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100-300GHz MIMO Communications: Transistors, ICs, Arrays, and Systems

SRC JUMP

ComSenTer
COMMUNICATIONS SENSING TERAHERTZ

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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

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

James Buckwalter, UC Santa Barbara — efficient PAs, III-V arrays

Alyosha Molnar, Cornell — N-path mixers, MIMO ADCs

Kenneth O, UT Dallas — 140-300GHz SiGe ICs

Elad Alon, UC Berkeley — design automation, equalizers

Muhannad Bakir, Georgia Tech — high-frequency packaging

Tim Fisher, UCLA — advanced packaging materials

Andrew Kummel, UCSD — advanced packaging materials

Transistors

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

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

Susanne Stemmer, UC Santa Barbara — transistors in novel materials

Debdeep Jena, Cornell — GaN HEMTs on Si

Srabanti Chowdhury, UC Davis — Diamond cooling for GaN

Massive MIMO demo. — **Borivoje Nikolic**, UC Berkeley — VLSI design automation, VLSI MIMO processors

Compressive imaging — **Amin Arbabian**, Stanford — 140GHz radar chipsets and arrays

140/210/280GHz arrays for demos. — **Mark Rodwell**, UC Santa Barbara — THz HBTs for PAs, THz HEMTs for LNAs

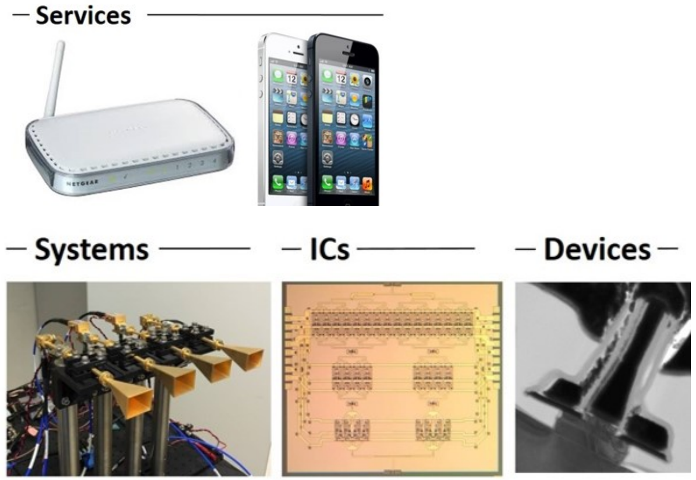
Also:
Kyocera: D. Kim, H. Horikawa, M. Imayoshi.
Samsung: G. Xu, N. Sharma, S. Abu-Surra, W. Choi
Pi-Radio: A. Dhananjay,

100-300GHz Wireless

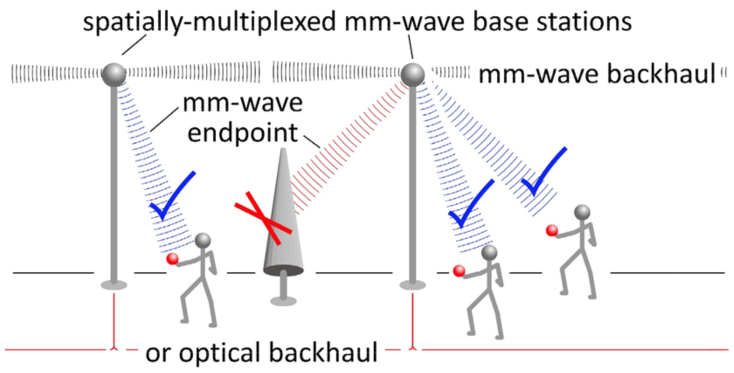
Wireless networks: exploding demand.

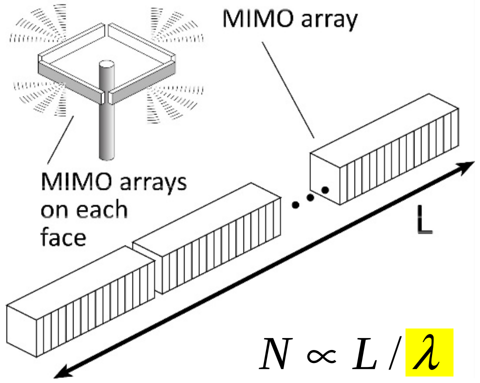
Immediate industry response: 5G.
~3~100 GHz
increased spectrum, extensive beamforming

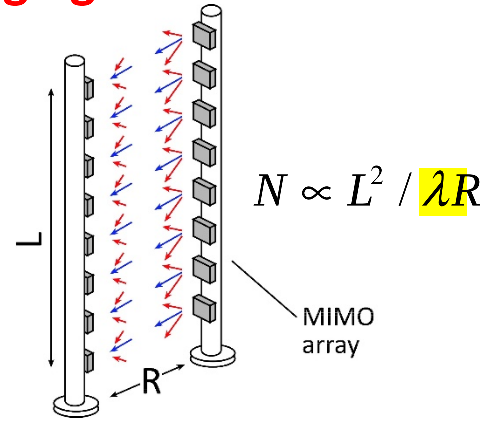
Next generation (6G ??): above 100GHz.. (???)
greatly increased spectrum, massive spatial multiplexing

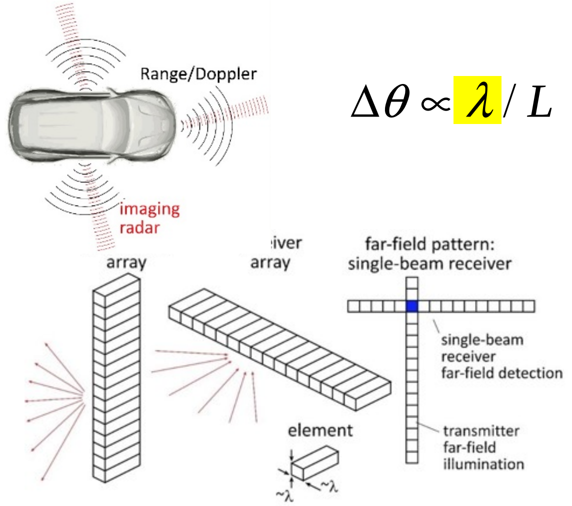


100-300GHz carriers, massive spatial multiplexing
→ Terabit hubs and backhaul links, high-resolution imaging radar



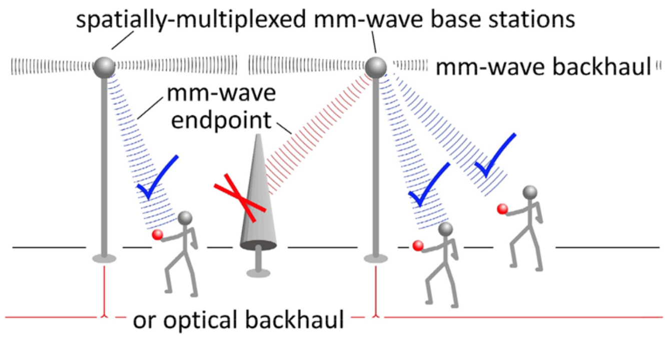


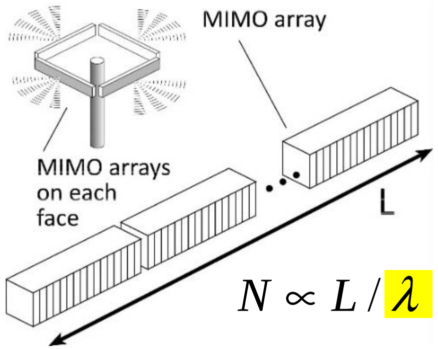




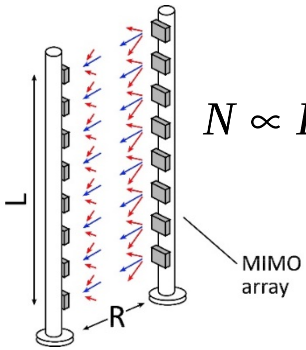
Benefits of Short Wavelengths

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

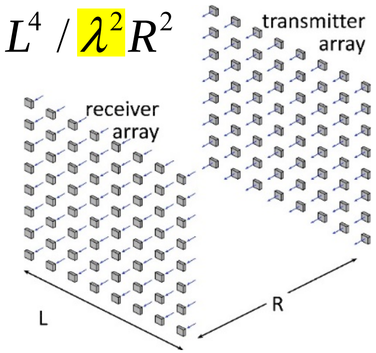




$N \propto L / \lambda$

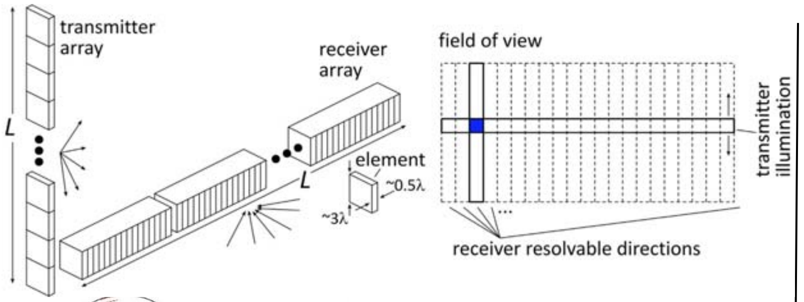


$N \propto L^2 / \lambda R$



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

Imaging: very fine angular resolution

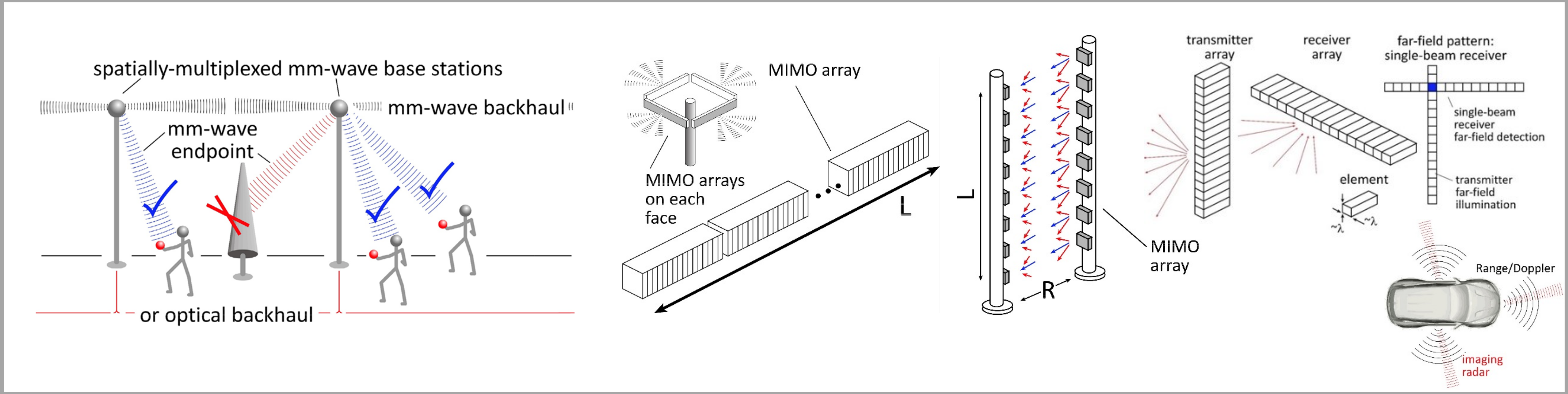


$\Delta\theta \propto \lambda / L$

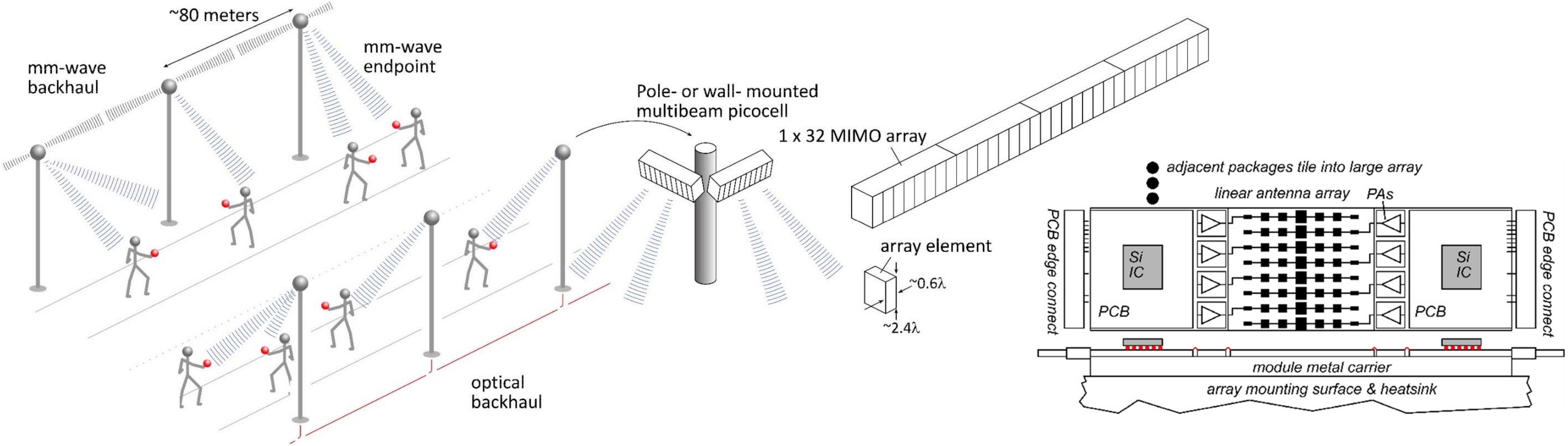
But:
High losses in foul or humid weather.
High λ^2/R^2 path losses.
ICs: poorer PAs & LNAs.
Beams easily blocked.

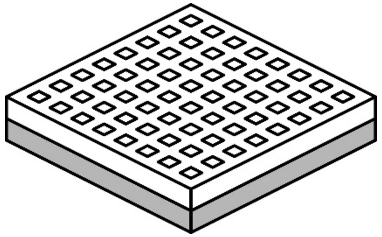
100-300GHz wireless:
terabit capacity,
short range,
highly intermittent

Applications



140GHz moderate-MIMO hub





Handset:
8 × 8 array
(9×9mm)

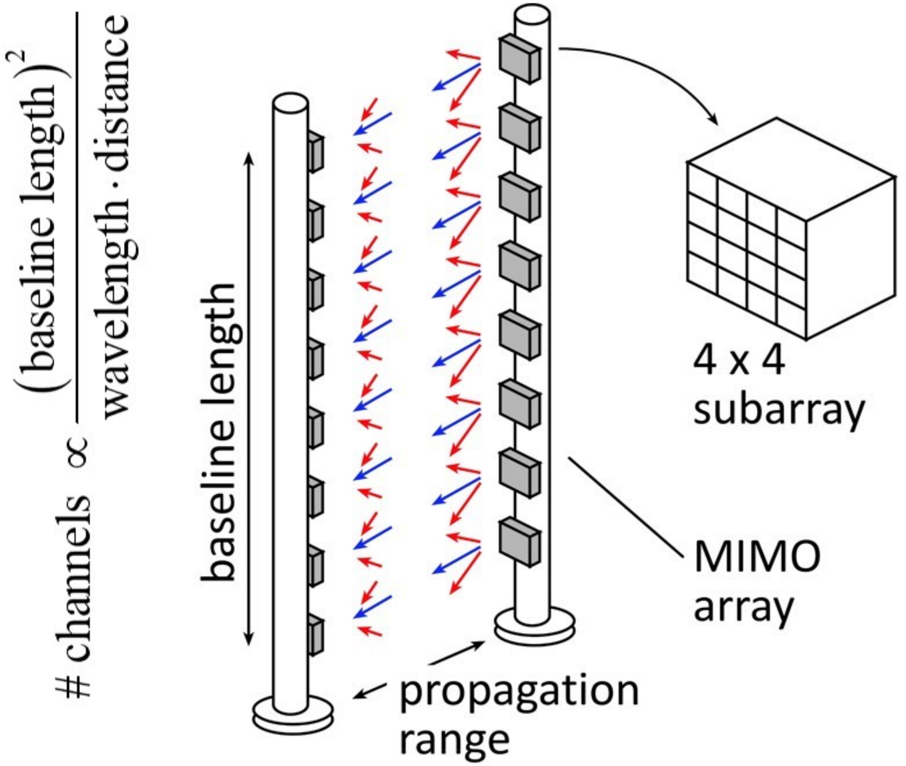
If demo uses 32-element array (four 1×8 modules):

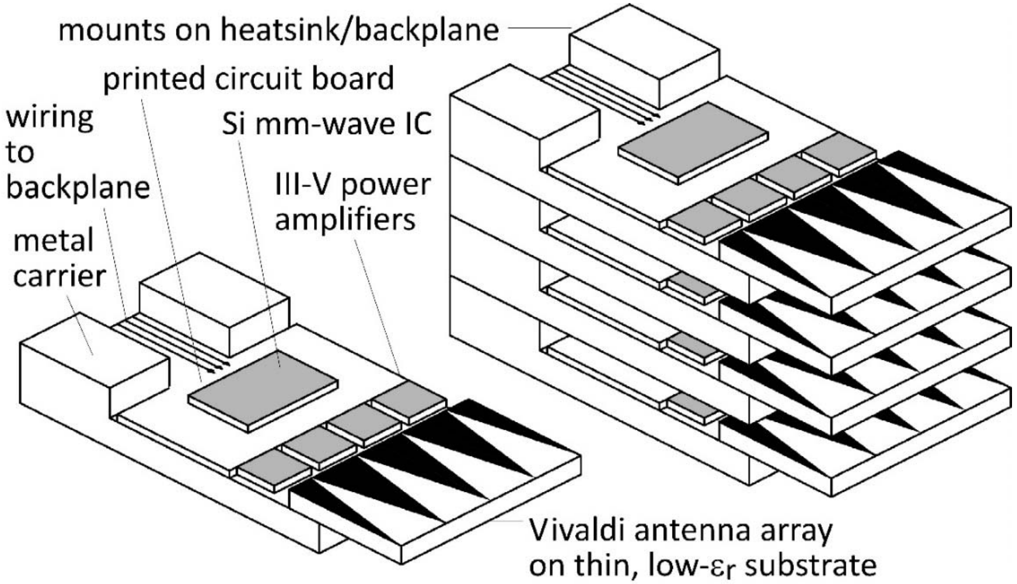
16 users/array. P_{1dB}=21 dB_m PAs, F=8dB LNAs

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

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

210 GHz, 640 Gb/s MIMO Backhaul

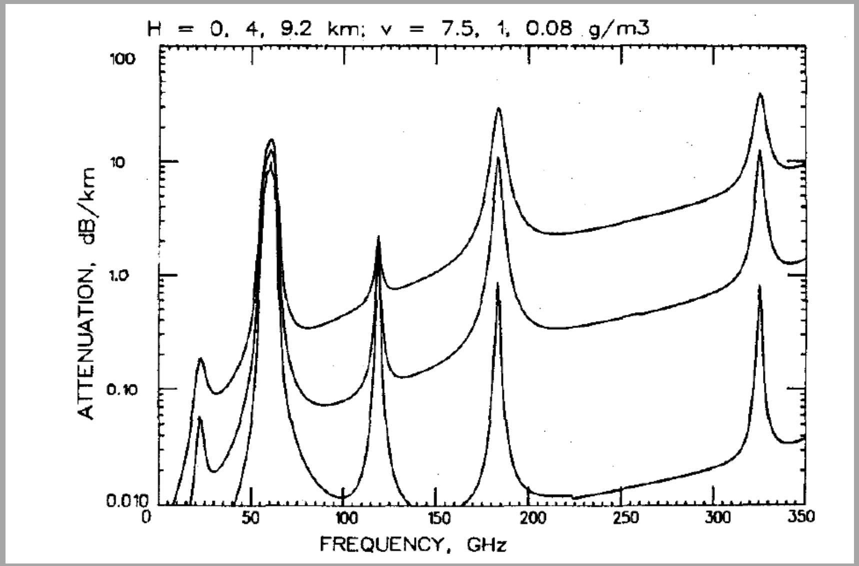




8-element MIMO array
2.1 m baseline.
80Gb/s/subarray→ 640Gb/s total
4 × 4 sub-arrays → 8 degree beamsteering

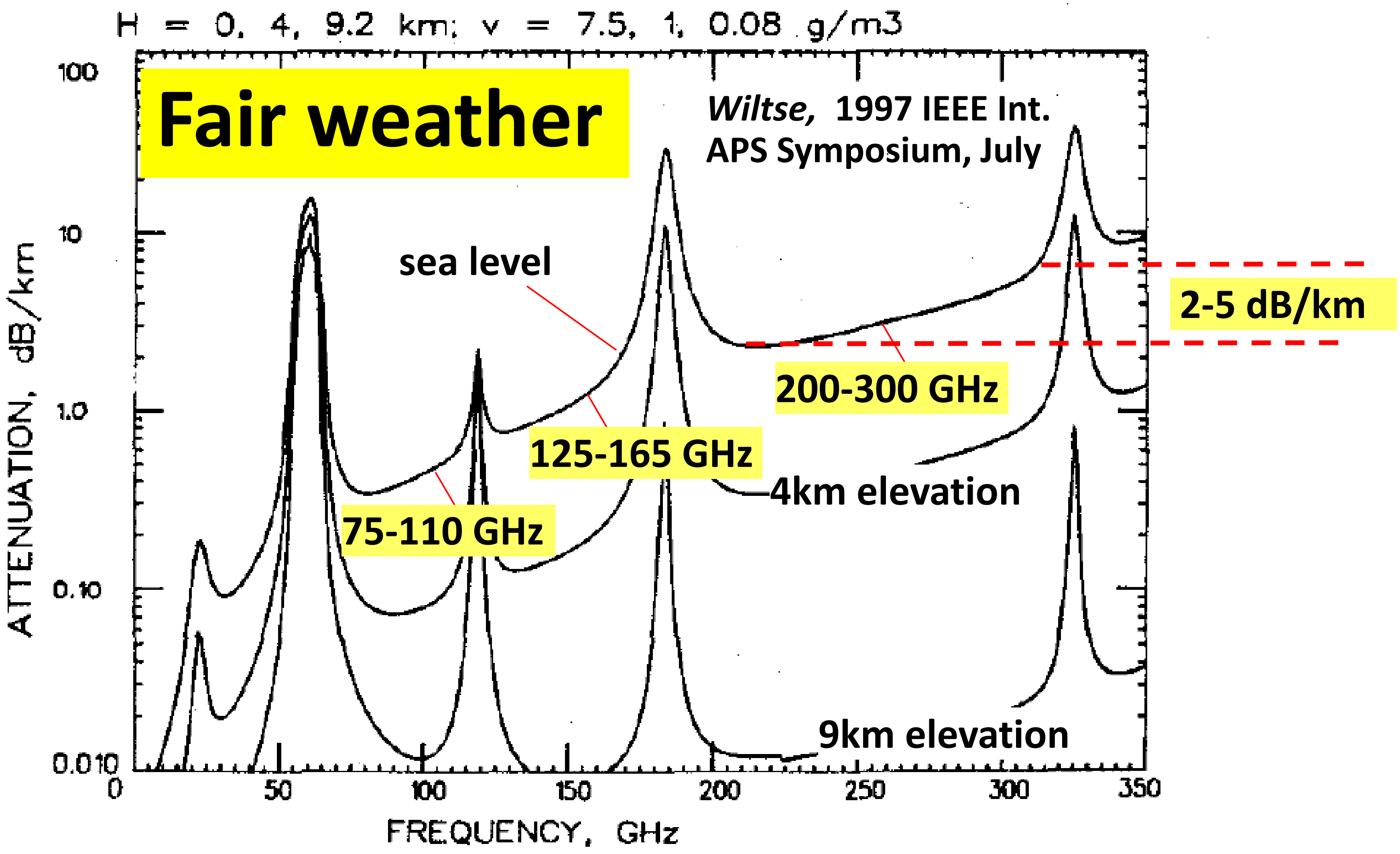
Key link parameters
500 meters range in 50 mm/hr rain; 23 dB/km
20 dB total margins:
packaging loss, obstruction, operating, design, aging
PAs: 18dBm =P_{1dB} (per element)
LNAs: 6dB noise figure

mm-wave propagation



?

