Short Course, IEEE BCICTS Conference, San Diego, October 14, 2018

Device, Circuit, and Systems Considerations for Highly Integrated 30-300GHz Wireless Systems

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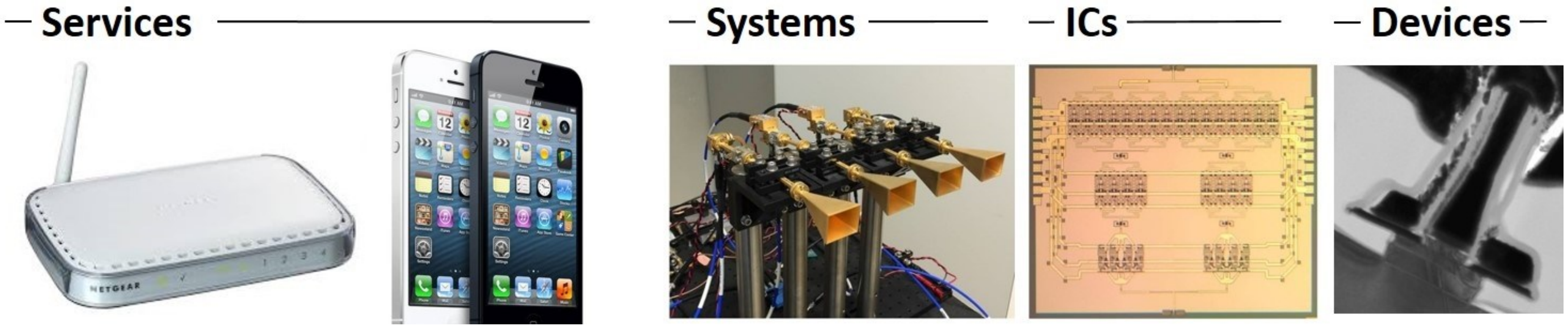
Why mm-wave wireless ?



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.

A very incomplete history of THz electronics

1950-1990: THz GaAs Schottky diodes in waveguide

Multipliers and mixers. Radio astronomy. Instruments. Spectroscopy.

1980's: THz spectroscopy using fs/ps pulsed lasers

ps/fs pulsed lasers, optical/electrical conversion, time-domain techniques

"optics is fast; electronics is slow"

1985-95: ps pulses using GaAs NLTLs + diode sampling ICs

100GHz commercial sampling scopes, fast network analyzers.

1995-2010: THz transistors, THz ICs

Can we make transistors work at 1THz ?

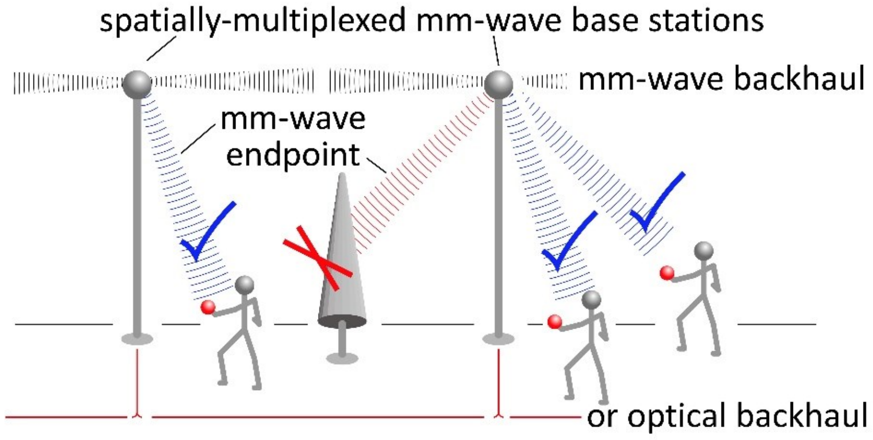
Abandon classical electrostatic barriers for quantum transitions ?

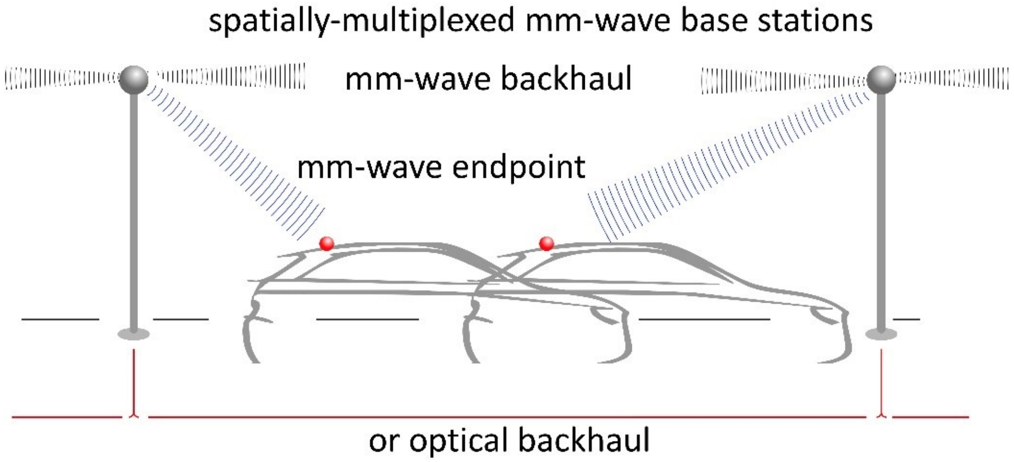
Can circuit concepts work at 1THz ? (of course, just need $D \ll \lambda$!)

Dead end: Detecting poison gas

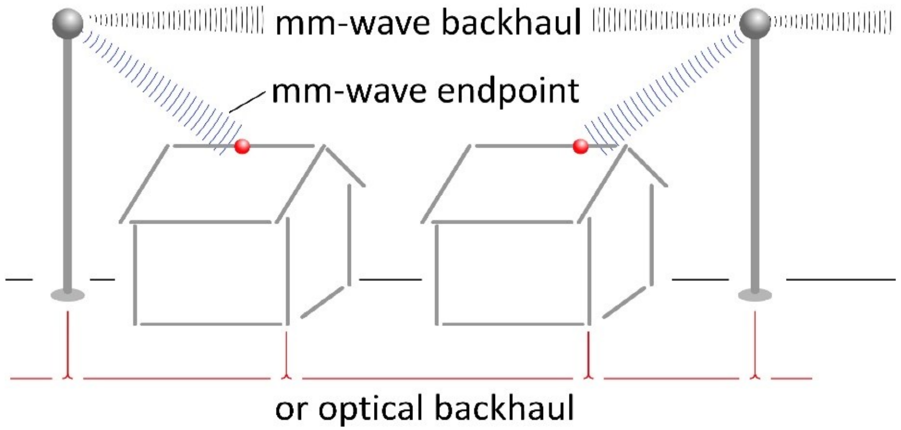
mm-waves: high-capacity mobile communications

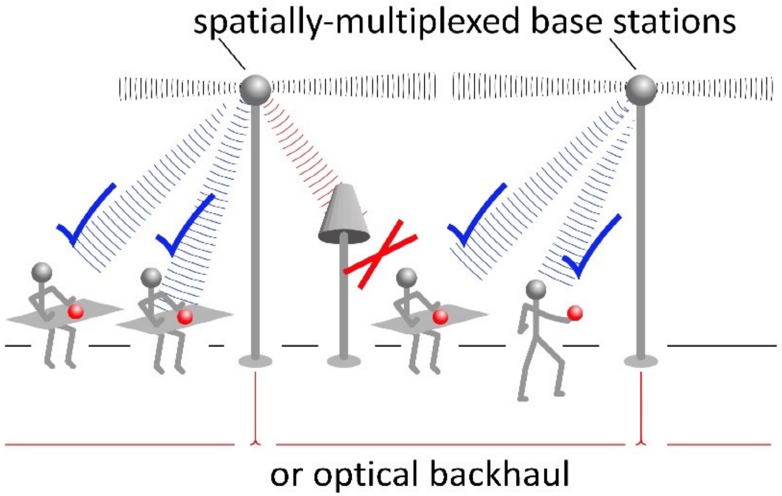
Gigabit mobile communication: Information anywhere, any time, without limits





Residential/office communication: Cellular/internet convergence: competition, low cost, broader deployment





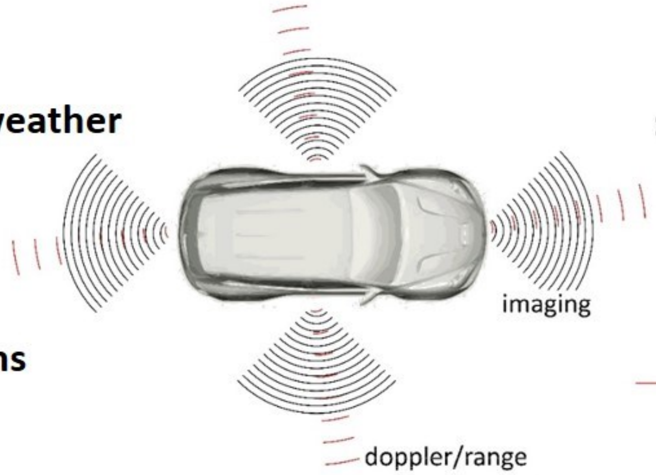
mm-wave imaging: fog/clouds/smoke/dust

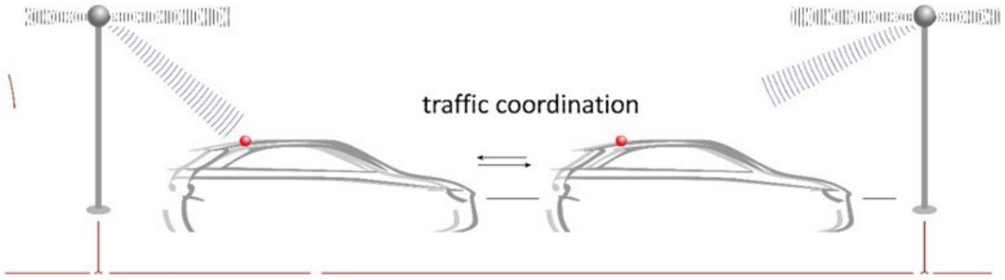
Automatic car, intelligent highway

340 GHz HDTV-resolution radar
drive safely in fog at 100 km/hr
self-driving: complements LIDAR, works in bad weather

Complements 70 GHz Doppler / ranging radar.
object near ? approaching ? Can't tell what.

Intelligent highway: coordinate traffic
anticipate & manage interactions, avoid collisions

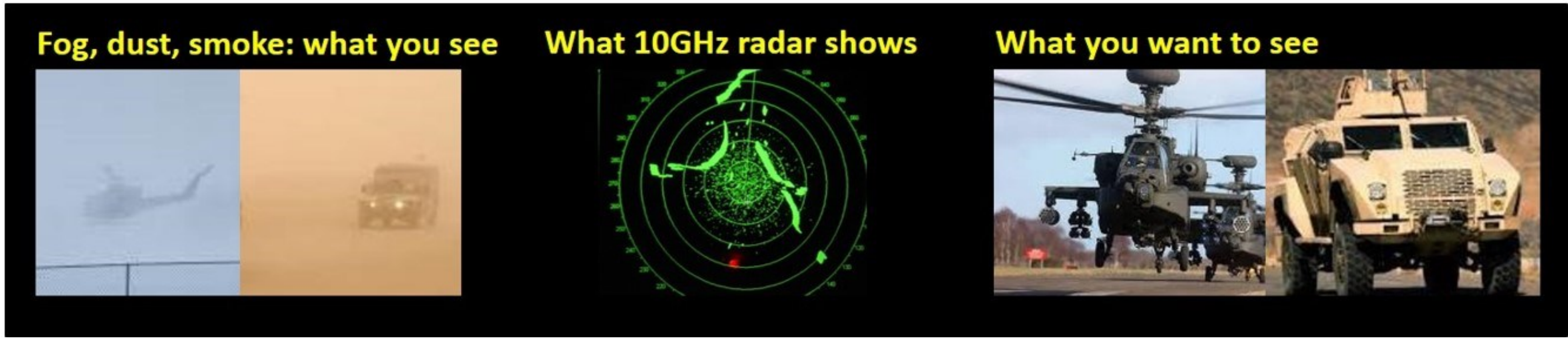




Sensing/imaging for national security

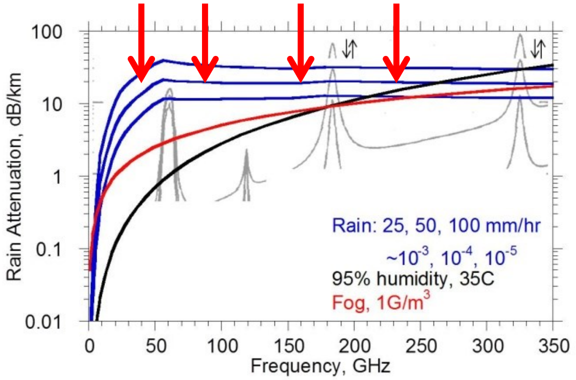
20/70/ 94 GHz radar: is something there ?
Long-range, low-resolution: can't tell what.

140-340GHz imaging radar: **what is it ?**
shorter range, TV-like resolution
small, light: jeep, helicopter, UAV.


Fog, dust, smoke: what you see
What 10GHz radar shows
What you want to see

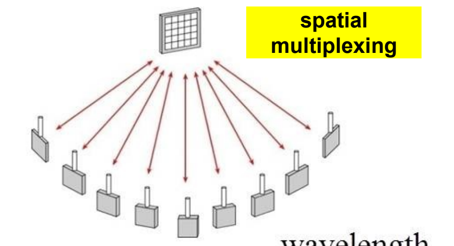
mm-waves: benefits & challenges

Large available spectrum

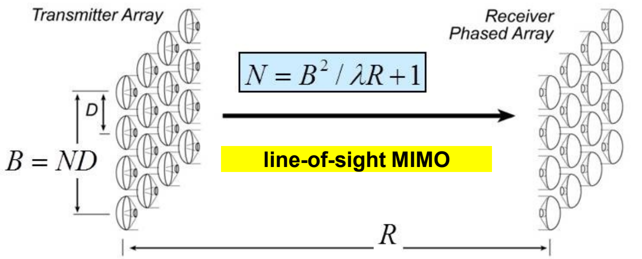


(note high attenuation in foul or humid weather)

Massive # parallel channels



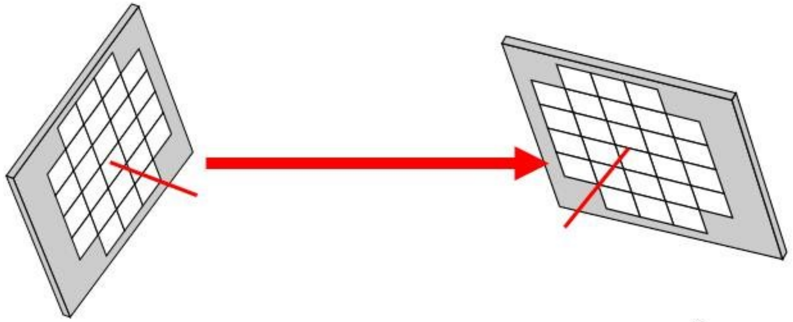
$$\text{angular resolution} \approx \frac{\text{wavelength}}{\text{array width}}$$



$$N = B^2/\lambda R + 1$$

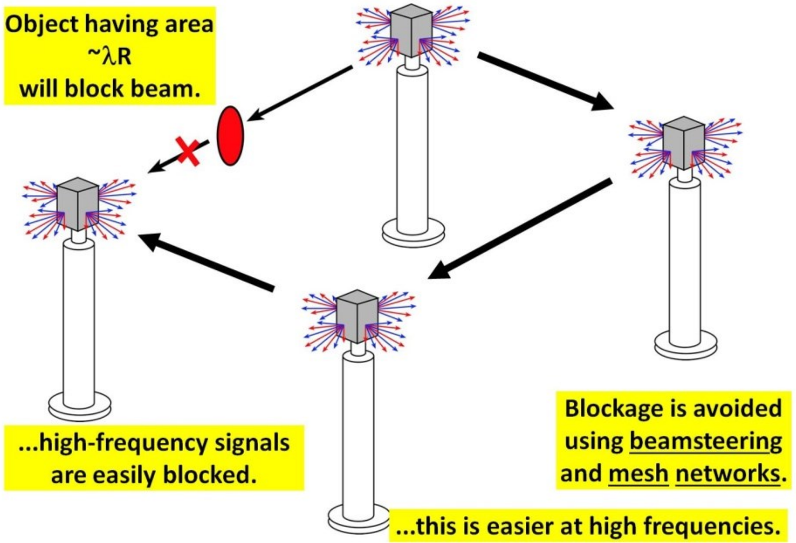
$$\#\text{channels} \propto (\text{aperturearea})^2/(\text{wavelength}\cdot\text{distance})^2$$

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



Object having area ~λR will block beam.

...high-frequency signals are easily blocked.

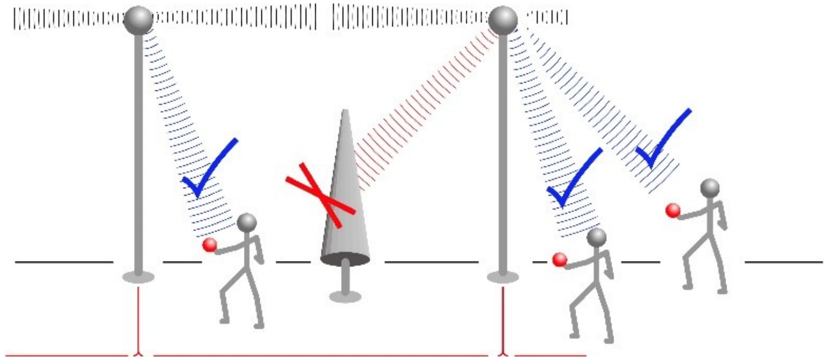
Blockage is avoided using beamsteering and mesh networks.

...this is easier at high frequencies.

mm-waves: potential applications

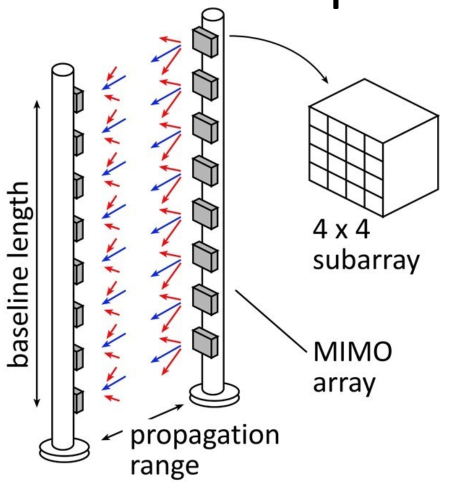
High-capacity hubs

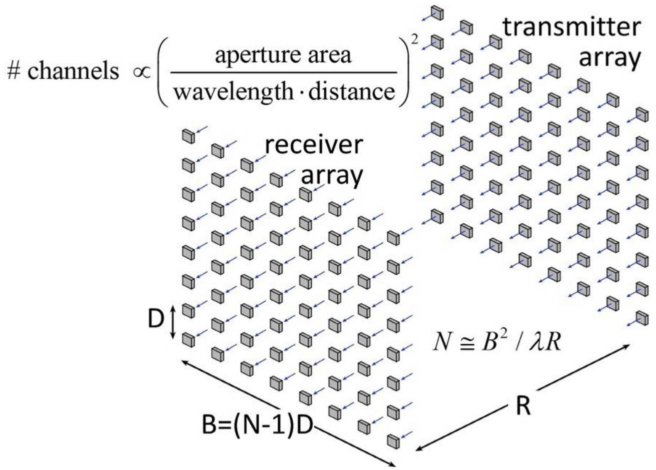
massive spatial multiplexing



High-capacity backhaul

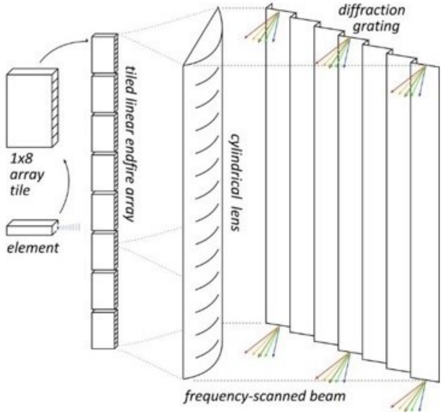
massive spatial multiplexing





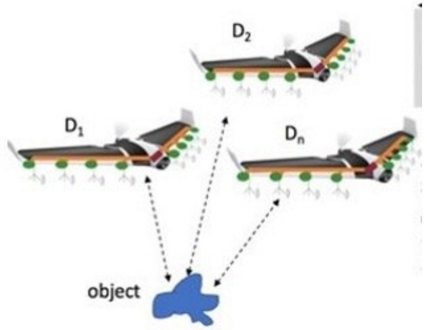
High-resolution imaging

drive through fog/rain/snow

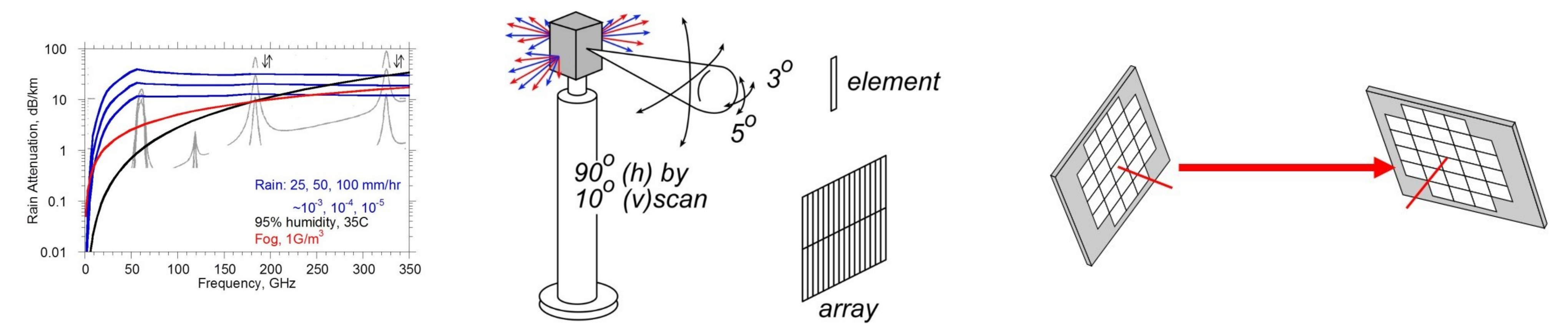


Compact imaging: drones

image through fog/smoke/rain

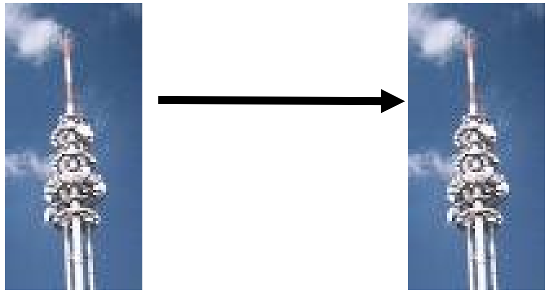


mm-wave fundamentals



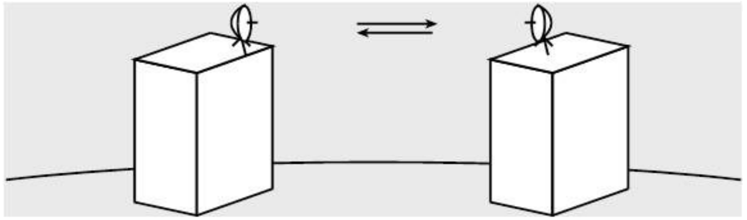
mm-Wave Wireless Needs Phased Arrays

isotropic antenna
→ weak signal
→short range



$$\left(\frac{P_{received}}{P_{transmitted}}\right) \propto \left(\frac{\lambda^2}{R^2}\right) e^{-\alpha R}$$

highly directional antenna
→ strong signal,
must be aimed



$$\left(\frac{P_{received}}{P_{transmitted}}\right) \propto D_t D_r \left(\frac{\lambda^2}{R^2}\right) e^{-\alpha R}$$

no good for mobile

must be precisely aimed →too expensive for telecom operators

beam steering arrays
→ strong signal,
steerable

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

32-element array → 30 (45?) dB increased SNR

Antenna & array basics

Overall array sets beamwidth and gain

$$\text{horizontal beamwidth} \cong \frac{\lambda}{\text{array width}} \text{ (radians)}$$

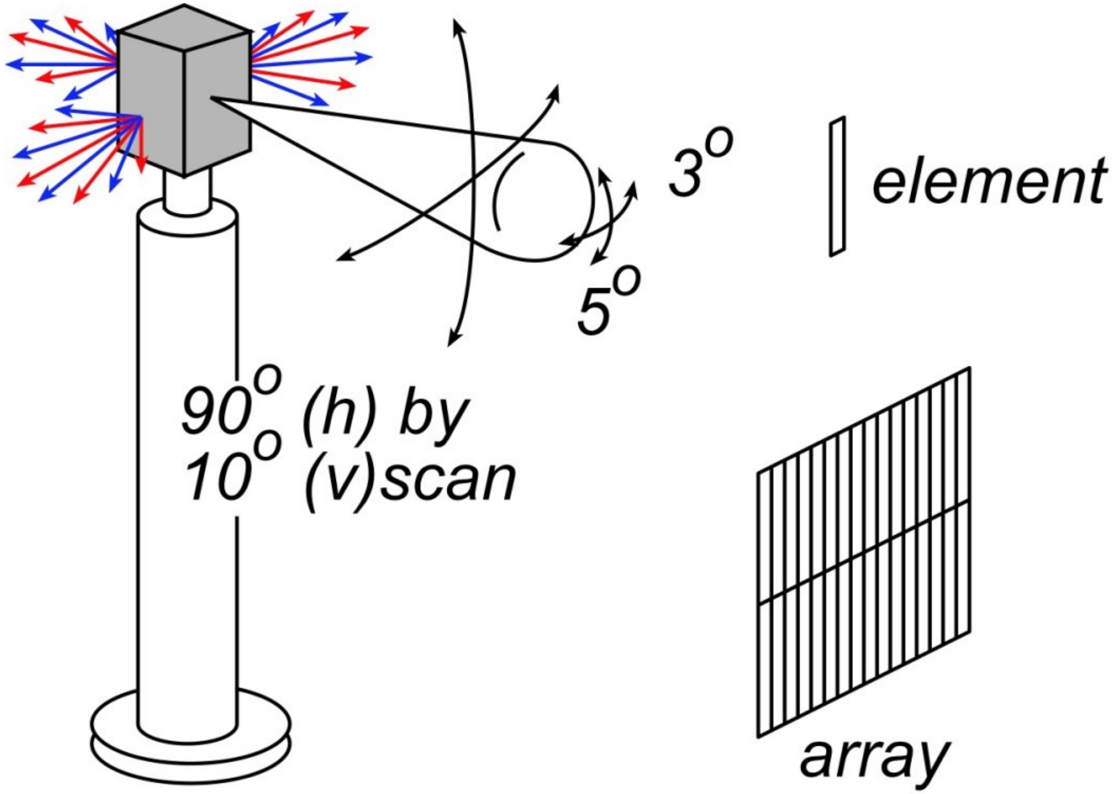
$$\text{vertical beamwidth} \cong \frac{\lambda}{\text{array height}}$$

$$\text{Gain (directivity)} \cong \frac{4\pi \cdot \text{array area}}{\lambda^2}$$

Individual element sets maximum beamsteering range.

$$\text{horizontal steering} \cong \frac{\lambda}{\text{element width}} \text{ (radians)}$$

$$\text{vertical steering} \cong \frac{\lambda}{\text{element height}}$$

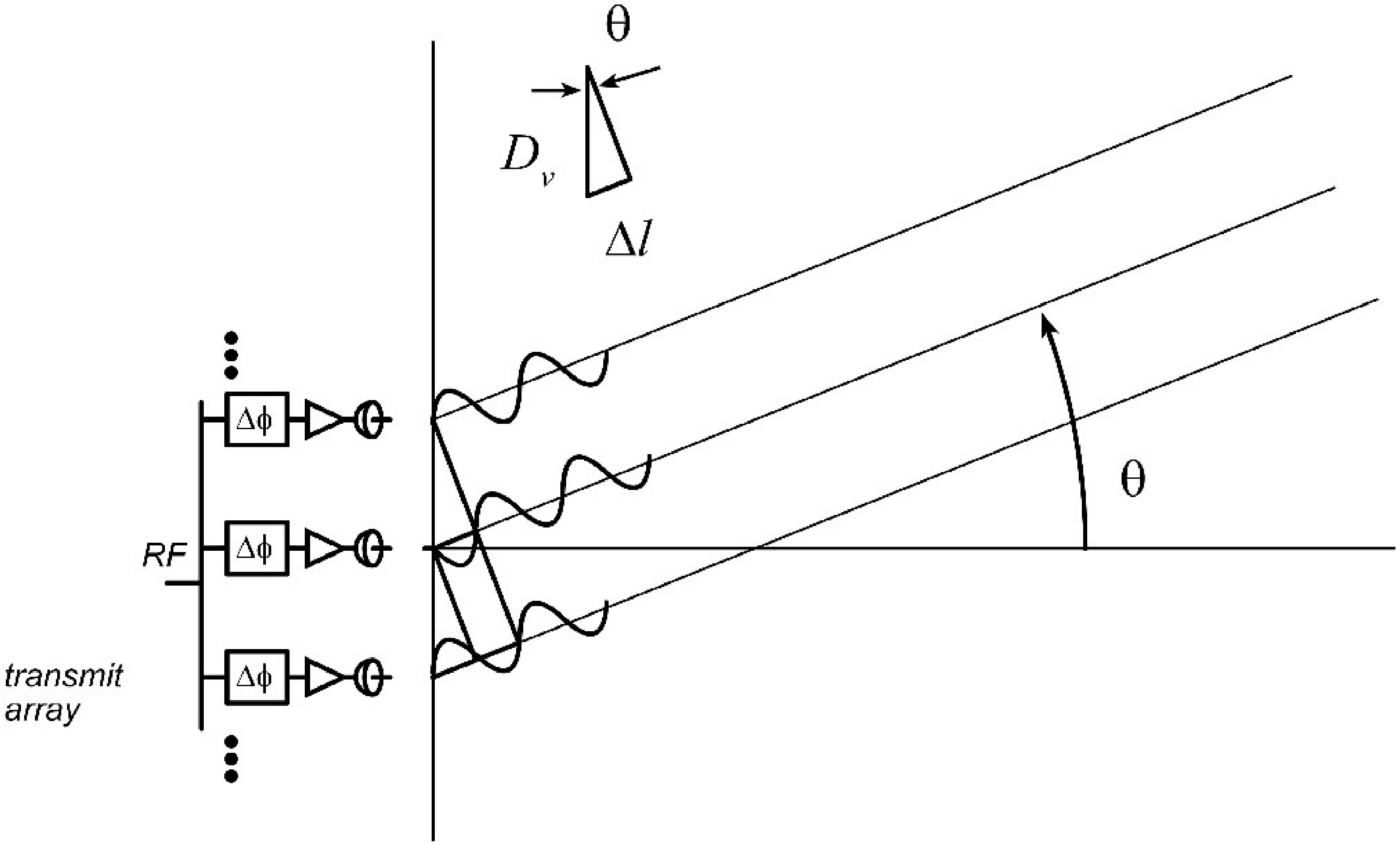


Electronic beamsteering, a.k.a. phased array

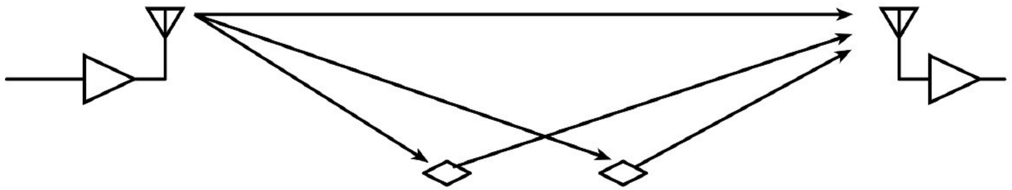
Phase - shifters bring signals back into phase at physical angle θ.

Path length difference $\Delta l = D_v \sin\theta$

Required electrical phase shift between adjacent elements $\Delta\phi = 2\pi \cdot \Delta l / \lambda$.

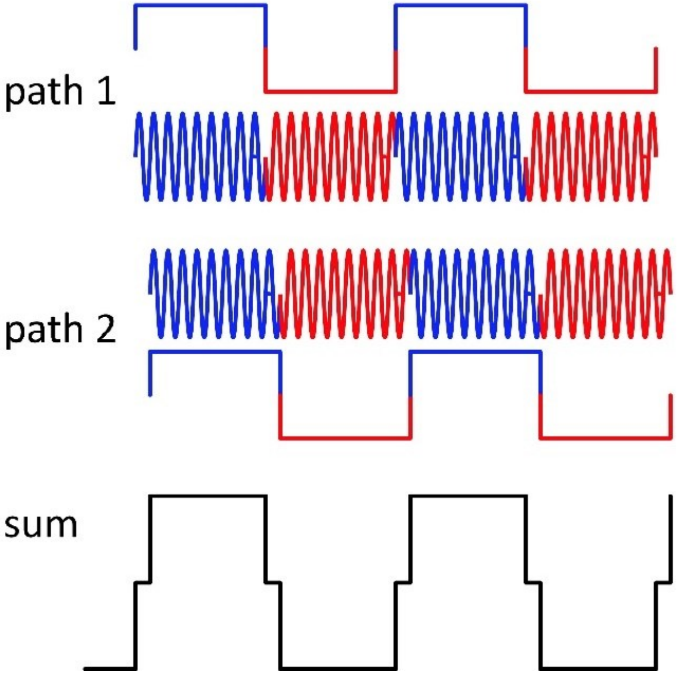


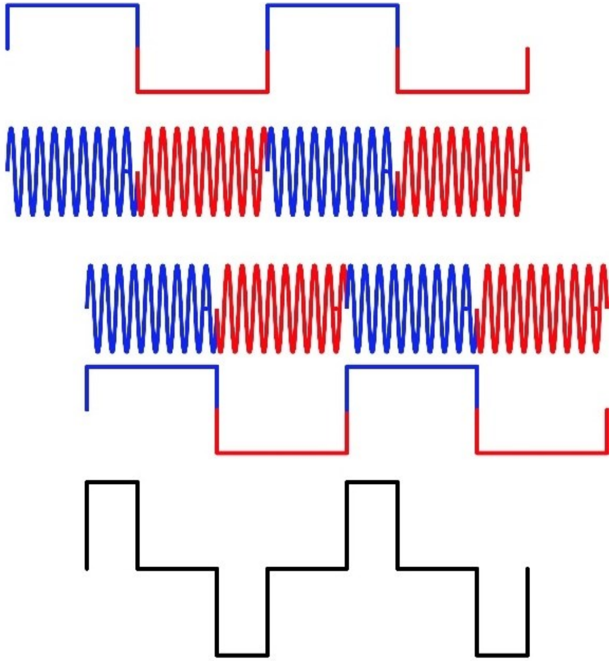
Multipath propagation: fading & ISI



(Delay spread<< symbol period): fading
LOS, NLOS arrive with aligned symbol periods.
LOS, NLOS possibly out-of-phase: weak signal.

(Delay spread ≥ symbol period): ISI
One bit period interferes with another.
Need adaptive equalization or OFDM.





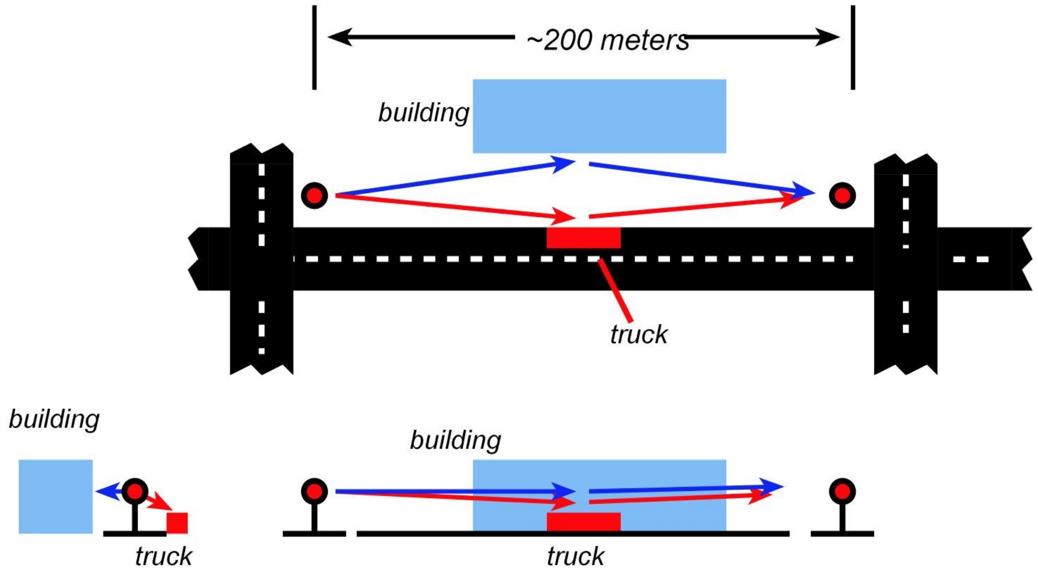
Beamforming can suppress ISI

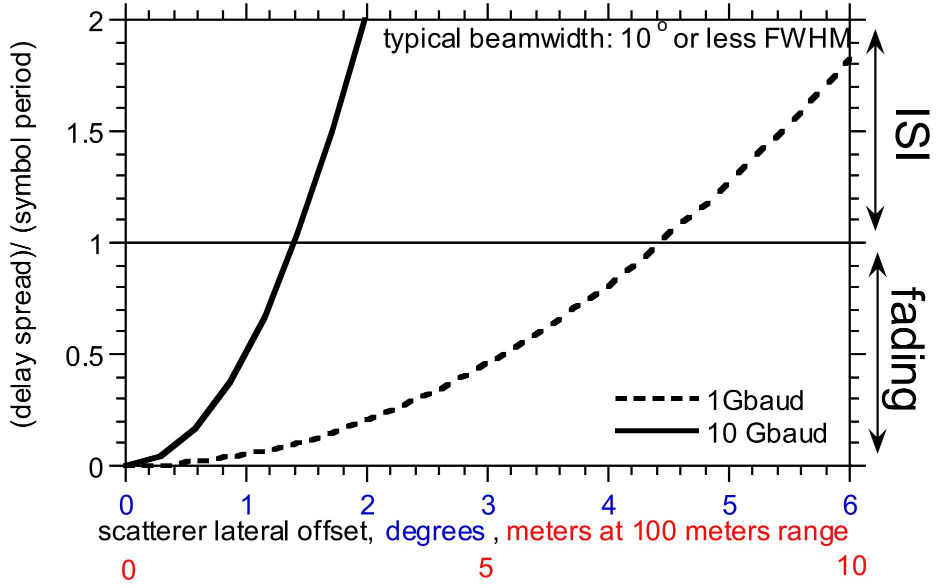
1 Gbaud with 10° array beamwidth :
multipath mostly causes fading
not much ISI

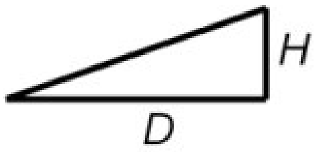
10 Gbaud with 10° array beamwidth :
significant fading and significant ISI

Solution 1: adaptive equalization or ODFM
cost, complexity @ high rates ?

