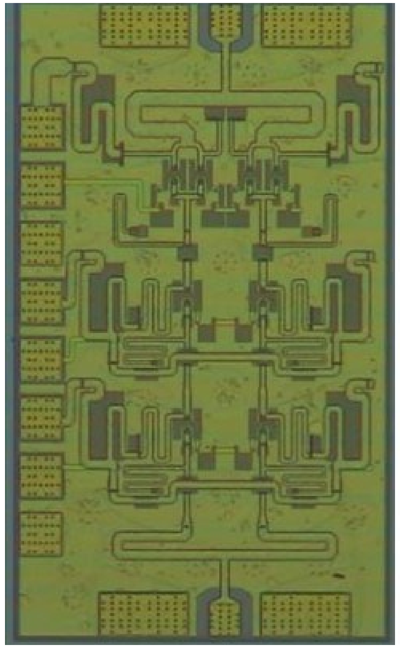




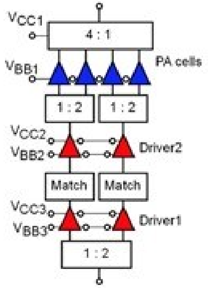
Recent high-efficiency 100-300GHz PAs

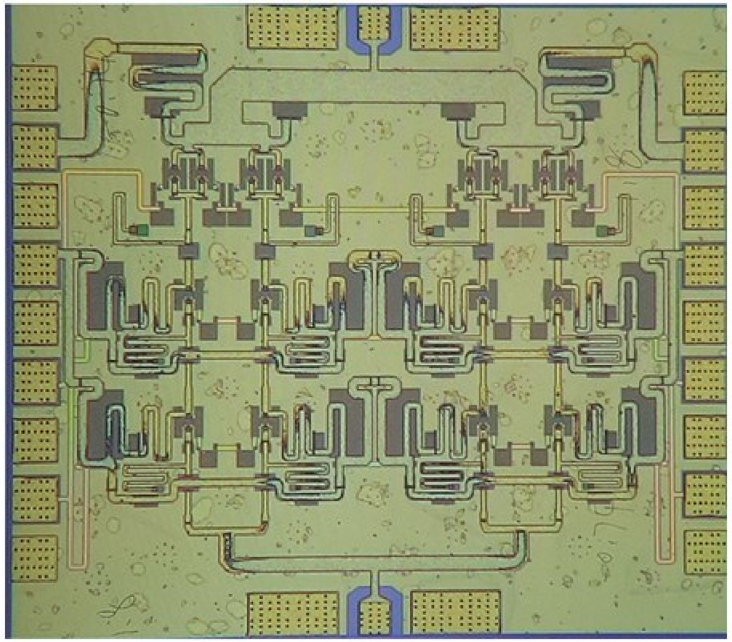
Teledyne 250nm InP HBT technology

Ahmed et al, 2020 IMS, 2020 EuMIC, 2021 IMS, 2021 RFIC

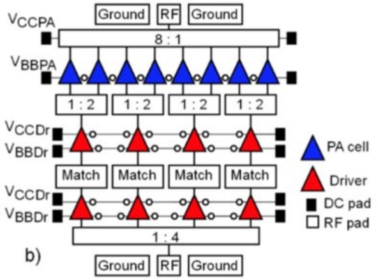


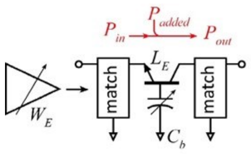
140GHz, 20.5dBm, 20.8% PAE

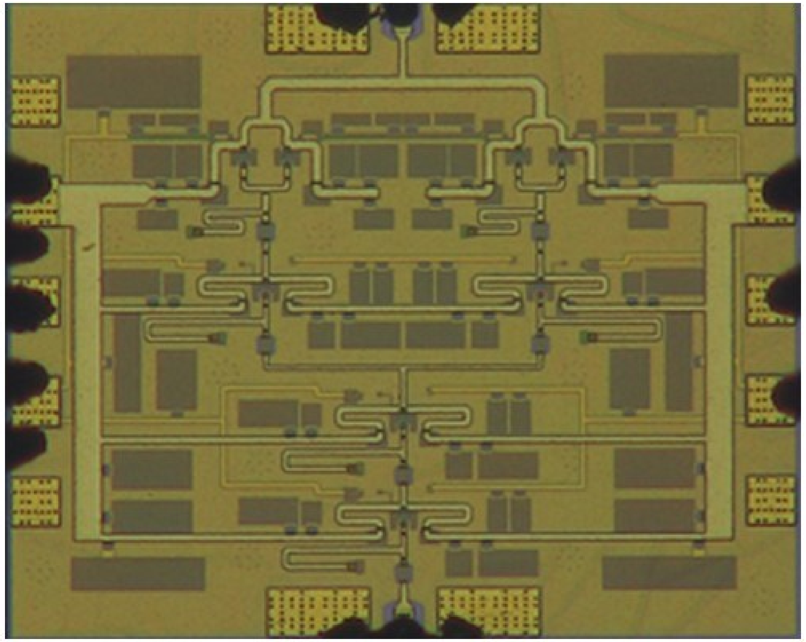




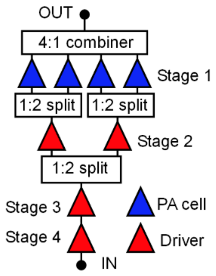
130GHz, 200mW, 17.8% PAE

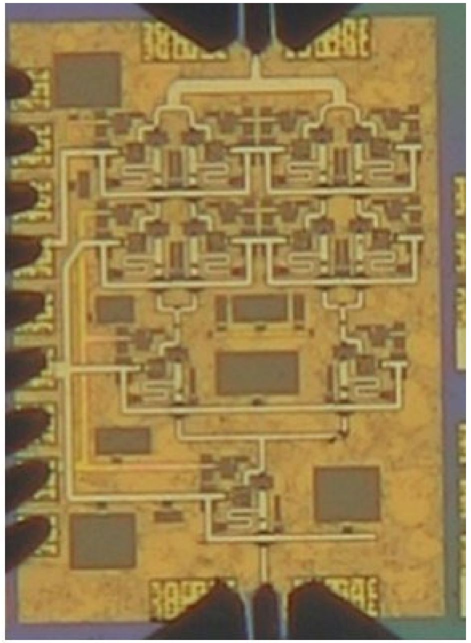




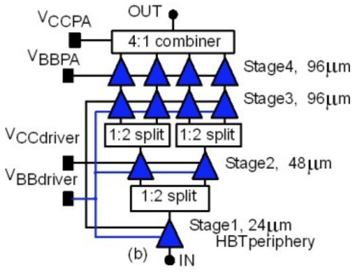


194GHz, 17.4dBm, 8.5% PAE



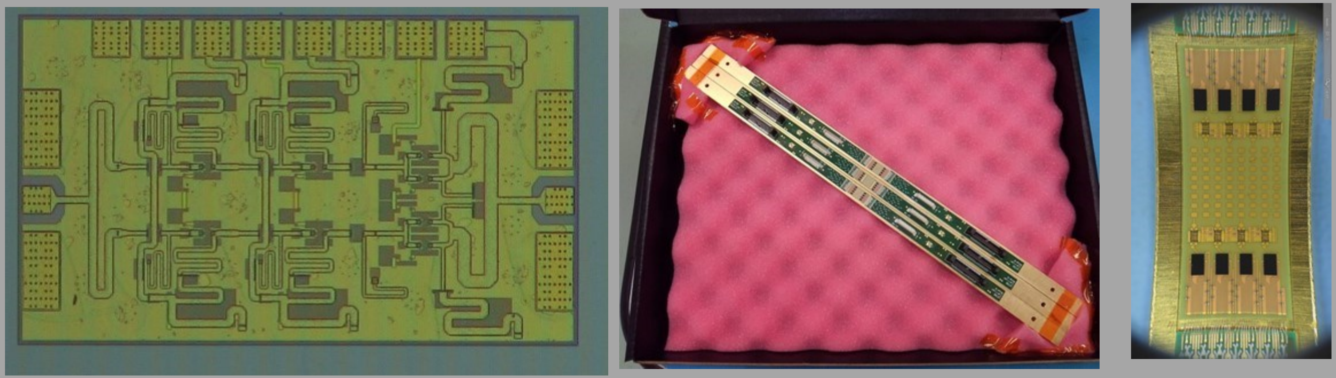


266GHz, 16.8dBm, 4.0% PAE



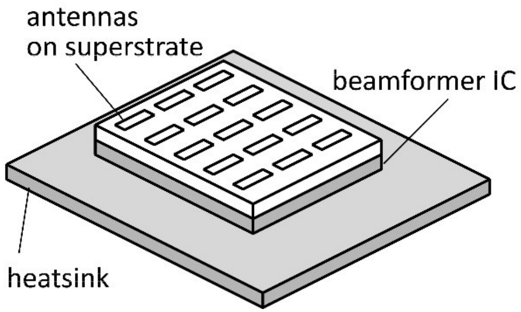
Mixture of corporate and cascade power-combining.