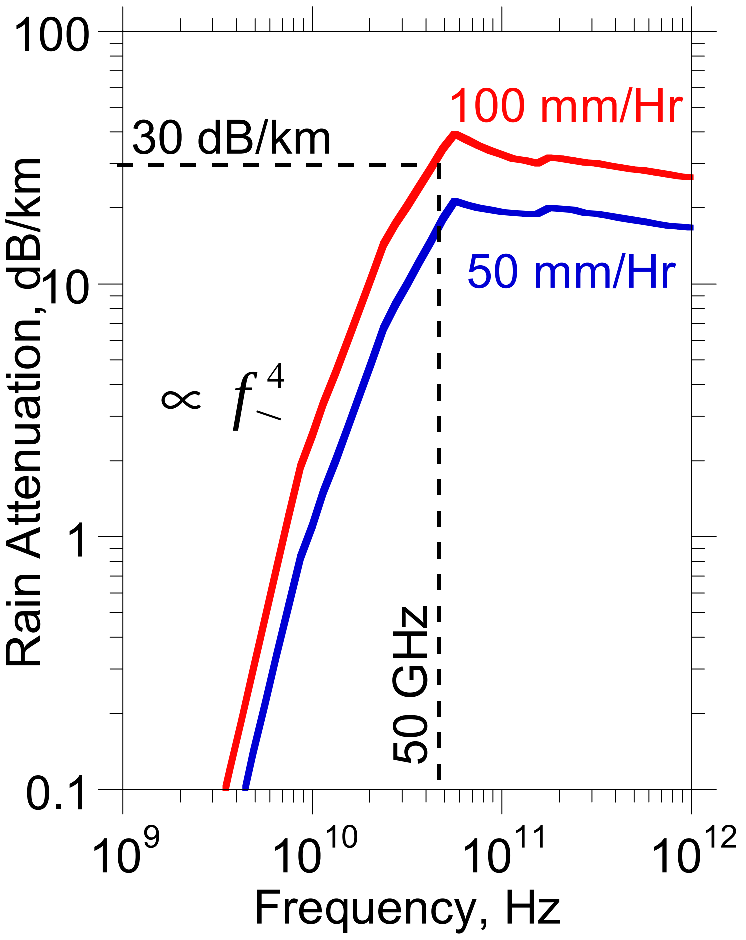
Fair-Weather Propagation



Caution: wireless services must work reliably, not only in best-case conditions.
Must consider worst-case (10^{-4}, 10^{-5} probability) atmospheric attenuation

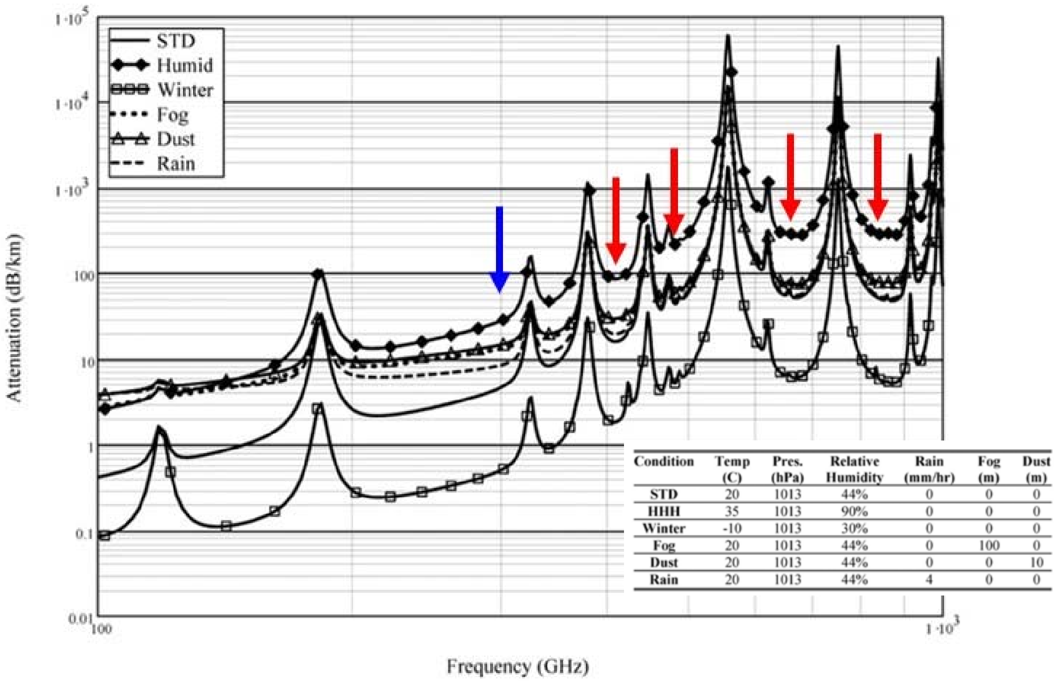
Systems must work in most weather

Rain:
10^{-4}: 50-85mm/hr, 19dB/km
10^{-5}: 100+mm/hr: 30dB/km



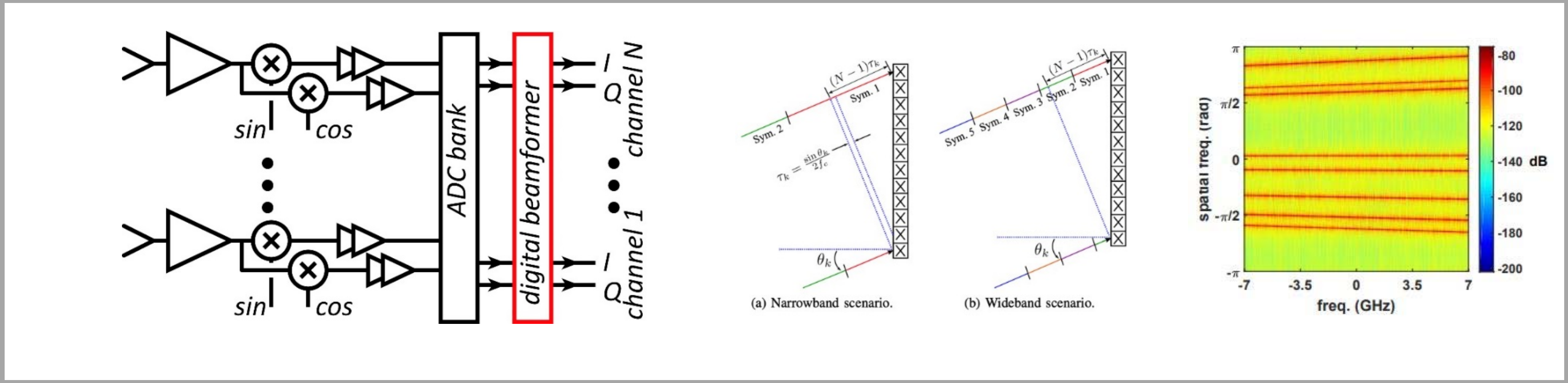
35°C, 90% Humidity
300GHz: 30 dB/km
400GHz: 100 dB/km
450GHz: 200 dB/km
650GHz: 300 dB/km
850GHz: 300 dB/km
1000GHz: 1000 dB/km

Appleby, Wallace, IEEE Trans Ant & Prop, Nov. 2007
Rosker; Wallace, 2007 IEEE IMS
Olsen, Rogers, Hodge, IEEE Trans Antennas & Propagation Mar 1978
Liebe, Manabe, Hufford, IEEE Trans Antennas and Propagation, Dec. 1989
Liebe, IEEE Trans Ant and Pro, Vol 31, No. 1, Jan 1983
Karasawa, Maekawa, IEEE Proc, Vol 85 , #6 , June 1997



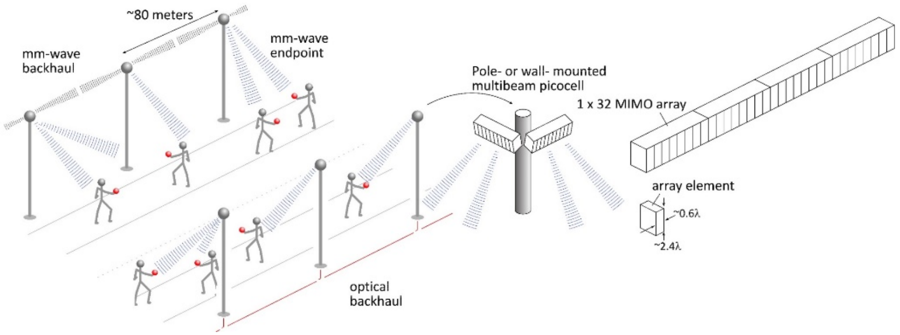
Condition	Temp (C)	Pres. (hPa)	Relative Humidity	Rain (mm/hr)	Fog (m)	Dust (m)
STD	20	1013	44%	0	0	0
HHH	35	1013	90%	0	0	0
Winter	-10	1013	30%	0	0	0
Fog	20	1013	44%	0	100	0
Dust	20	1013	44%	0	0	10
Rain	20	1013	44%	4	0	0

Systems



sin
cos
ADC bank
digital beamformer
I
Q
channel N
channel 1
Sym. 1
Sym. 2
Sym. 3
Sym. 4
Sym. 5
$(N-1)\tau_k$
$\tau_k = \frac{\sin\theta_k}{2f_c}$
θ_k
(a) Narrowband scenario.
(b) Wideband scenario.
spatial freq. (rad)
freq. (GHz)
dB

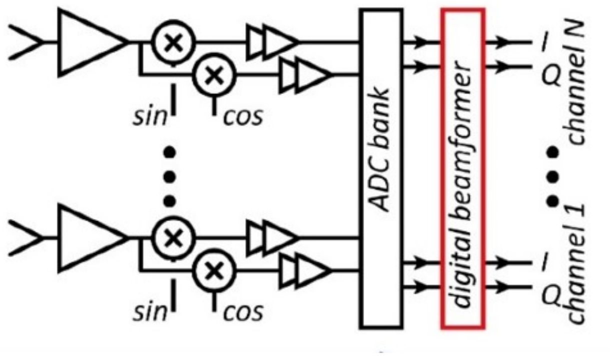
MIMO System Design



M antennas, *K* signals: **spatial oversampling**.

ADCs/DACs[1]: effective # bits increased by $\log_4(M/K)$
Given QPSK, 2:1 spatial oversampling, only need 3-4 bits

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



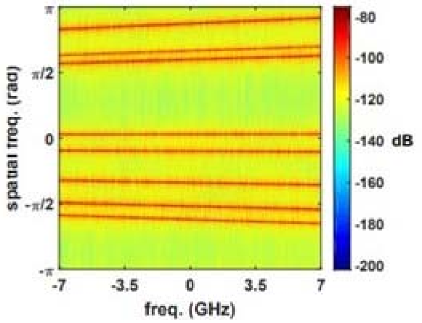
Phase noise[2,3]: Requirements similar to SISO

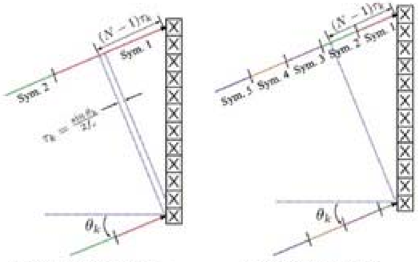
Efficient digital beamforming[4,5]: beamspace algorithm

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

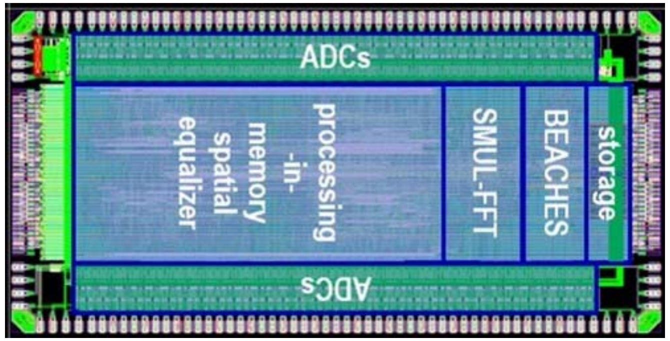
Efficient beamforming in broadband arrays[7]: combined spatial & temporal FFTs.

1) M. Abdelghany et al, IEEE Trans. Wireless Comm, Sept. 2021
2) M. E. Rasekh et al, IEEE Trans. Wireless Comm, Oct. 2021
3) A. Puglielli et al, 2016 IEEE ICC
4) M. Abdelghany, et. al, , 2019 IEEE SPAWC
5) S. H. Mirfarshbafan et al, IEEE Trans CAS 1, 2020
6) O Castañeda Fernández et. al, 2021 ESSCIRC
7) M. Abdelghany et al 2019 IEEE GLOBECOM

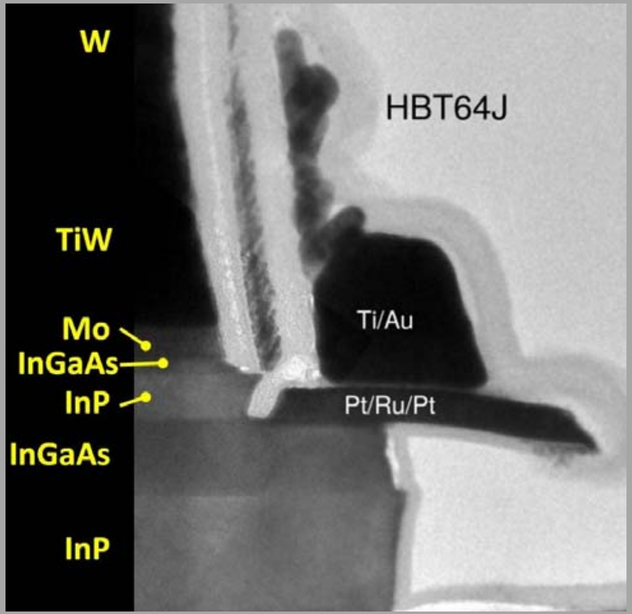


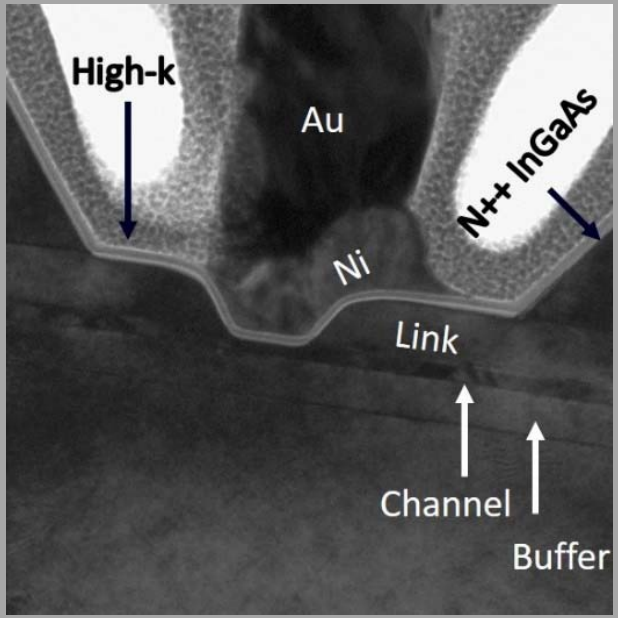


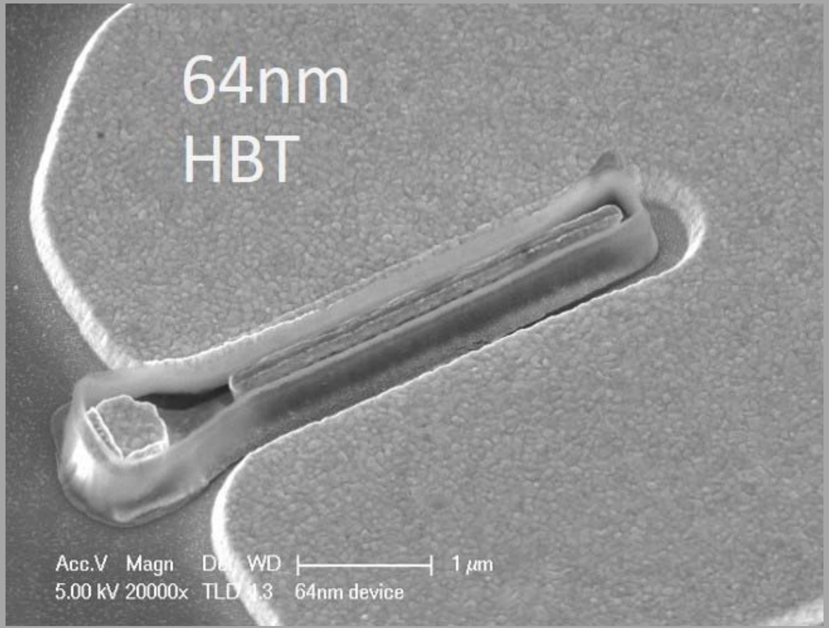
(a) Narrowband scenario.
(b) Wideband scenario.



Transistors







Transistors for 100-300GHz

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

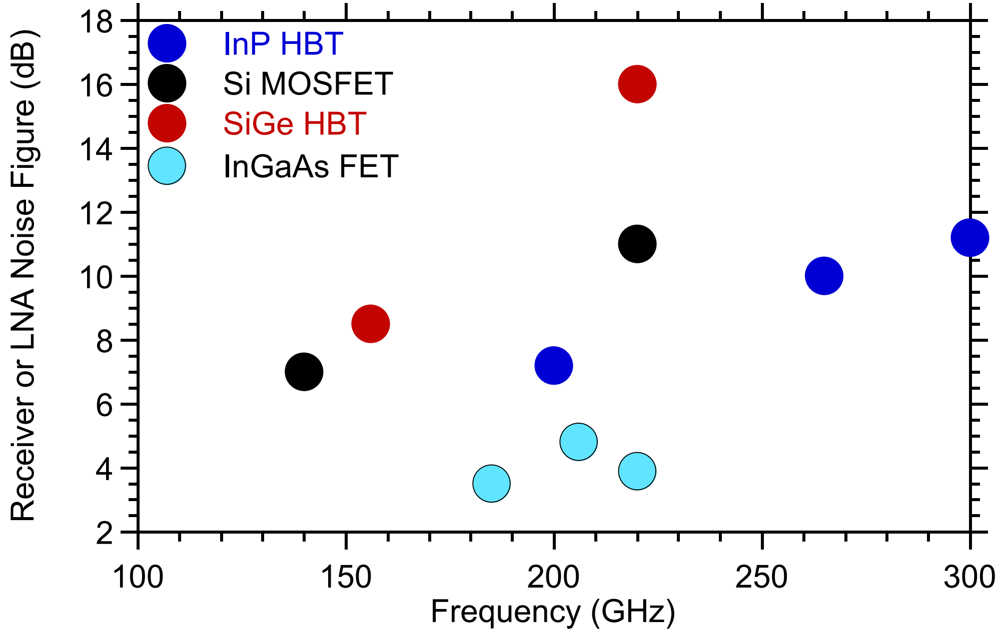
InP HBT: record 100-300GHz PAs

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

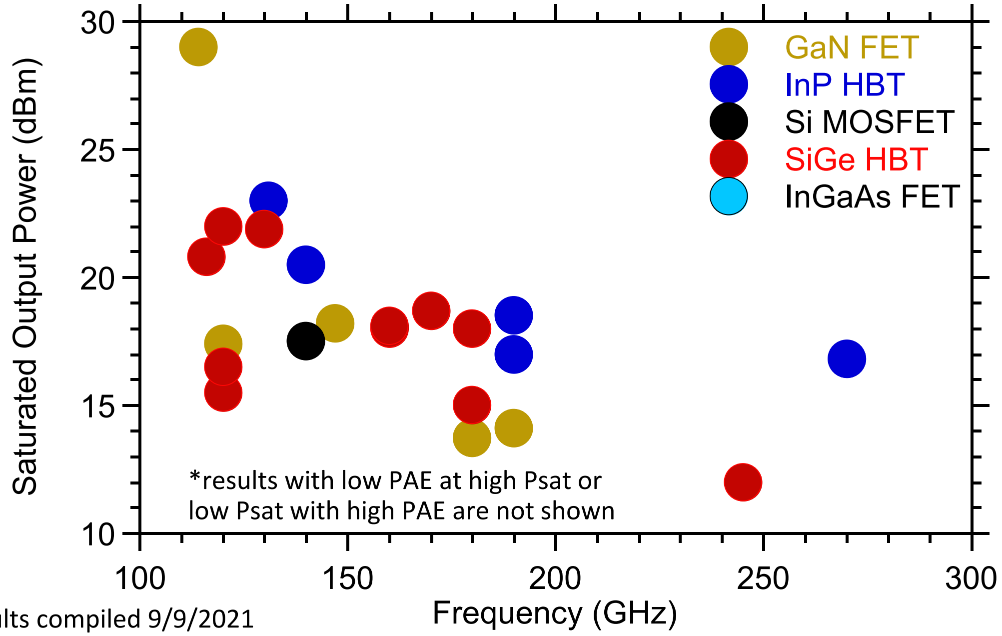
GaN HEMT: record power below 100GHz. Bandwidth improving

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

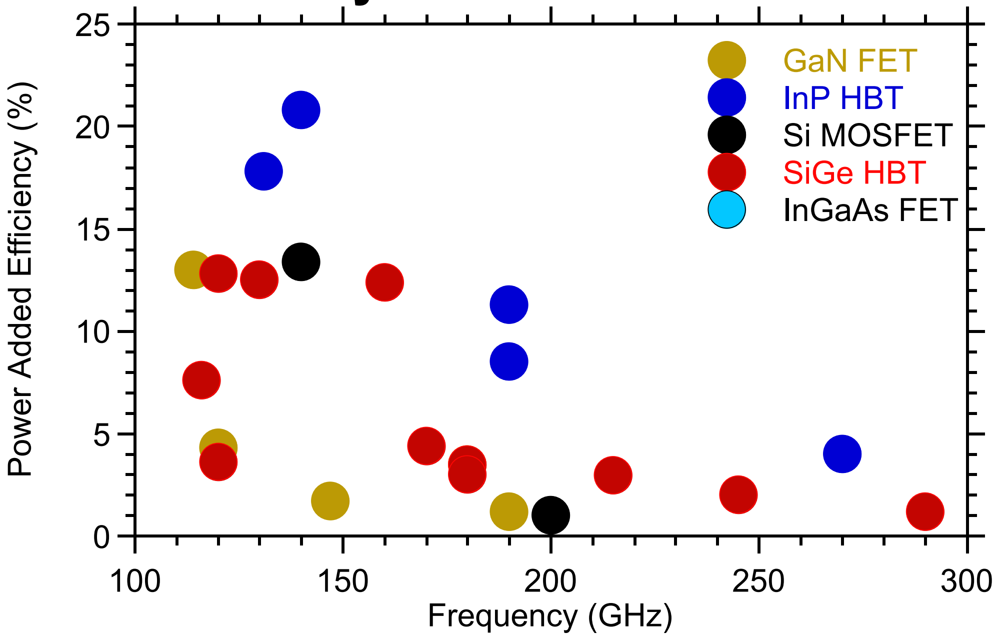
Noise



Power



Efficiency

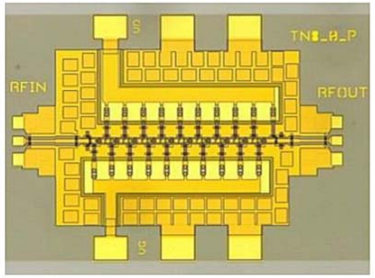


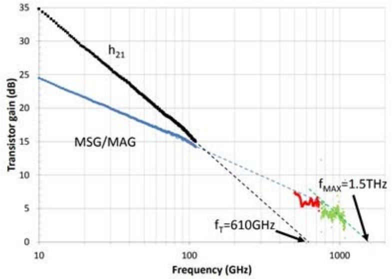
Results compiled 9/9/2021

InP Transistors and ICs

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

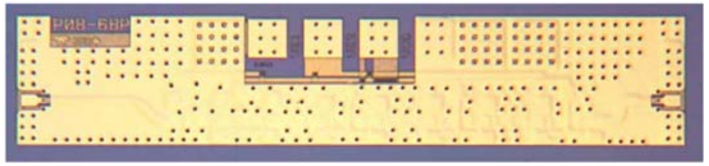
W. Deal et al, 2016 IEDM (Northrop-Grumman)

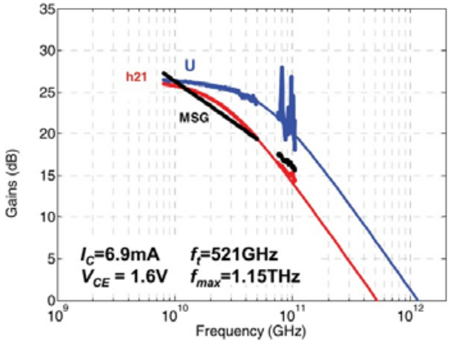


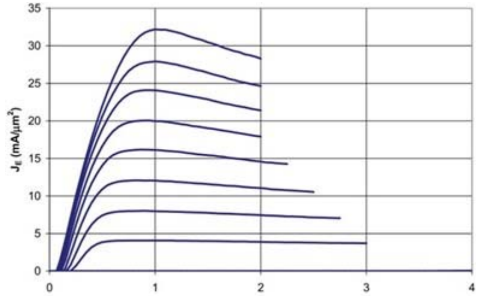


130nm InP HBTs: 1.1THz f_{max}, 3.5V. 670 GHz amplifiers

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



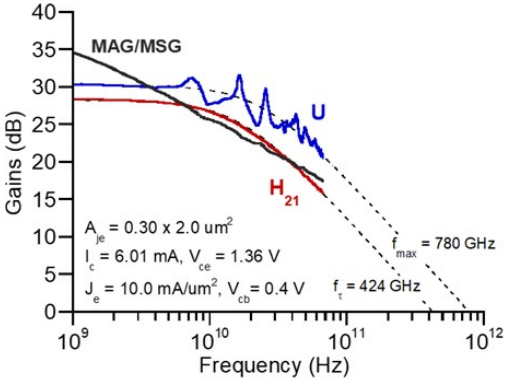


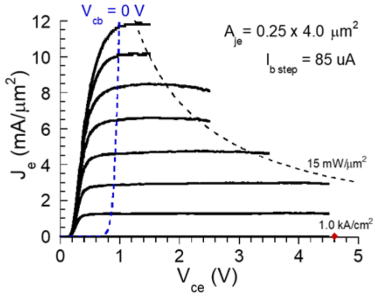


250nm InP HBTs: 650GHz f_{max}, 4.5V.

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

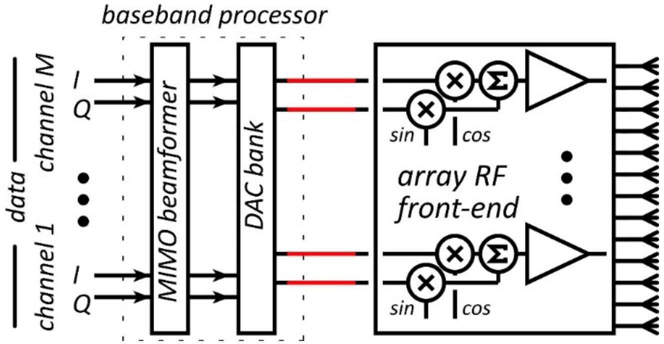
M. Urteaga, et al, IEEE Proceedings June 2017 (Teledyne)



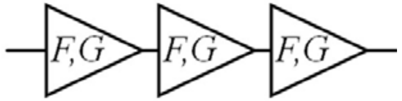


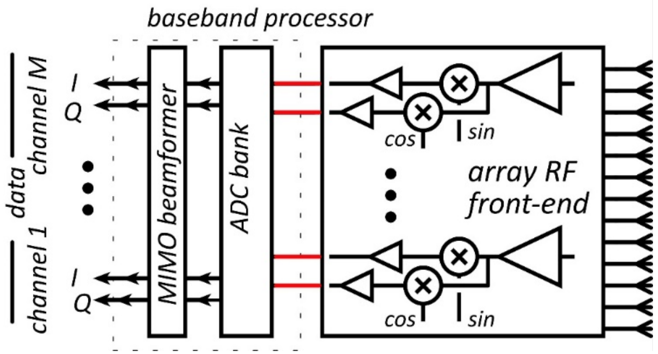
100-300GHz wireless: transistor requirements

Transmitters need:
high power-added efficiency $PAE = (P_{out} - P_{in})/P_{DC}$
high added power density (P_{out}-P_{in})/(gate width, emitter length)

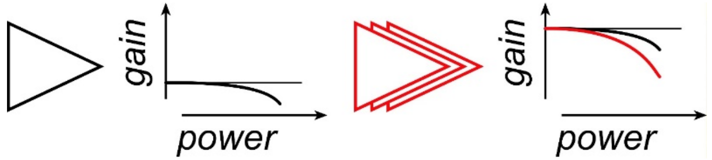


Receivers need:
low cascaded noise $F_{casc} = F + (F-1)/G + (F-1)/G^2 + \cdots$





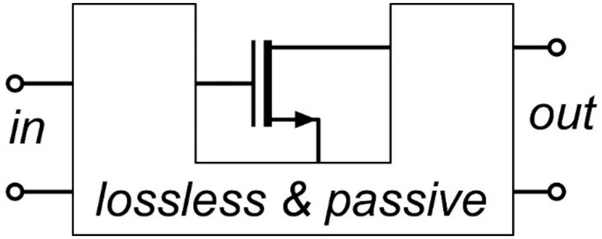
Need reasonable gain/stage.
die area, power,
accumulated gain compression

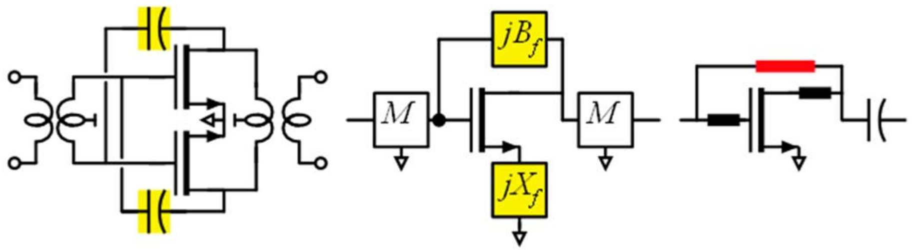


(gain in PAs, LNAs is less than MAG/MSG, U, ...)