Solution 2: larger arrays
narrower beamwidth

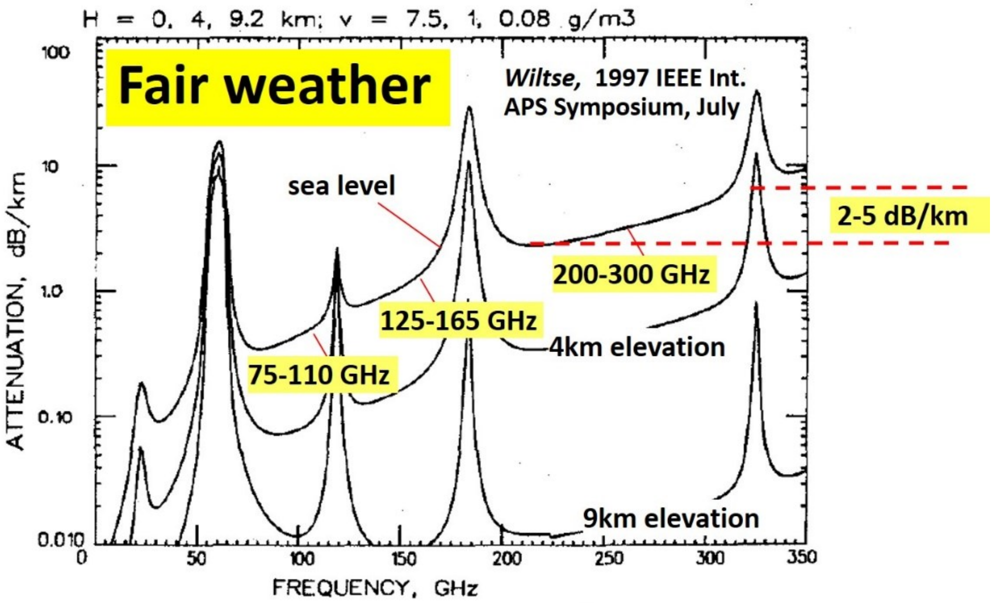






$$\text{Delay spread} \cong \frac{H^2}{2Dc}$$

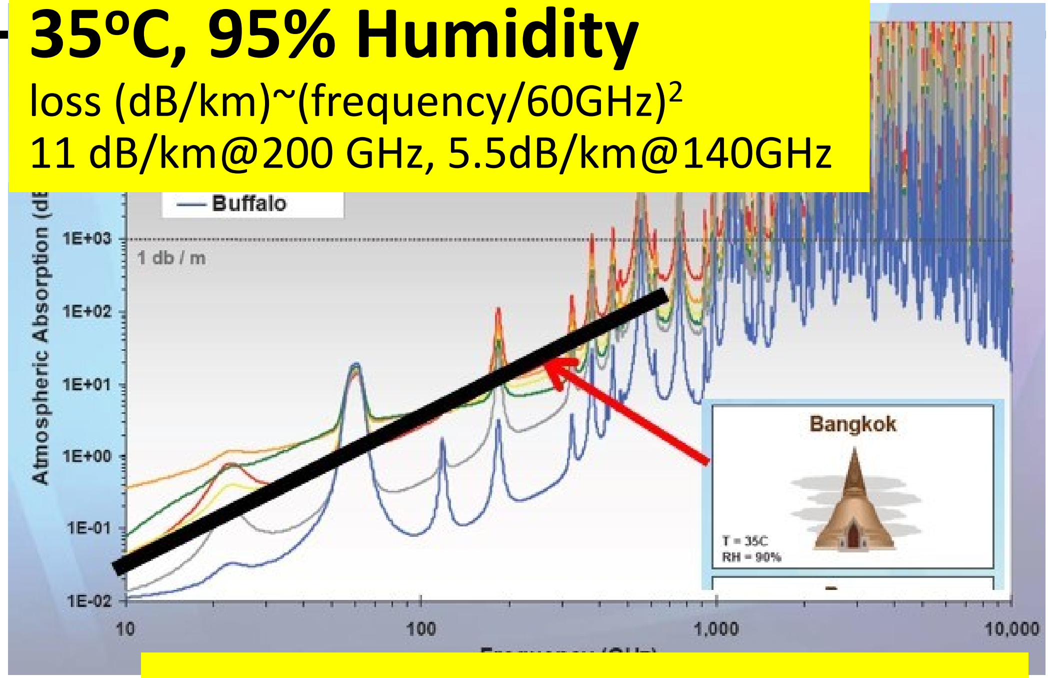
Propagation, rain or shine



35ºC, 95% Humidity

loss (dB/km)~(frequency/60GHz)^2

11 dB/km@200 GHz, 5.5dB/km@140GHz

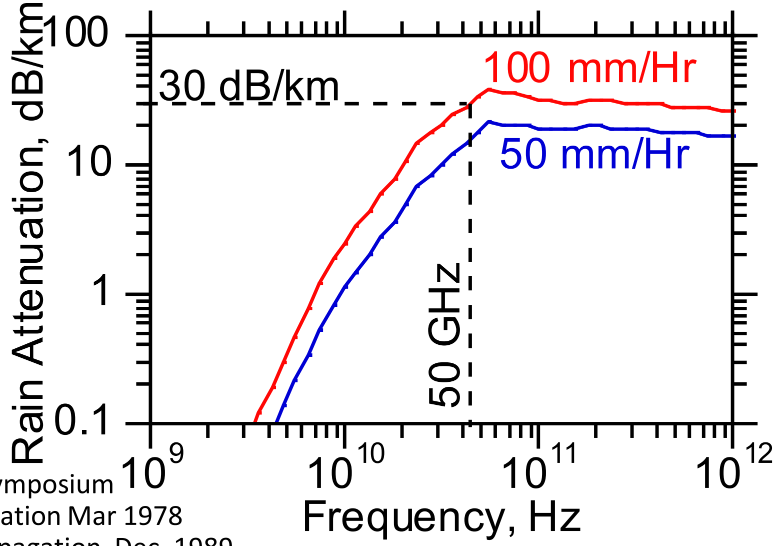


Rain:

10^{-3}: 25mm/hr, 11dB/km

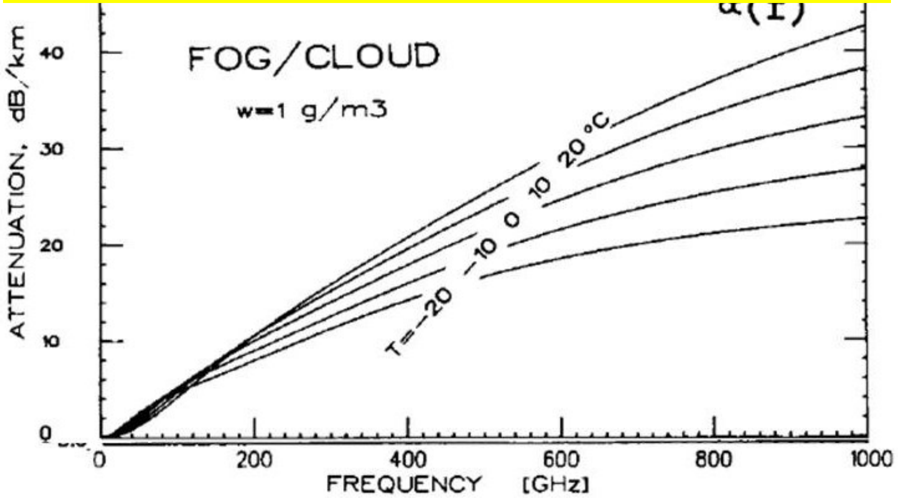
10^{-4}: 50-85mm/hr, 19dB/km

10^{-5}: 100+mm/hr: 30dB/km



Extreme Fog (1g/m^3)

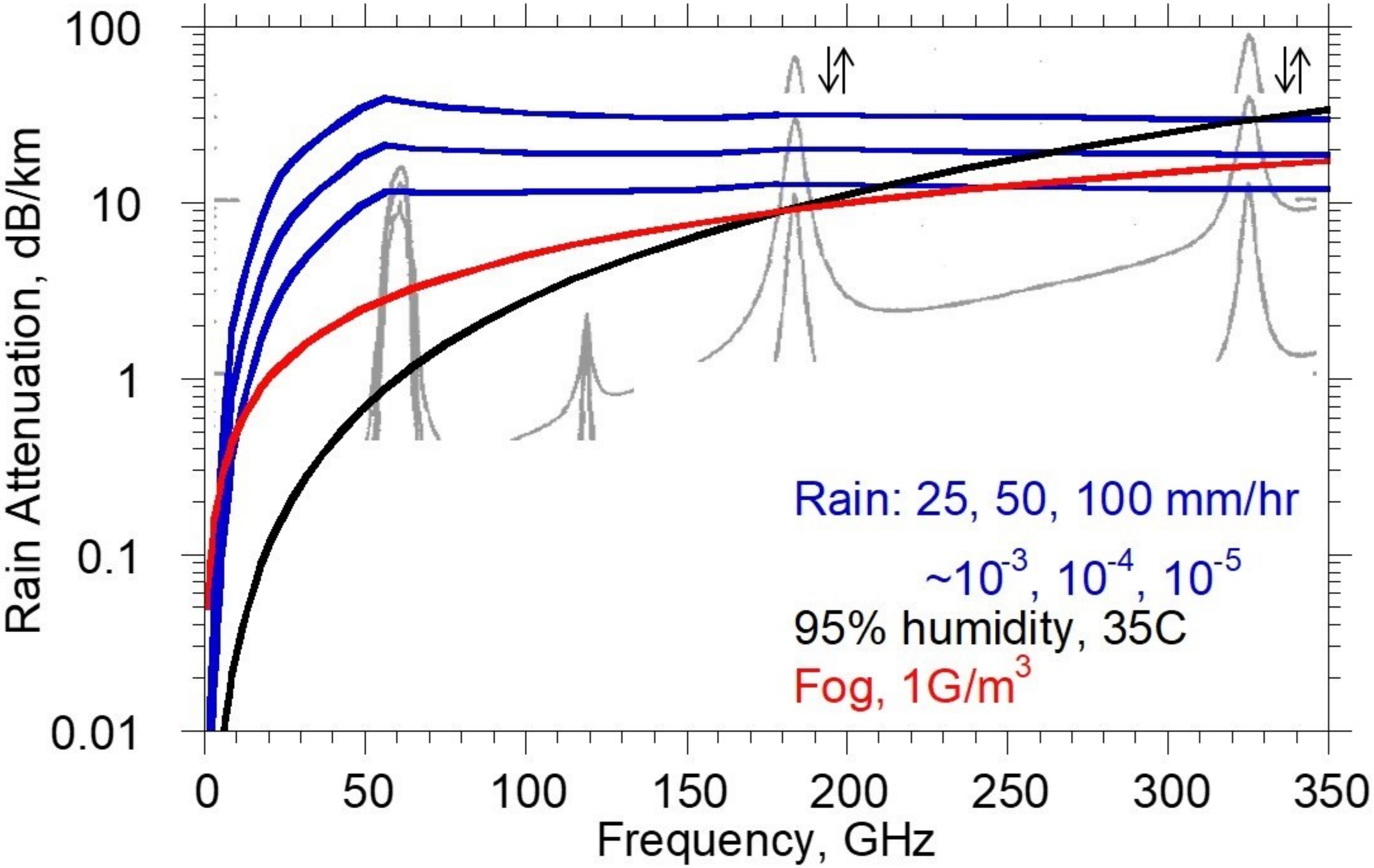
~(25 dB/km)x(frequency/500 GHz)



Rosker, Wallace, 2007 IEEE International microwave symposium
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

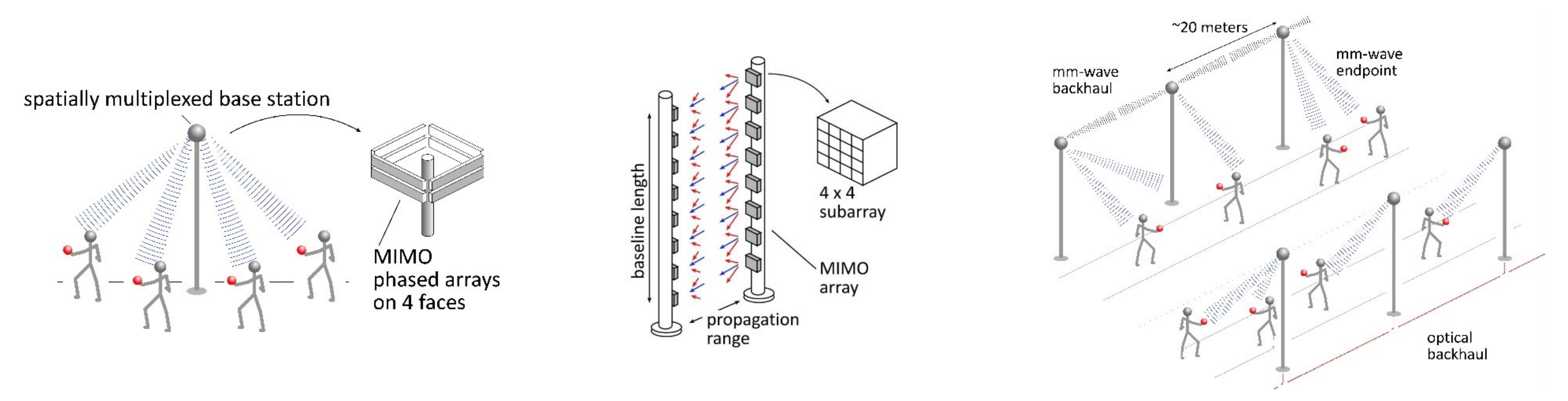
Atmospheric Attenuation: Implications

Worst-case attenuation: ~constant over 50-250 GHz.
10^{-5} outage rate: equal losses over 50-300 GHz
10^{-3} outage rate: equal losses over 50-200 GHz



Hardware favors lower frequencies
Propagation environment is similar for 50-250GHz links
...but don't forget λ^2/R^2 term !
Exclusive use of VLSI Si processes would force use of ~ < 180GHz

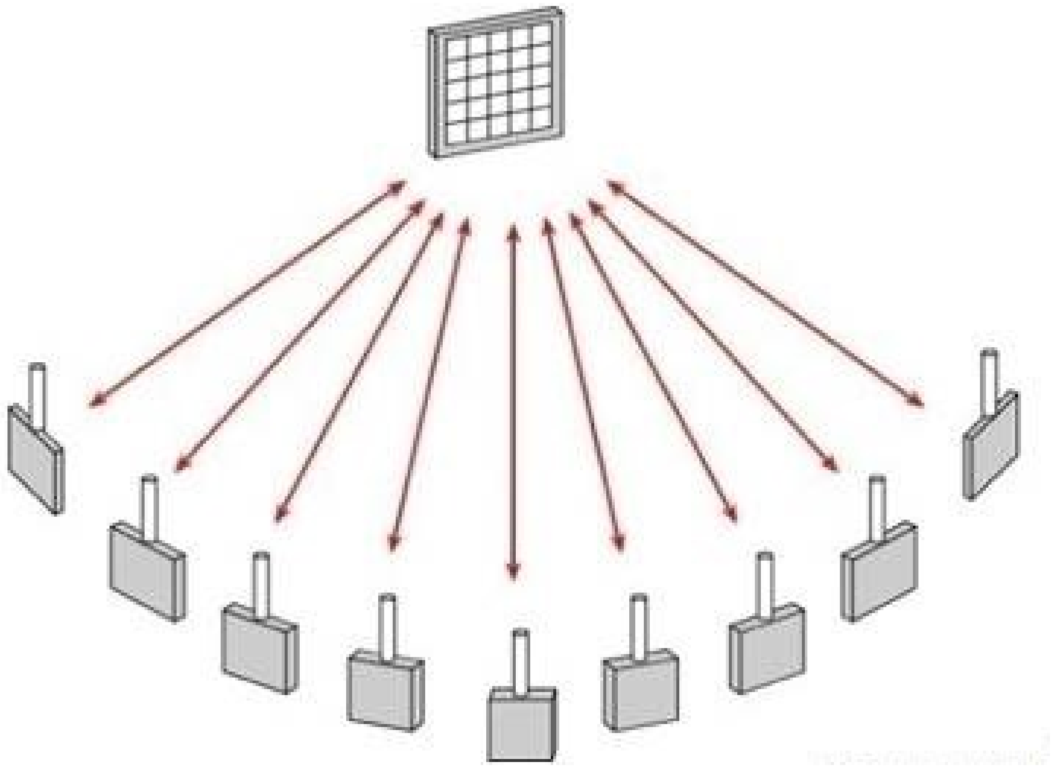
140-340 GHz: Possible Systems



Spatial Multiplexing: massive capacity RF networks

$\#\text{beams} \leq \#\text{array elements}$

$\text{angular resolution} \approx \lambda / (\text{array width})$

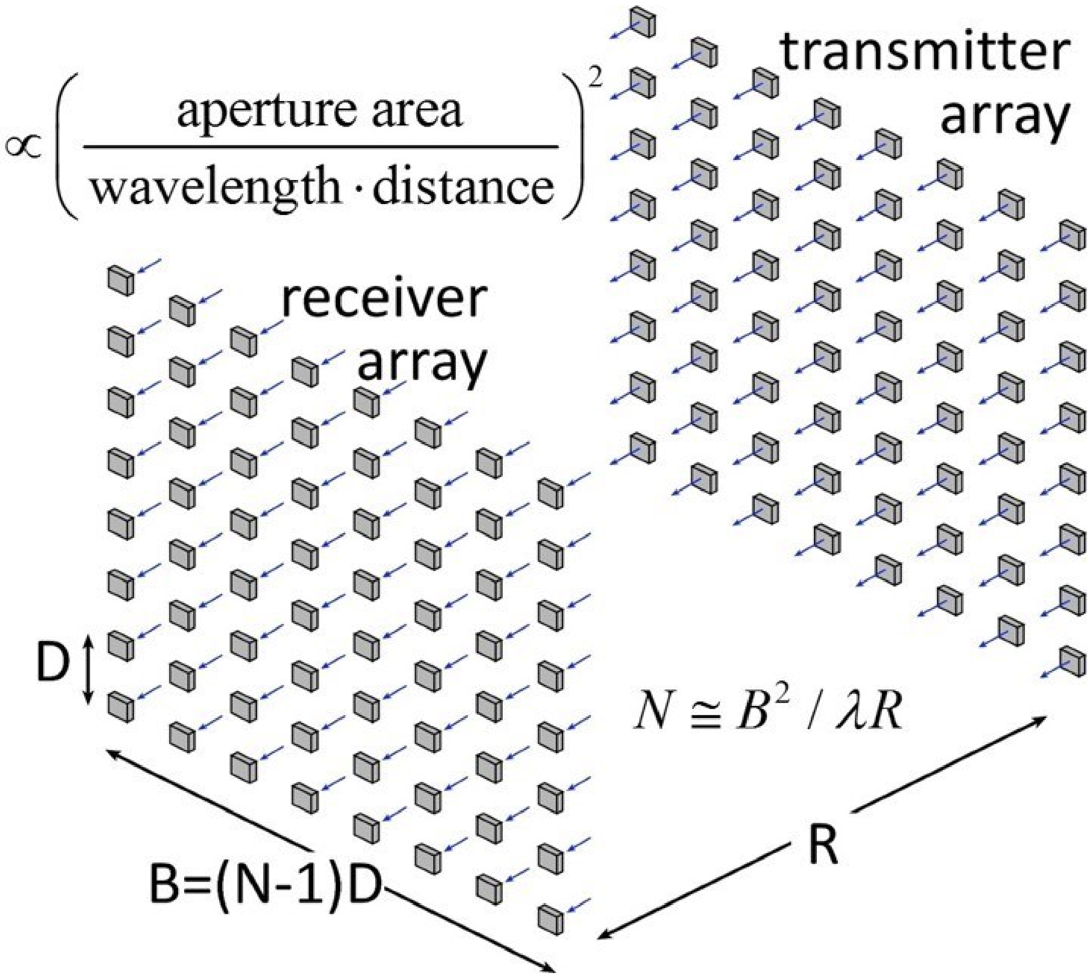


multiple independent beams
- each carrying different data
- each independently aimed
- # beams approaches # array elements
- small: 1000 elements @220 GHz=3 square inches

Hardware: multi-beam phased array ICs

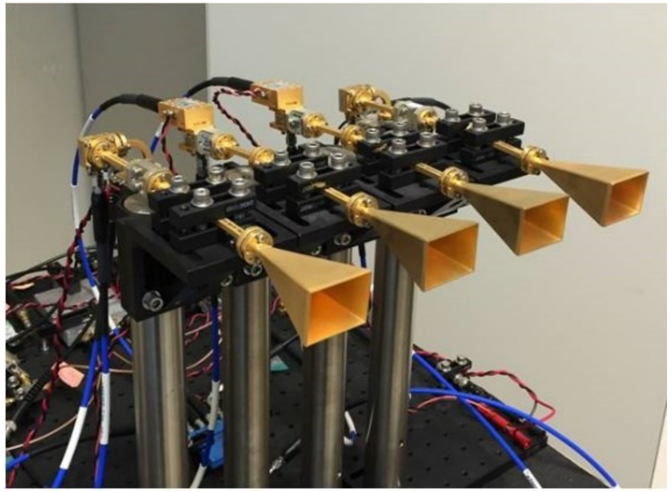
mm-Wave LOS MIMO: multi-channel for high capacity

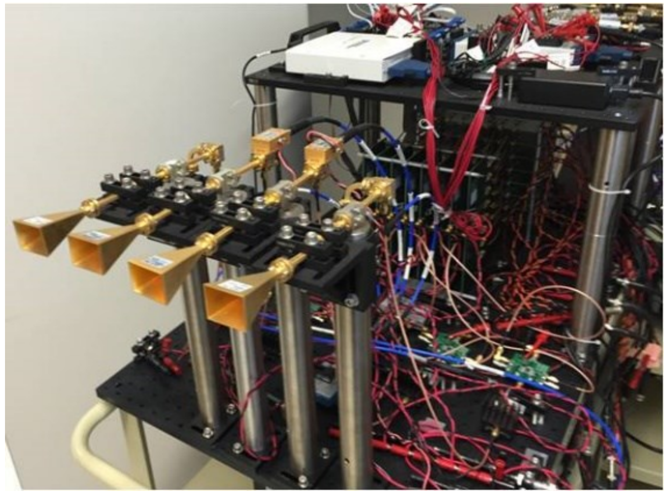
$$\#\text{ channels} \propto \left(\frac{\text{aperture area}}{\text{wavelength} \cdot \text{distance}} \right)^2$$



$$\theta_{res} \approx \lambda / ND = D / R$$

$$\rightarrow N \approx B^2 / \lambda R$$





Massive capacity wireless; physically small

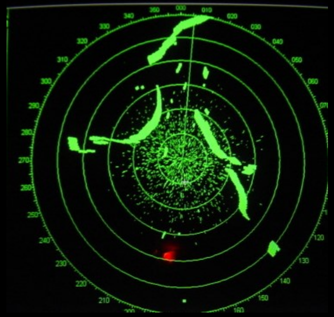
Torklinson : 2006 Allerton Conference
Sheldon : 2010 IEEE APS-URSI
Torklinson : 2011 IEEE Trans Wireless Comm.

mm-wave imaging: TV-like resolution, small array

mm-waves → high resolution from small antenna apertures

What you see in fog

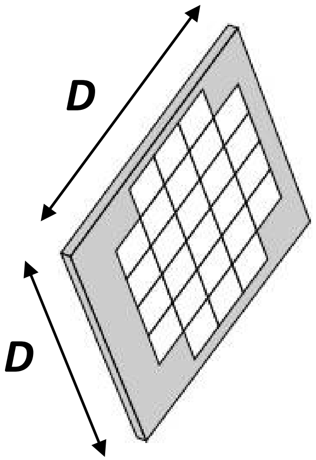
What 10GHz radar shows



What you want to see

goal: ~0.2^o resolution, 10^3-10^6 pixels

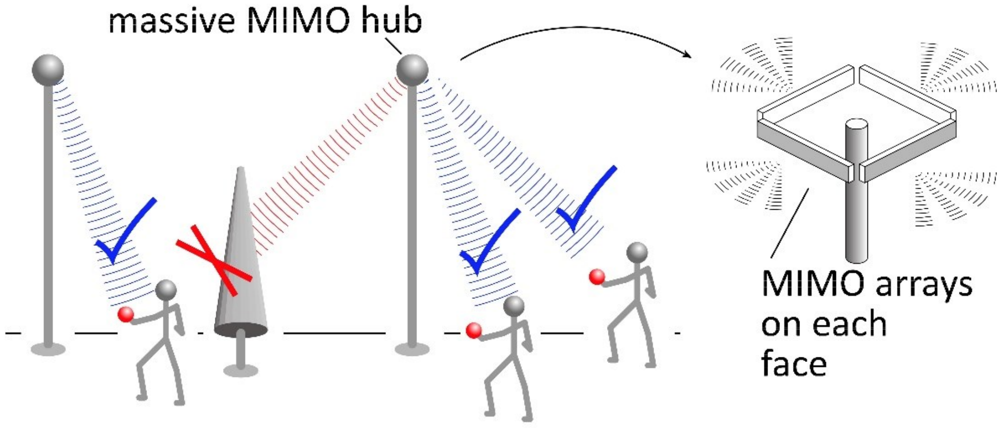
NxN phased array

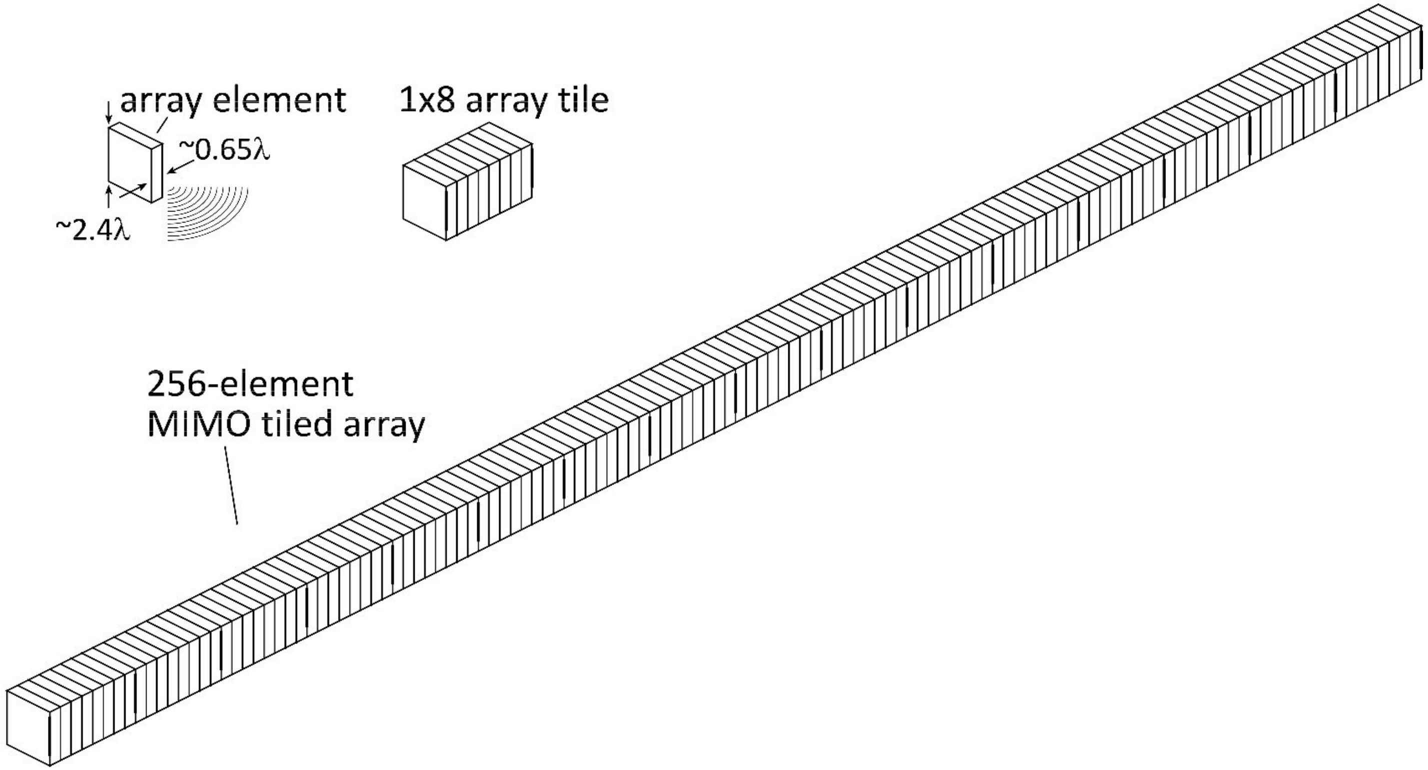


angular resolution = λ /D (radians)
340 GHz, 35 cm/14 inch aperture → 0.14 degree resolution

HDTV-like resolution, fits on car, plane, UAV

140 GHz spatially multiplexed base station

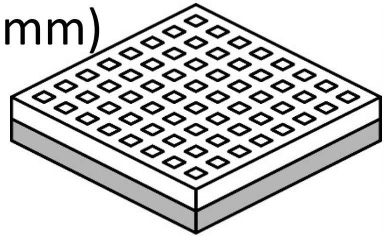




1 Tb/s spatially-multiplexed base station

256 users/face, 4 faces
1024 total users @ 1 user/beam, 1 Gb/s/beam;
225 m range

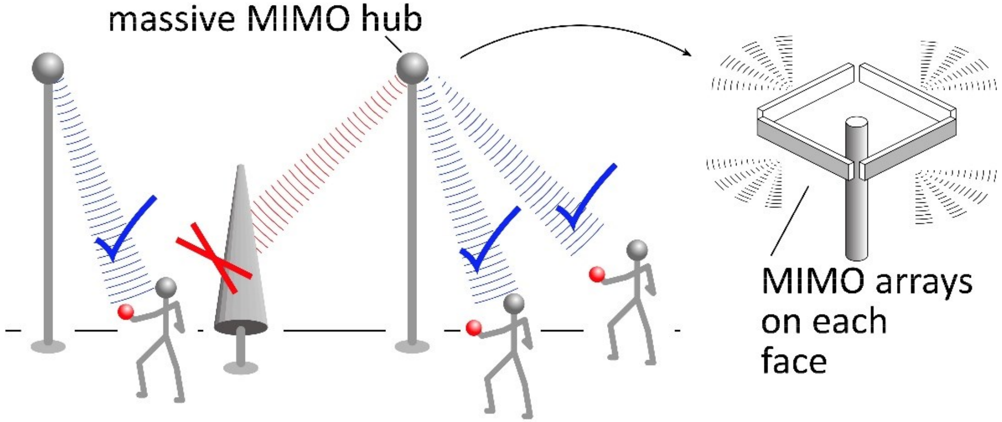
Handset:
8 × 8 array
(9×9mm)

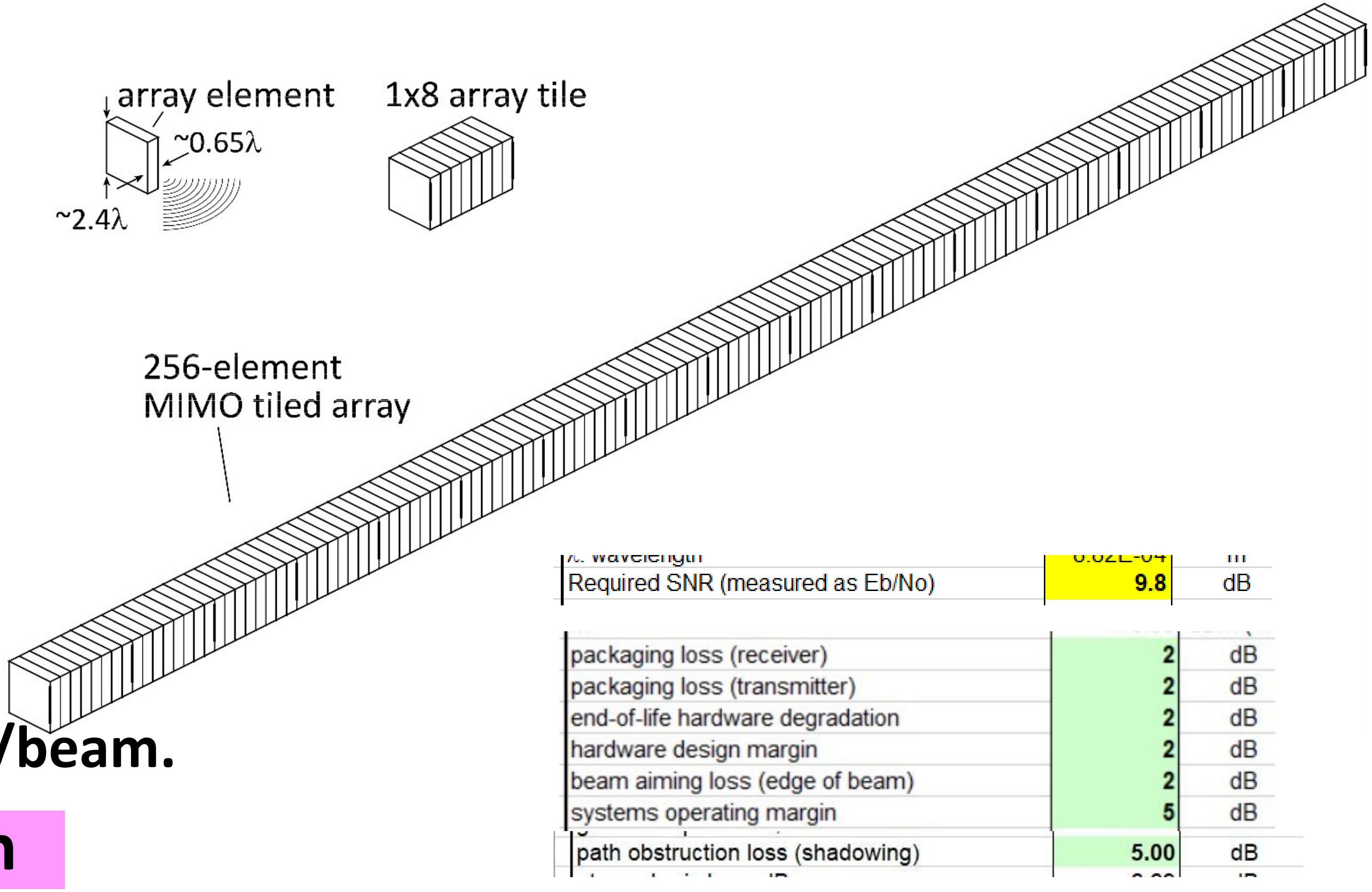


Link budget is feasible, but...

Required component dynamic range ?
Required complexity of back-end beamformer ?

140 GHz spatially multiplexed base station





λ: wavelength	[illegible]	m
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.

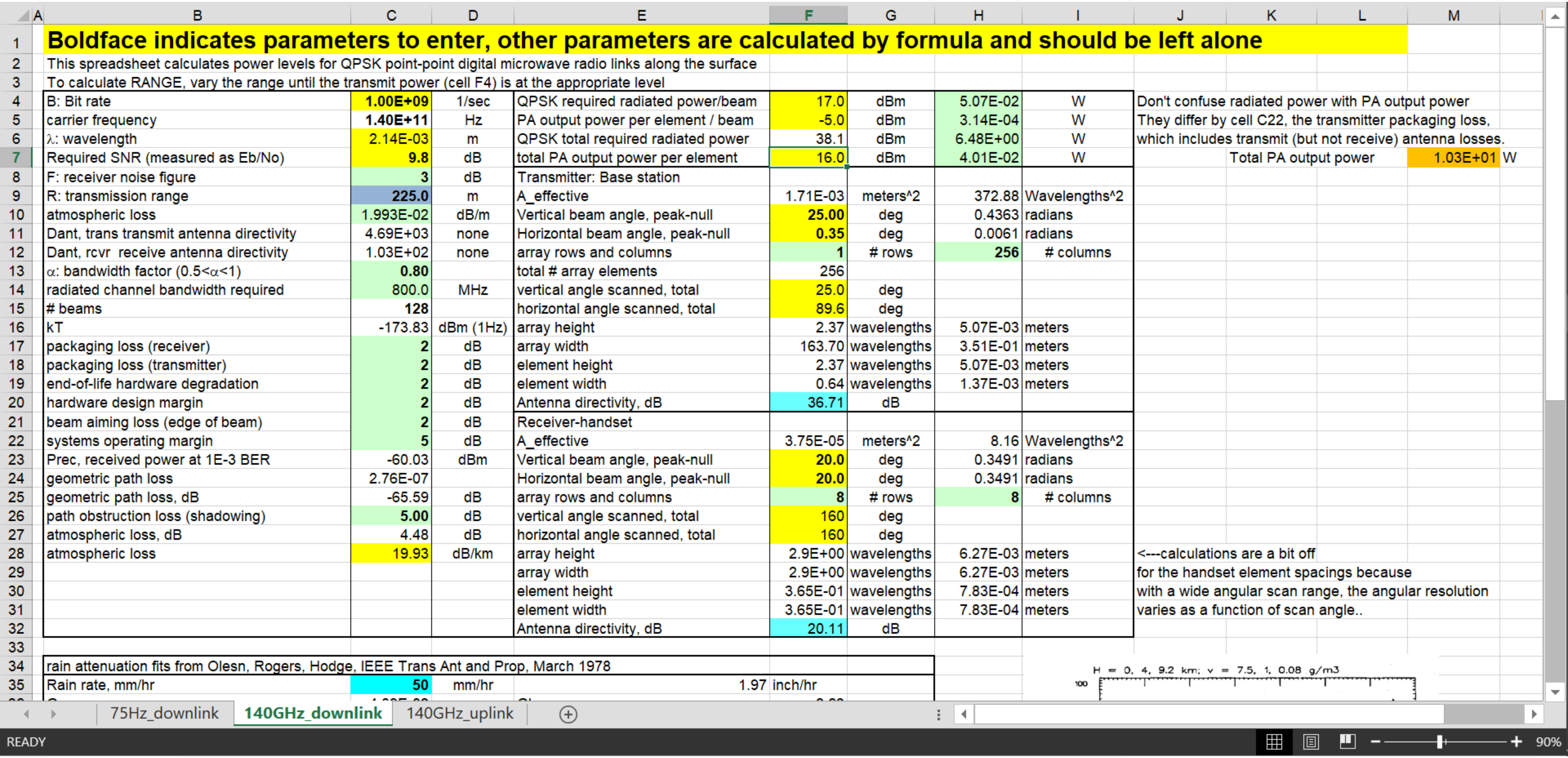
225 meters range in 50 mm/hr rain

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

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

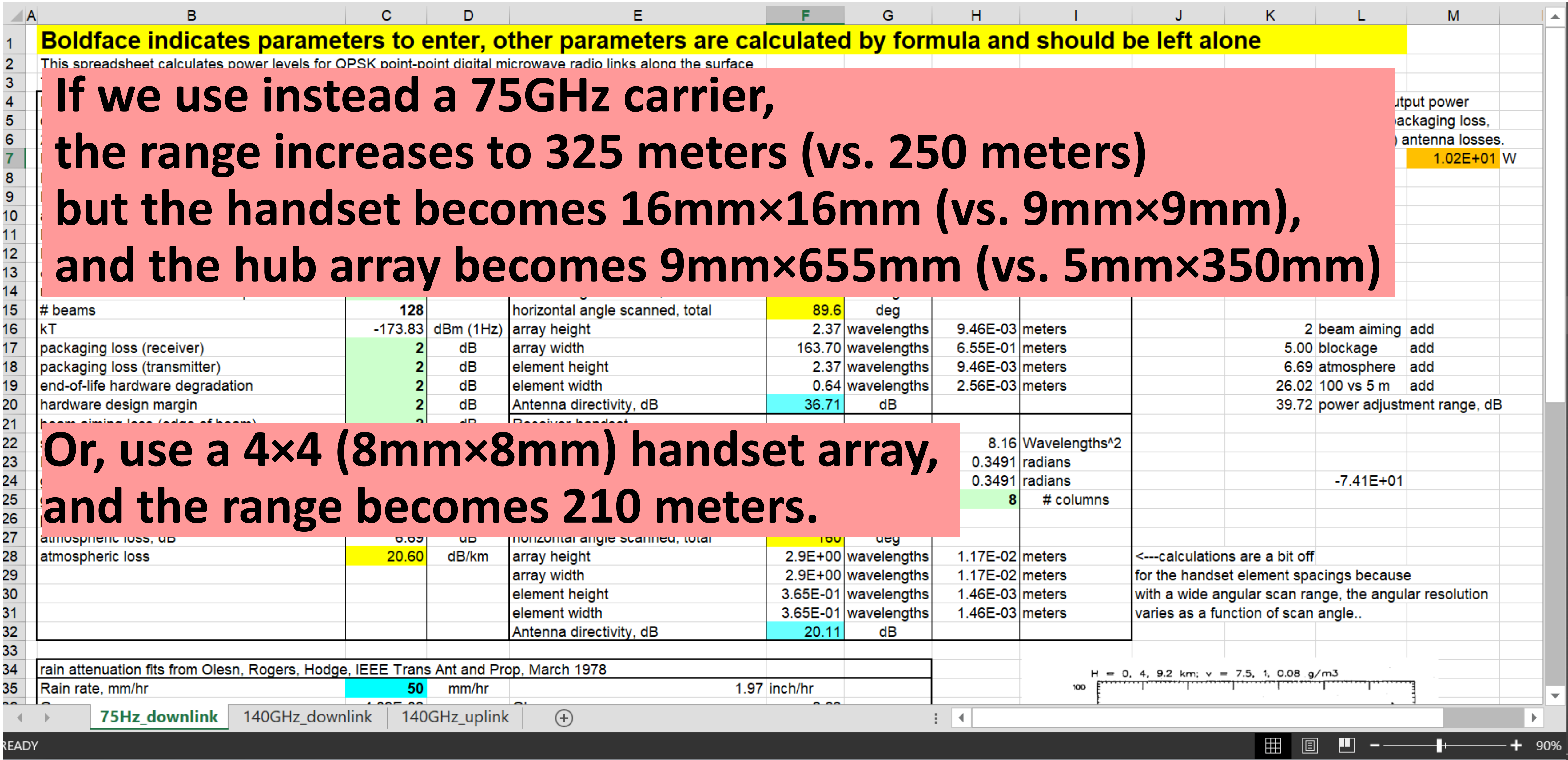
LNAs: 3 dB noise figure

140 GHz spatially multiplexed base station



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

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)

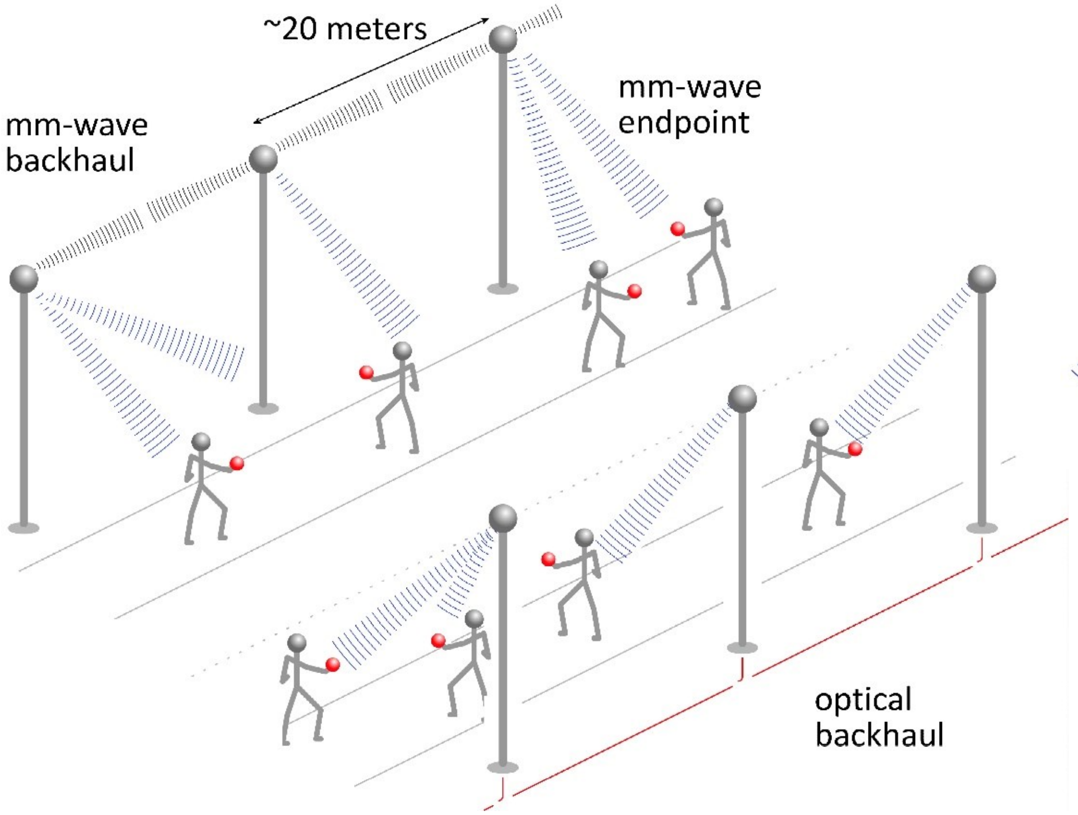
Or, use a 4×4 (8mm×8mm) handset array,
and the range becomes 210 meters.