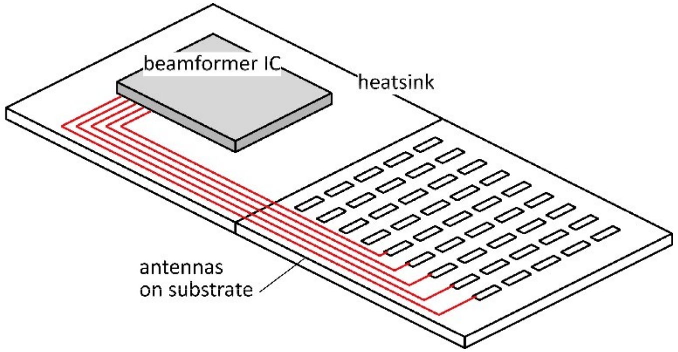
140 GHz
Array Modules



The mm-wave module design problem

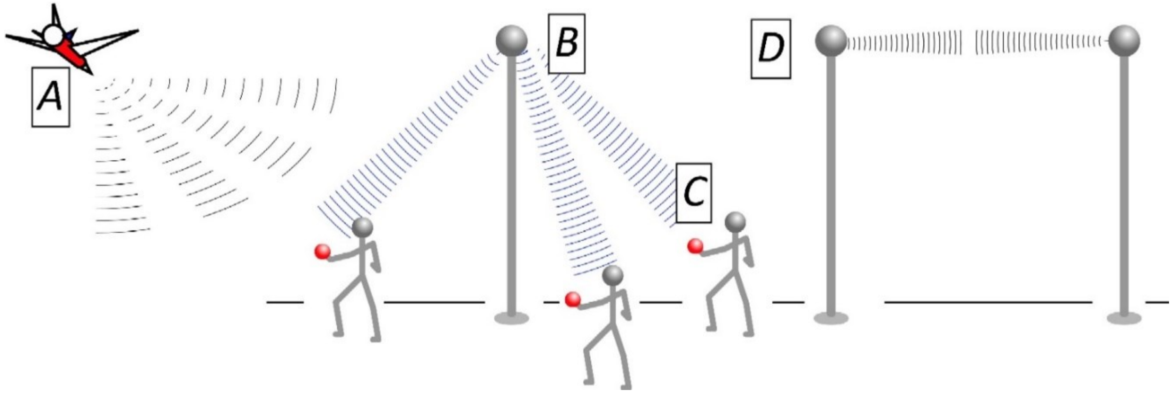
How to make the IC electronics fit ?
How to avoid catastrophic signal losses ?
How to remove the heat ?

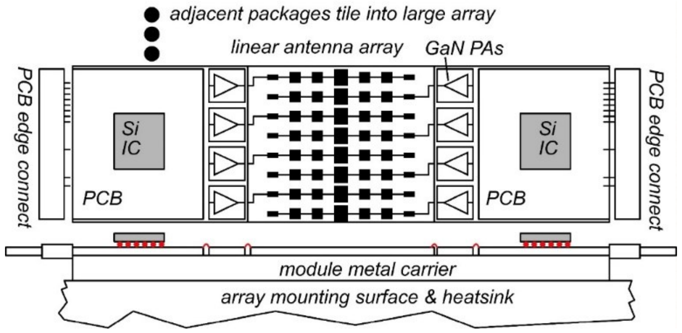


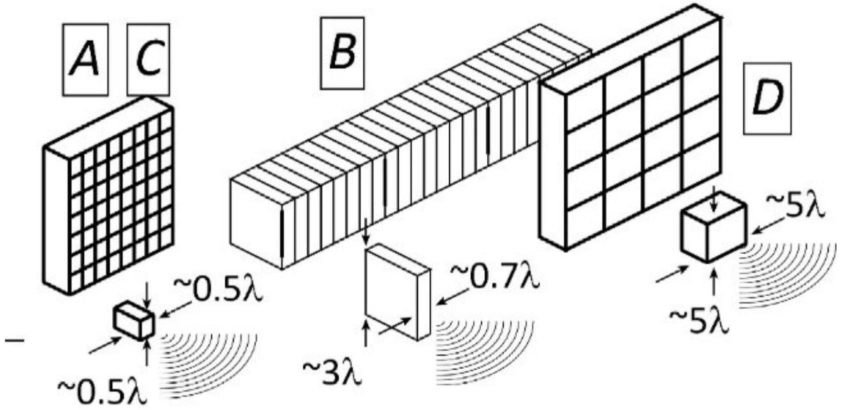


Not all systems steer in two planes...
...some steer in only one.

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





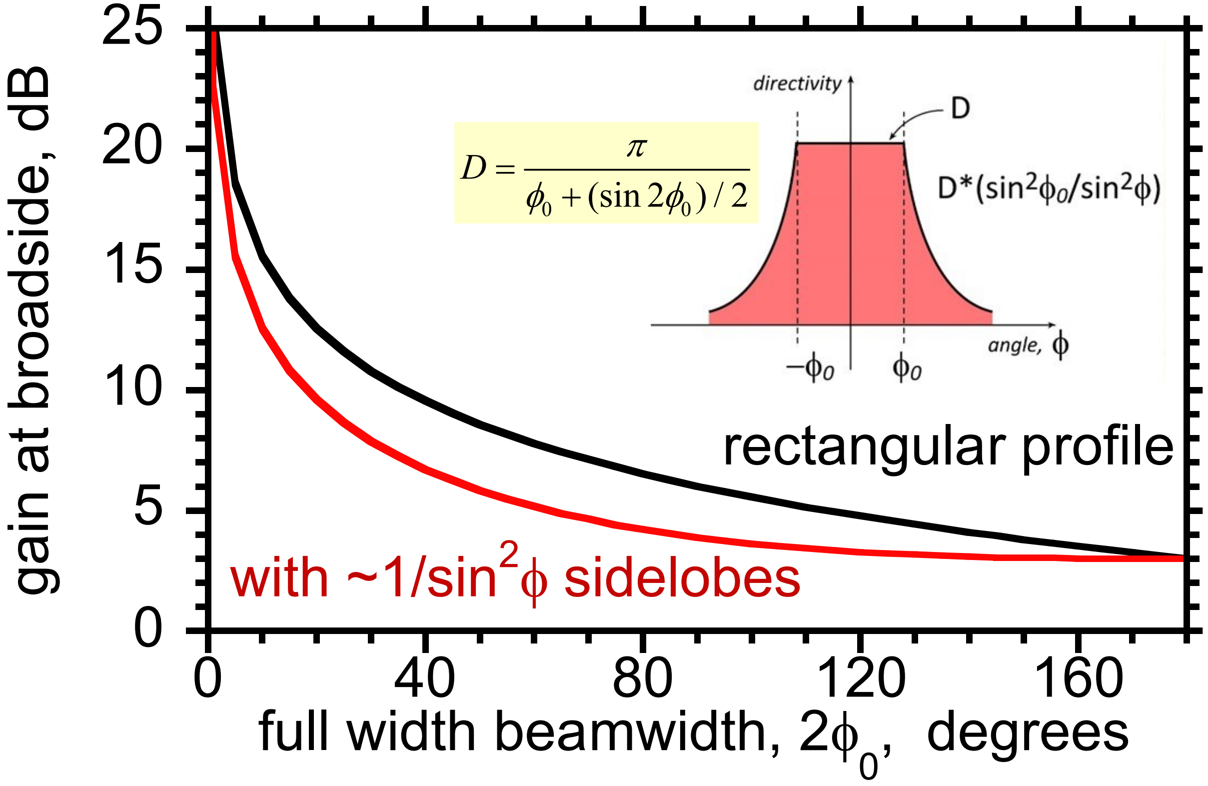


Do we need 2D arrays ? 1D steering might be fine.

