Short Course: Device Research Conference, June 23, 2019, University of Michigan

Beyond 5G:
100-340GHz Transistor, IC, and System Design

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JUMP ComSenTer: Wireless Research

ComSenTer
COMMUNICATIONS SENSING TERAHERTZ

Center for Converged Communications & Sensing at THz.

Duration:
5-years; 1/2018-12/2022.

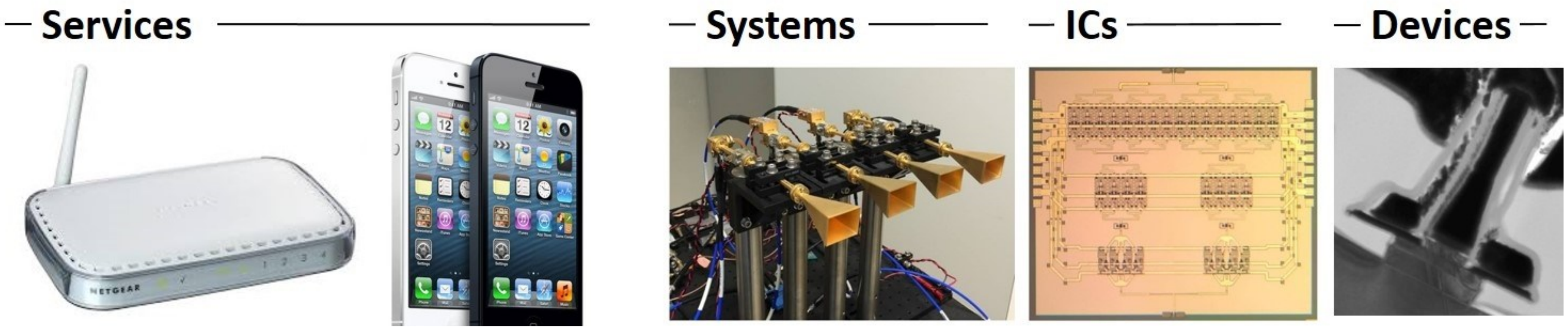
Funding:
about $36 million total.

Team:
21 Professors,
~65 Ph.D. students

Sponsors:
SRC, DARPA

Focus:
wireless systems,
10-15 years out,
100-340GHz

Wireless above 100GHz



Wireless networks: exploding demand.

Immediate industry response: 5G.
28, 38, 57-71(WiGig), 71-86GHz
increased spectrum, extensive beamforming

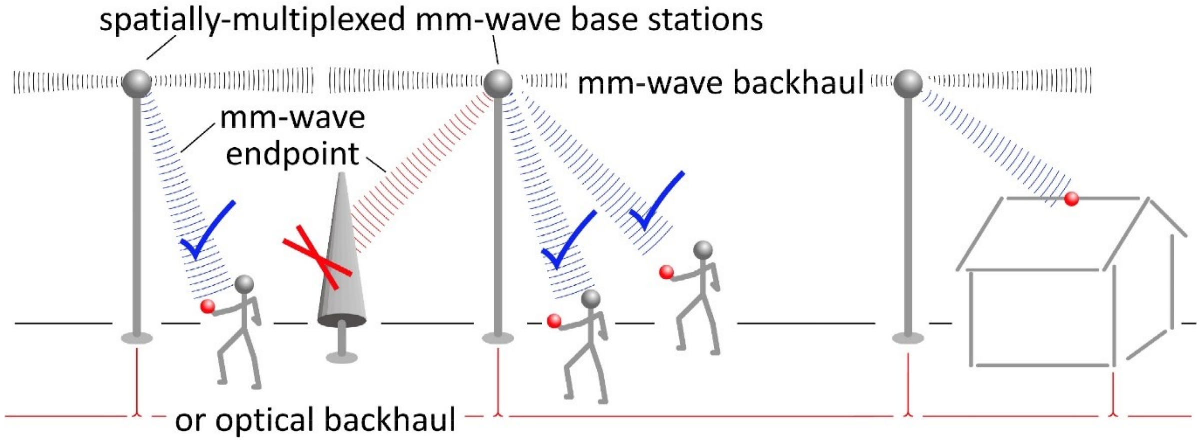
Next generation (6G ??): above 100GHz..
greatly increased spectrum, massive spectral multiplexing

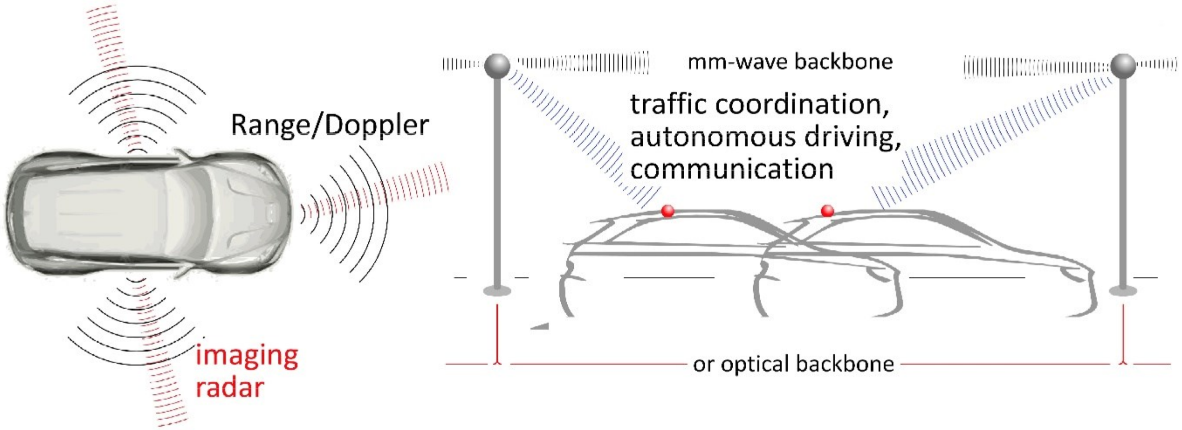
DOD applications: Imaging/sensing/radar, comms.

140-340GHz Wireless

10Gb mobile communications:
Unlimited information, anywhere.
Capacity well beyond 5G.

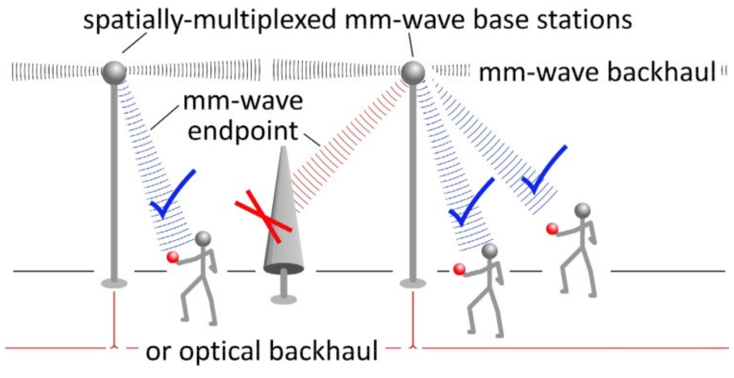
TV-resolution wireless imaging:
See, fly, drive perfectly in any conditions.

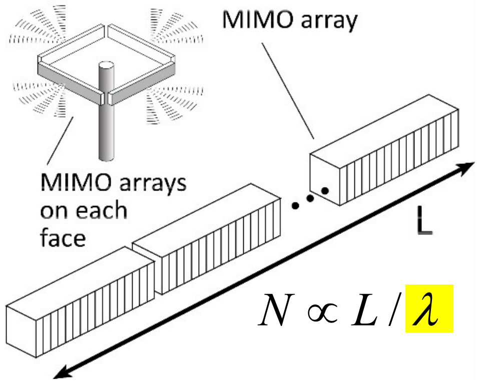


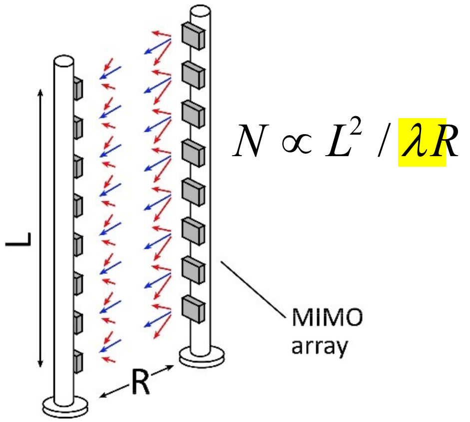


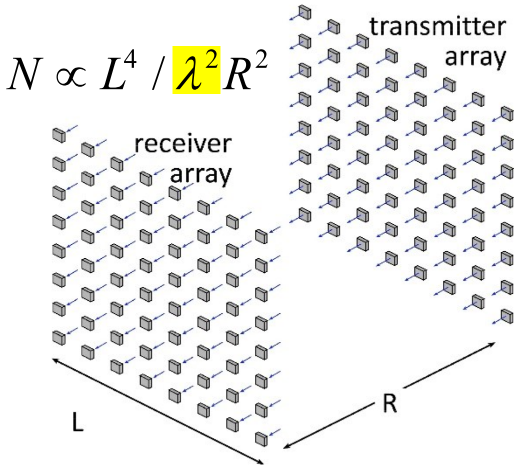
Benefits of Short Wavelengths

Communications: Massive spatial multiplexing, massive # of parallel channels

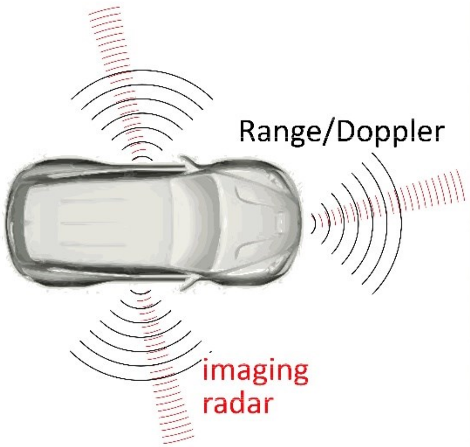


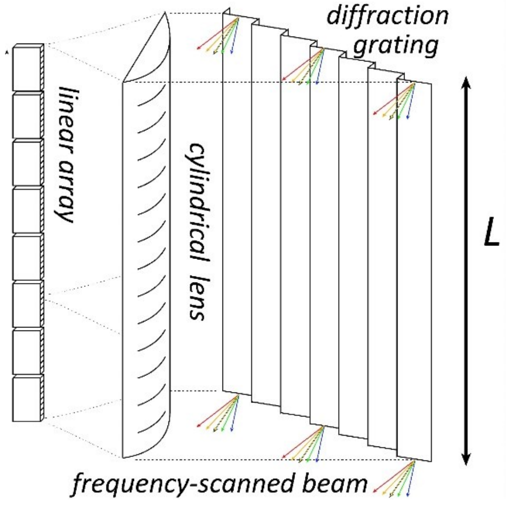






Imaging: very fine angular resolution





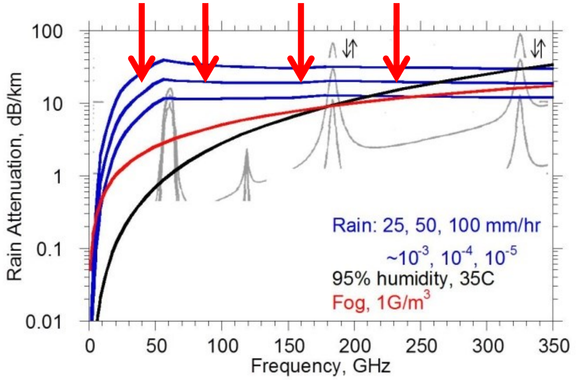
$\Delta\theta \propto \lambda / L$

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

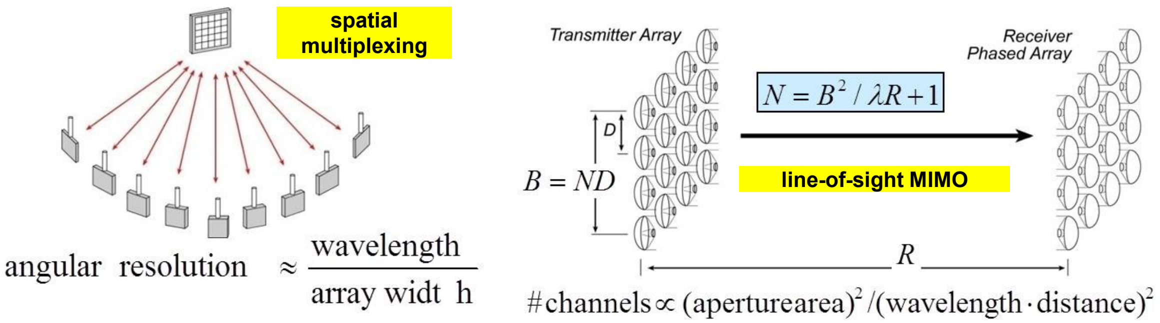
mm-waves: benefits & challenges

Large available spectrum



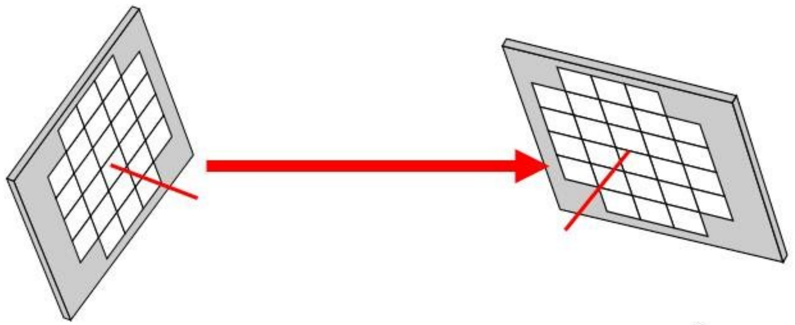
(note high attenuation in foul or humid weather)

Massive # parallel channels



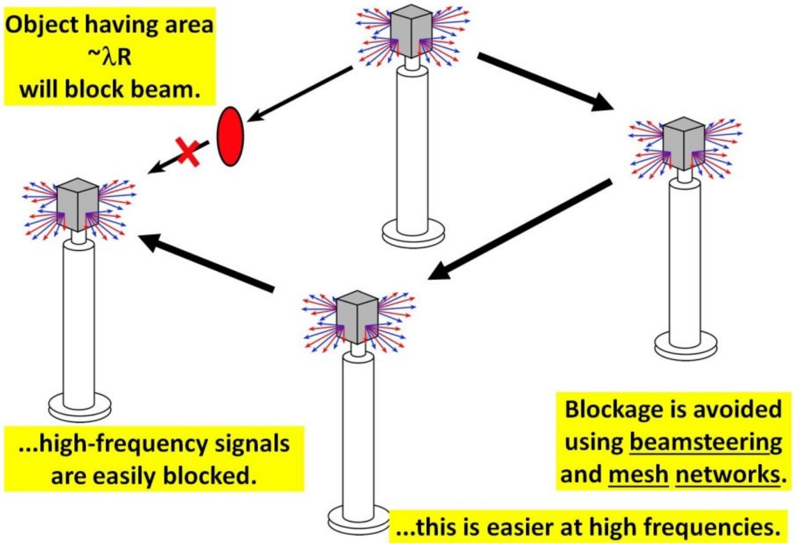
Torklinson : 2006 Allerton Conference
Sheldon : 2010 IEEE APS-URSI
Torklinson : 2011 IEEE Trans Wireless Comm.

Need phased arrays (overcome high attenuation)

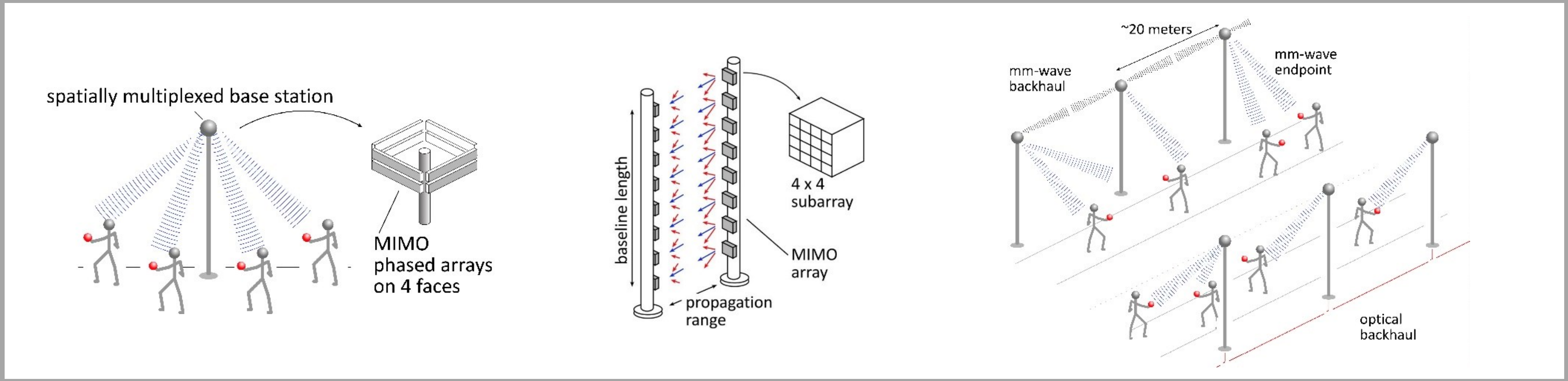


$$\frac{P_{received}}{P_{transmit}} \propto N_{receive} N_{transmit} \frac{\lambda^2}{R^2} e^{-\alpha R}$$

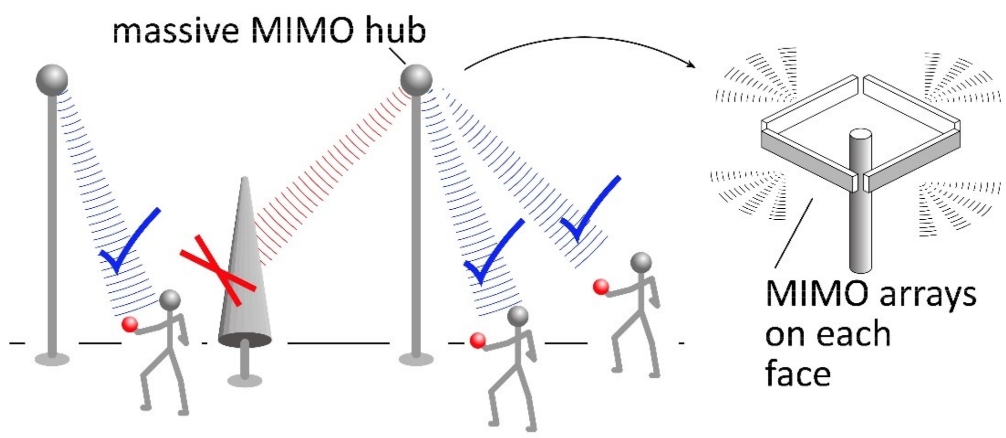
Need mesh networks

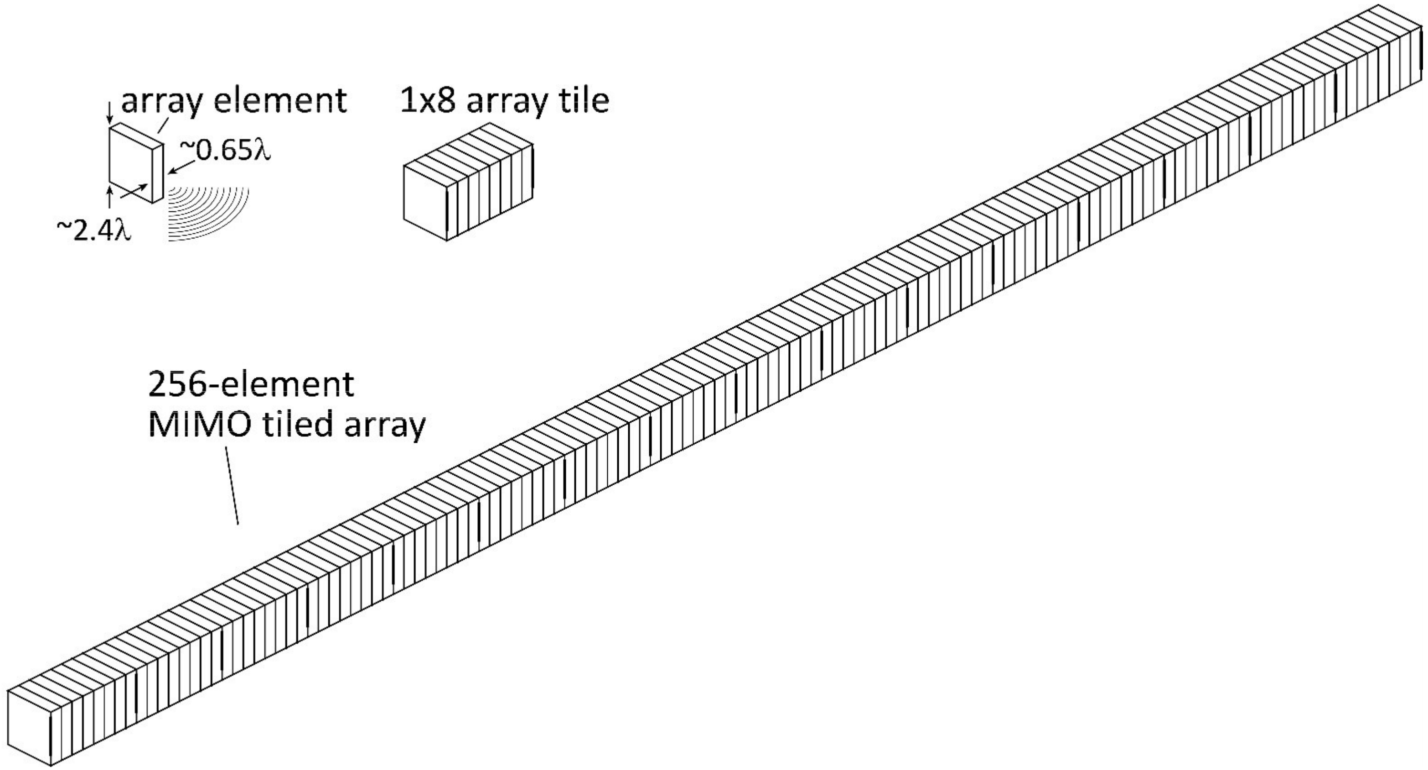


140-340 GHz: Applications



140 GHz spatially multiplexed base station





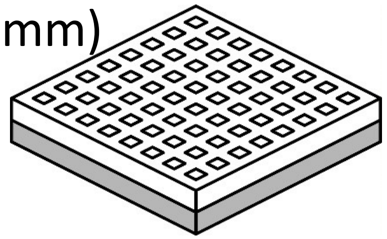
1 Tb/s spatially-multiplexed base station

256 users/face, 4 faces

1024 total users @ 1 user/beam, 1 Gb/s/beam;

225 m range

Handset:
8 × 8 array
(9×9mm)

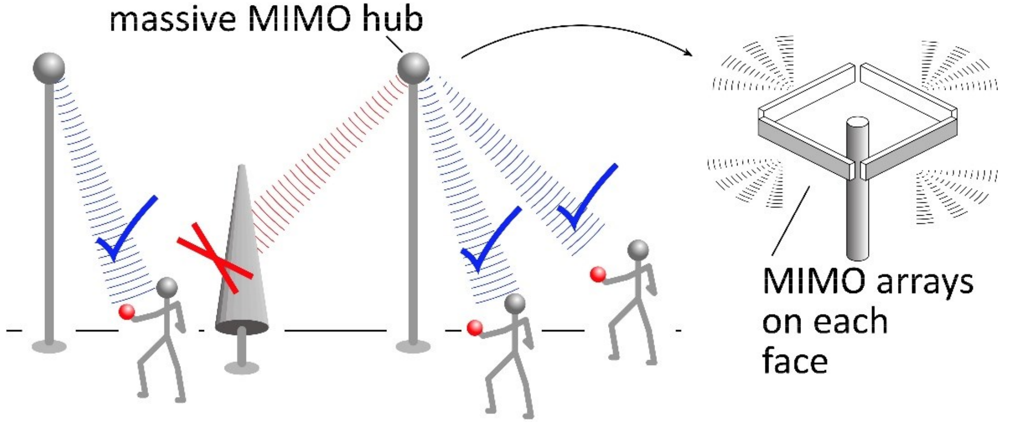


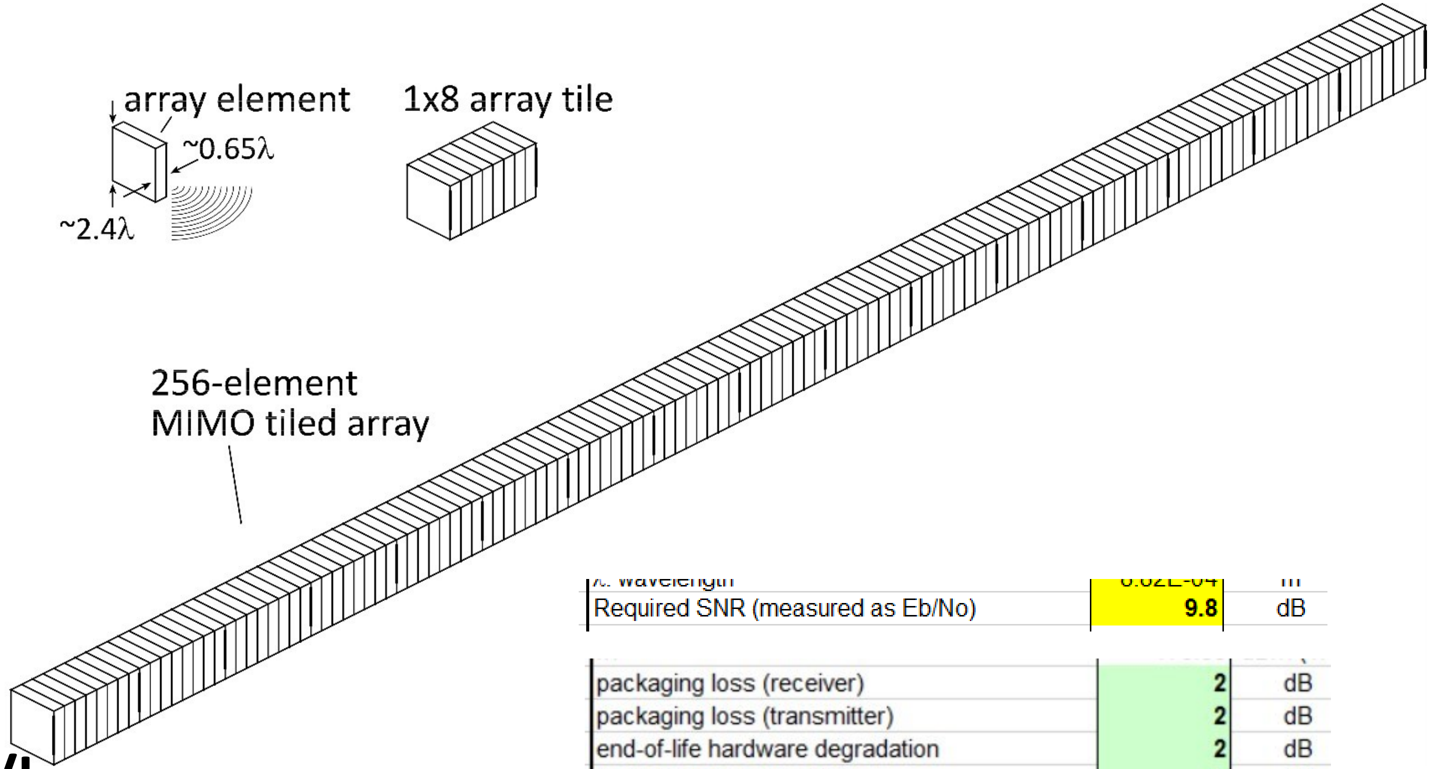
Link budget is feasible, but...

Required component dynamic range ?

Required complexity of back-end beamformer ?

140 GHz spatially multiplexed base station





Required SNR (measured as Eb/No)	9.8	dB
packaging loss (receiver)	2	dB
packaging loss (transmitter)	2	dB
end-of-life hardware degradation	2	dB
hardware design margin	2	dB
beam aiming loss (edge of beam)	2	dB
systems operating margin	5	dB
path obstruction loss (shadowing)	5.00	dB

Each face supports 256 beams @ 1Gb/s/beam.

225 meters range in 50 mm/hr rain

Realistic packaging loss, operating & design margins (20dB total)

PAs: 16 dBm P_{out} (per element)

LNAs: 3 dB noise figure

75 GHz spatially multiplexed base station

**If we use instead a 75GHz carrier,
but constrain the handset to a similar size (8mm×8mm)
and the hub to the same number of elements
then the range becomes 210 meters (vs. 225 meters)**

**Would be similar performance;
except that PAs, LNAs are poorer @ 140GHz**

$$\frac{P_{received}}{P_{trans}} = \frac{D_{hub} D_{hand}}{16\pi^2} \left(\frac{\lambda}{R}\right)^2 e^{-\alpha R} \qquad D_{hand} = 4\pi A_{hand} / \lambda^2 \qquad D_{hub} = D_{element} N_{hub}$$

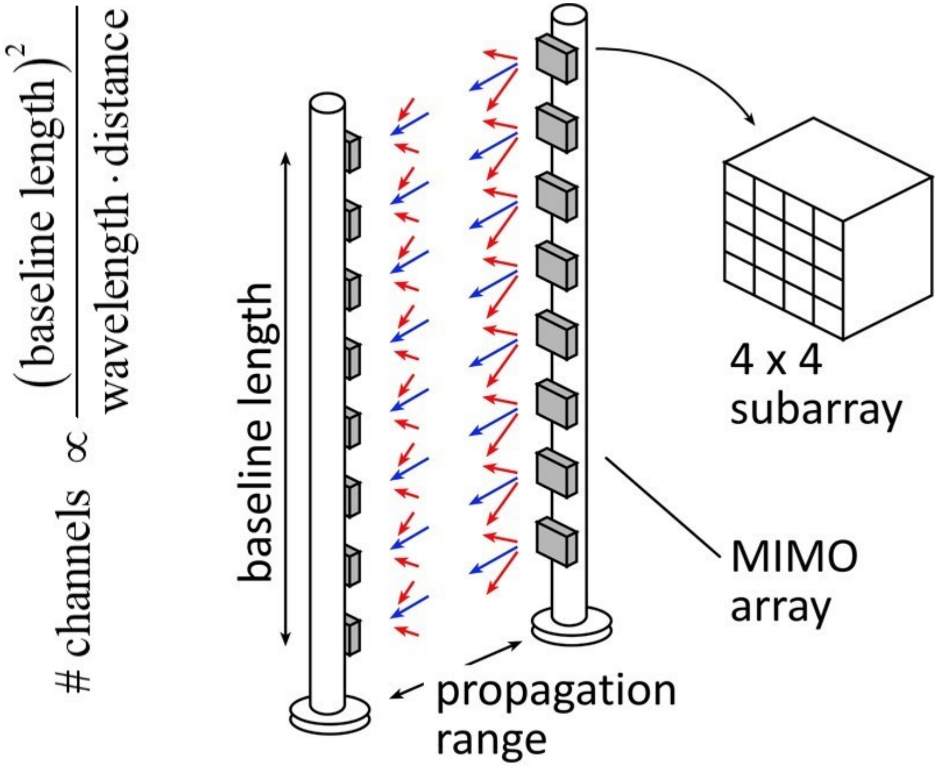
$$\downarrow$$

$$\frac{P_{received}}{P_{trans}} = \frac{D_{hub,element} N_{hub} A_{hand}}{4\pi} \left(\frac{1}{R}\right)^2 e^{-\alpha R} \propto R^0 \cdot e^{-\alpha R}$$

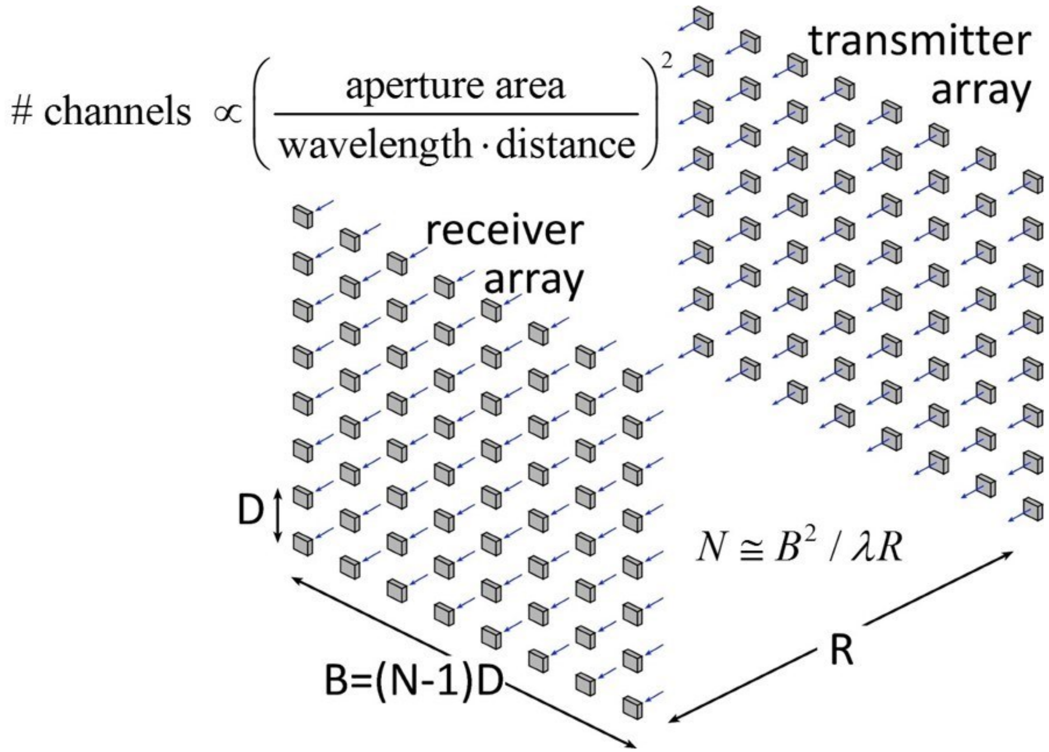
***The hub array is now 9mm×655mm (vs. 5mm×350mm)**

340 GHz (or even 650 GHz) backhaul

linear array



square array



Sub-mm-wave line-of-sight MIMO network backbone

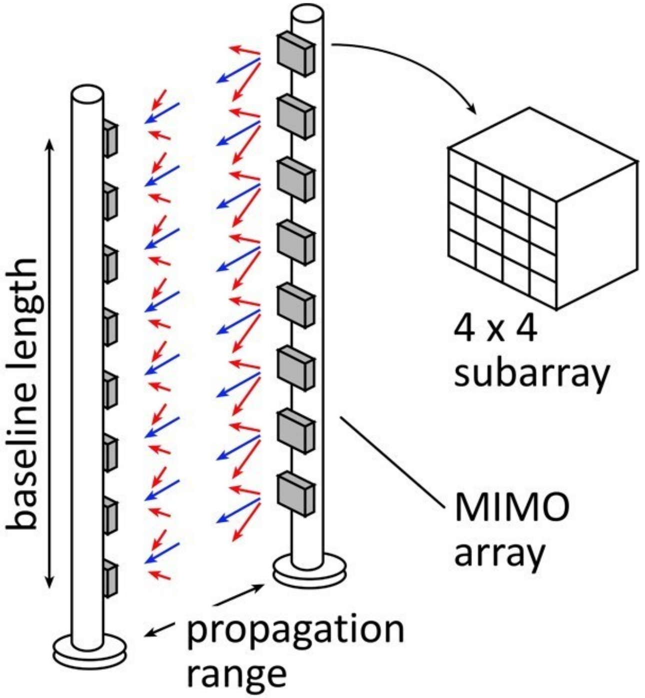
wireless @ optical speed; link network where fiber is too expensive to place.