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

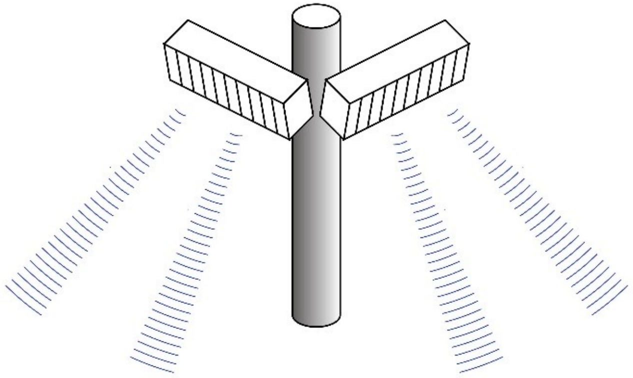
This spreadsheet calculates power levels for QPSK point-point digital microwave radio links along the surface

	B	C	D	E	F	G	H	I	J	K	L	M
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				
27	atmospheric loss, dB	6.69	dB	horizontal angle scanned, total	160	deg						
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						

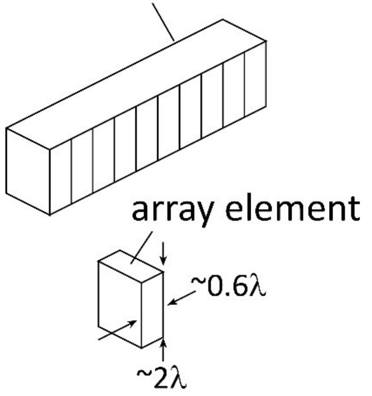
75GHz or 140GHz spatially multiplexed femtocells



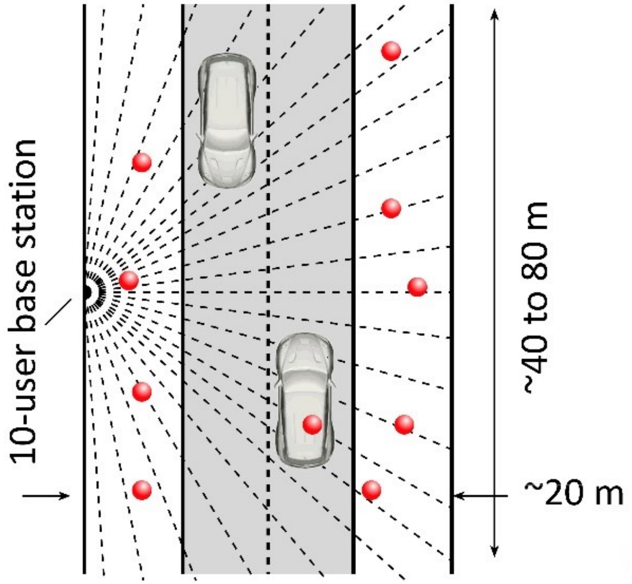
Pole- or wall- mounted multibeam picocell



1 x 10 MIMO array

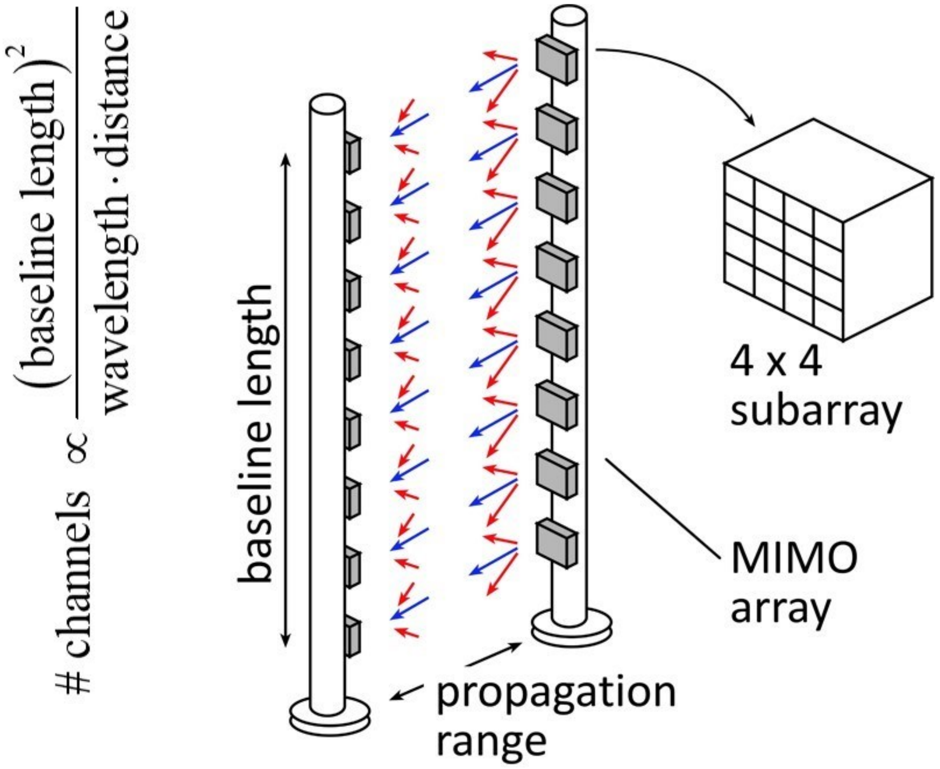


pedestrians on sidewalks, cars on street

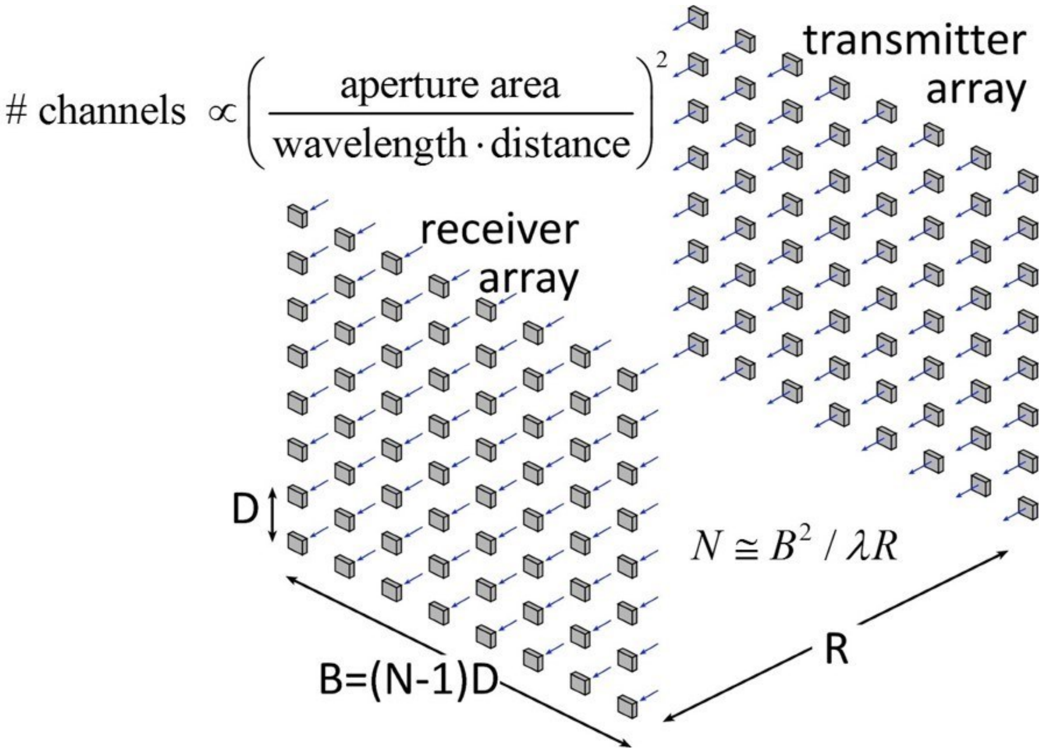


340 GHz (or even 650 GHz) backhaul

linear array



square array



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

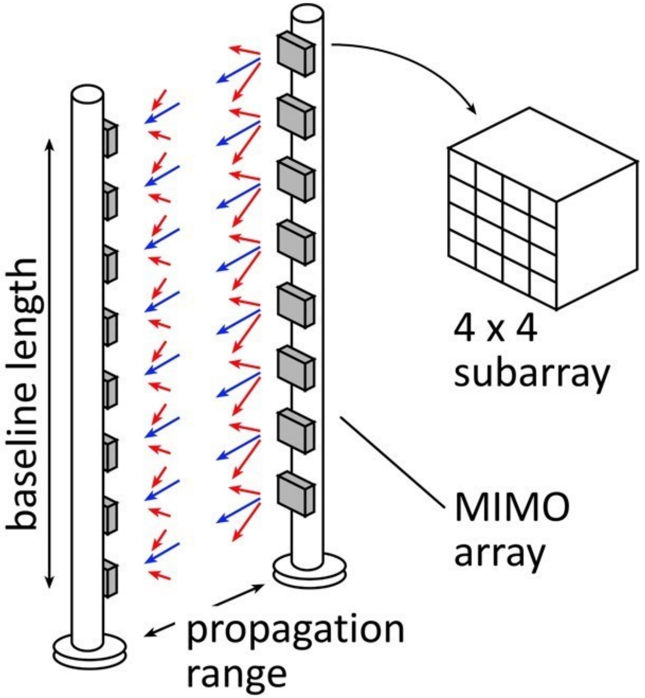
wireless @ optical speed; link network where fiber is too expensive to place.

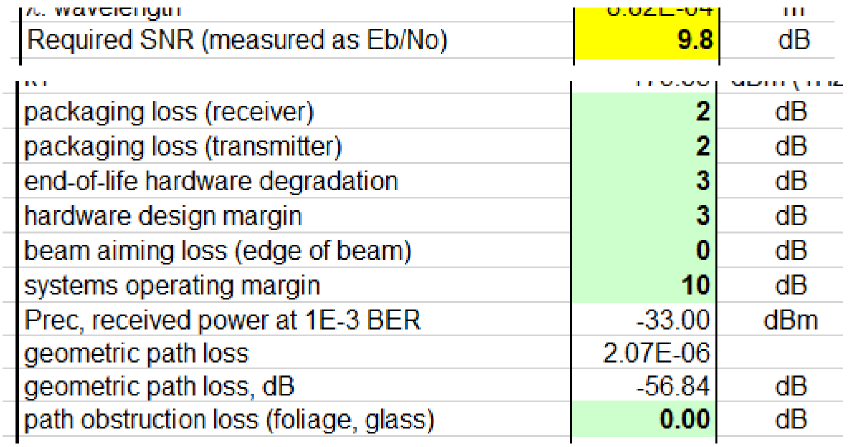
340 GHz: 640Gb/s @ 500 meters range; 1.6 meter linear array **(5Tb/s for 8×8 square array)**.

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

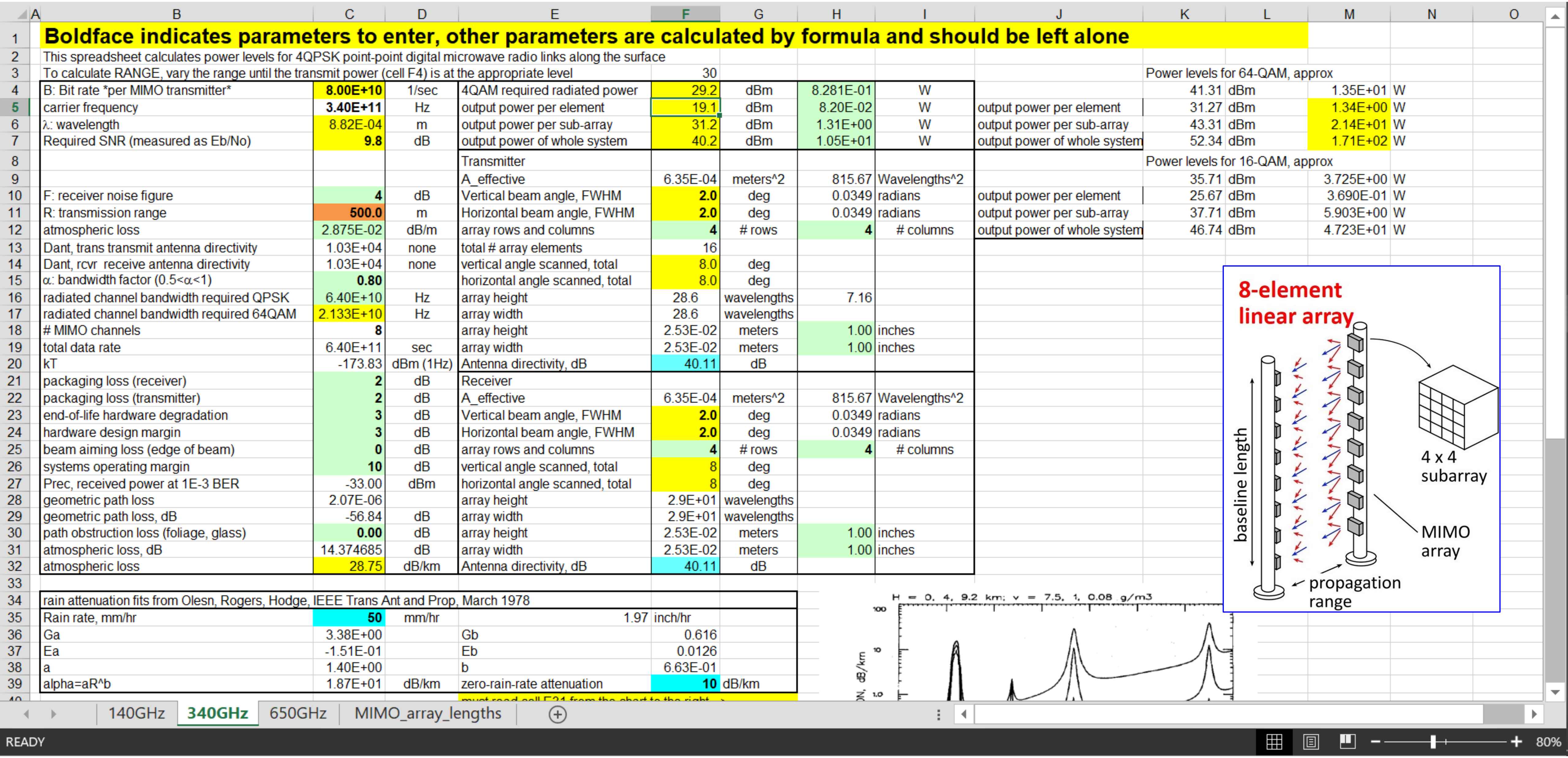
500 meters range in 50 mm/hr rain; 29 dB/km

Realistic packaging loss, operating & design margins

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

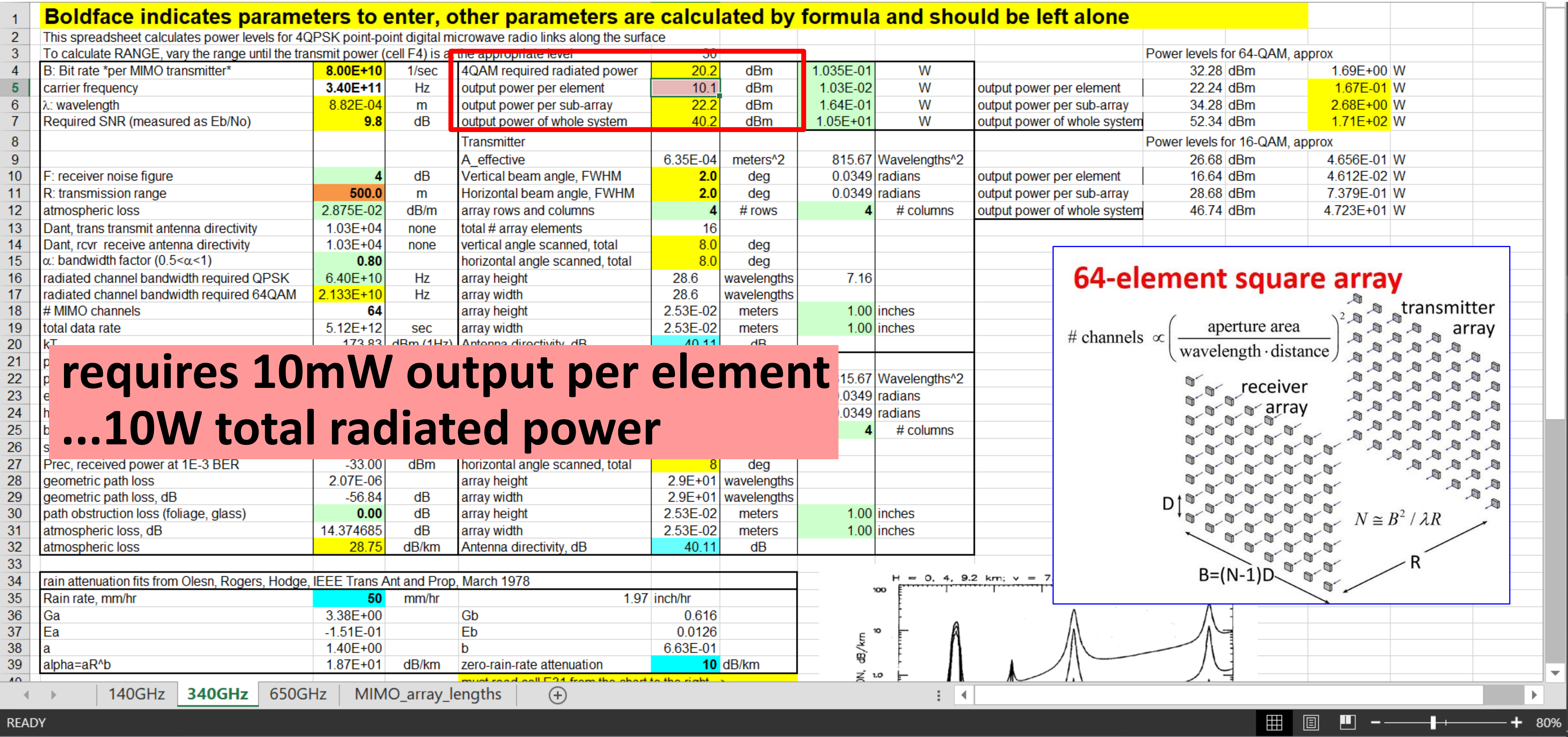
LNAs: 4 dB noise figure

340 GHz 640 Gb/s MIMO backhaul



	B	C	D	E	F	G	H	I	J	K	L	M	N
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							

340 GHz 5 Tb/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	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							
40				must read cell F21 from the chart to the right -->									

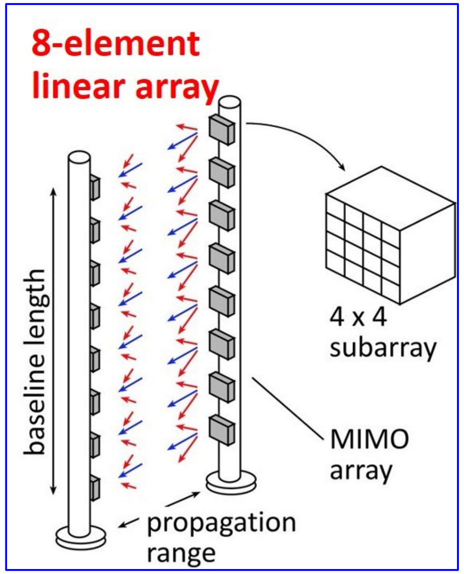
requires 10mW output per element

...10W total radiated power

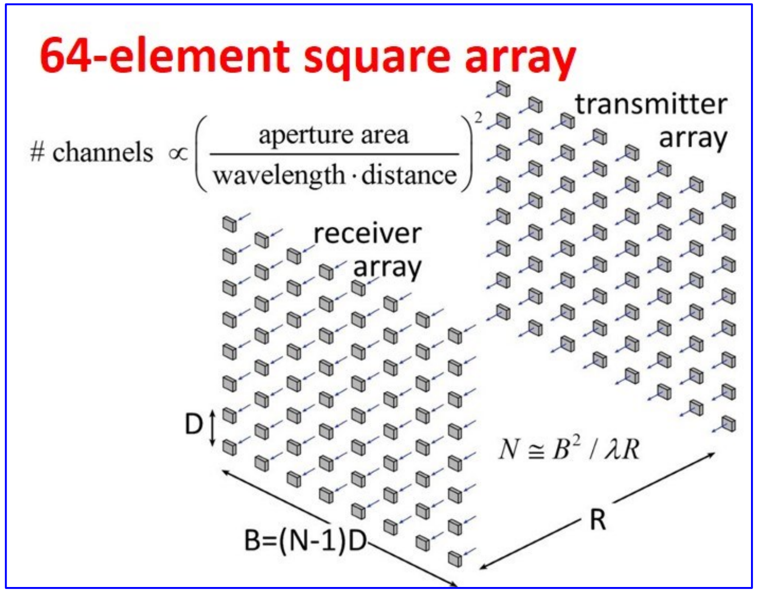
140 GHz, 640 Gb/s MIMO backhaul

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



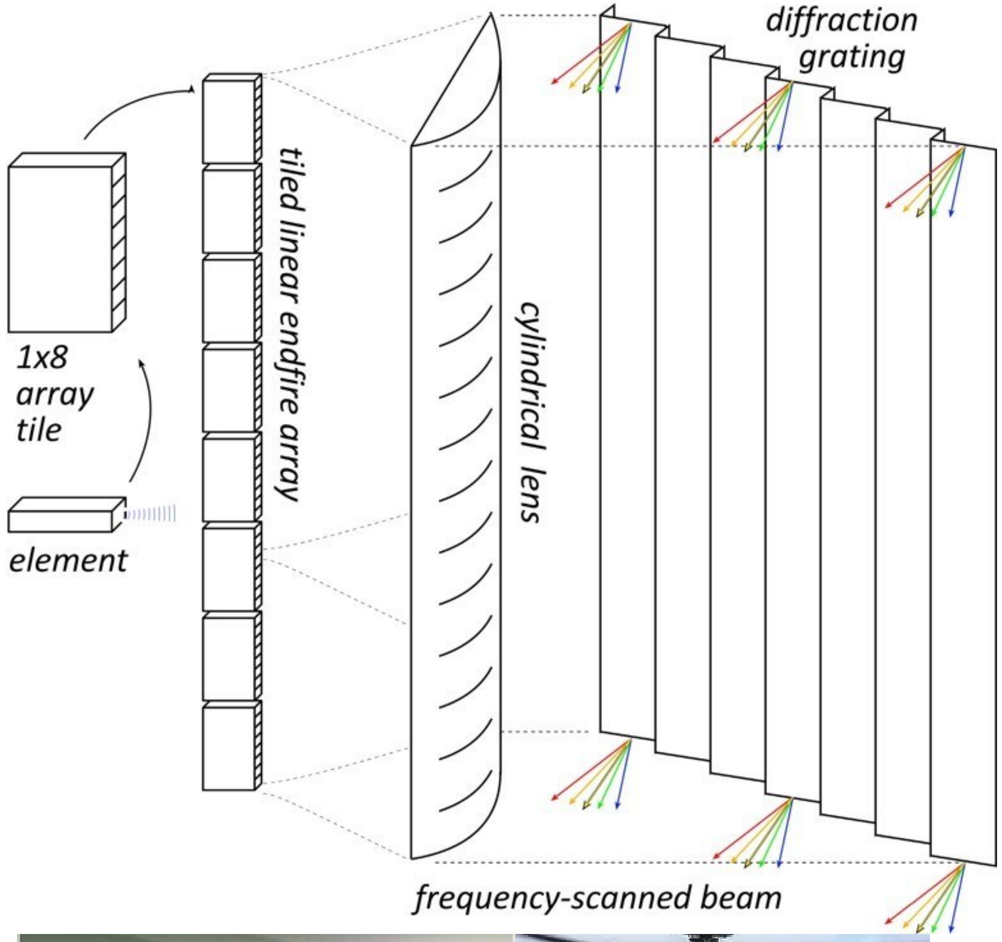
340 GHz frequency-scanned imaging car radar

Imaging for cars, aircraft
drive safely @ 65MPH in heavy fog
fly in heavy dust/fog/smoke

Short wavelengths:
HDTV-resolution imaging,
small: helicopter, drone, car

The challenge: complexity
standard array: # pixels = # RF channels
HDTV image: ~2×10^6 pixels.
Need 2×10^6 RF channels !

Hardware-efficient imaging
RF channels << # pixels
several techniques



340 GHz frequency-scanned imaging car radar

See a soccer ball at 300 meters in heavy fog
(10 seconds warning @ 100 km/hr.)
(5 dB SNR, 35 dB/km, 30cm diameter target, 10% reflectivity)

Image refresh rate: 60 Hz

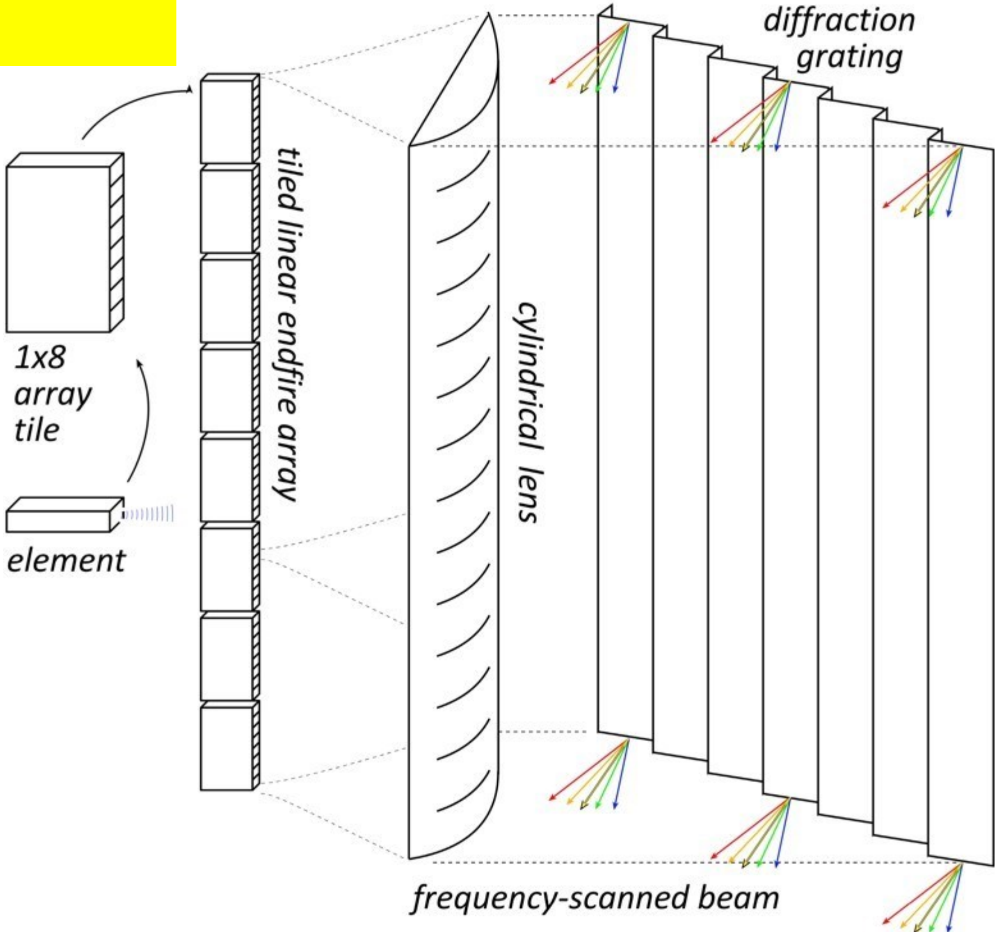
Resolution 64×512 pixels

Angular resolution: 0.14 degrees

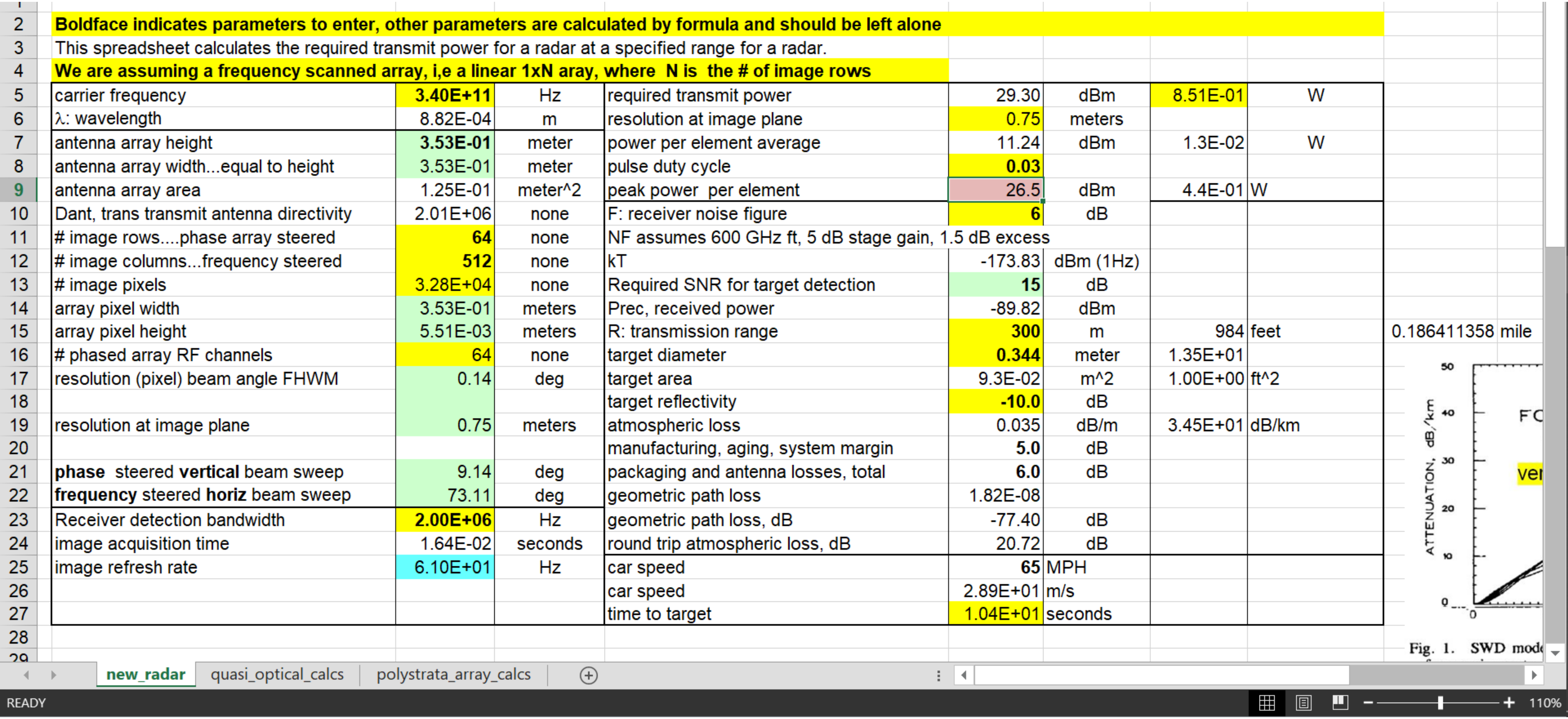
Angular field of view: 9 by 73 degrees

Aperture: 35 cm by 35 cm

Component requirements:
44 mW peak power/element,
3% pulse duty factor
6 dB noise figure,
3 dB package losses (each: trx, rcvr)
5 dB manufacturing/aging margin

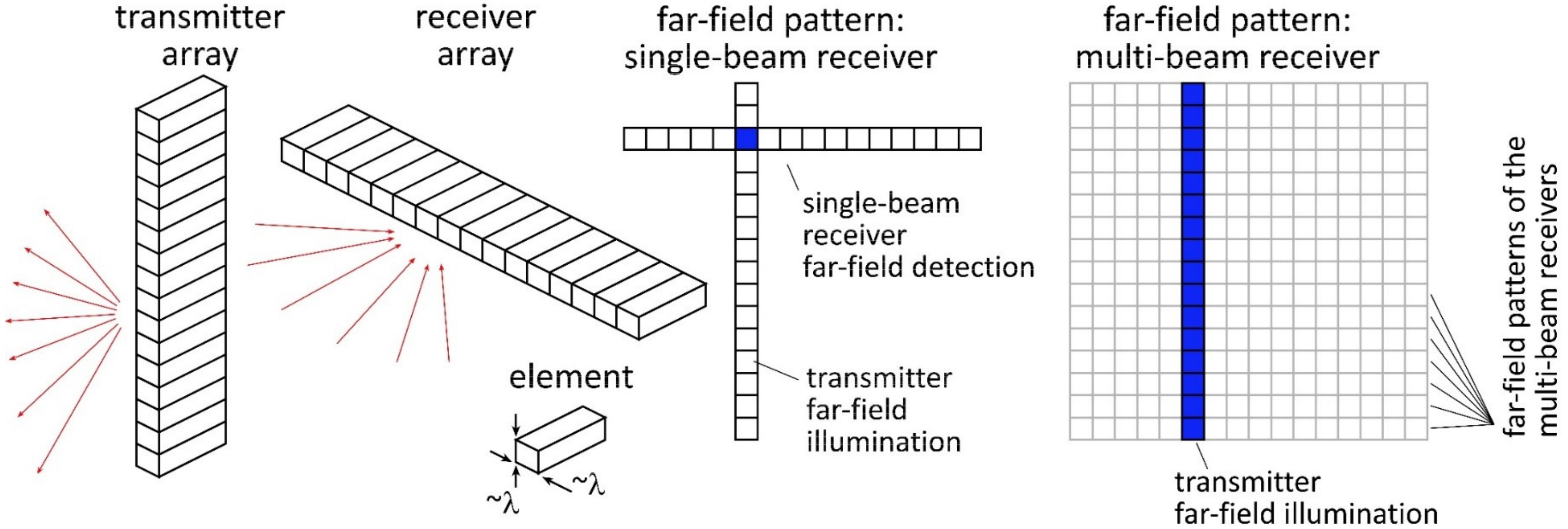


340 GHz frequency-scanned imaging car radar



2	**Boldface indicates parameters to enter, other parameters are calculated by formula and should be left alone**								
3	This spreadsheet calculates the required transmit power for a radar at a specified range for a radar.								
4	**We are assuming a frequency scanned array, i,e a linear 1xN aray, where N is the # of image rows**								
5	carrier frequency	**3.40E+11**	Hz	required transmit power	29.30	dBm	8.51E-01	W	
6	λ: wavelength	8.82E-04	m	resolution at image plane	0.75	meters			
7	antenna array height	**3.53E-01**	meter	power per element average	11.24	dBm	1.3E-02	W	
8	antenna array width...equal to height	3.53E-01	meter	pulse duty cycle	**0.03**				
9	antenna array area	1.25E-01	meter^2	peak power per element	26.5	dBm	4.4E-01	W	
10	Dant, trans transmit antenna directivity	2.01E+06	none	F: receiver noise figure	**6**	dB			
11	# image rows....phase array steered	**64**	none	NF assumes 600 GHz ft, 5 dB stage gain, 1.5 dB excess					
12	# image columns...frequency steered	**512**	none	kT	-173.83	dBm (1Hz)			
13	# image pixels	3.28E+04	none	Required SNR for target detection	**15**	dB			
14	array pixel width	3.53E-01	meters	Prec, received power	-89.82	dBm			
15	array pixel height	5.51E-03	meters	R: transmission range	**300**	m	984	feet	0.186411358 mile
16	# phased array RF channels	64	none	target diameter	**0.344**	meter	1.35E+01		
17	resolution (pixel) beam angle FHWM	0.14	deg	target area	9.3E-02	m^2	1.00E+00	ft^2	
18				target reflectivity	**-10.0**	dB			
19	resolution at image plane	0.75	meters	atmospheric loss	0.035	dB/m	3.45E+01	dB/km	
20				manufacturing, aging, system margin	**5.0**	dB			
21	**phase** steered **vertical** beam sweep	9.14	deg	packaging and antenna losses, total	**6.0**	dB			
22	**frequency** steered **horiz** beam sweep	73.11	deg	geometric path loss	1.82E-08				
23	Receiver detection bandwidth	**2.00E+06**	Hz	geometric path loss, dB	-77.40	dB			
24	image acquisition time	1.64E-02	seconds	round trip atmospheric loss, dB	20.72	dB			
25	image refresh rate	6.10E+01	Hz	car speed	**65**	MPH			
26				car speed	2.89E+01	m/s			
27				time to target	1.04E+01	seconds			

mm-wave imaging with crossed linear arrays



Established approach.

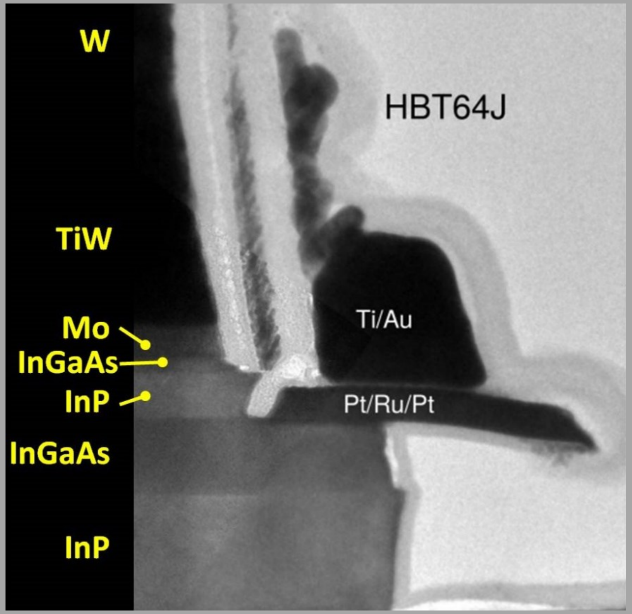
Transmitter illuminates vertical stripe. Receiver detects horizontal stripe.

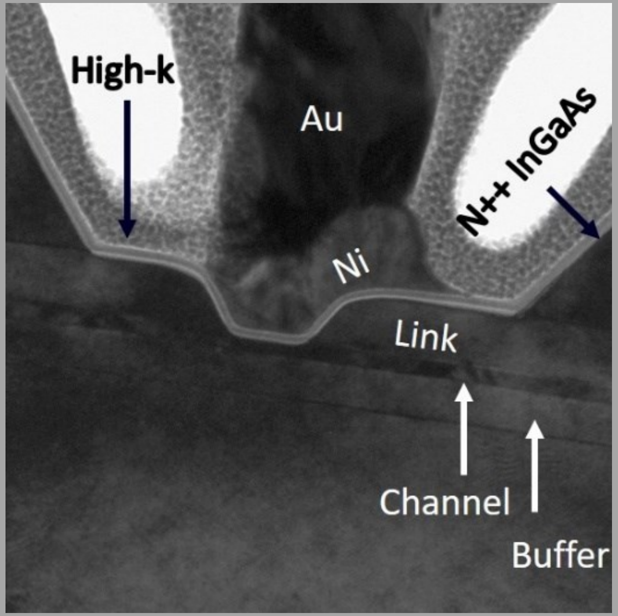
Requires 1×N arrays to form N×N image.