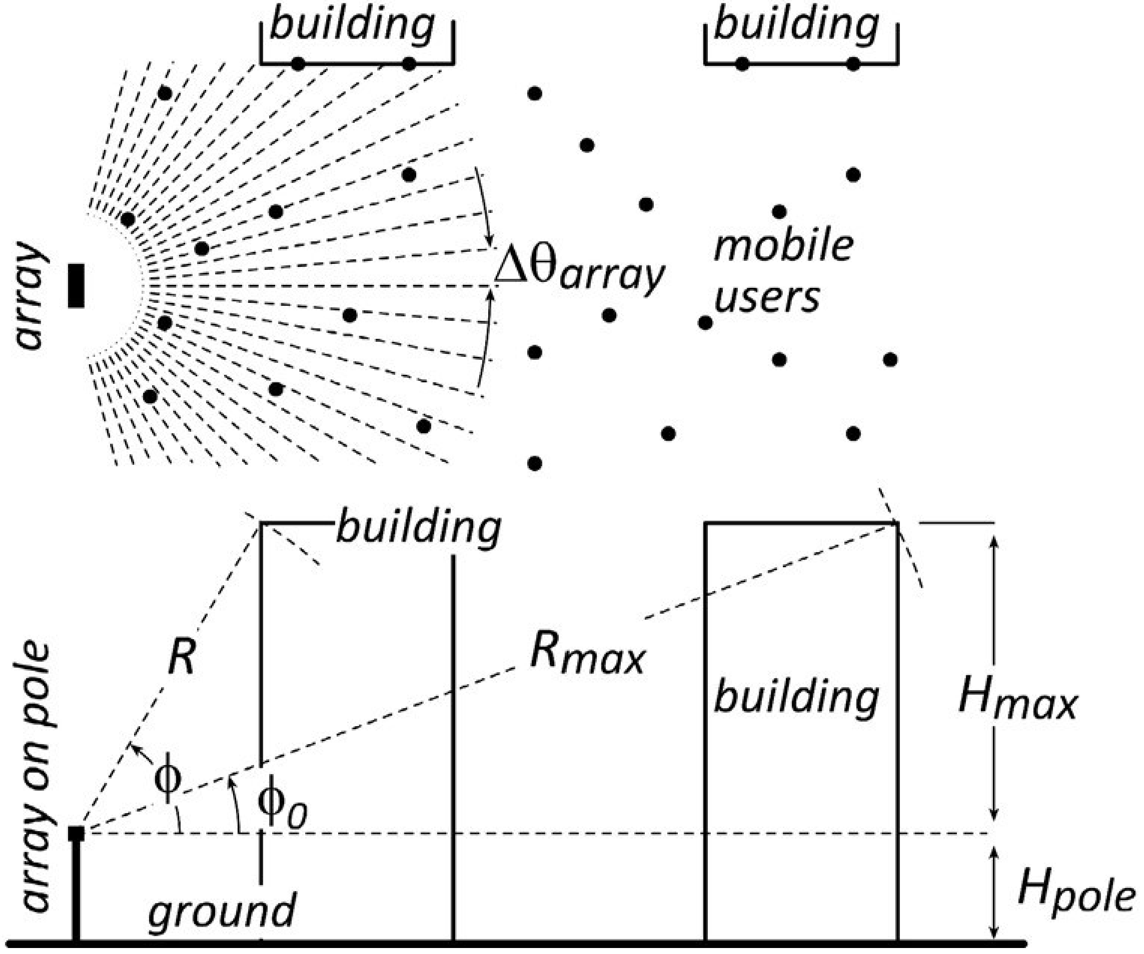
$1/\sin^2\phi$ sidelobes provide strong signals to tall buildings.

Providing sidelobes reduces broadside gain by less than 3dB.

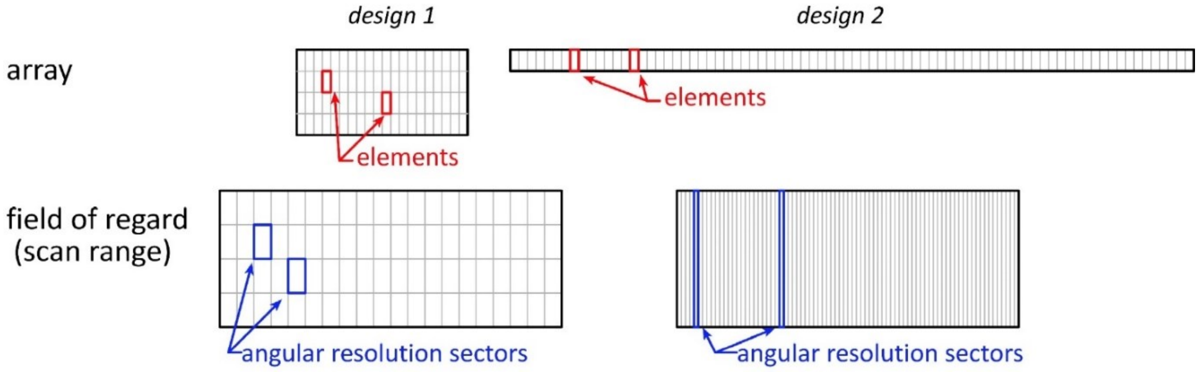
→ Don't need 2D arrays to serve tall buildings