340 GHz: 640Gb/s @ 500 meters range; 1.6 meter linear array **(5Tb/s for 8×8 square array)**.

650 GHz: 1.28Tb/s @ 500 meter range; 1.6 meter linear array.

Capacity doubles again if we use both polarizations.

340 GHz 640 Gb/s MIMO backhaul



Required SNR (measured as Eb/No)	9.8	dB
packaging loss (receiver)	2	dB
packaging loss (transmitter)	2	dB
end-of-life hardware degradation	3	dB
hardware design margin	3	dB
beam aiming loss (edge of beam)	0	dB
systems operating margin	10	dB
Prec, received power at 1E-3 BER	-33.00	dBm
geometric path loss	2.07E-06	
geometric path loss, dB	-56.84	dB
path obstruction loss (foliage, glass)	0.00	dB

1.6m MIMO array: 8-elements, each 80 Gb/s QPSK; 640Gb/s total
4 × 4 sub-arrays → 8 degree beamsteering

500 meters range in 50 mm/hr rain; 29 dB/km

Realistic packaging loss, operating & design margins

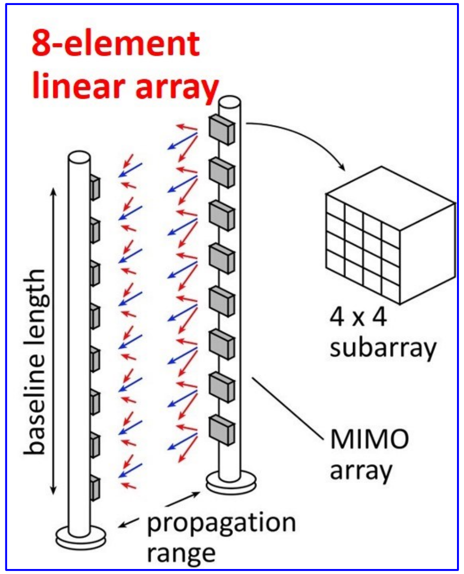
PAs: 82mW P_{out} (per element)

LNAs: 4 dB noise figure

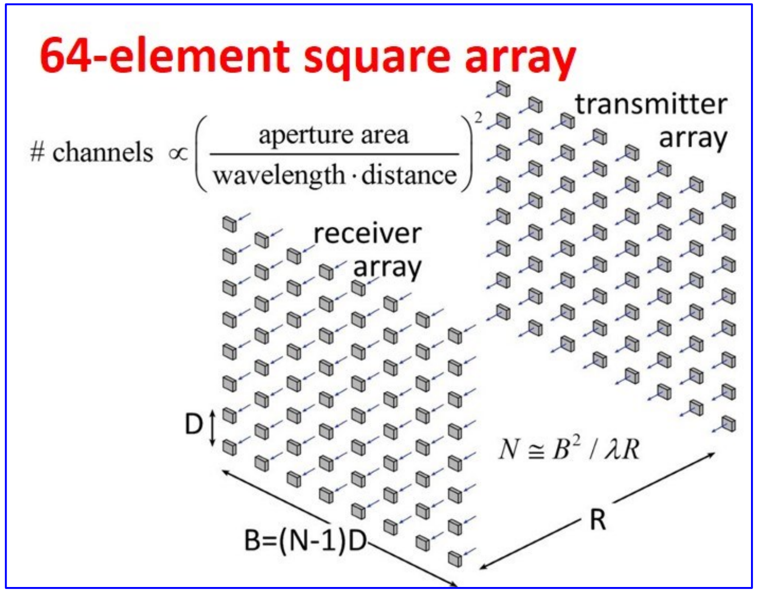
340 GHz 5 Tb/s MIMO backhaul

500m range in 50mm/hr. rain.

8-element 640Gb/s linear array:
requires 80mW power/element
requires 1.6m linear array



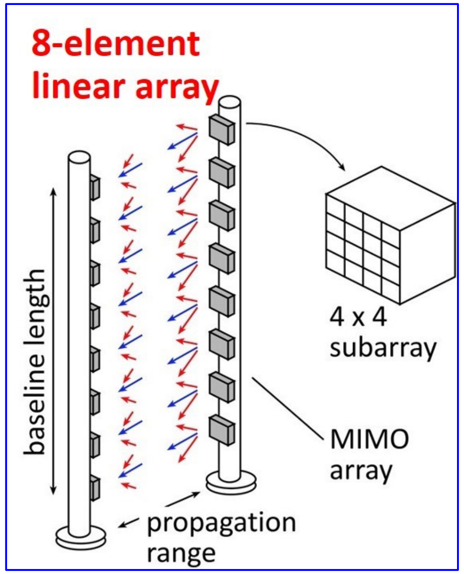
8-element 5Tb/s square array:
same link assumptions
requires 10mW power/element
...10W total radiated power
requires 1.6m square array



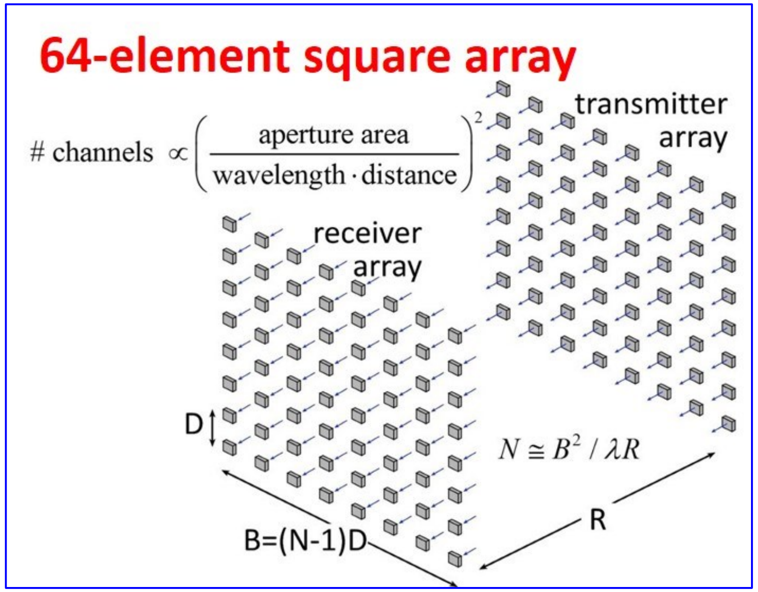
140 GHz, 640 Gb/s MIMO backhaul

Why not use a lower-frequency carrier, e.g. 140 GHz ?

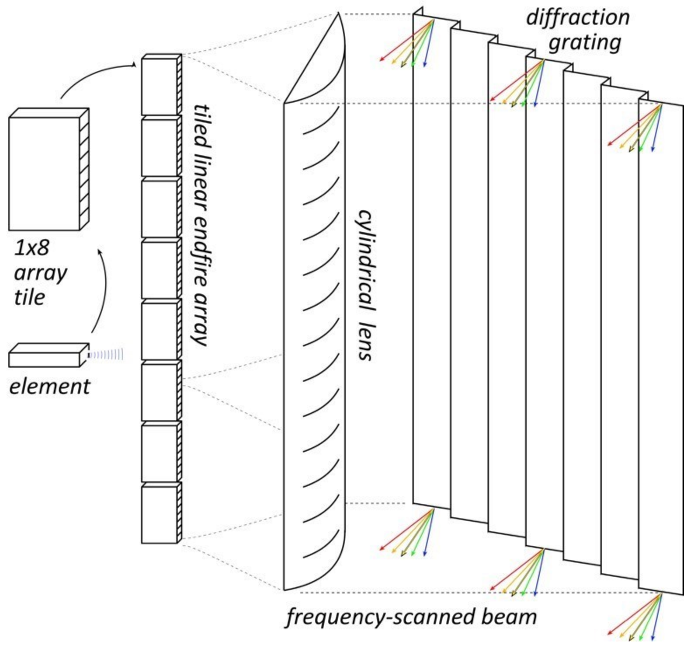
8-element 640Gb/s linear array:
same link assumptions
requires 2mW (vs. 80mW) power/element
requires 2.6m (vs. 1.6m) linear array

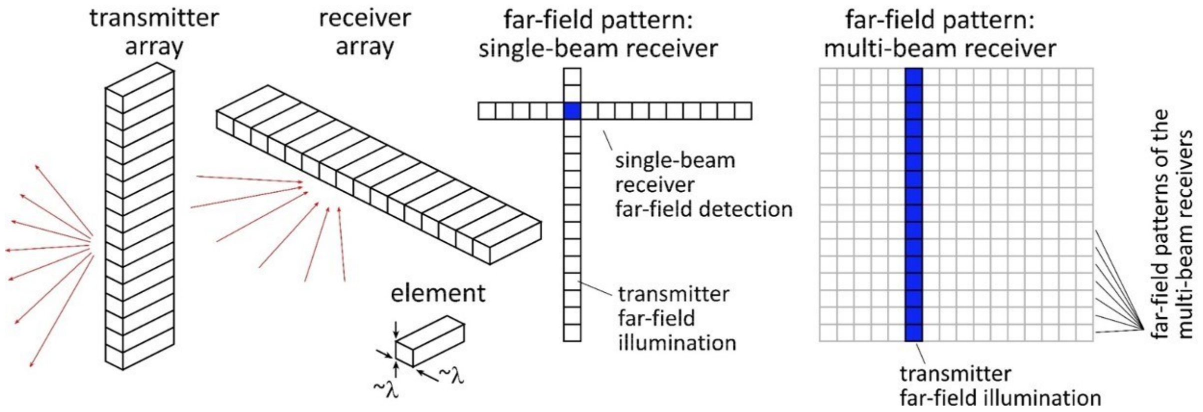


8-element 5Tb/s square array:
same link assumptions
requires 0.25mW (vs. 10mW) power/element
requires 2.6m (vs. 1.6m) square array



High-resolution imaging radar





Proposed demo: 220GHz frequency-scanned system

64×512 pixels, 60Hz refresh
35cm × 35cm aperture
64-element linear array

Target:

0.3m diameter, 10% reflectivity, 300m range
detect with 5dB SNR in 35dB/km fog.

System:

F=6dB, $P_{element}$= 10dBm (10% duty cycle)

DOD-relevant: 140GHz close-range system

256×256 pixels, 10ms image acquisition time
27 cm linear arrays, 256 elements

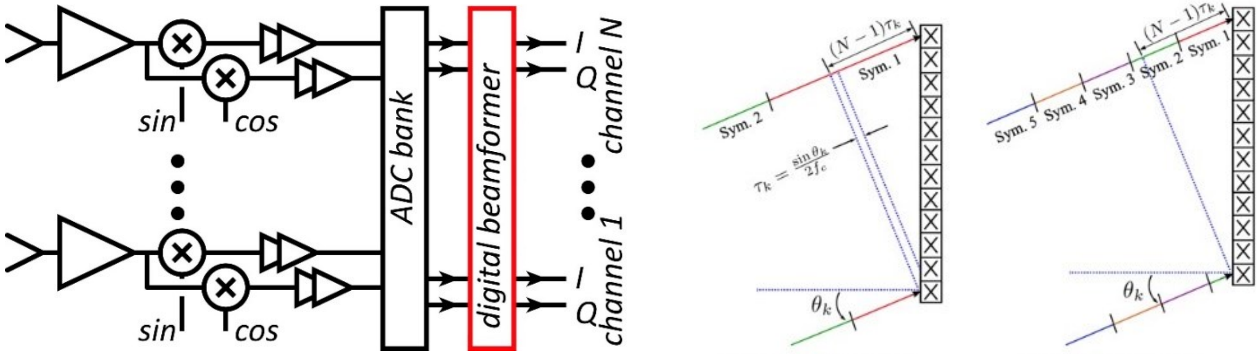
Target (large bullet):

2cm diameter , 10% reflectivity, 100m
detect with 10dB SNR in 20dB/km rain.

System

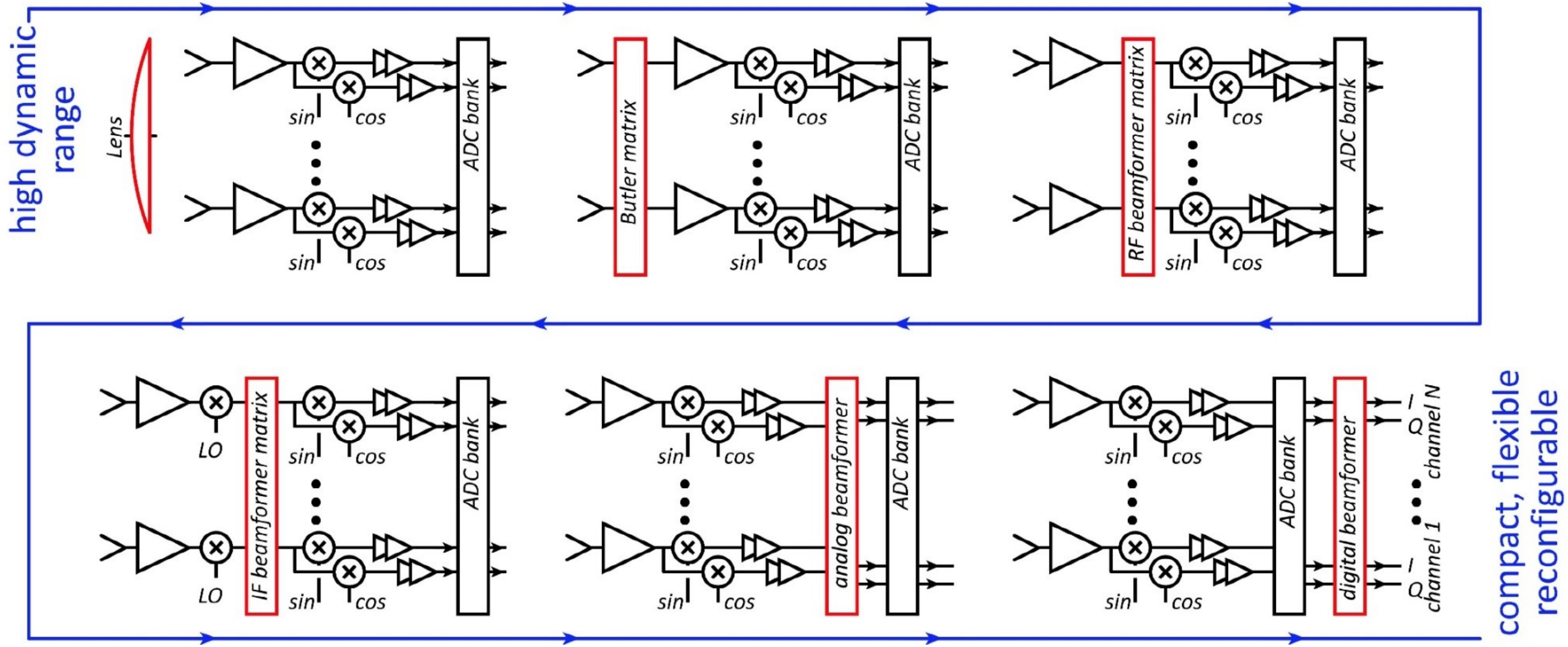
F=6dB, → Need 0.4W PAs (10% duty cycle)
(reasonable margins)

Systems



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

Beamforming for massive spatial multiplexing

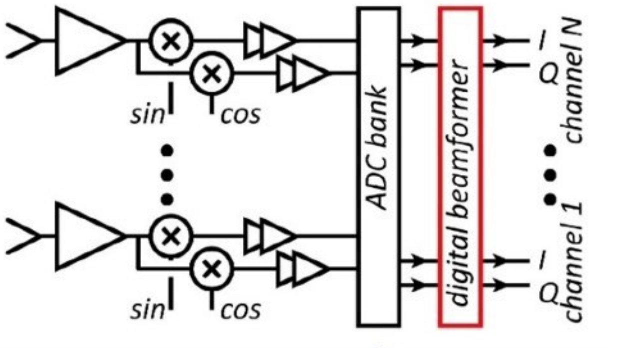


Pure digital beamforming:
dynamic range & phase noise requirements: appear to be manageable ✓✓✓
Digital back-end processing requirements (die area, DC power): being investigated ???

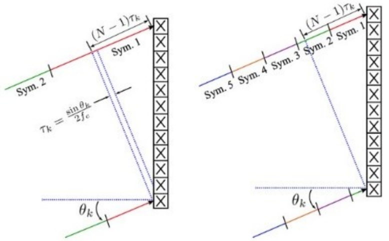
Pure RF beamforming: (focal plane, Butler matrixes, RF beamforming)
Established approach in DOD systems (high dynamic range). Issues of array tiling.

Beamforming for massive spatial multiplexing

Digital beamforming



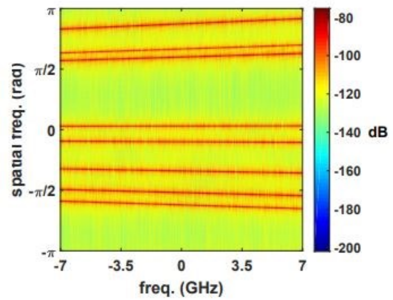
- ✓**ADCs/DACs**: only 3-4 bit ADC/DACs required (Madhow, Studer, Rodwell)
- ✓**Linearity**: Amplifier P_{1dB} need be only 3dB above average power (Madhow).
- ✓**Phase noise**: Requirements same as for SISO (Alon, Madhow, Niknejad, Rodwell)
- **Efficient digital beamforming**: beamspace algorithm=complexity ~N× log(N) (Madhow)
- **Efficient digital beamforming**: low-resolution matrix (Studer)
- **Efficient channel estimation** : fast beamspace algorithm (Studer)
- **Efficiently addressing true-time-delay problem**: "rainbow" FFT algorithm (Madhow)


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

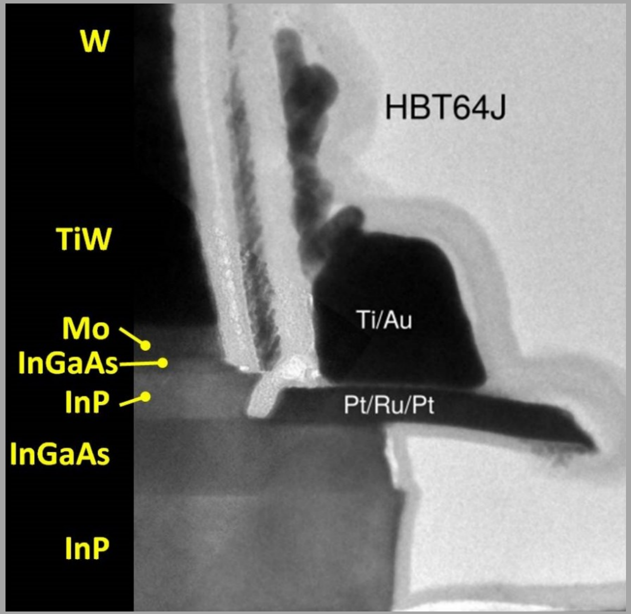
- ✓**Array-to-backplane interconnect power**: low-power analog baseband 50Ω links (Rodwell)

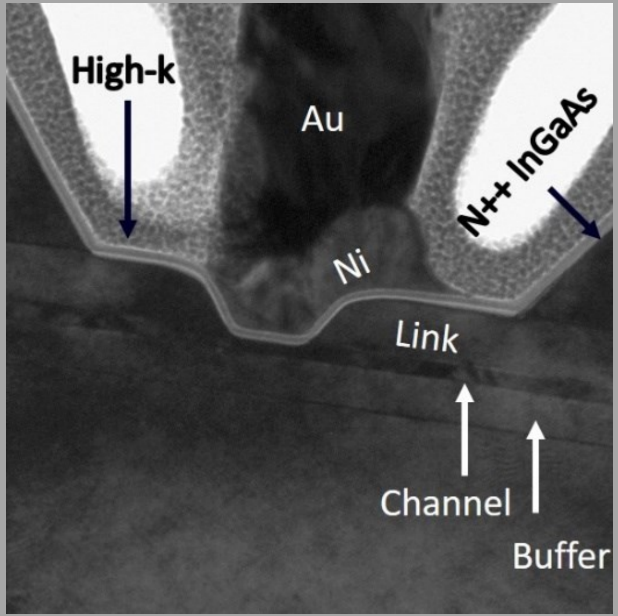
In progress…

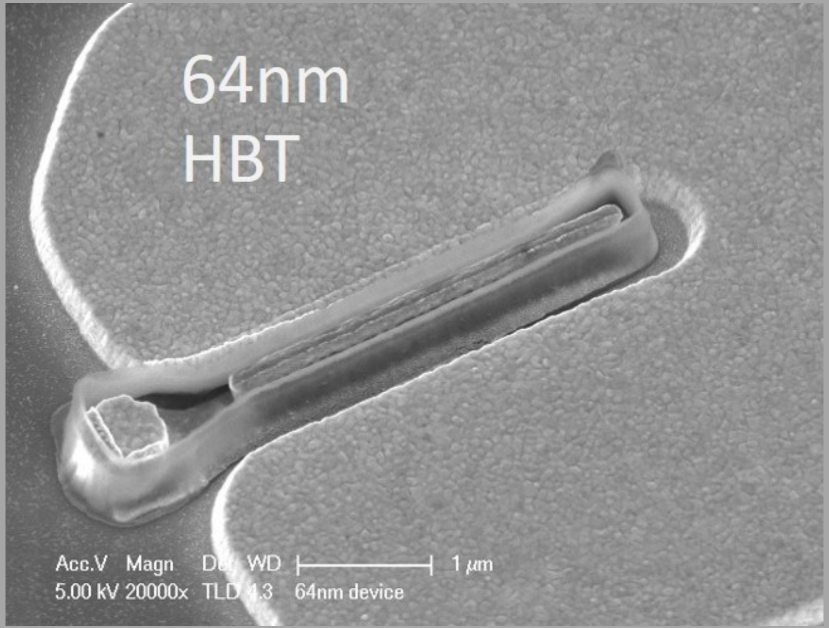
- **Propagation models and measurements**: (Molisch)
- **Blockage probability, mesh networks, network protocols**: (Rangan, Cabric)
- **MIMO system power analysis**: (Rangan, Cabric, Buckwalter)



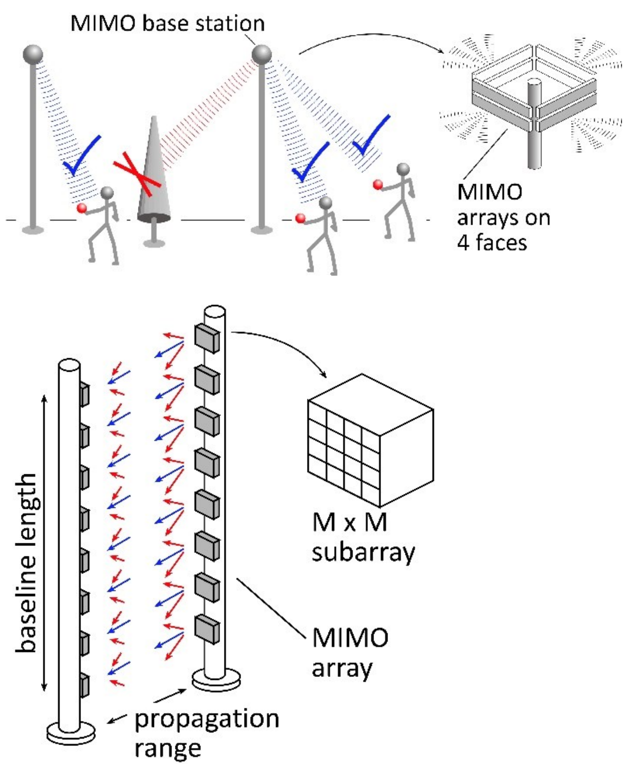
Transistors

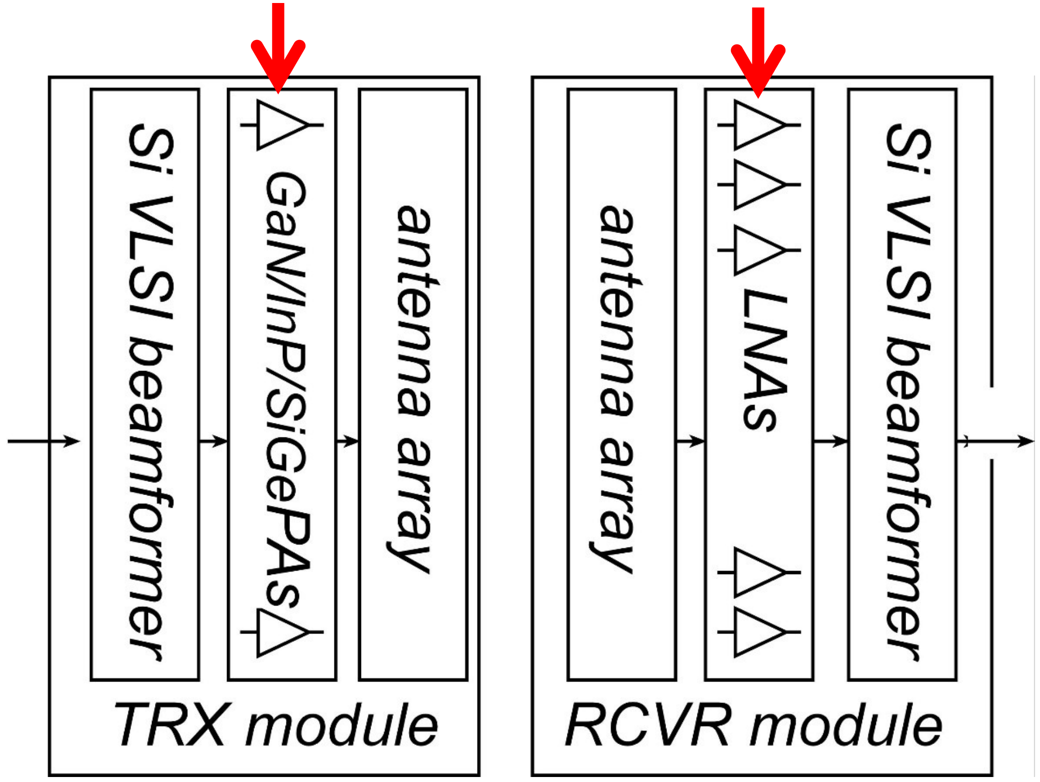






mm-Wave Wireless Transceiver Architecture





custom PAs, LNAs → power, efficiency, noise
Si CMOS beamformer→ integration scale

...similar to today's cell phones.

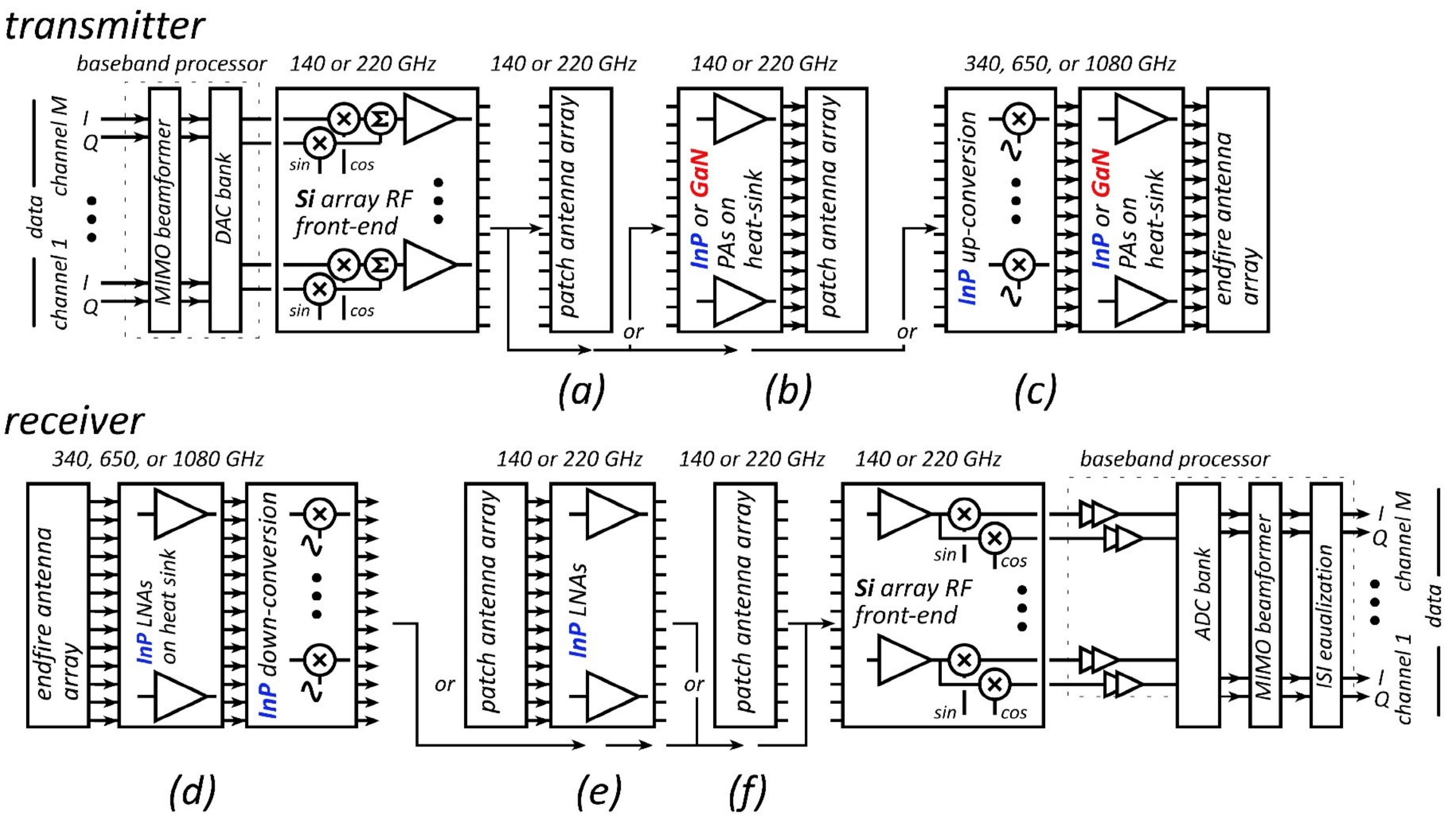
IC Technologies for 100 + GHz systems

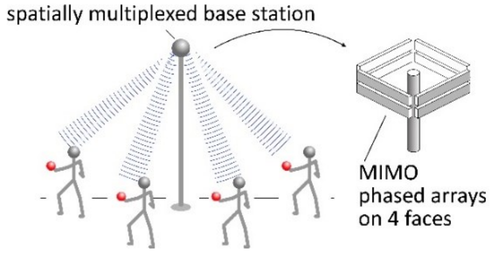
Silicon
baseband processing at all frequencies
RF sections @ 140, 200GHz
PAs, LNAs in short-range 140, 220 GHz links

GaN
high-power amplifiers in long-range 140,220GHz links
(possibly 340GHz ?)