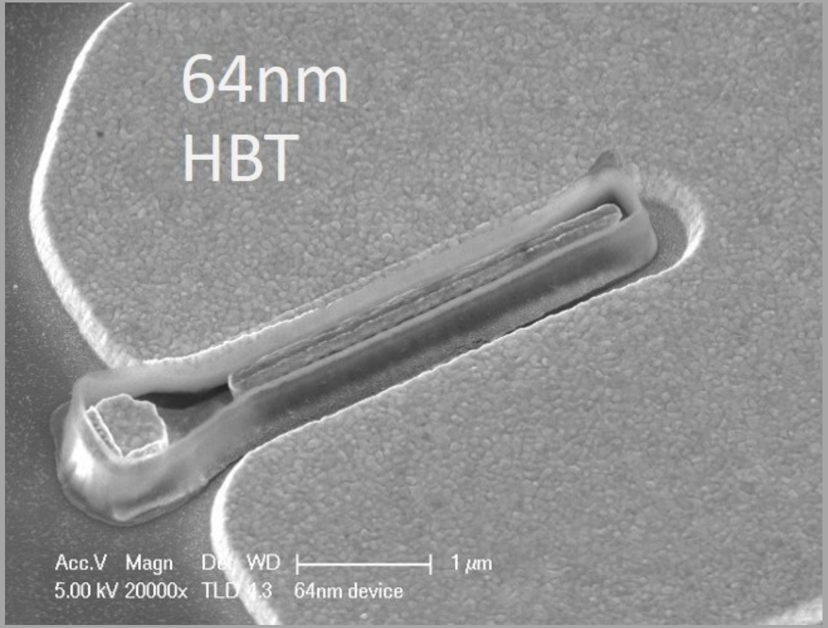
N^2:1 SNR degradation with single-beam receiver
- Only 1/N of transmitter power is detected
- Receiver directivity is N:1 smaller than if focused on one image pixel

N^1:1 SNR degradation with multi-beam receiver
- Receiver detects all transmitter power
- Receiver directivity is N:1 smaller than if focused on one image pixel

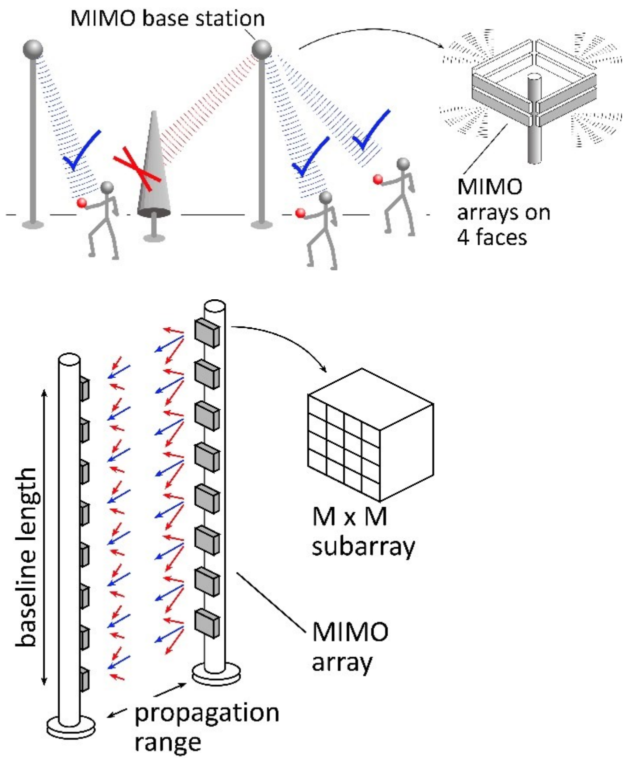
Transistors

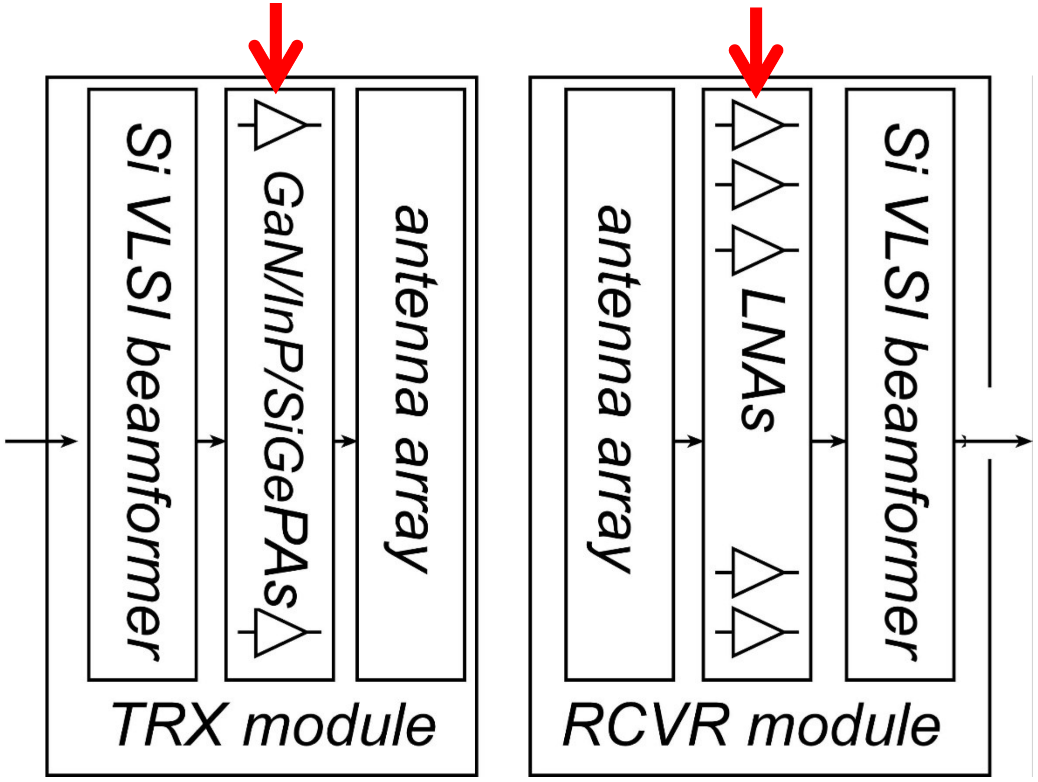






mm-Wave Wireless Transceiver Architecture





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

...similar to today's cell phones.

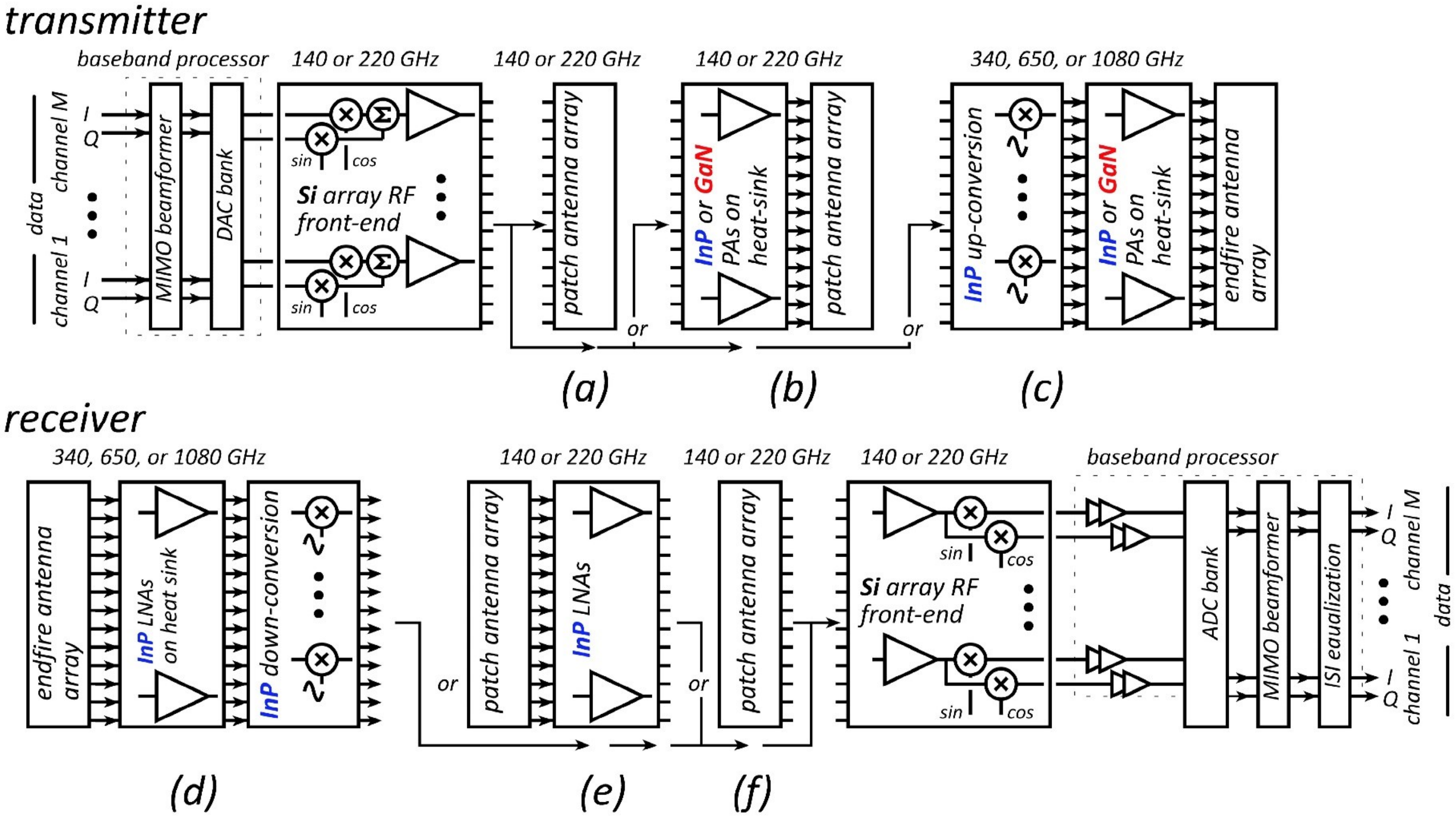
IC Technologies for 100 + GHz systems

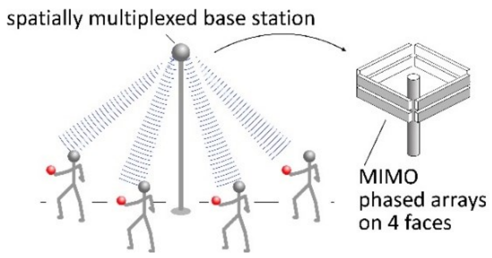
Silicon
baseband processing at all frequencies
RF sections @ 140, 200GHz
PAs, LNAs in short-range 140, 220 GHz links

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

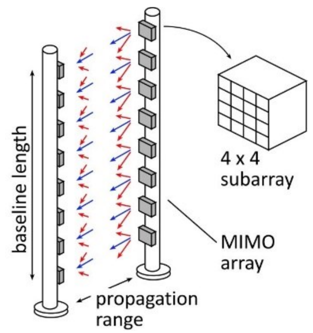
InP HEMT
low-noise amplifiers in long-range 140,220GHz links
low-noise amplifiers @ 340, 650GHz

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**

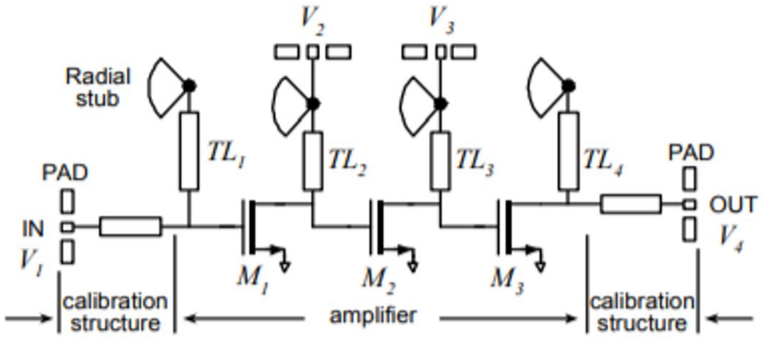


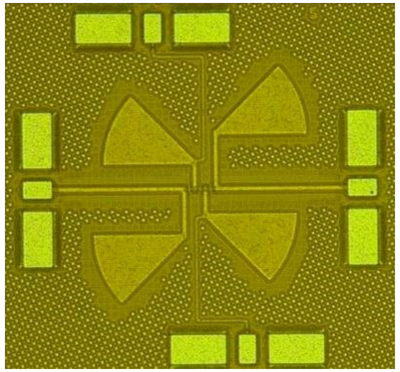
Point-point MIMO:
340GHz: F= **4dB**, P_{avg}=9.9dBm, P_{sat}≅**13.9dBm**
650GHz: F= **4dB**, P_{avg}=14.5dBm, P_{sat}≅**18.5dBm?**

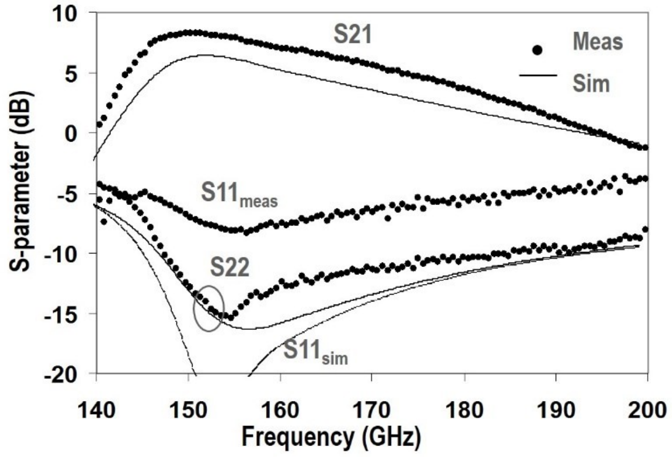
mm-wave CMOS (UCSB examples)

150 GHz amplifier:

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

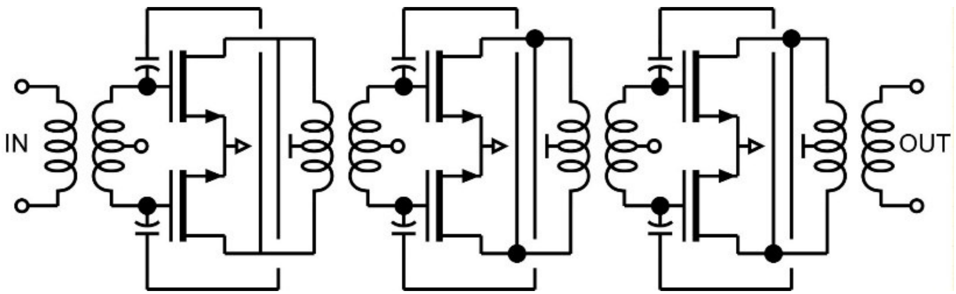


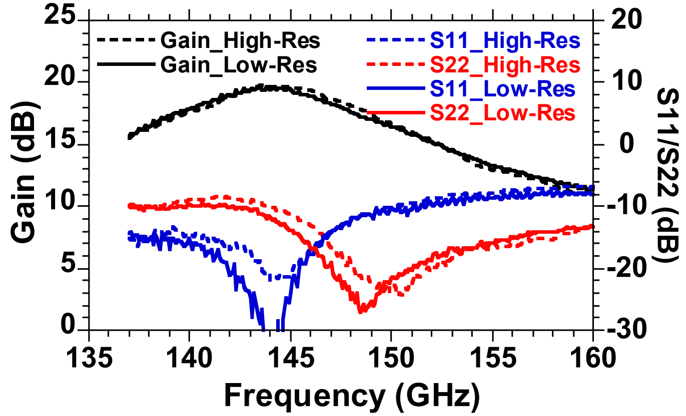




145 GHz amplifier

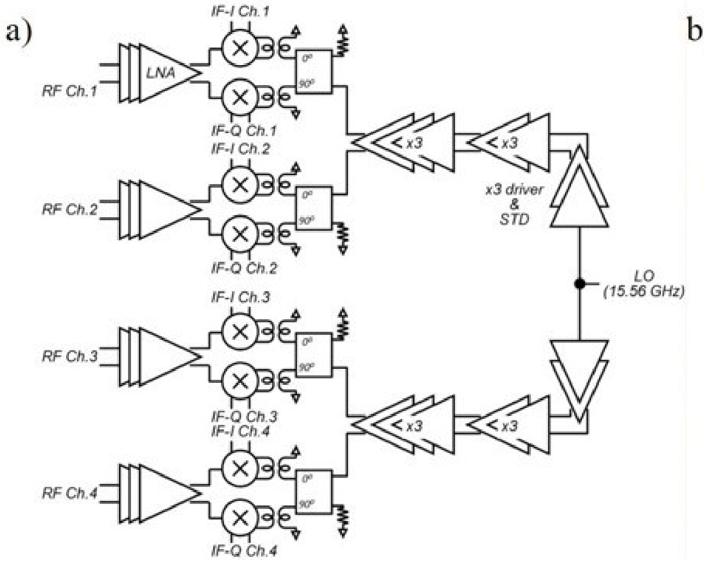
GF 45 nm SOI CMOS, 6.3 dB gain per stage Kim, Simseck, 2017 BCICTS

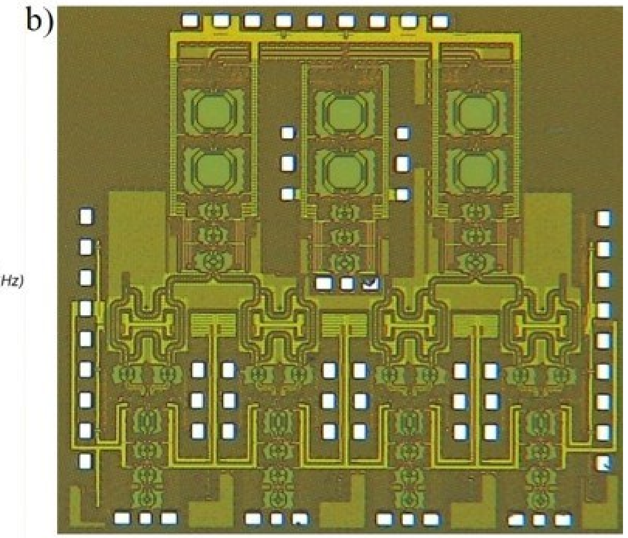


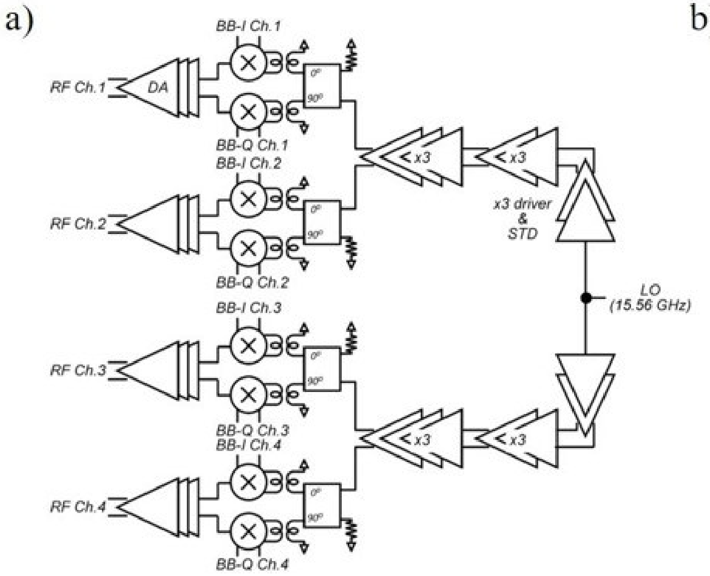


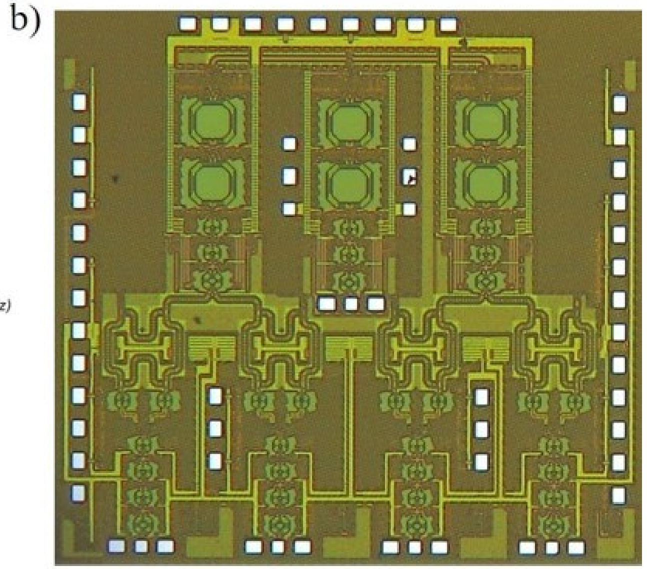
140GHz MIMO transceiver front-end ICs

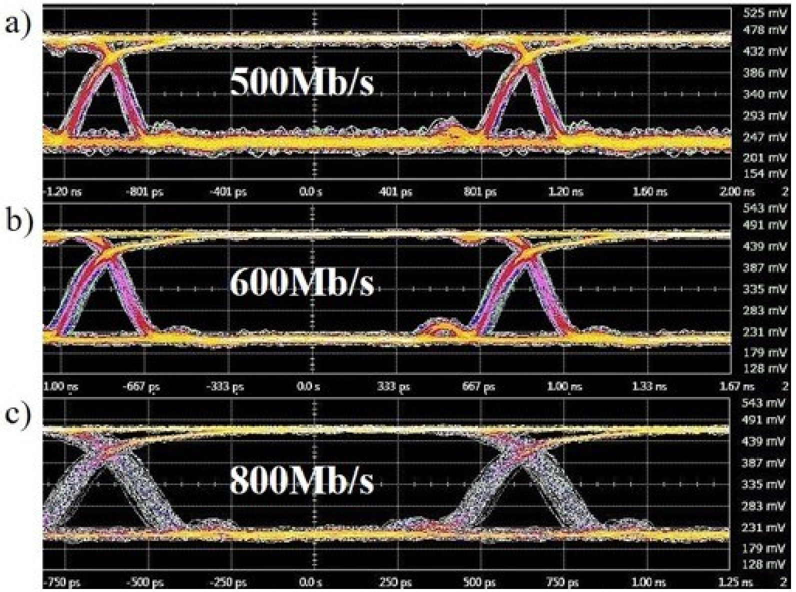
S. Lee, A. Simseck, UCSB, 2018 BCICTS, to be presented





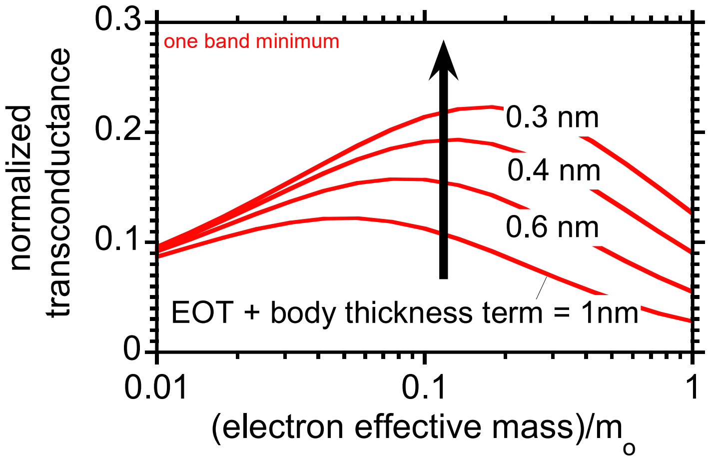




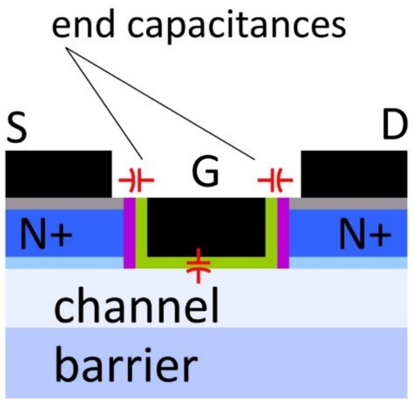


mm-Wave CMOS won't scale much further

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

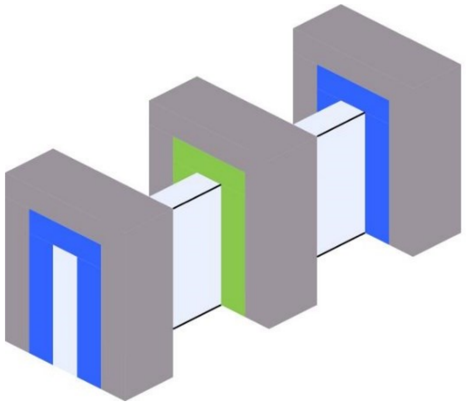


Maximum *g_m*, minimum *C*→ upper limit on *f_τ*.
about 350-400 GHz.

Tungsten via resistances reduce the gain

Inac et al, CSICS 2011

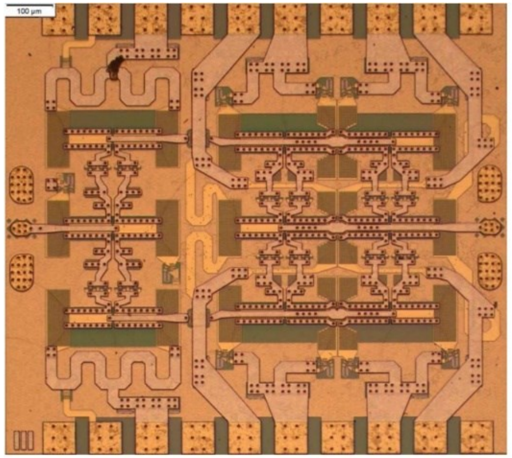
Present finFETs have yet <u>larger</u> end capacitances



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

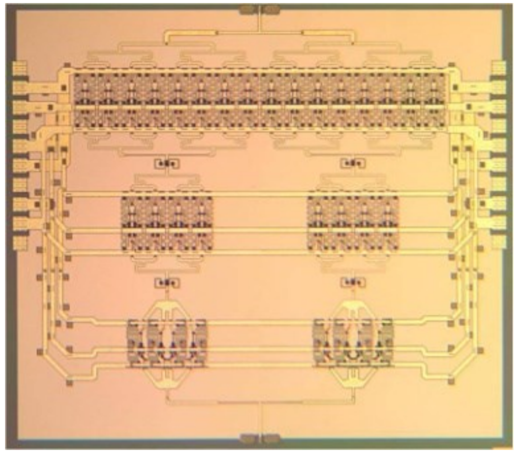
Cell phones & WiFi: GaAs PAs, LNAs

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



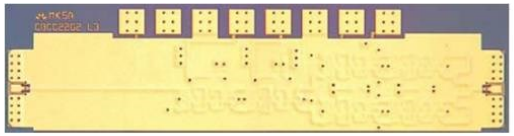
0.47 W @86GHz

H Park, UCSB, IMS 2014



0.18 W @220GHz

T Reed, UCSB, CSICS 2013

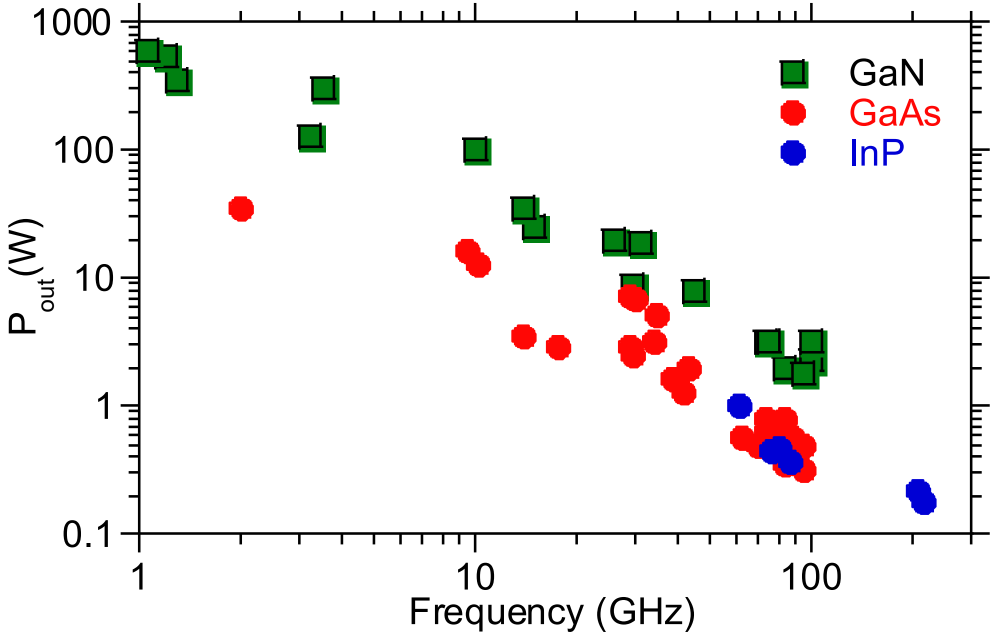


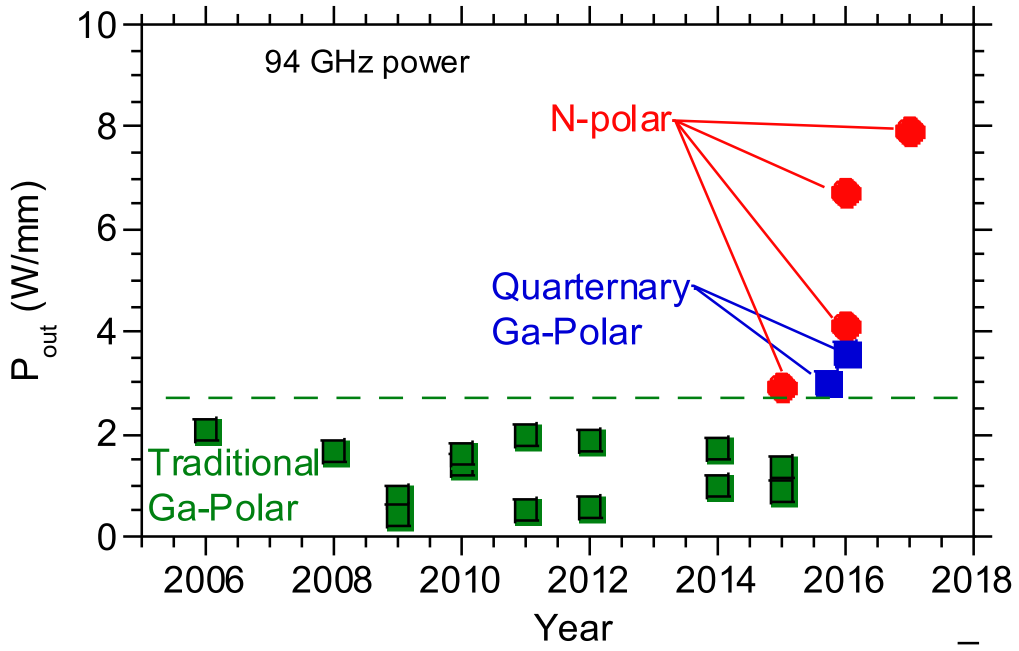
1.9mW @585GHz

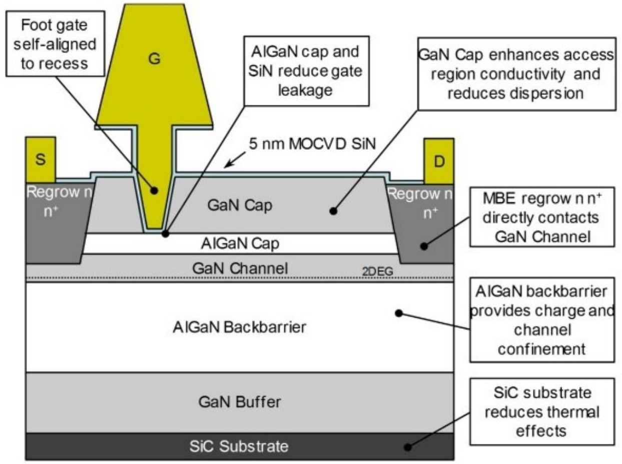
M Seo, TSC, IMS 2013

Gallium Nitride Power Technologies

GaN is the leading high-frequency power technology



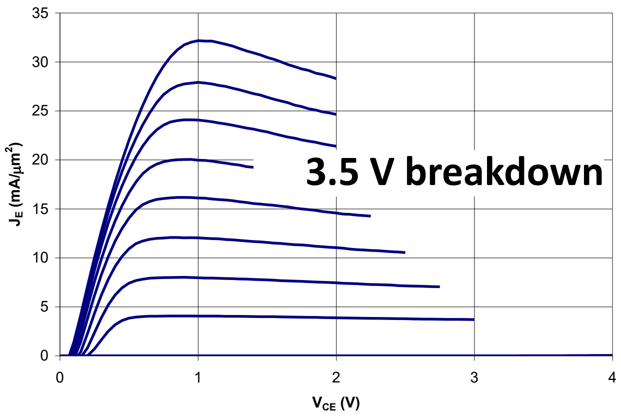




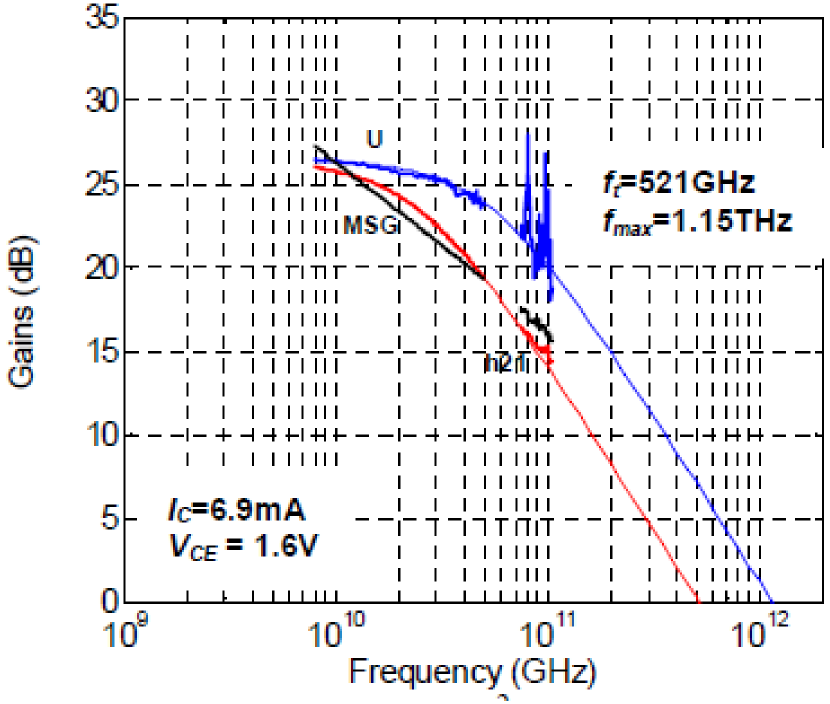
N-polar GaN: Mishra

130nm / 1.1THz InP HBT Technology

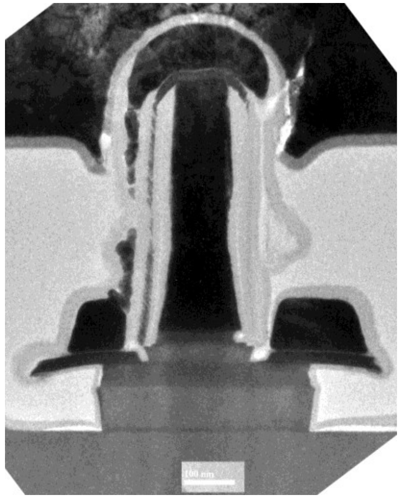
Teledyne: M. Urteaga *et al*: 2011 DRC

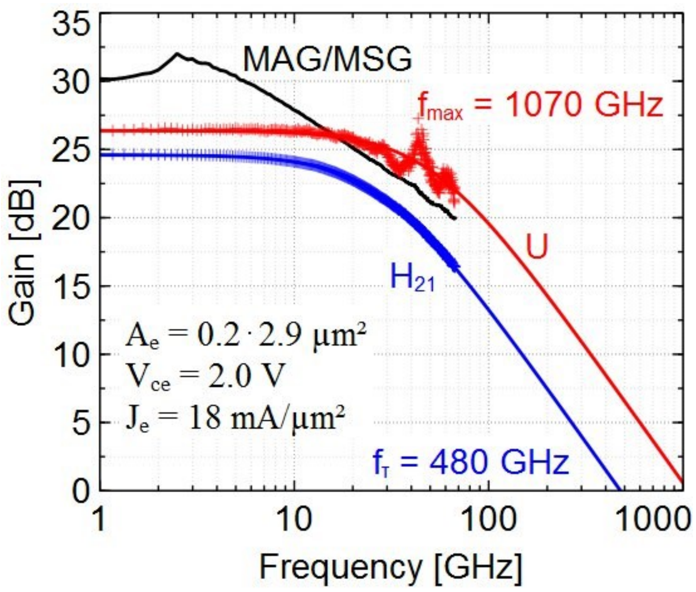


3.5 V breakdown



Rode (UCSB), IEEE TED, 2015

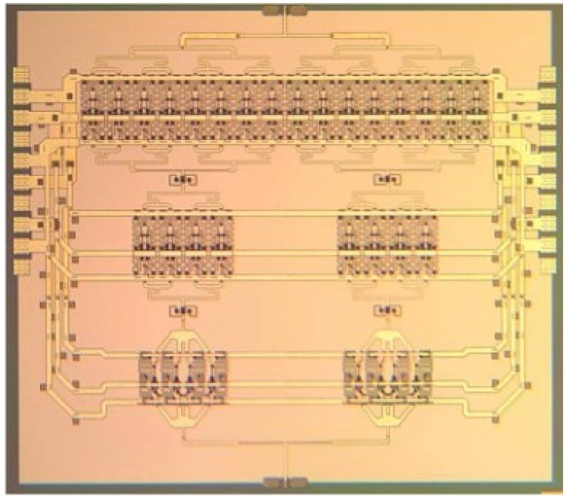




130nm / 1.1THz InP HBT: IC Examples

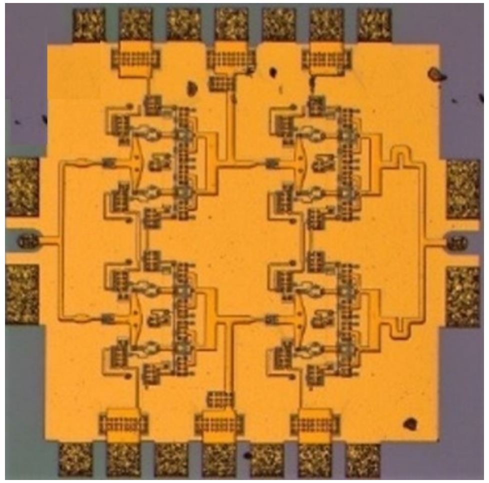
220 GHz 0.18W power amplifier

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



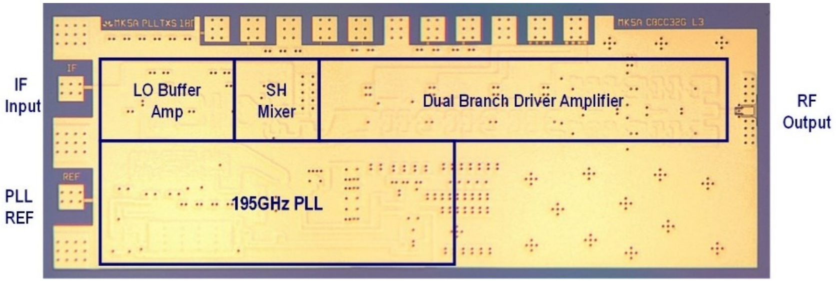
325 GHz, 16mW power amplifier

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

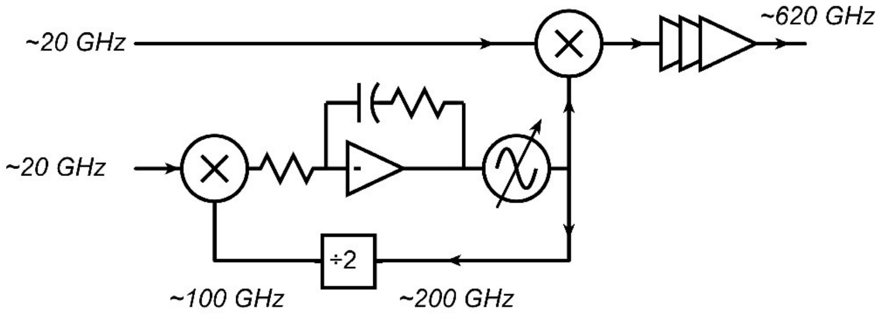


Integrated ~600GHz transmitter

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

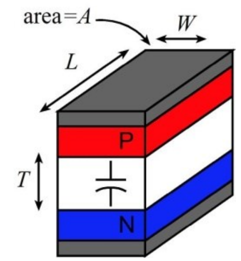


but, only ~1 mW output power

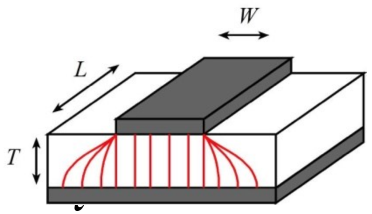


Transistor scaling laws: (V,I,R,C,τ) vs. geometry

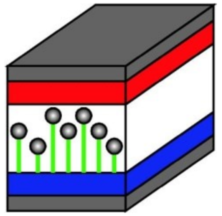
Depletion Layers



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

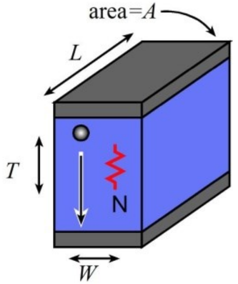


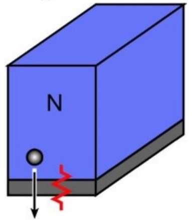
$2v$



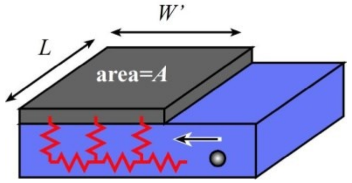
$$\frac{I_{\max}}{A} = \frac{4\varepsilon v_{sat}(V_{appl} + \phi)}{T^2}$$