$$D=\frac{\pi}{\phi_0+(\sin 2\phi_0)/2}$$



2D vs. 1D: user spatial distribution

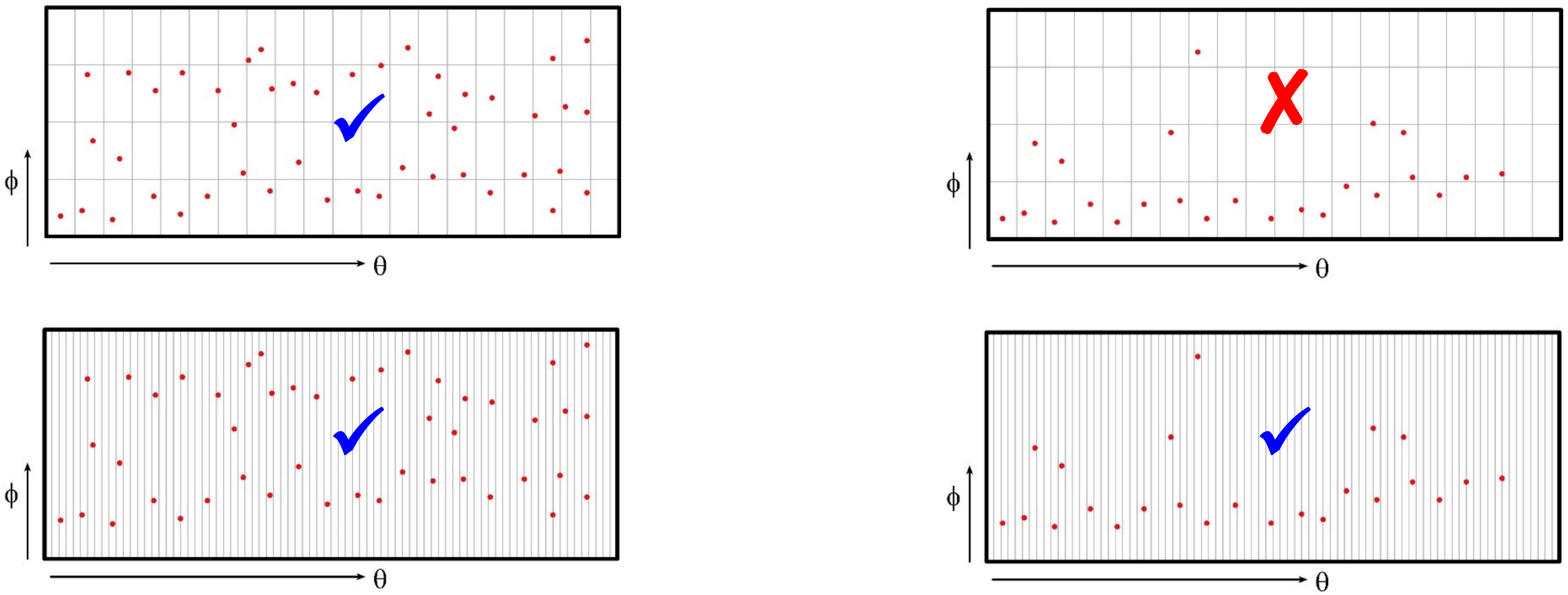


uniform horizontal & vertical user distributions

uniform horizontal, nonuniform vertical

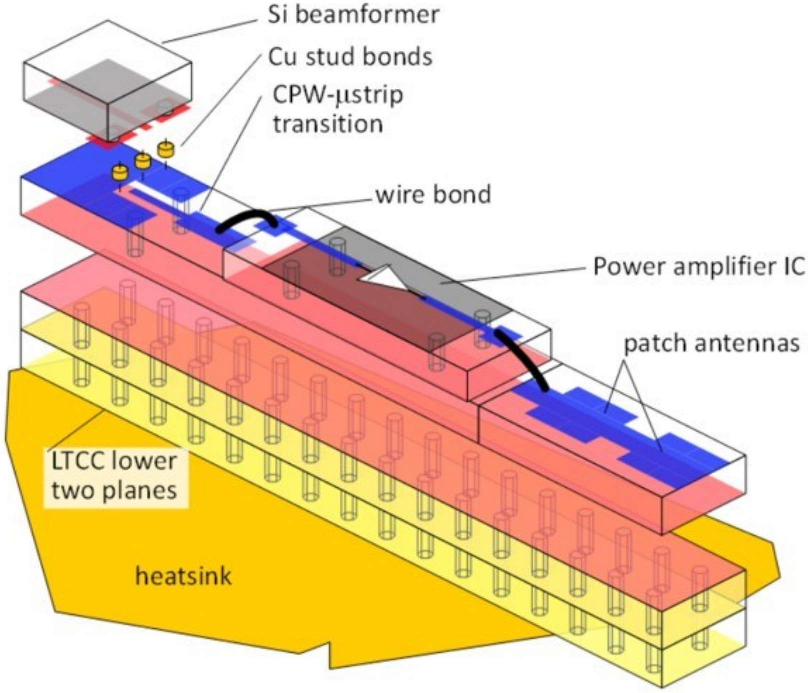
design 1: 2D array

design 2: 1D array

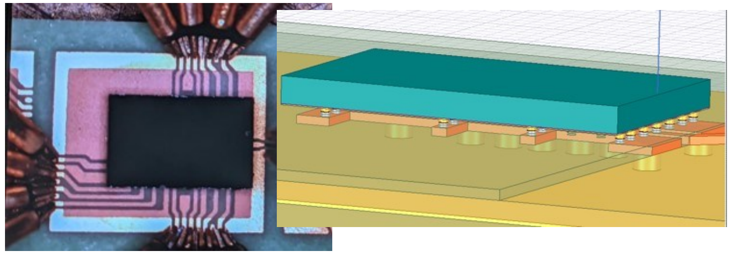


Spatial distribution of users, and of scattering objects, guides choice of array geometry.

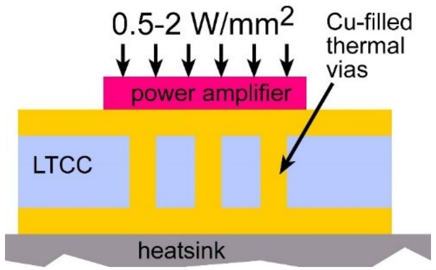
140GHz hub: packaging challenges



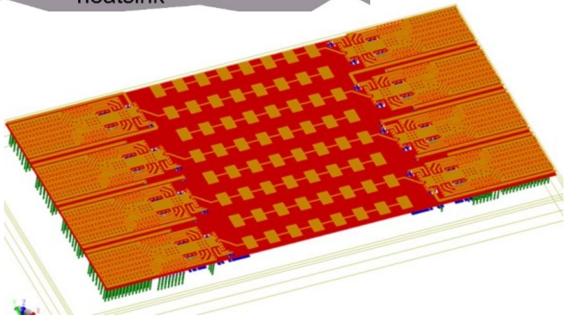
IC-package interconnects
Difficult at > 100 GHz



Removing heat
Thermal vias are marginal



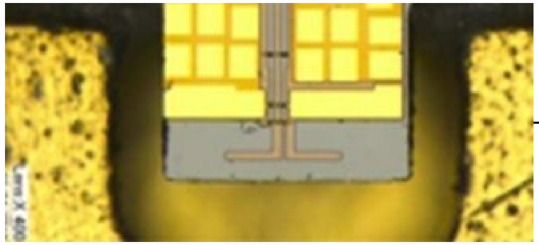
Interconnect density
Dense wiring for DC, LO, IF, control.
Hard to fit these all in.



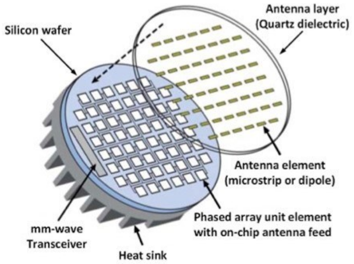
Economies of scale
Advanced packaging standards require sophisticated tools
High-volume orders only
Hard for small-volume orders (research, universities)
Packaging industry is moving offshore

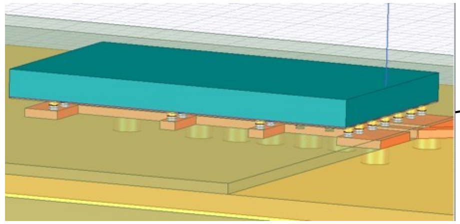
100-300GHz IC-package connections

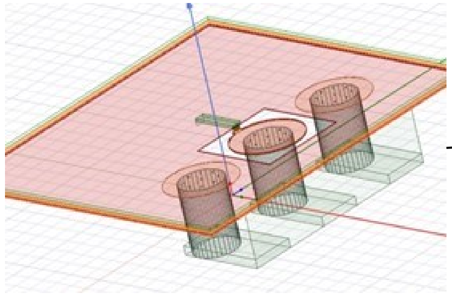
Deal, IEEE Trans THz, Sept 2011



G. Rebeiz



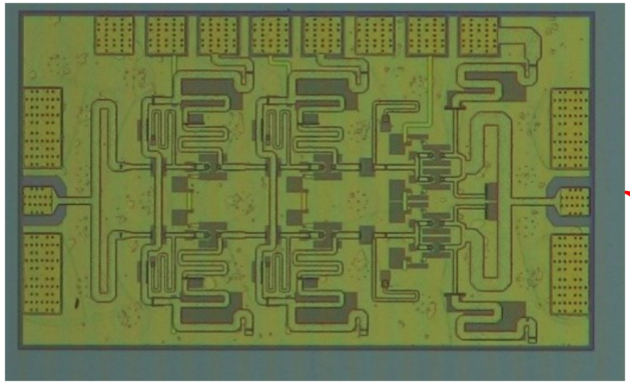




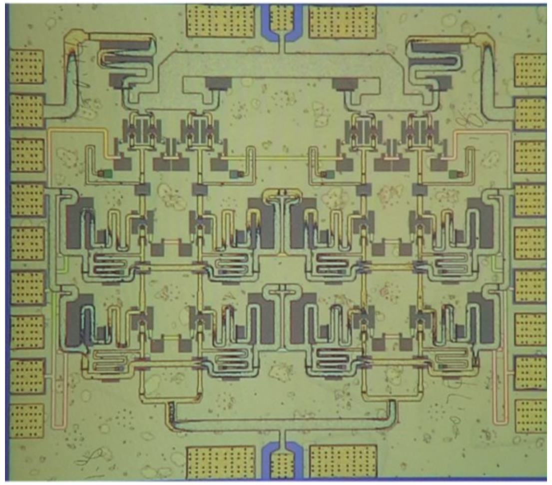
type	Frequency	technology	cost	heatsinking
micromachined waveguide interface	1000 GHz	Research. Cheap one day ?	**high** ✗	good
ribbon, mesh bond	200 GHz	Handcrafted.	**high** ✗	good
patch antennas on superstrate	1000 GHz	Straightforward	low	good
Cu stud flip-chip	>200 GHz	Industry standard	low	ok, **marginal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