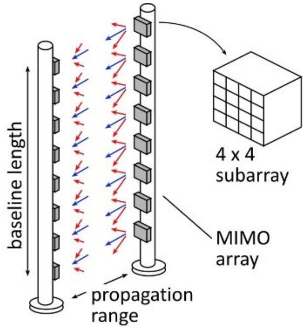
InP HEMT
low-noise amplifiers in long-range 140,220GHz links
low-noise amplifiers @ 340, 650GHz

InP HBT
medium-power amplifiers in long-range 140,220GHz links
power amplifiers @340, 650GHz
RF sections @ 340, 650GHz





MIMO hub:
140GHz: F= 4dB, P_{avg}=17.5dBm, P_{sat}≅21.5dBm
220GHz: F= 4dB, P_{avg}=21dBm, P_{sat}≅25dBm

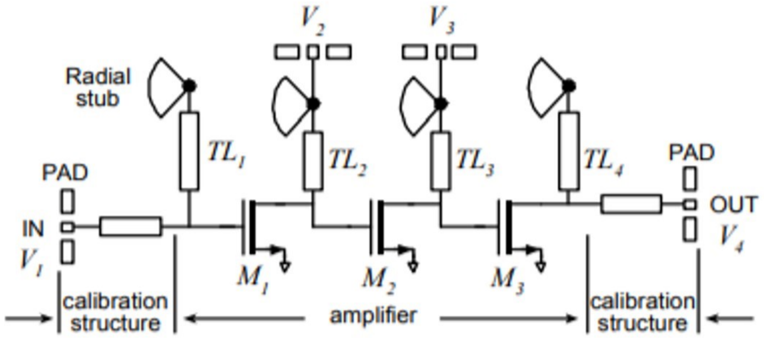


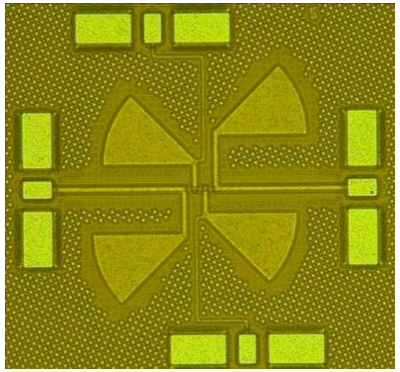
Point-point MIMO:
340GHz: F= 4dB, P_{avg}=9.9dBm, P_{sat}≅13.9dBm
650GHz: F= 4dB, P_{avg}=14.5dBm, P_{sat}≅18.5dBm?

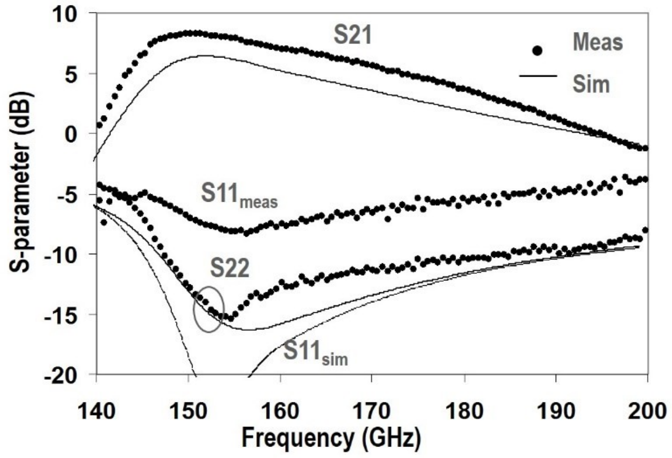
mm-wave CMOS (UCSB examples)

150 GHz amplifier:

IBM 65 nm bulk CMOS, 2.7dB gain per stage Seo et al., JSSC, Dec. 2009

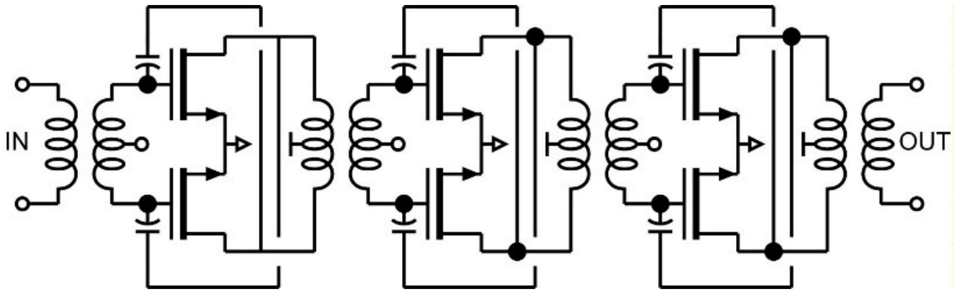


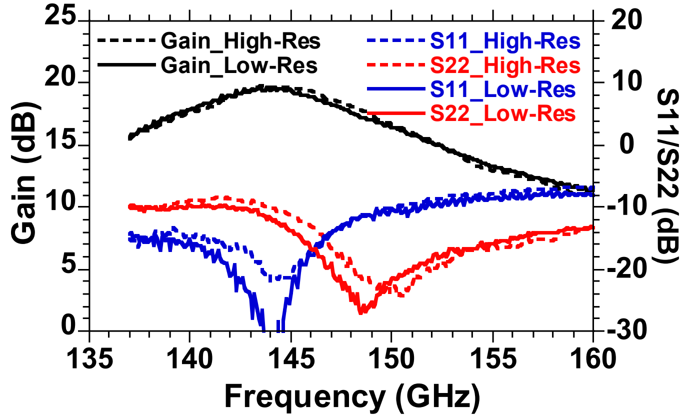




145 GHz amplifier

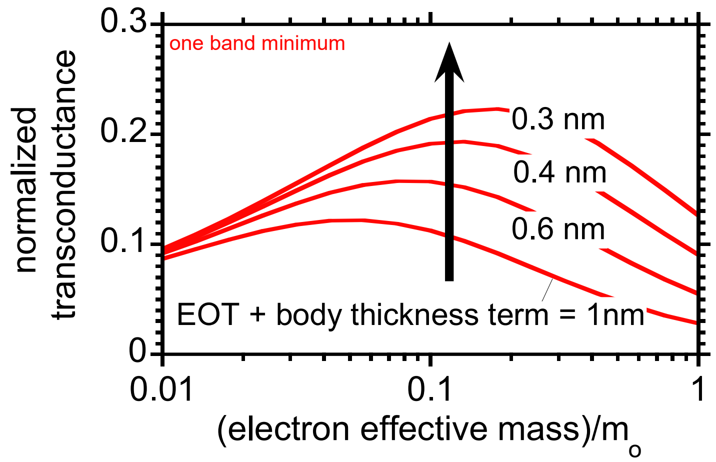
GF 45 nm SOI CMOS, 6.3 dB gain per stage Kim, Simseck, 2017 BCICTS



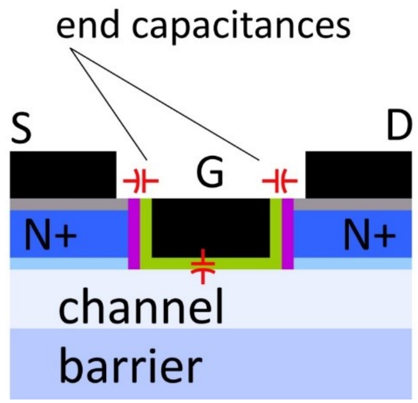


mm-Wave CMOS won't scale much further

Gate dielectric can't be thinned
→ on-current, g_m can't increase



Shorter gates give no less capacitance
dominated by ends; ~1fF/μm total

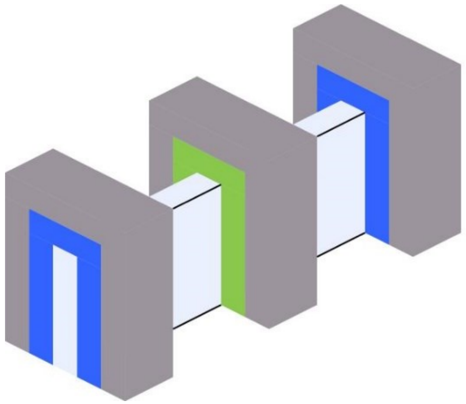


Maximum g_m, minimum C→ upper limit on f_τ.
about 350-400 GHz.

Tungsten via resistances reduce the gain

Inac et al, CSICS 2011

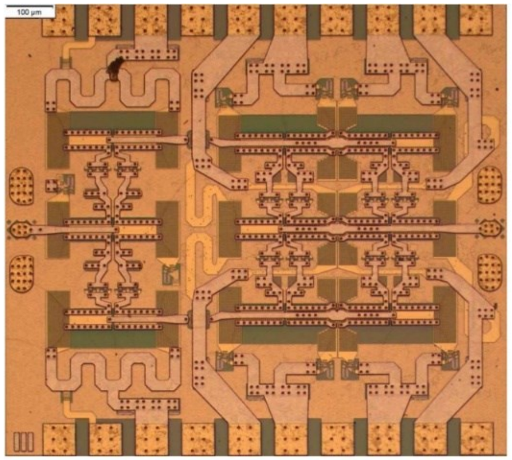
Present finFETs have yet <u>larger</u> end capacitances



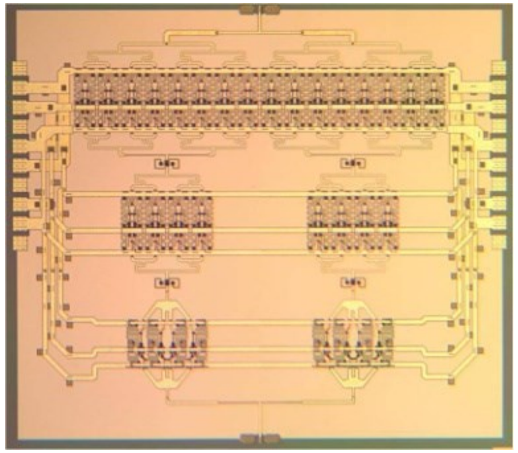
III-V high-power transmitters, low-noise receivers

Cell phones & WiFi: GaAs PAs, LNAs

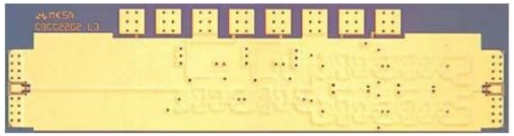
mm-wave links need:
high transmit power, low receiver noise



0.47 W @86GHz
H Park, UCSB, IMS 2014



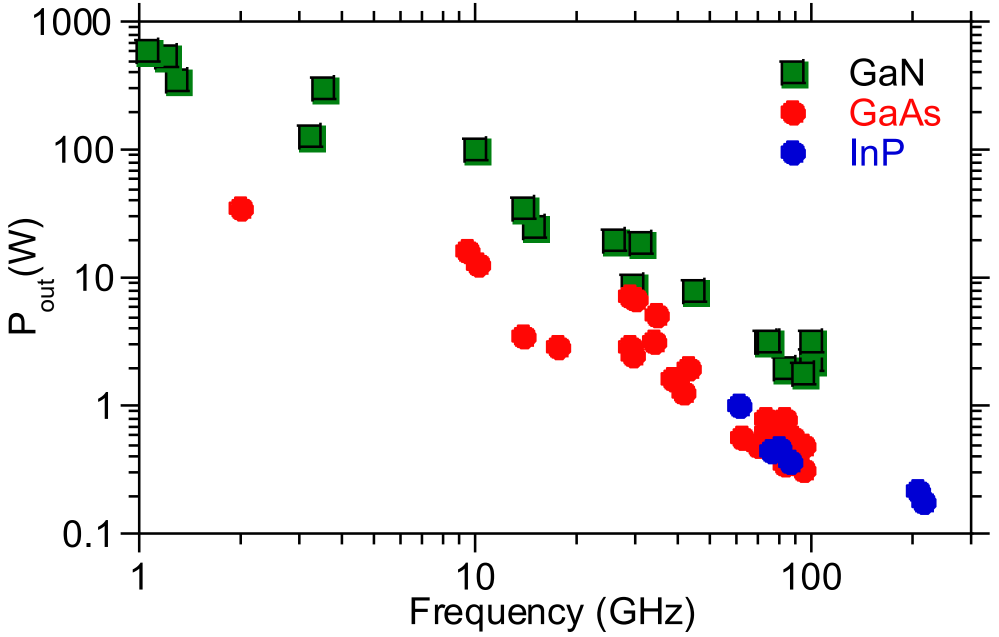
0.18 W @220GHz
T Reed, UCSB, CSICS 2013

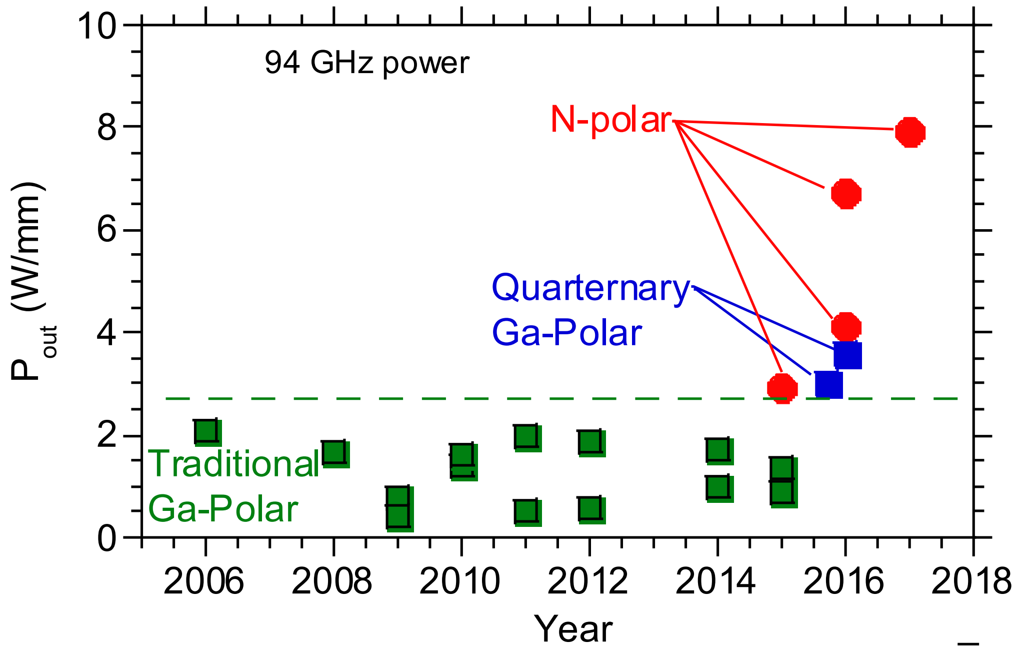


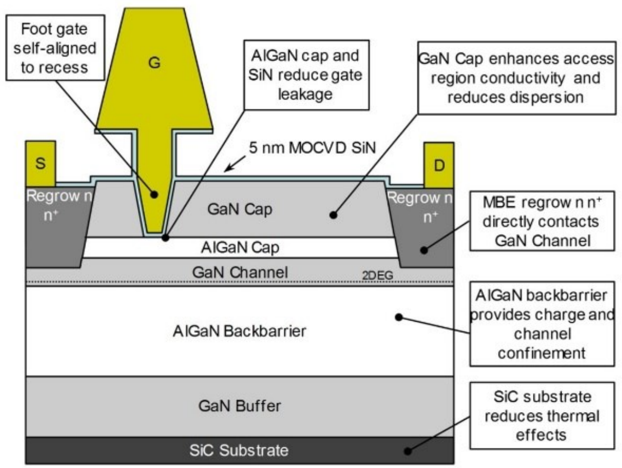
1.9mW @585GHz
M Seo, TSC, IMS 2013

Gallium Nitride Power Technologies

GaN is the leading high-frequency power technology



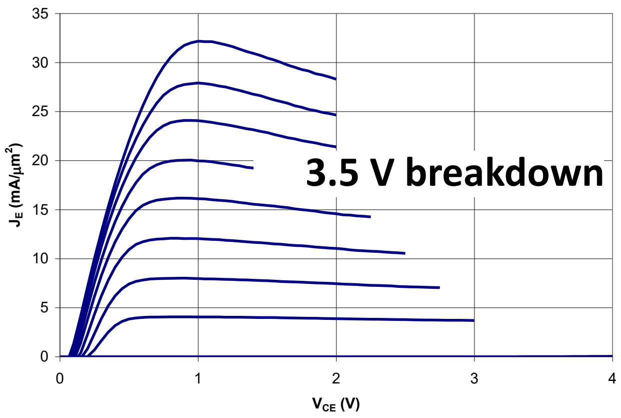


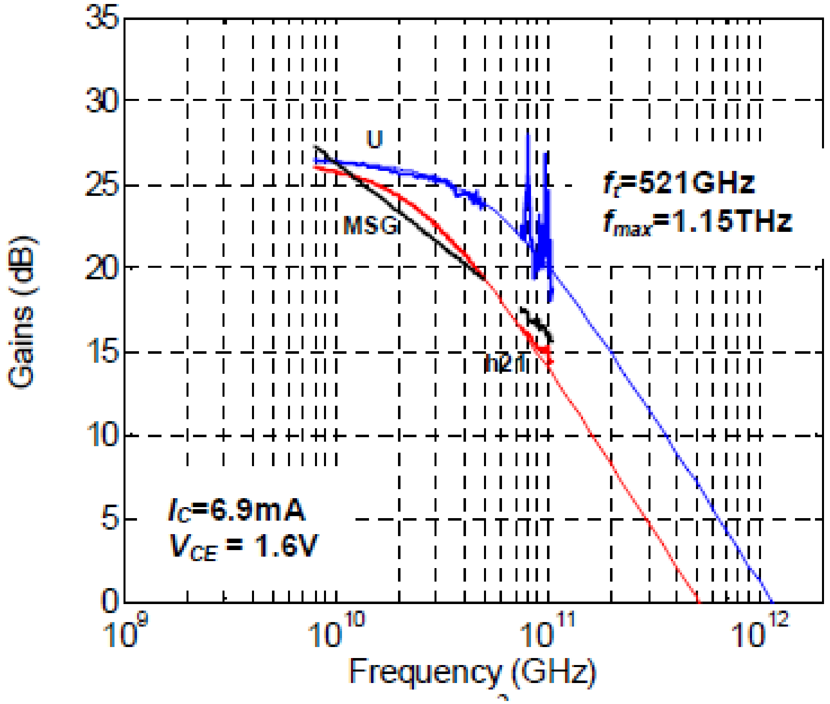


N-polar GaN: Mishra

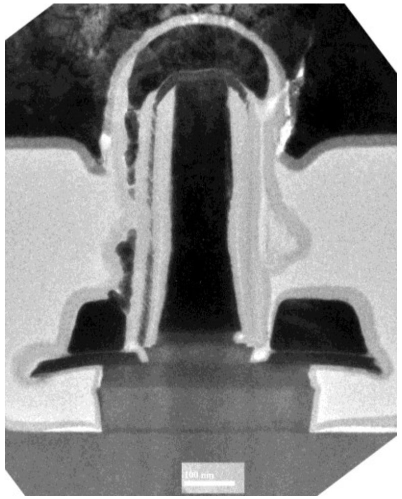
130nm / 1.1THz InP HBT Technology

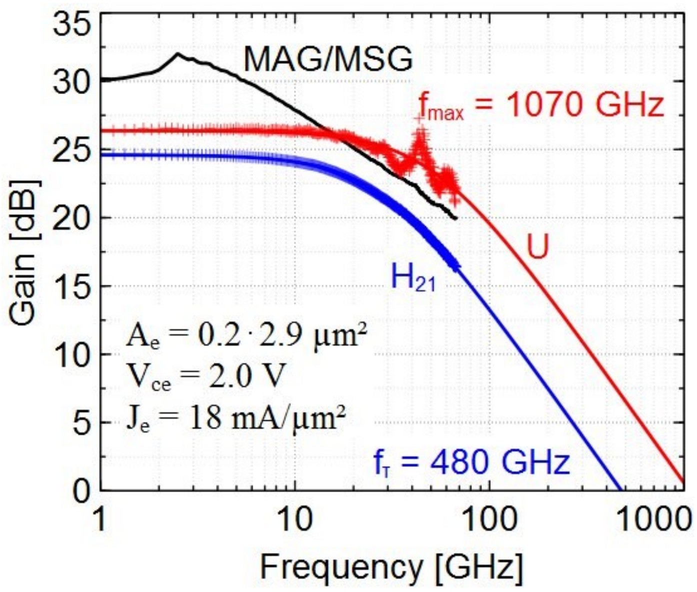
Teledyne: M. Urteaga *et al*: 2011 DRC





Rode (UCSB), IEEE TED, 2015

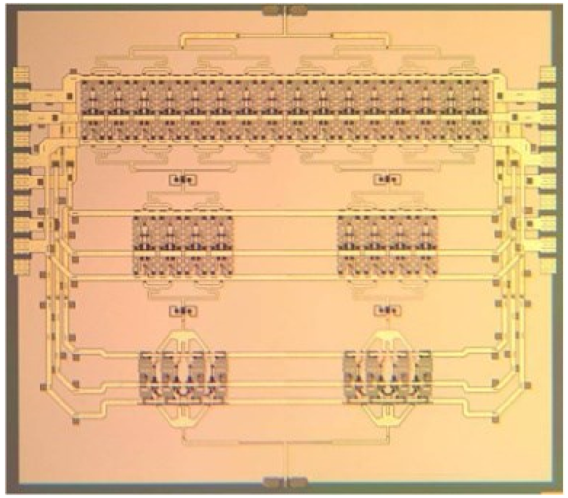




130nm / 1.1THz InP HBT: IC Examples

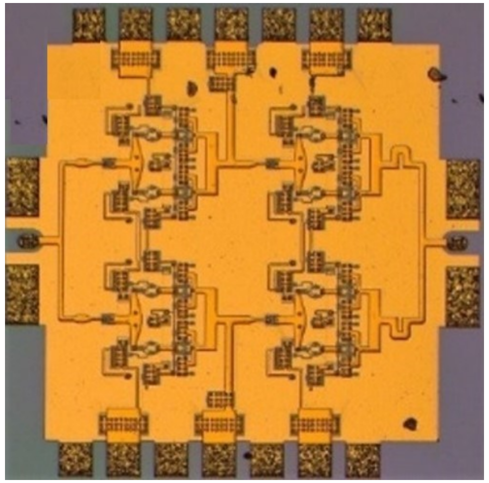
220 GHz 0.18W power amplifier

UCSB/Teledyne: T. Reed *et al*: 2013 CSICS



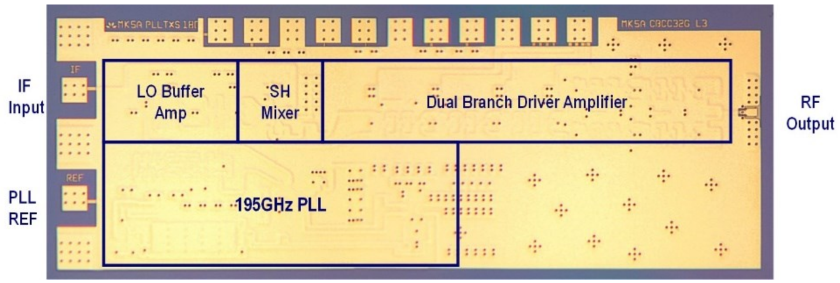
325 GHz, 16mW power amplifier

UCSB/Teledyne: A. Ahmed, 2018 EuMIC Symp.

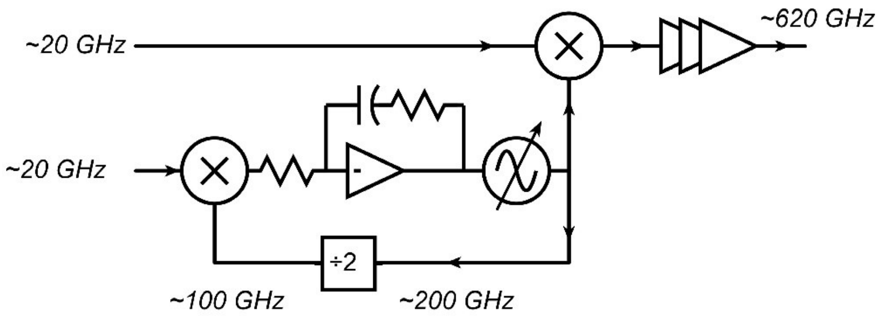


Integrated ~600GHz transmitter

Teledyne: M. Urteaga *et al*: 2017 IEEE Proceedings

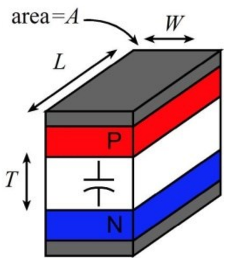


but, only ~1 mW output power

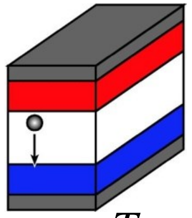


Transistor scaling laws: (V,I,R,C,τ) vs. geometry

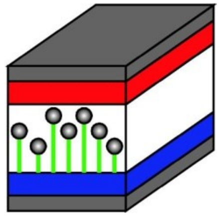
Depletion Layers



$$C = \varepsilon \cdot \frac{A}{T}$$

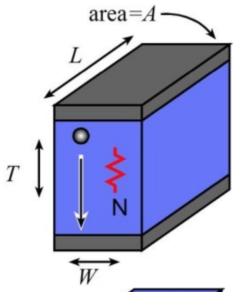


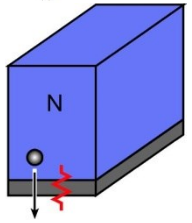
$$\tau = \frac{T}{2v}$$



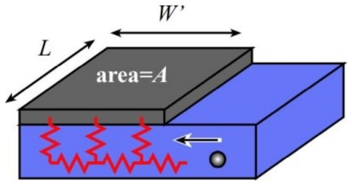
$$\frac{I_{\max}}{A} = \frac{4\varepsilon v_{sat}(V_{appl} + \phi)}{T^2}$$

Bulk and Contact Resistances





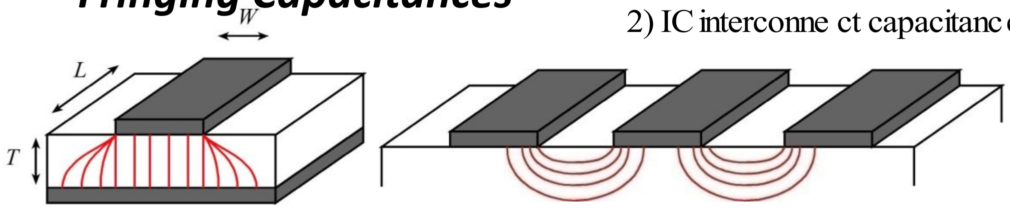
$$R \cong \rho_{contact} / A$$



contact terms dominate

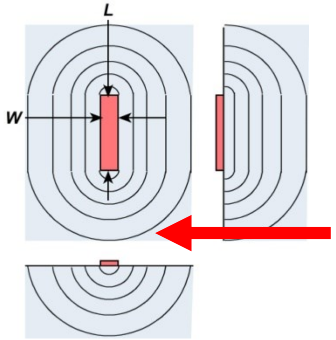
Fringing Capacitances

1) FET fringing capacitances
2) IC interconnect capacitances

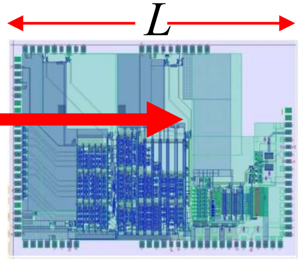


$$C_{finging} / L \sim \varepsilon \qquad C_{finging} / L \sim \varepsilon$$

Thermal Resistance

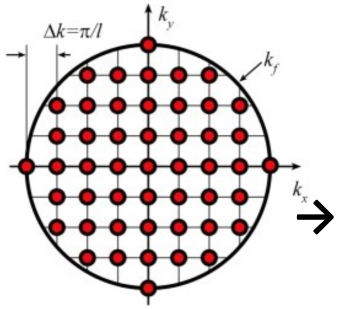


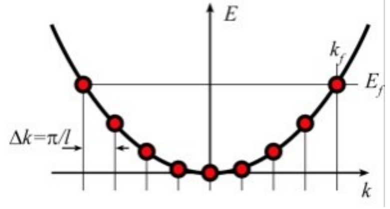
$$\Delta T_{IC} \propto \frac{P_{IC}}{K_{th} L}$$



$$\Delta T_{transistor} \sim \frac{P}{\pi K_{th} L} \ln\left(\frac{L}{W}\right)$$

Available quantum states to carry current





→ ***capacitance, transconductance contact resistance***

Frequency Limits and Scaling Laws of (most) Electron Devices

$$\tau \propto \text{thickness}$$

$$C \propto \text{area} / \text{thickness}$$

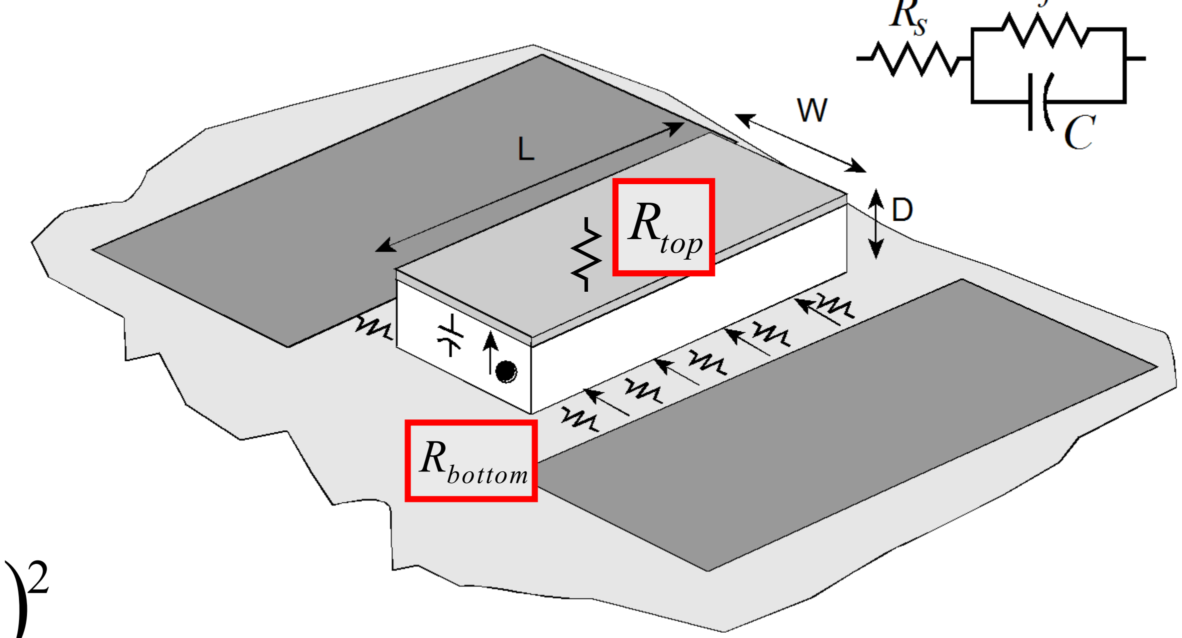
$$R_{top} \propto \rho_{contact} / \text{area}$$

$$R_{bottom} \propto \frac{\rho_{contact}}{\text{area}} + \cancel{\frac{\rho_{sheet}}{4} \cdot \frac{\text{width}}{\text{length}}}$$

$$I_{\text{max, space-charge-limit}} \propto \text{area} / (\text{thickness})^2$$

$$\Delta T \propto \frac{\text{power}}{\text{length}} \times \log\left(\frac{\text{length}}{\text{width}}\right)$$

PIN photodiode



To double bandwidth:

- Reduce thicknesses 2:1
- Improve contacts 4:1
- Reduce width 4:1,
- Keep constant length
- Increase current density 4:1

Bipolar Transistor Design

$$\tau_b \approx T_b^2 / 2D_n$$

$$\tau_c = T_c / 2v_{sat}$$

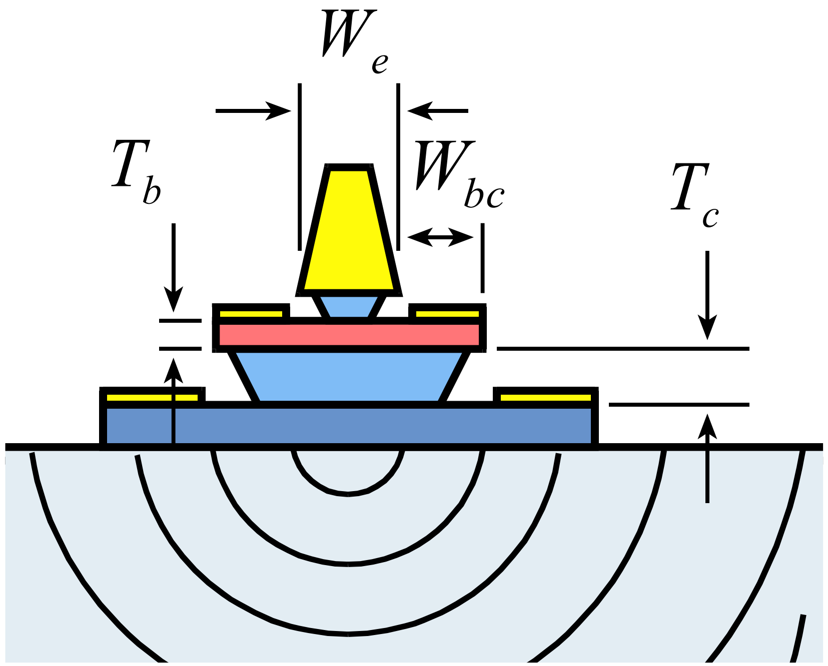
$$C_{cb} = \varepsilon A_c / T_c$$

$$I_{c,\max} \propto v_{sat} A_e \left(V_{\text{ce,operating}} + V_{\text{ce,punch-through}}\right) / T_c^2$$

$$\Delta T \propto \frac{P}{L_E}\left[1 + \ln\left(\frac{L_e}{W_e}\right)\right]$$

$$R_{ex} = \rho_{\text{contact}} / A_e$$

$$R_{bb} = \rho_{\text{sheet}}\left(\frac{W_e}{12L_e} + \frac{W_{bc}}{6L_e}\right) + \frac{\rho_{\text{contact}}}{A_{\text{contacts}}}$$



(emitter length L_E)