Bulk and Contact Resistances





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

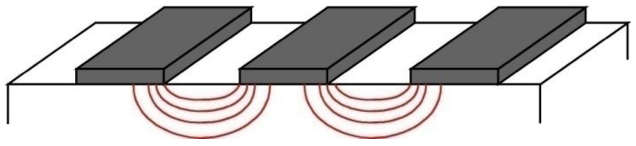


contact terms dominate

Fringing Capacitances

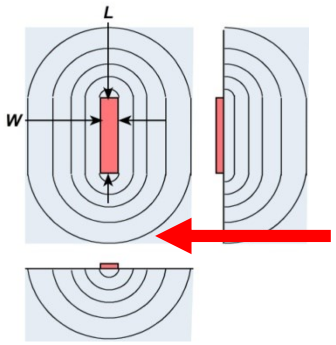
1) FET fringing capacitances

2) IC interconnect capacitances

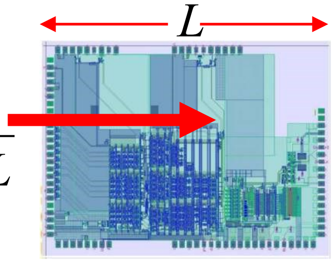


$$C_{finging} / L \sim \varepsilon \qquad C_{finging} / L \sim \varepsilon$$

Thermal Resistance

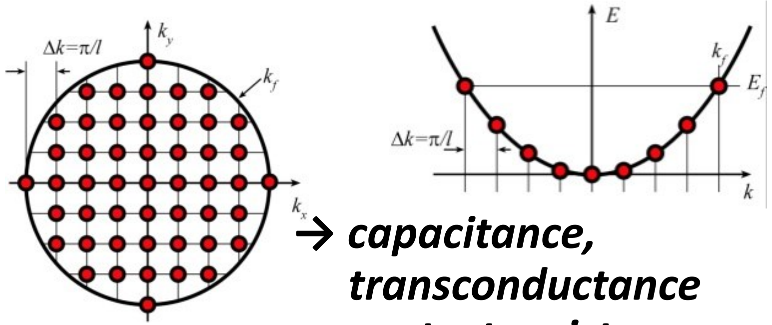


$$\Delta T_{IC} \propto \frac{P_{IC}}{K_{th} L}$$



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

Available quantum states to carry current



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

Frequency Limits and Scaling Laws of (most) Electron Devices

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

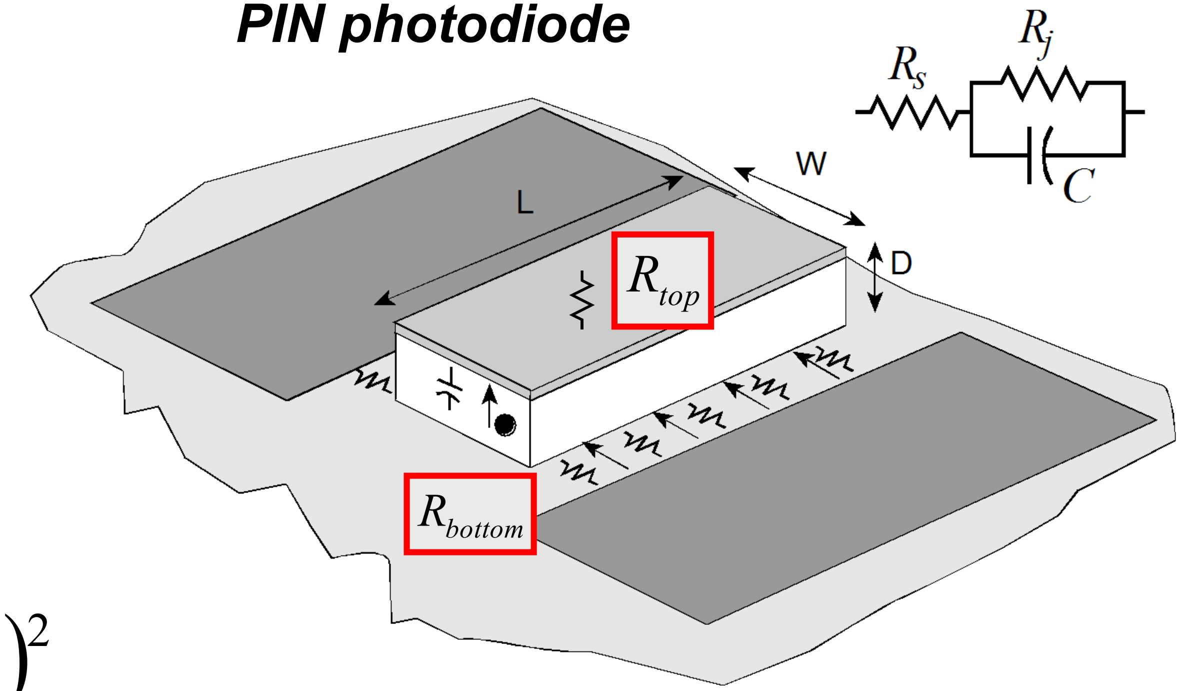
$$C \propto \text{area} \,/\, \text{thickness}$$

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

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

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

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



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

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

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

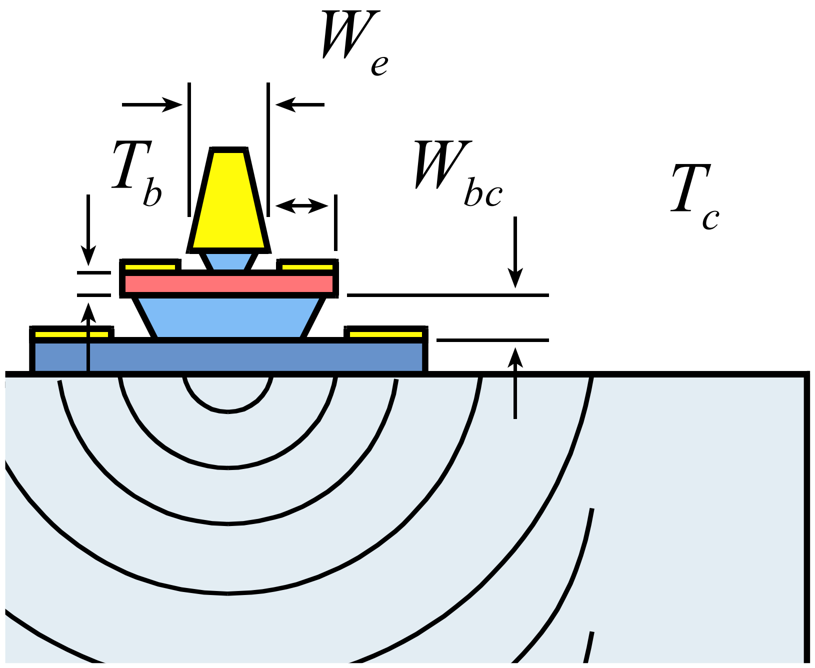
$$C_{cb} = \varepsilon A_c / T_c$$

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

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

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

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



(emitter length L_E)

Bipolar Transistor Design: Scaling

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

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

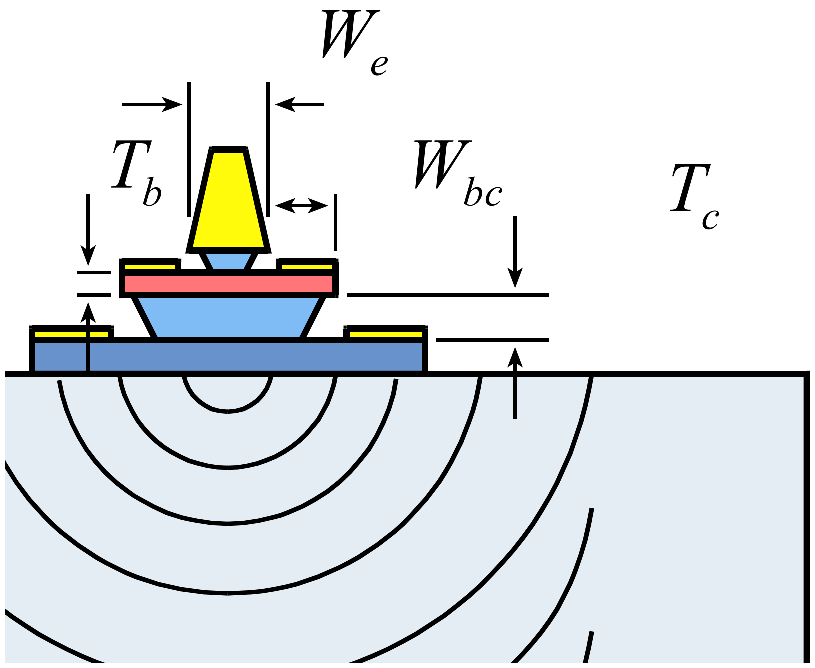
$$C_{cb} = \varepsilon A_c / T_c$$

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

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

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

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



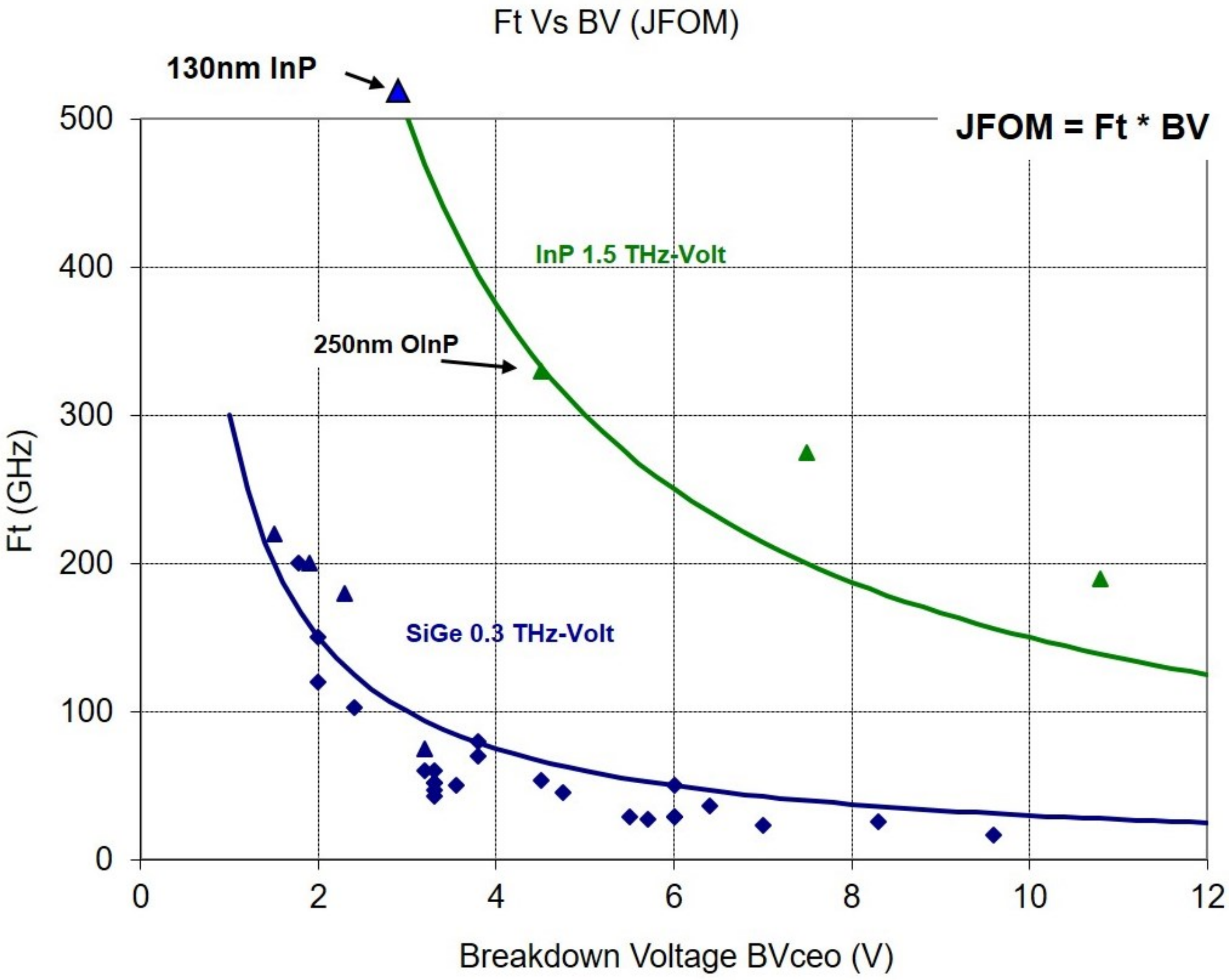
(emitter length L_E)

Why InP Bipolar Transistors ?

InP: better electron transport than Si
higher electron velocity: 3.5 vs 1.0 × 10^7 cm/s
plus wider bandgap→ higher breakdown field

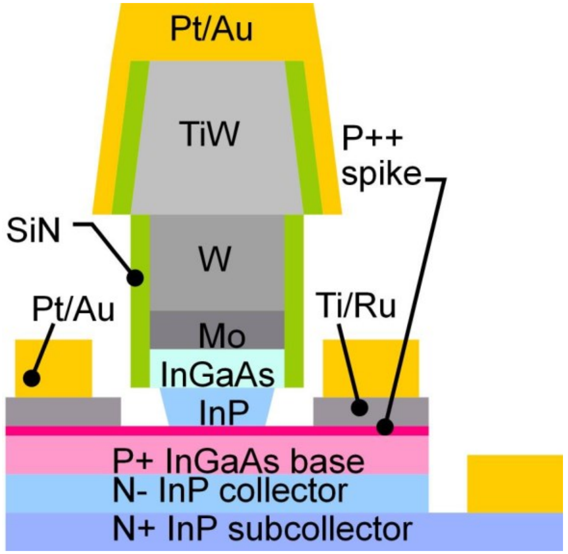
InGaAs base, base-emitter heterojunction:
very low base sheet resistance

Implications:
Higher (f_τ, f_{max}) at a given scaling node
Higher breakdown* at a given (f_τ, f_{max})



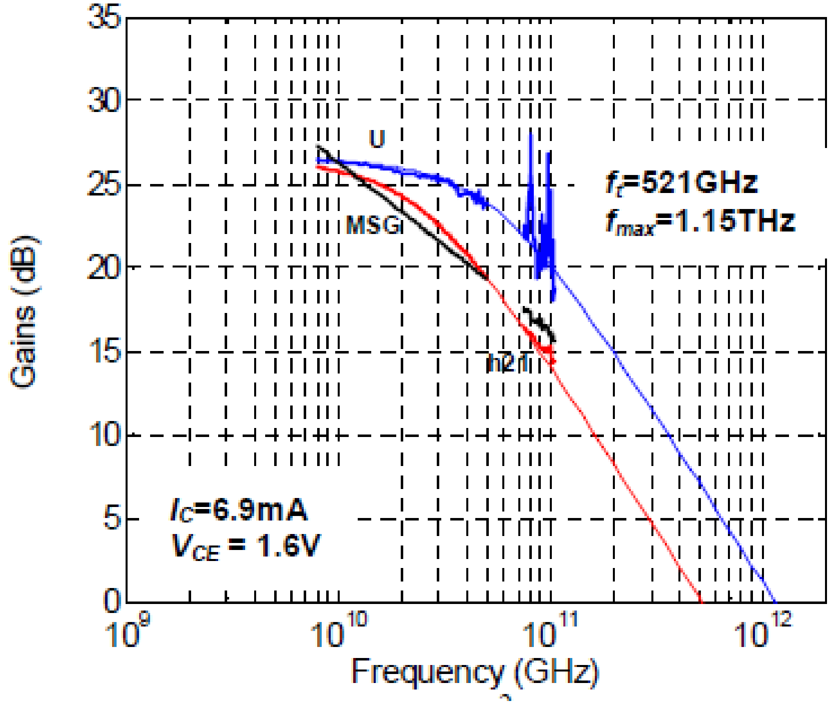
*Breakdown is too complicated to summarize with BVCEO.
BVCBO vs. BVCEO vs. safe operating area ?
Bottom line: look at V_{ce} used in published IC data for a given IC technology.

Making faster bipolar transistors



to double the bandwidth:	change
emitter & collector junction widths	decrease 4:1
current density (mA/μm^2)	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

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



Narrow junctions.

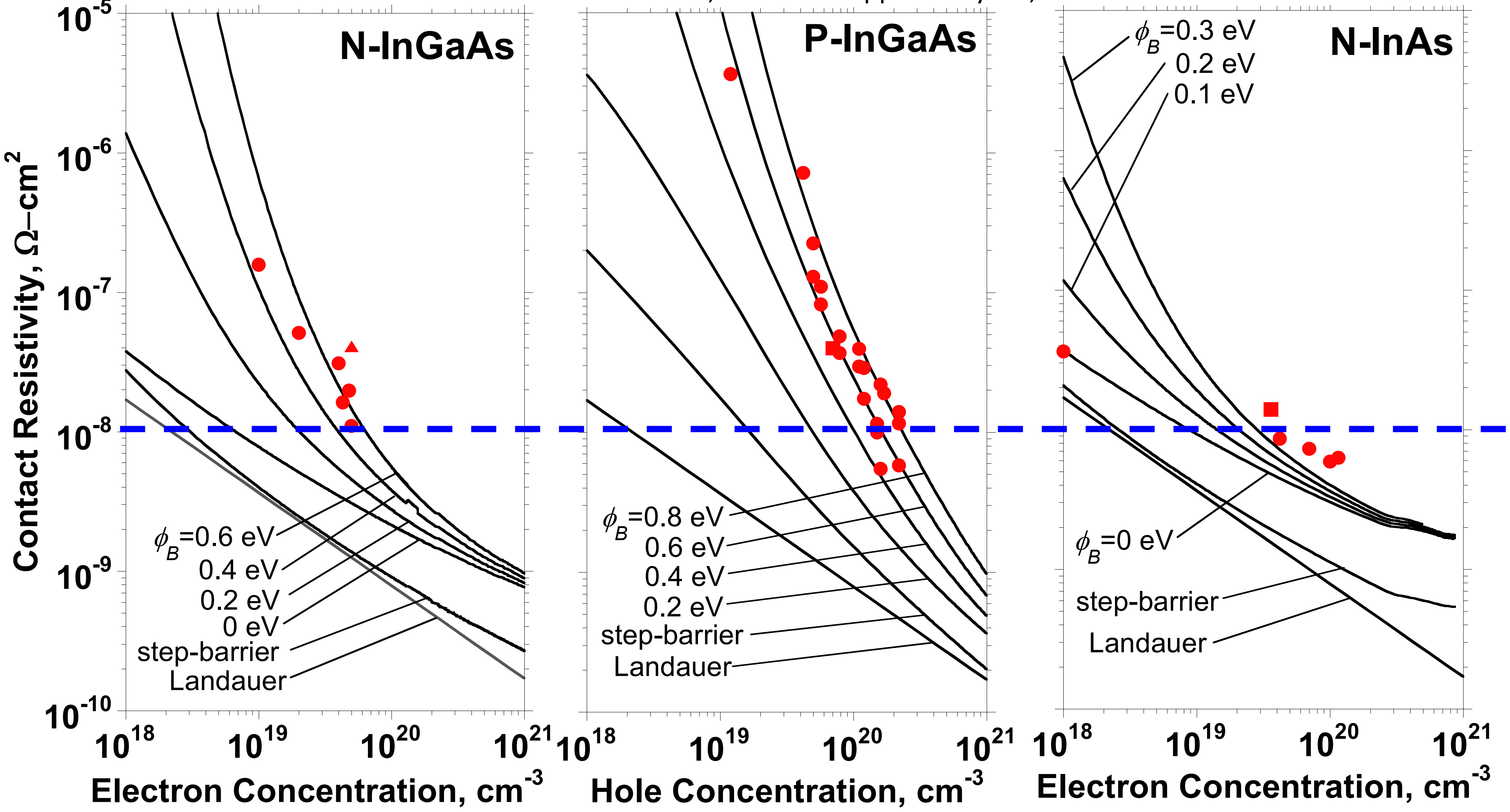
Thin layers

High current density

Ultra low resistivity contacts

Refractory Ohmic Contacts to In(Ga)As

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



32 nm (2.8THz) node requirements

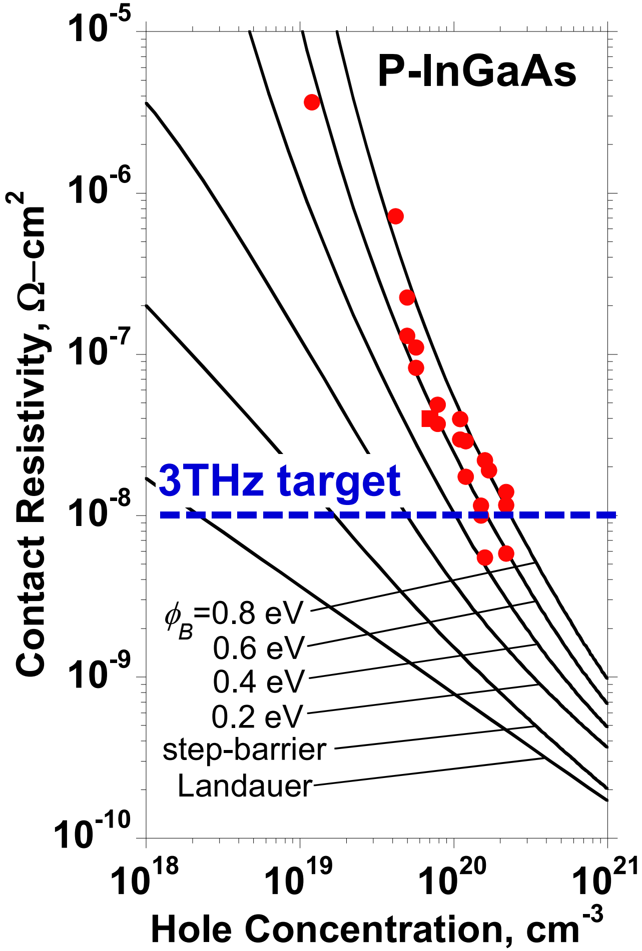
Refractory: robust under high-current operation / Low penetration depth: ~ 1 nm

Why no ~2THz HBTs today? Problem: reproducing these base contacts in full HBT process flow

THz HBTs: The key challenges

Obtaining good base contacts

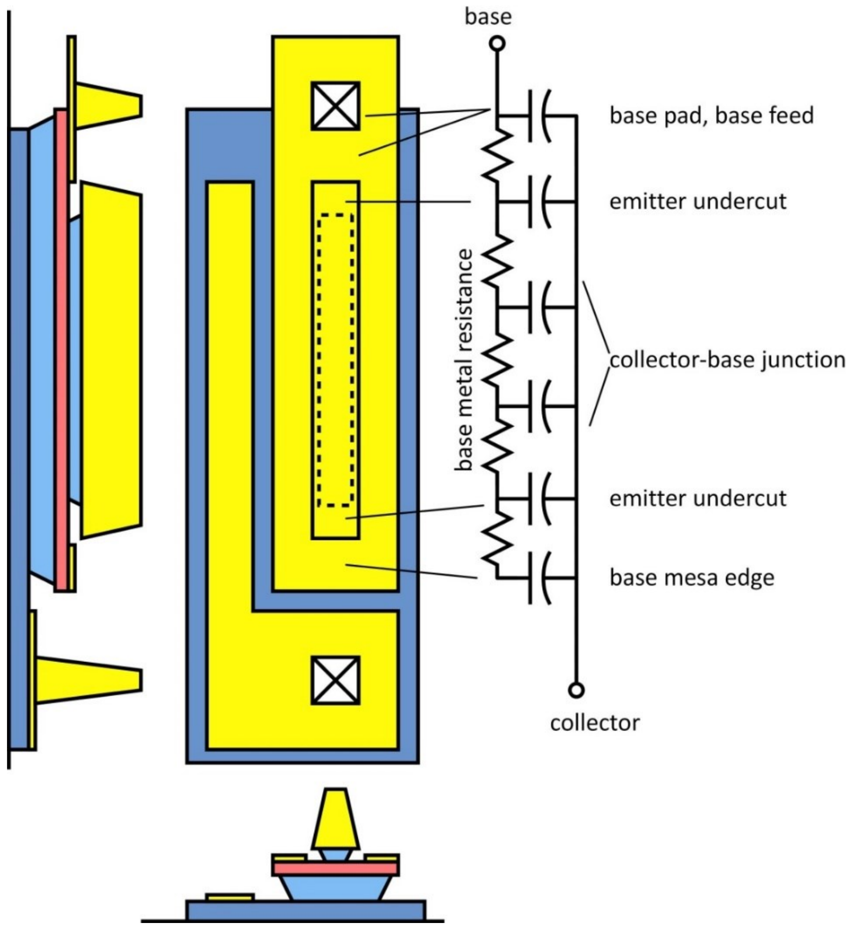
in HBT vs. in contact test structure
(emitter contacts are fine)



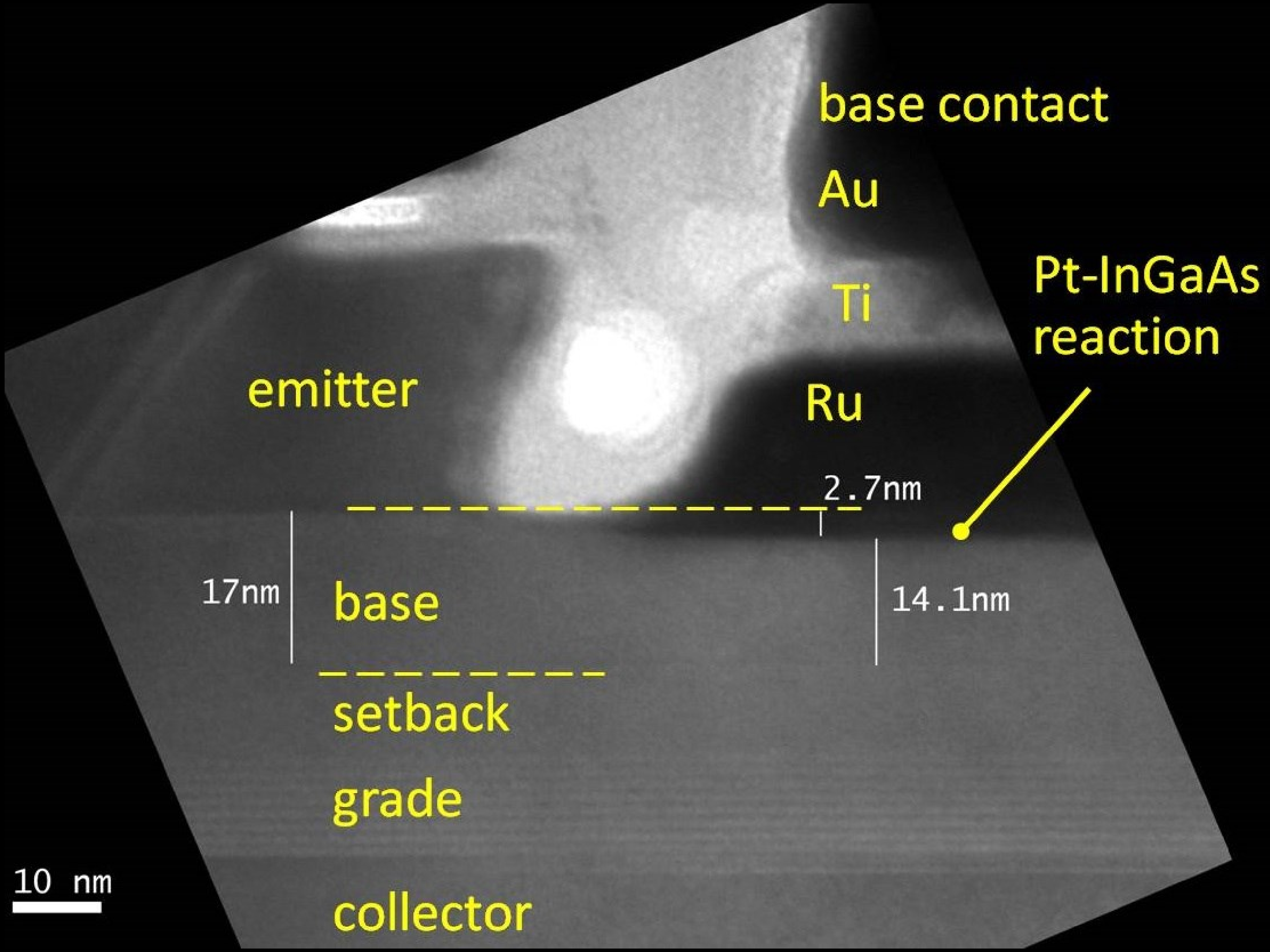
Baraskar *et al*, Journal of Applied Physics, 2013

RC parasitics along finger length

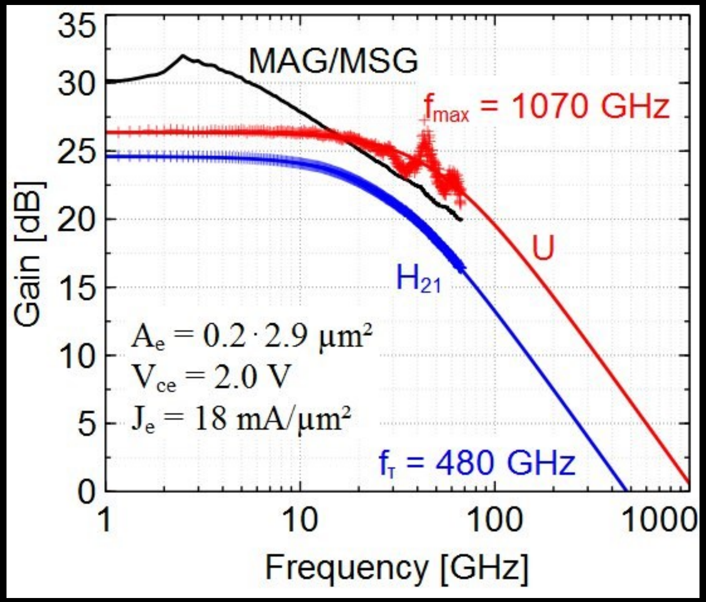
metal resistance, excess junction areas

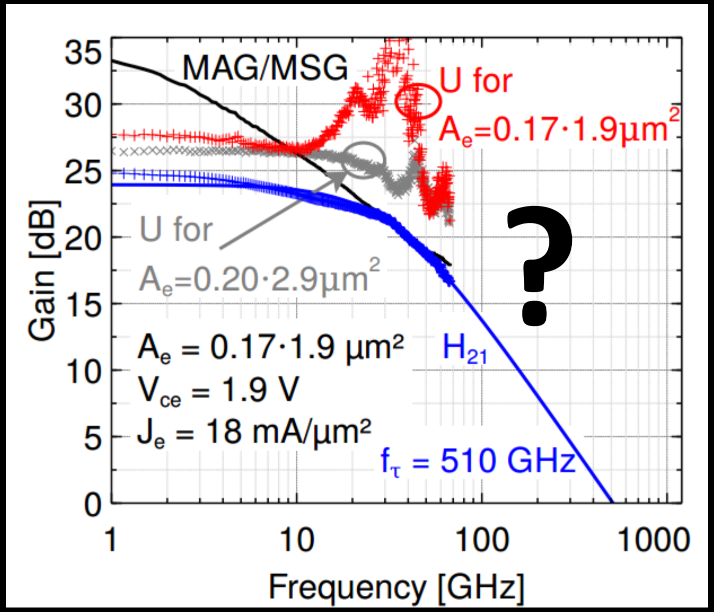


InP HBTs: 1.07 THz @200nm, ?? @ 130nm



Rode et al., IEEE TED, Aug. 2015

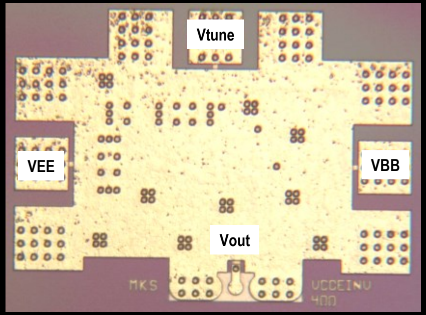




130nm /1.1 THz InP HBT ICs to 670 GHz

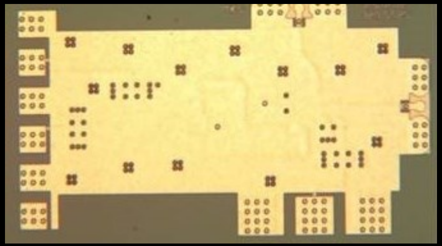
614 GHz fundamental VCO

M. Seo, TSC / UCSB



340 GHz dynamic frequency divider

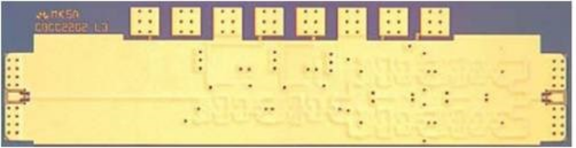
M. Seo, UCSB/TSC
IMS 2010



620 GHz, 20 dB gain amplifier

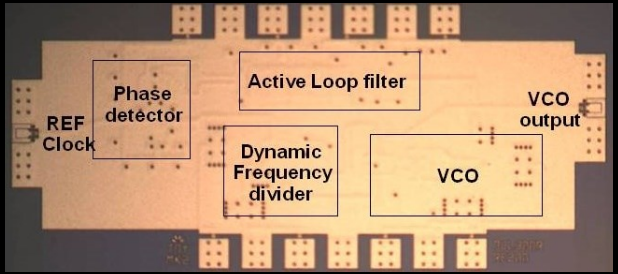
M Seo, TSC
IMS 2013

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



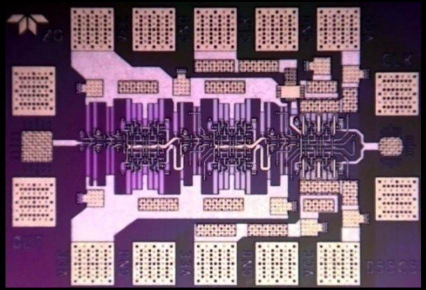
300 GHz fundamental PLL

M. Seo, TSC
IMS 2011



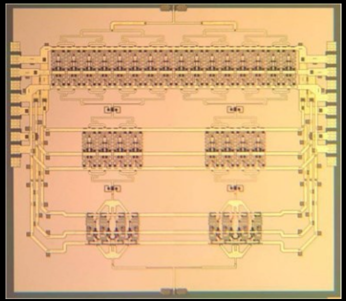
204 GHz static frequency divider (ECL master-slave latch)

Z. Griffith, TSC / UCSB
CSIC 2010



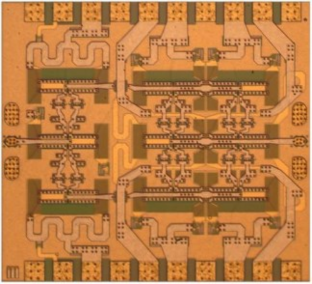
220 GHz 180 mW power amplifier

T. Reed, UCSB
CSICS 2013

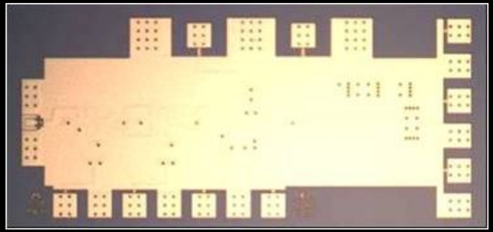


81 GHz 470 mW power amplifier

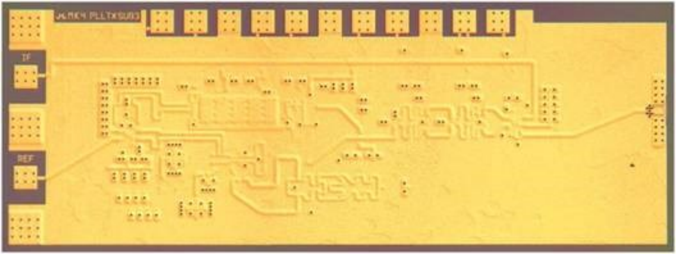
H-C Park UCSB
IMS 2014



Integrated 300/350GHz Receivers:
LNA/Mixer/VCO
M. Seo TSC



600 GHz Integrated Transmitter
PLL + Mixer
M. Seo TSC



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**	$\Omega-\mu m^2$
base			
contact width	64	18	nm
contact resistivity	2.5	**0.7**	$\Omega-\mu m^2$
collector			
thickness	53	15	nm
current density	36	**125**	$mA/\mu m^2$
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

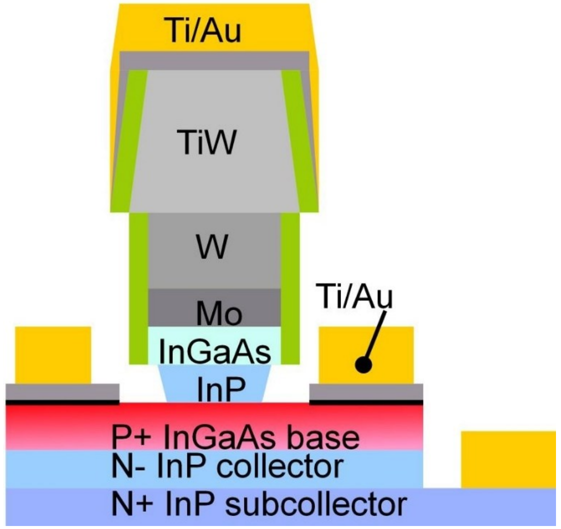
Towards the 2 THz / 64nm Node: 1st step = scaling

Narrow junctions.