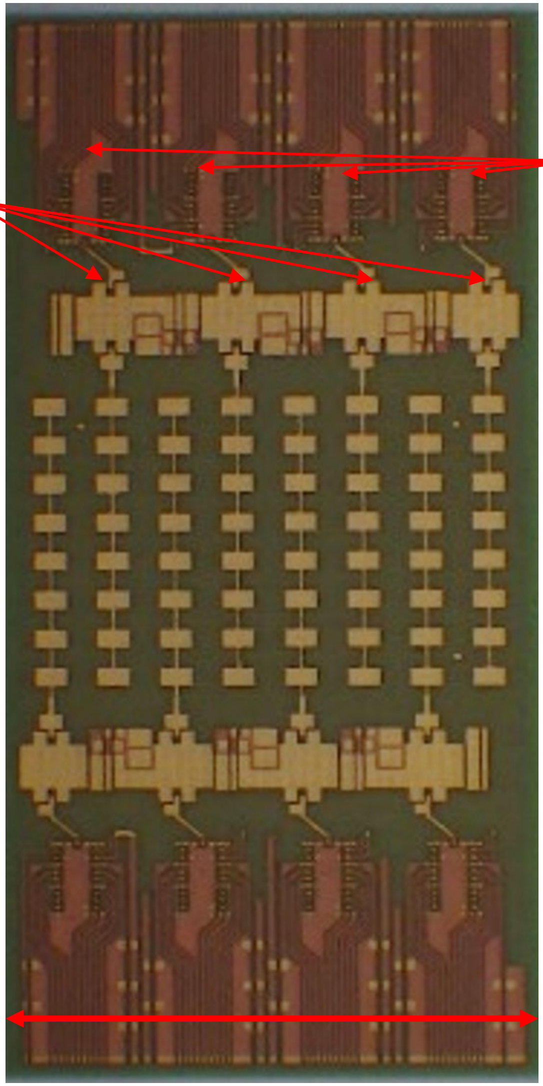


190mW InP Power Amplifier
16.7% PAE



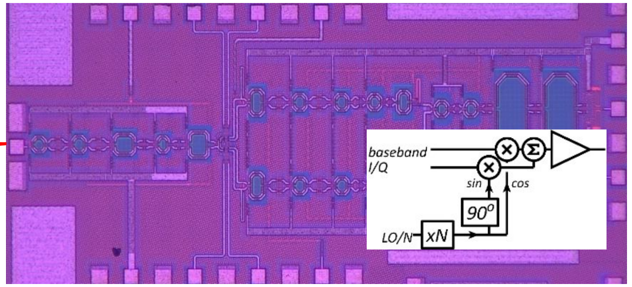
Teledyne InP HBT

LTCC Array module

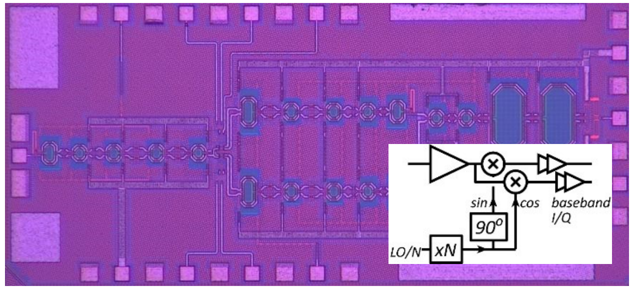


Kyocera

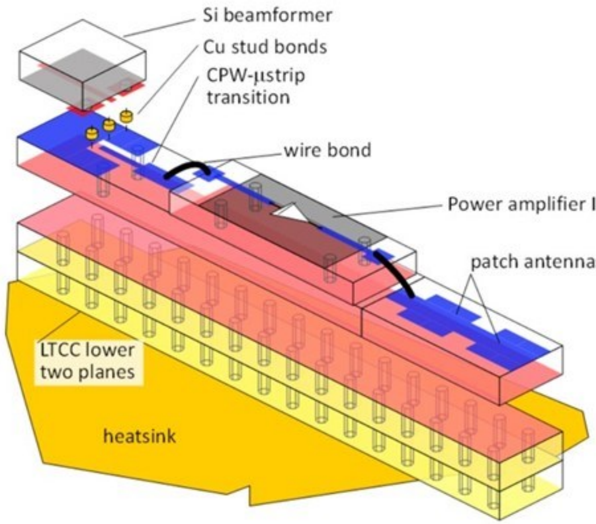
CMOS Transmitter IC
22nm SOI CMOS.



Receiver IC
22nm SOI CMOS.



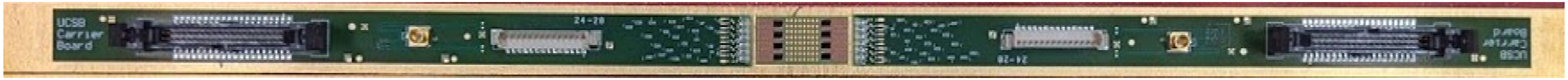
GlobalFoundries 22nm SOI CMOS

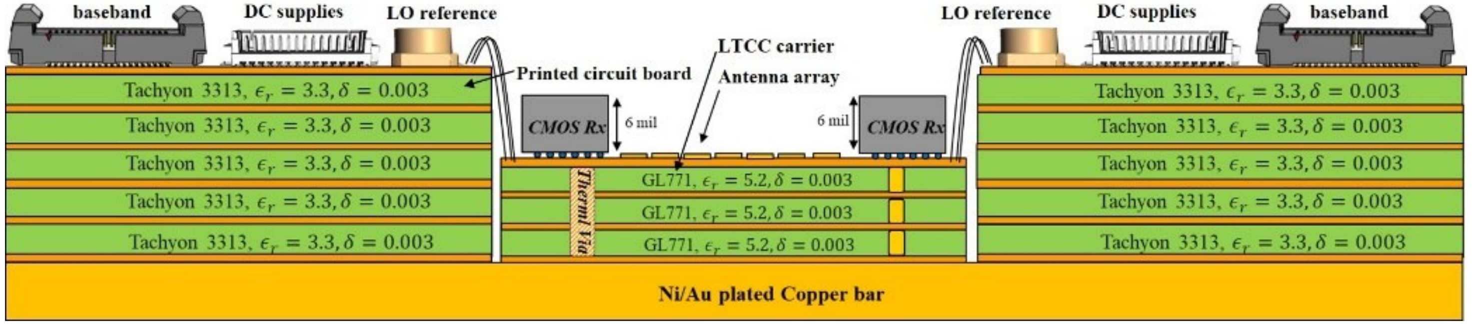


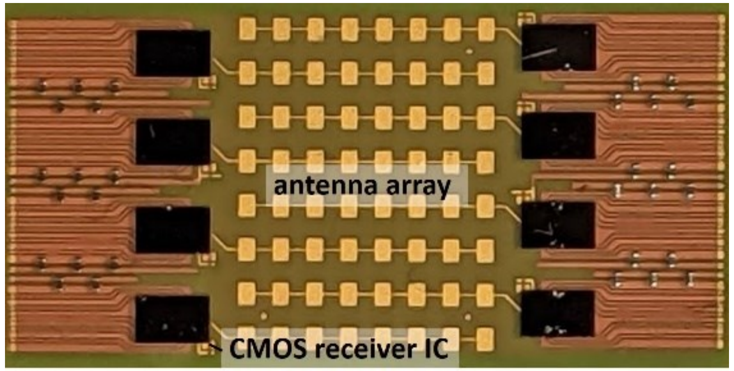
Farid, Ahmed, Rodwell, UCSB; Flynn, Dunn, Niknejad, Nikolic, BWRC; Rebeiz, UCSD