Bipolar Transistor Design: Scaling

$$\tau_b \approx T_b^2 / 2D_n$$

$$\tau_c = T_c / 2v_{sat}$$

$$C_{cb} = \varepsilon A_c / T_c$$

$$I_{c,\max} \propto v_{sat} A_e (V_{\text{ce,operating}} + V_{\text{ce,punch-through}}) / T_c^2$$

$$\Delta T \propto \frac{P}{L_E}\left[1 + \ln\left(\frac{L_e}{W_e}\right)\right]$$

$$R_{ex} = \rho_{\text{contact}} / A_e$$

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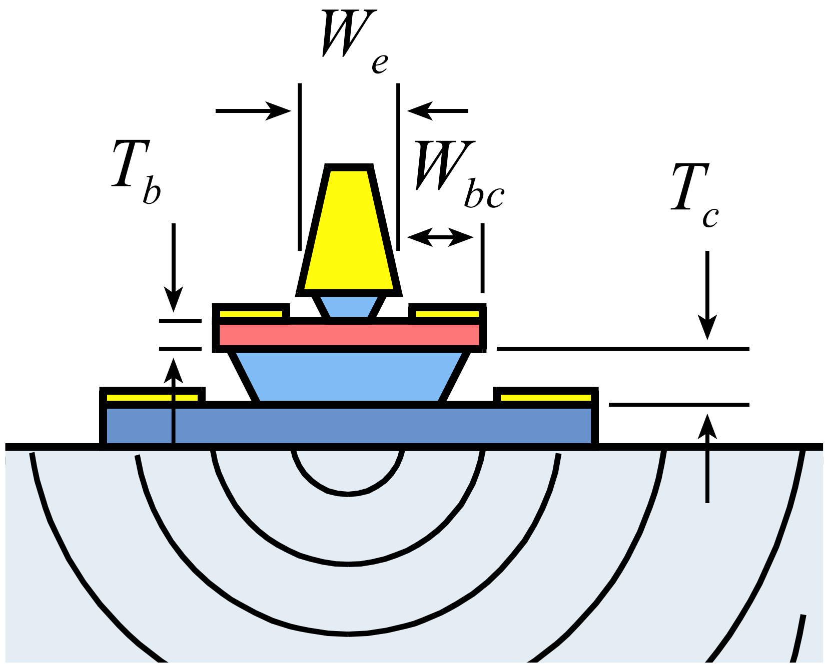
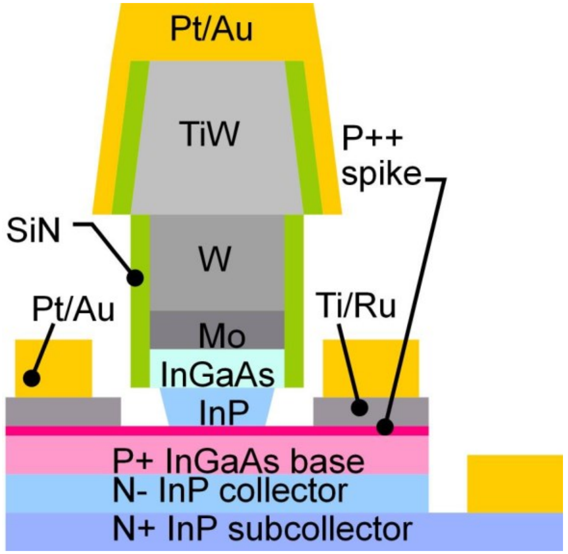


(emitter length L_E)

Making faster bipolar transistors



to double the bandwidth:	change
emitter & collector junction widths	decrease 4:1
current density (mA/µm²)	increase 4:1
current density (mA/µm)	constant
collector depletion thickness	decrease 2:1
base thickness	decrease 1.4:1
emitter & base contact resistivities	decrease 4:1

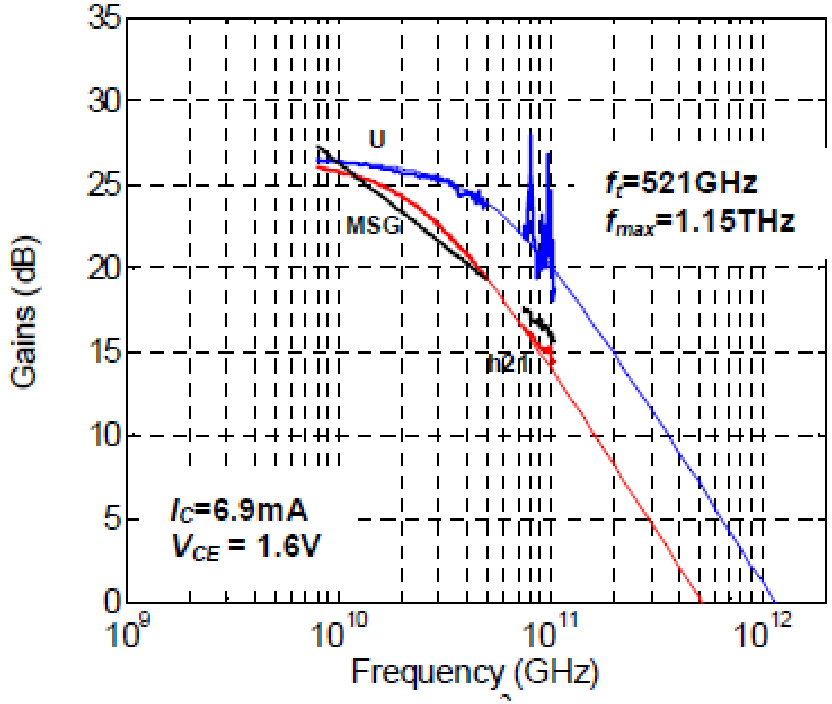
Narrow junctions.

Thin layers

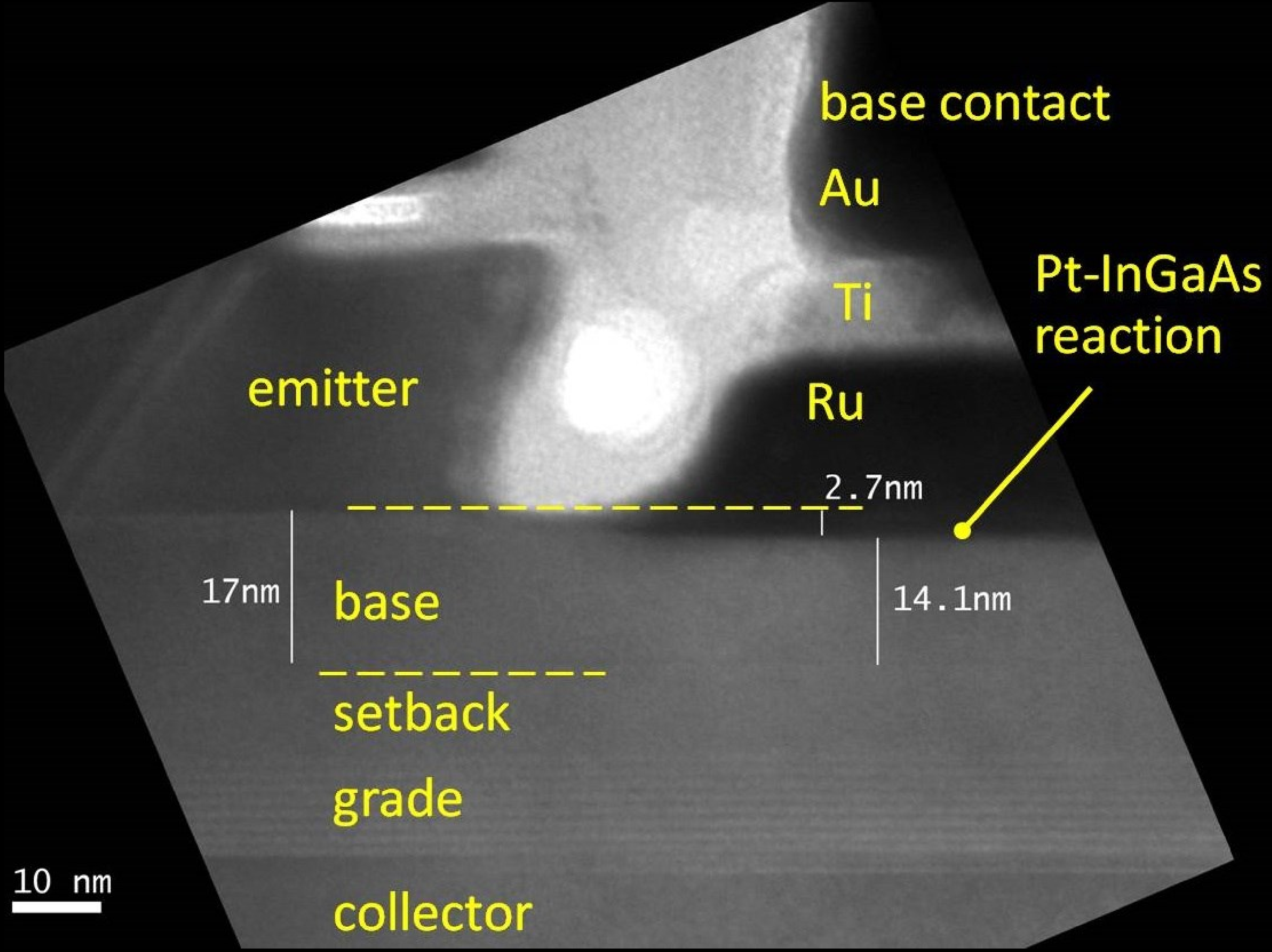
High current density

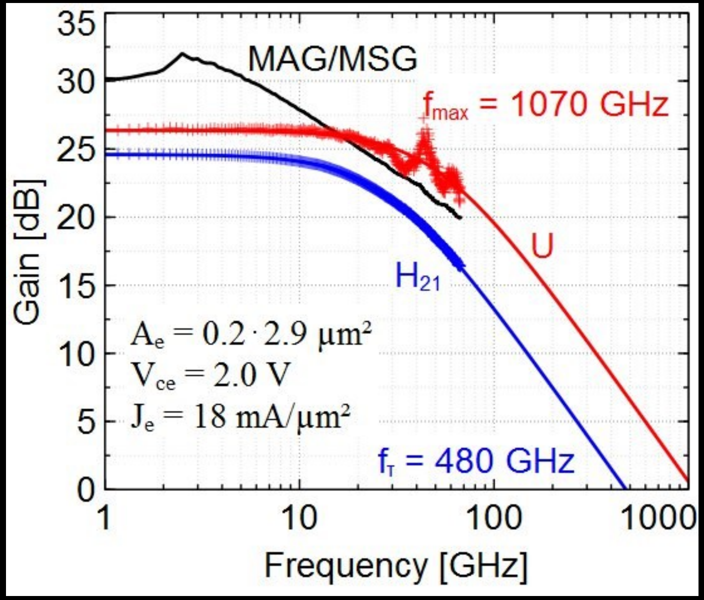
Ultra low resistivity contacts

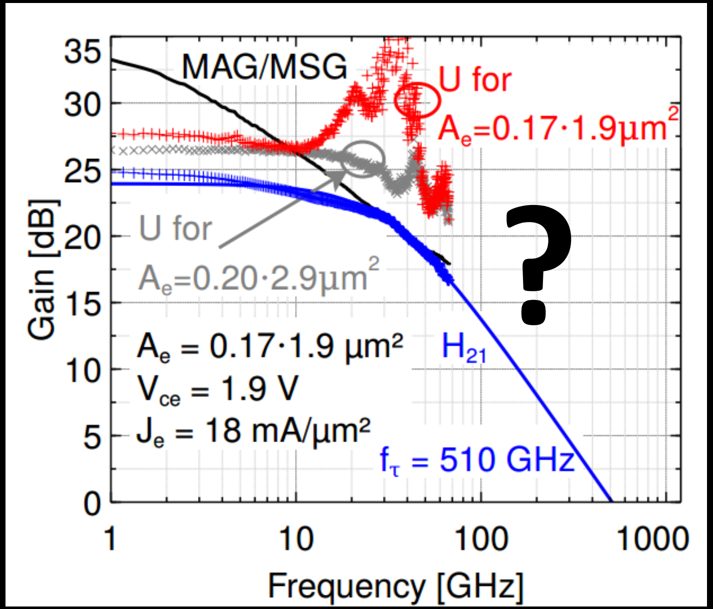
Teledyne: M. Urteaga *et al*: 2011 DRC



InP HBTs: 1.07 THz @200nm, ?? @ 130nm



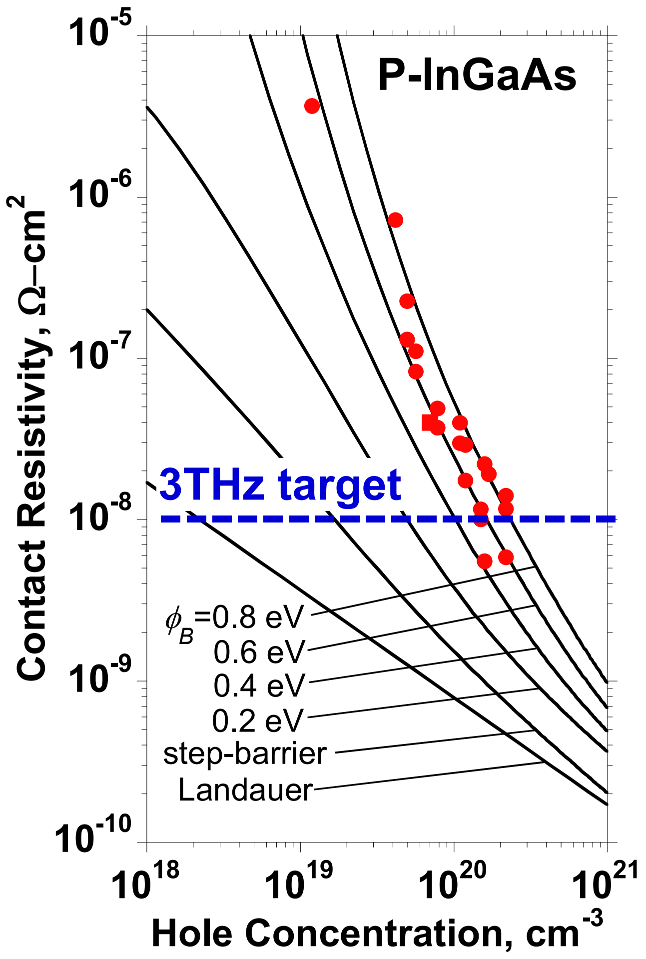




Rode et al., IEEE TED, Aug. 2015

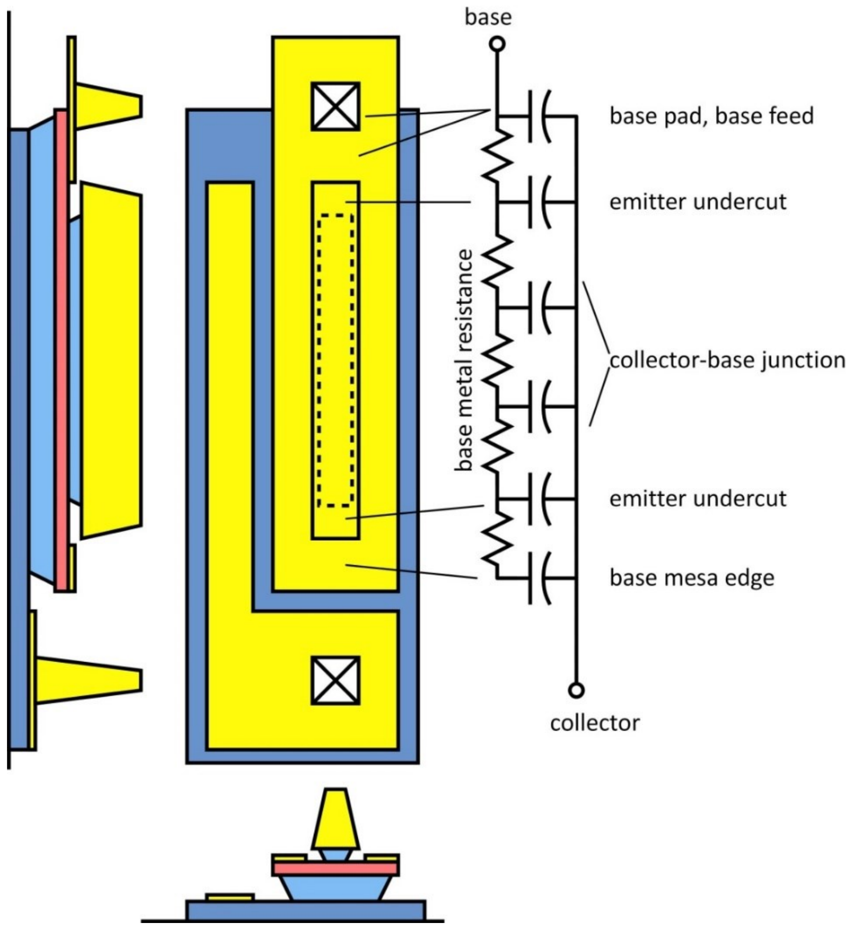
THz HBTs: The key challenges

Obtaining good base contacts
in HBT vs. in contact test structure
(emitter contacts are fine)



Baraskar *et al*, Journal of Applied Physics, 2013

RC parasitics along finger length
metal resistance, excess junction areas



Towards a 2 THz SiGe Bipolar Transistor

Similar scaling
InP: 3:1 higher collector velocity
SiGe: good contacts, buried oxides

Key distinction: Breakdown
InP has:
thicker collector at same f_τ,
wider collector bandgap

Key requirements:
low resistivity Ohmic contacts
note the high current densities

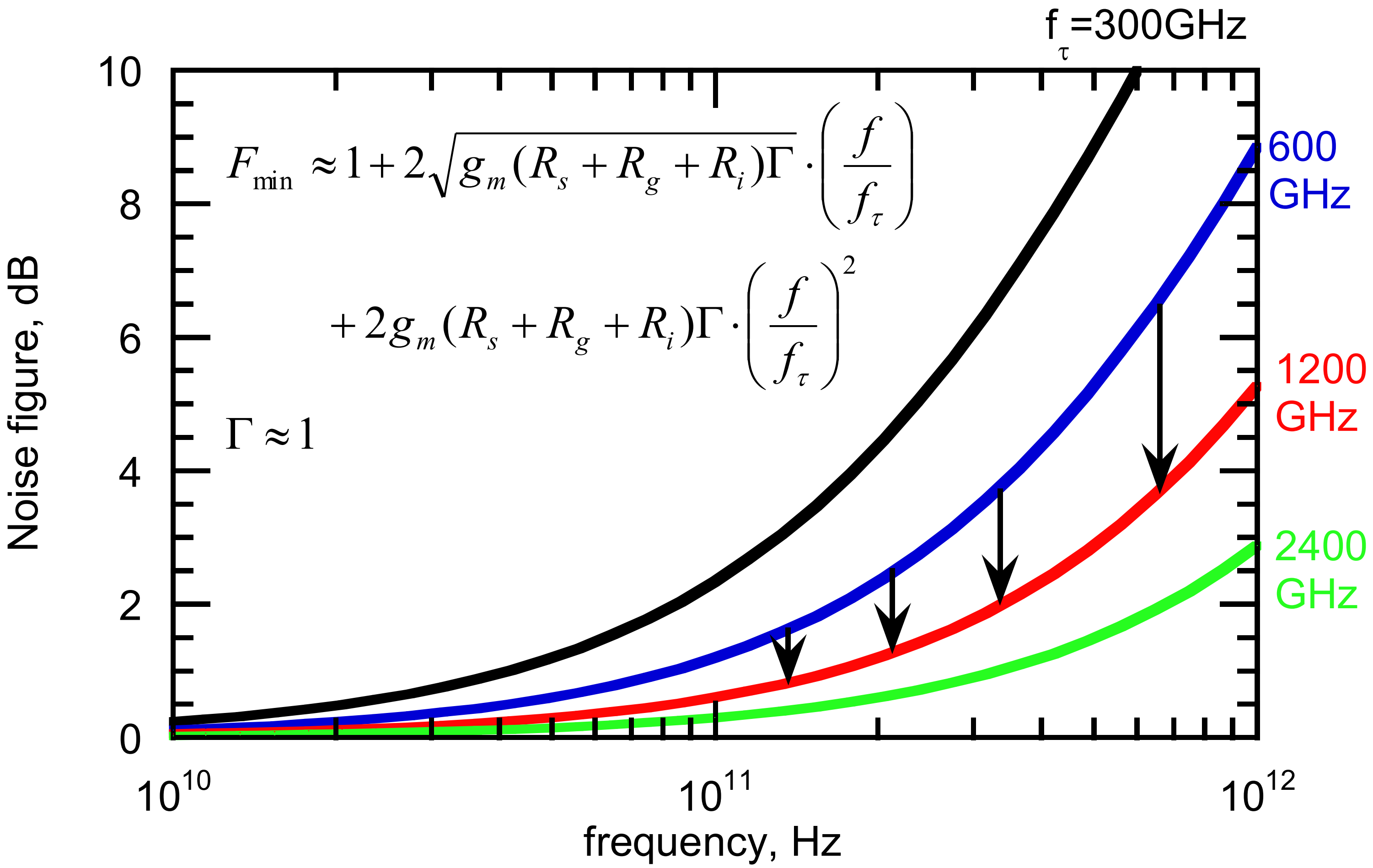
	InP	SiGe	
emitter			
junction width	64	**18**	nm
access resistivity	2	**0.6**	Ω–μm^2
base			
contact width	64	18	nm
contact resistivity	2.5	**0.7**	Ω–μm^2
collector			
thickness	53	15	nm
current density	36	**125**	mA/μm^2
breakdown	2.75	1.3?	V
f_τ	1000	1000	GHz
f_{max}	2000	2000	GHz

Assumes collector junction 3:1 wider than emitter.
Assumes SiGe contacts no wider than junctions

FETs (HEMTs): key for low noise

2:1 to 4:1 increase in f_τ :
- ***improved noise***
- ***less required transmit power***
- ***smaller PAs, less DC power***

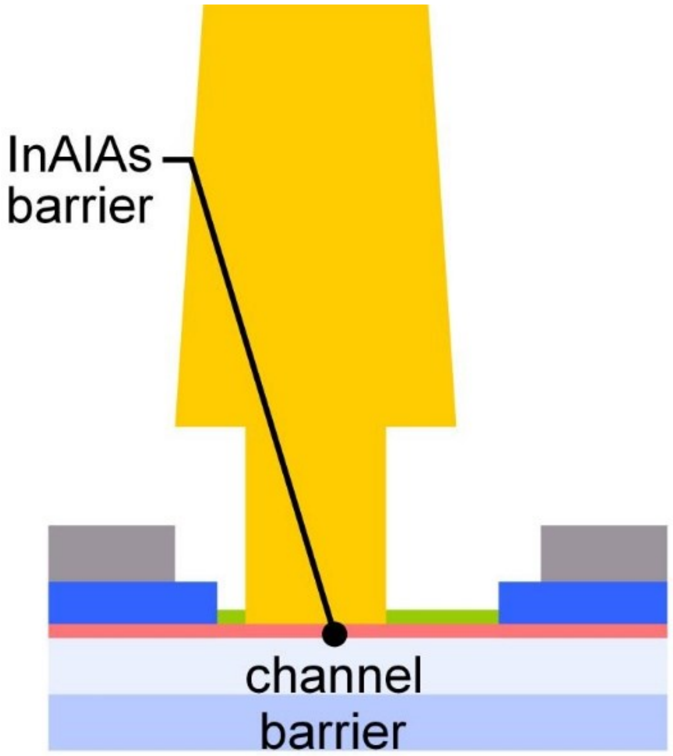
or higher-frequency systems

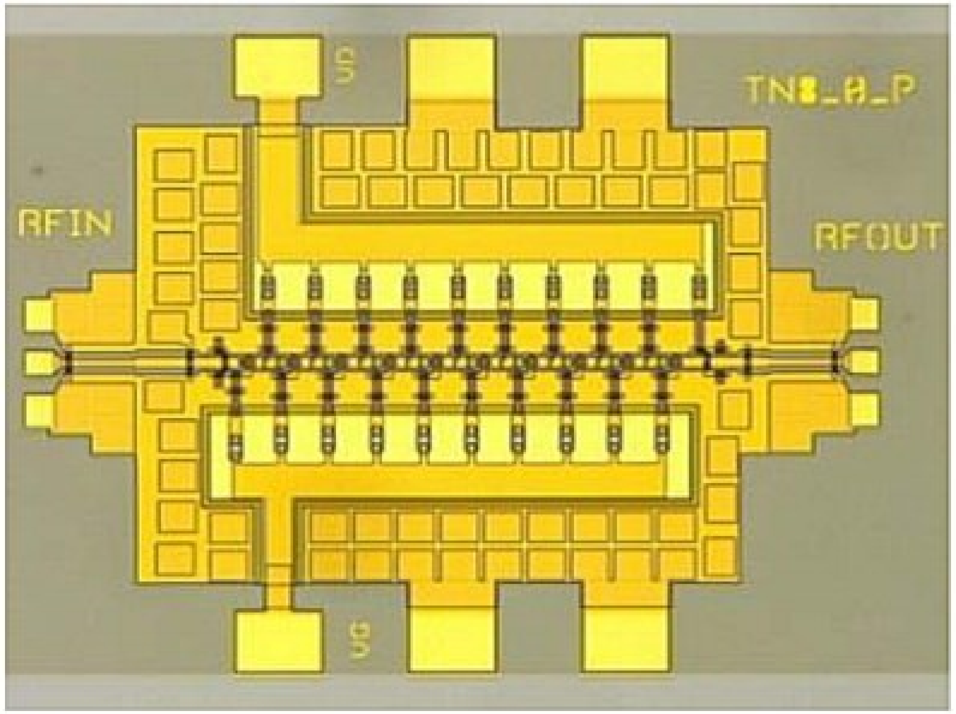


InP HEMTs: state of the art

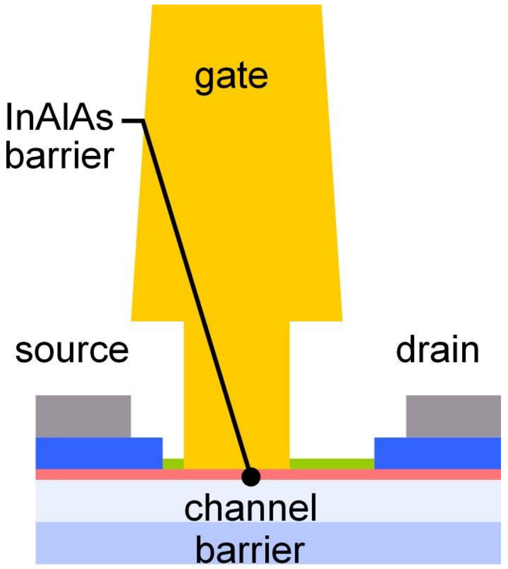
First Demonstration of Amplification at 1 THz Using 25-nm InP High Electron Mobility Transistor Process

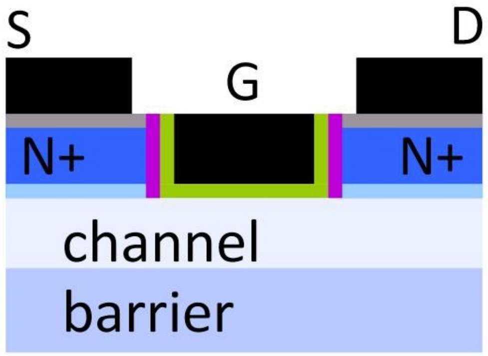
Xiaobing Mei, et al, IEEE EDL, April 2015 **(Northrop-Grumman)**





FET Scaling Laws (these now broken)

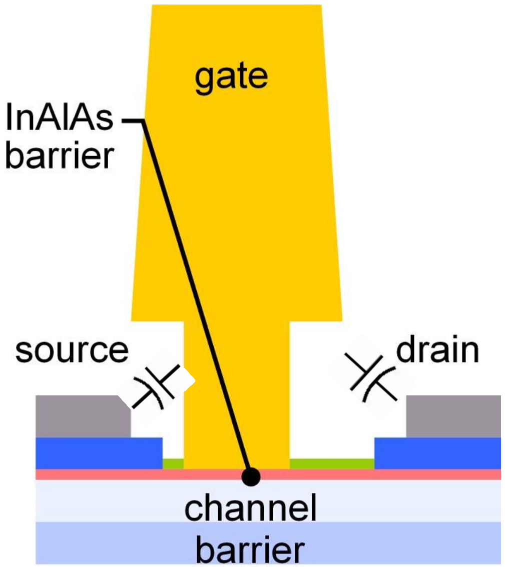


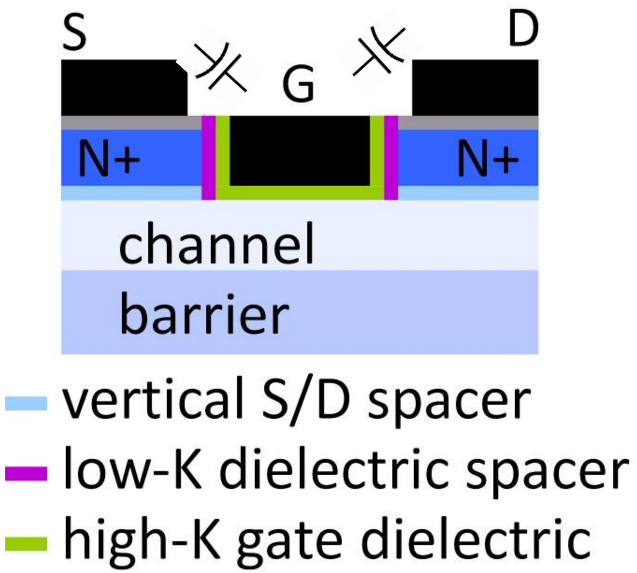


- vertical S/D spacer
- low-K dielectric spacer
- high-K gate dielectric

FET parameter	change
gate length	decrease 2:1
current density (mA/mm)	increase 2:1
specific transconductance (mS/mm)	increase 2:1
transport mass	constant
2DEG electron density	increase 2:1
gate-channel capacitance density	increase 2:1
dielectric equivalent thickness	decrease 2:1
channel thickness	decrease 2:1
channel state density	increase 2:1
contact resistivities	decrease 4:1

FET Scaling Laws (these now broken)





FET parameter	change
gate length	decrease 2:1
current density (mA/mm)	increase 2:1
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gate-channel capacitance density	increase 2:1
dielectric equivalent thickness	decrease 2:1
channel thickness	decrease 2:1
channel state density	increase 2:1
contact resistivities	decrease 4:1

Gate dielectric can't be much further scaled.
Not in CMOS VLSI, not in mm-wave HEMTs

g_m/W_g (mS/μm) hard to increase→ C_{end}/g_m prevents f_τ scaling.

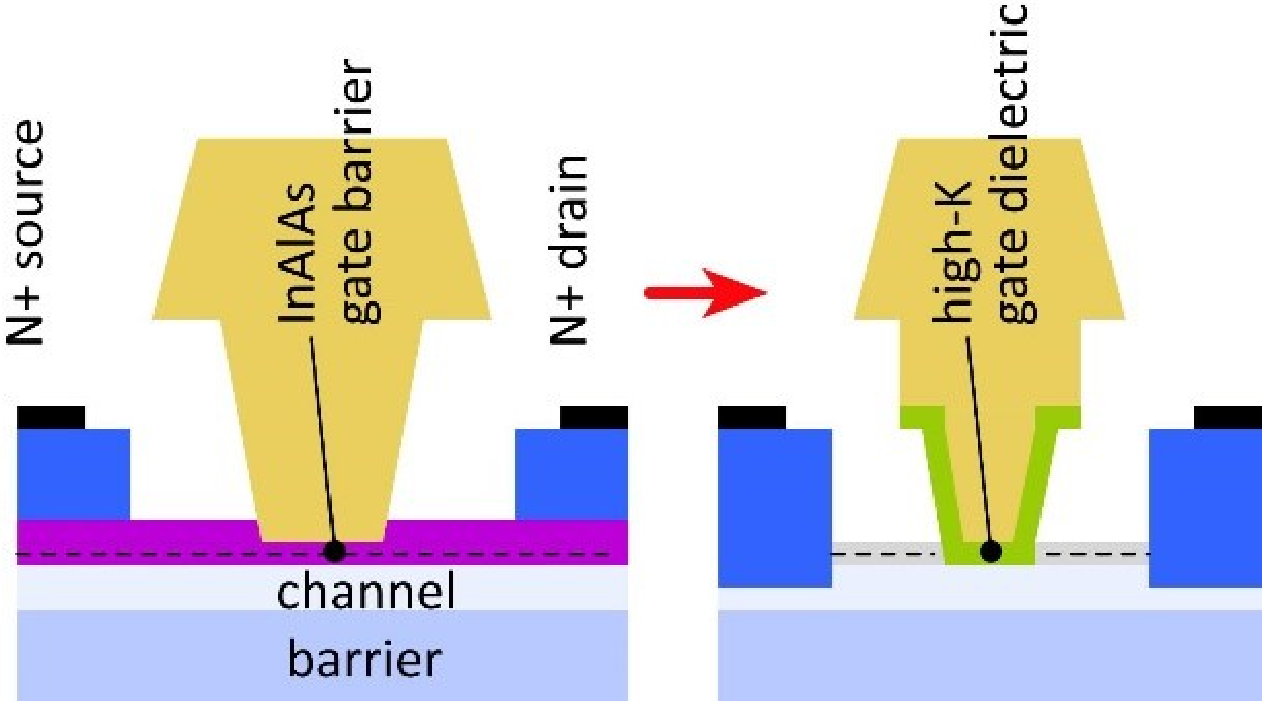
Shorter gate lengths degrade electrostatics→ reduced g_m/G_{ds} → reduced f_{max}, f_τ

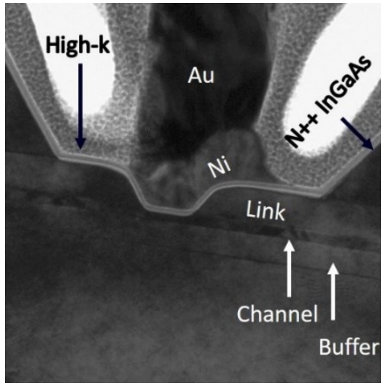
Towards faster HEMTs: MOS-HEMTs

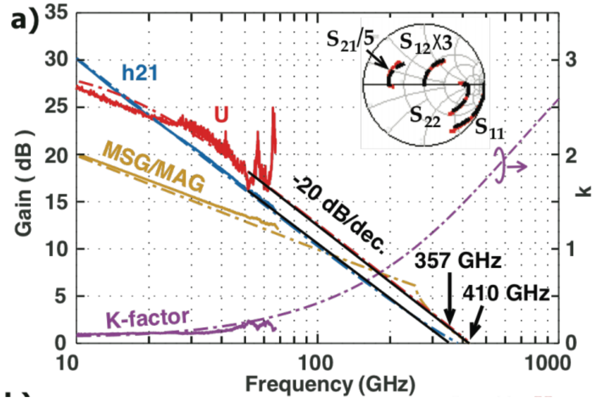
Scaling limit: gate insulator thickness
HEMT: InAlAs barrier: tunneling, thermionic leakage
solution: replace InAlAs with high-K dielectric
2nm ZrO_2 (ε_r=25): adequately low leakage

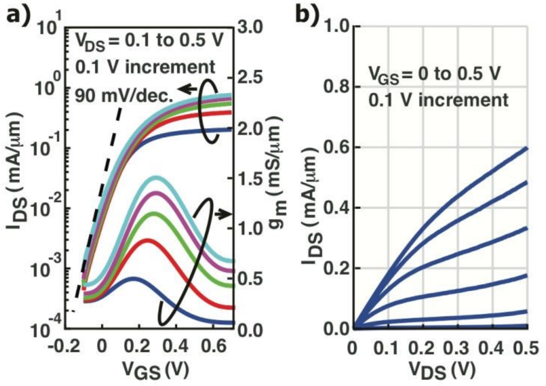
Scaling limit: source access resistance
HEMT: InAlAs barrier is under N+ source/drain
solution: regrowth, place N+ layer <u>on</u> InAs channel

Target ~10nm node
~0.3nm EOT, 3nm thick channel
1.2 to 1.5 THz f_τ.