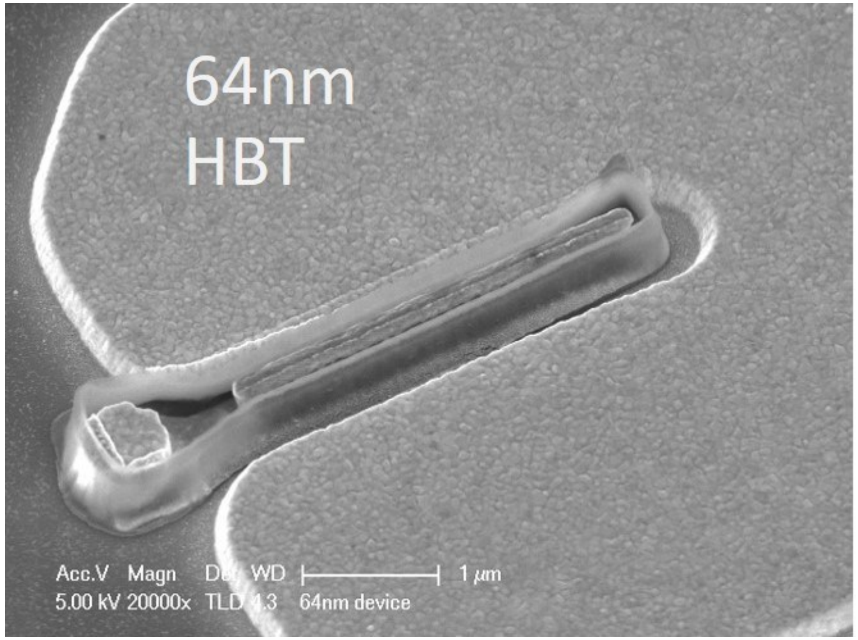
Thin semiconductor layers

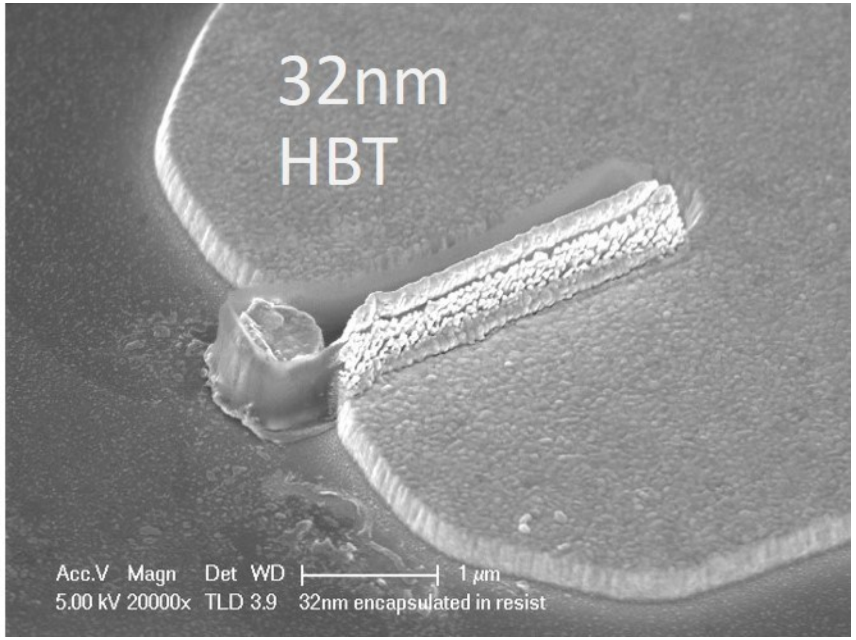
High current density

Ultra low resistivity contacts

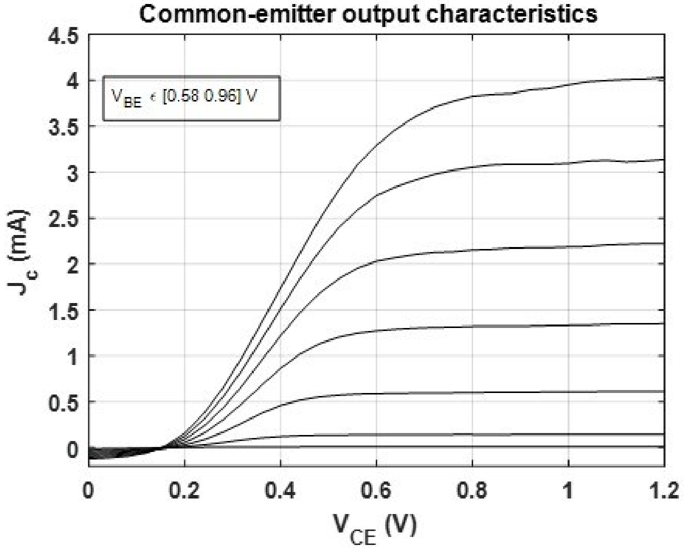


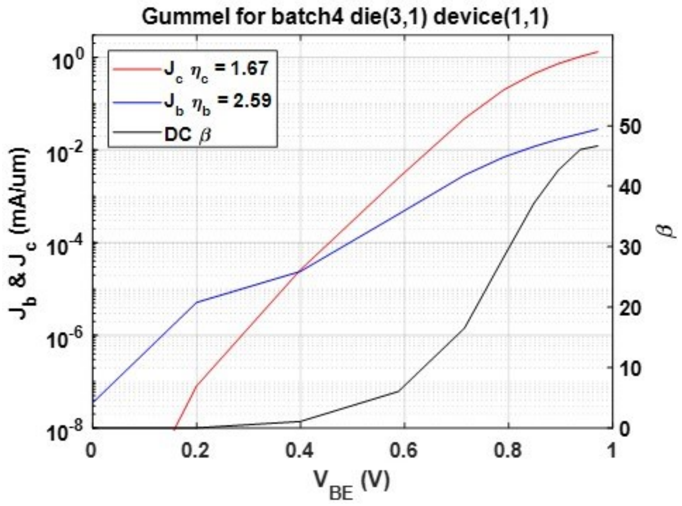
Initial DC data with 90nm devices





Yihao Fang, UCSB, submitted to DRC 2018





FETs (HEMTs): key for low noise

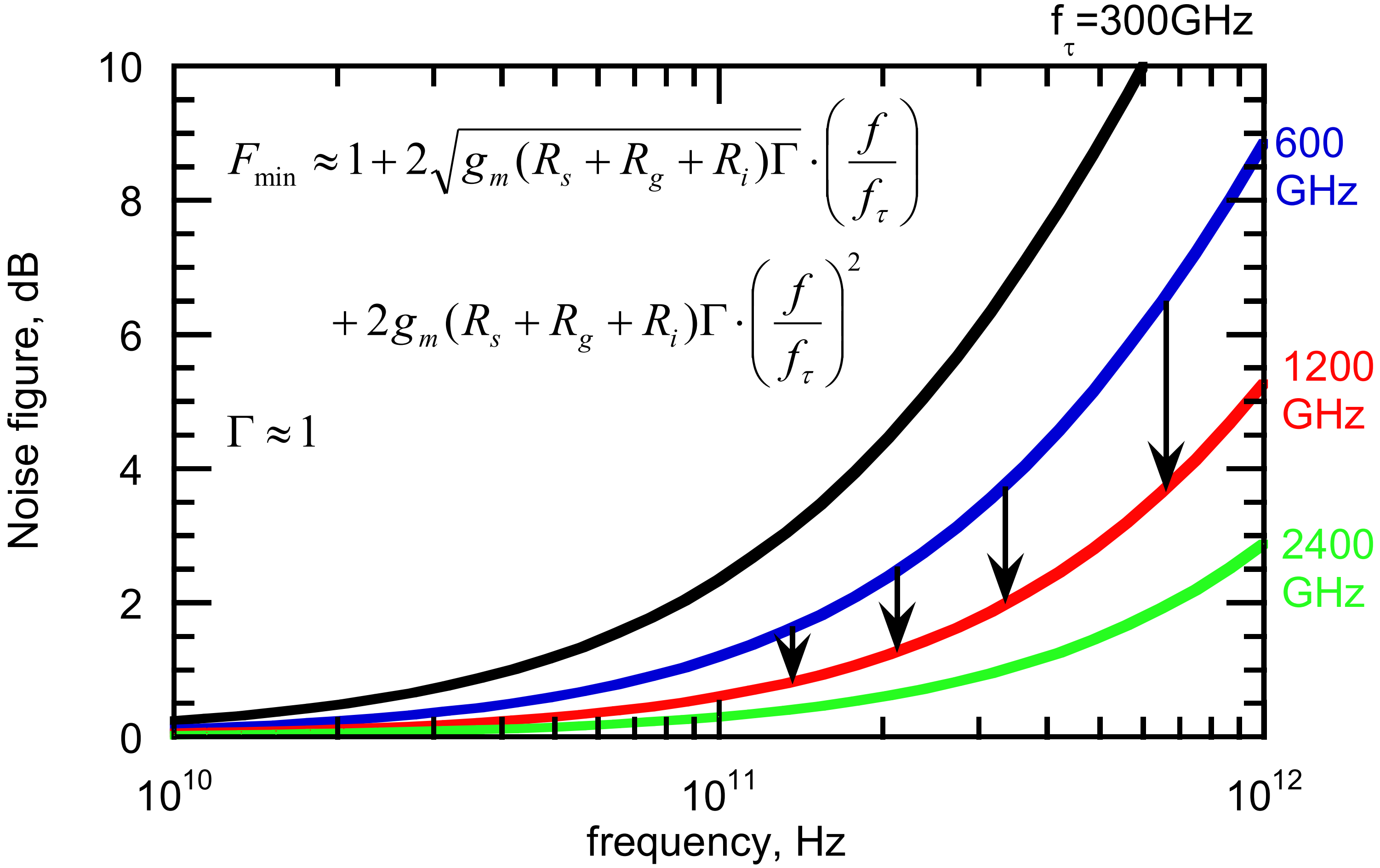
2:1 to 4:1 increase in f_τ :

improved noise

less required transmit power

smaller PAs, less DC power

or higher-frequency systems



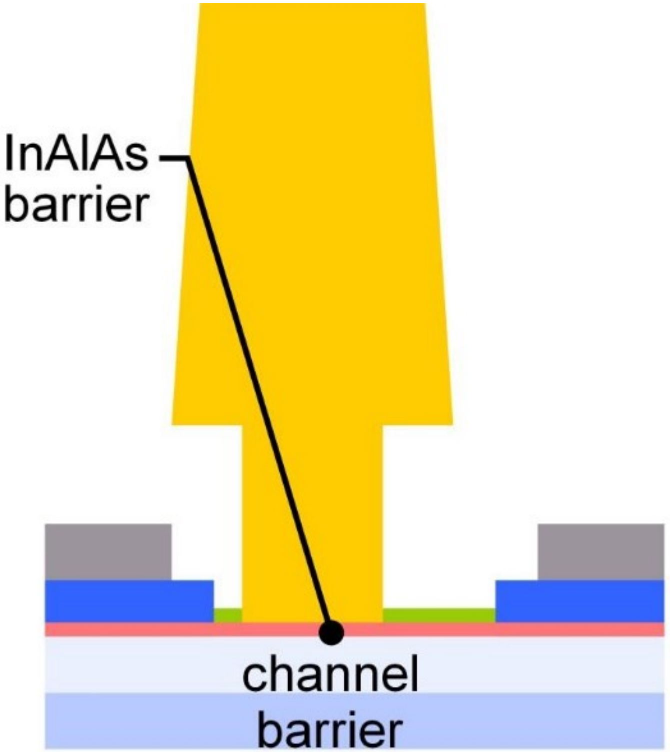
$$F_{\min} \approx 1 + 2\sqrt{g_m(R_s + R_g + R_i)\Gamma} \cdot \left(\frac{f}{f_\tau}\right) + 2g_m(R_s + R_g + R_i)\Gamma \cdot \left(\frac{f}{f_\tau}\right)^2$$

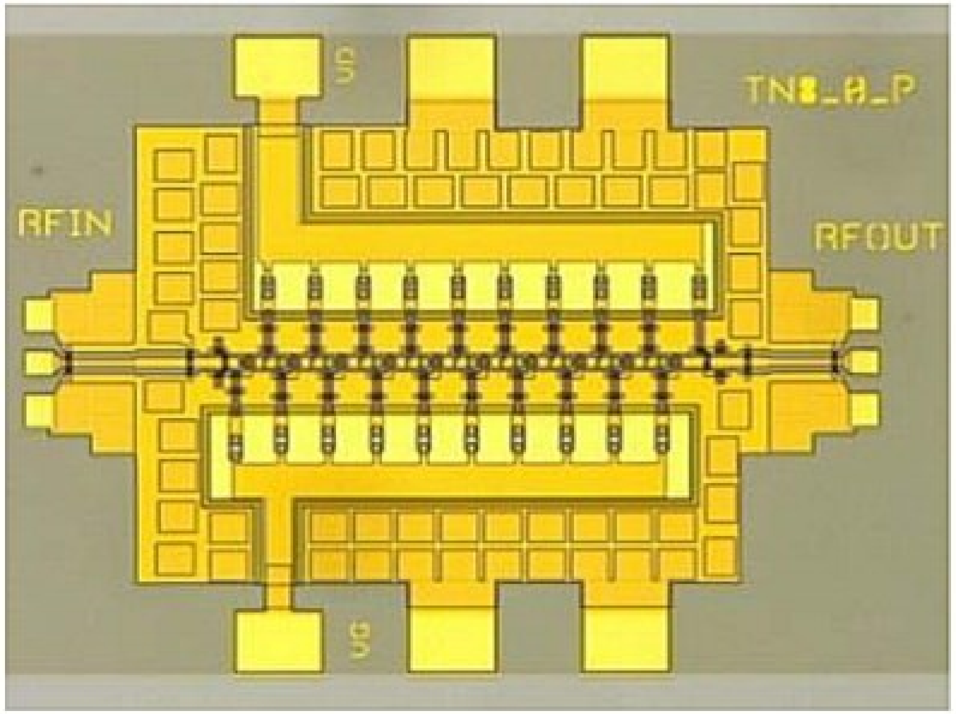
$$\Gamma \approx 1$$

InP HEMTs: state of the art

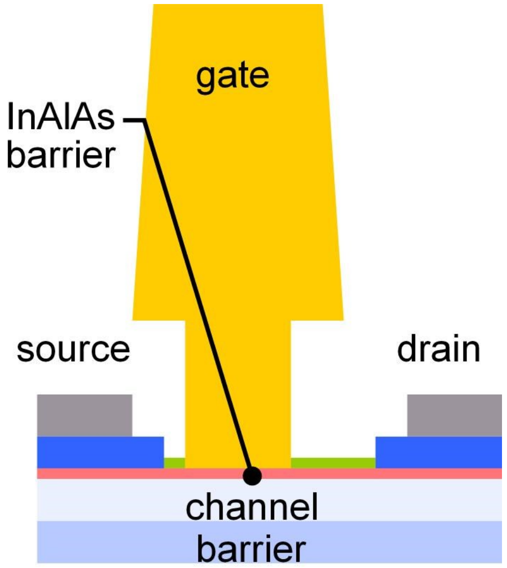
First Demonstration of Amplification at 1 THz Using 25-nm InP High Electron Mobility Transistor Process

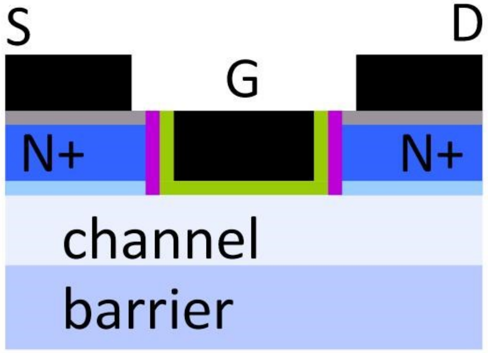
Xiaobing Mei, et al, IEEE EDL, April 2015 **(Northrop-Grumman)**





FET Scaling Laws (these now broken)

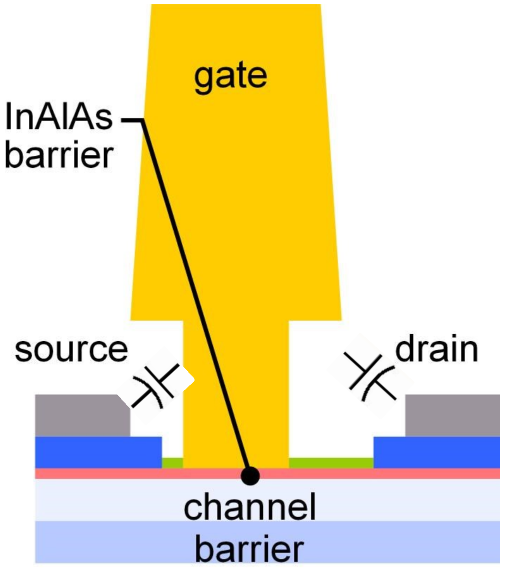


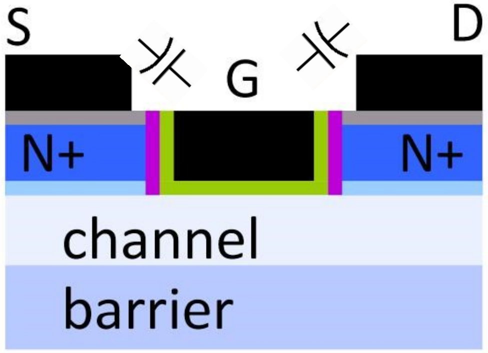


▬ vertical S/D spacer
▬ low-K dielectric spacer
▬ high-K gate dielectric

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)





- 🟦 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
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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

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.

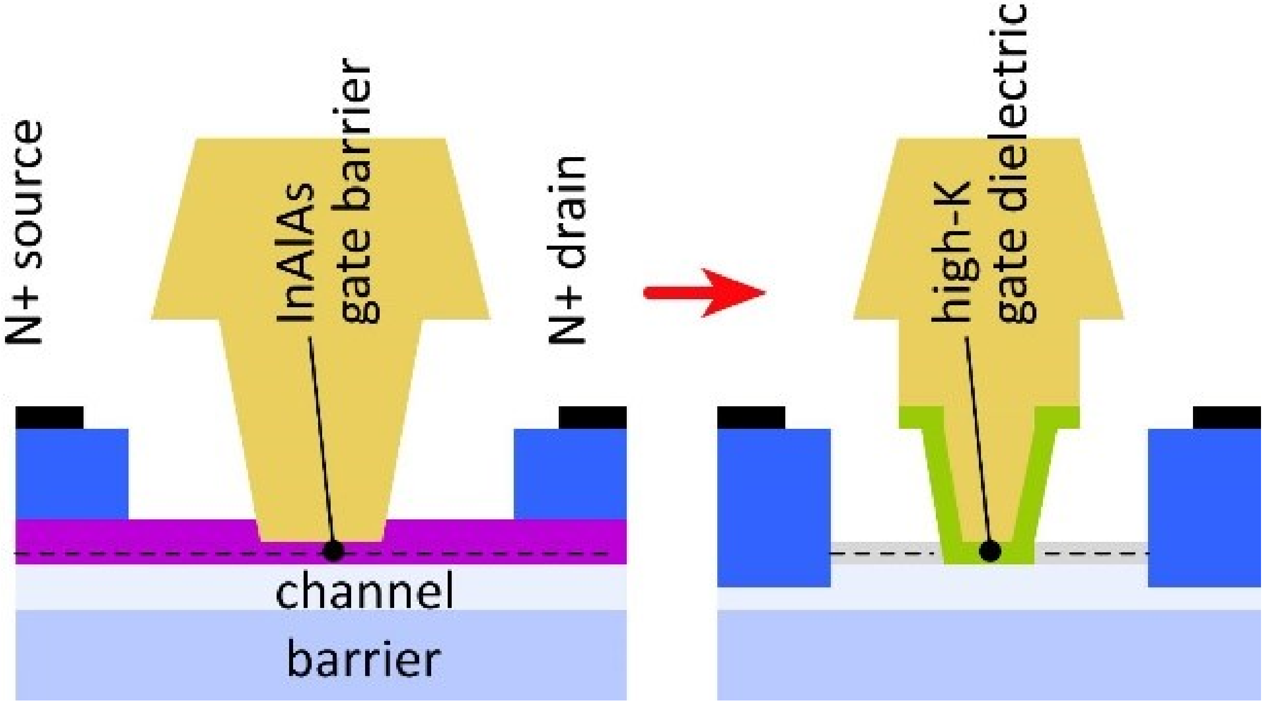
Shorter gate lengths degrade electrostatics→ reduced g_m/G_{ds} → reduced f_{max}, f_τ

Towards faster HEMTs

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 on InAs channel

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

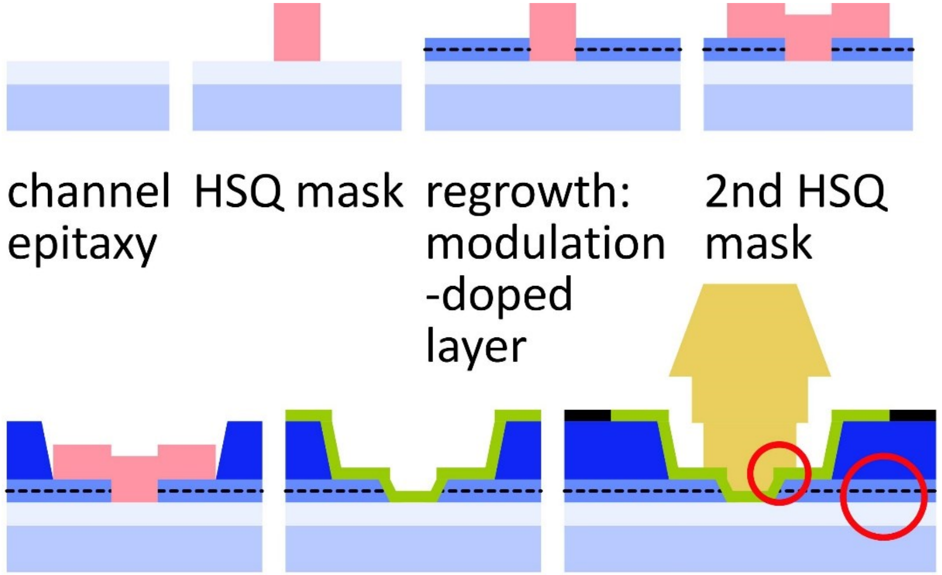


Towards faster HEMTs: 1st results

Double regrowth
modulation-doped access regions
N+ contacts

High-K gate dielectric
3 nm ZrO2.

Highly scaled
5nm InAs channel
10-30nm gate lengths



channel epitaxy

HSQ mask

regrowth: modulation-doped layer

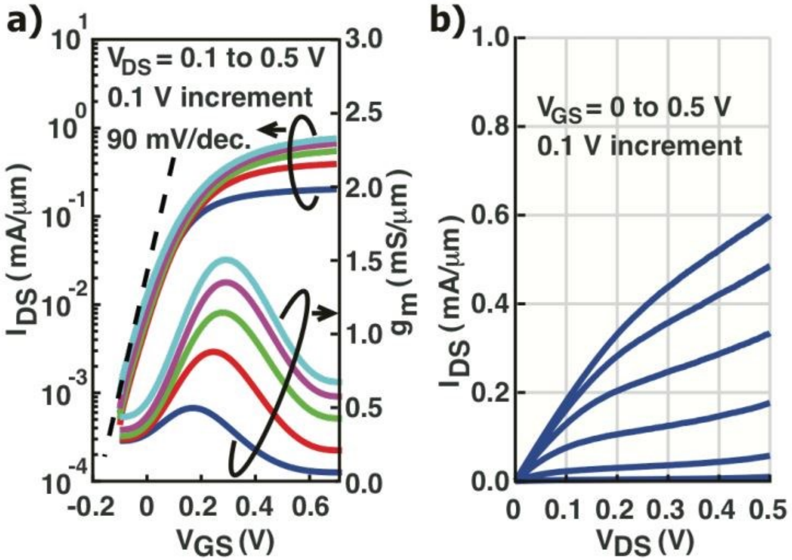
2nd HSQ mask

regrowth: N+ S/D

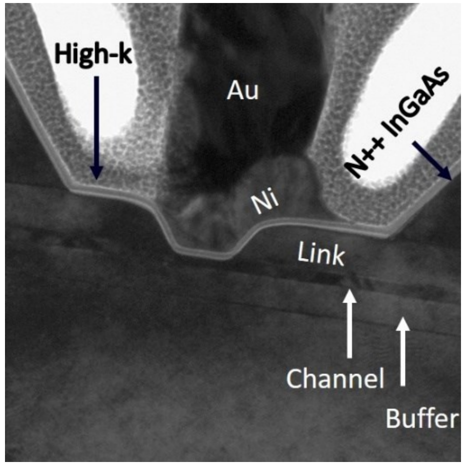
dielectric ALD

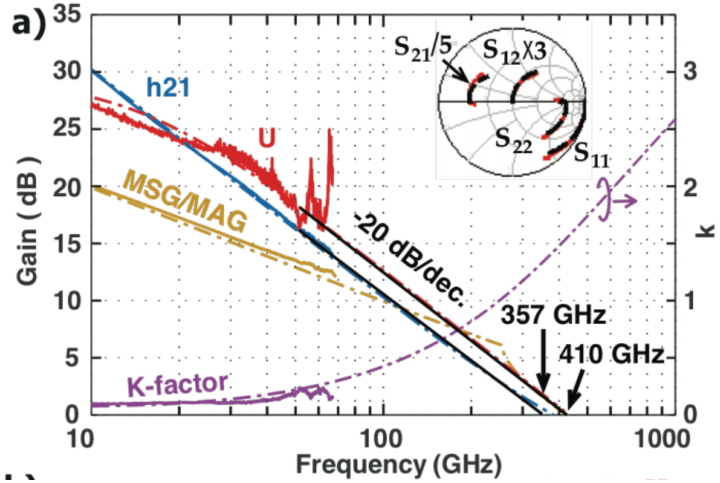
liftoff gate
liftoff S/D

Jun Wu, UCSB, IEEE EDL, 2018



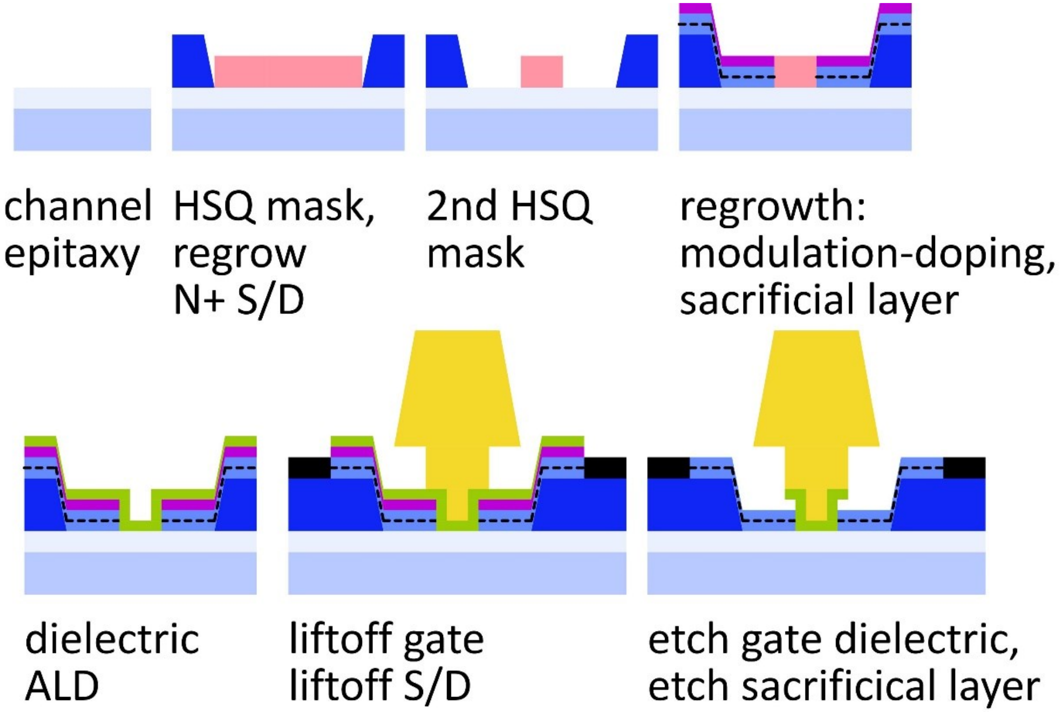
Things to fix
S/D contacts too far from gate
widegap barrier under N+ S/D
gate too wide: landed partly on access regions

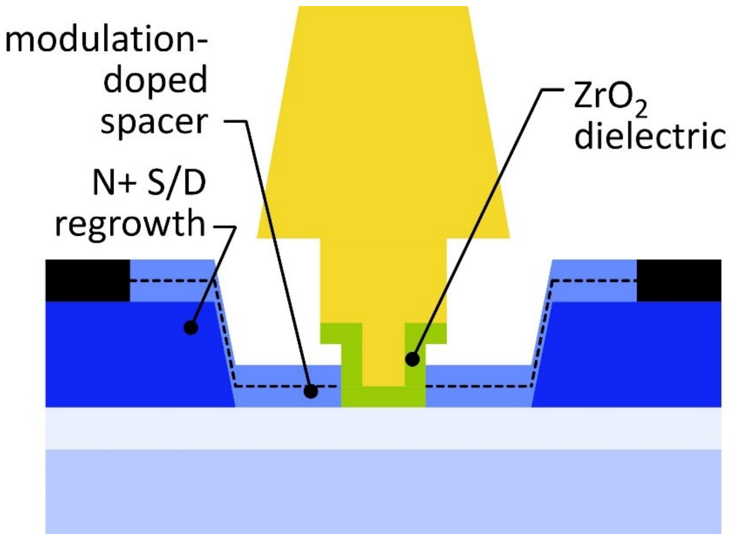




Towards faster HEMTs: next step

Jun Wu, UCSB, Unpublished



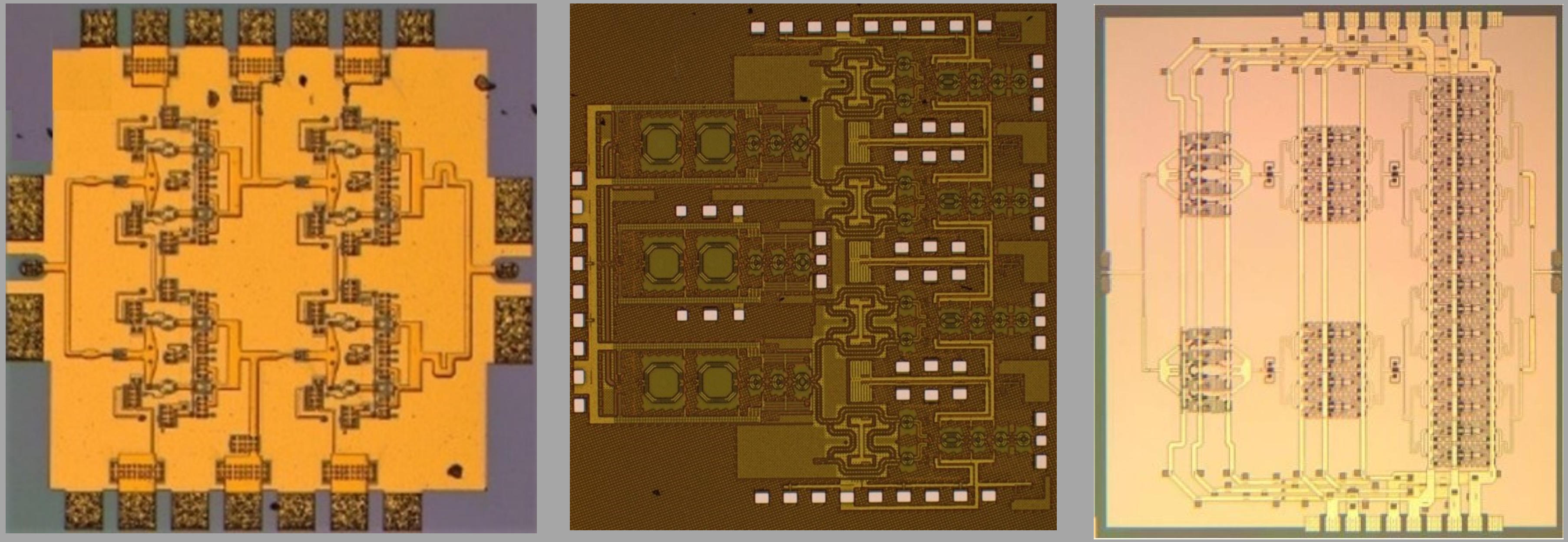


Revised process: no N- material between channel and contacts
reduced source/drain access resistance

Revised process: sacrificial layer
reduces parasitic gate-channel overlap: less gate-source capacitance

Thinner gate dielectric (2nm ZrO_2), thinner channel (3nm InAs)
higher g_m , lower g_{ds}

ICs



mm-Wave IC design: the challenges

Transistor gains are low: f_{signal} is significant fraction of f_{max}.

usually must match for optimum gain, noise, or power.

(Transistor, resistor, capacitor) dimensions are a significant fraction of a wavelength

Even short lengths of random wiring add serious inductance and/or capacitance

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.

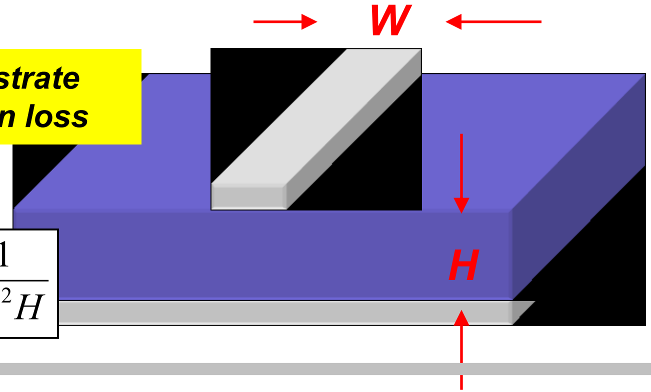
First consider the IC wiring stack

(the next 5-6 slides are very old, predate modern mm-wave CMOS)

III-V MIMIC Interconnects: Classic Substrate Microstrip

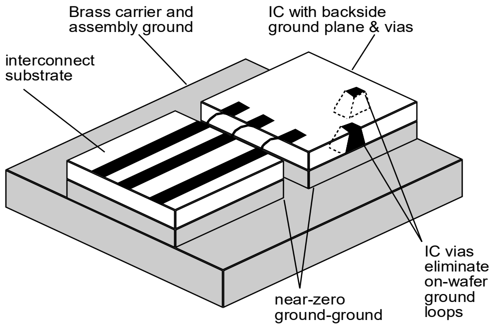
Thick Substrate
→ low skin loss

$$\alpha_{skin} \propto \frac{1}{\varepsilon_r^{1/2} H}$$

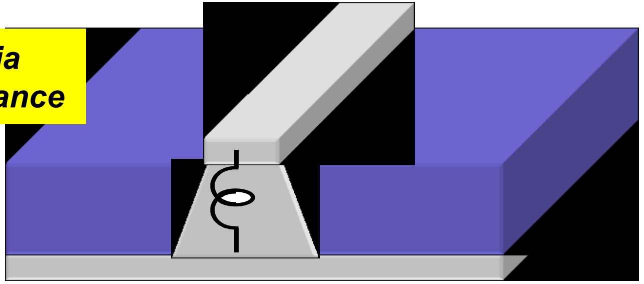


Zero ground inductance in package

No ground plane breaks in IC

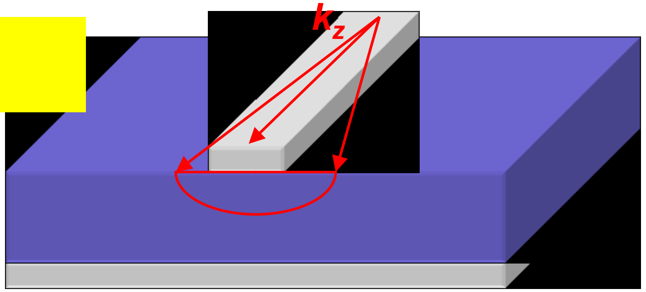


High via inductance



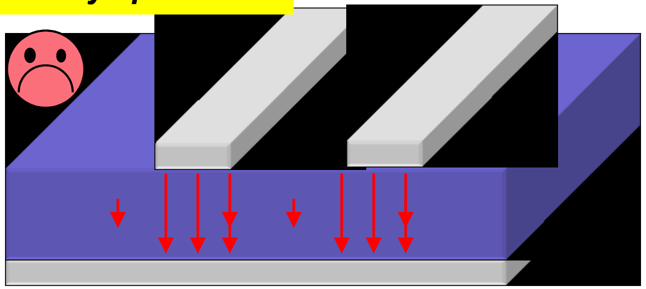
12 pH for 100 μm substrate -- 7.5 Ω @ 100 GHz

TM substrate mode coupling



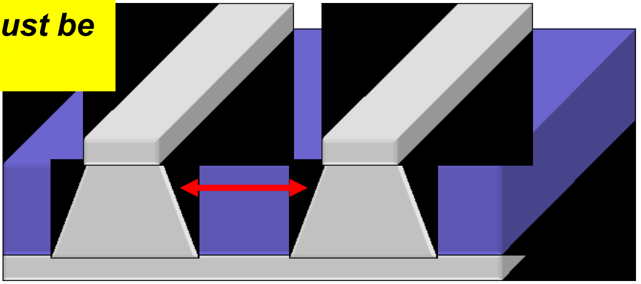
Strong coupling when substrate approaches ~λ_d / 4 thickness

lines must be widely spaced



Line spacings must be ~3(substrate thickness)*

ground vias must be widely spaced

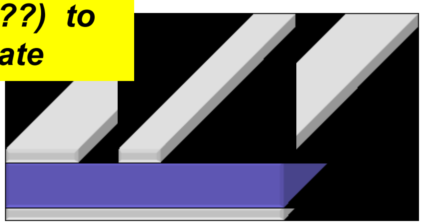


all factors require very thin substrates for >100 GHz ICs
→ lapping to ~50 μm substrate thickness typical for 100+ GHz

Coplanar Waveguide

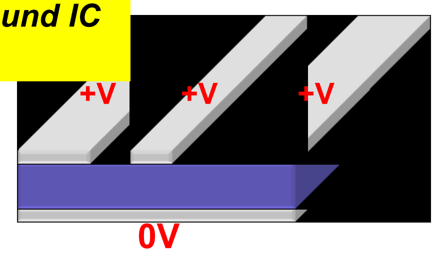
No ground vias
No need (???) to thin substrate

☺

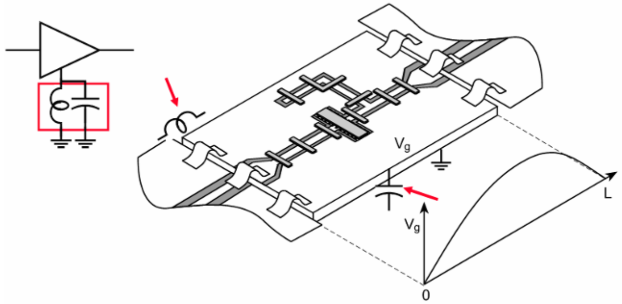


Hard to ground IC to package

☹

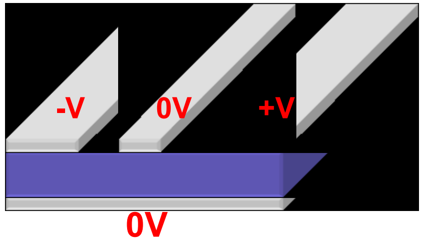


Parasitic microstrip mode



ground plane breaks → loss of ground integrity

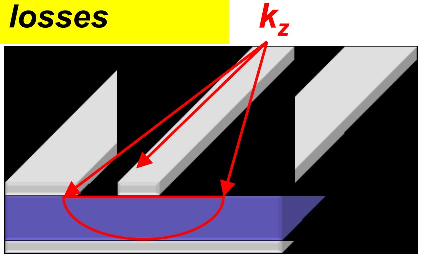
☹



Parasitic slot mode

substrate mode coupling or substrate losses

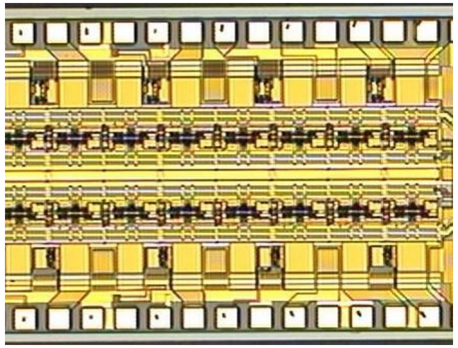
☹



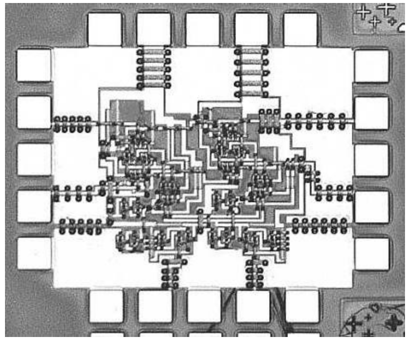
III-V:
semi-insulating substrate→ substrate mode coupling

Silicon conducting substrate → substrate conductivity losses

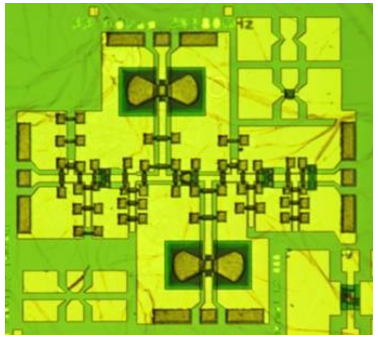
Repairing ground plane with ground straps is effective only in simple ICs
In more complex CPW ICs, ground plane rapidly vanishes
→ common-lead inductance → strong circuit-circuit coupling



40 Gb/s differential TWA modulator driver
note CPW lines, fragmented ground plane



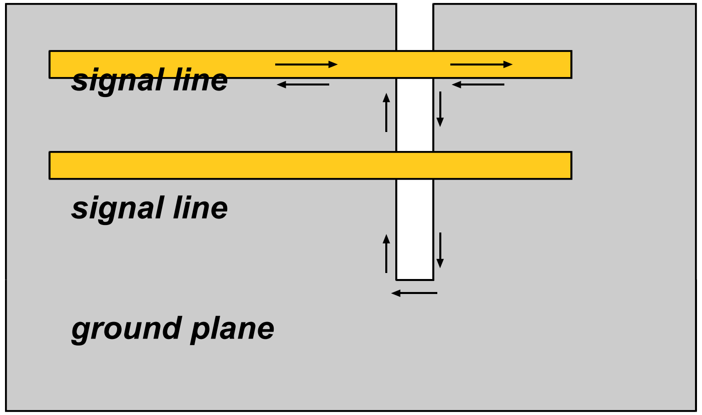
35 GHz master-slave latch in CPW
note fragmented ground plane

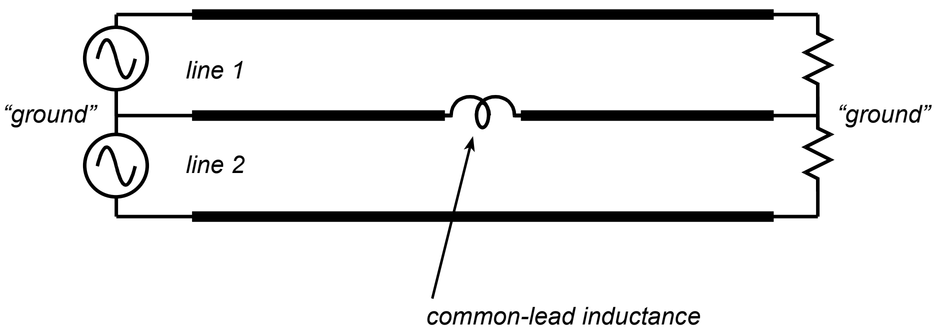


175 GHz tuned amplifier in CPW
note fragmented ground plane

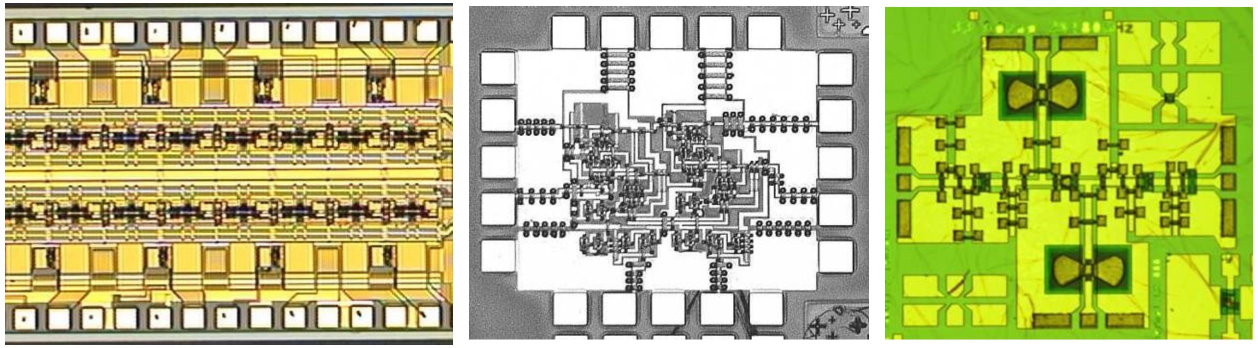
poor ground integrity ☹
↓
loss of impedance control ☹
↓
ground bounce ☹
↓
coupling, EMI, oscillation ☹

If It Has Breaks, It Is Not A Ground Plane !





coupling / EMI due to poor ground system integrity is common in high-frequency systems
whether on PC boards
...or on ICs.