Where the IC designer can't help

mm-wave transistor gain is low: gain-boosting is common
Common-source vs. common-gate.
Capacitive neutralization. Unconditionally stable positive feedback (Singhakowinta, Int. J. Electronics, 1966)



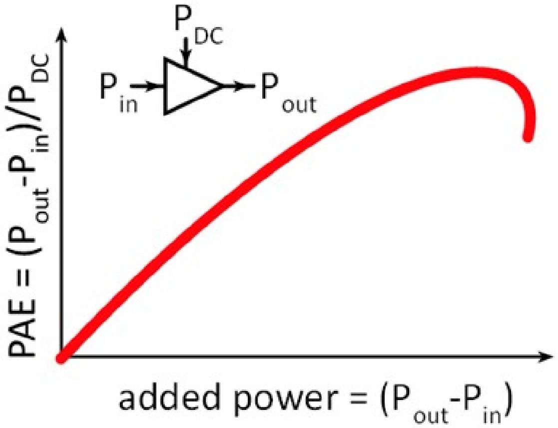


Such circuits don't improve the parameters that matter the most.

The circuit* doesn't change the transistor minimum cascaded noise figure. (Haus, Adler, Proc. IRE, 1958)

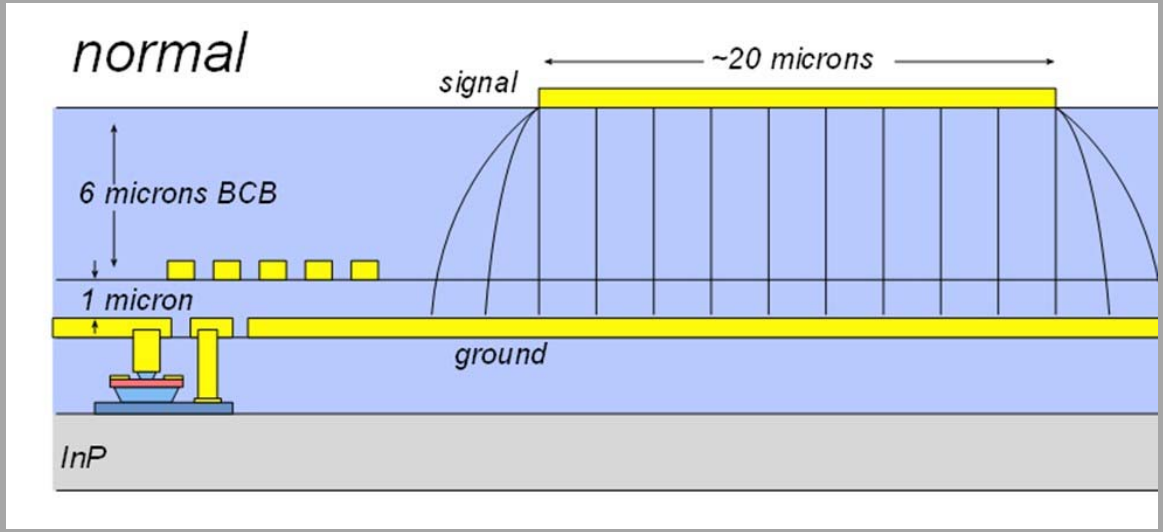
The circuit* doesn't change the transistor maximum efficiency vs. added power curve.

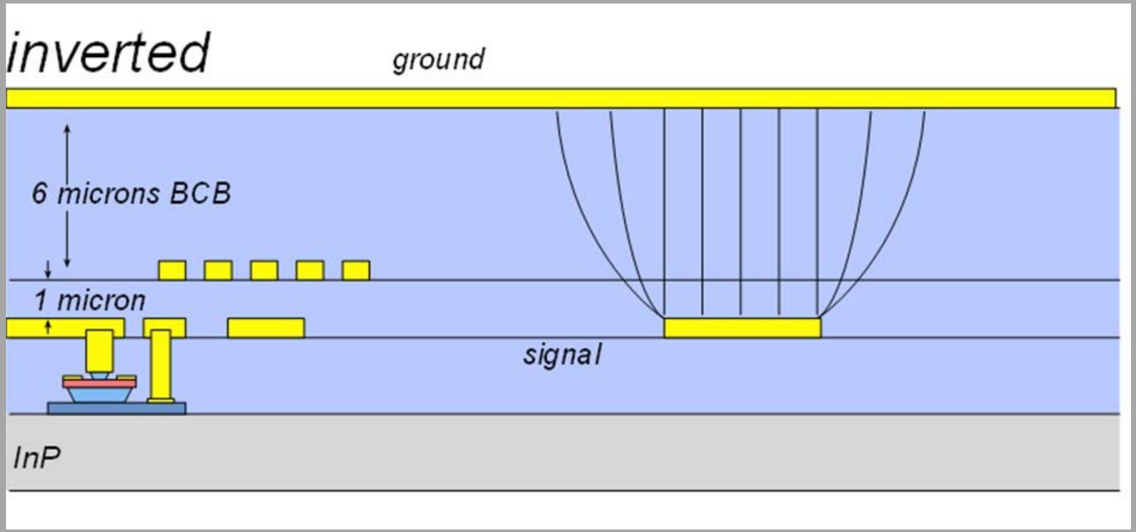
$$F_{casc} = 1 + M = F + (F-1)/G + (F-1)/G^2 + \cdots$$



*If lossless, and given the correct source and load impedances.

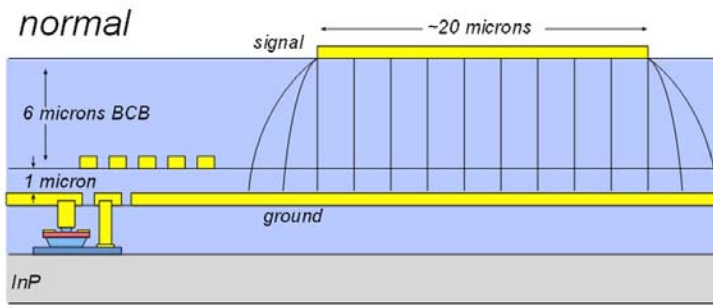
Interconnects

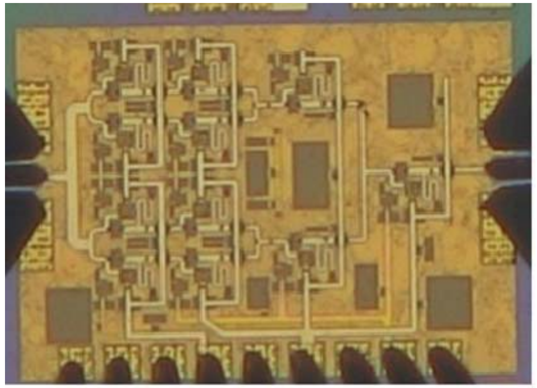




Normal & inverted microstrip

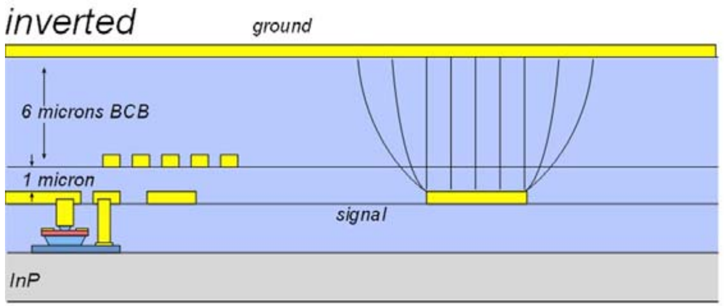
Normal: PAs, LNAs
smaller skin-effect losses ✓
ground-plane holes at transistors ✗

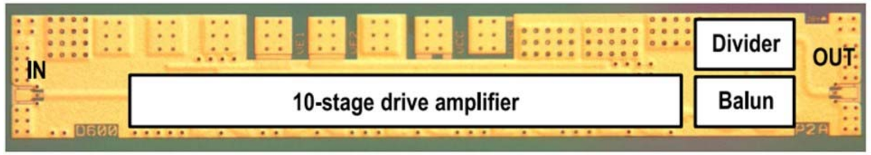


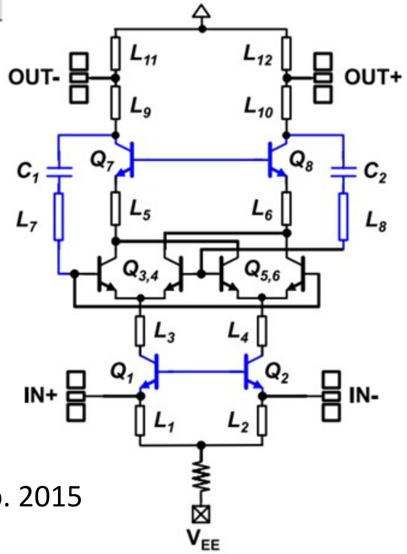


266GHz, 16.8dBm PA: A. Ahmed et. al, 2021 IMS

Inverted: high-density blocks (mixers, phase shifters,…)
higher skin-effect losses ✗
no ground-plane breaks: better ground integrity ✓







529GHz dynamic divider: M. Seo et al, IEICE Electronics Express, Feb. 2015

On-Wafer Interconnect Losses

Interconnects in packages and on PCBs:

$H \propto$ 1/frequency (to control radiation loss)

$\text{loss (dB/mm)} \propto (\text{frequency})^{3/2}$

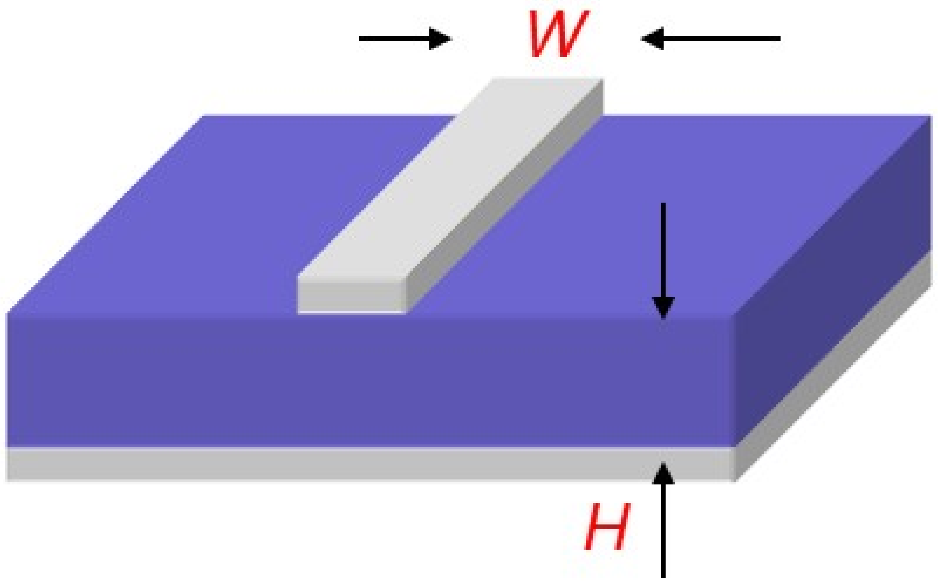
$\text{loss (dB/wavelength)} \propto \sqrt{\text{frequency}}$

Interconnects in ICs:

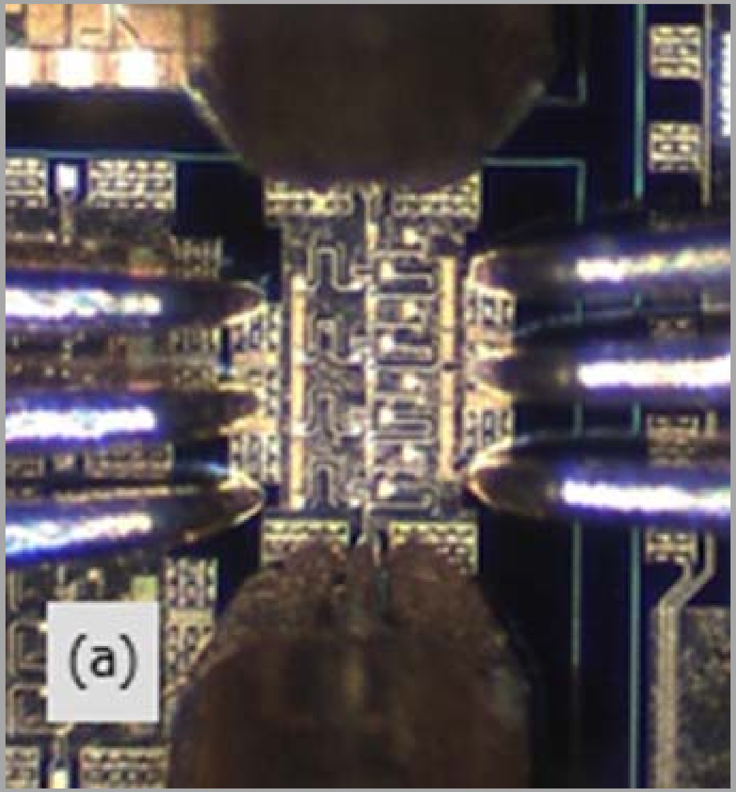
H is independent of frequency

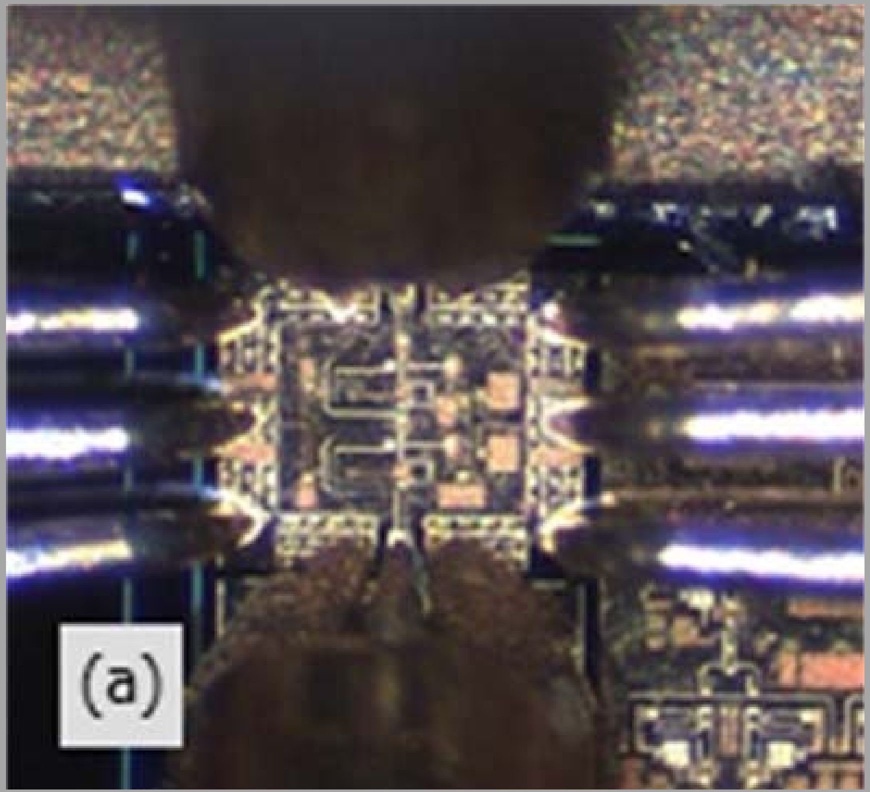
$\text{loss (dB/mm)} \propto \sqrt{\text{frequency}}$

$\text{loss (dB/wavelength)} \propto 1/\sqrt{\text{frequency}}$



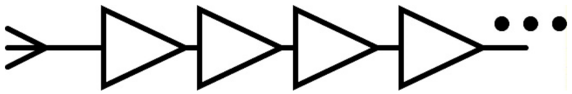
Low-Noise Amplifiers





LNA design: noise close to transistor limits

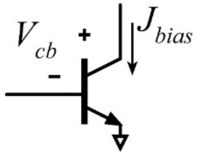
1) Goal: low noise measure, not noise figure

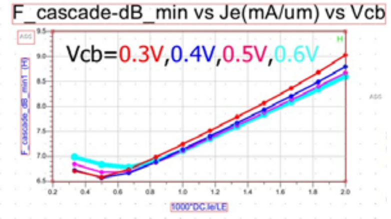


$$F_{\text{cascade}} = M + 1 = F + \frac{F-1}{G} + \frac{F-1}{G^2} + \ldots = \frac{F - 1/G}{1 - 1/G}$$

F = noise figure, M = noise measure

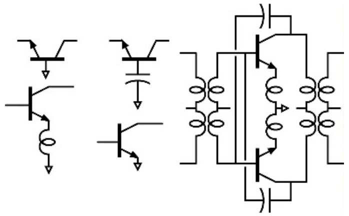
2) Find bias current density for lowest noise measure





@210GHz,
$F_{cascade,min}$= 6.57 dB
given:
J_e=0.5 mA/um,
V_{cb}=0.3V

3) Minimum M is independent of circuit configuration*; pick for high bandwidth or high gain/stage (= low P_{DC})

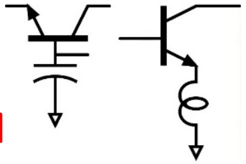


<-- all give the same minimum M…

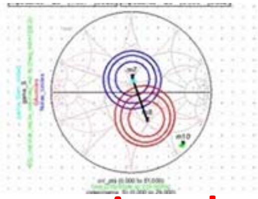
…but common-base gives highest gain (InP HBT @210GHz).

*HA Haus, RB Adler, Proceedings of the IRE, 1958

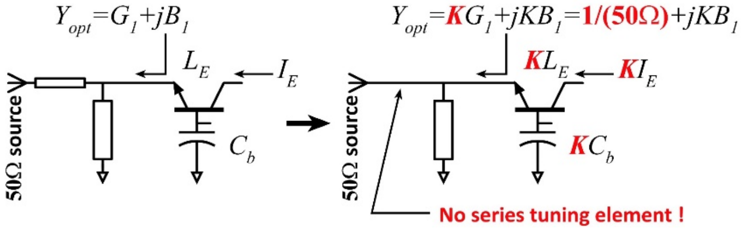
4) Capacitance in common-base; just like inductance in common-emitter, allows simultaneous tuning for zero reflection coefficient and minimum M



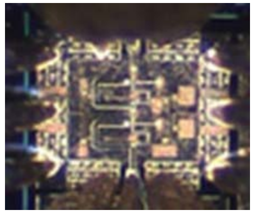
5) Write ADS Python code to display source impedance for minimum M.

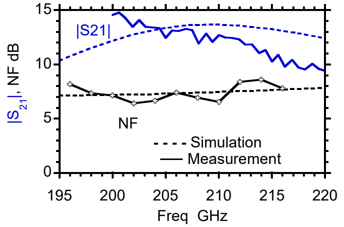


6) Scale transistor size to eliminate series tuning element. Less input tuning→ less noise from passive element loss.



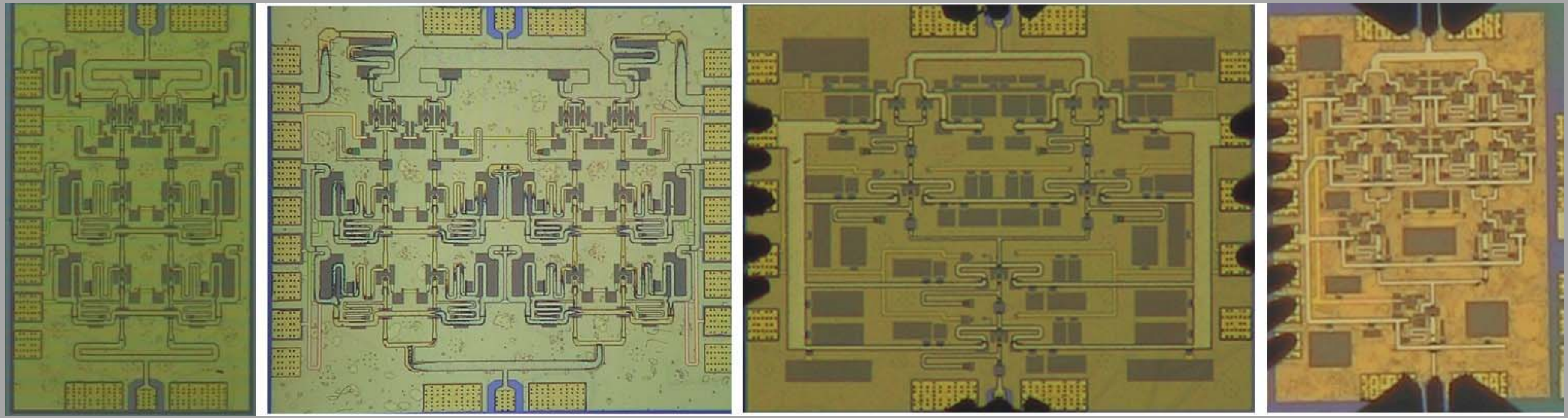
Result: 7.2-7.4dB LNA noise given 6.6dB transistor $F_{cascade}$.





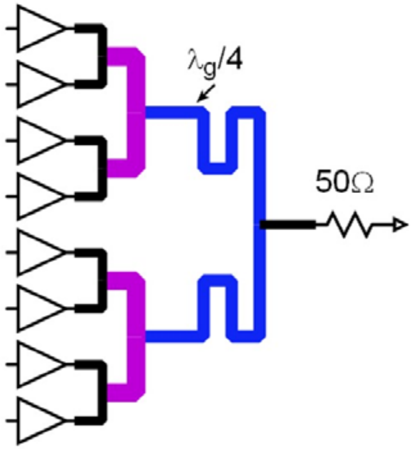
U. Solyu et. al, 2021 EuMIC Conference

Power Amplifiers



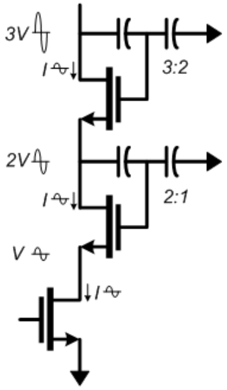
100-300GHz Power combining: what is best ?