135GHz 8-channel MIMO hub array tile modules

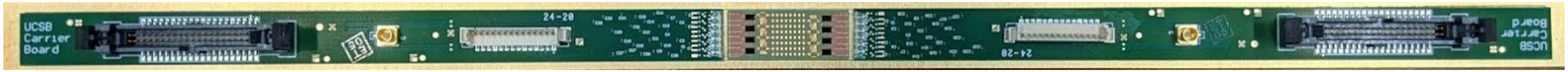
Receiver: A. Farid et. al, 2021 IEEE BCICTS Symposium

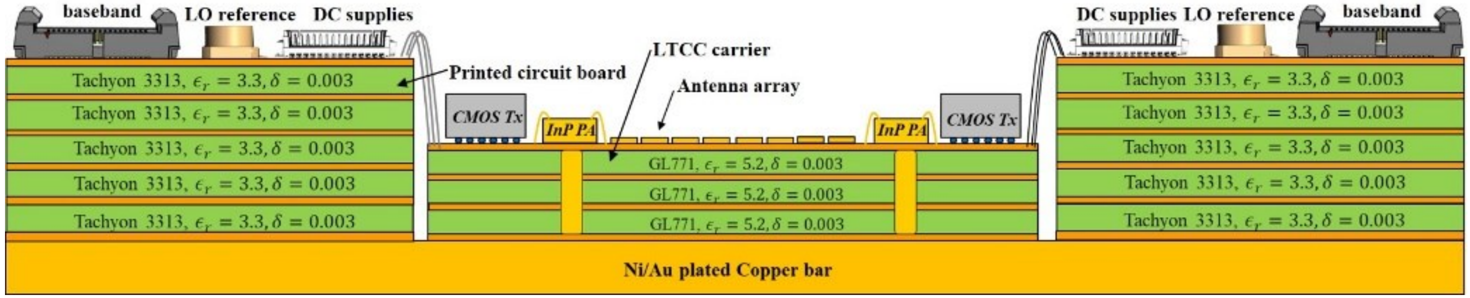


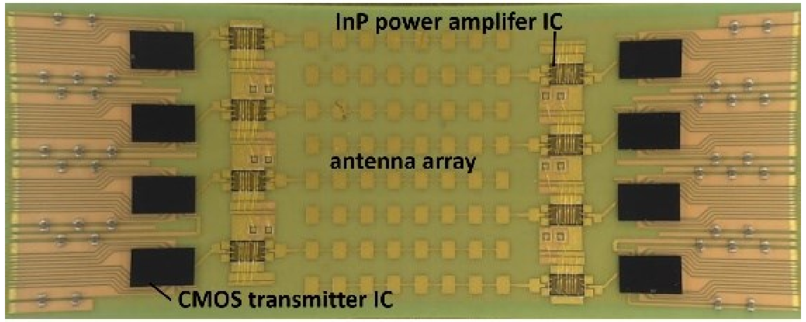




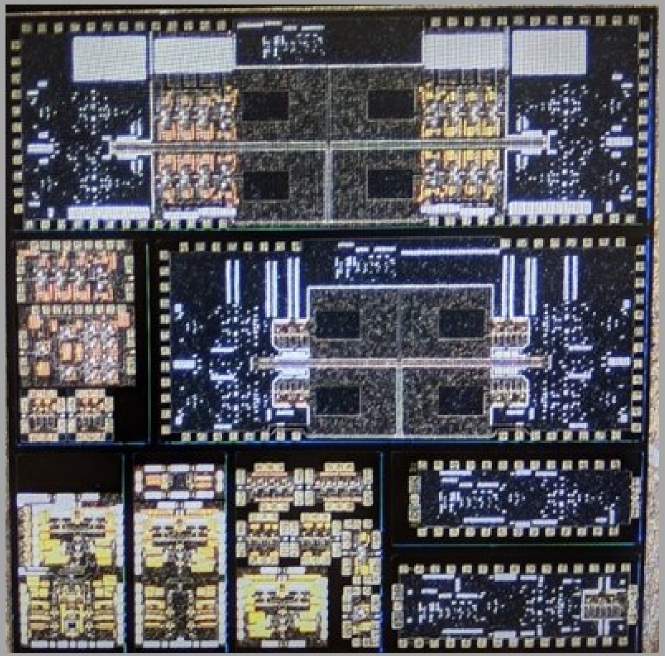
Transmitter: Results to be submitted

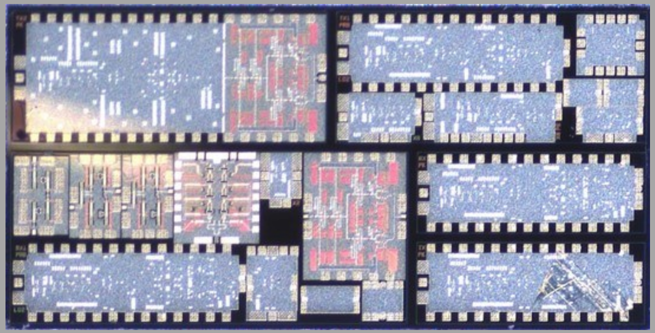




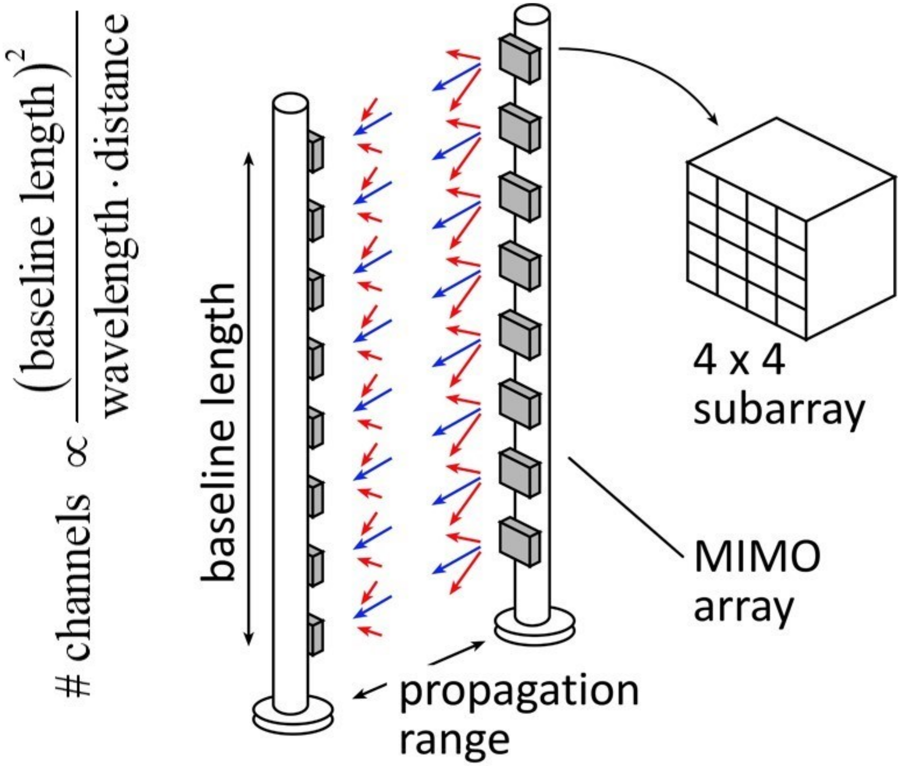


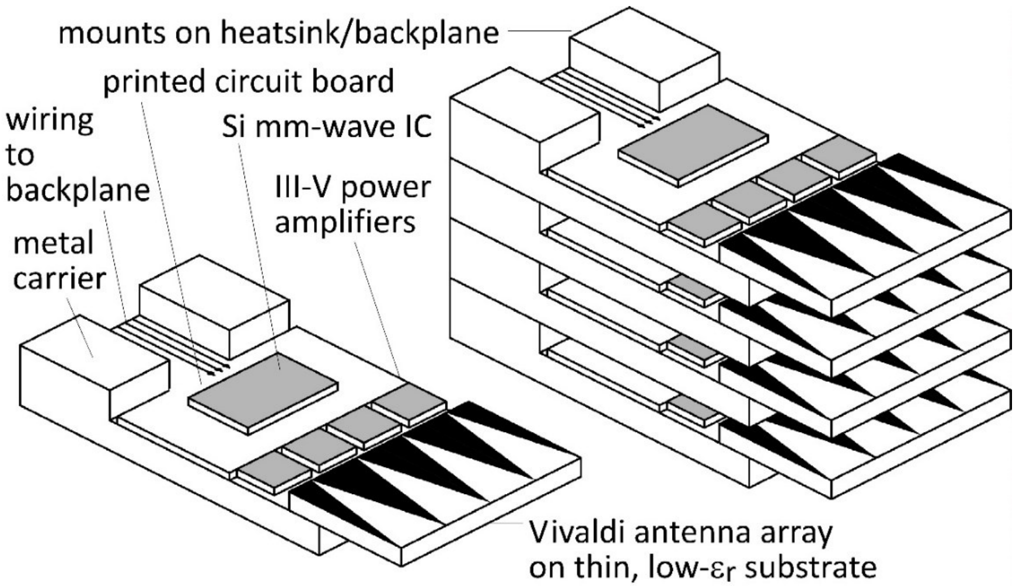
210 GHz and 280 GHz Array Modules





210 GHz MIMO backhaul demo