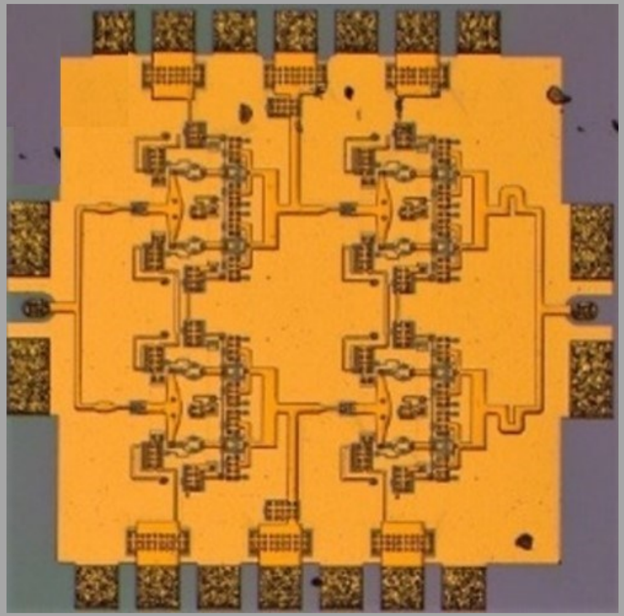


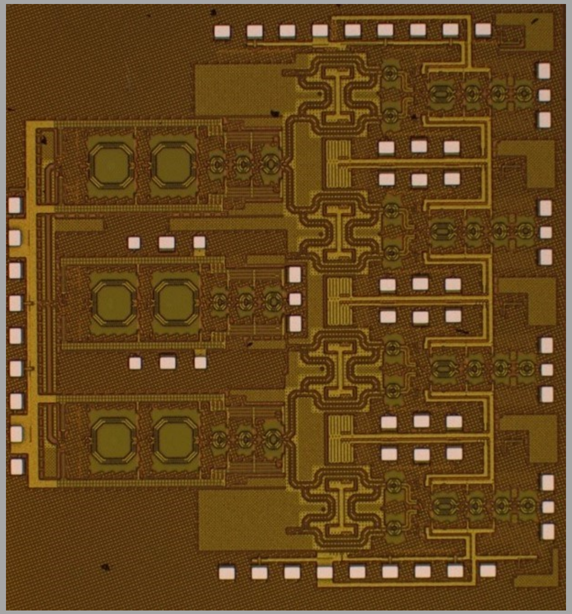


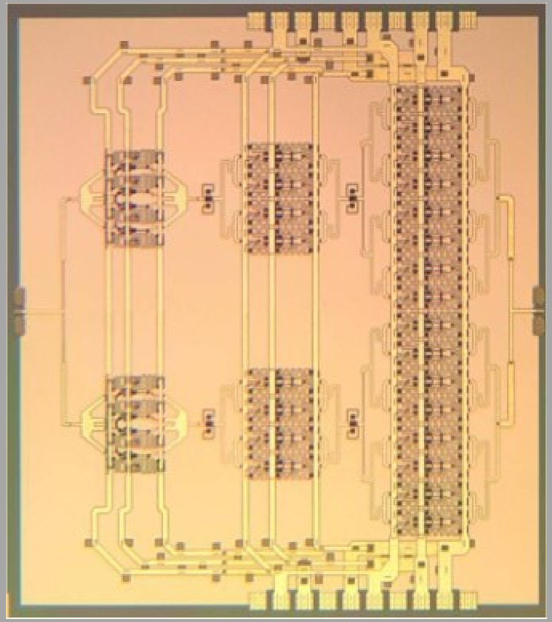


Jun Wu, UCSB, IEEE EDL, 2018

ICs







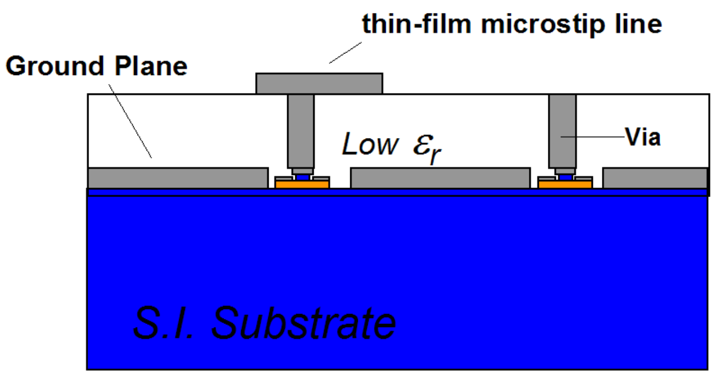
mm-Wave IC design: the challenges

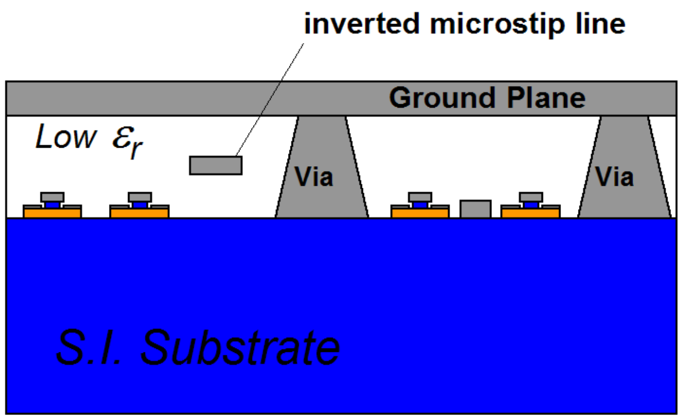
Transistor gains are low: f_{signal} is significant fraction of f_{max}.
match for optimum gain, noise, or power.

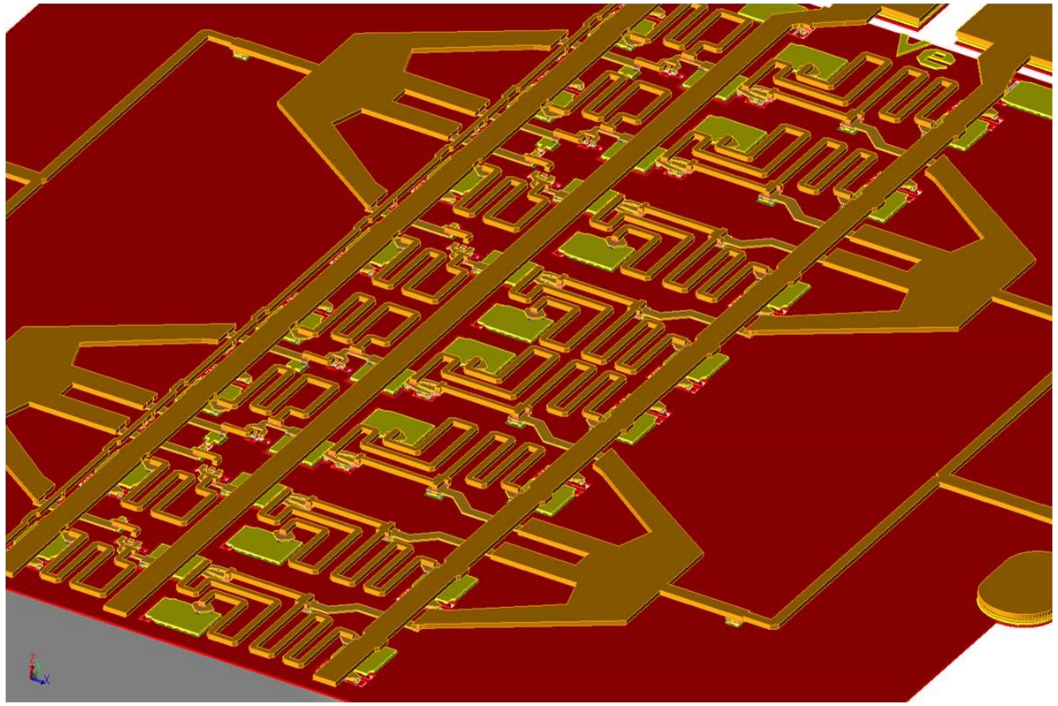
Device dimensions are a significant fraction of a wavelength
Even short lengths of wiring add serious parasitics

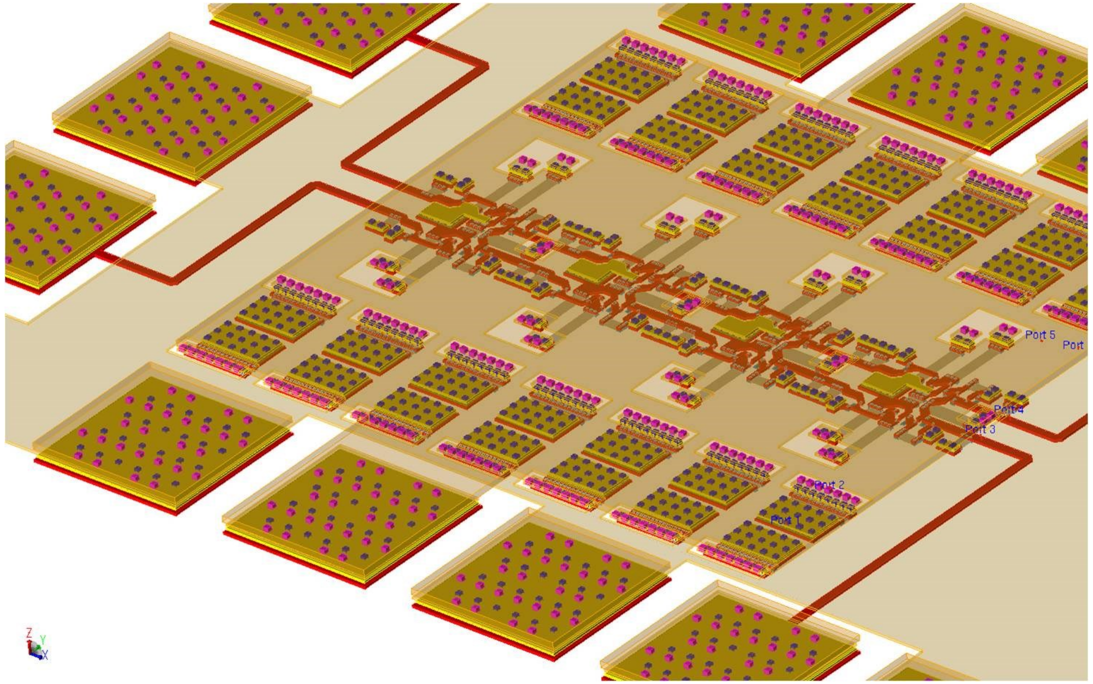
Transmission-line losses are high
low Q in VCO resonators and filters
high combining losses in PAs: low power, low efficiency
several dB added noise in LNAs.

Thin-film microstrip: inverted or right-side-up









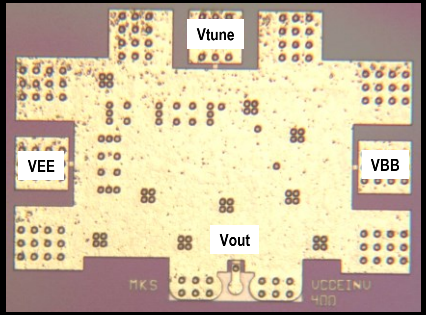
130nm /1.1 THz InP HBT ICs to 670 GHz

TELEDYNE SCIENTIFIC COMPANY
A Teledyne Technologies Company

UCSB

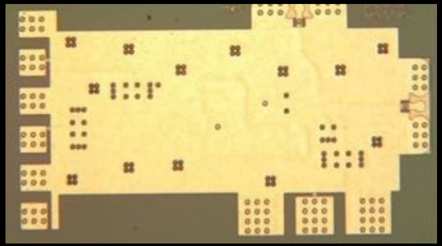
614 GHz fundamental VCO

M. Seo, TSC / UCSB



340 GHz dynamic frequency divider

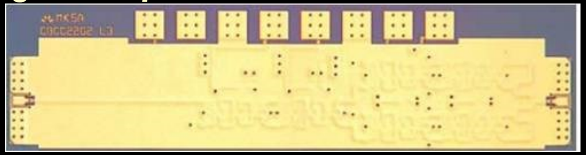
M. Seo, UCSB/TSC
IMS 2010



620 GHz, 20 dB gain amplifier

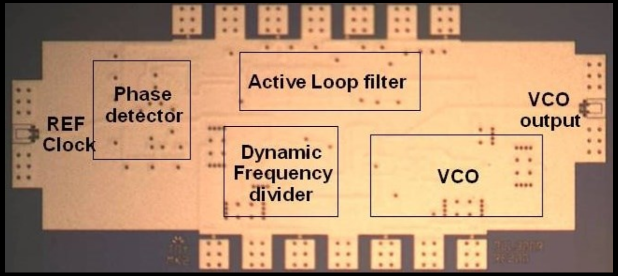
M Seo, TSC
IMS 2013

also: 670GHz amplifier
J. Hacker , TSC
IMS 2013 (not shown)



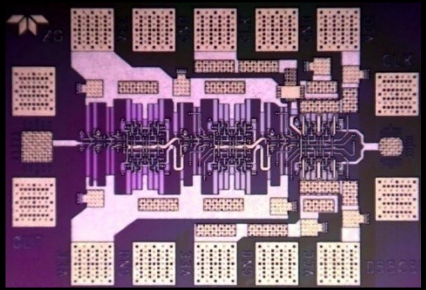
300 GHz fundamental PLL

M. Seo, TSC
IMS 2011



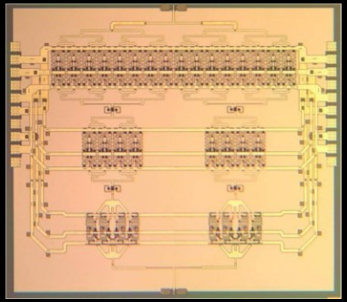
204 GHz static frequency divider (ECL master-slave latch)

Z. Griffith, TSC / UCSB
CSIC 2010



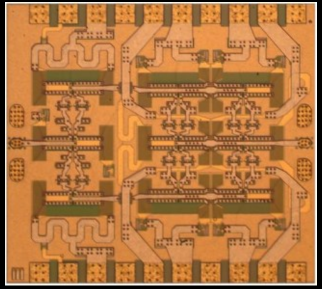
220 GHz 180 mW power amplifier

T. Reed, UCSB
CSICS 2013



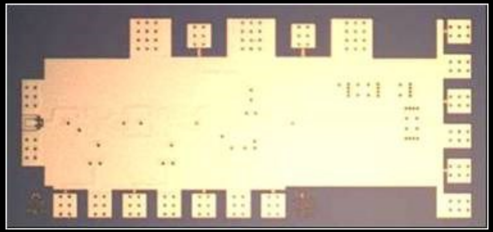
81 GHz 470 mW power amplifier

H-C Park UCSB
IMS 2014



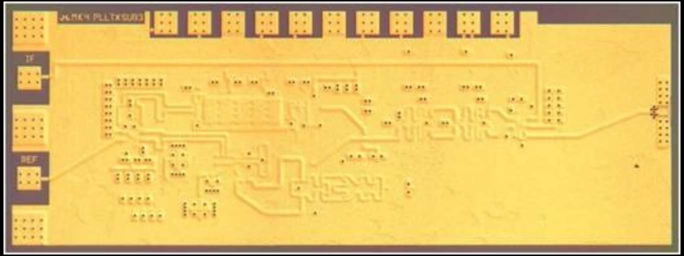
Integrated 300/350GHz Receivers:

LNA/Mixer/VCO
M. Seo TSC

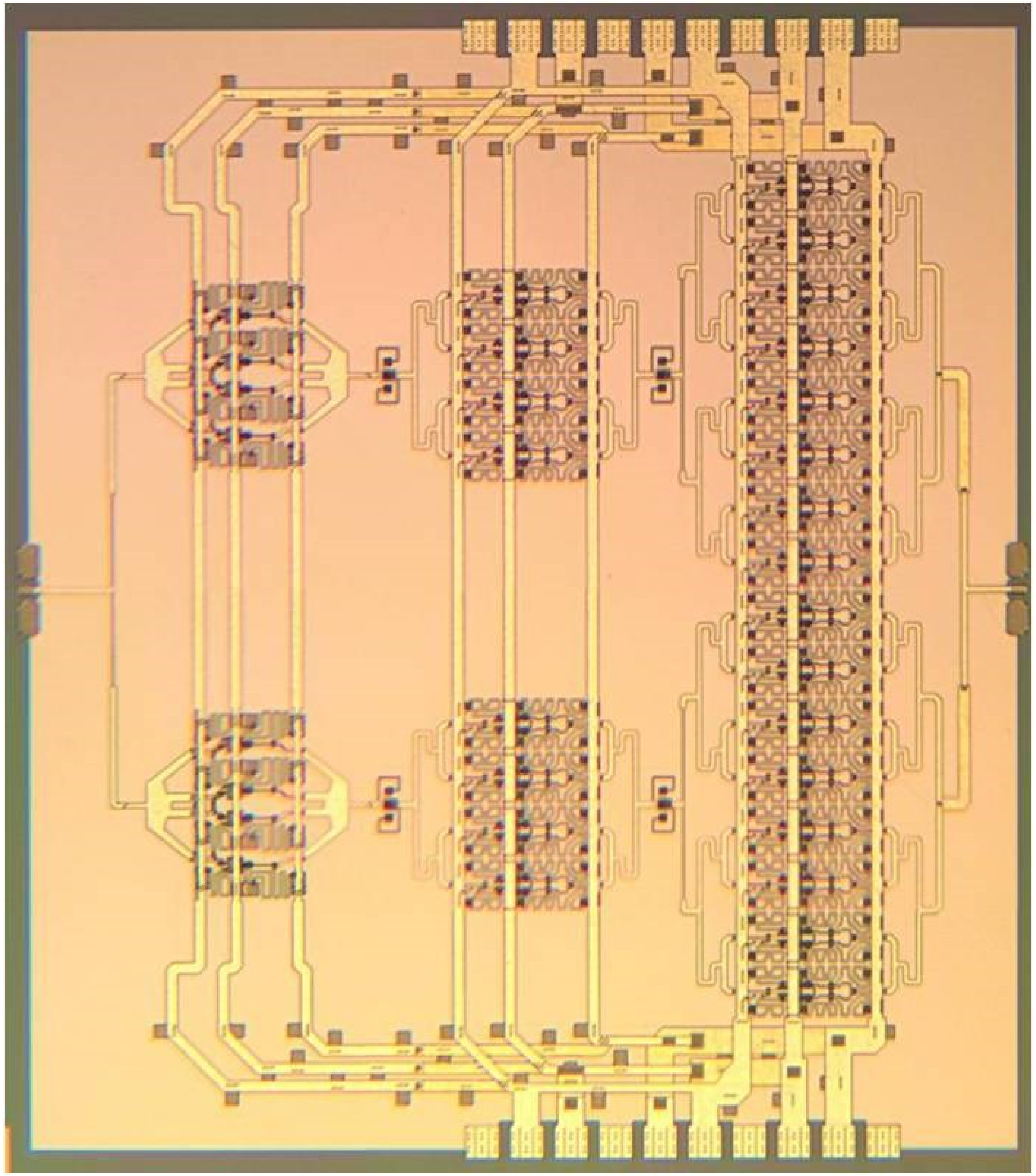


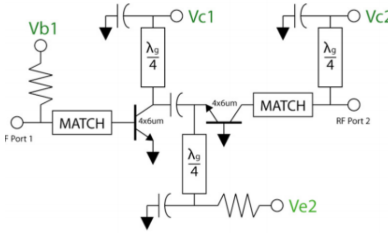
600 GHz Integrated Transmitter

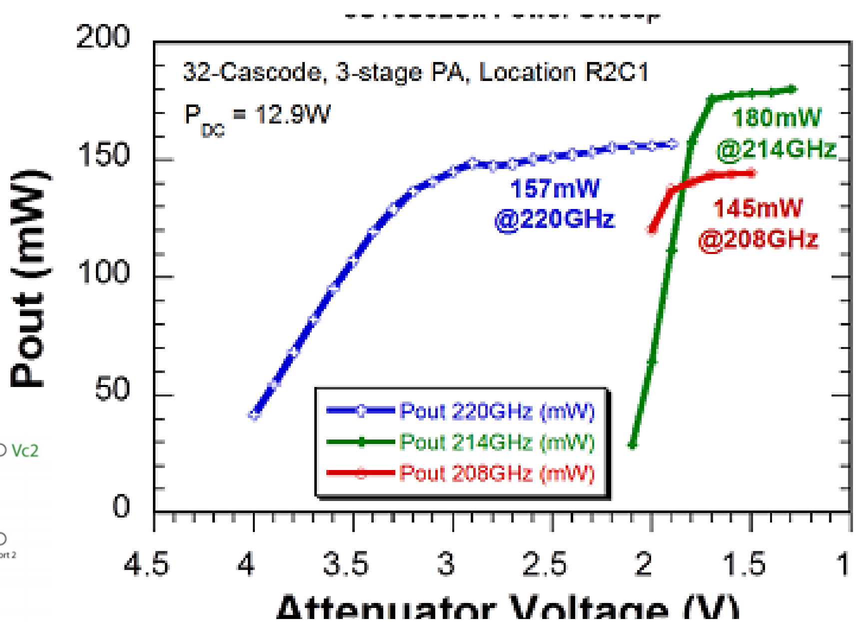
PLL + Mixer
M. Seo TSC

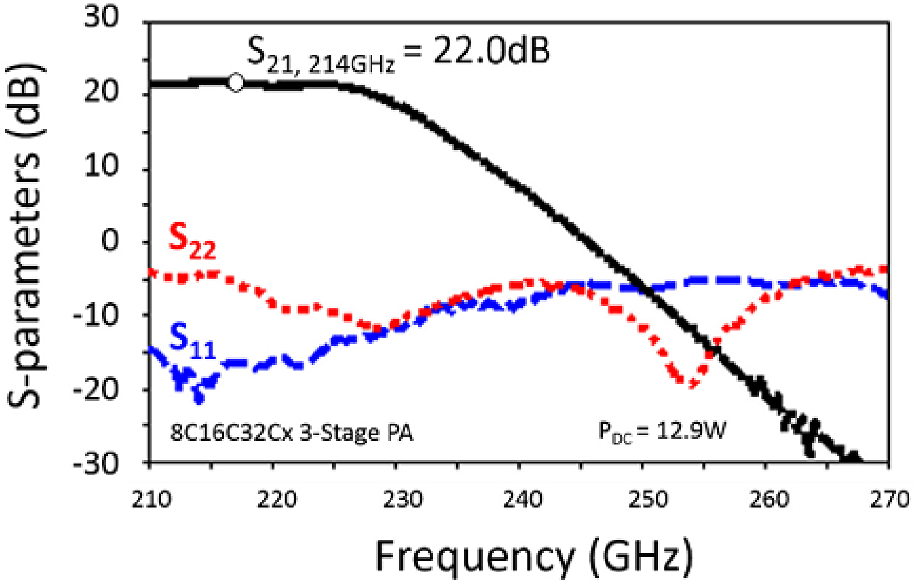


214 GHz, 180mW Power Amplifier (330 mW design)





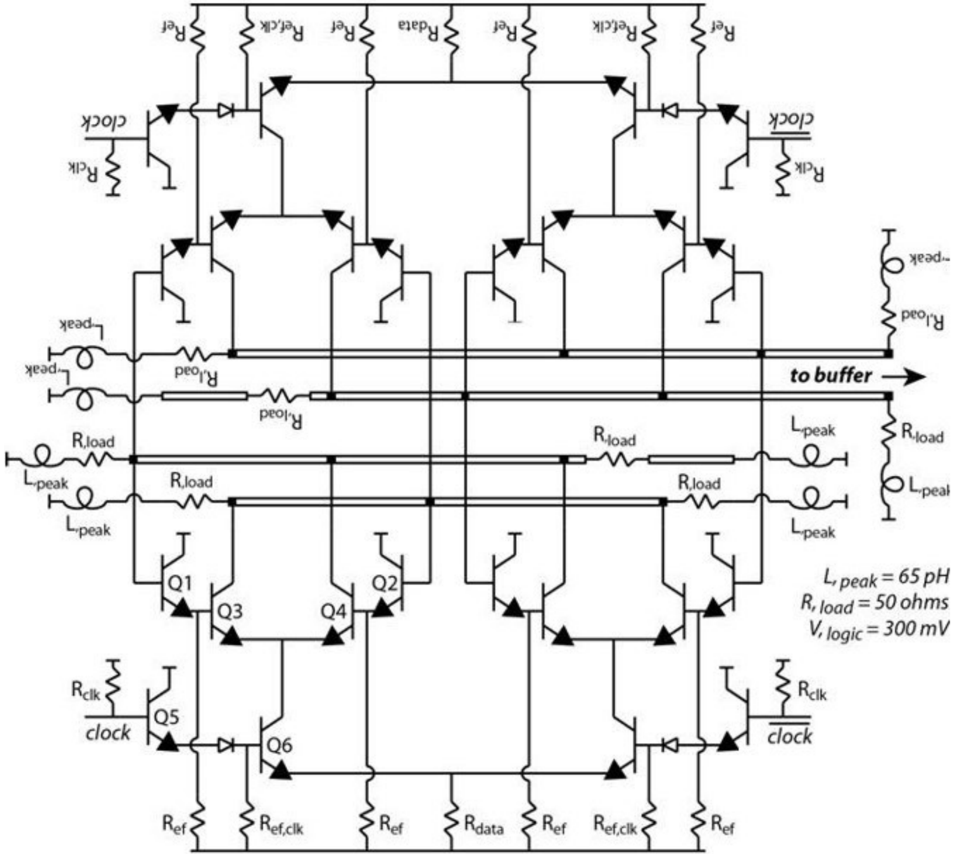


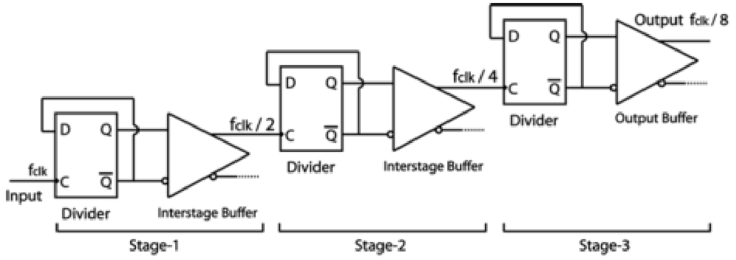


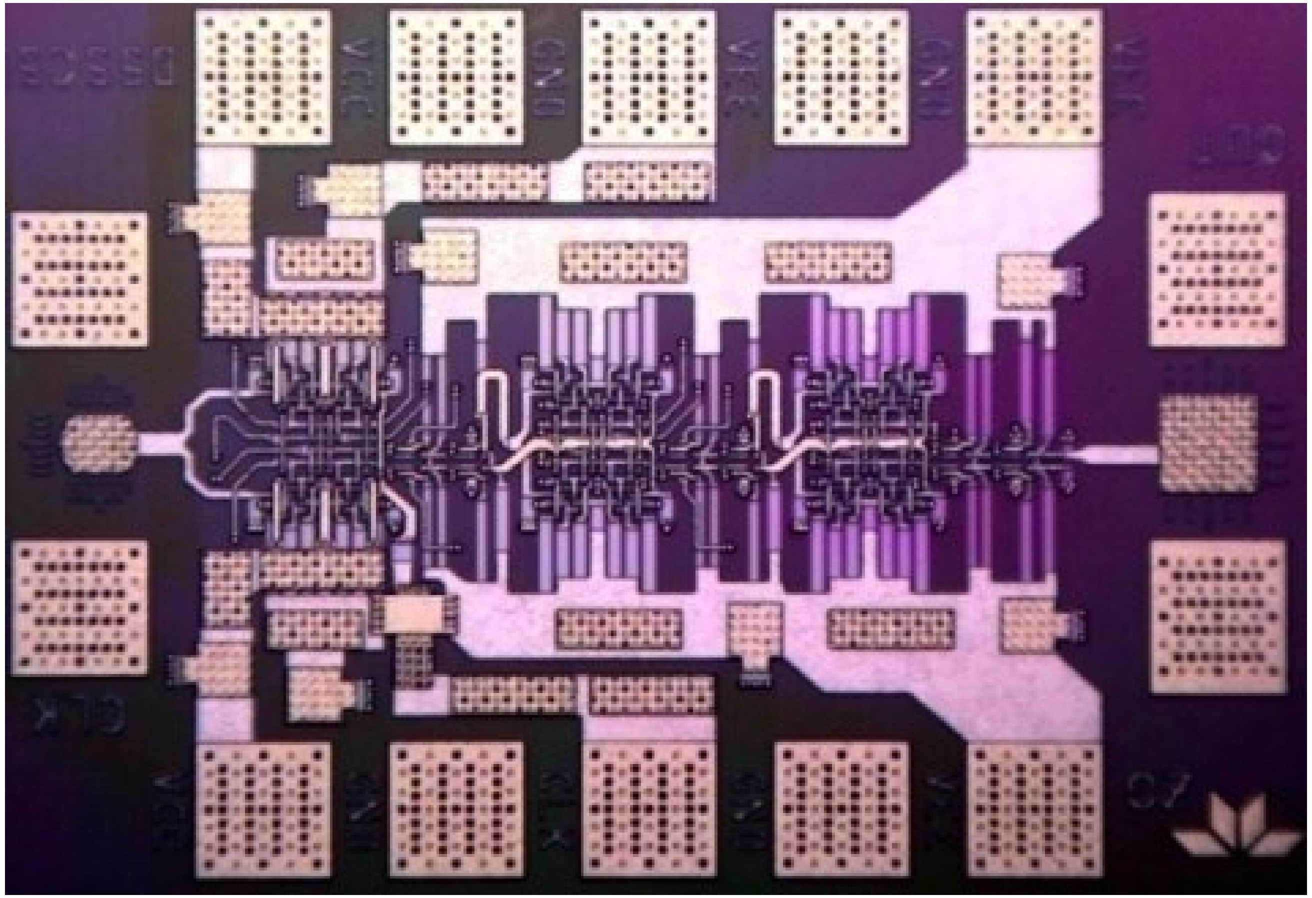
2.3 mm x 2.5 mm

T. Reed, Z. Griffith, 2014 CSICS http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=6659187&tag=1

205GHz Logic in Thin-Film Inverted Microstrip



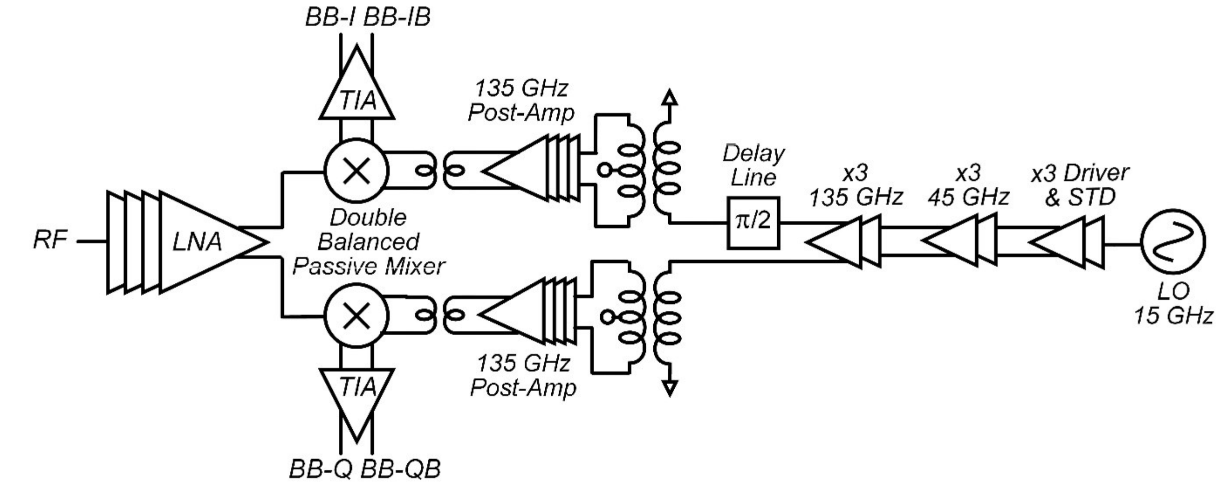


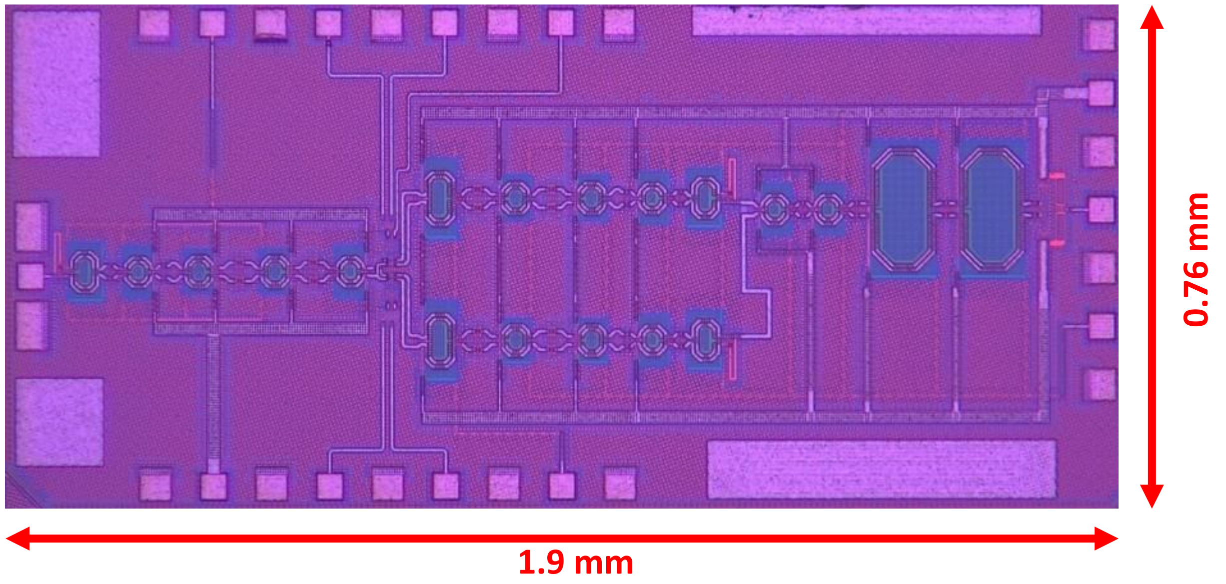


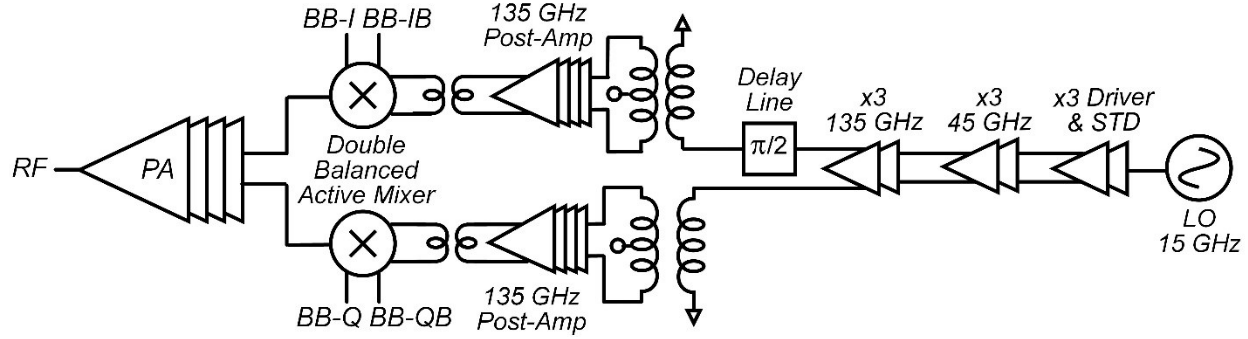
205 GHz divider, Griffith et al, IEEE CSICS, Oct. 2010