Corporate T-line



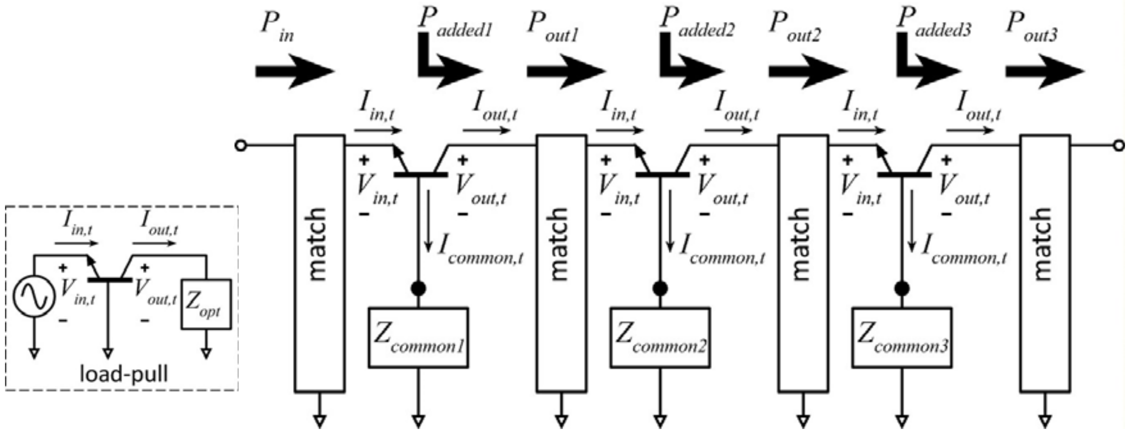
Direct series-connected

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



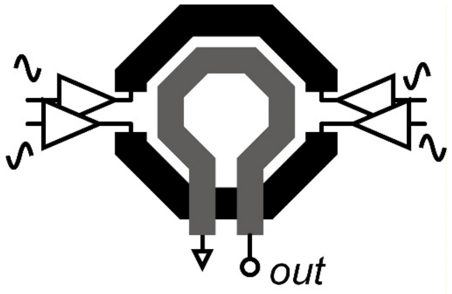
Cascaded combining

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



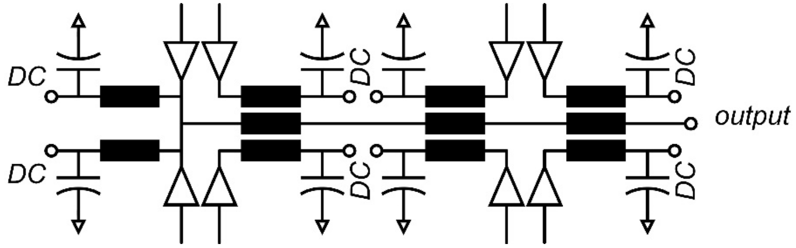
Distributed Active Transformer

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



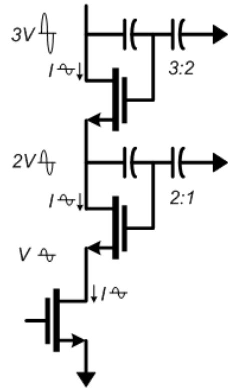
Balun series-connected

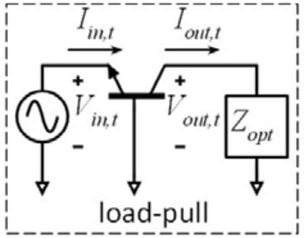
λ/4 baluns: Y. Yoshihara, 2008 IEEE Asian Solid-State Circuits Conference **(Toshiba)**
sub-λ/4 baluns: H. Park, et al, IEEE JSSC, Oct. 2014 **(UCSB)**

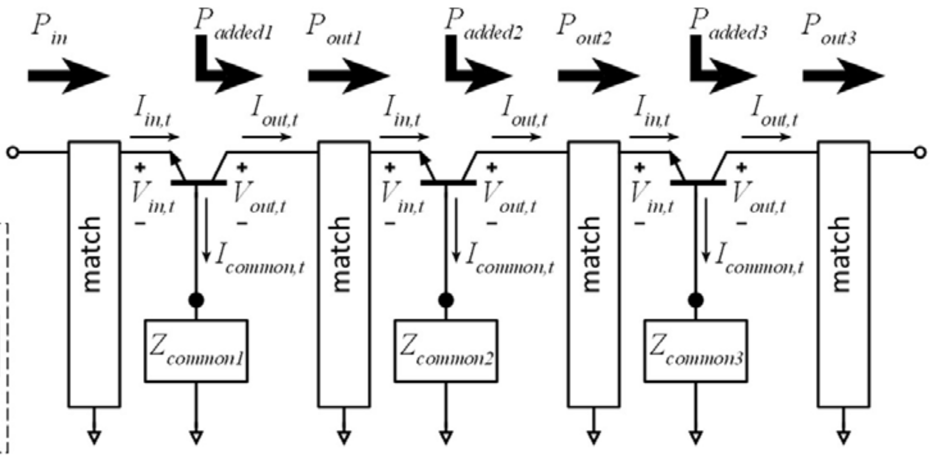


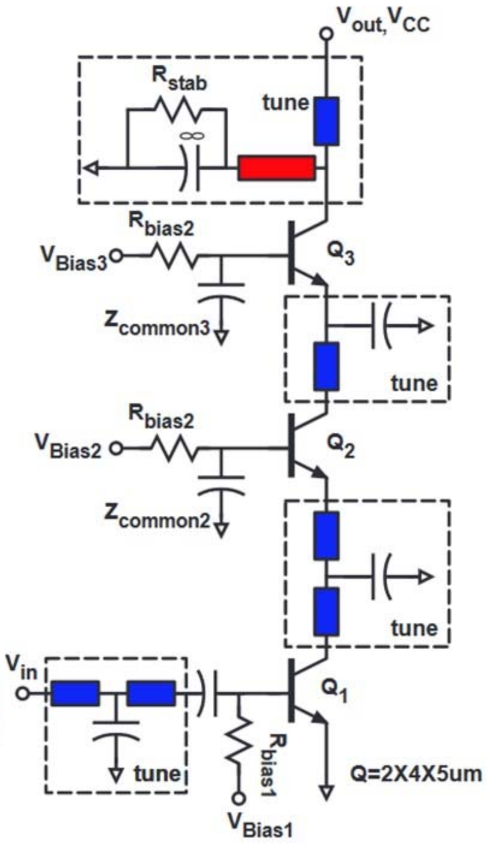
Cascade combining as stacking plus matching

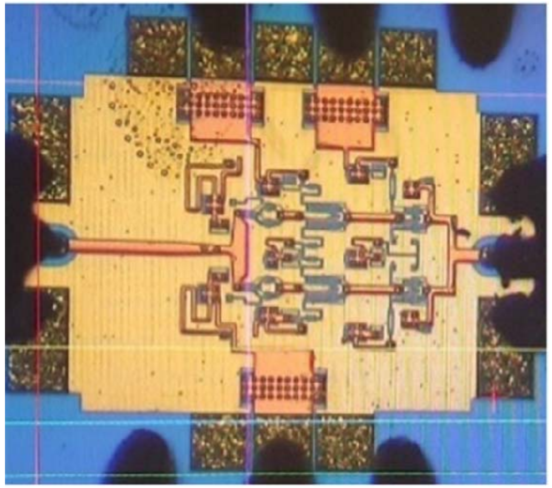
A. S. H. Ahmed et al, 2018 EuMIC (UCSB)

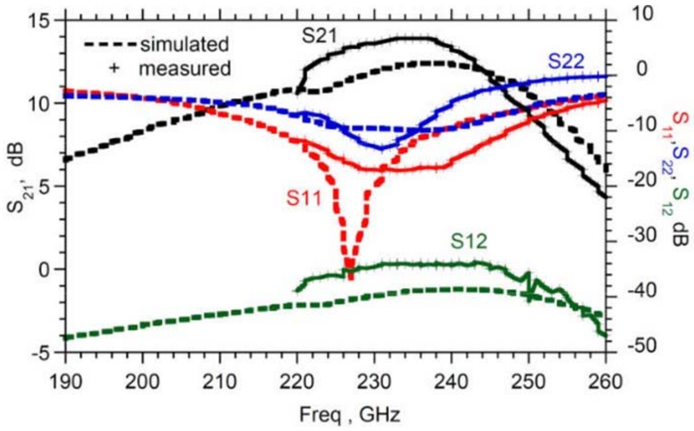


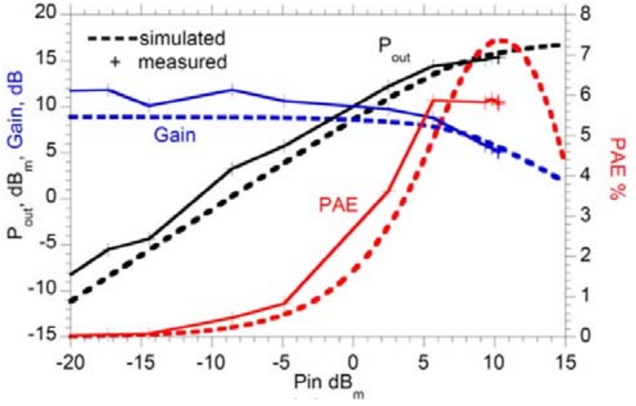




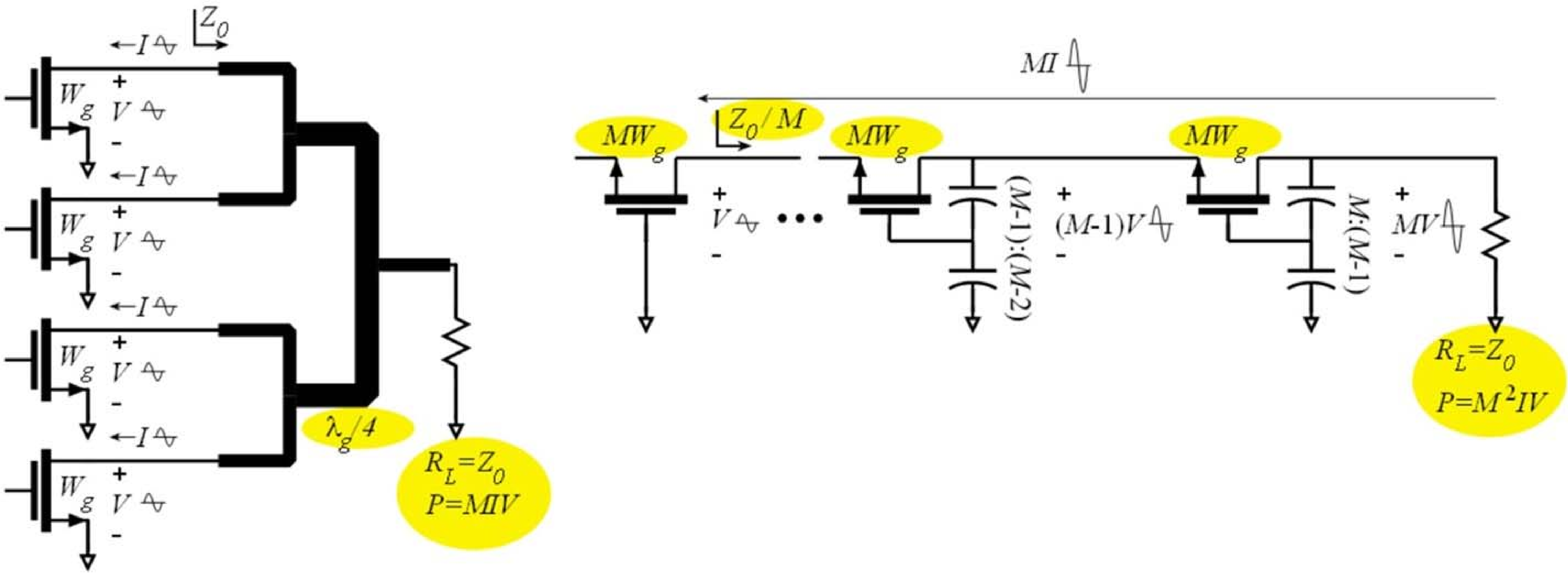








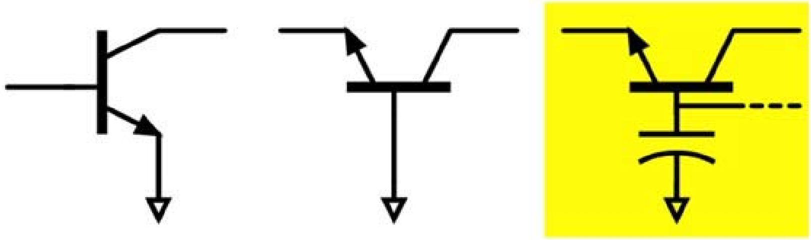
Transistor stacking. Why ? Why not ?

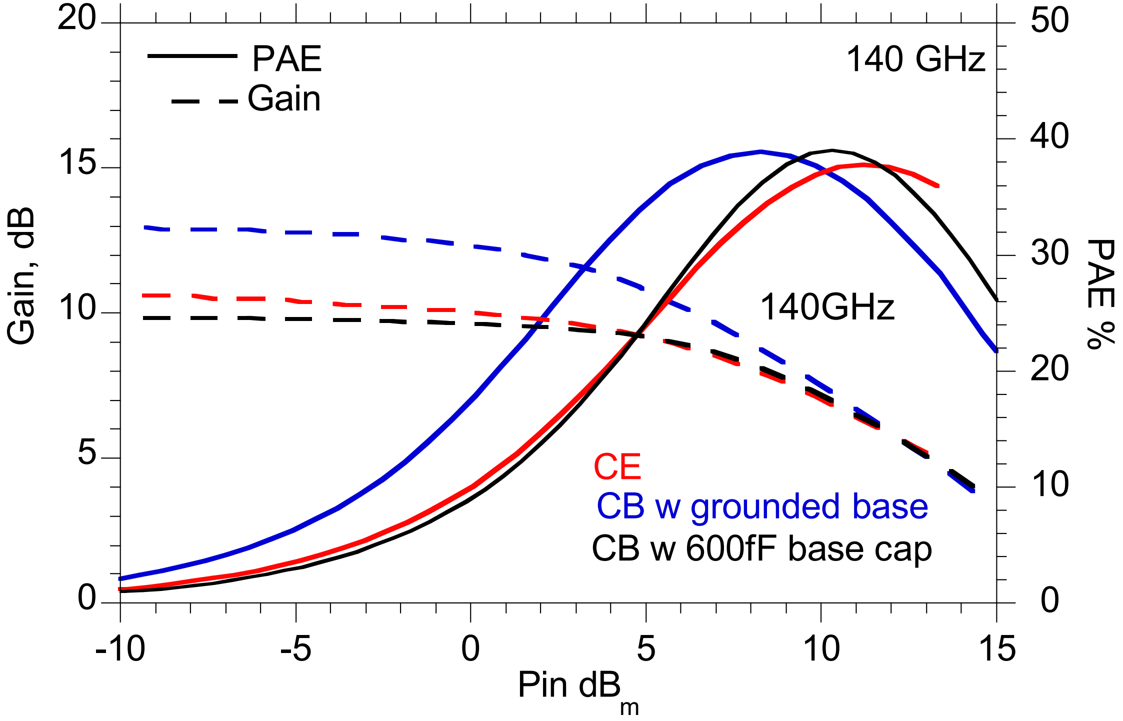


	Lower frequencies	Higher frequencies
Corporate combining	length $\propto 1/f \rightarrow$ large die area ✗ dB loss $\propto 1/\sqrt{f} \rightarrow$ high loss ✗	length $\propto 1/f \rightarrow$ small die area ✓ dB loss $\propto 1/\sqrt{f} \rightarrow$ low loss ✓
Series-connected	more transistor fingers per cell → ok ✓	more transistor fingers per cell→ parasitics ✗

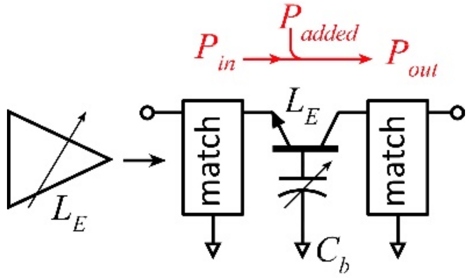
Capacitively degenerated common-base

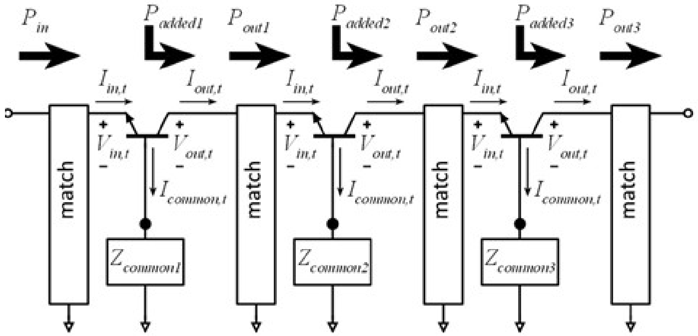
Lower gain, same peak PAE, higher PAE at P_{1dB}.

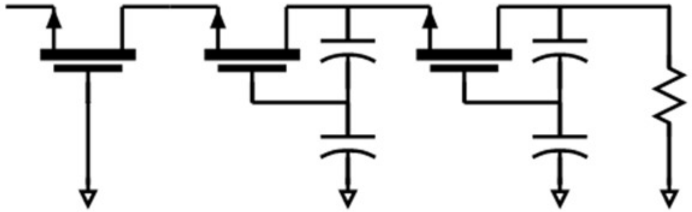


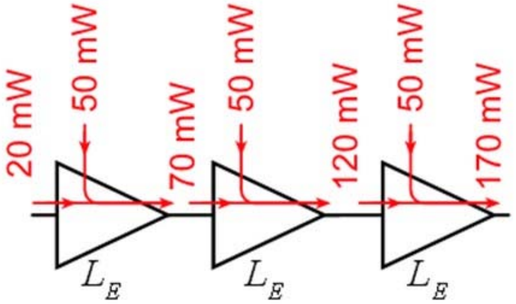


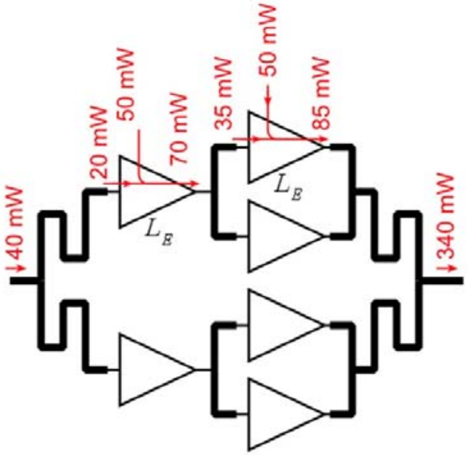
How does this differ from stacking ?







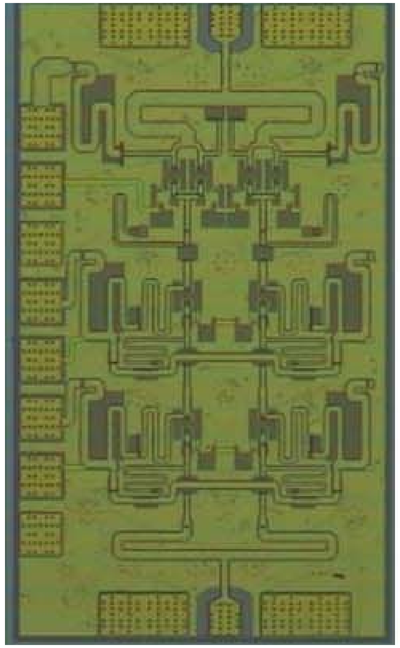


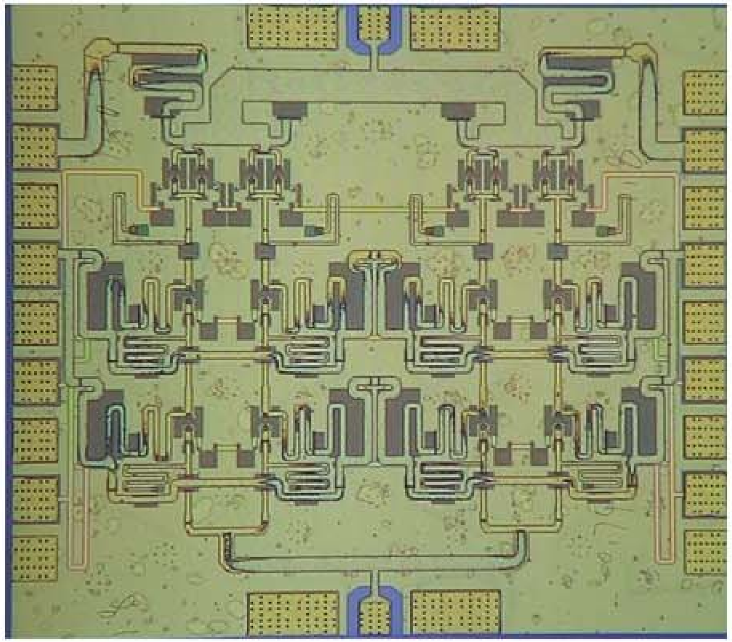


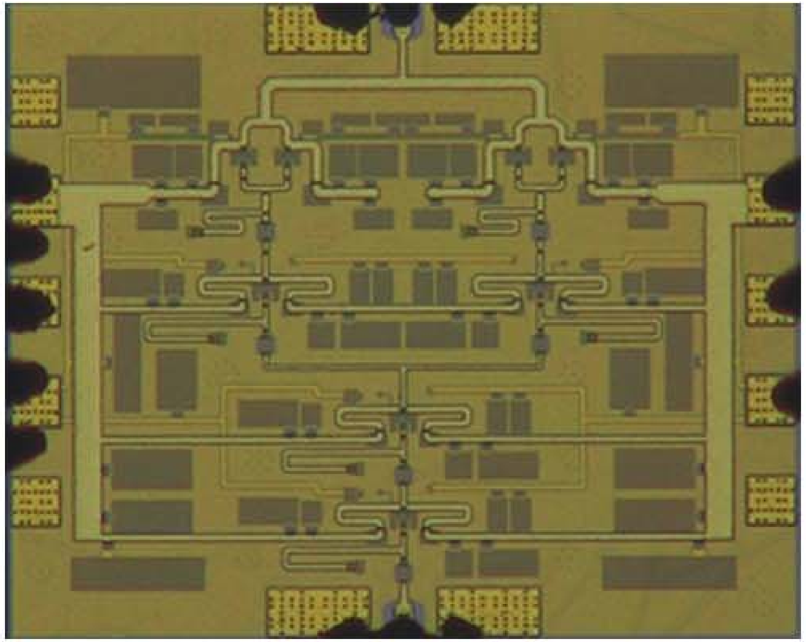
Recent high-efficiency 100-300GHz PAs

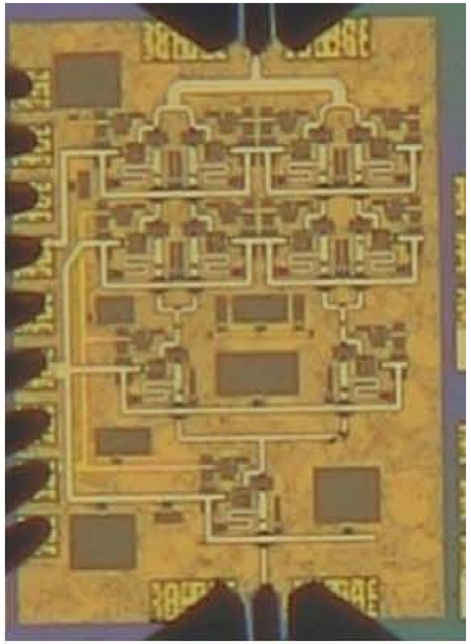
Teledyne 250nm InP HBT technology

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







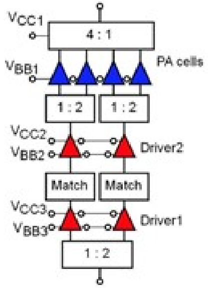


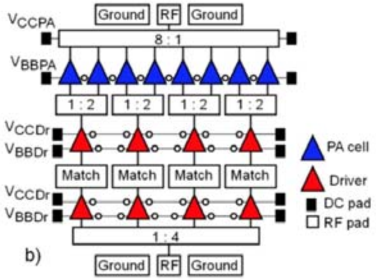
140GHz, 20.5dBm, 20.8% PAE

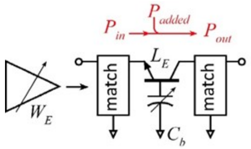
130GHz, 200mW, 17.8% PAE

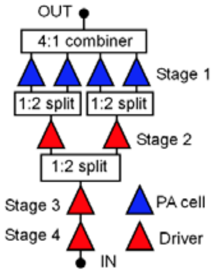
194GHz, 17.4dBm, 8.5% PAE

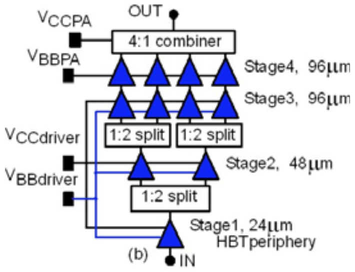
266GHz, 16.8dBm, 4.0% PAE



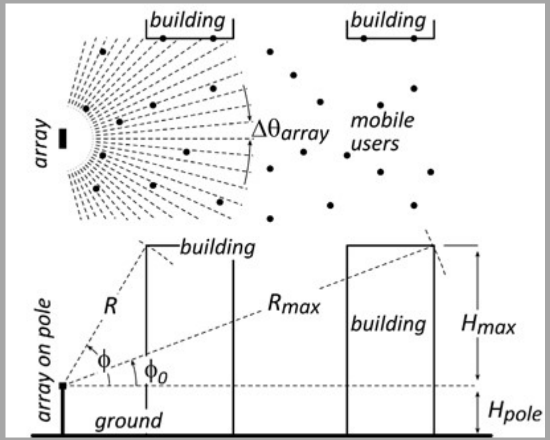


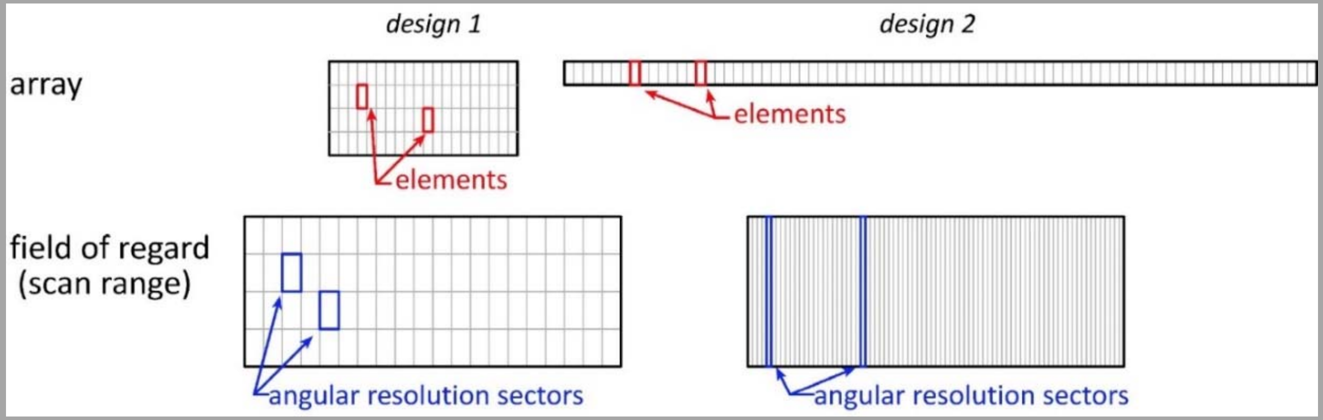






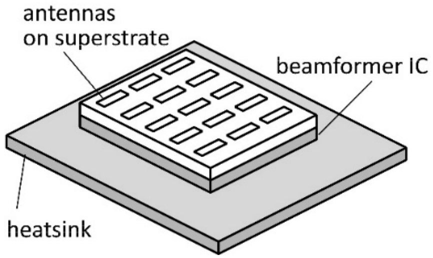
1D and 2D Array Design

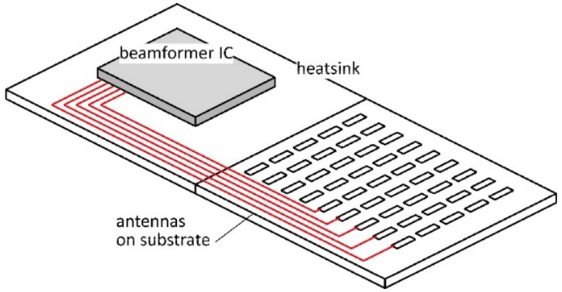




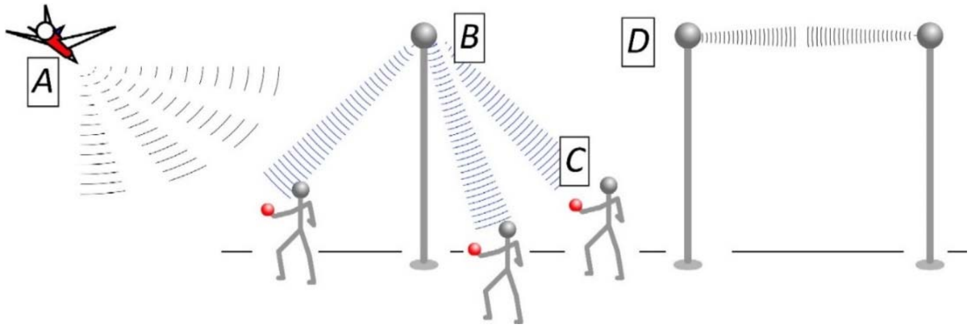
The mm-wave module design problem

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

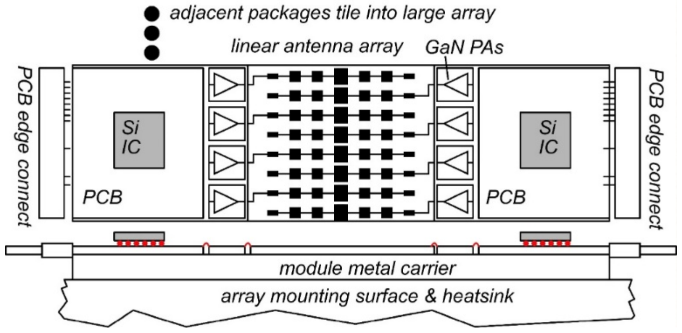


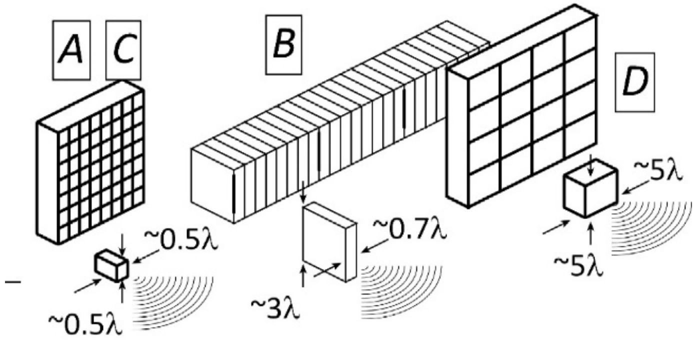


Not all systems steer in two planes...
...some steer in only one.