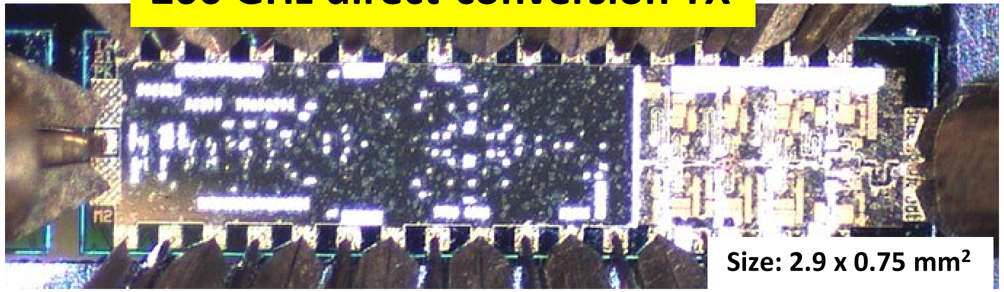
8-element MIMO array
3.1 m baseline for 500m link.
80Gb/s/subarray→ 640Gb/s total
4 × 4 sub-arrays → 8 degree beamsteering

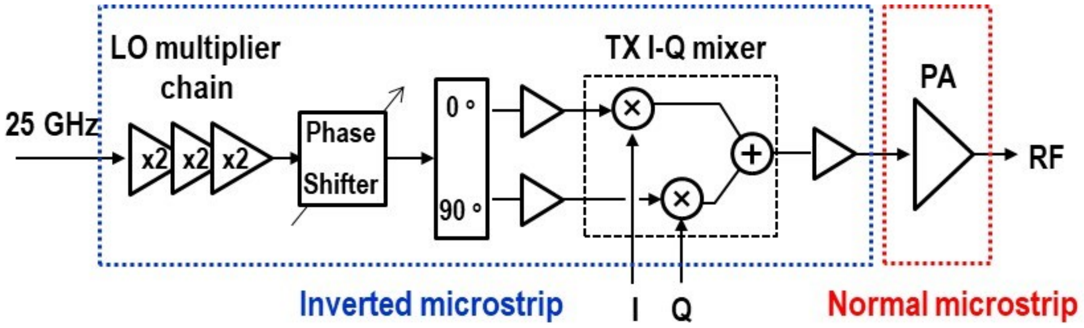
Key link parameters
500 meters range in 50 mm/hr rain; 23 dB/km
20 dB total margins:
packaging loss, obstruction, operating, design, aging
PAs: 63mW =P_{1dB} (per element)
LNAs: 6dB noise figure

210 GHz Transmitter and Receiver ICs

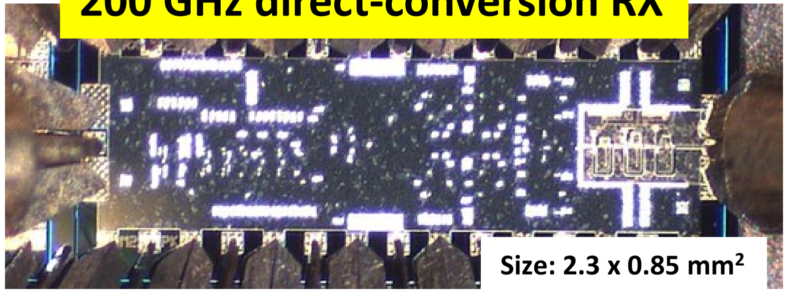
M. Seo et al, 2021 IMS; Teledyne 250nm InP HBT