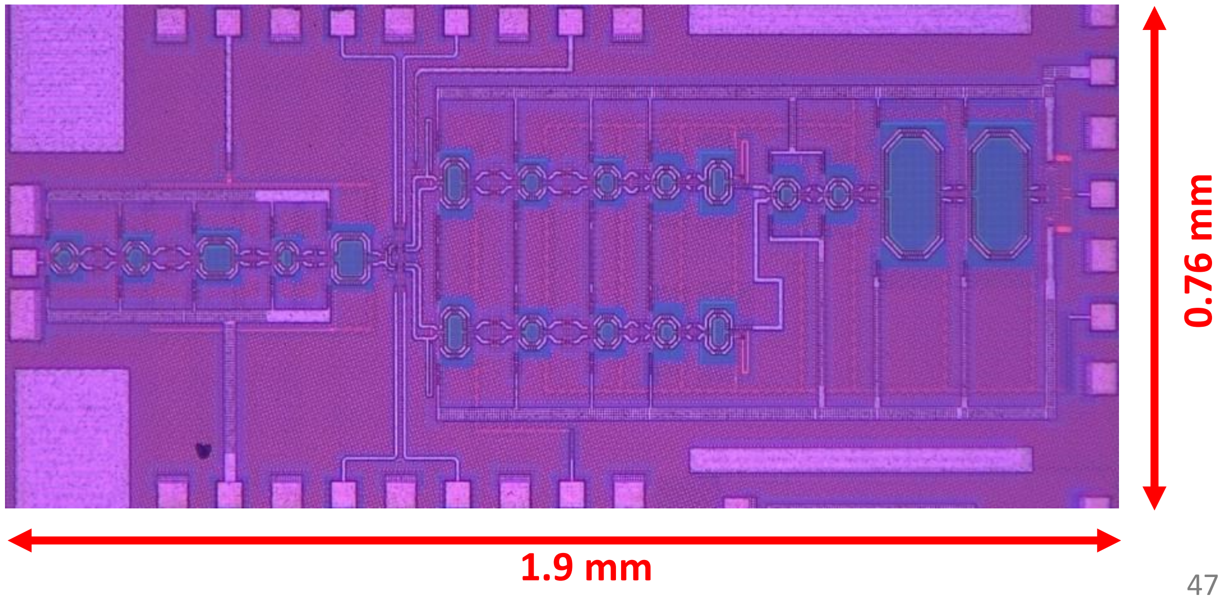
8:1, 205 GHz static divider in 256 nm InP HBT. Image taken before top metal (ground plane) deposition

140GHz Transceivers: GF 22nm SOI CMOS



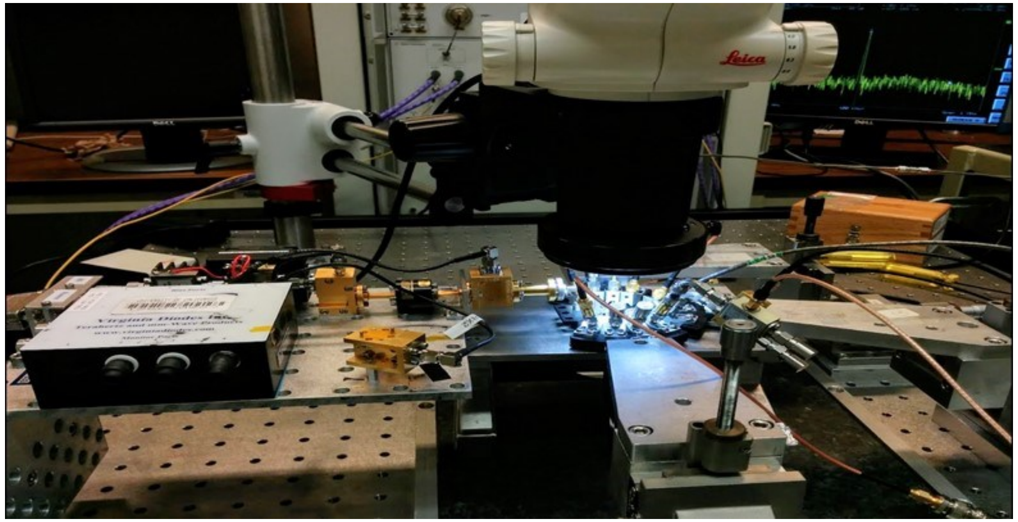


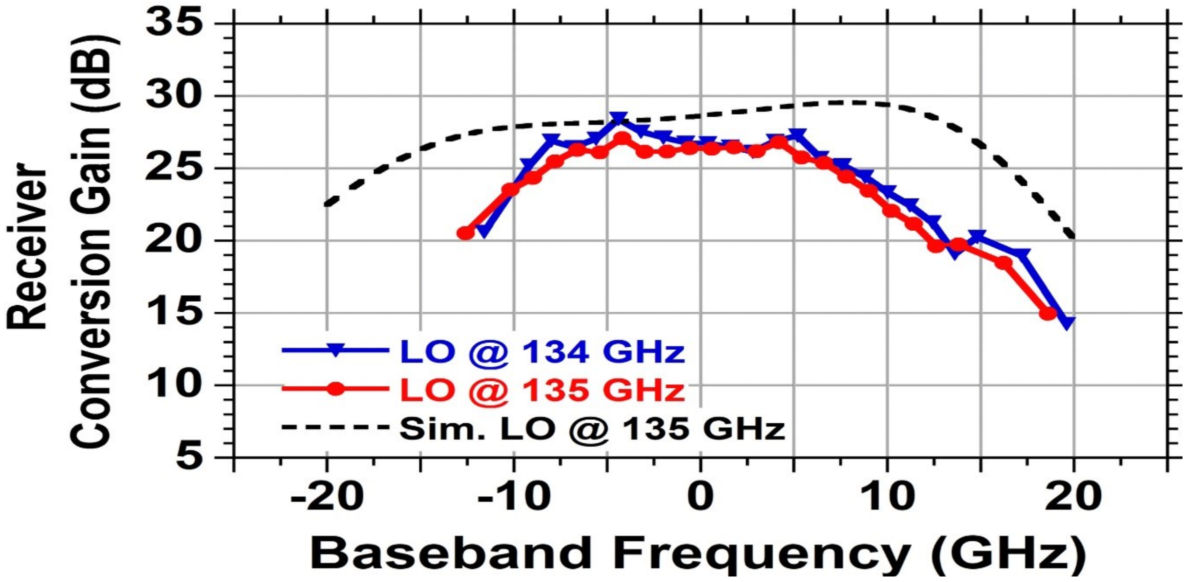


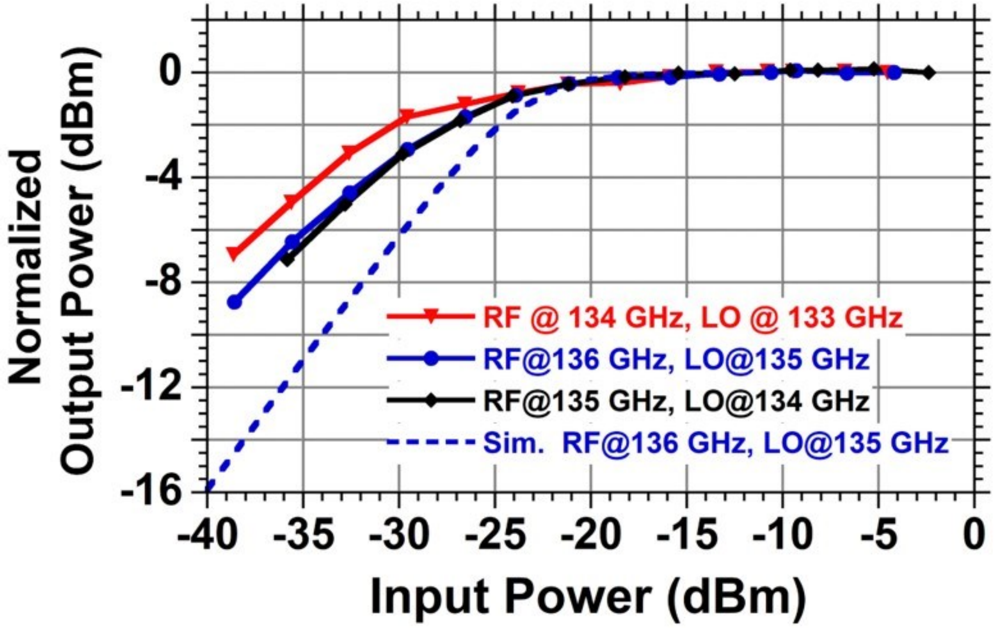


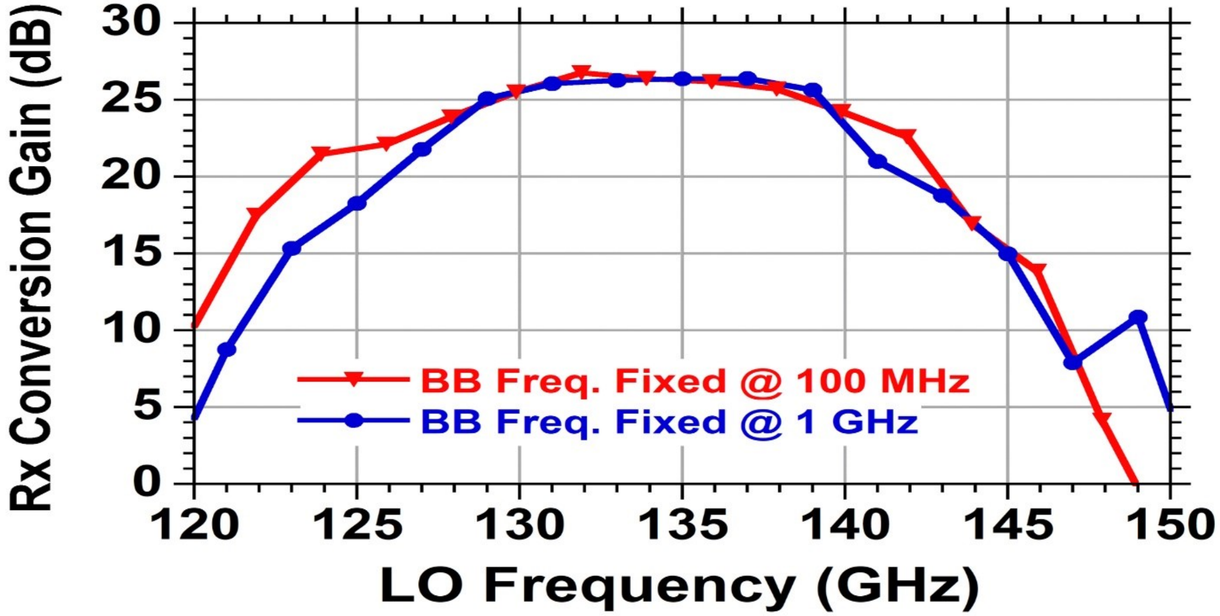
A. Farid UCSB, 2019 RFIC symposium

RX Characterization

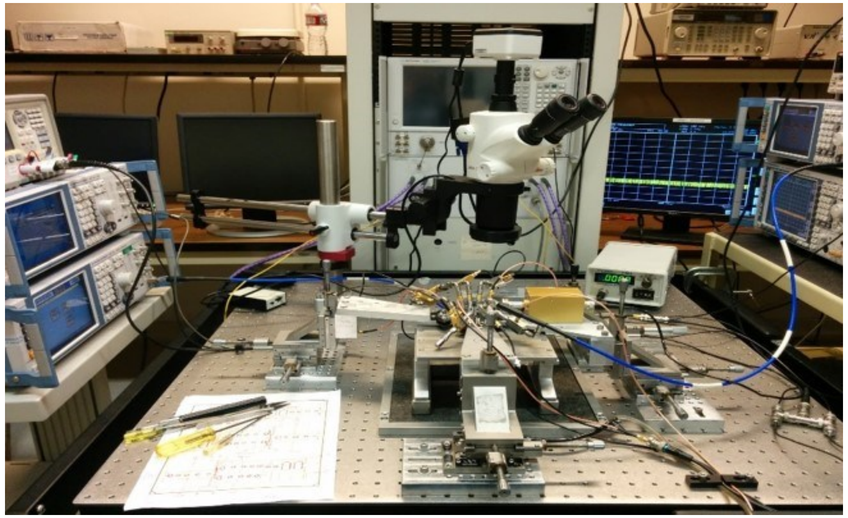


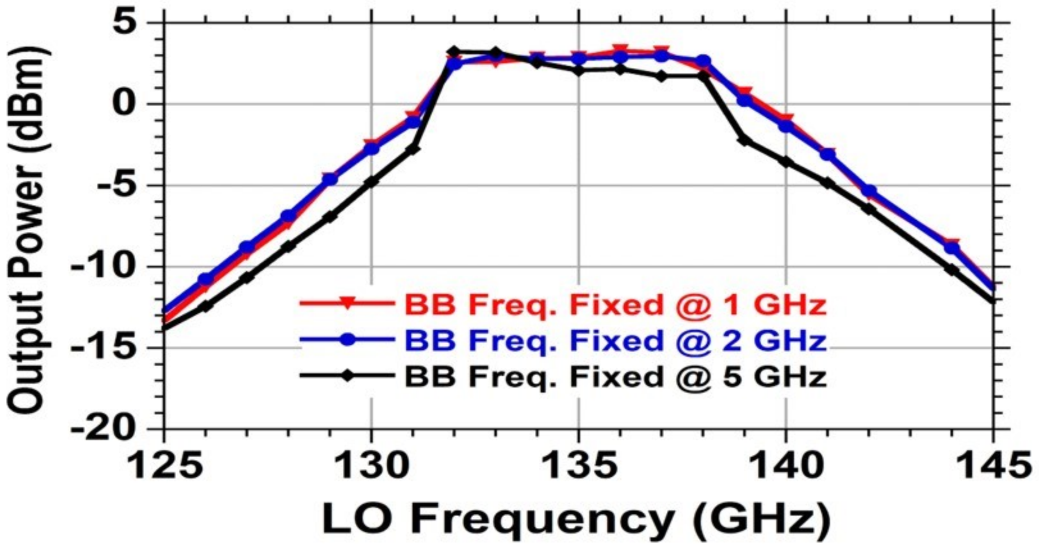


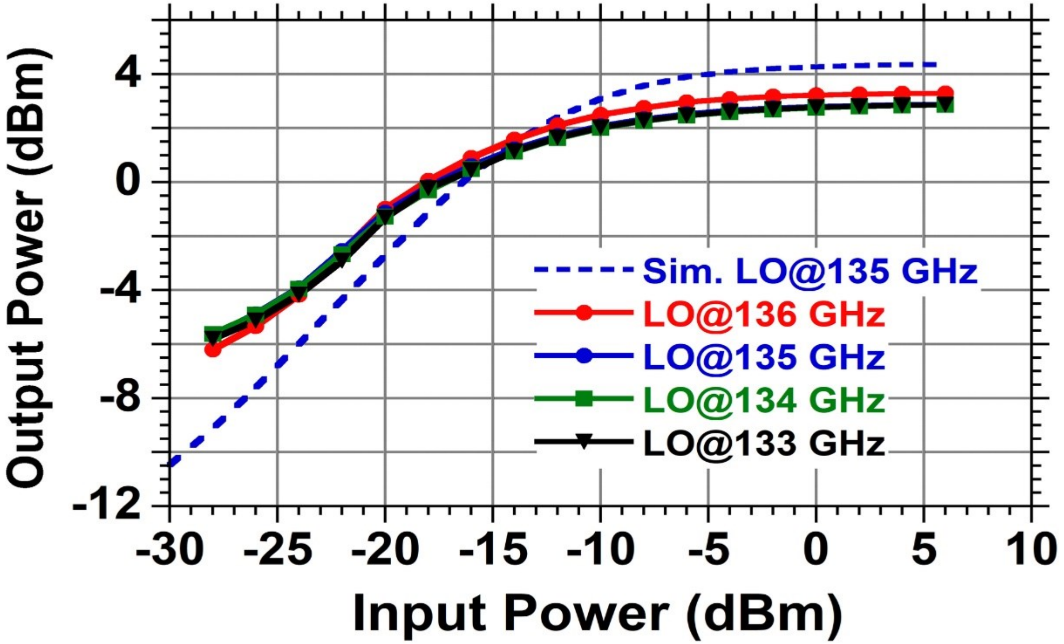


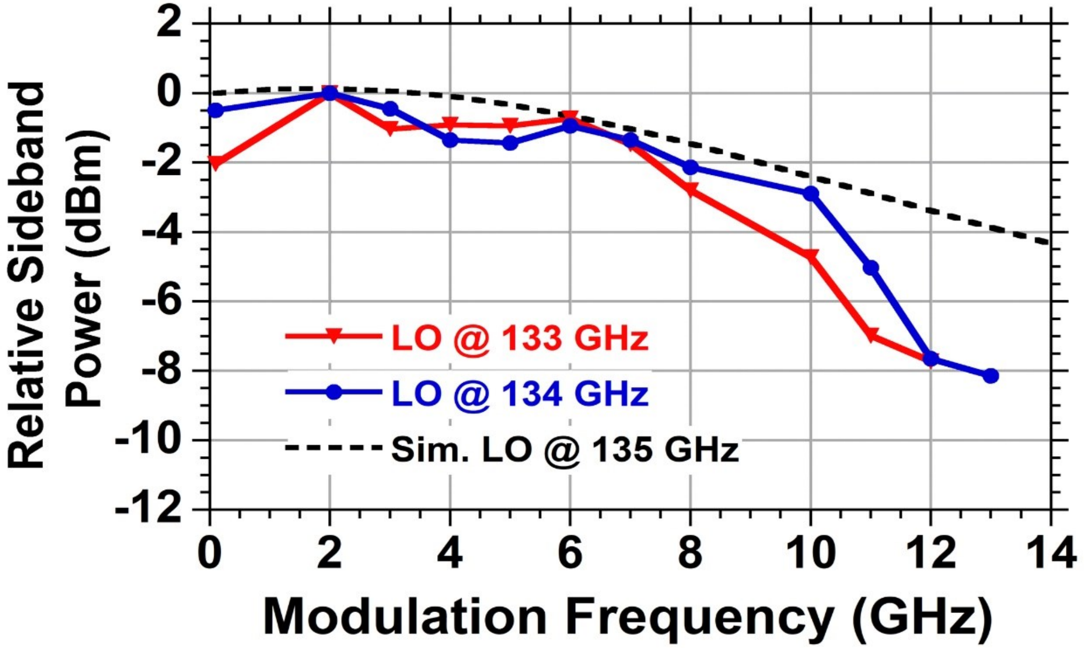


TX Characterization







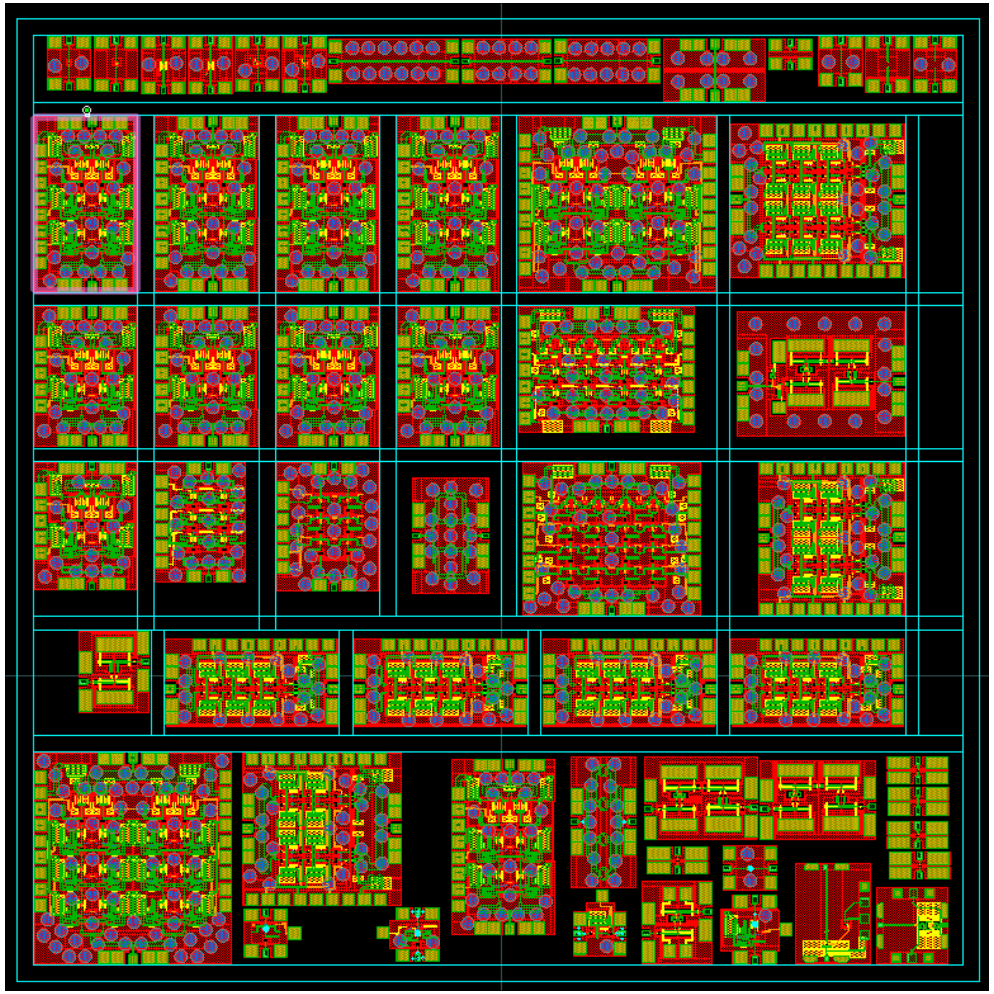


InP Power Amplifier Design

Class-A mm-Wave Power Amplifiers
120, 140, 220, 300GHz designs
Power: 50-100-200mW
140GHz efficiencies: 17%

Class-B mm-Wave Power Amplifiers
120GHz designs
Power: 30 mW
140GHz efficiencies: 28%

ICs taped out Feb. 2019
Presently in fabrication
Expected test: late summer

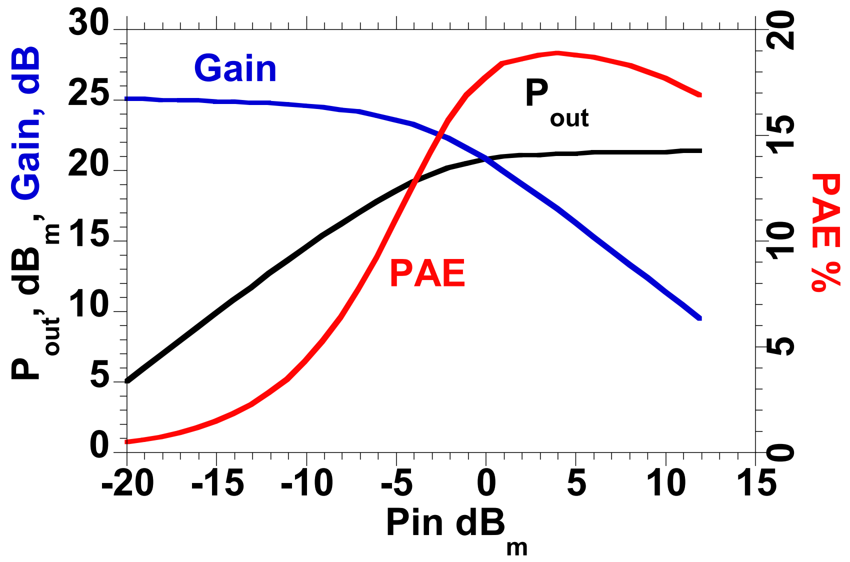


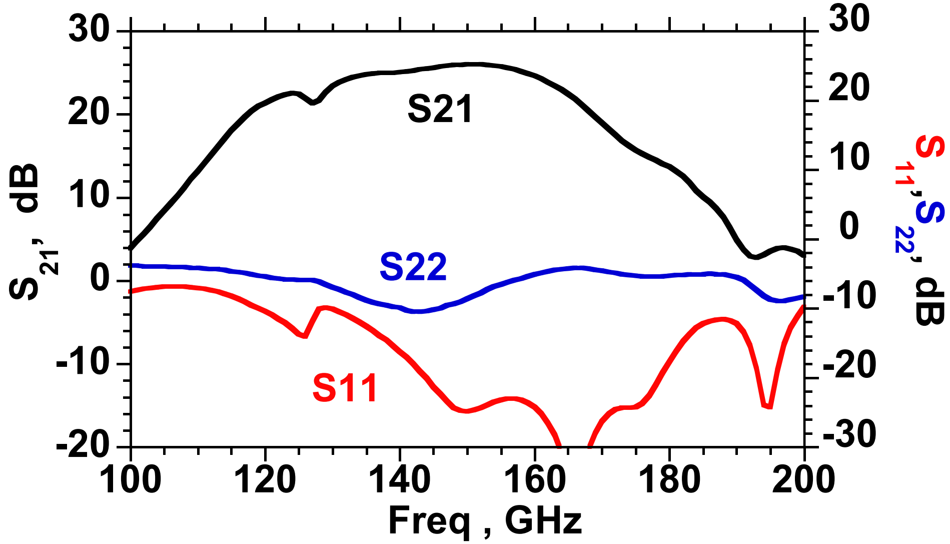
#	Description	Area(mm×mm)
1	140GHz,P_{out}=19.3dB_m, PAE=13%, Gain=23.2dB	0.63×1.08
2	140GHz, P_{out}=21.8dB_m, PAE=13.5%, Gain=23.4dB	1.2 ×1.09
3	140GHz,P_{out}=19.8dB_m, PAE=6.6%, Gain=24.8dB	0.95×1.07
4	140GHz,P_{out}=19.5dB_m, PAE=17.9%, Gain=14.5dB	0.63× 0.86
5	220GHz,P_{out}=20.2dB_m, PAE=7.8%, Gain=19.7dB	1.09×0.78
6	140GHz,P_{out}=19.3dB_m, PAE=17.1%, Gain=14.4dB	0.6×0.79
7	220GHz,P_{out}=15.9dB_m, PAE=10.2%, Gain=17.9dB	0.56×0.79
8	300GHz,P_{out}=13.5dB_m, PAE=4.2%, Gain=13.5dB	0.63×0.8
9	300GHz,P_{out}=17.8dB_m, PAE=3.5%, Gain=15.8dB	1.1×0.94
10	140GHz,P_{out}=19.7dB_m, PAE=8.1%, Gain=17.7dB	0.95×0.9
11	140GHz,P_{out}=21.7dB_m, PAE=10.4%, Gain=30.7dB	1.2×1.3
12	120GHz, P_{out}=20.4dB_m, PAE=9.2%, Gain=20.4dB	0.95×0.98
13	140GHz, P_{out}=17.3dB_m, PAE=7.5%, Gain=25.3dB	1.07×0.54
14	140GHz, P_{out}=15dB_m, PAE=28%, Gain=16dB	

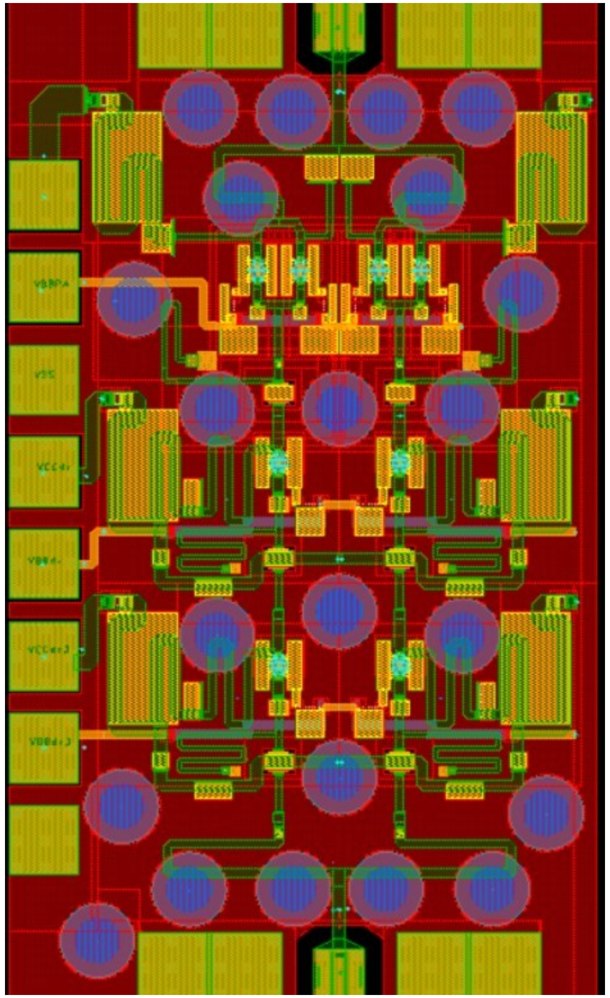
James Buckwalter, Mark Rodwell: UCSB

140GHz PA: power and S-parameter simulations

Technology	250-nm InP HBT
Freq, GHz	140
VCC, V	2.5
J_{bias},mA/um	1.3
S21, dB	25
P_{out} ,dB_m, 2dB	19.1
PAE % , 2dB	12.6
P_{sat} ,dB_m	20.9
PAE_{sat} %	18.3
BW_{3dB}, GHz	43
P_{DC}, W	0.65