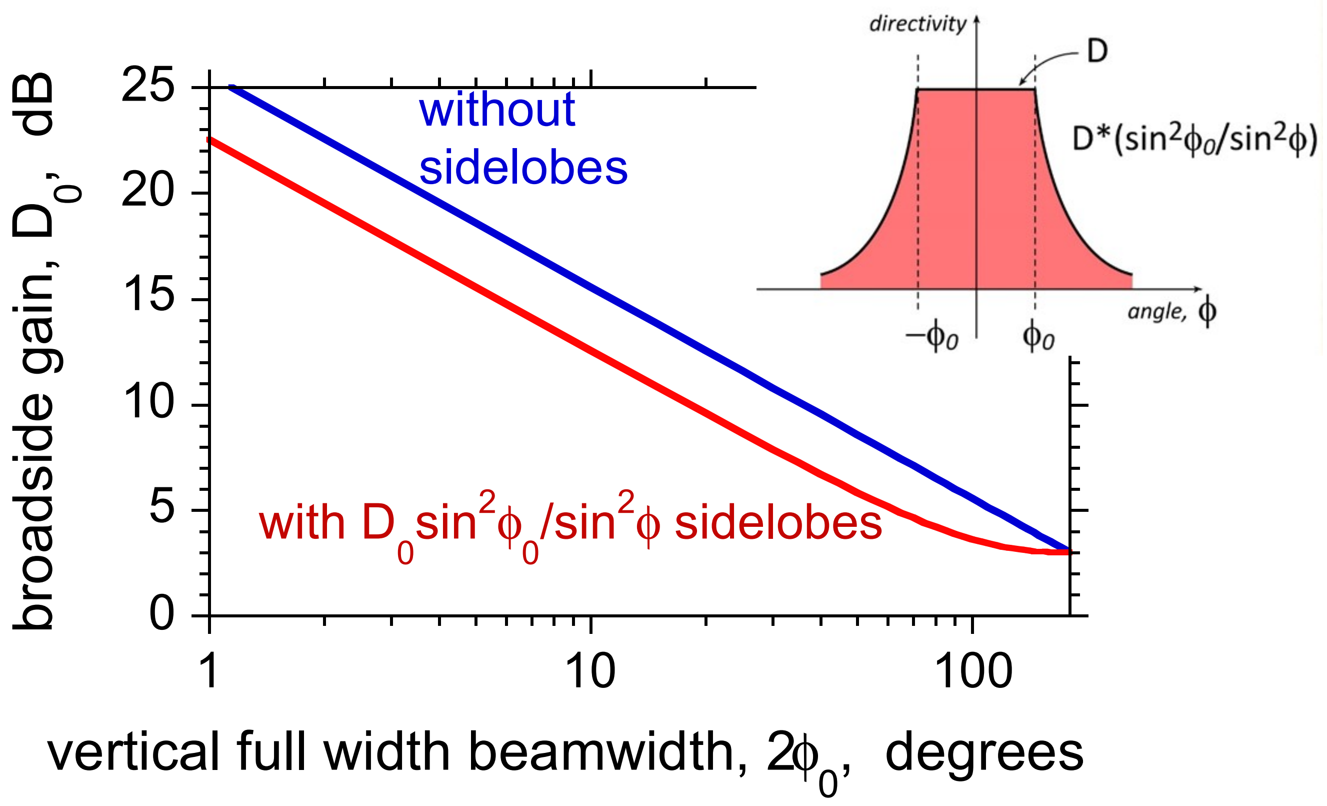
Not all systems steer over 180 degrees...
...some steer a smaller angular range

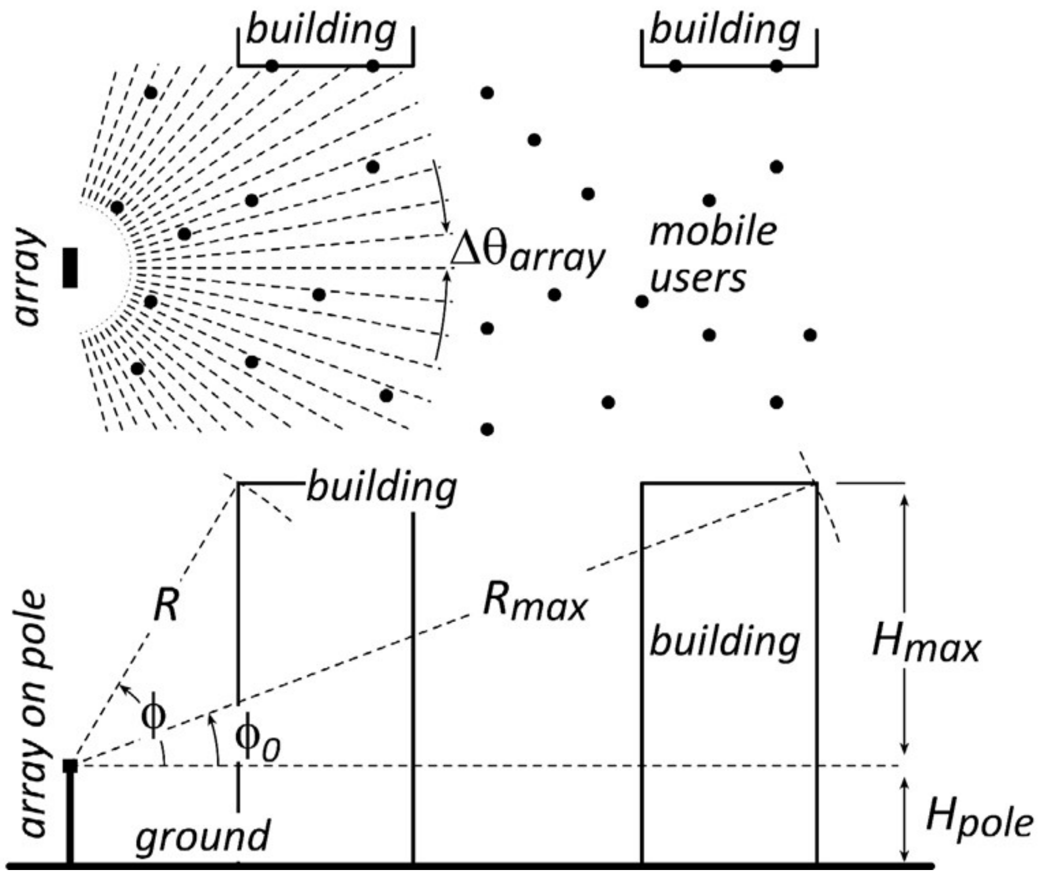




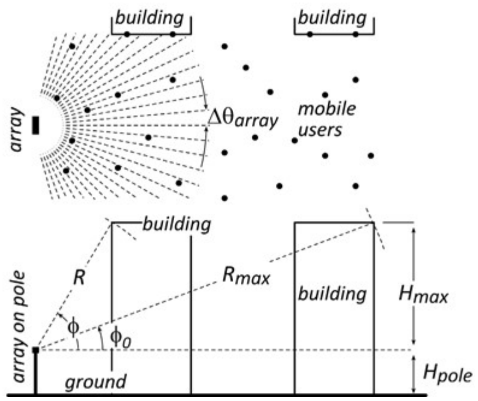
Do we need 2D arrays ? 1D might be fine.

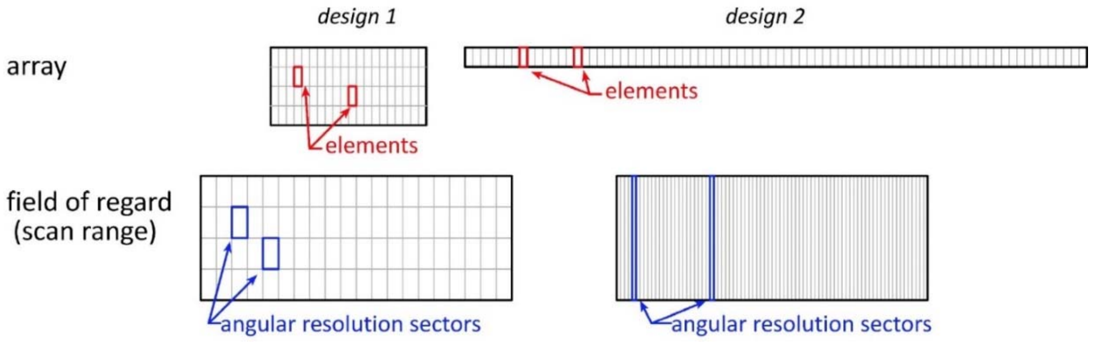
$1/\sin^2\phi$ sidelobes provide strong signals to tall buildings.
Providing sidelobes reduces broadside gain by less than 3dB.
→ Don't need 2D arrays to serve tall buildings





2D vs. 1D: user spatial distribution

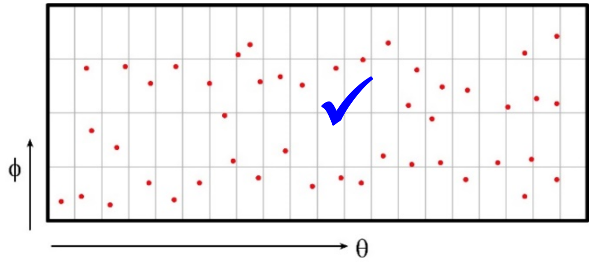


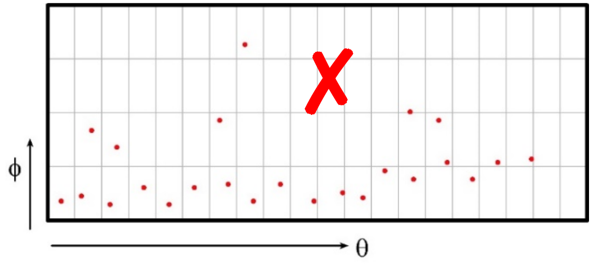


uniform horizontal & vertical user distributions

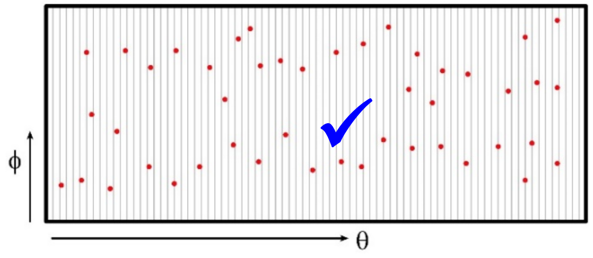
uniform horizontal, nonuniform vertical

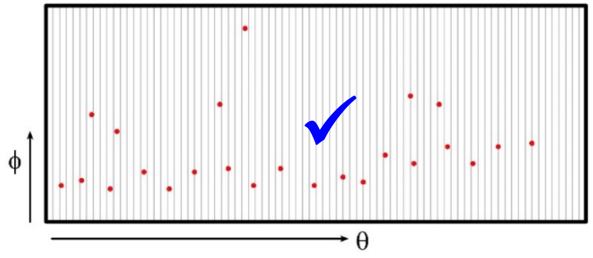
design 1: 2D array





design 2: 1D array

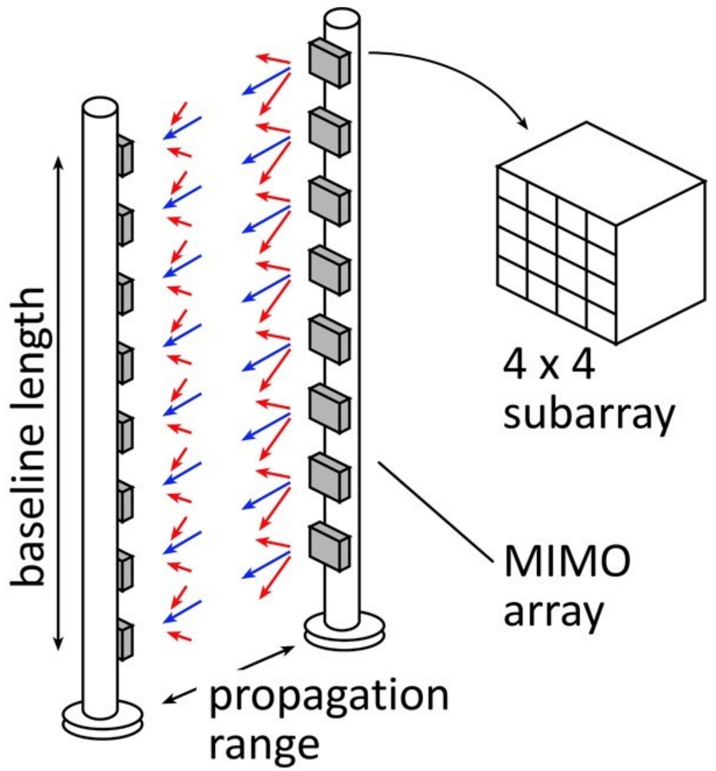


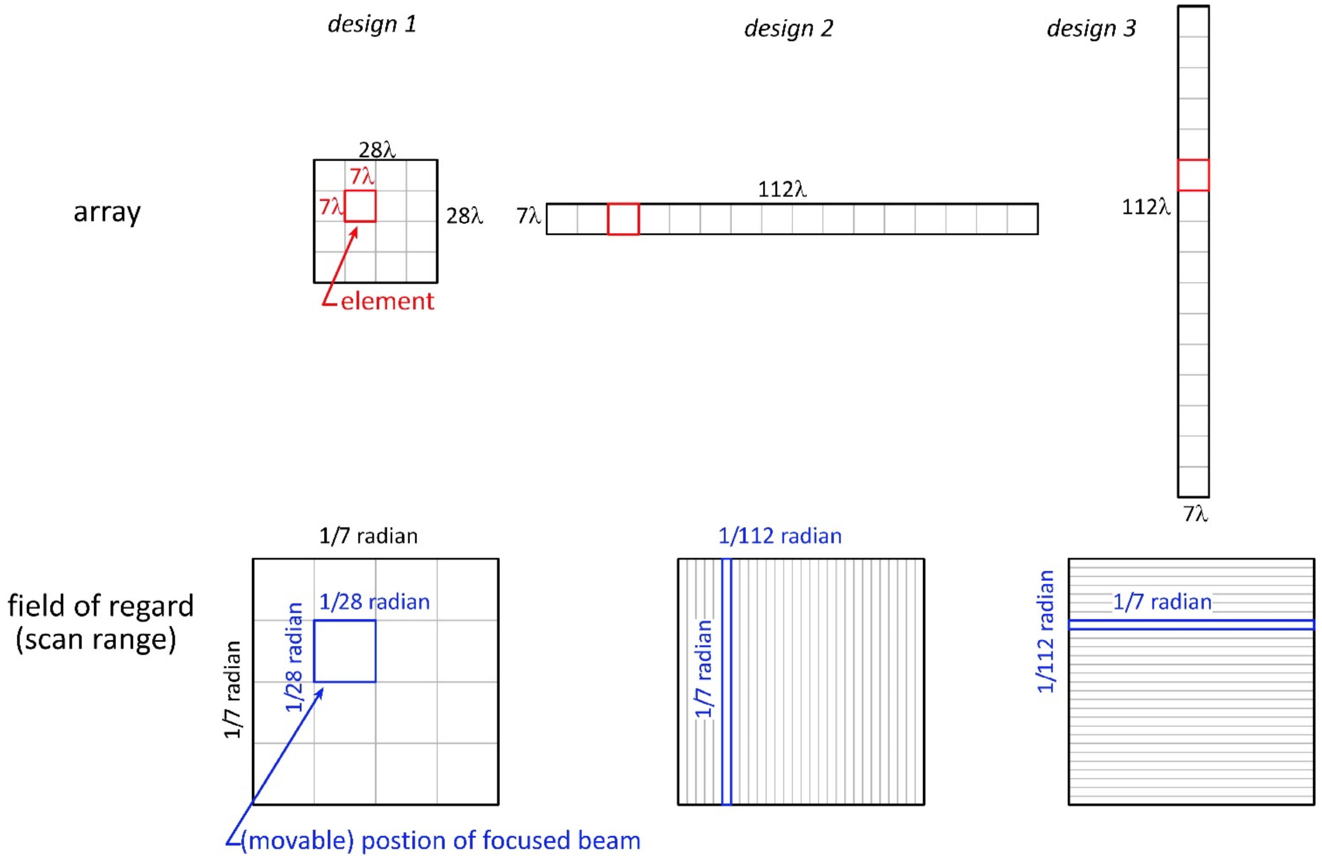


Spatial distribution of users, and of scattering objects, guides choice of array geometry.

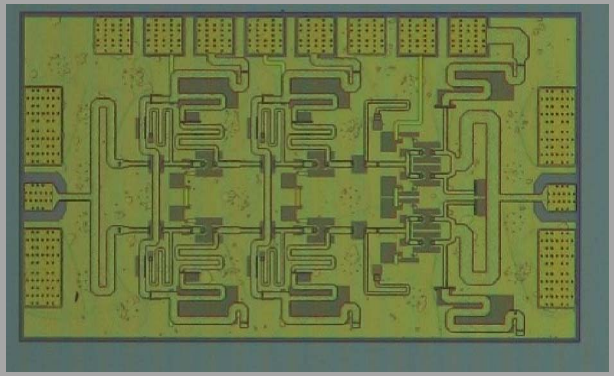
1D or 2D subarray for backhaul ?

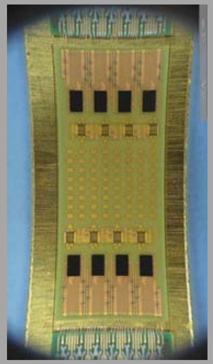
Should we use 4x4 array, 1x16, or 16x1 array ?
All provide same system link budget, same # RF channels, same angular scanning range.





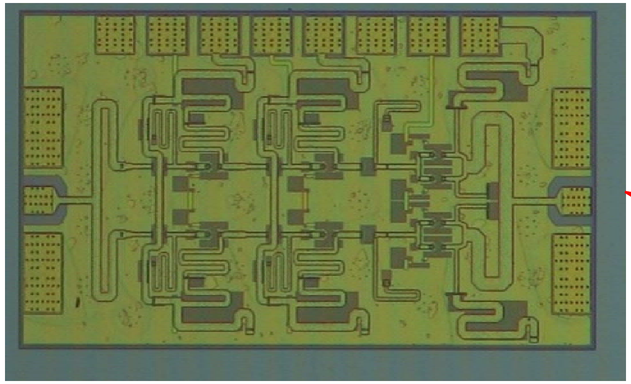
140 GHz
Array Modules



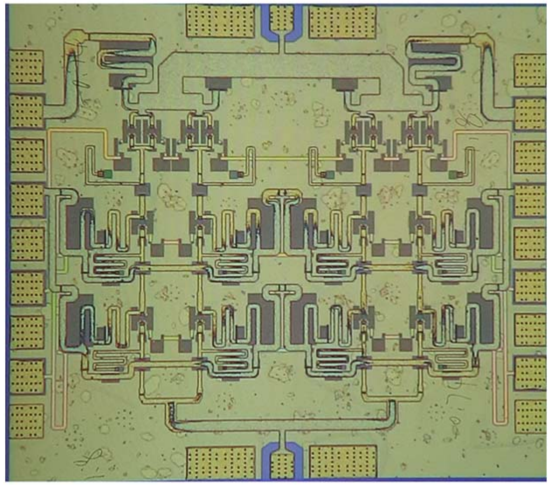


Gen. I 140GHz MIMO hub modules

110mW InP Power Amplifier[a]
20.8% PAE

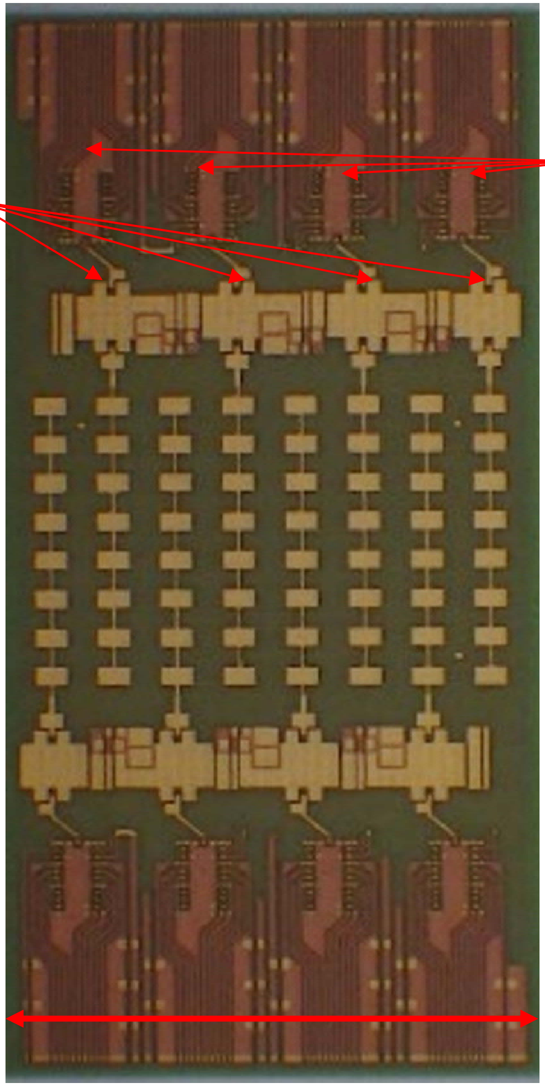


190mW InP Power Amplifier[b]
16.7% PAE



Teledyne 250nm InP HBT

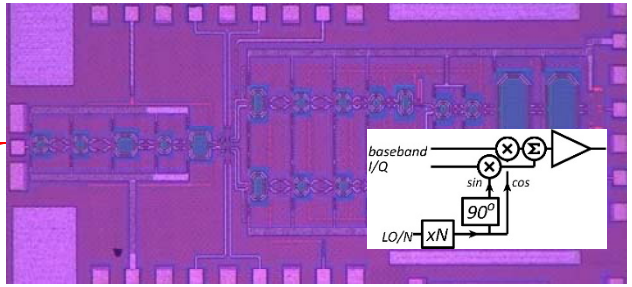
LTCC Array module



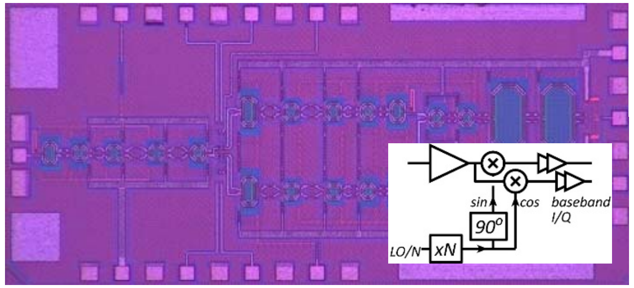
1 cm

Kyocera

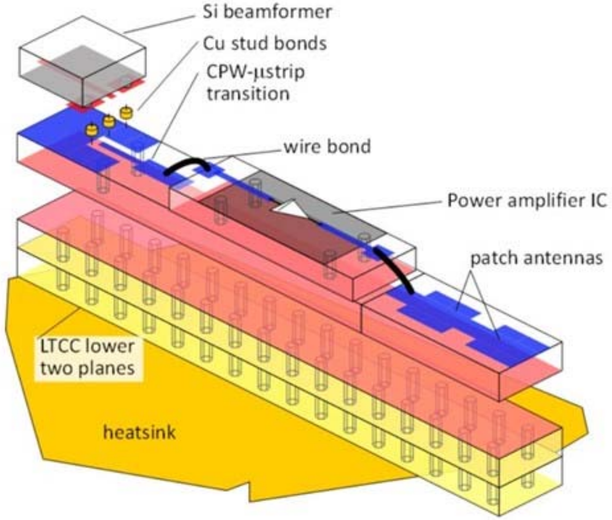
CMOS Transmitter IC[c]
22nm SOI CMOS.



Receiver IC[c]
22nm SOI CMOS.