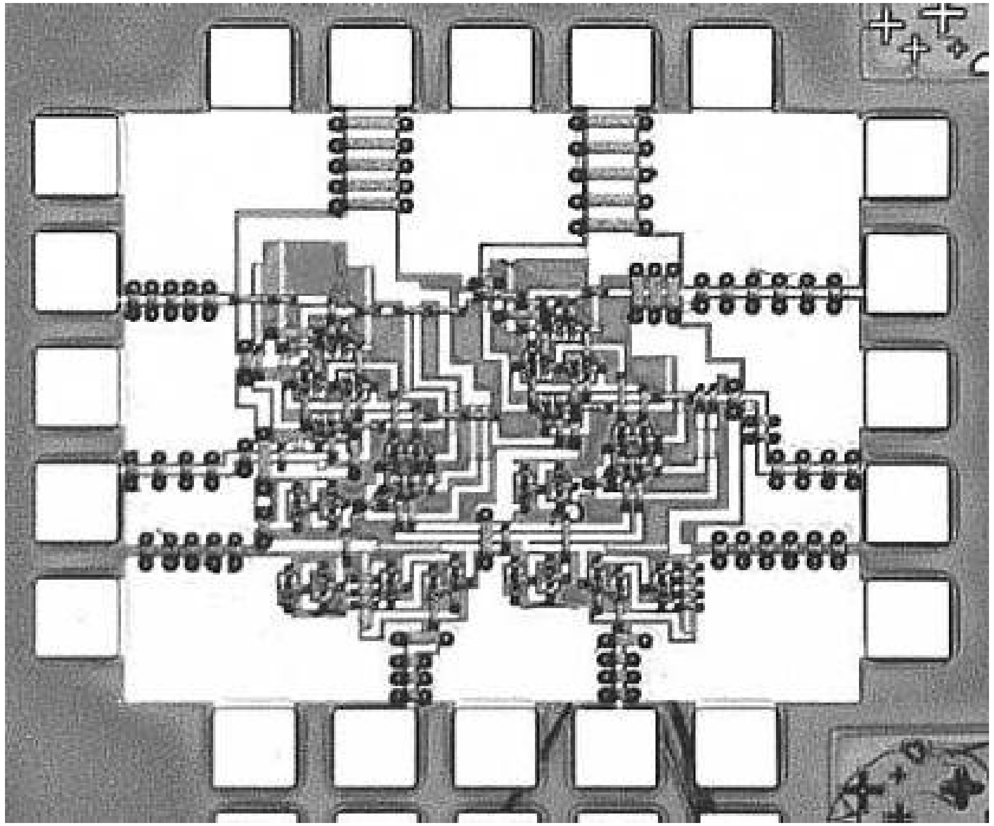
No clean ground return ? → interconnects hard to model

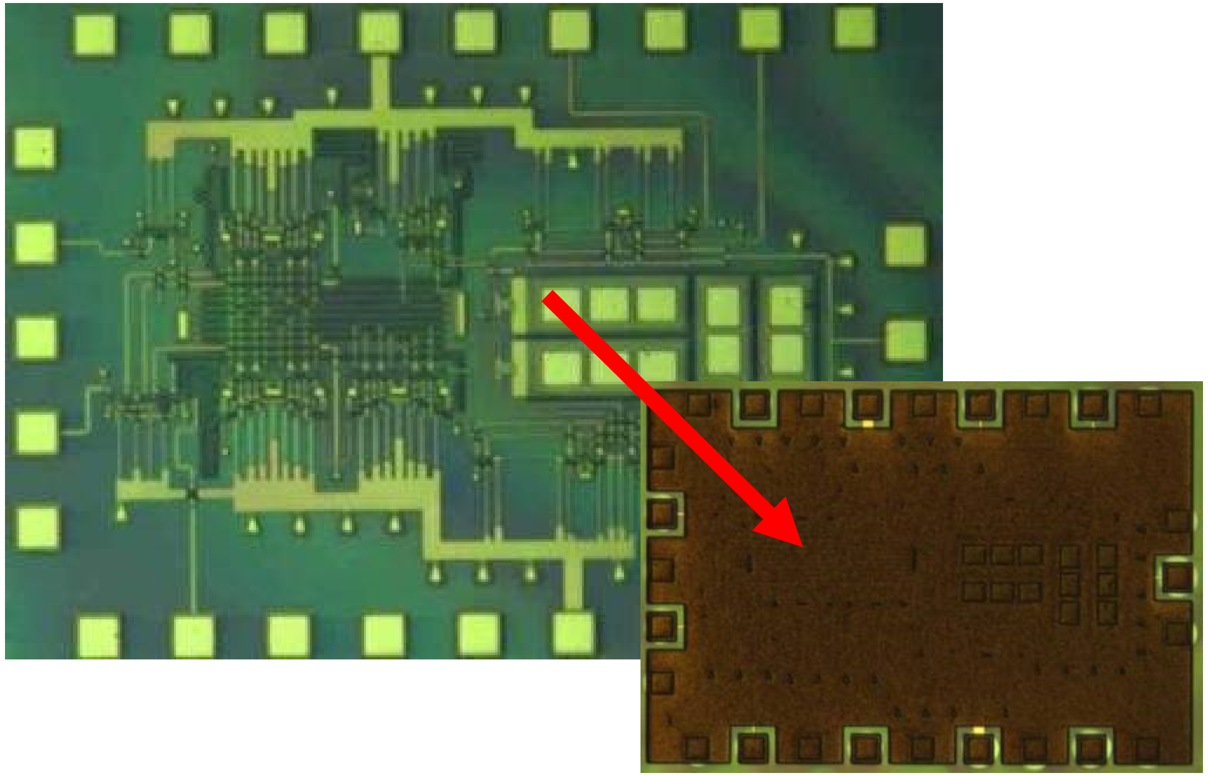
35 GHz static divider

interconnects have no clear local ground return
interconnect inductance is non-local
interconnect inductance has no compact model

8 GHz clock-rate delta-sigma ADC

thin-film microstrip wiring
every interconnect can be modeled as microstrip
some interconnects are terminated in their Zo
some interconnects are not terminated
...but ALL are precisely modeled





InP 8 GHz clock rate delta-sigma ADC

III-V MIMIC Interconnects: Thin-Film Microstrip

narrow line spacing → IC density 🙂

no substrate radiation, no substrate losses 🙂

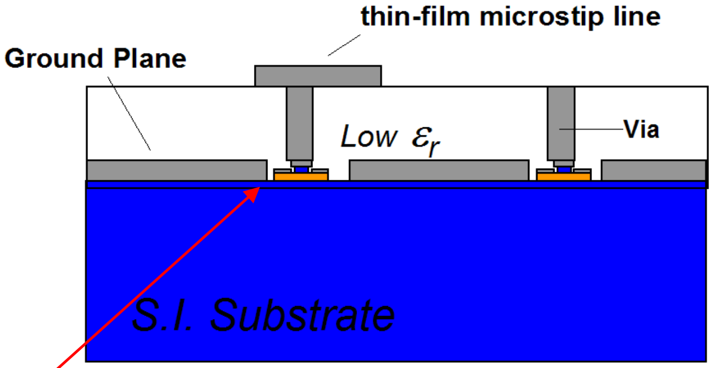
fewer breaks in ground plane than CPW 🙂

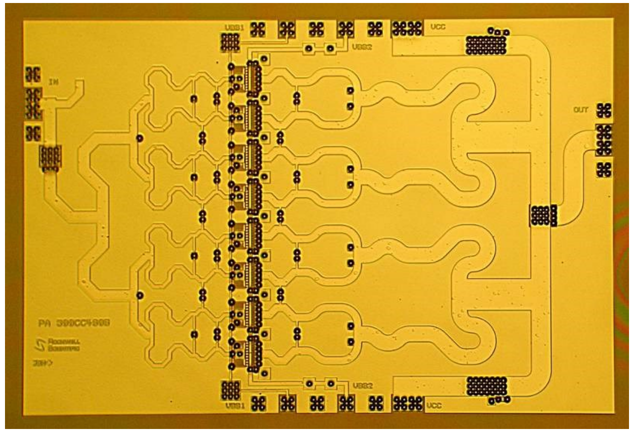
... but ground breaks at device placements 🙁

still have problem with package grounding 🙁

...need to flip-chip bond

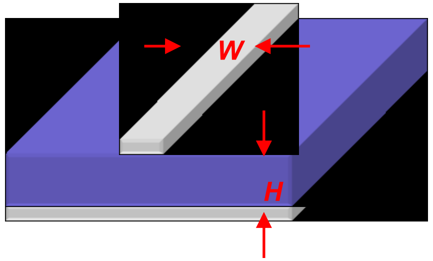
thin dielectrics → narrow lines 🙁
→ high line losses
→ low current capability
→ no high-Z_o lines





InP 34 GHz PA
(Jon Hacker , Teledyne)

$$Z_o \sim \frac{\eta_o}{\varepsilon_r^{1/2}}\left(\frac{H}{W+H}\right)$$



III-V MIMIC Interconnects: Inverted Thin-Film Microstrip

narrow line spacing → IC density ☺

Some substrate radiation / substrate losses ☹

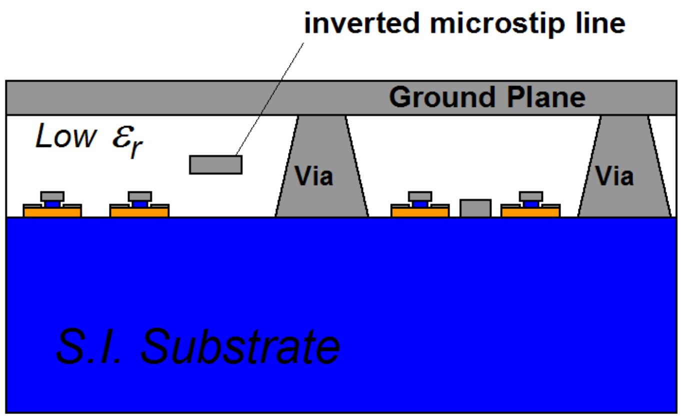
No breaks in ground plane ☺

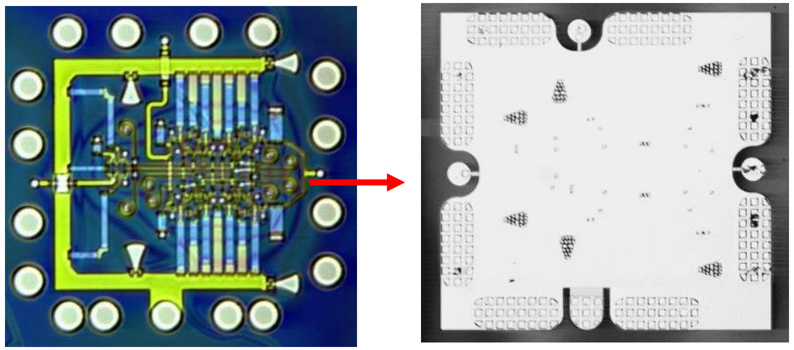
... no ground breaks at device placements ☺

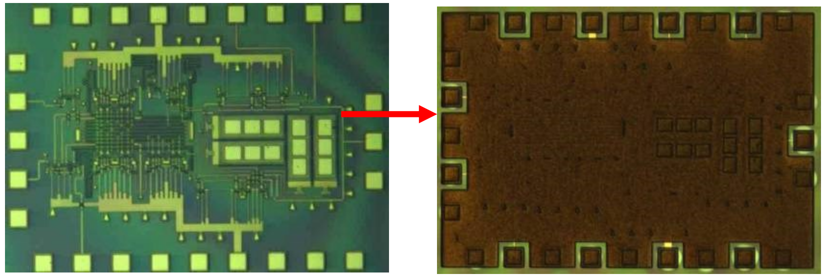
still have problem with package grounding ☹

...need to flip-chip bond

thin dielectrics → narrow lines
→ high line losses
→ low current capability
→ no high-Z_o lines ☹




InP 150 GHz master-slave latch


InP 8 GHz clock rate delta-sigma ADC

VLSI mm-wave interconnects with ground integrity

narrow line spacing → IC density ☺

no substrate radiation, no substrate losses ☺

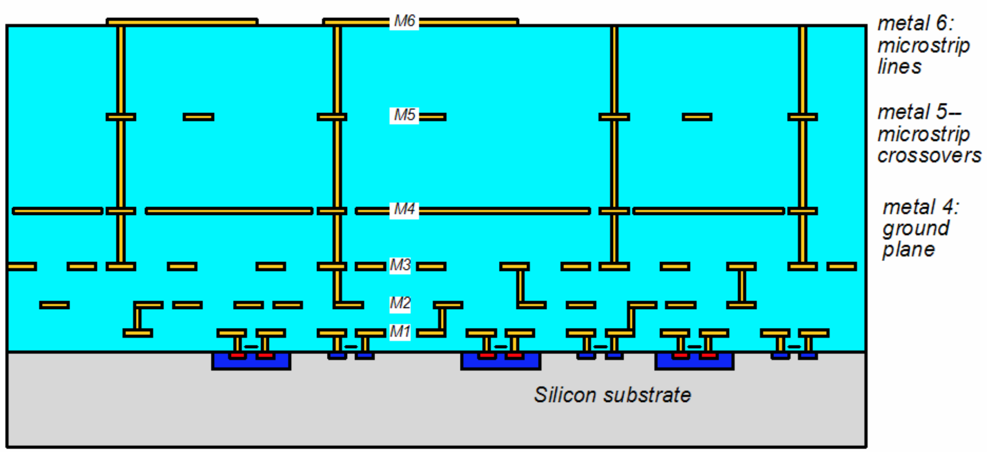
negligible breaks in ground plane ☺

negligible ground breaks @ device placements ☺

still have problem with package grounding ☹

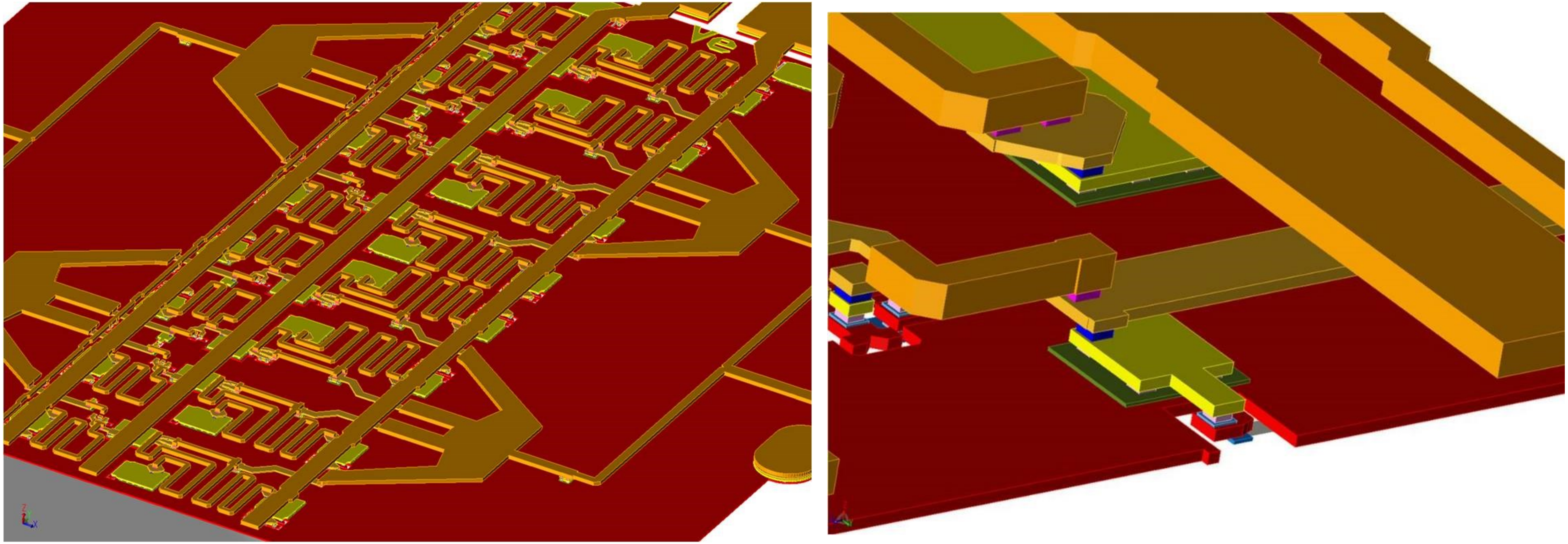
...need to flip-chip bond

thin dielectrics → narrow lines
→ high line losses
→ low current capability
→ no high-Z_o lines ☹



Also:
Ground plane at *intermediate level* permits critical signal paths to cross supply lines, or other interconnects without coupling.
(critical signal line is placed above ground, other lines and supplies are placed below ground)

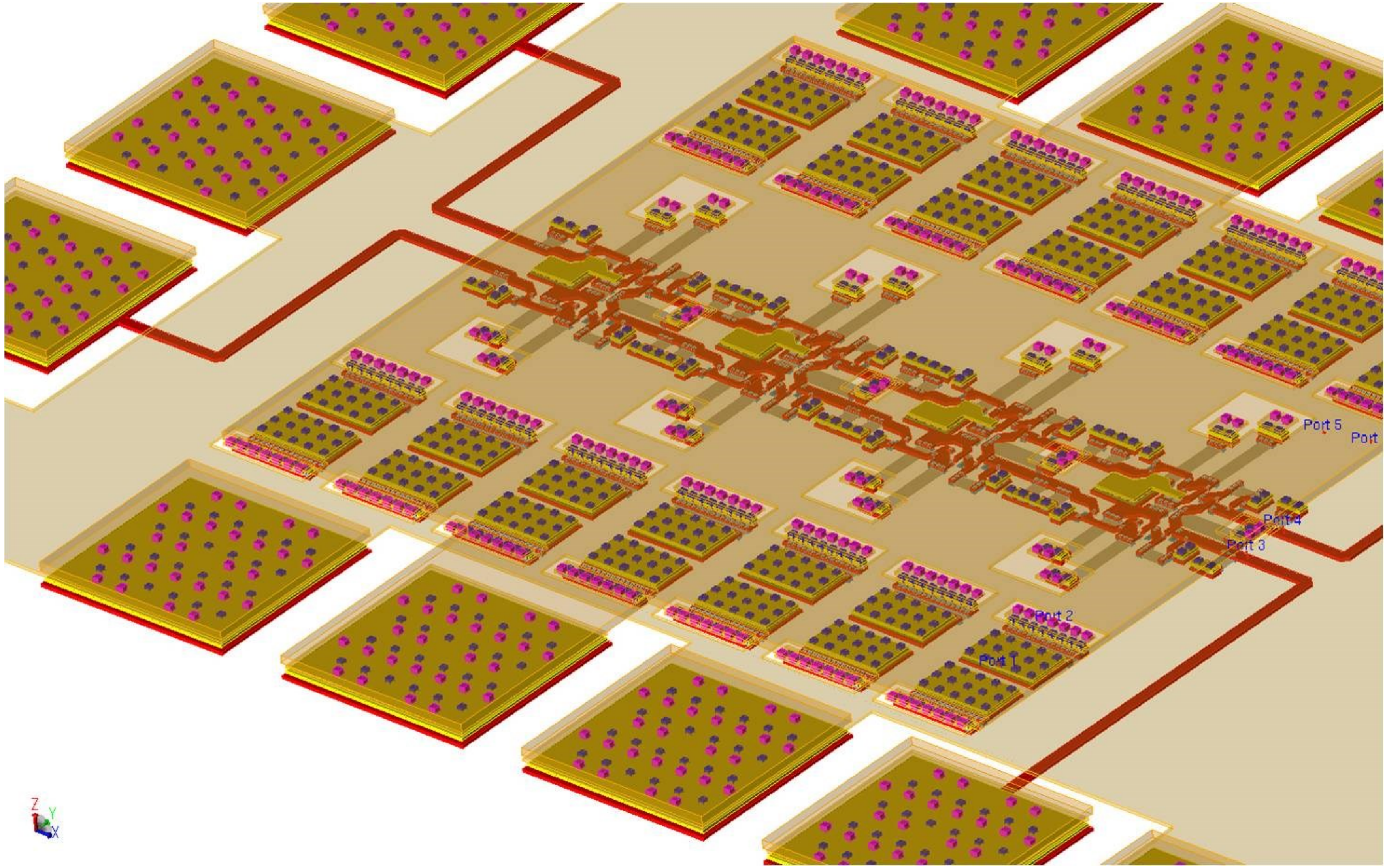
ICs in Thin-Film (Not Inverted) Microstrip



Note breaks in ground plane at transistors, resistors, capacitors

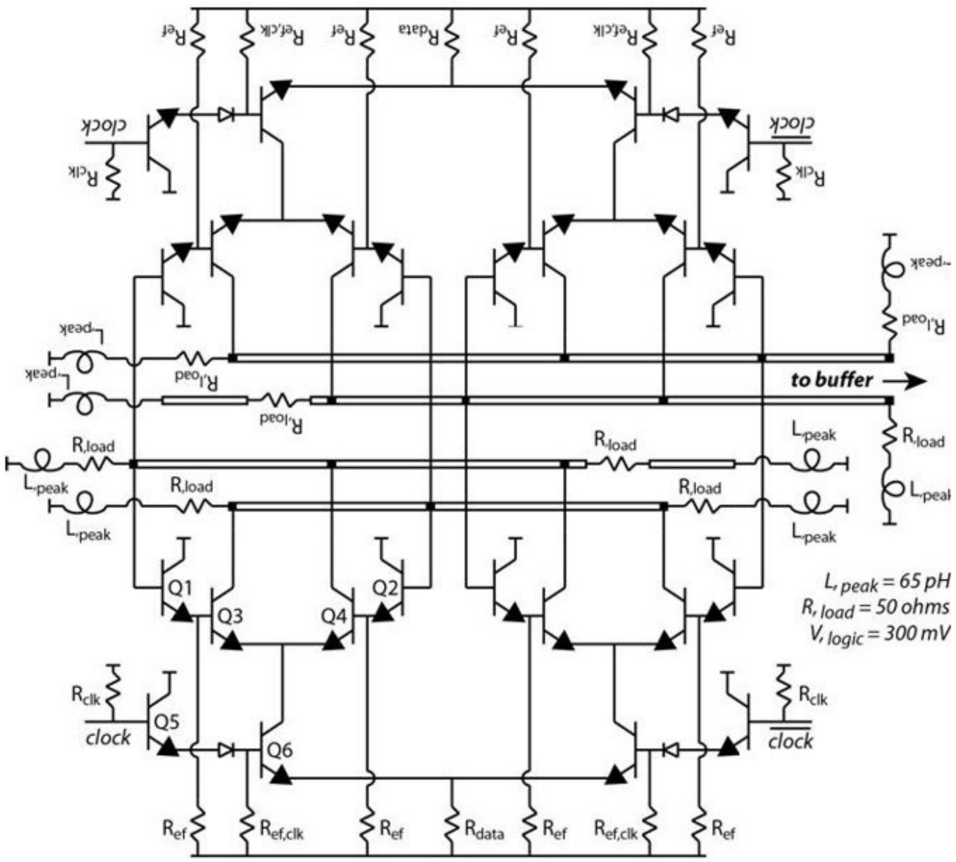
Interconnects within these breaks will be more difficult to model.

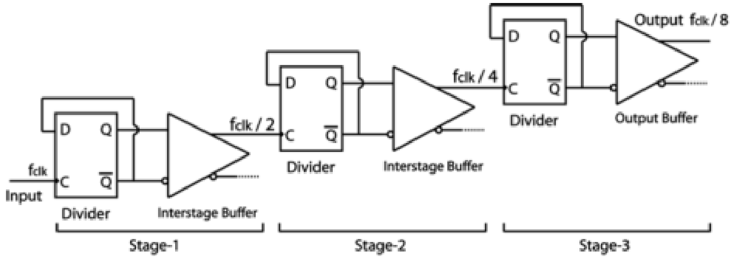
ICs in Thin-Film Inverted Microstrip

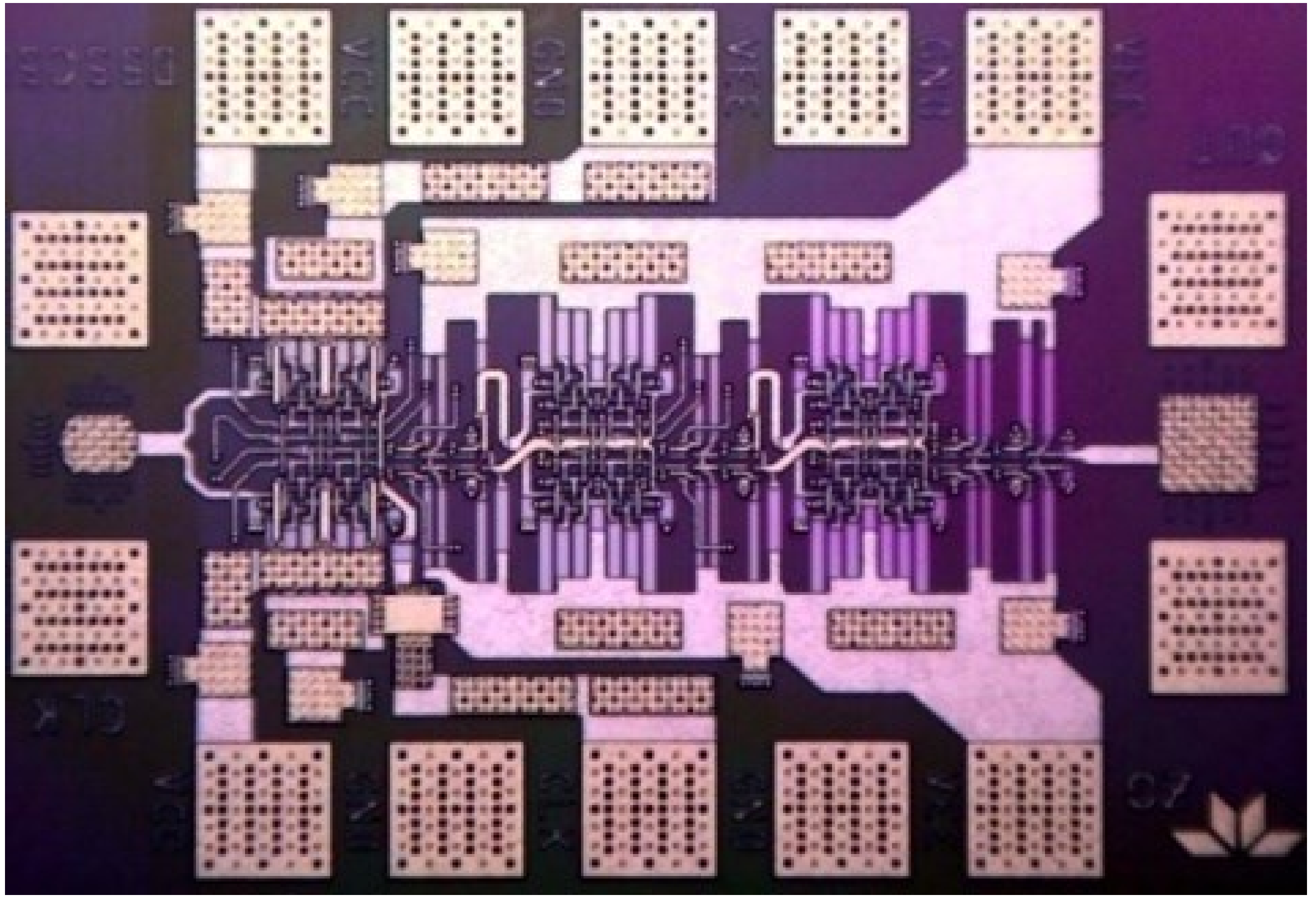


100 GHz differential TASTIS Amp.   512nm InP HBT

ICs in Thin-Film Inverted Microstrip





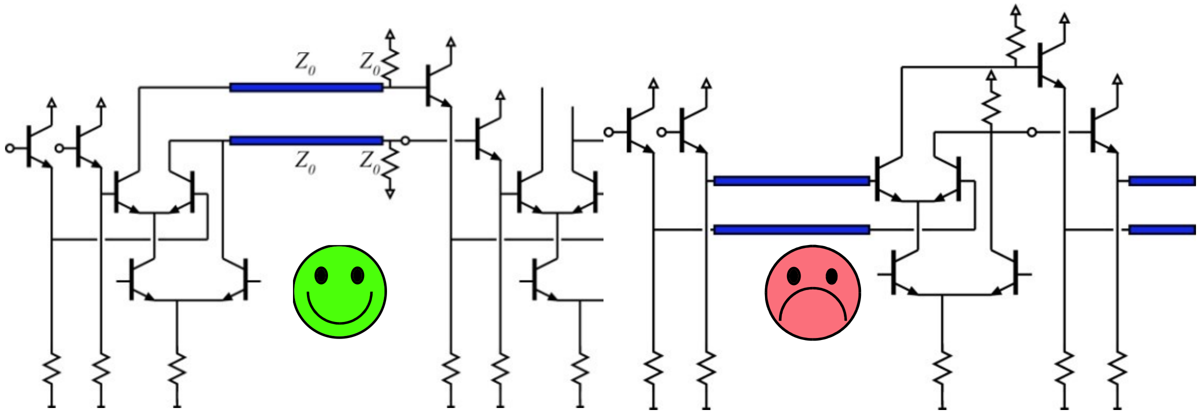


205 GHz divider, Griffith et al, IEEE CSIC, Oct. 2010

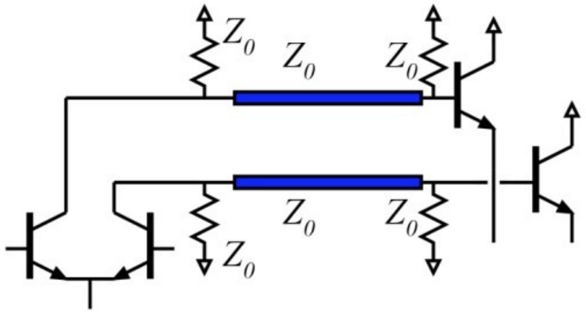
8:1, 205 GHz static divider in 256 nm InP HBT. Image taken before top metal (ground plane) deposition

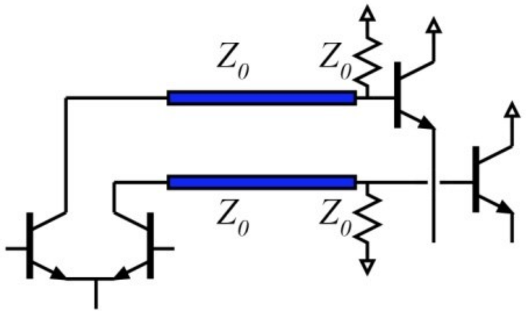
High Speed ECL Design: transmission-lines

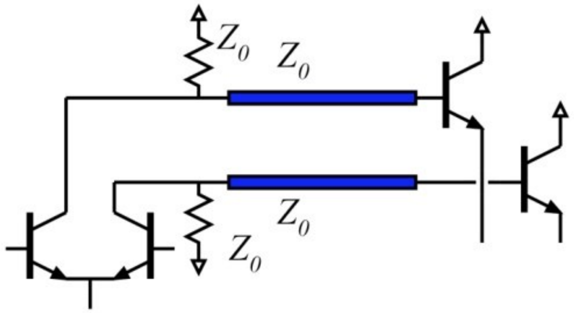
Followers associated with inputs, not outputs
Emitters never drive long wires.
(instability with capacitive load)

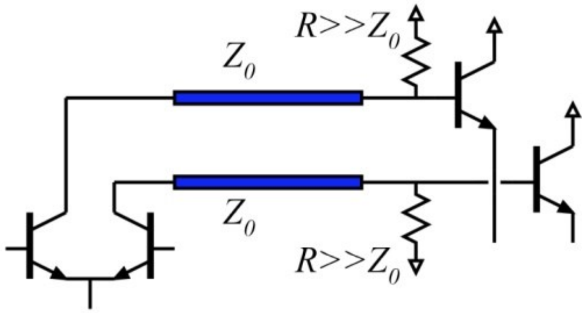


Double termination for least ringing,
send or receive termination for moderate-length lines,
high-Z loading saves power but kills speed.

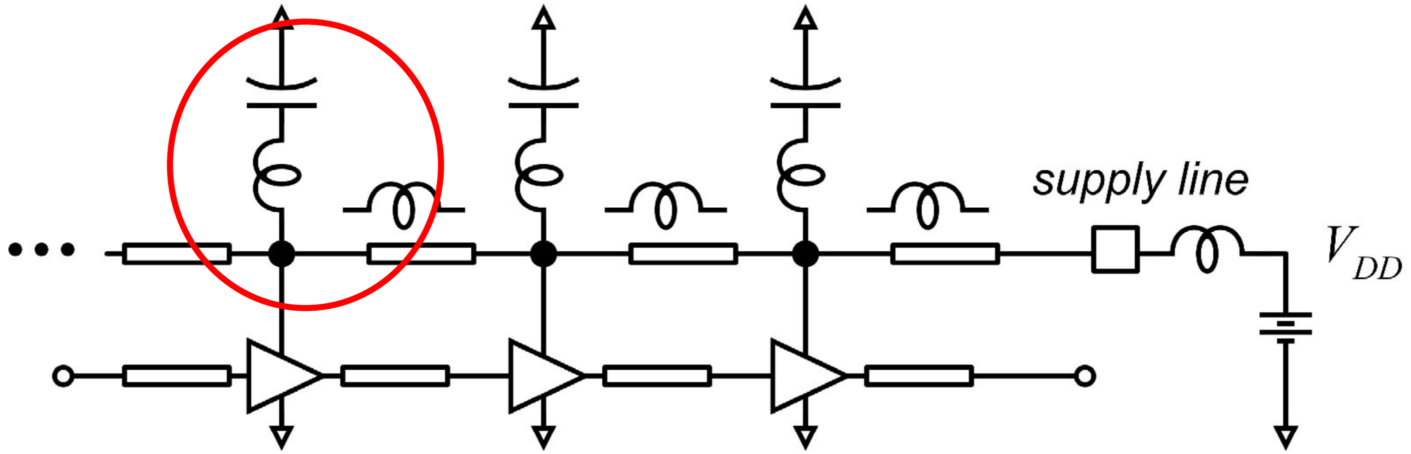






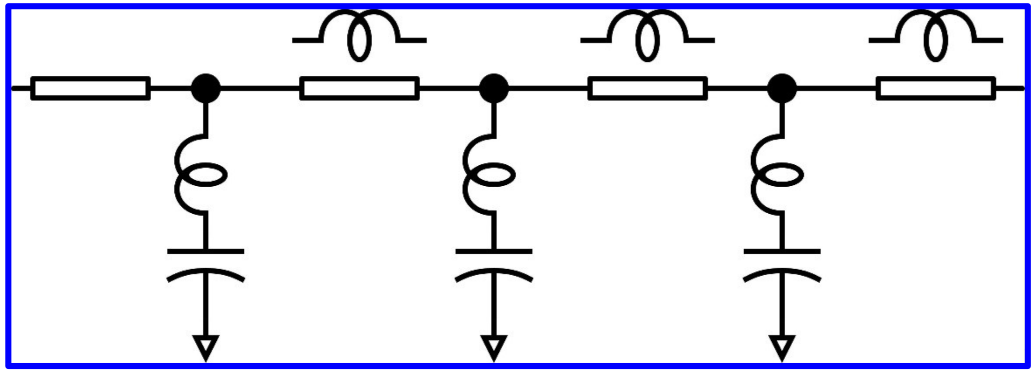


Power supply problems



local resonances between bypass cap and supply interconnects

global LC standing-wave resonances on supply bus

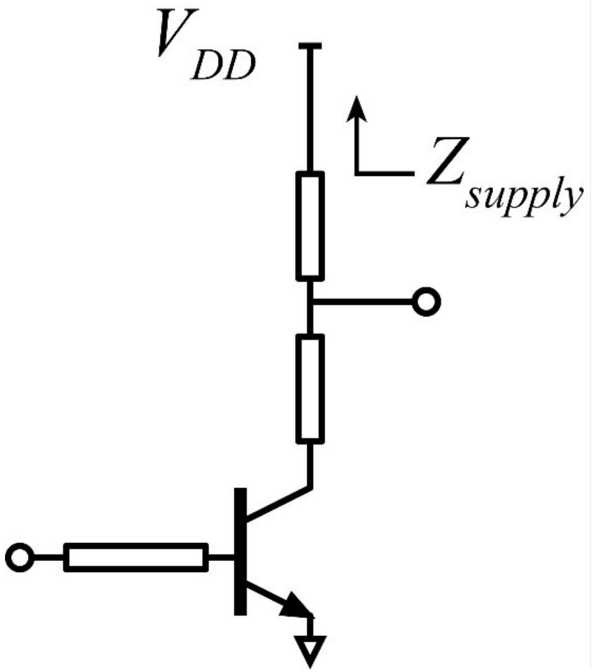


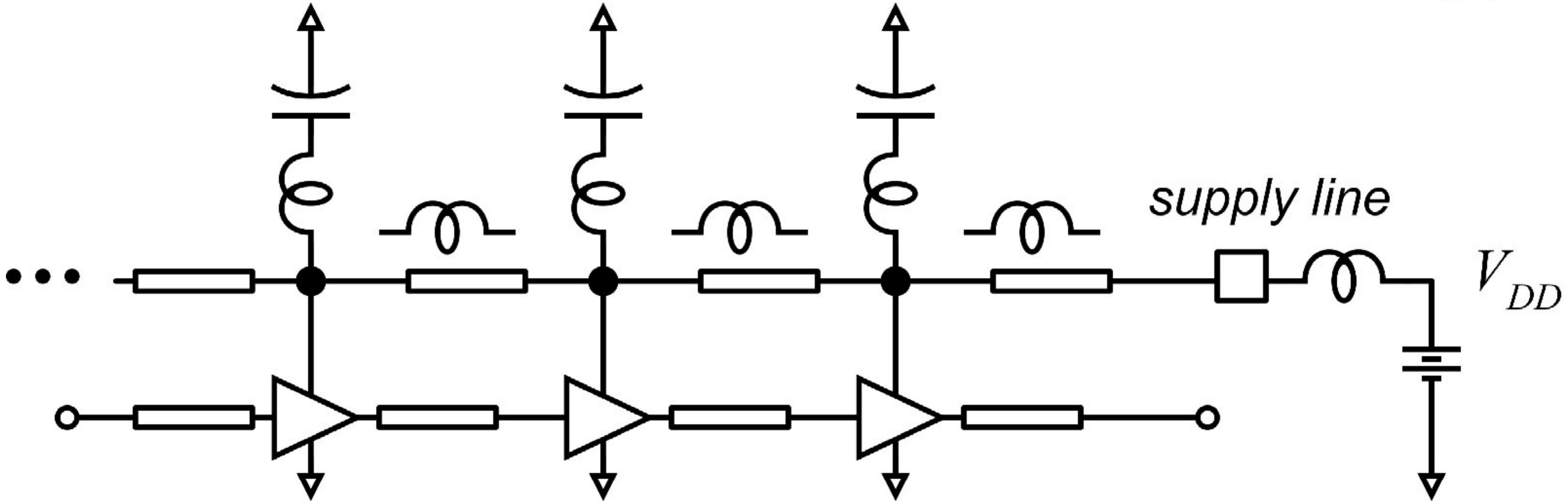
Detuning of individual stages

Coupling, feedback via supply→ oscillation, loss of path isolation

Power supply problems

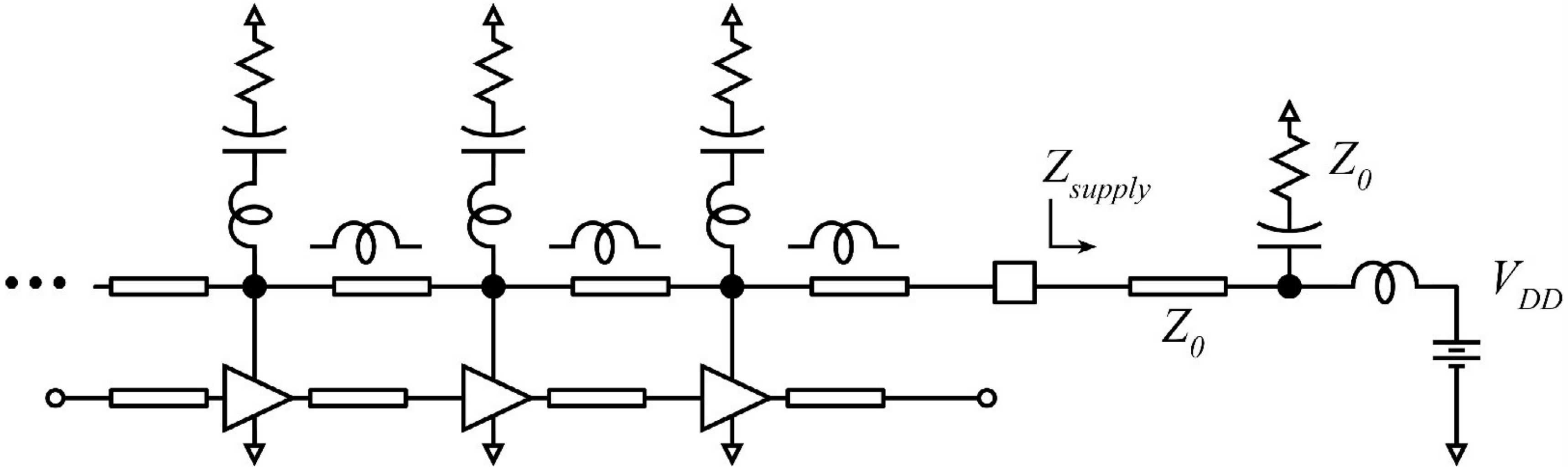
The supply impedance will detune individual stages.





Power supply problems

Model the supply in all simulations.
"If it is on the {IC, PCB, probe station}, put it in the simulation."