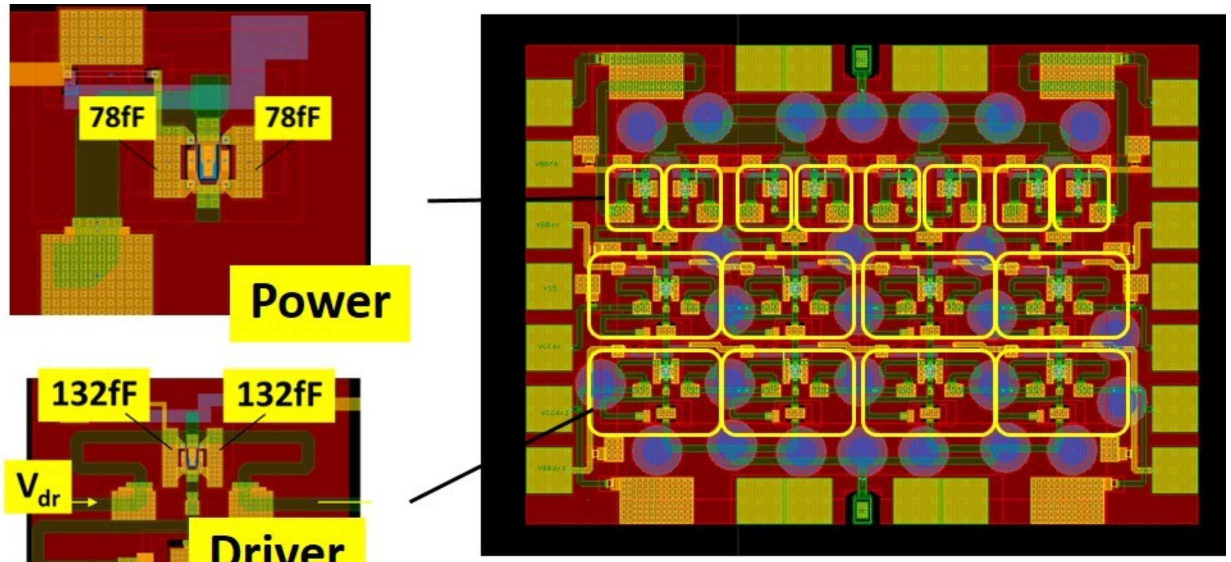
JUMP 220GHz PA (CB version)

Power cell:

- Smaller base capacitor,
- SRF=679GHz
- Decrease the shunt inductor

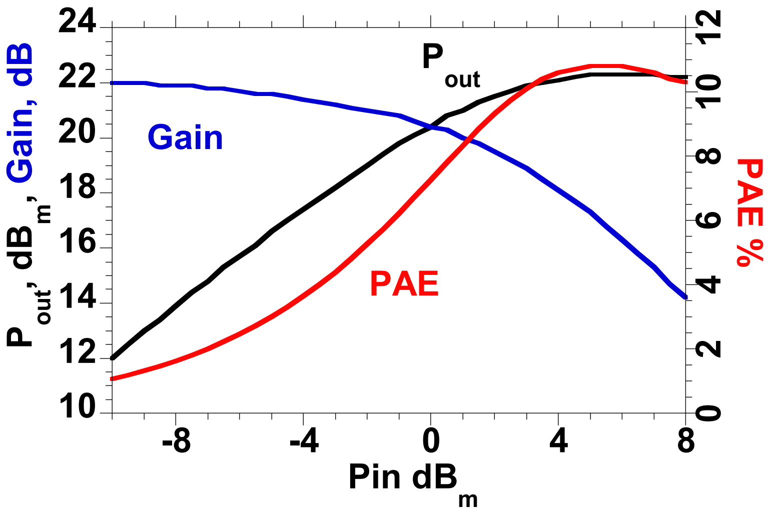
Two stage drivers:

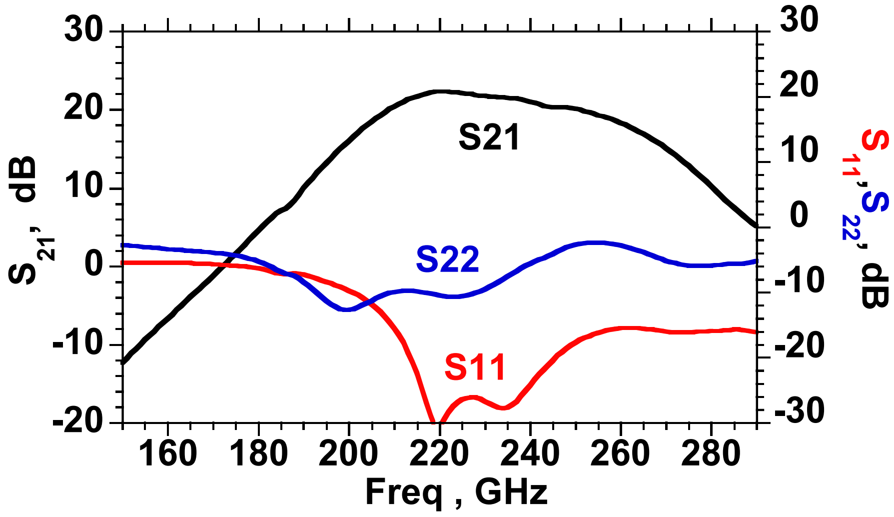
- Similar to power cell with higher cap
- SRF=512GHz



Area=1.09 mm × 0.78mm

Technology	250-nm InP HBT
Freq, GHz	220
VCC, V	2.8
J_{bias},mA/um	1.3
S21, dB	22.3
P_{out} ,dB_m, 2dB	21
PAE % , 2dB	8.3
P_{sat} ,dB_m	22
PAE_{sat} %	10.4
BW_{3dB}, GHz	48
P_{DC}, W	1.5





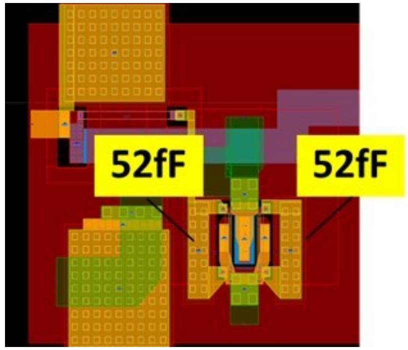
300GHz PA (CB version)

power cell and driver:

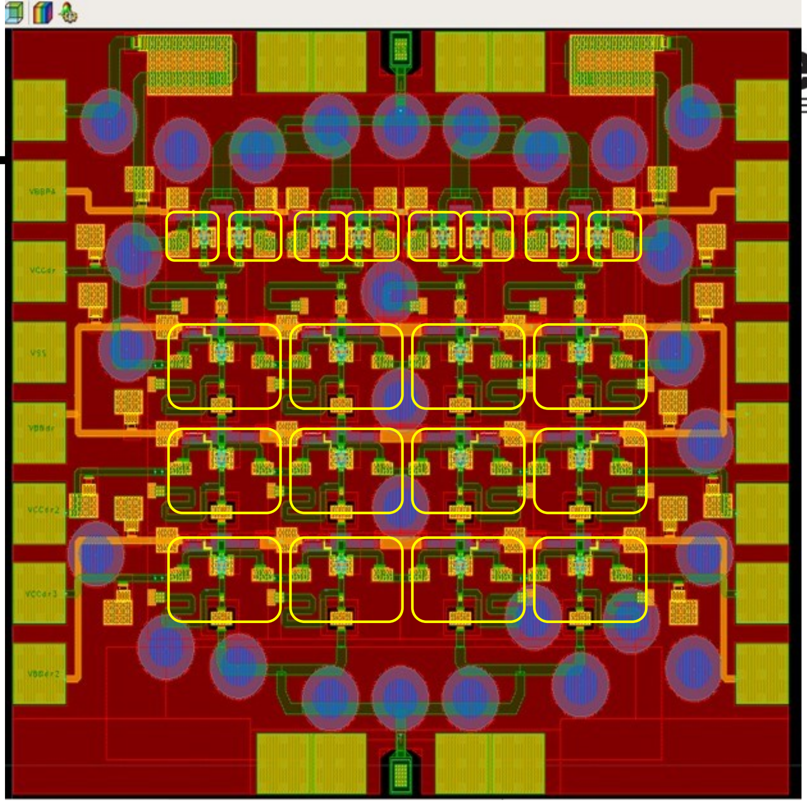
Decrease base cap and inductor

SRF=714GHz

Three driver stages

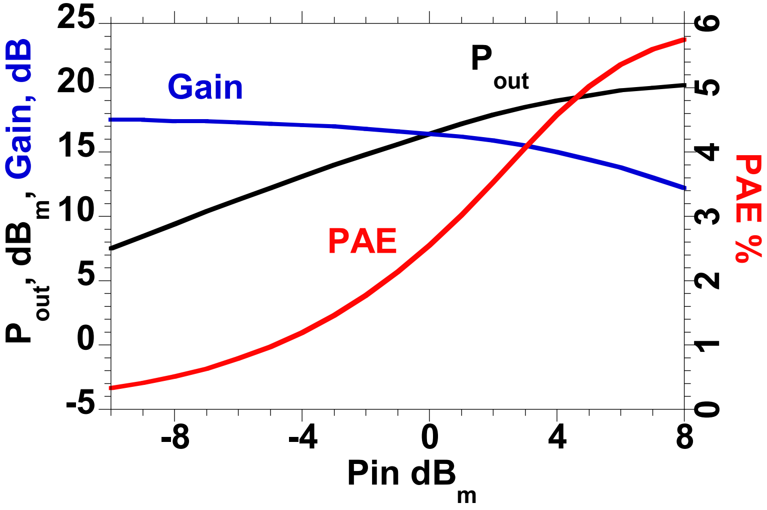


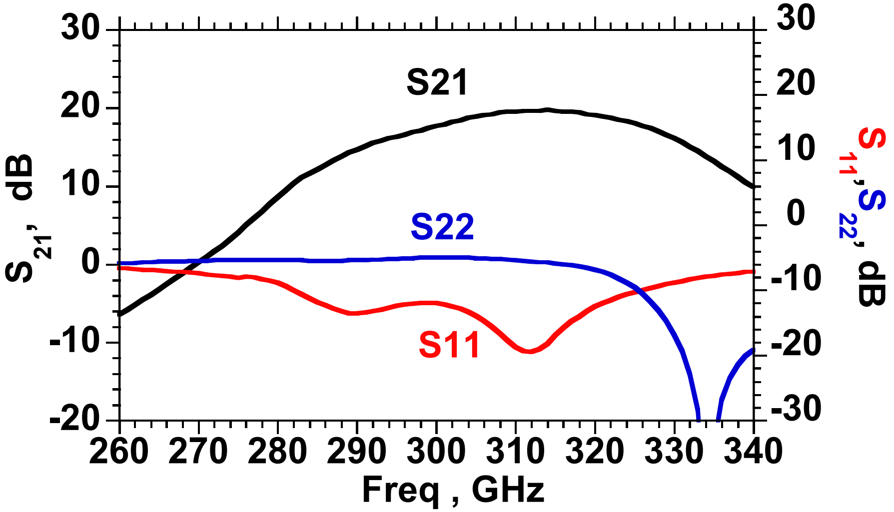
Four fingers, LE =6um.



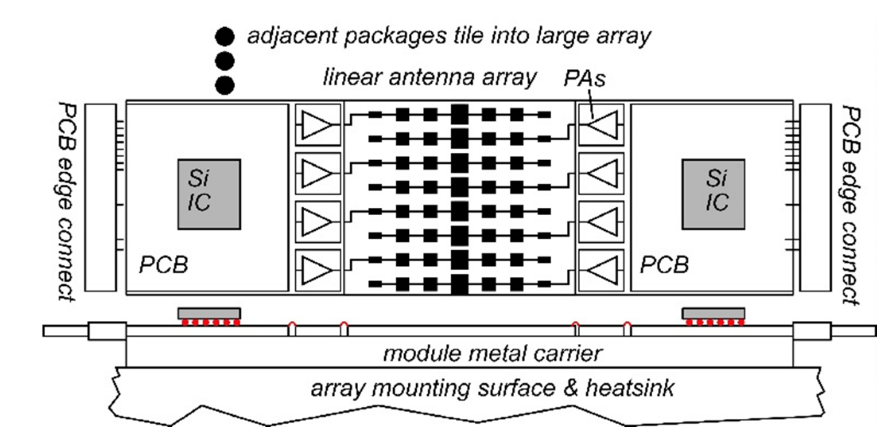
Area=1.1 mm × 0.94mm

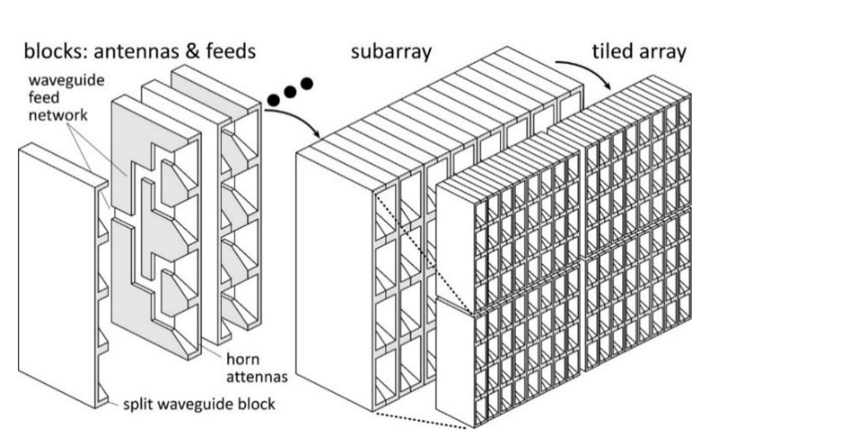
Technology	250-nm InP HBT
Freq, GHz	300
VCC, V	2.5
J_{bias},mA/um	1.3
S21, dB	17.6
P_{out} ,dB_m, 2dB	17.8
PAE % , 2dB	3.5
P_{sat} ,dB_m	19.4
PAE_{sat} %	5
BW_{3dB}, GHz	43
P_{DC}, W	1.65





Packages


adjacent packages tile into large array
linear antenna array
PAs
PCB edge connect
Si
IC
PCB
Si
IC
PCB
PCB edge connect
module metal carrier
array mounting surface & heatsink


blocks: antennas & feeds
waveguide
feed
network
subarray
tiled array
horn
attennas
split waveguide block

The mm-wave module design problem

How to make the IC electronics fit ?

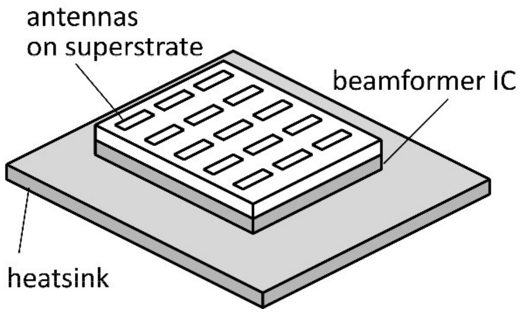
100+ GHz arrays: $\lambda_0/2$ element spacing is very small.
Antennas on or above IC → IC channel spacing = antenna spacing
→ ***limited IC area to place circuits***

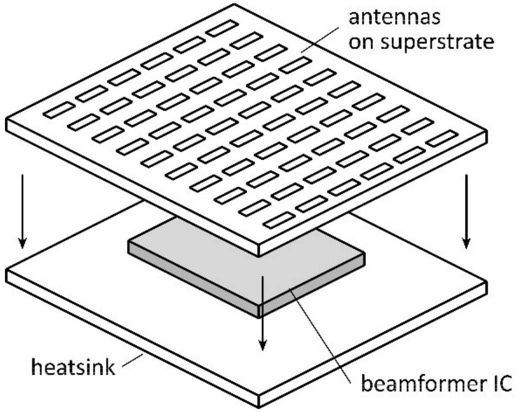
How to avoid catastrophic signal distribution losses ?

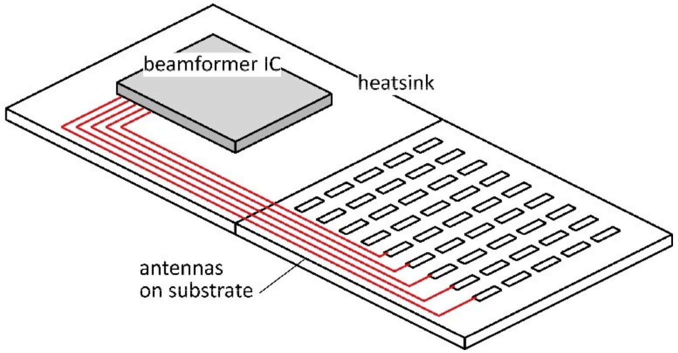
long-range, high-gain arrays: array size can be large.
ICs beside array → very long wires between beam former and antenna
→ ***potential for very high signal distribution losses***

How to remove the heat ?

100+ GHz arrays: element spacing is very small.
If antenna spacing = IC channel spacing, then power density is very large



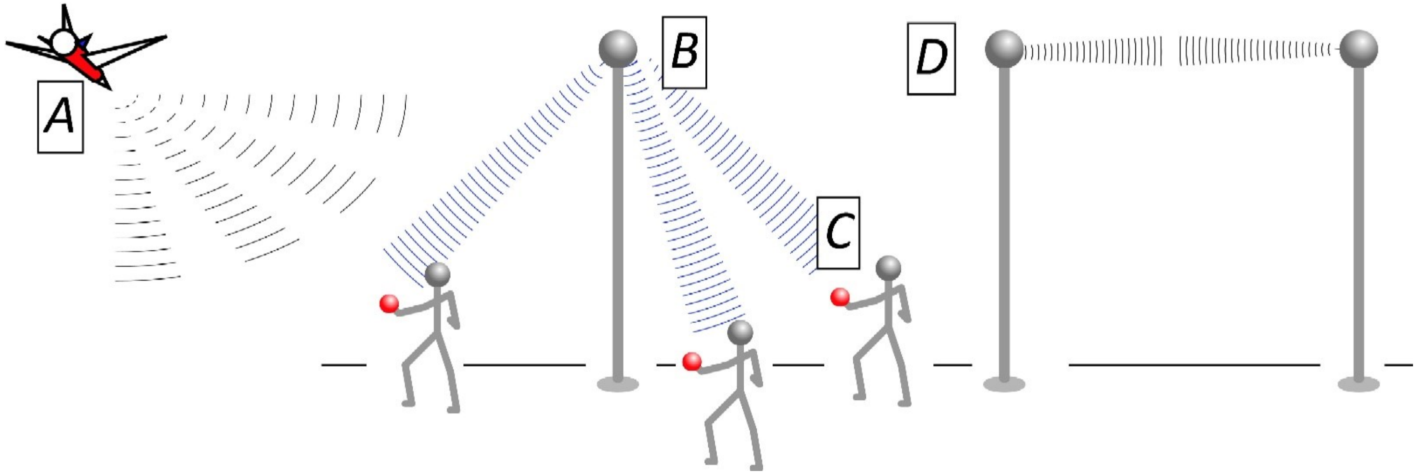




mm-wave/sub-mm-wave packaging

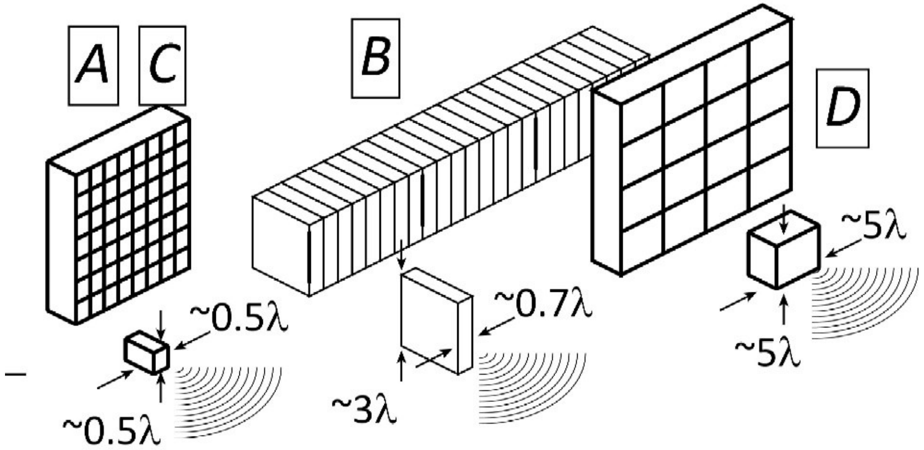
Not all systems steer in two planes...
...some steer in only one.

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

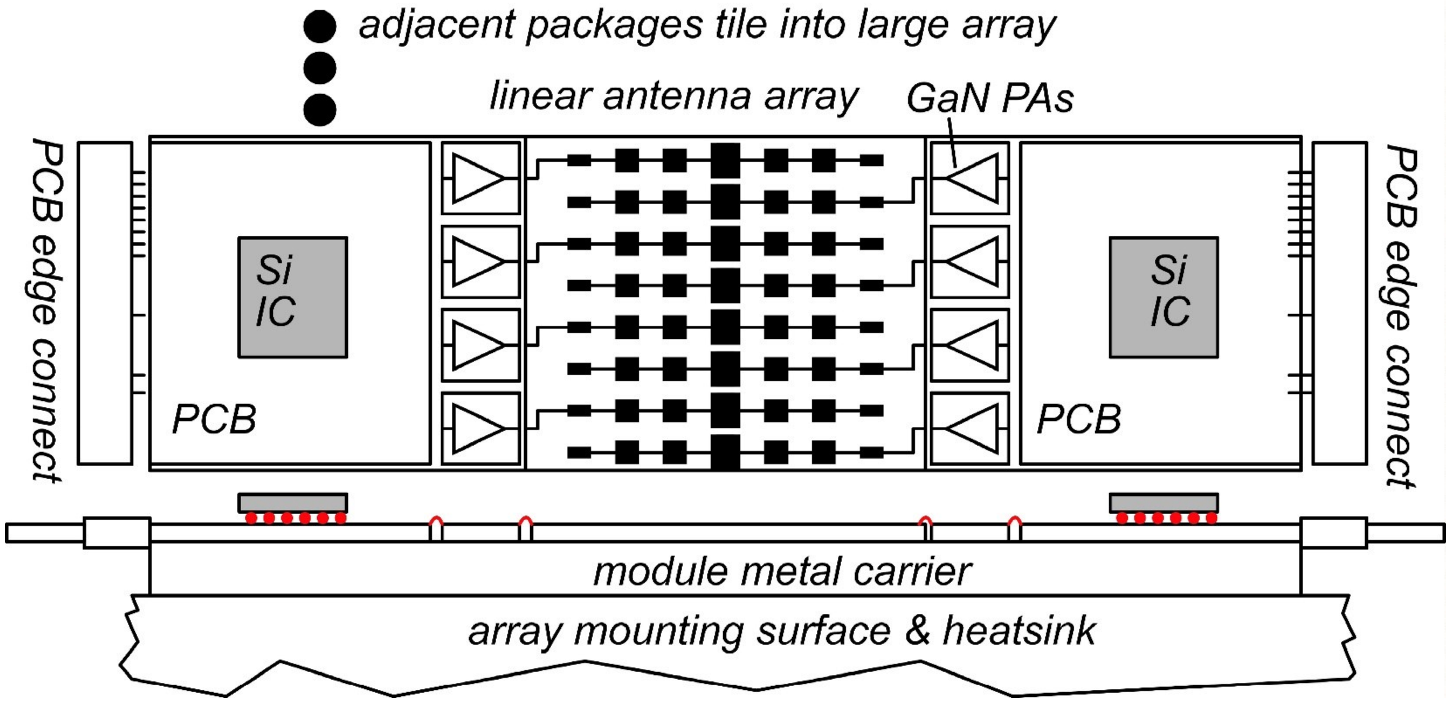


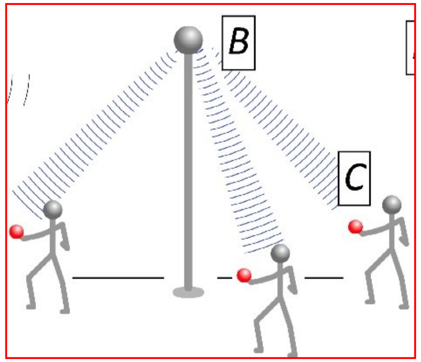
Arrays can often be linear (1D), instead of rectangular (2D)
Element spacing can often be greater than λ/2.

→ Array packaging then greatly simplified.



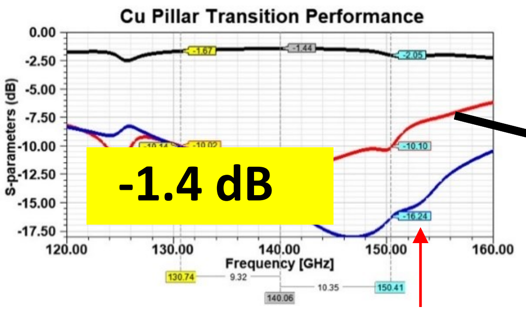
Concept: Tile for linear arrays

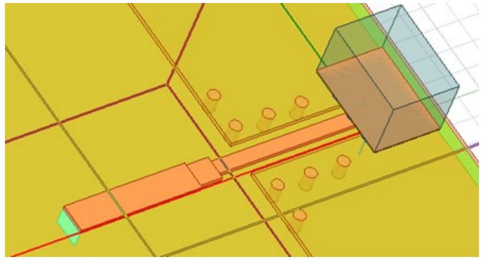


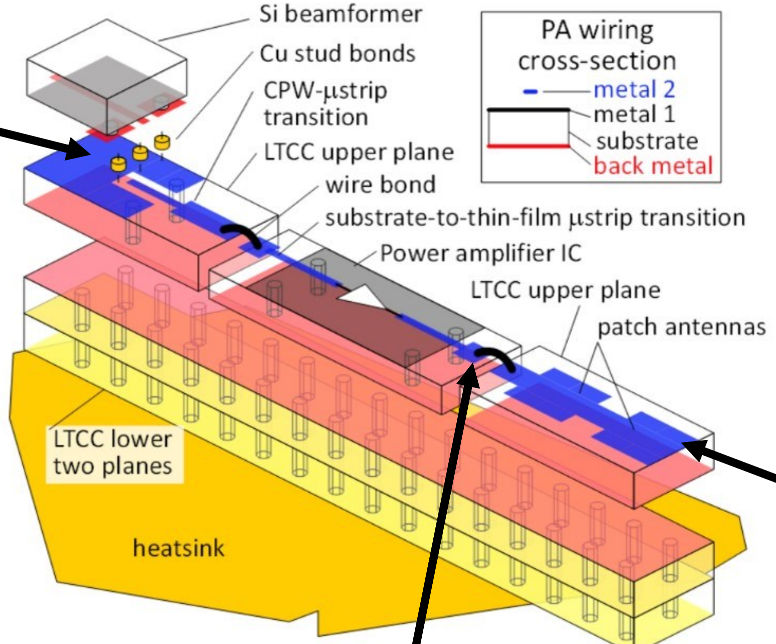


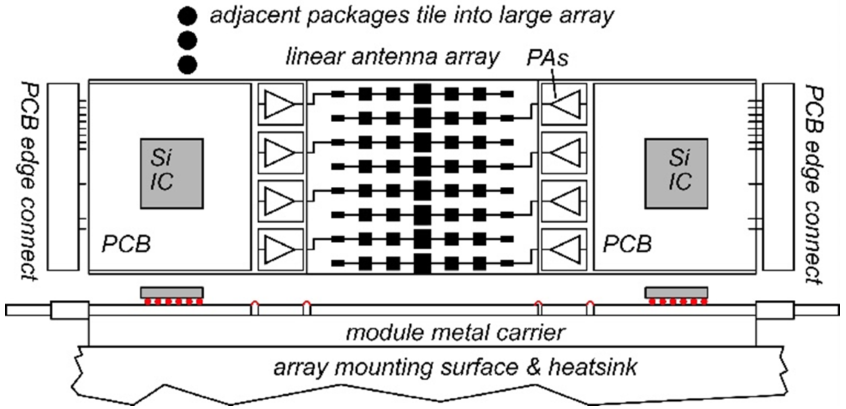
Terrestrial system: horizontal steering only→ linear array.
Space at edges of linear array: room for III-V PAs, LNAs.
Alternating-sides feed: 2mm pitch→ room for large GaN PAs.
Mounting directly on metal carrier→ heatsinking.

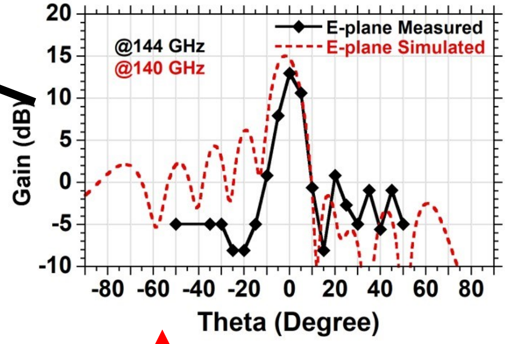
140GHz array module design

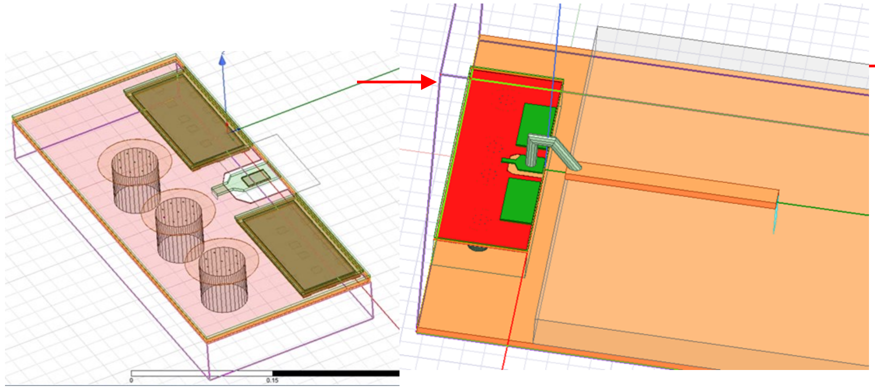


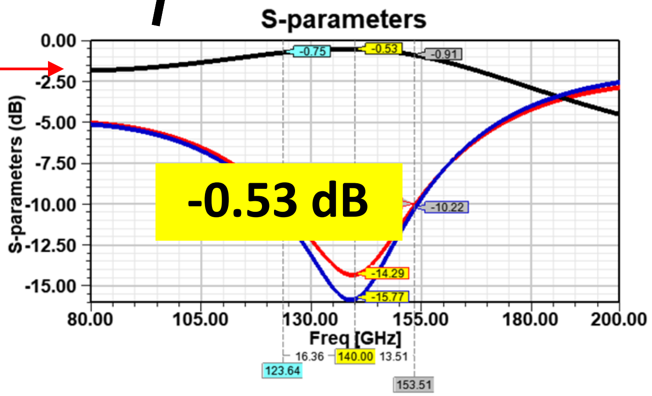


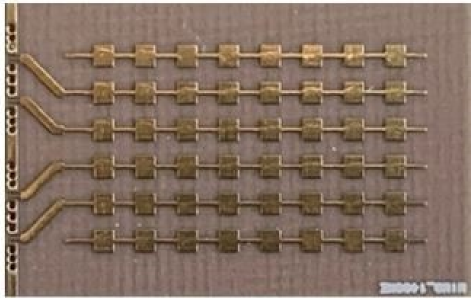


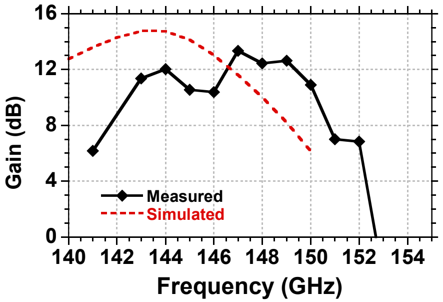






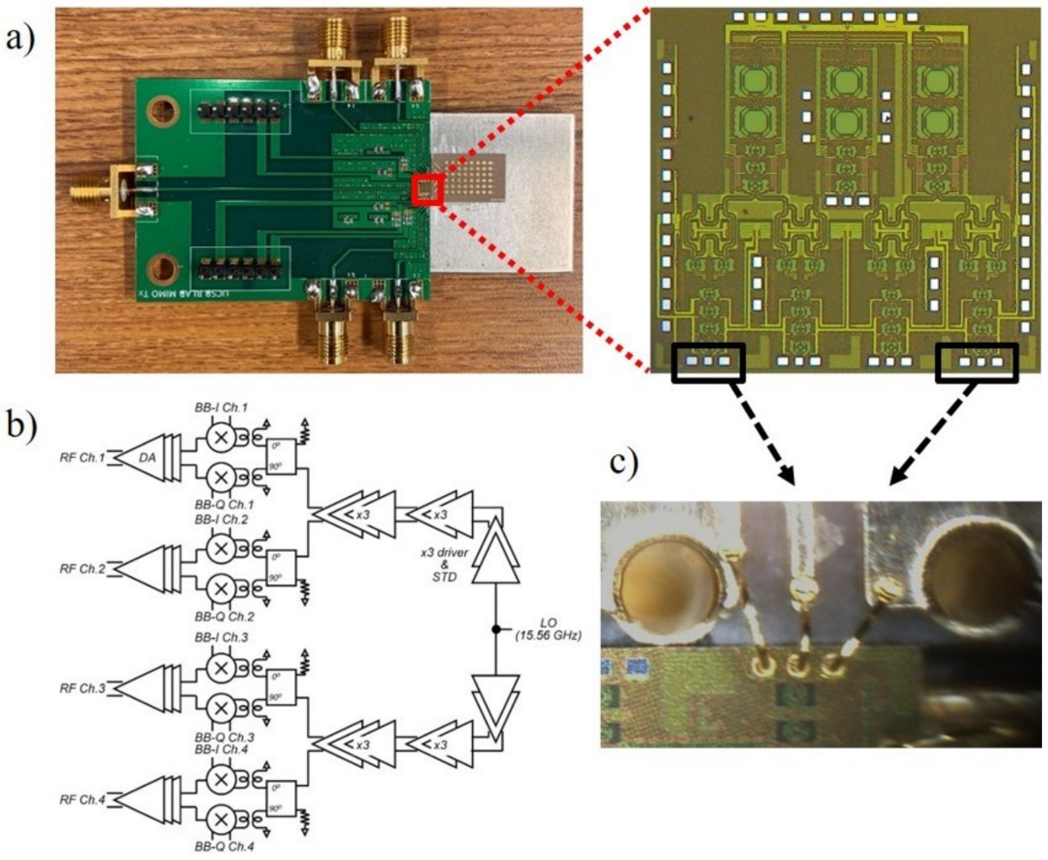


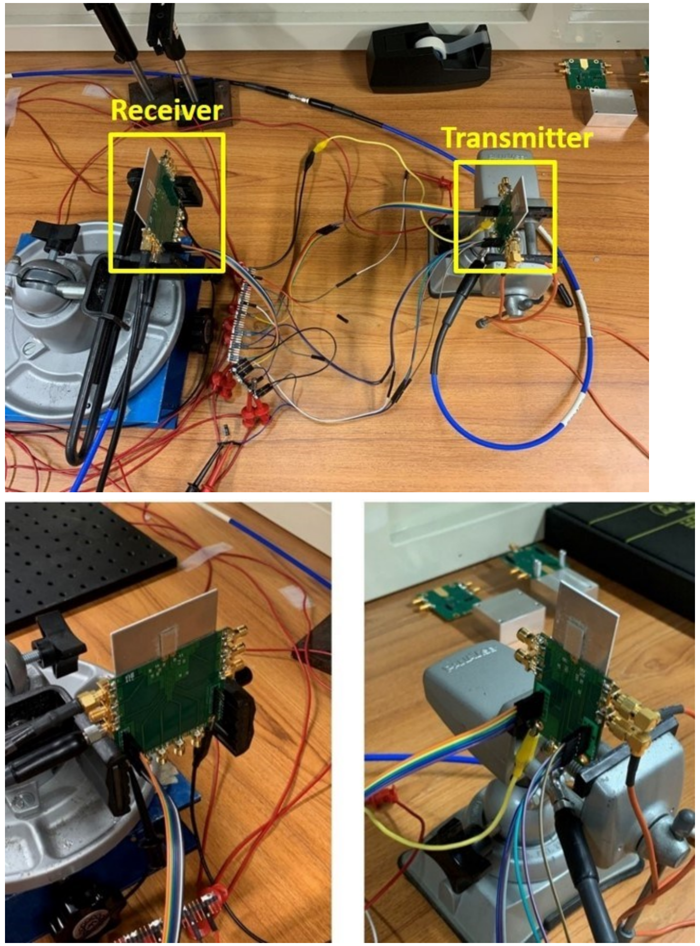


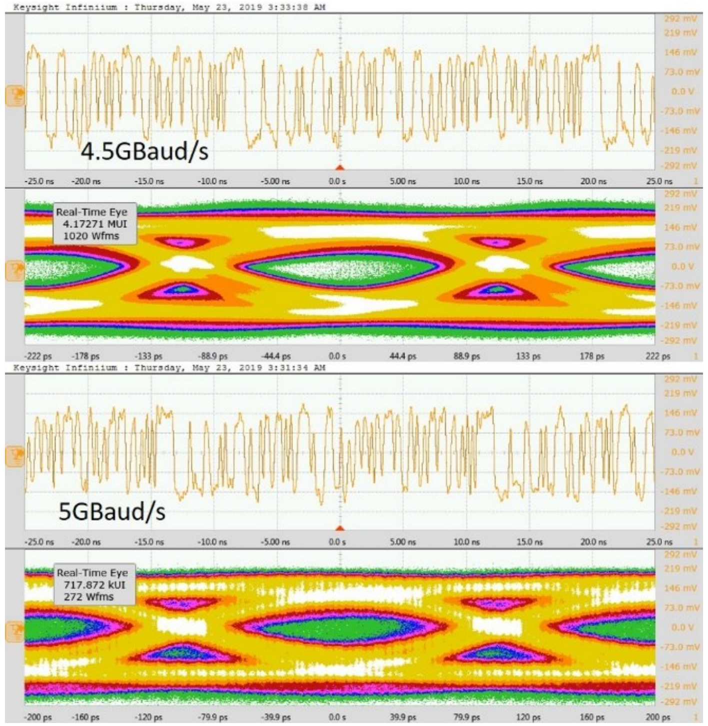


Simulations good: working with Kyocera. June tapeout ?