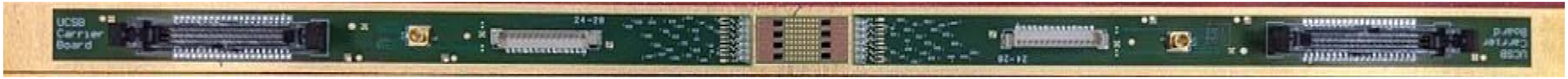
GlobalFoundries 22nm SOI CMOS



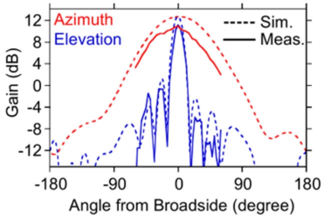
(a) A. S. H. Ahmed et al., 2020 IMS
(b) A. S. H. Ahmed et al., 2021 EuMIC
(c) A. Farid et al., 2019 RFIC

Gen. I 140GHz MIMO hub receivers

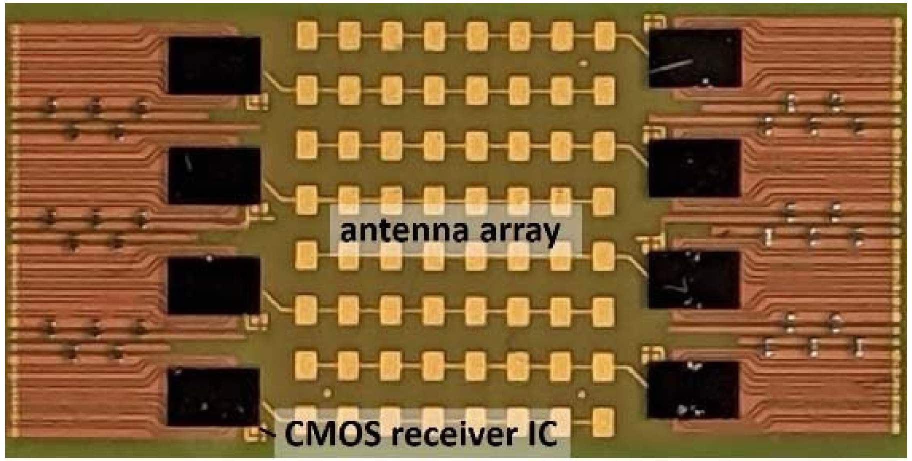
A. Farid et. al, 2021 IEEE BCICTS

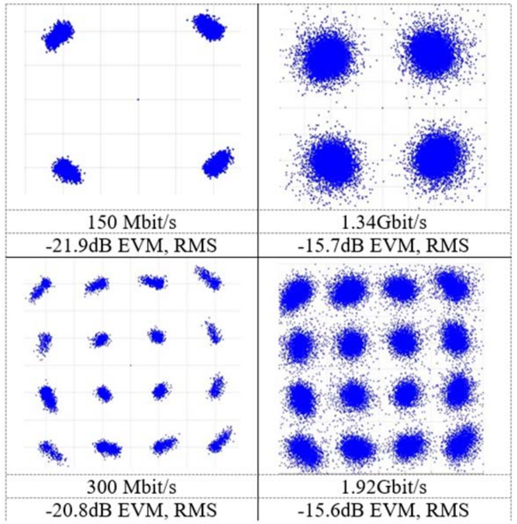


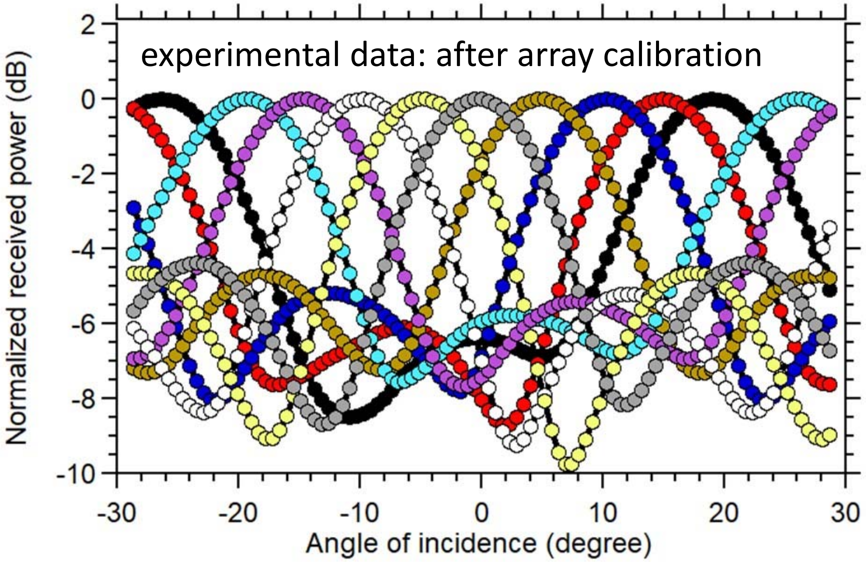
Demonstrated MIMO beamforming
Demonstrated 1.9Gb/s 16QAM transmission
Baseband connector limits data rate
Low assembly yield: ~60% working channels on most modules

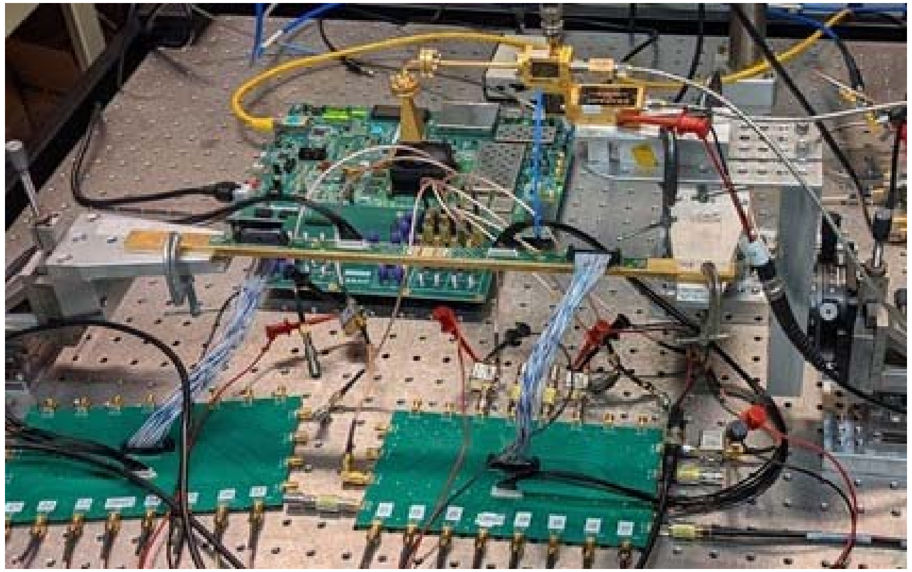


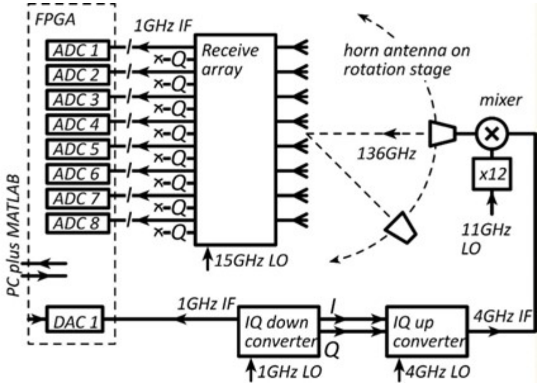
←pattern of 1 array element.





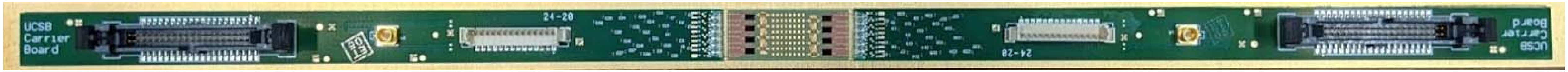




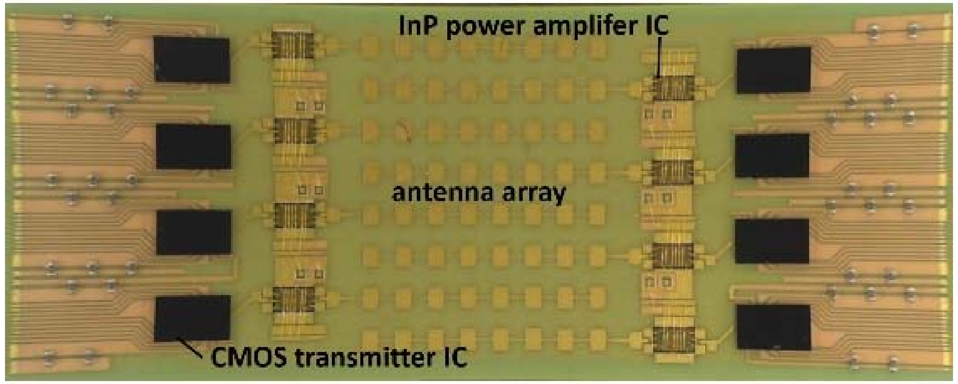


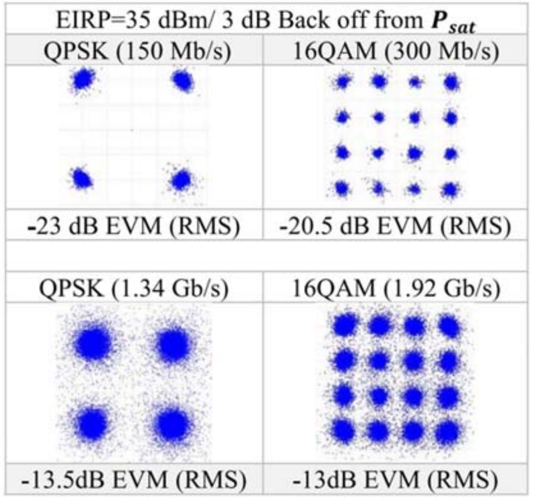
Gen. I 140GHz MIMO hub transmitters

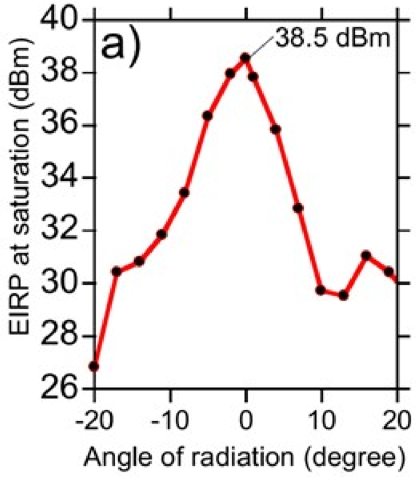
A. Farid et. al, IEEE Trans. MTT 4/2022

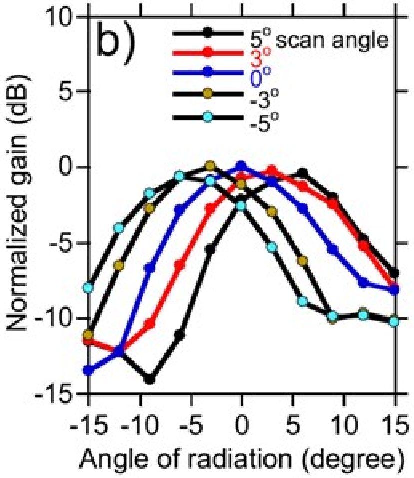


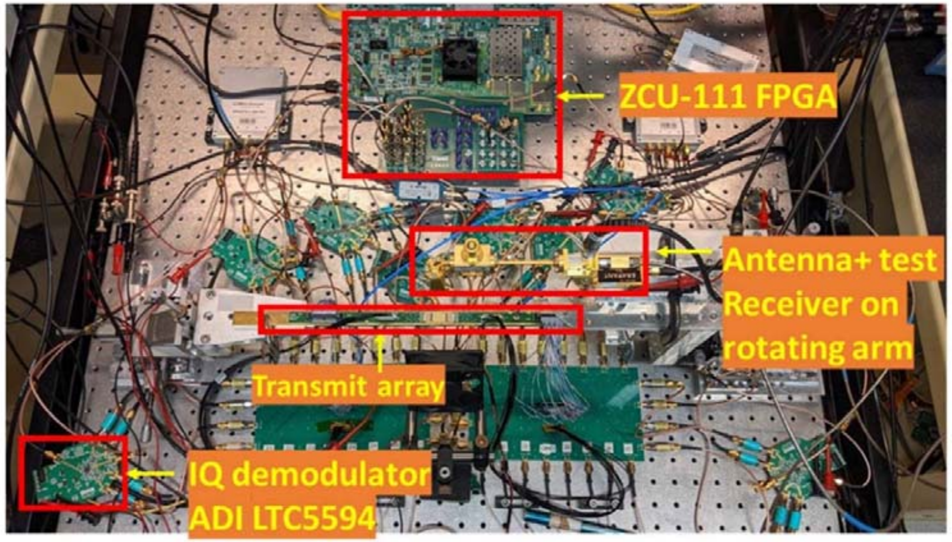
Demonstrated 1.9Gb/s 16QAM transmission
Baseband connector limits data rate
Low assembly yield: ~50% working channels
Degrades beamsteering, EIRP, MIMO operation

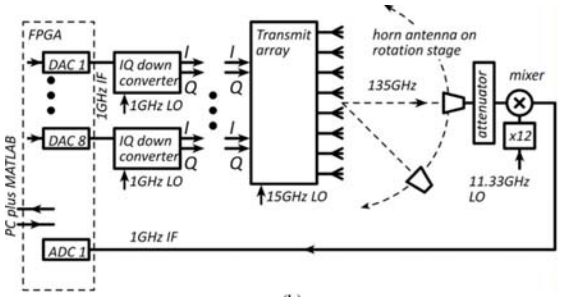






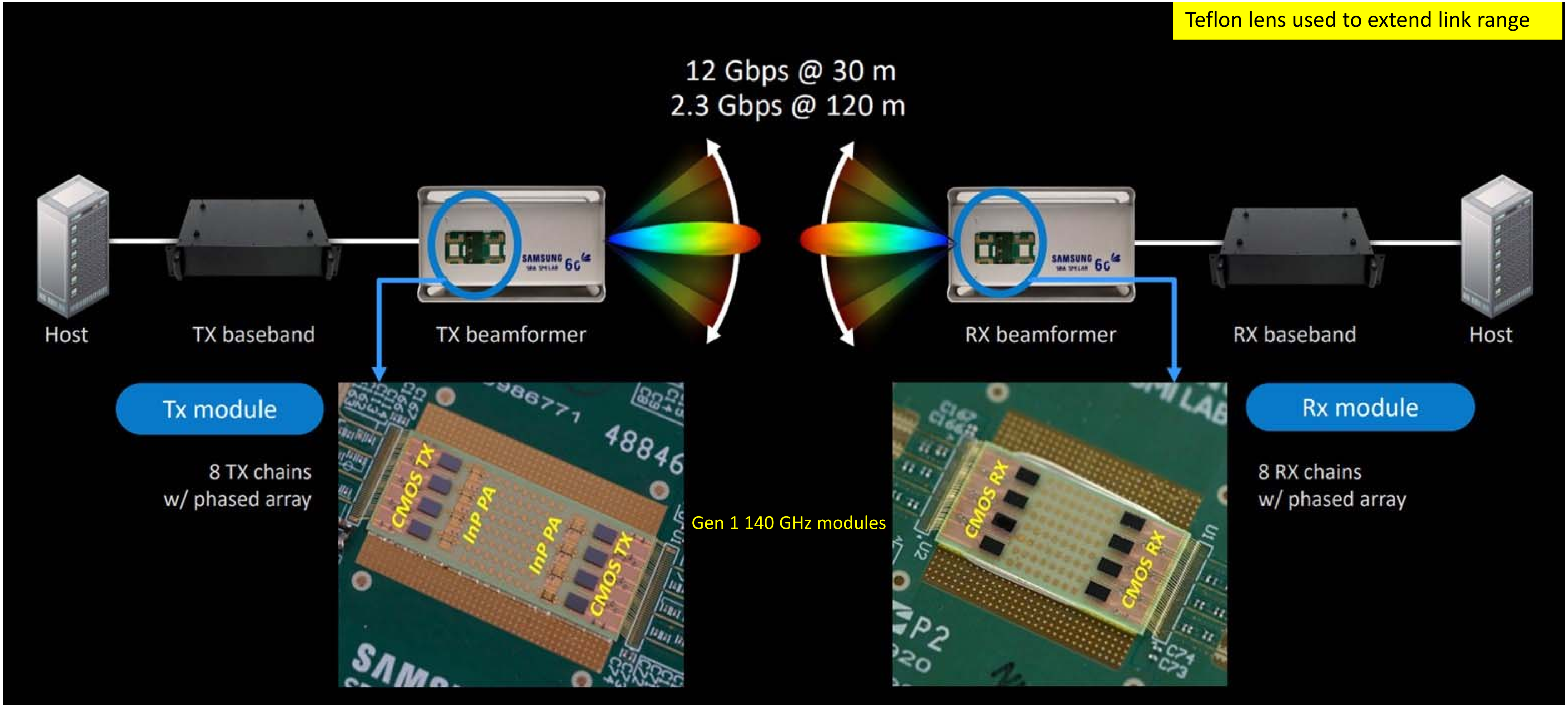






Samsung/ComSenTer 140 GHz Link Demo

Teflon lens used to extend link range

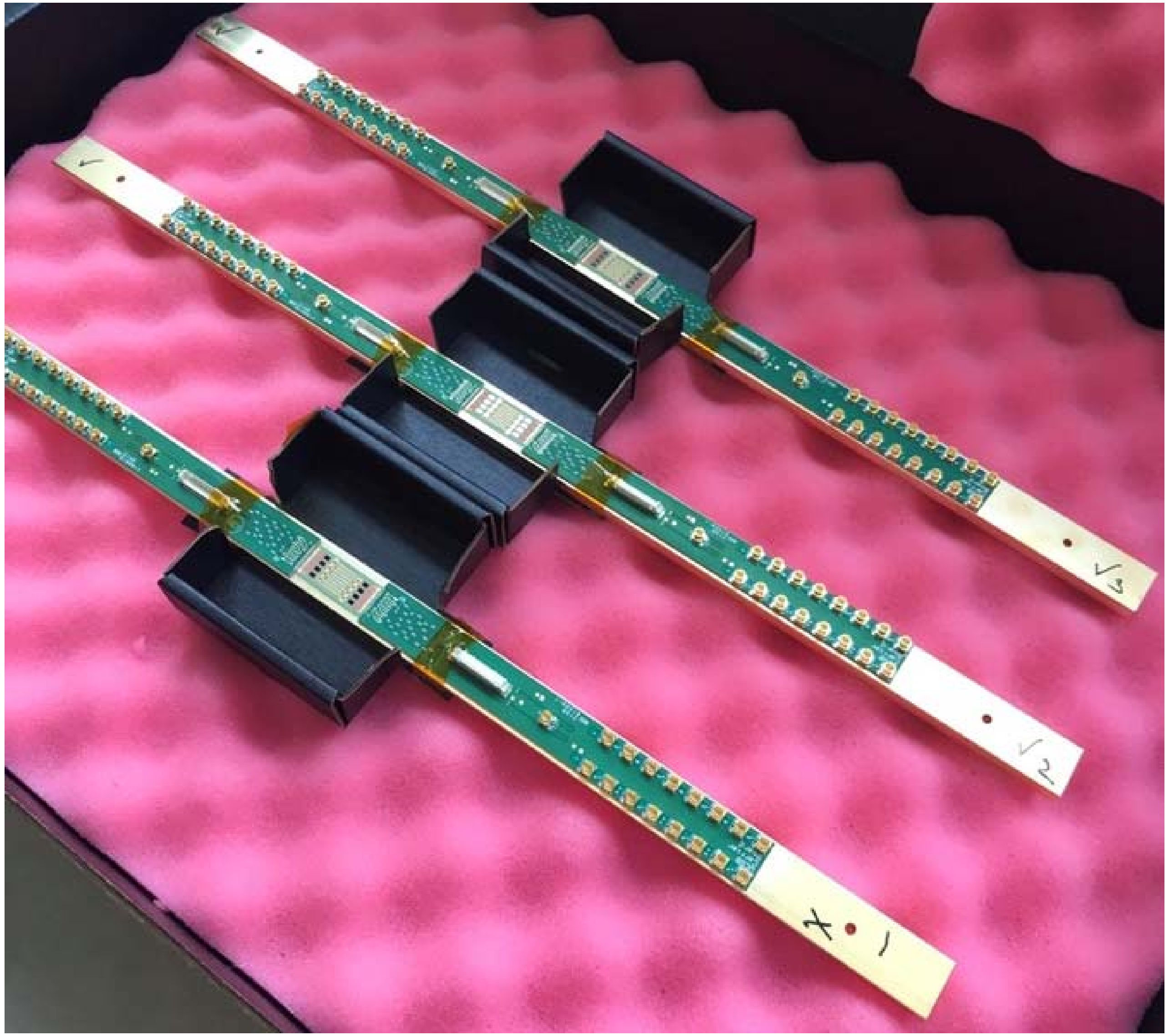


Gen 1 140 GHz modules

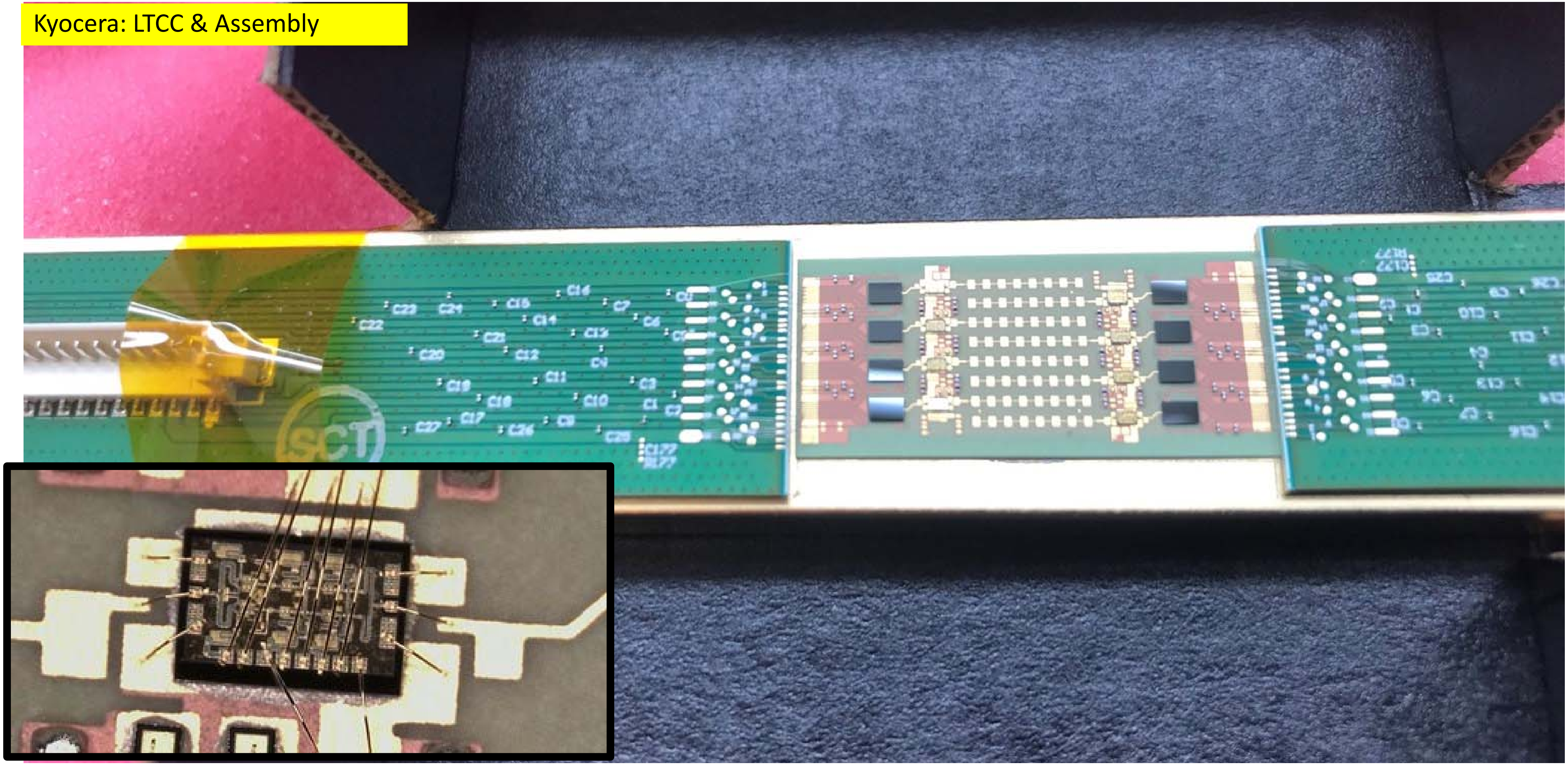
Abu-Surra et. al. (Samsung) 2022 IEEE International Conference on Communications, 16 -20 May 2022, Seoul, Korea,

Gen-II 140GHz MIMO hub modules

Use C4 flip-chip bonds, not 50 μm Cu stud; higher yield given LTCC lithographic dimensions

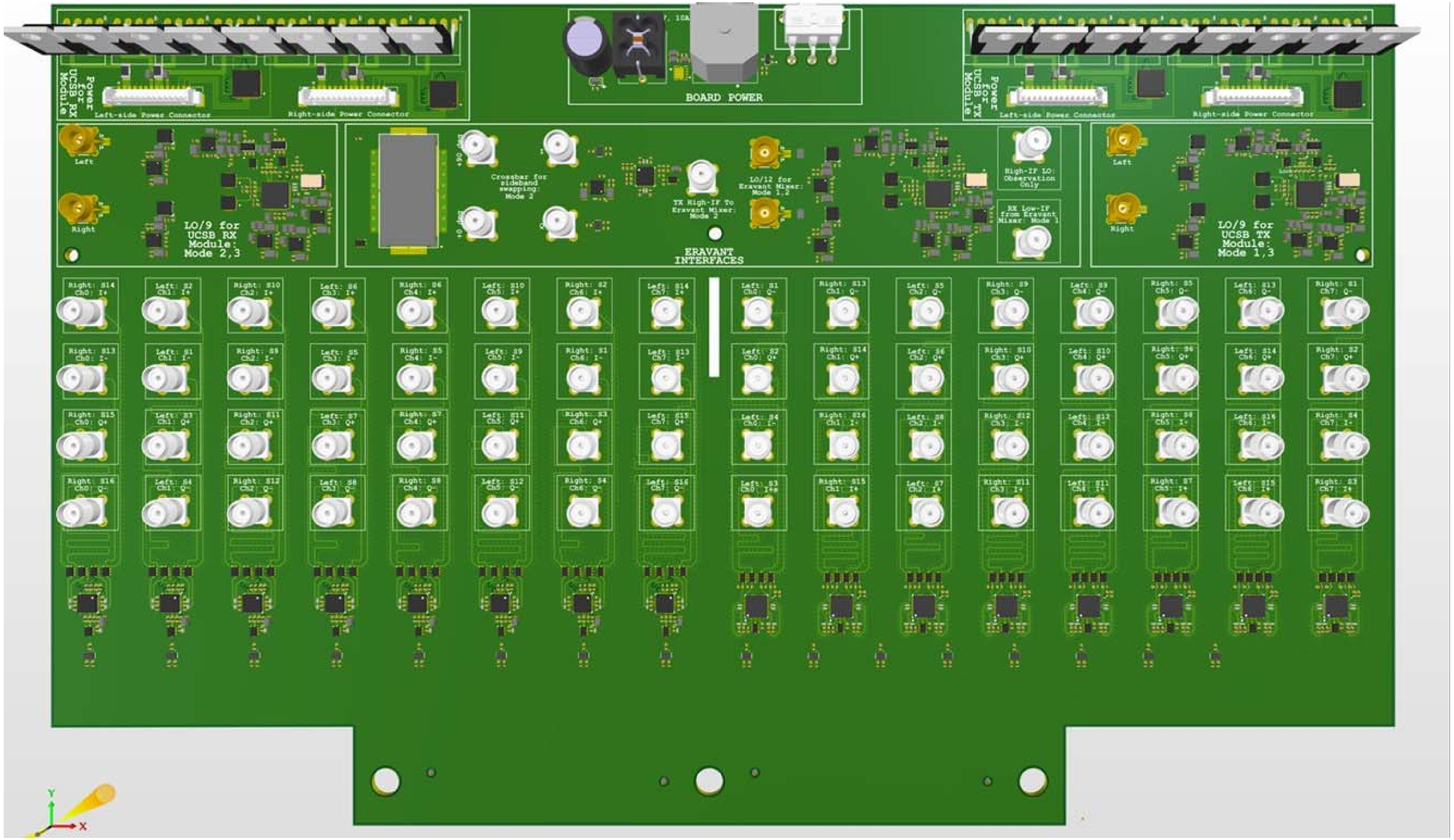


Gen-II 140GHz MIMO hub modules

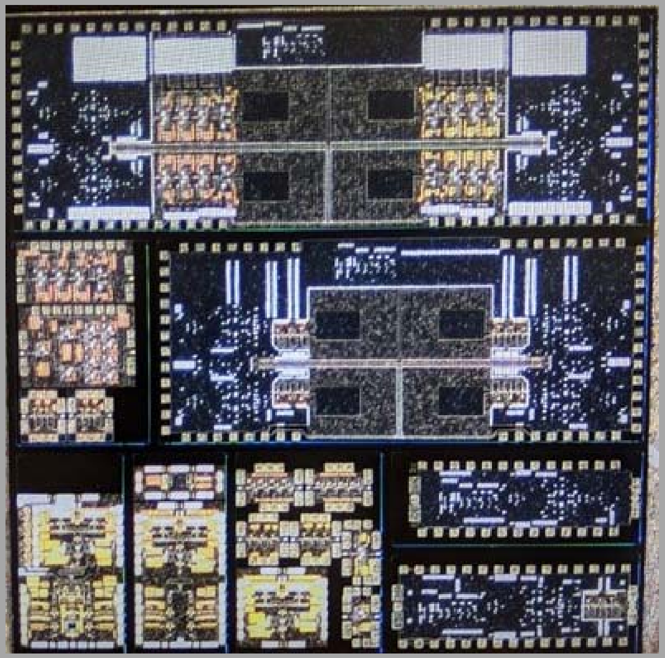


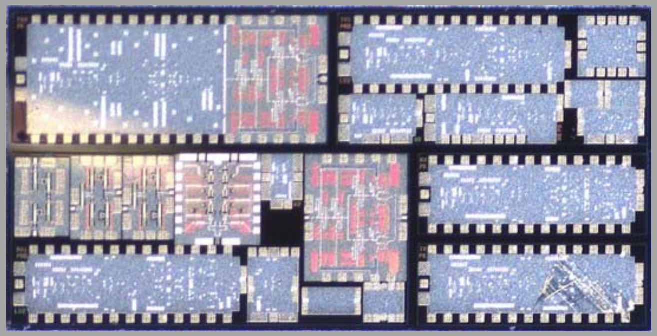
Interface PCB: 140 GHz Modules to RF-SOC PFGA

Michael Zappe, Aditya Dhananjay, Pi-Radio, Inc.