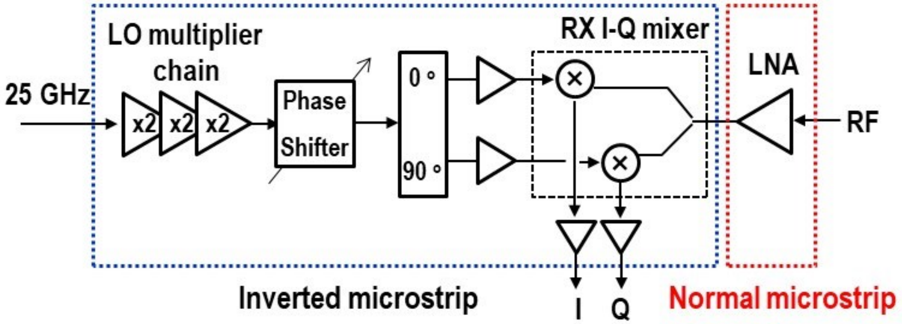
200 GHz direct-conversion TX

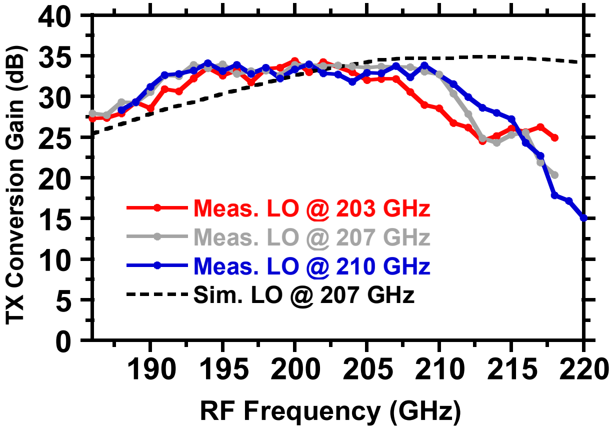

Size: 2.9 x 0.75 mm^2

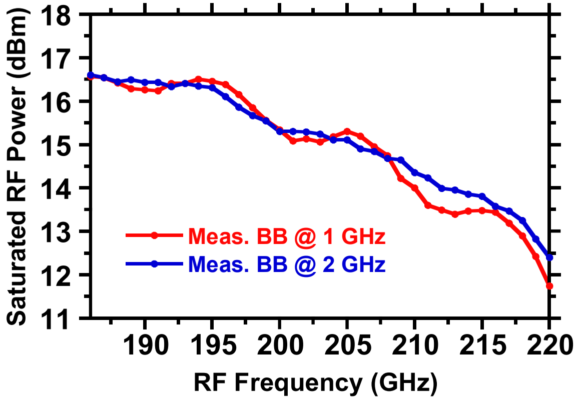


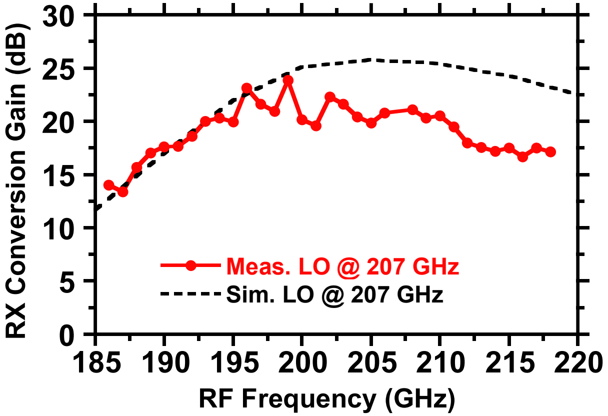
200 GHz direct-conversion RX

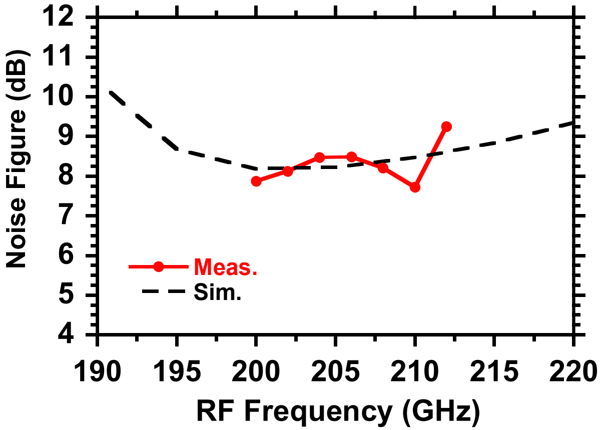

Size: 2.3 x 0.85 mm^2







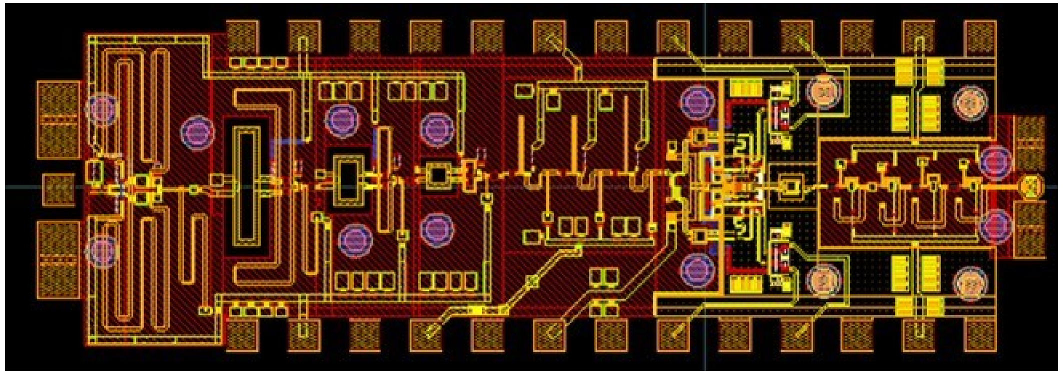




280GHz transmitter and receiver IC designs

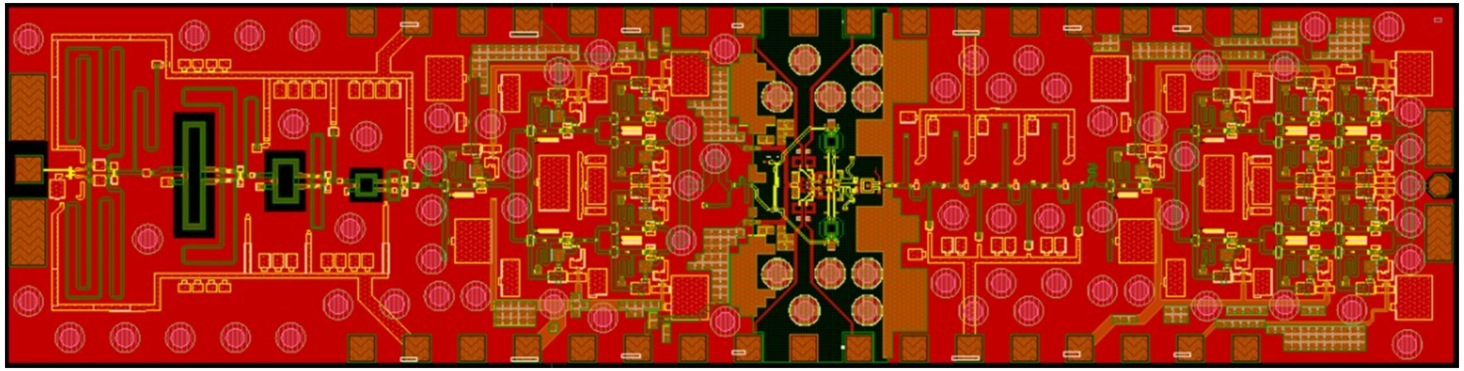
Solyu, Alz, Ahmed, Seo; UCSB/Sungkyunkwan
Teledyne 250nm InP HBT technology

Receiver



simulations: 11dB noise figure, 40GHz bandwidth

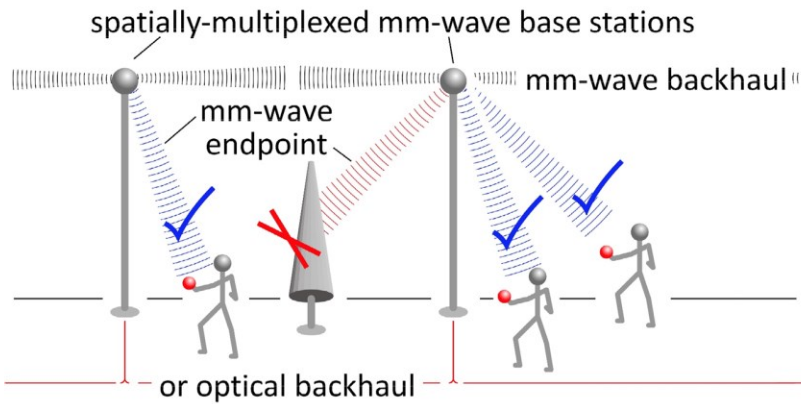
Transmitter

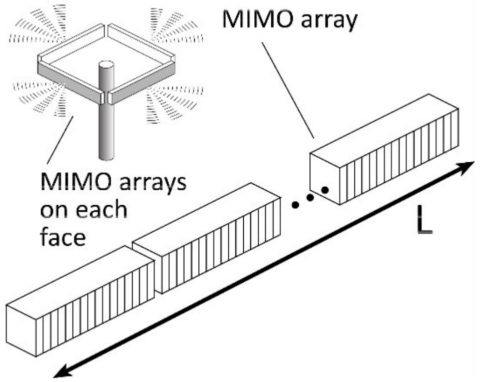


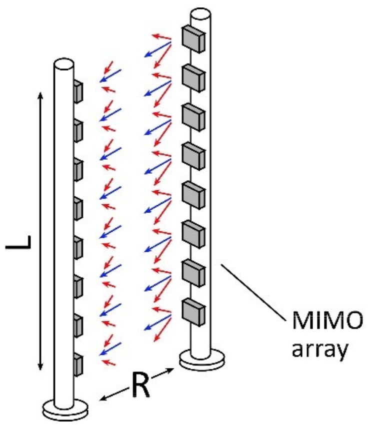
simulations: 17dB saturated output power.

Application: point-point MIMO backhaul links

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)