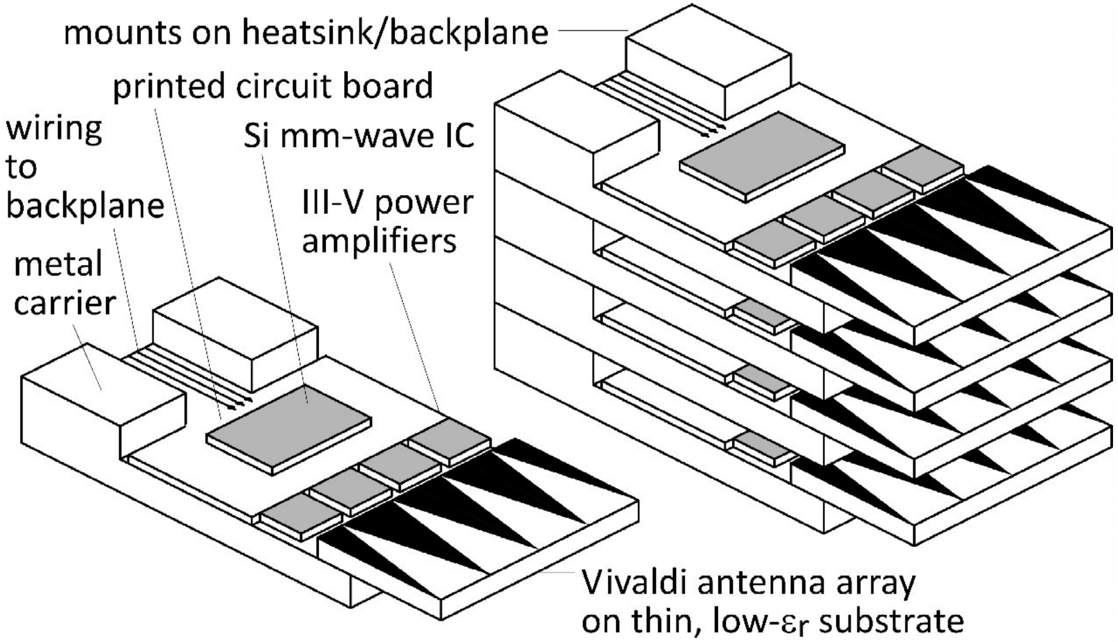
140GHz Indoor Gigabit Network Demonstration

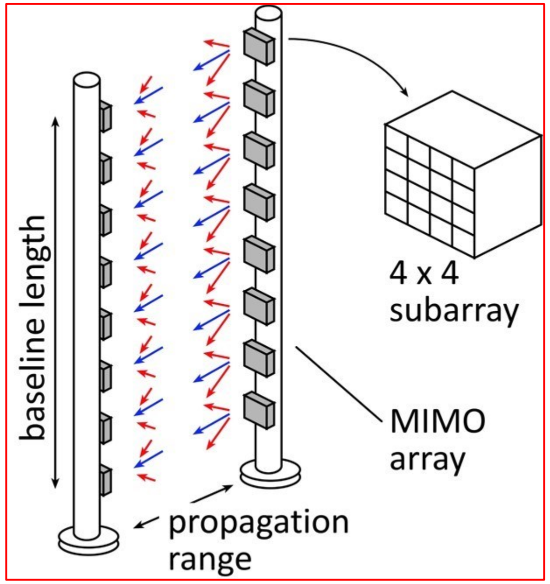






Concept: module for small angular scanning



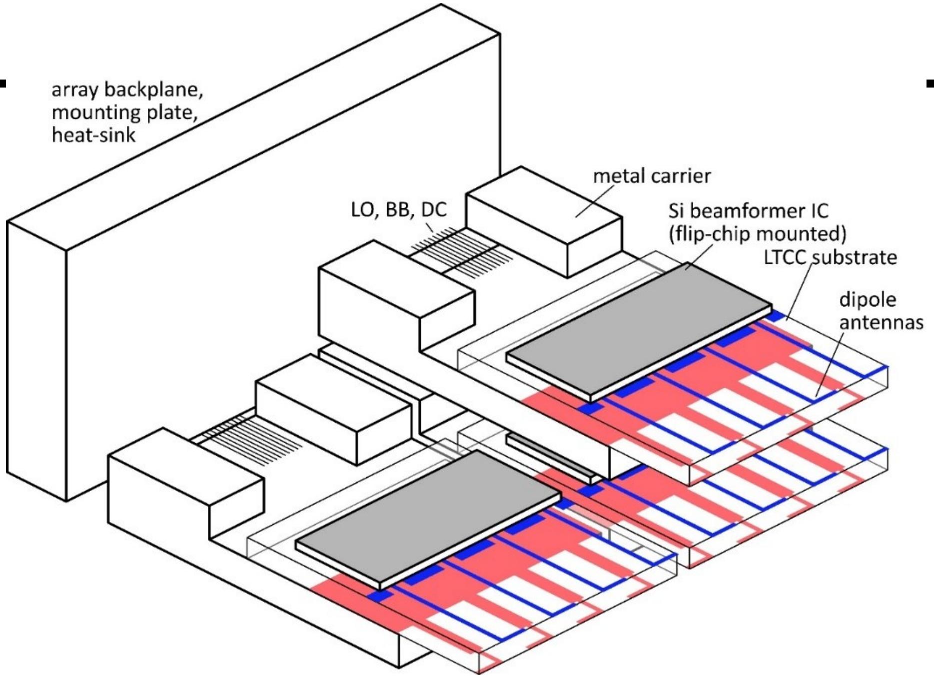


Terrestrial system: horizontal + vertical steering → rectangular array.
Limited angular steering range (installation)→ spacing >> $\lambda/2$
Endfire / edge-card geometry: room for III-V PAs, LNAs.
Mounting directly on metal carrier→ heatsinking.

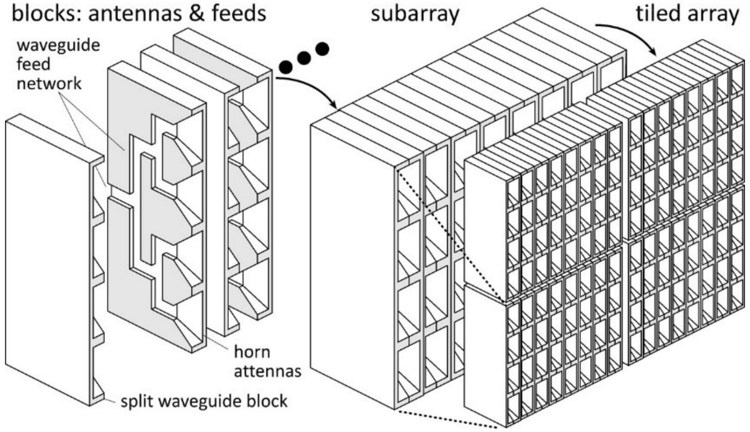
If Vivaldi's are replaced with dipoles, element spacing can be reduced to $\lambda/2$.
→ potential for wider angular scanning

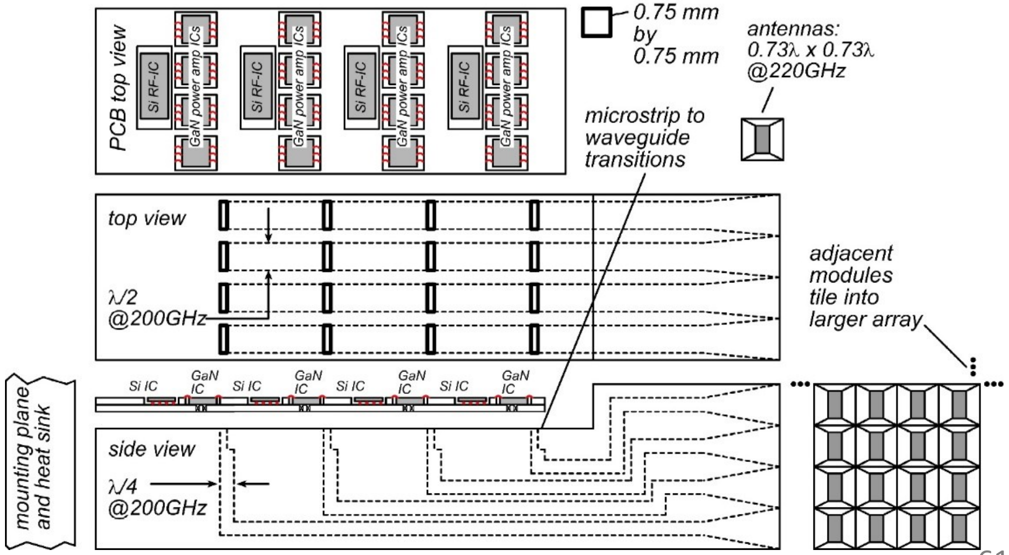
λ/2-spaced 2-D Arrays

Tray design
Vertical spacings become very small
difficult to remove heat

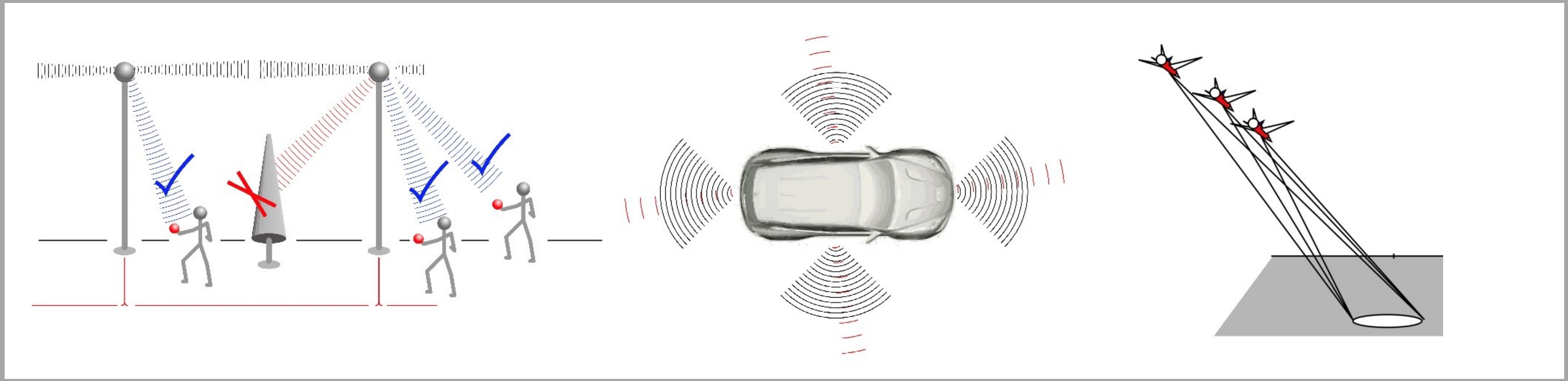


Split-block / waveguide design
heatsinking maintained
difficult to manufacture





Wireless above 100GHz



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 250 GHz.
III-V LNAs and PAs for longer-range links. Just like cell phones today
III-V frequency extenders for 340GHz and beyond

The challenges
spatial multiplexing: computational complexity
packaging: fitting signal channels in very small areas

In case of questions

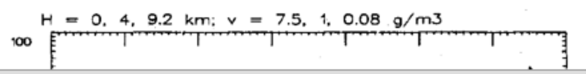
140 GHz spatially multiplexed base station

Boldface indicates parameters to enter, other parameters are calculated by formula and should be left alone

This spreadsheet calculates power levels for QPSK point-point digital microwave radio links along the surface

To calculate RANGE, vary the range until the transmit power (cell F4) is at the appropriate level

Row	B	C	D	E	F	G	H	I	J–M
4	B: Bit rate	**1.00E+09**	1/sec	QPSK required radiated power/beam	17.0	dBm	5.07E-02	W	Don't confuse radiated power with PA output power
5	carrier frequency	**1.40E+11**	Hz	PA output power per element / beam	-5.0	dBm	3.14E-04	W	They differ by cell C22, the transmitter packaging loss,
6	λ: wavelength	2.14E-03	m	QPSK total required radiated power	38.1	dBm	6.48E+00	W	which includes transmit (but not receive) antenna losses.
7	Required SNR (measured as Eb/No)	**9.8**	dB	total PA output power per element	16.0	dBm	4.01E-02	W	Total PA output power 1.03E+01 W
8	F: receiver noise figure	**3**	dB	Transmitter: Base station					
9	R: transmission range	**225.0**	m	A_effective	1.71E-03	meters^2	372.88	Wavelengths^2	
10	atmospheric loss	1.993E-02	dB/m	Vertical beam angle, peak-null	**25.00**	deg	0.4363	radians	
11	Dant, trans transmit antenna directivity	4.69E+03	none	Horizontal beam angle, peak-null	**0.35**	deg	0.0061	radians	
12	Dant, rcvr receive antenna directivity	1.03E+02	none	array rows and columns	**1**	# rows	**256**	# columns	
13	α: bandwidth factor (0.5<α<1)	**0.80**		total # array elements	256				
14	radiated channel bandwidth required	800.0	MHz	vertical angle scanned, total	25.0	deg			
15	# beams	**128**		horizontal angle scanned, total	89.6	deg			
16	kT	-173.83	dBm (1Hz)	array height	2.37	wavelengths	5.07E-03	meters	
17	packaging loss (receiver)	**2**	dB	array width	163.70	wavelengths	3.51E-01	meters	
18	packaging loss (transmitter)	**2**	dB	element height	2.37	wavelengths	5.07E-03	meters	
19	end-of-life hardware degradation	**2**	dB	element width	0.64	wavelengths	1.37E-03	meters	
20	hardware design margin	**2**	dB	Antenna directivity, dB	36.71	dB			
21	beam aiming loss (edge of beam)	**2**	dB	Receiver-handset					
22	systems operating margin	**5**	dB	A_effective	3.75E-05	meters^2	8.16	Wavelengths^2	
23	Prec, received power at 1E-3 BER	-60.03	dBm	Vertical beam angle, peak-null	**20.0**	deg	0.3491	radians	
24	geometric path loss	2.76E-07		Horizontal beam angle, peak-null	**20.0**	deg	0.3491	radians	
25	geometric path loss, dB	-65.59	dB	array rows and columns	**8**	# rows	**8**	# columns	
26	path obstruction loss (shadowing)	**5.00**	dB	vertical angle scanned, total	160	deg			
27	atmospheric loss, dB	4.48	dB	horizontal angle scanned, total	160	deg			
28	atmospheric loss	19.93	dB/km	array height	2.9E+00	wavelengths	6.27E-03	meters	<---calculations are a bit off
29				array width	2.9E+00	wavelengths	6.27E-03	meters	for the handset element spacings because
30				element height	3.65E-01	wavelengths	7.83E-04	meters	with a wide angular scan range, the angular resolution
31				element width	3.65E-01	wavelengths	7.83E-04	meters	varies as a function of scan angle..
32				Antenna directivity, dB	20.11	dB			
33									
34	rain attenuation fits from Olesn, Rogers, Hodge, IEEE Trans Ant and Prop, March 1978								
35	Rain rate, mm/hr	**50**	mm/hr	1.97	inch/hr				



75Hz_downlink | 140GHz_downlink | 140GHz_uplink

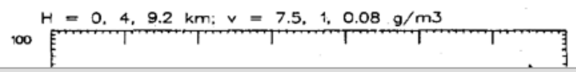
READY 90%

75 GHz spatially multiplexed base station

If we use instead a 75GHz carrier,
the range increases to 325 meters (vs. 250 meters)
but the handset becomes 16mm×16mm (vs. 9mm×9mm),
and the hub array becomes 9mm×655mm (vs. 5mm×350mm)

Or, use a 4×4 (8mm×8mm) handset array,
and the range becomes 210 meters.

	B	C	D	E	F	G	H	I	J	K	L	M	
1	**Boldface indicates parameters to enter, other parameters are calculated by formula and should be left alone**												
2	This spreadsheet calculates power levels for QPSK point-point digital microwave radio links along the surface												
4											utput power		
5											ackaging loss,		
6											antenna losses.		
7												1.02E+01	W
15	# beams	**128**		horizontal angle scanned, total	89.6	deg							
16	kT	-173.83	dBm (1Hz)	array height	2.37	wavelengths	9.46E-03	meters		2	beam aiming	add	
17	packaging loss (receiver)	**2**	dB	array width	163.70	wavelengths	6.55E-01	meters		5.00	blockage	add	
18	packaging loss (transmitter)	**2**	dB	element height	2.37	wavelengths	9.46E-03	meters		6.69	atmosphere	add	
19	end-of-life hardware degradation	**2**	dB	element width	0.64	wavelengths	2.56E-03	meters		26.02	100 vs 5 m	add	
20	hardware design margin	**2**	dB	Antenna directivity, dB	36.71	dB				39.72	power adjustment range, dB		
22							8.16	Wavelengths^2					
23							0.3491	radians					
24							0.3491	radians			-7.41E+01		
25							**8**	# columns					
28	atmospheric loss	20.60	dB/km	array height	2.9E+00	wavelengths	1.17E-02	meters	<---calculations are a bit off				
29				array width	2.9E+00	wavelengths	1.17E-02	meters	for the handset element spacings because				
30				element height	3.65E-01	wavelengths	1.46E-03	meters	with a wide angular scan range, the angular resolution				
31				element width	3.65E-01	wavelengths	1.46E-03	meters	varies as a function of scan angle..				
32				Antenna directivity, dB	20.11	dB							
34	rain attenuation fits from Olesn, Rogers, Hodge, IEEE Trans Ant and Prop, March 1978												
35	Rain rate, mm/hr	**50**	mm/hr	1.97	inch/hr								

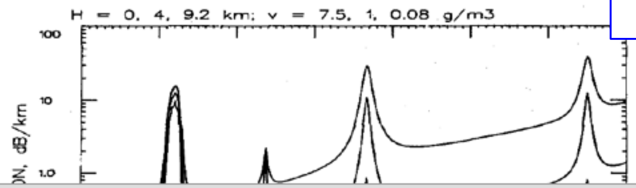


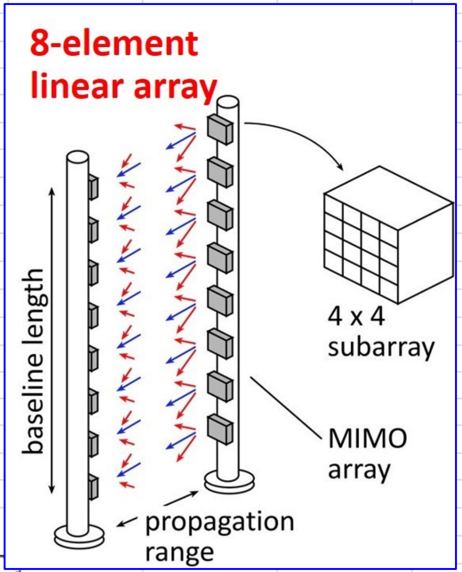
75Hz_downlink | 140GHz_downlink | 140GHz_uplink

READY

340 GHz 640 Gb/s MIMO backhaul

	A	B	C	D	E	F	G	H	I	J	K	L	M
1		**Boldface indicates parameters to enter, other parameters are calculated by formula and should be left alone**											
2		This spreadsheet calculates power levels for 4QPSK point-point digital microwave radio links along the surface											
3		To calculate RANGE, vary the range until the transmit power (cell F4) is at the appropriate level				30					Power levels for 64-QAM, approx		
4		B: Bit rate *per MIMO transmitter*	**8.00E+10**	1/sec	4QAM required radiated power	29.2	dBm	8.281E-01	W		41.31	dBm	1.35E+01 W
5		carrier frequency	**3.40E+11**	Hz	output power per element	19.1	dBm	8.20E-02	W	output power per element	31.27	dBm	1.34E+00 W
6		λ: wavelength	8.82E-04	m	output power per sub-array	31.2	dBm	1.31E+00	W	output power per sub-array	43.31	dBm	2.14E+01 W
7		Required SNR (measured as Eb/No)	**9.8**	dB	output power of whole system	40.2	dBm	1.05E+01	W	output power of whole system	52.34	dBm	1.71E+02 W
8					Transmitter						Power levels for 16-QAM, approx		
9					A_effective	6.35E-04	meters^2	815.67	Wavelengths^2		35.71	dBm	3.725E+00 W
10		F: receiver noise figure	**4**	dB	Vertical beam angle, FWHM	**2.0**	deg	0.0349	radians	output power per element	25.67	dBm	3.690E-01 W
11		R: transmission range	**500.0**	m	Horizontal beam angle, FWHM	**2.0**	deg	0.0349	radians	output power per sub-array	37.71	dBm	5.903E+00 W
12		atmospheric loss	2.875E-02	dB/m	array rows and columns	**4**	# rows	**4**	# columns	output power of whole system	46.74	dBm	4.723E+01 W
13		Dant, trans transmit antenna directivity	1.03E+04	none	total # array elements	16							
14		Dant, rcvr receive antenna directivity	1.03E+04	none	vertical angle scanned, total	8.0	deg						
15		α: bandwidth factor (0.5<α<1)	**0.80**		horizontal angle scanned, total	8.0	deg						
16		radiated channel bandwidth required QPSK	6.40E+10	Hz	array height	28.6	wavelengths	7.16					
17		radiated channel bandwidth required 64QAM	2.133E+10	Hz	array width	28.6	wavelengths						
18		# MIMO channels	**8**		array height	2.53E-02	meters	1.00	inches				
19		total data rate	6.40E+11	sec	array width	2.53E-02	meters	1.00	inches				
20		kT	-173.83	dBm (1Hz)	Antenna directivity, dB	40.11	dB						
21		packaging loss (receiver)	**2**	dB	Receiver								
22		packaging loss (transmitter)	**2**	dB	A_effective	6.35E-04	meters^2	815.67	Wavelengths^2				
23		end-of-life hardware degradation	**3**	dB	Vertical beam angle, FWHM	**2.0**	deg	0.0349	radians				
24		hardware design margin	**3**	dB	Horizontal beam angle, FWHM	**2.0**	deg	0.0349	radians				
25		beam aiming loss (edge of beam)	**0**	dB	array rows and columns	**4**	# rows	**4**	# columns				
26		systems operating margin	**10**	dB	vertical angle scanned, total	8	deg						
27		Prec, received power at 1E-3 BER	-33.00	dBm	horizontal angle scanned, total	8	deg						
28		geometric path loss	2.07E-06		array height	2.9E+01	wavelengths						
29		geometric path loss, dB	-56.84	dB	array width	2.9E+01	wavelengths						
30		path obstruction loss (foliage, glass)	**0.00**	dB	array height	2.53E-02	meters	1.00	inches				
31		atmospheric loss, dB	14.374685	dB	array width	2.53E-02	meters	1.00	inches				
32		atmospheric loss	28.75	dB/km	Antenna directivity, dB	40.11	dB						
33													
34		rain attenuation fits from Olesn, Rogers, Hodge, IEEE Trans Ant and Prop, March 1978											
35		Rain rate, mm/hr	**50**	mm/hr		1.97	inch/hr						
36		Ga	3.38E+00		Gb	0.616							
37		Ea	-1.51E-01		Eb	0.0126							
38		a	1.40E+00		b	6.63E-01							
39		alpha=aR^b	1.87E+01	dB/km	zero-rain-rate attenuation	**10**	dB/km						





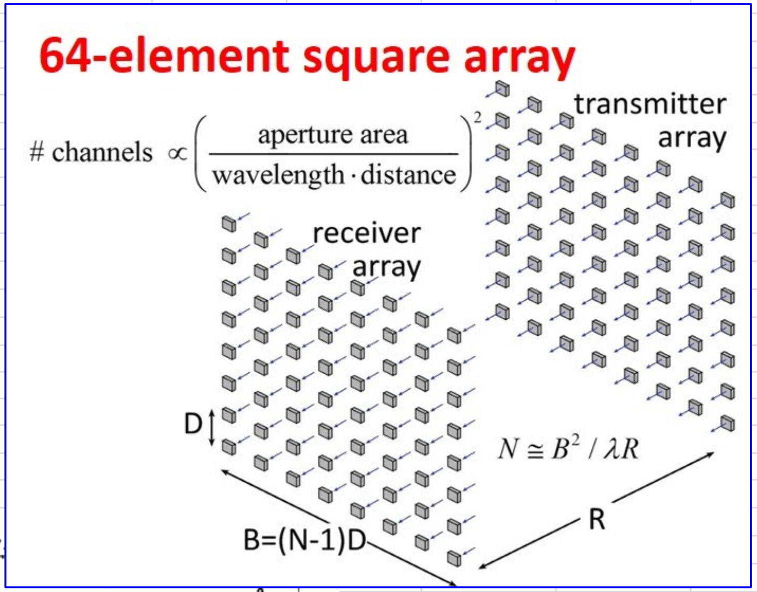
140GHz | 340GHz | 650GHz | MIMO_array_lengths

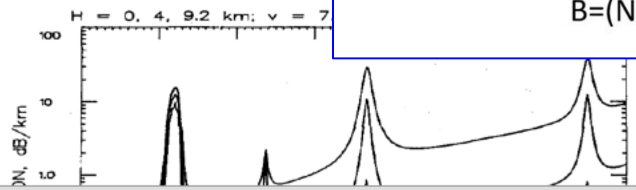
READY 80%

340 GHz 5 Tb/s MIMO backhaul

1	**Boldface indicates parameters to enter, other parameters are calculated by formula and should be left alone**												
2	This spreadsheet calculates power levels for 4QPSK point-point digital microwave radio links along the surface												
3	To calculate RANGE, vary the range until the transmit power (cell F4) is at the appropriate level				30					Power levels for 64-QAM, approx			
4	B: Bit rate *per MIMO transmitter*	**8.00E+10**	1/sec	4QAM required radiated power	20.2	dBm	1.035E-01	W		32.28	dBm	1.69E+00	W
5	carrier frequency	**3.40E+11**	Hz	output power per element	10.1	dBm	1.03E-02	W	output power per element	22.24	dBm	1.67E-01	W
6	λ: wavelength	8.82E-04	m	output power per sub-array	22.2	dBm	1.64E-01	W	output power per sub-array	34.28	dBm	2.68E+00	W
7	Required SNR (measured as Eb/No)	**9.8**	dB	output power of whole system	40.2	dBm	1.05E+01	W	output power of whole system	52.34	dBm	1.71E+02	W
8				Transmitter					Power levels for 16-QAM, approx				
9				A_effective	6.35E-04	meters^2	815.67	Wavelengths^2		26.68	dBm	4.656E-01	W
10	F: receiver noise figure	**4**	dB	Vertical beam angle, FWHM	**2.0**	deg	0.0349	radians	output power per element	16.64	dBm	4.612E-02	W
11	R: transmission range	**500.0**	m	Horizontal beam angle, FWHM	**2.0**	deg	0.0349	radians	output power per sub-array	28.68	dBm	7.379E-01	W
12	atmospheric loss	2.875E-02	dB/m	array rows and columns	**4**	# rows	**4**	# columns	output power of whole system	46.74	dBm	4.723E+01	W
13	Dant, trans transmit antenna directivity	1.03E+04	none	total # array elements	16								
14	Dant, rcvr receive antenna directivity	1.03E+04	none	vertical angle scanned, total	8.0	deg							
15	α: bandwidth factor (0.5<α<1)	**0.80**		horizontal angle scanned, total	8.0	deg							
16	radiated channel bandwidth required QPSK	6.40E+10	Hz	array height	28.6	wavelengths	7.16						
17	radiated channel bandwidth required 64QAM	2.133E+10	Hz	array width	28.6	wavelengths							
18	# MIMO channels	**64**		array height	2.53E-02	meters	1.00	inches					
19	total data rate	5.12E+12	sec	array width	2.53E-02	meters	1.00	inches					
20	kT	173.83	dBm (1Hz)	Antenna directivity, dB	40.11	dB							
21	p												
22	p						15.67	Wavelengths^2					
23	e						.0349	radians					
24	h						.0349	radians					
25	b						4	# columns					
26	s												
27	Prec, received power at 1E-3 BER	-33.00	dBm	horizontal angle scanned, total	8	deg							
28	geometric path loss	2.07E-06		array height	2.9E+01	wavelengths							
29	geometric path loss, dB	-56.84	dB	array width	2.9E+01	wavelengths							
30	path obstruction loss (foliage, glass)	**0.00**	dB	array height	2.53E-02	meters	1.00	inches					
31	atmospheric loss, dB	14.374685	dB	array width	2.53E-02	meters	1.00	inches					
32	atmospheric loss	28.75	dB/km	Antenna directivity, dB	40.11	dB							
33													
34	rain attenuation fits from Olesn, Rogers, Hodge, IEEE Trans Ant and Prop, March 1978												
35	Rain rate, mm/hr	**50**	mm/hr		1.97	inch/hr							
36	Ga	3.38E+00		Gb	0.616								
37	Ea	-1.51E-01		Eb	0.0126								
38	a	1.40E+00		b	6.63E-01								
39	alpha=aR^b	1.87E+01	dB/km	zero-rain-rate attenuation	**10**	dB/km							

requires 10mW output per element
...10W total radiated power





140GHz | 340GHz | 650GHz | MIMO_array_lengths

READY 80%