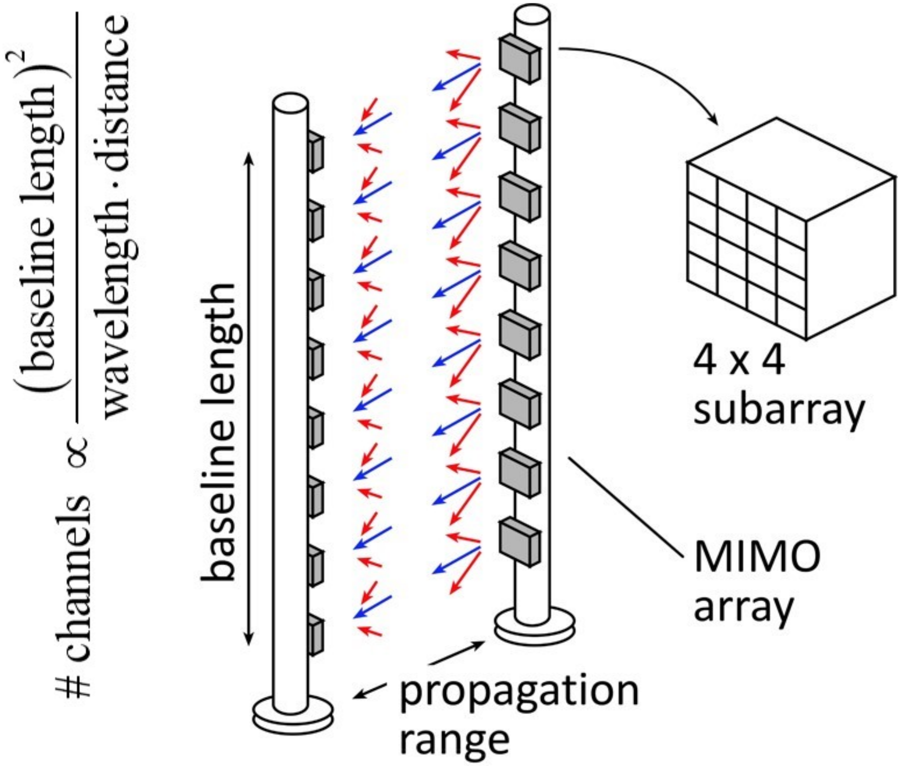


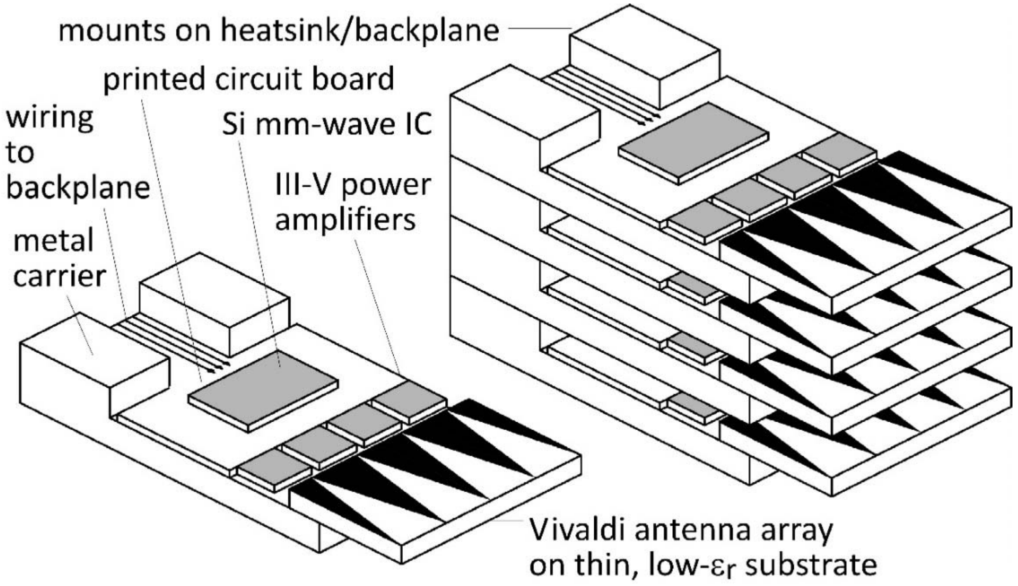
210 GHz and 280 GHz Array Modules





210 GHz, 640 Gb/s MIMO Backhaul



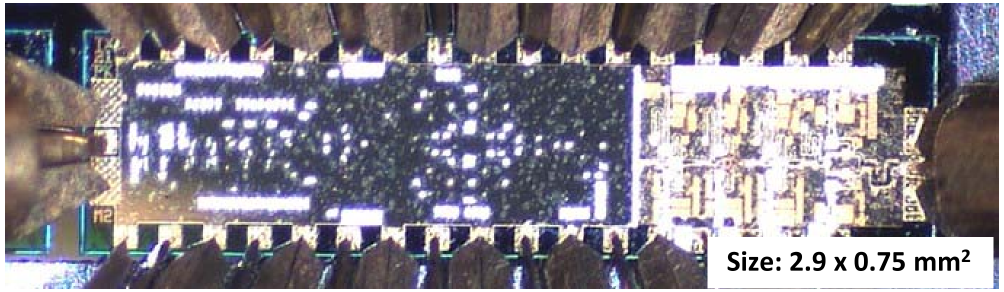


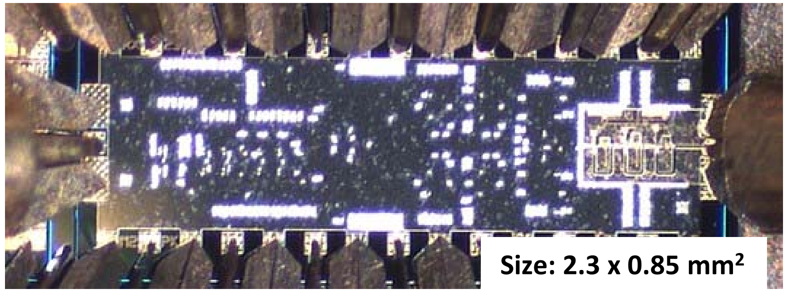
8-element MIMO array
2.1 m baseline.
80Gb/s/subarray→ 640Gb/s total
4 × 4 sub-arrays → 8 degree beamsteering

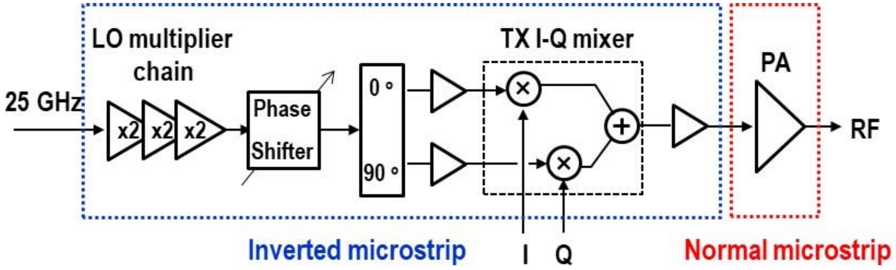
Key link parameters
500 meters range in 50 mm/hr rain; 23 dB/km
20 dB total margins:
packaging loss, obstruction, operating, design, aging
PAs: 18dBm $=P_{1dB}$ (per element)
LNAs: 6dB noise figure

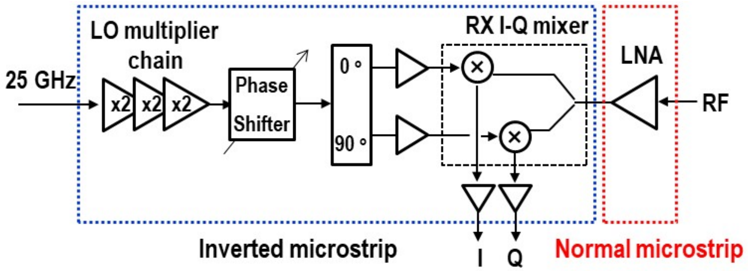
210 GHz Transmitter and Receiver ICs

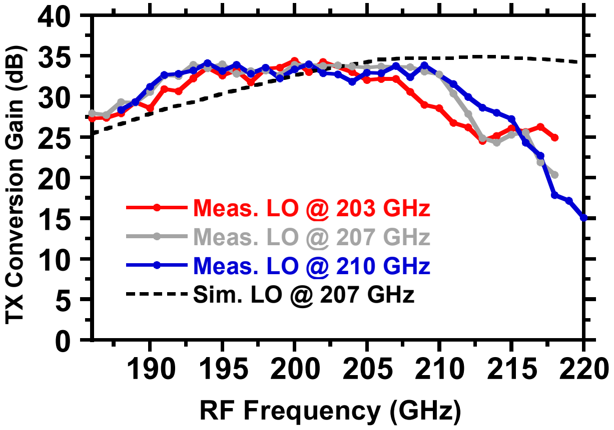
M. Seo et al, 2021 IMS; Teledyne 250nm InP HBT

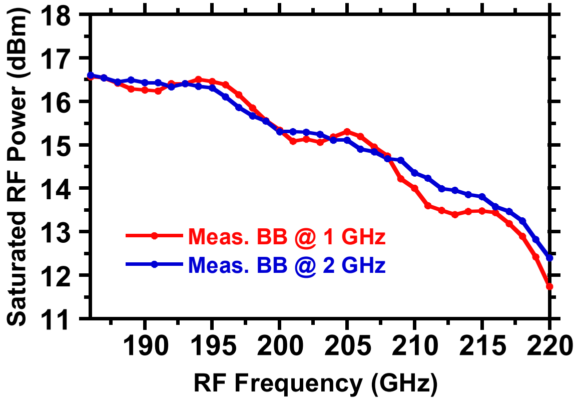


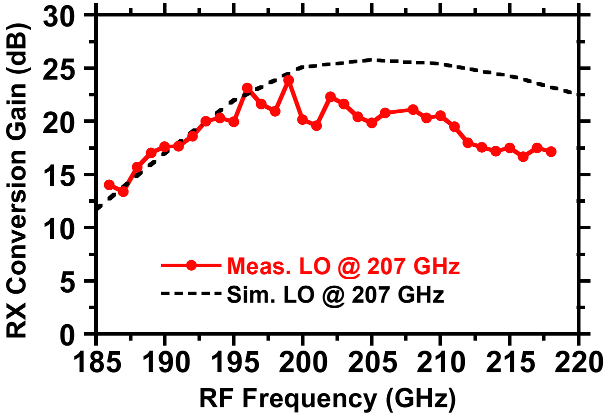


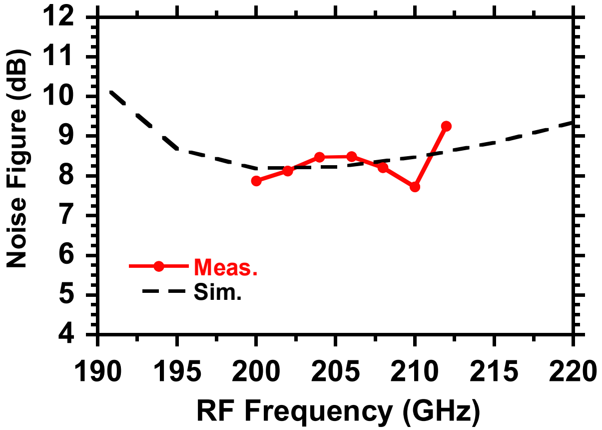




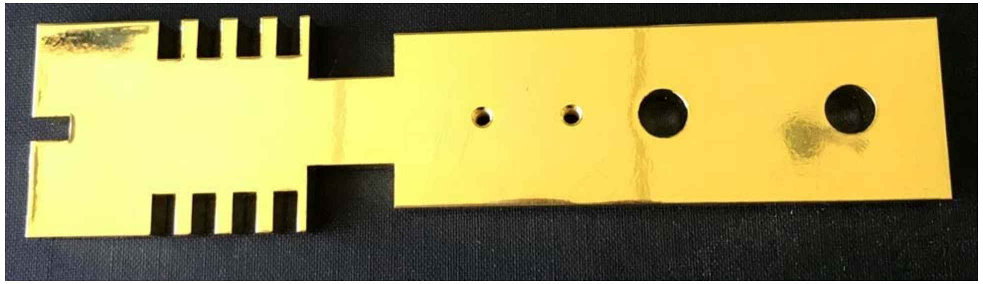


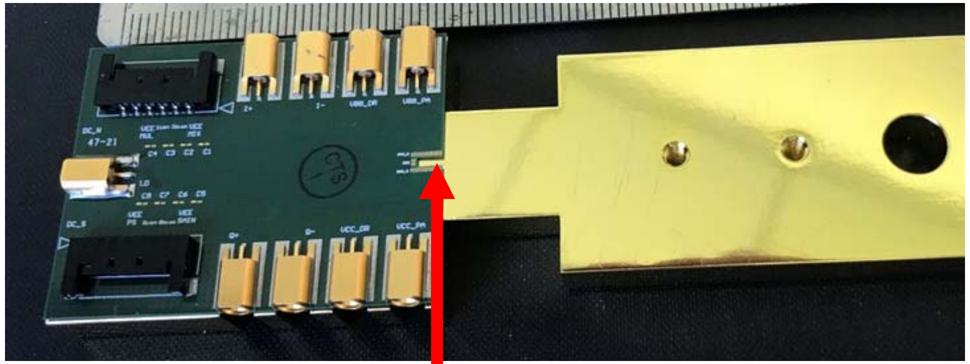


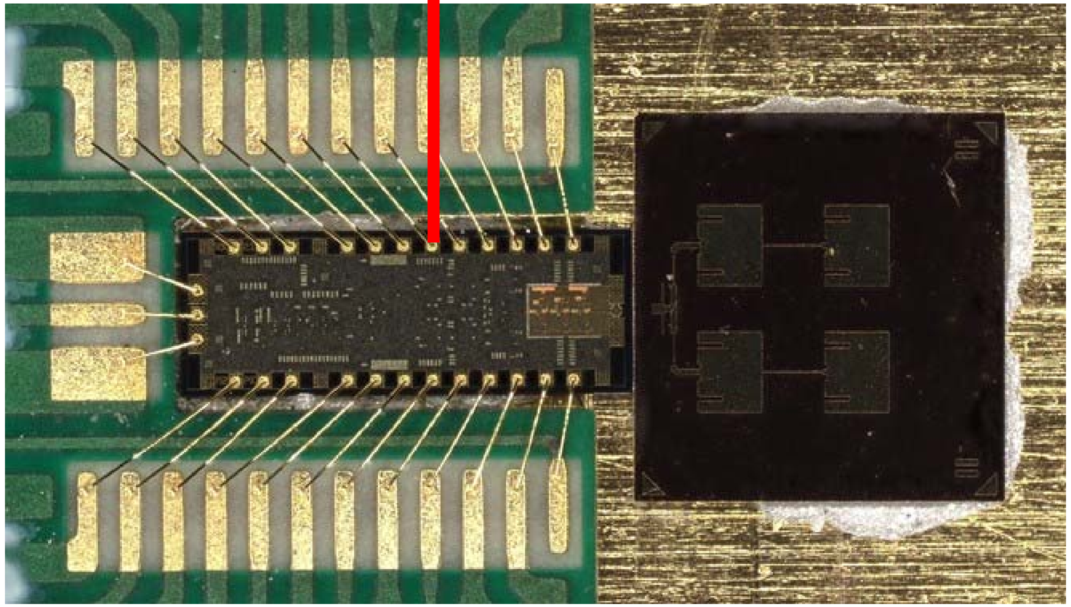


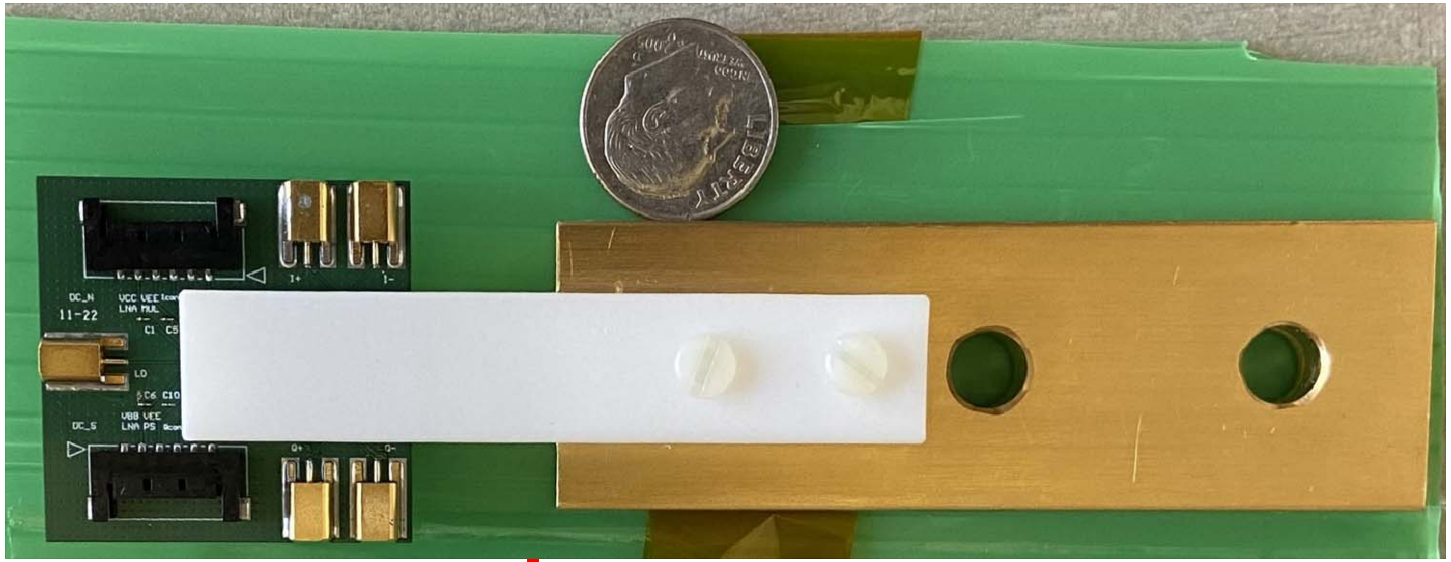


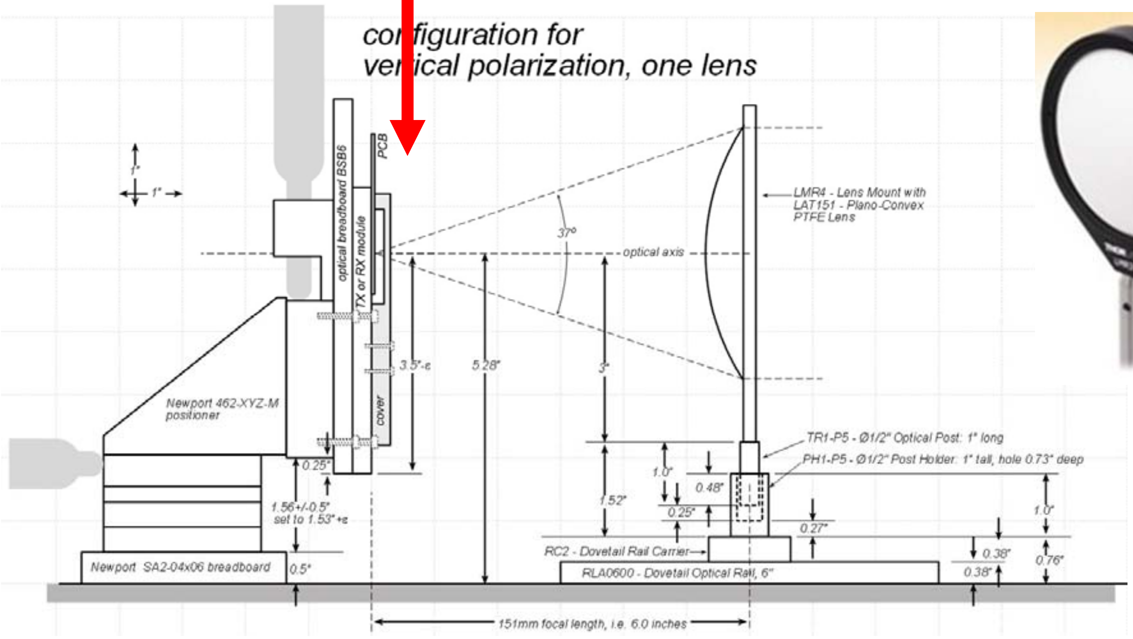
200GHz MIMO backhaul modules





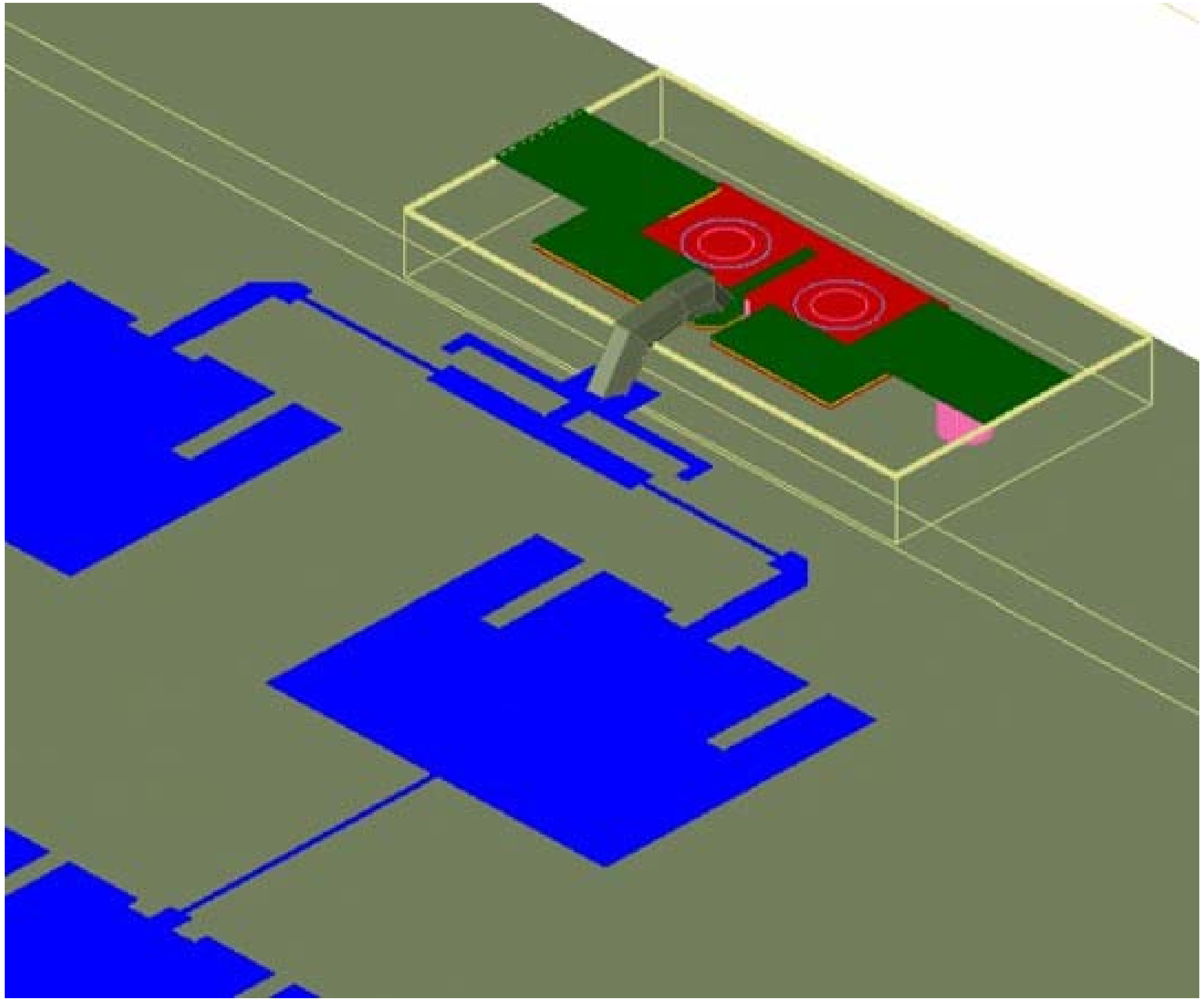


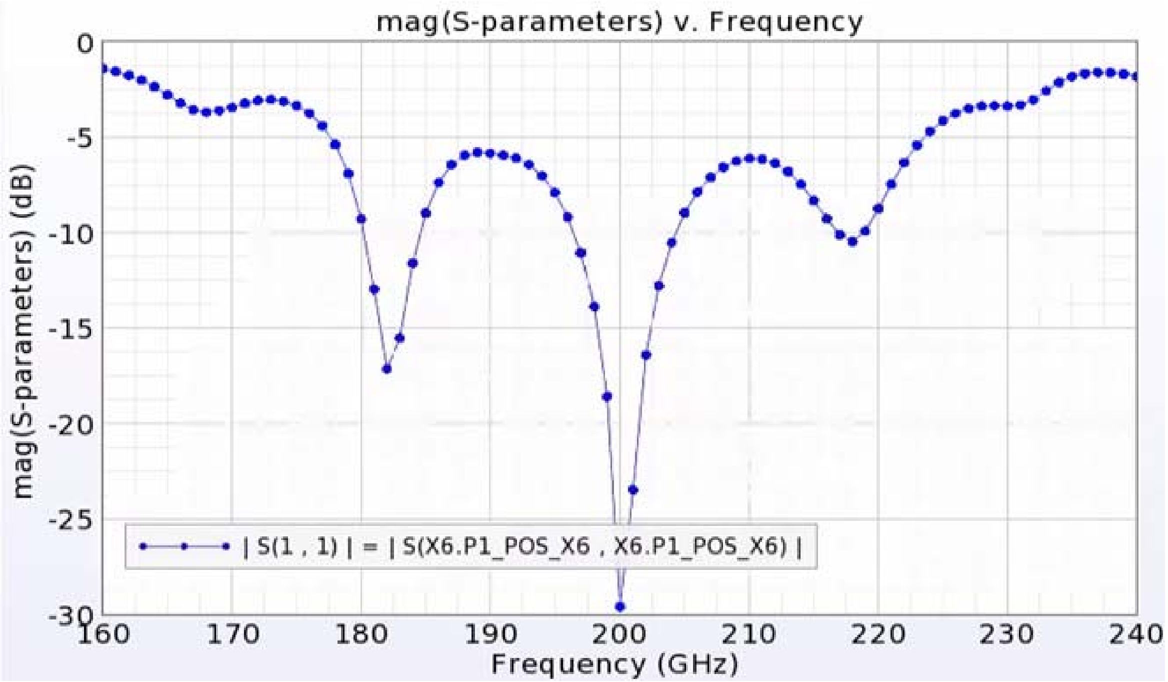




200 GHz IC-Antenna Interface

20 μm spacing between pad and antenna edge

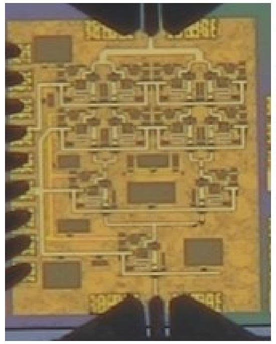


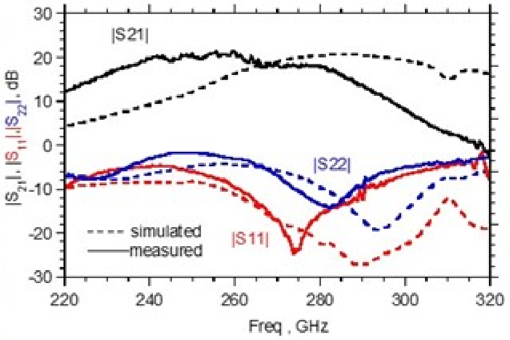


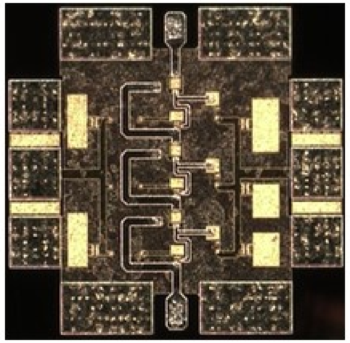
280GHz MIMO backhaul development

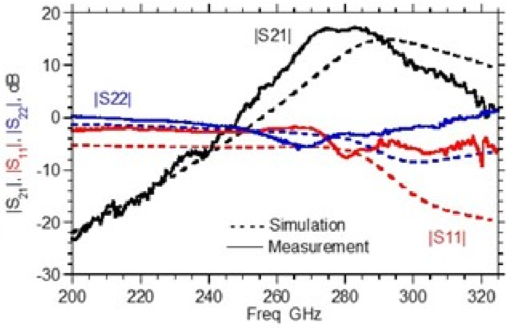
Amidreza, Solyu, Ahmed, Seo, UCSB

1st tapeout: PA, LNA
PA: 270 GHz, 16.7 dBm Psat, 4% PAE.✓
LNA: 280 GHz, 15 dB gain, NF= ?? ✓

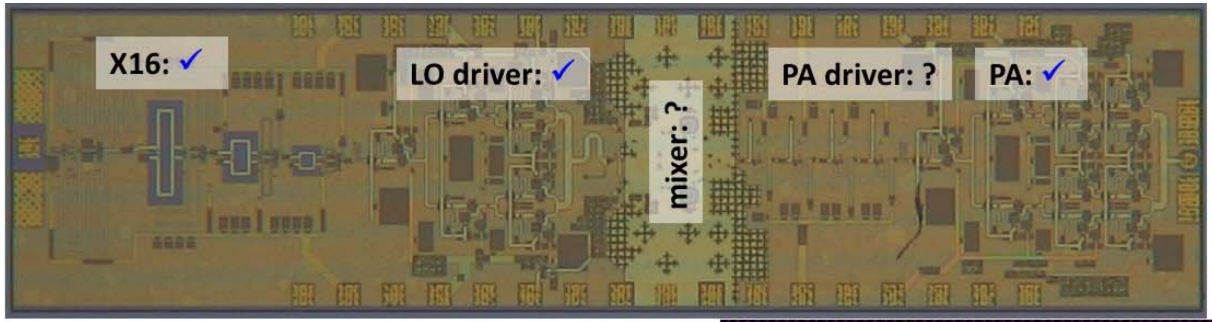


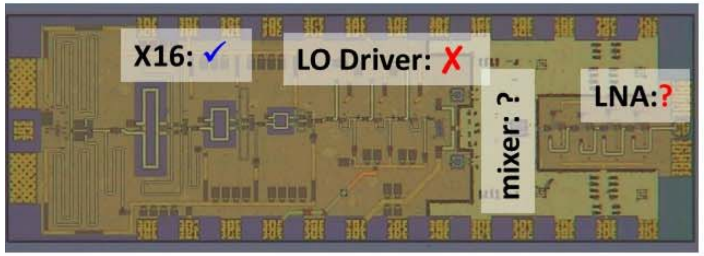


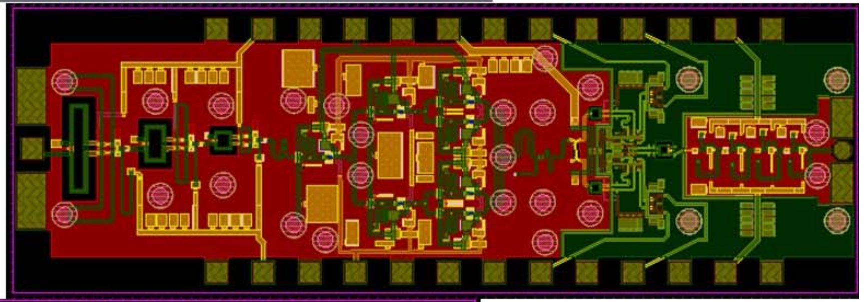




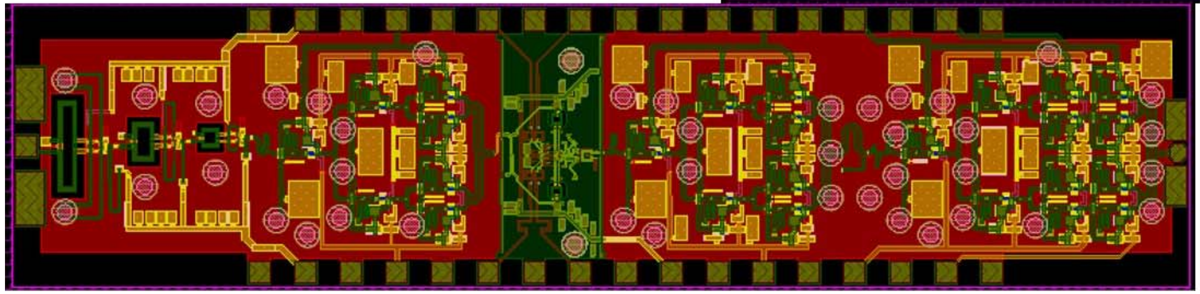
2nd tapeout: transmitter, receiver
Not all blocks yet tested
Working LO multiplier ✓
Working high-power LO driver✓
Failed low-power LO driver ✗
Failed low-power PA driver ✗
→ transmitters, receivers failed ✗



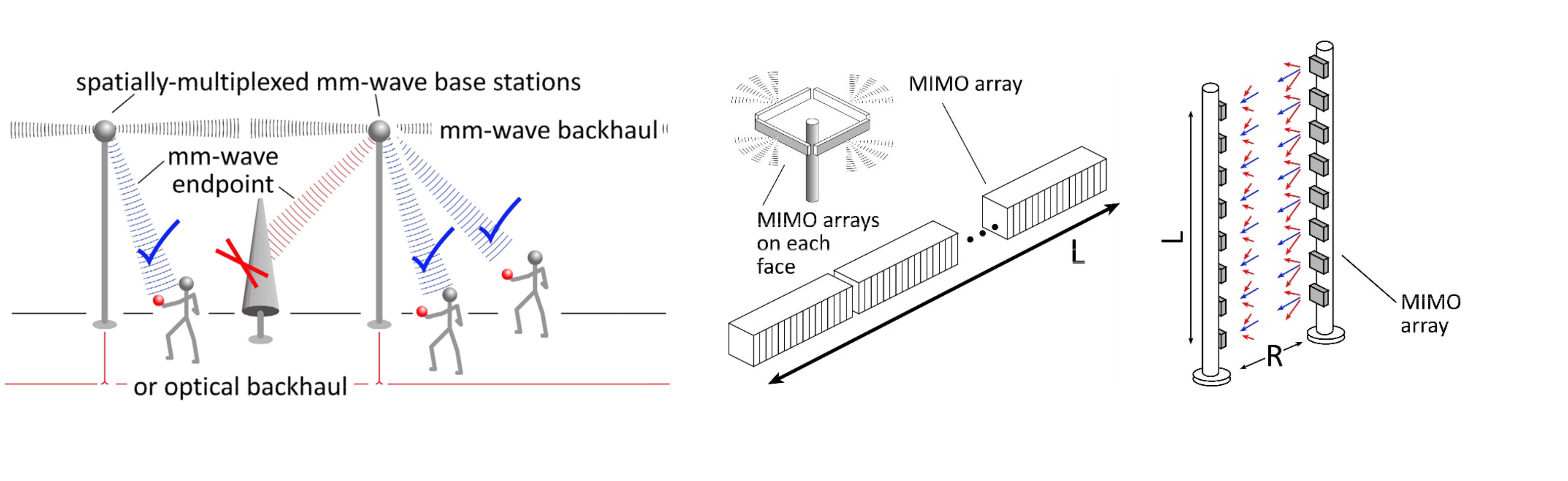




3rd tapeout: transmitter, receiver
Redesigned, LNA, LO and PA drivers
In fabrication: expected 9/2022.



100-300GHz Wireless



100-300 GHz Wireless

Massive capacities
large available bandwidths
massive spatial multiplexing in base stations and point-point links

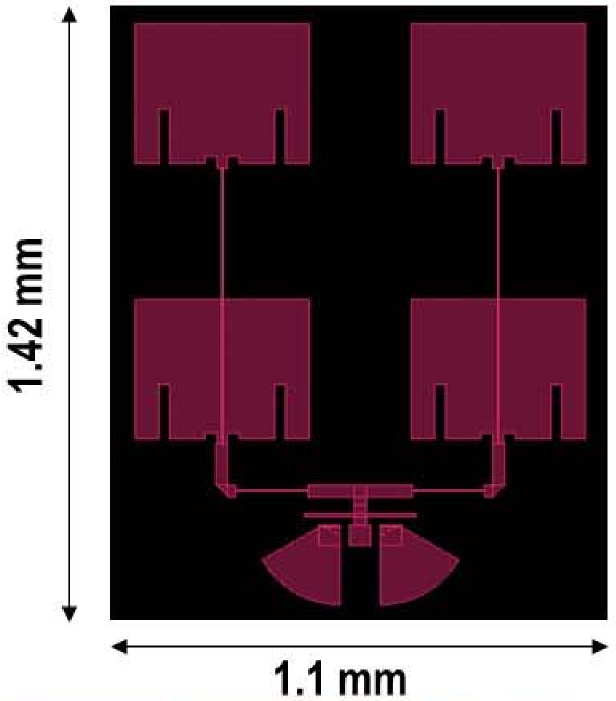
Very short range: few 100 meters
short wavelength, high atmospheric losses. Easily-blocked beams.

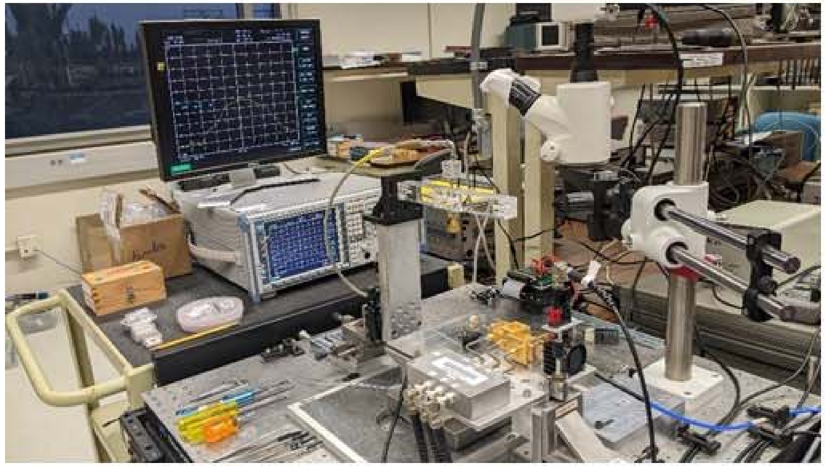
IC Technology
All-silicon for short ranges below 200 GHz.
SiGe or III-V LNAs and PAs for longer-range links. Just like cell phones today
III-V frequency extenders for 340GHz and beyond

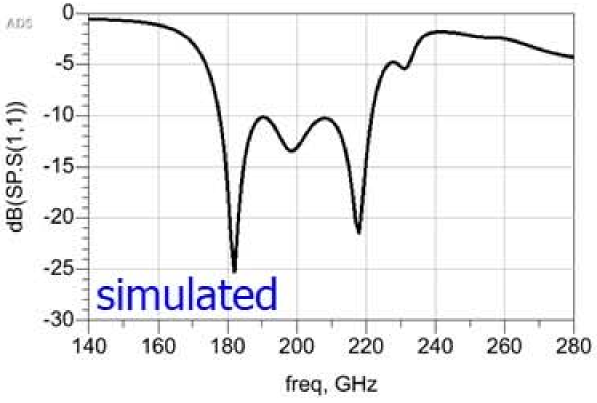
The challenges
beamformer computational complexity: looks good.
packaging: fitting signal channels in very small areas, removing the heat
packaging: accessing advanced industry technologies in low volumes
mesh networking to accommodate beam blockage
driving the technologies to low cost

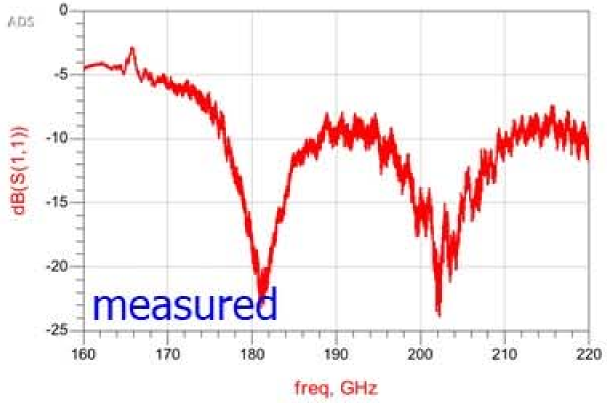
(backup files follow)

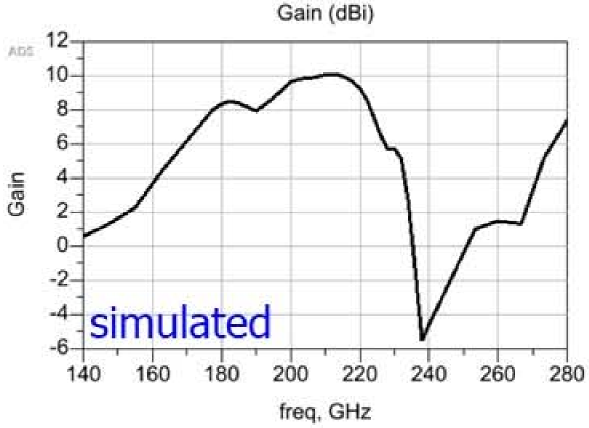
200 GHz Modules: Antennas

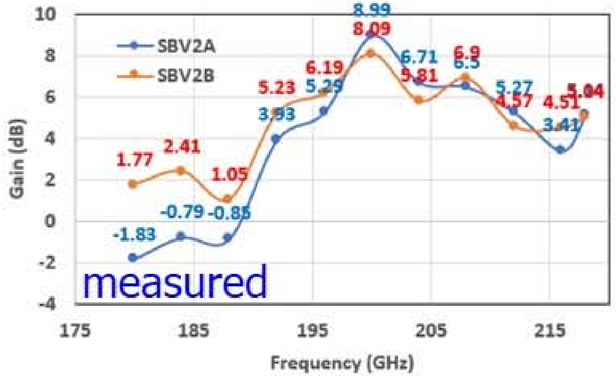


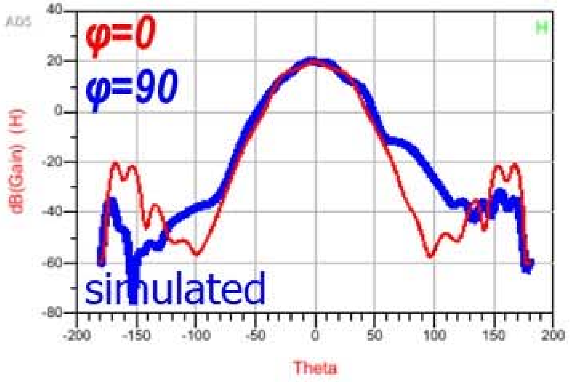


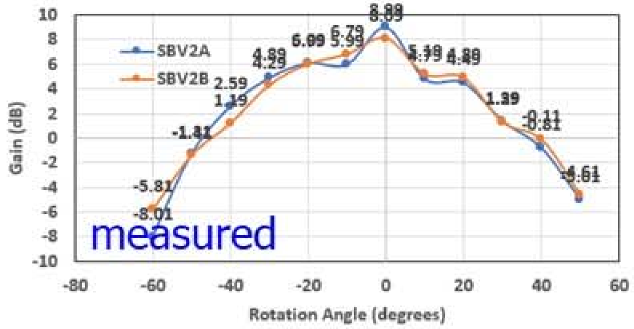












In case
of questions

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)

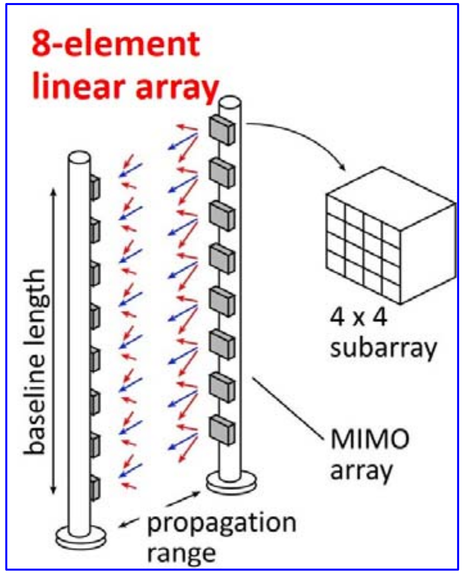
Or, use a 4×4 (**8mm×8mm**) handset array,
and the range becomes ..**about 40 meters**.

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

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:

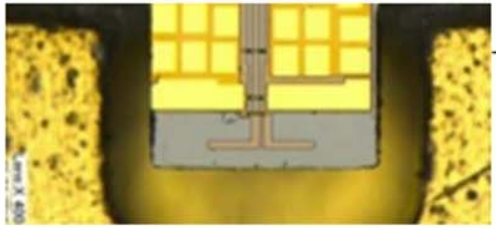
requires 16dB$_m$ transmit power/element (P_{out})

requires 3.5m linear array

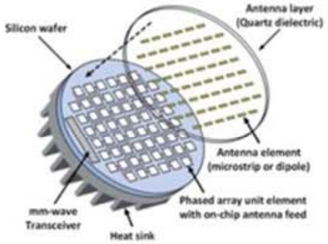
Similar RF power output, physically larger

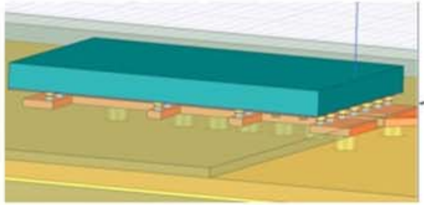
100-300GHz IC-package connections

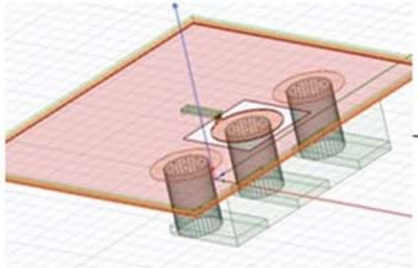
Deal, IEEE Trans THz, Sept 2011



G. Rebeiz

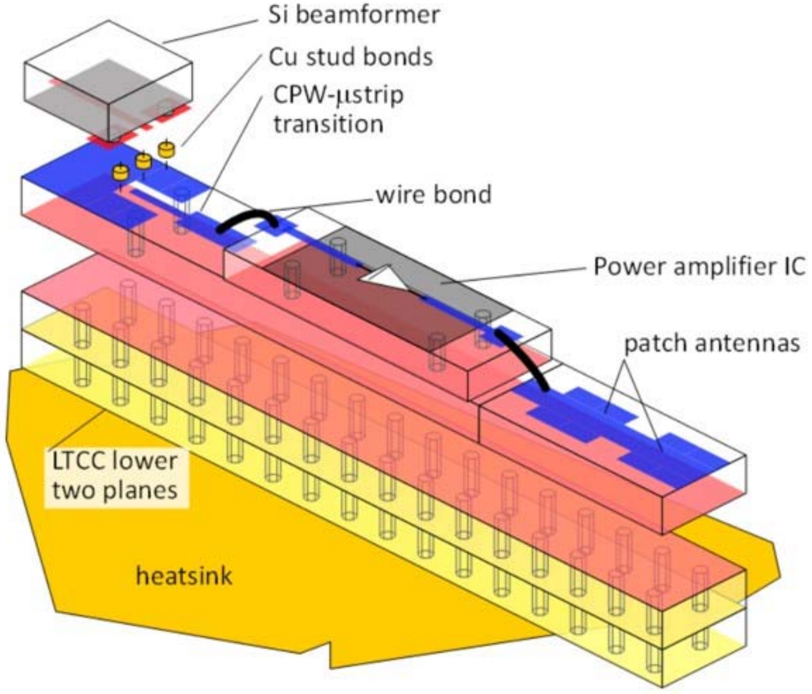




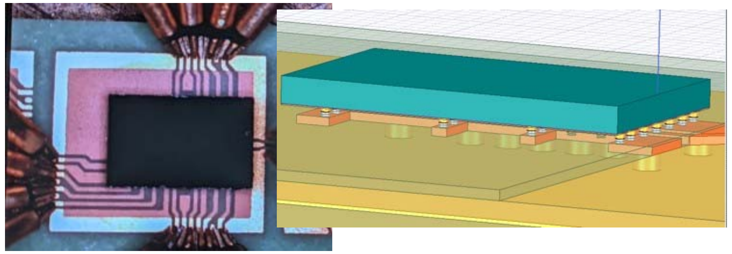


type	Frequency	technology	cost	heatsinking
micromachined waveguide interface	1000 GHz	Research. Cheap one day ?	high ✗	good
ribbon, mesh bond	200 GHz	Handcrafted.	high ✗	good
patch antennas on superstrate	1000 GHz	Straightforward	low	good
Cu stud flip-chip	>200 GHz	Industry standard	low	ok, marginal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

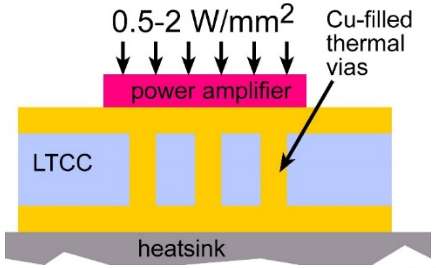
140GHz hub: packaging challenges



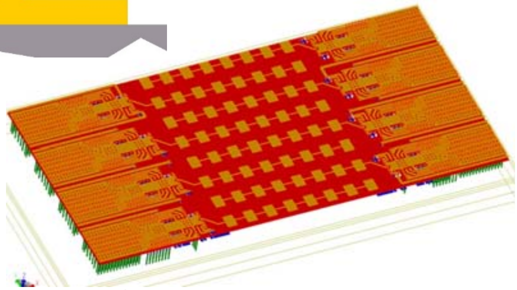
IC-package interconnects
Difficult at > 100 GHz



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

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