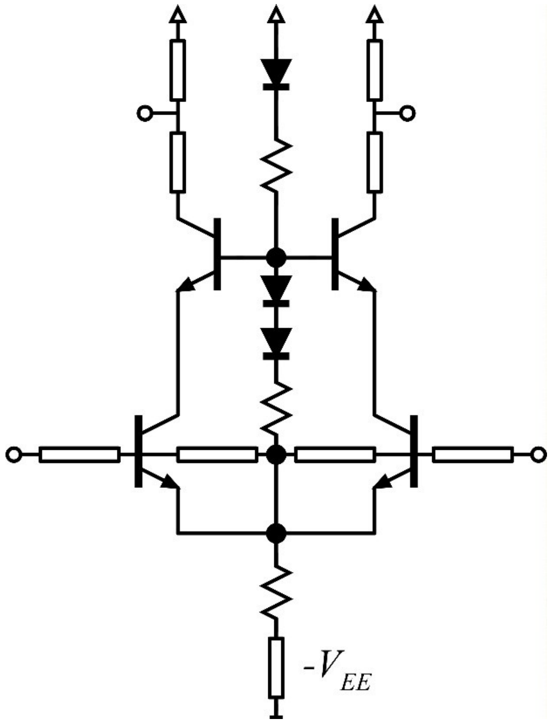


Here, the supply is terminated by 50 Ohms through a bias T.
This avoids resonances.

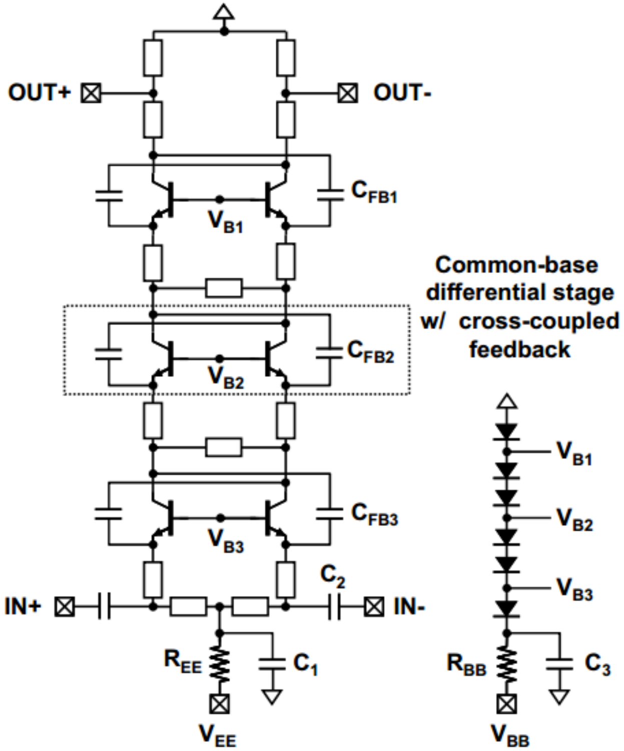
More generally, we must simulate system
for wide range of external supply impedance.

Differential mm-wave stages

Common-emitter
M. Seo, Teledyne

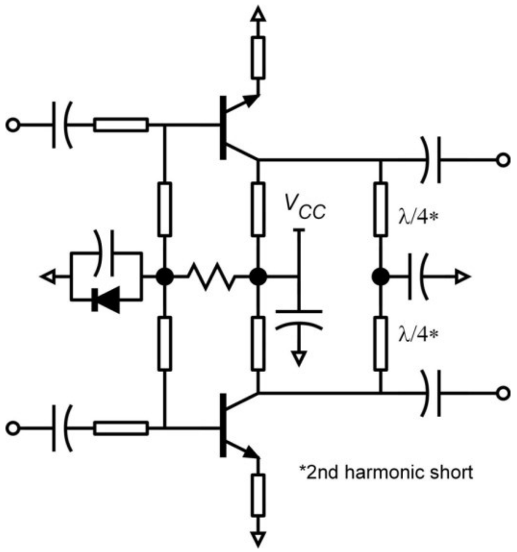


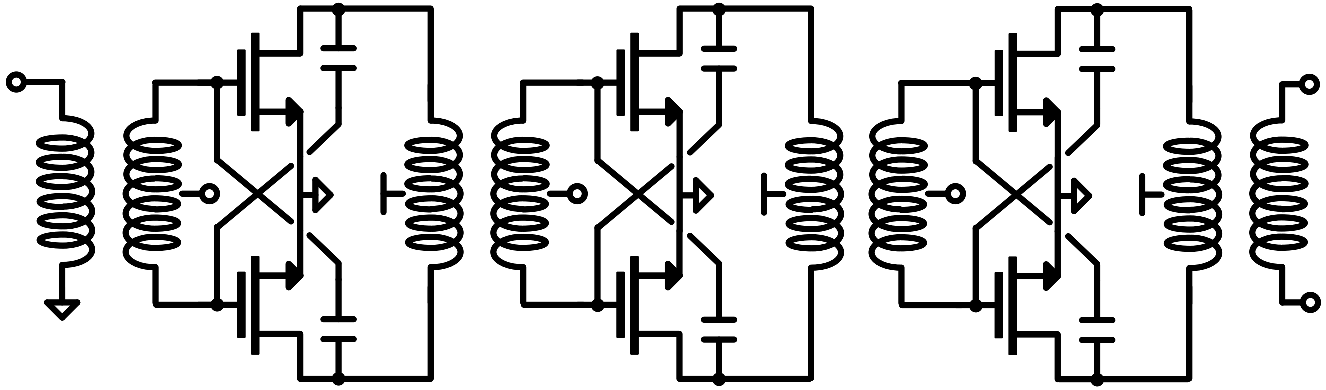
Common-base
M. Seo, 2013 IMS

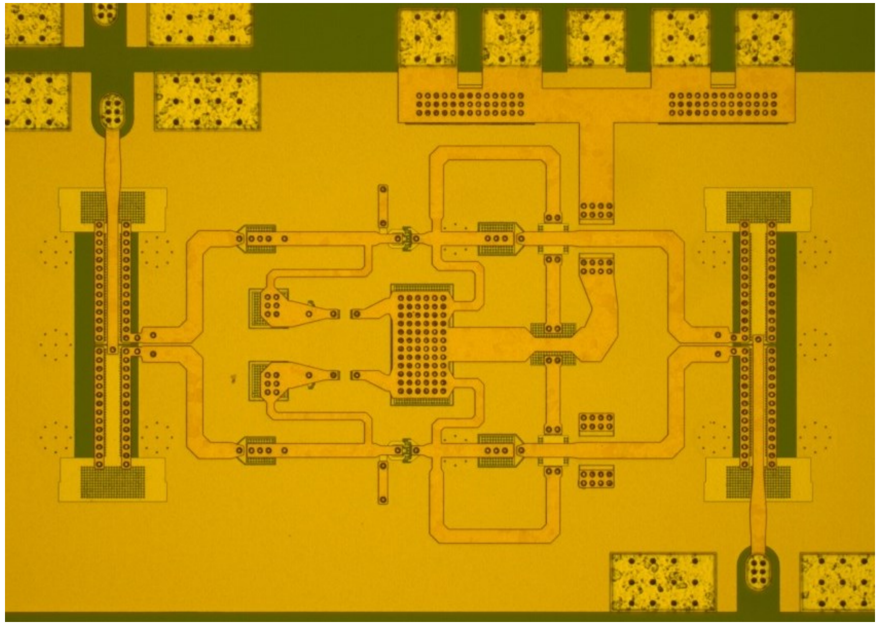


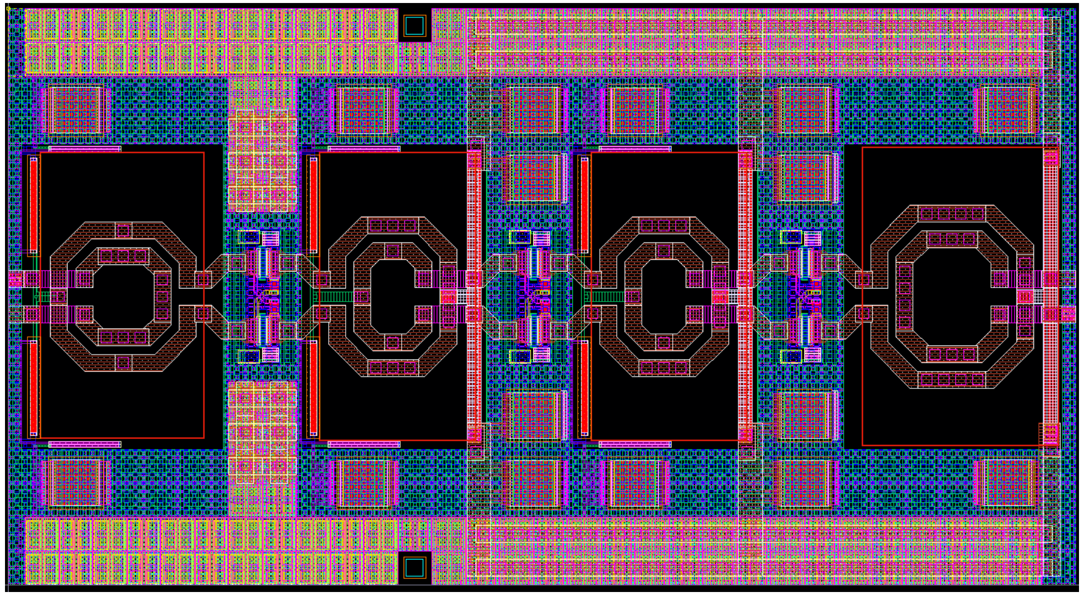
Virtual ground→ avoids ground via inductance ✓
Avoids power-supply coupling ✓
Potential problems with common mode ✗

Pseudo-Differential Stages









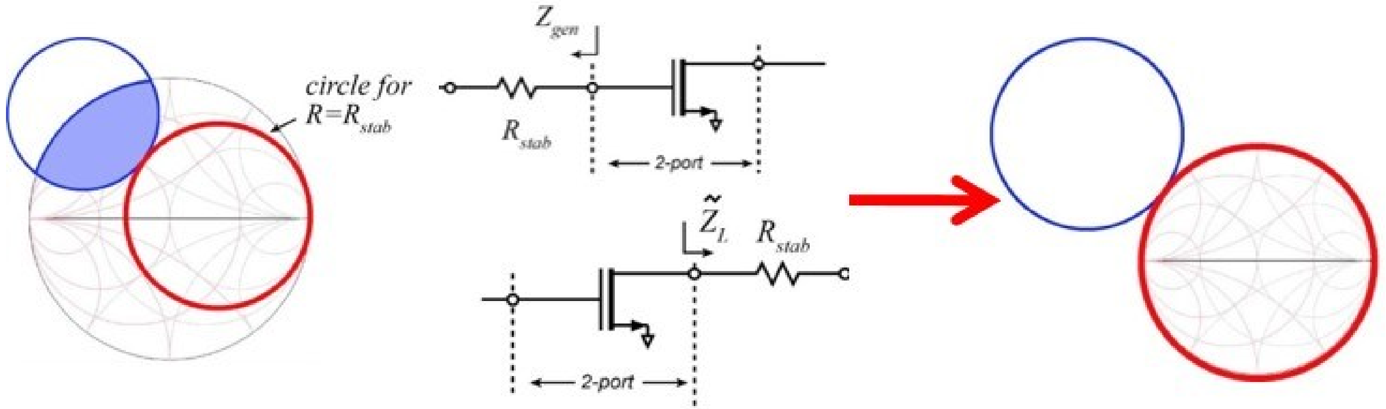
RF-IC Design: Simple & Well-Known Procedures

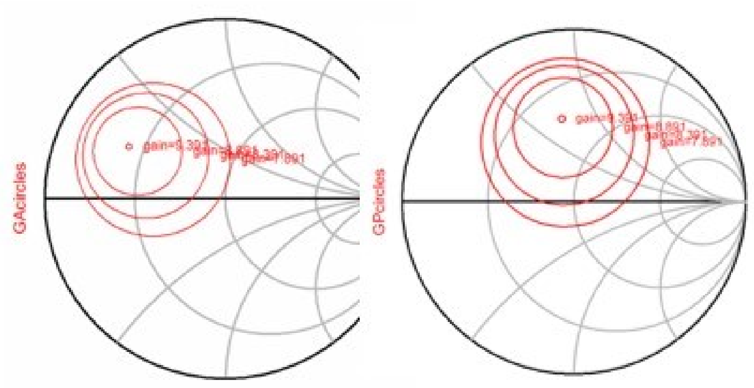
1: (over)stabilize at the design frequency
guided by stability circles

2: Tune input for F_{min} (LNAs) or output for P_{sat} (PAs)

3: Tune remaining port for maximum gain

4: Add out-of-band stabilization.





This seems simple: so where are the challenges ?

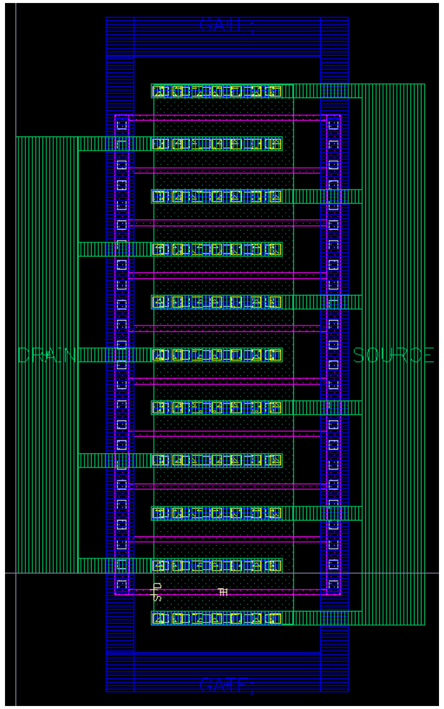
mm-Wave IC design: the challenges

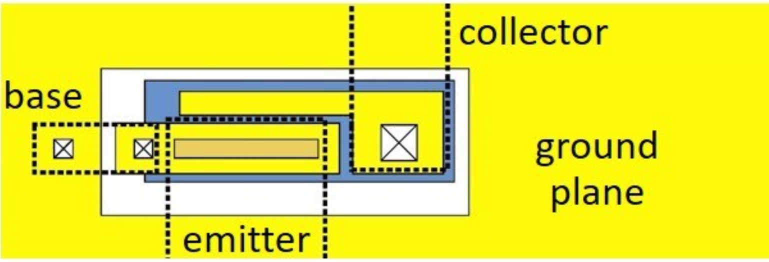
Transistor gains are low: f_{signal} is significant fraction of $f_{\max}$.
usually must match for optimum gain, noise, or power.

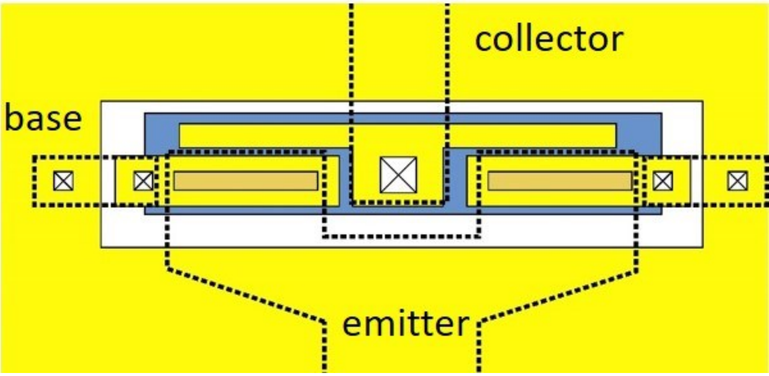
(Transistor, resistor, capacitor) dimensions are a significant fraction of a wavelength
Even short lengths of random wiring add serious inductance and/or capacitance

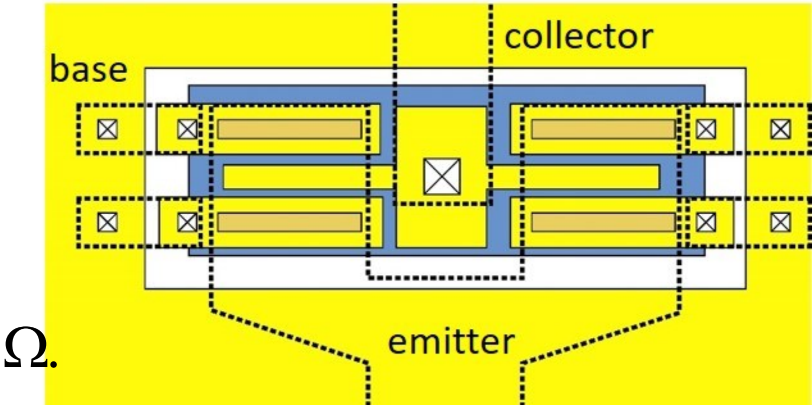
Transmission-line losses are high
low Q in VCO resonators and filters
high combining losses in PAs: low power, low efficiency
several dB added noise in LNAs.

Multi-finger transistor cell layout









Individual transistor finger

- low current
- optimum port impedances well above 50Ω.
- can't be matched

Mult-finger (n-finger) layout

- transistor fingers wired in parallel.
- wiring (L, R) are often in series
- $R_{wire}C_{transistor}$, $\sqrt{L_{wire}C_{transistor}}$ scale as N^1 or as N^2.
- limits # of fingers.

If we are fortunate, we can incorporate sufficient fingers to match to 50Ω.

Futher levels of combining: corporate transmission-line combiners, etc.

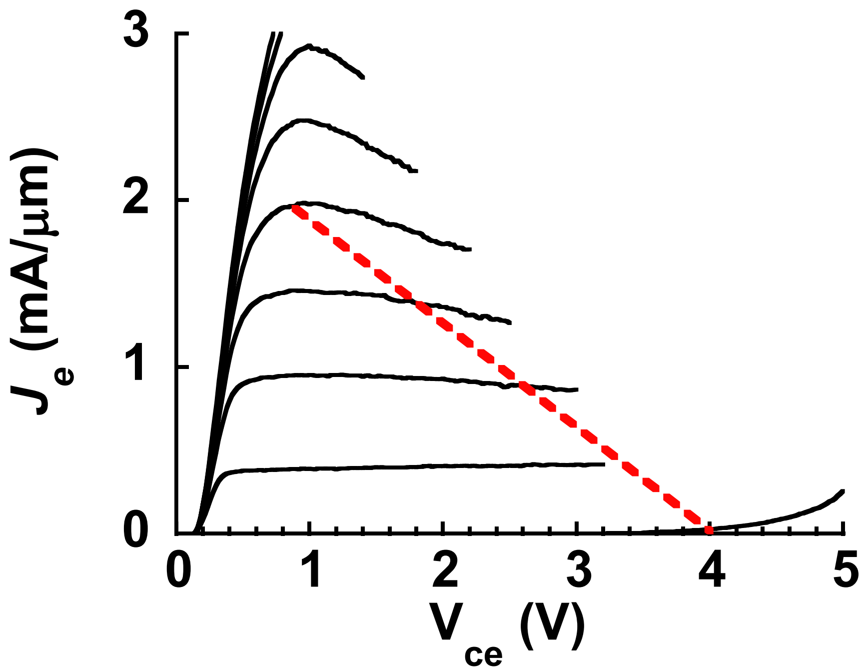
Sub-mm-wave PAs: need more current

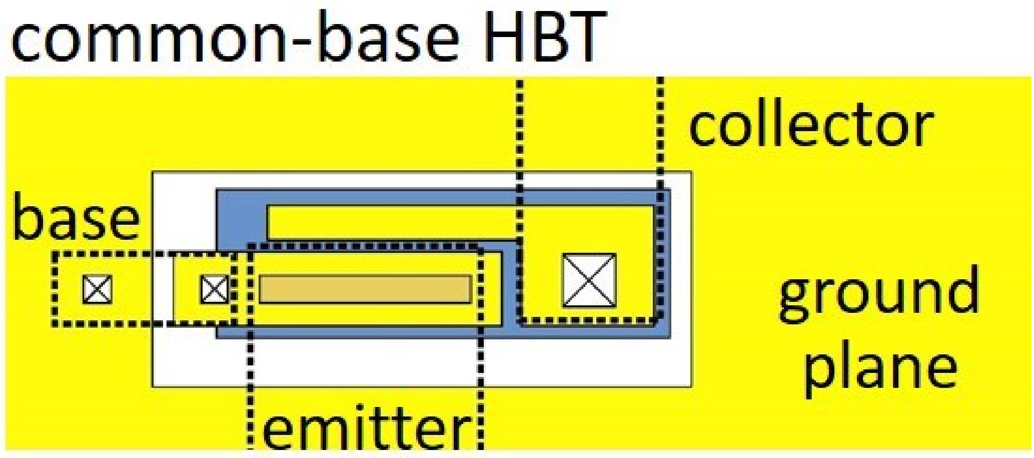
3 μm max emitter length (> 1 THz f_{max})
2 mA/μm max current density: I_{max}= 6 mA

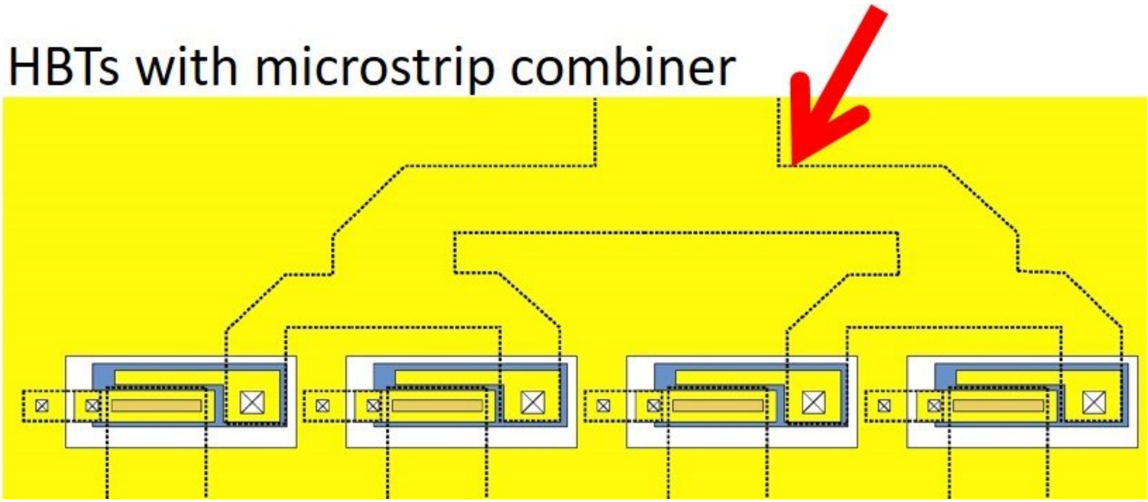
Maximum 3 Volt p-p output

Load: 3V/6mA= 500 Ω

Combiner cannot provide 500 Ω loading

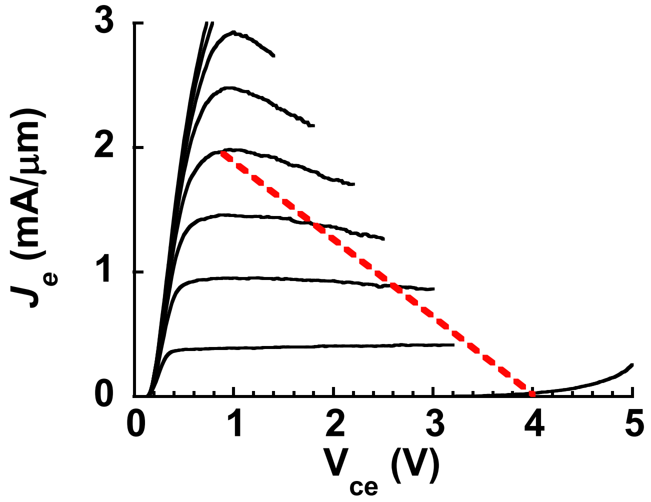


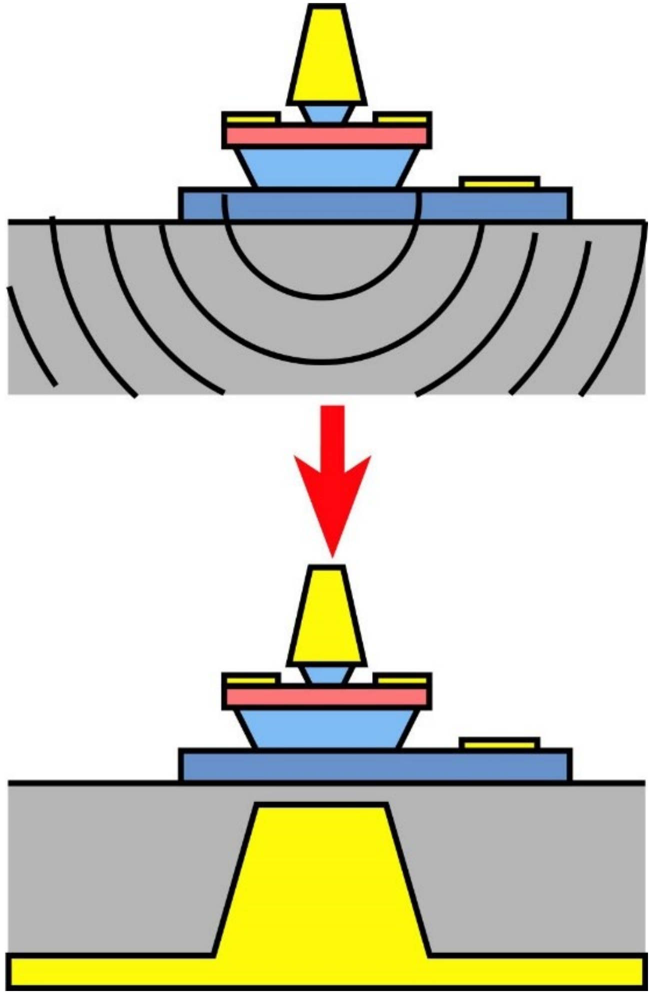




mm-wave PAs: need more current

InP HBTs:
thinner collector→ more current
hotter→ improve heat-sinking
or: longer emitters→ thicker base metal





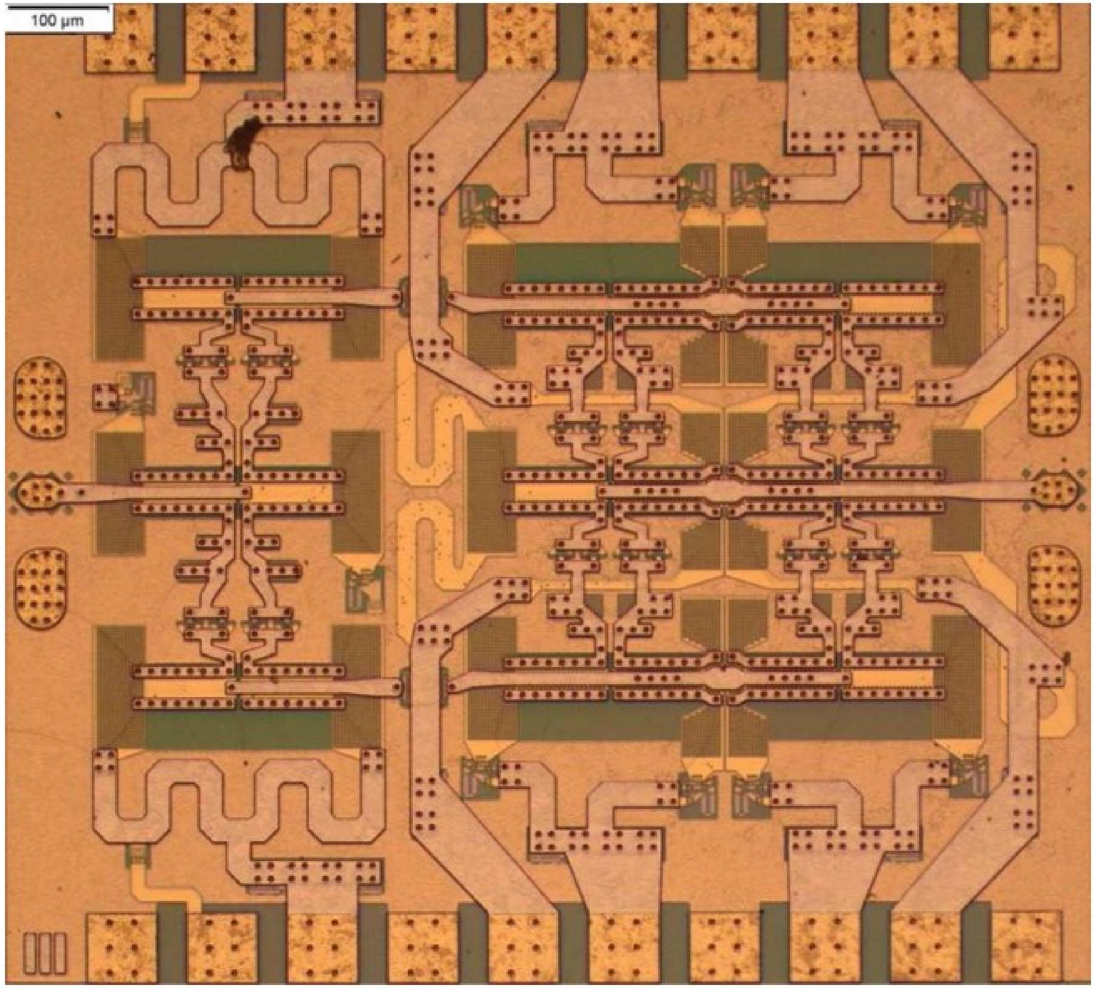
GaN HEMTs:
much higher voltage
100+ GHz: large multi-finger FETs not feasible
Need high current to exploit high voltage.

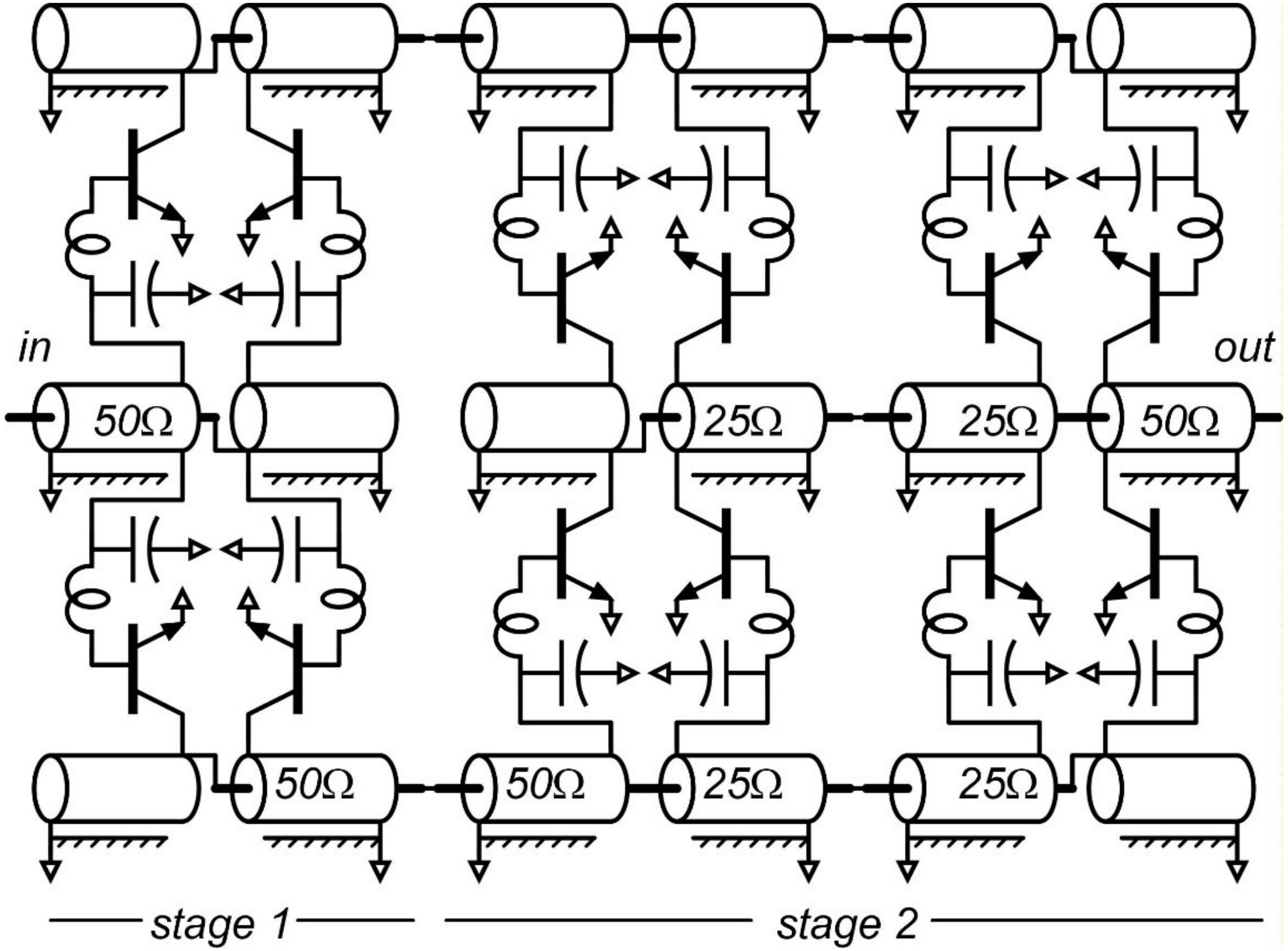
Example:
2mA/μm, 100 μm max gate width, 50 Volts
200mA maximum current
50 Volts/200mA= 250 Ω load→ unrealizable.

Need more mA/μm or longer fingers

4:1 series-connected 81GHz power amplifier

Park *et al.*, 2014 IEEE-IMS

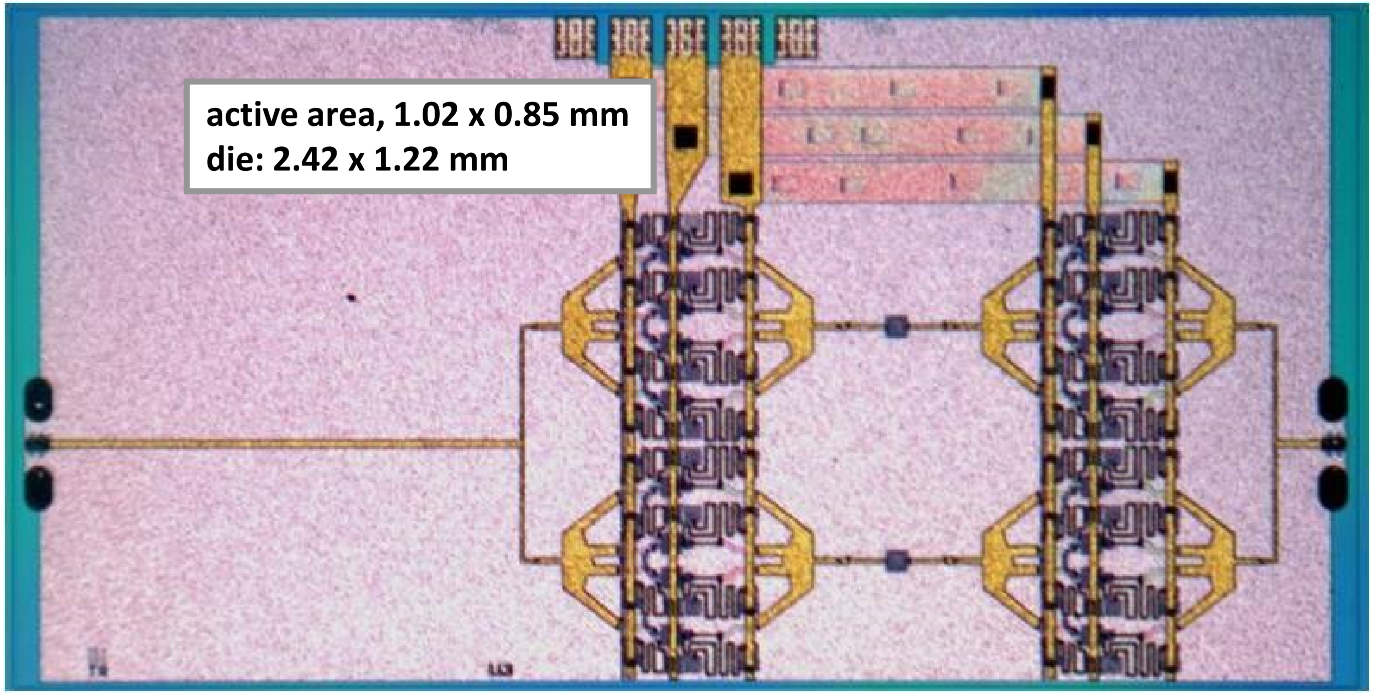


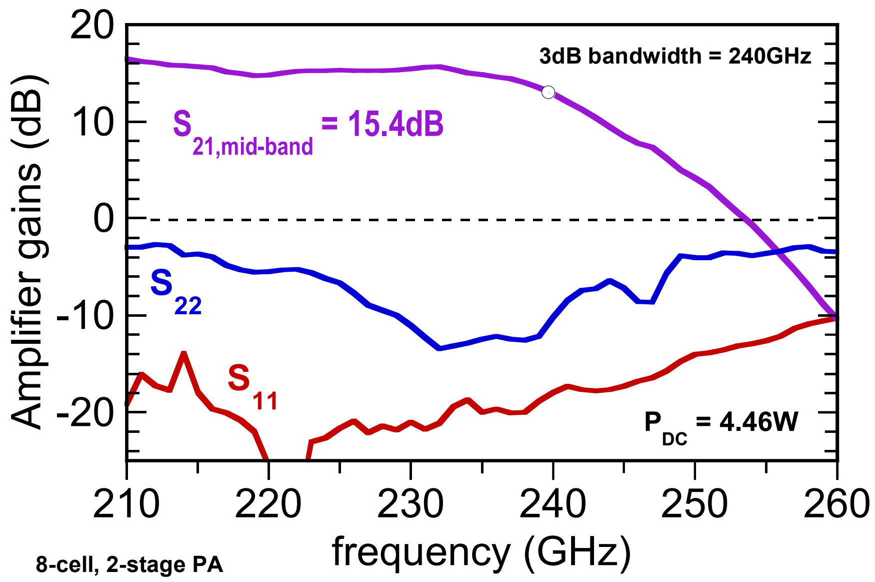


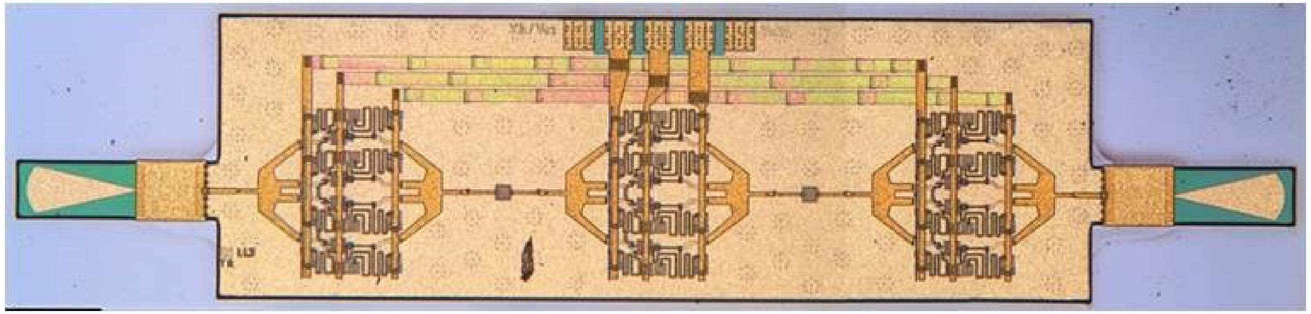
17 dB Gain, 470 mW P_{sat} , 23% PAE

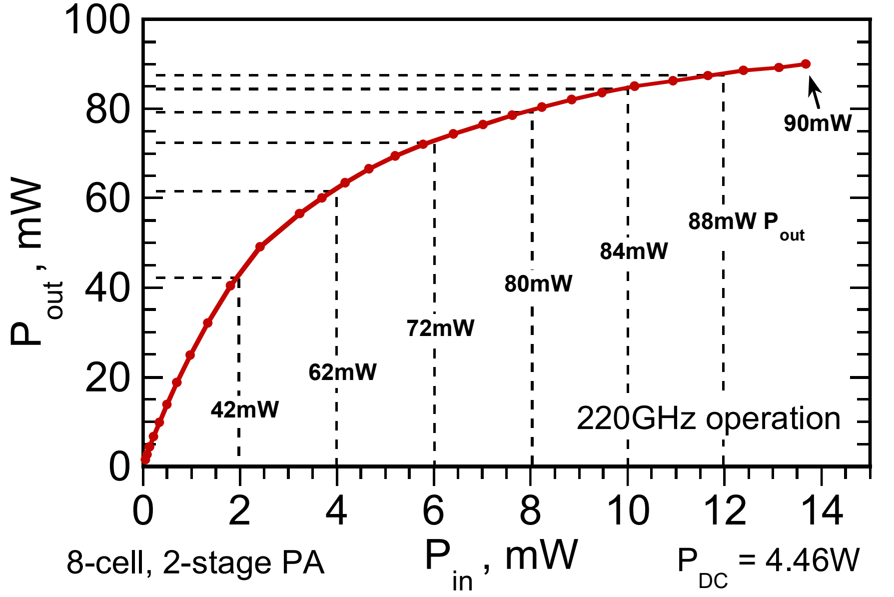
Teledyne 250 nm InP HBT, 2 stages, 1.0 mm^2(incl pads)

90 mW, 220 GHz Power Amplifier


active area, 1.02 x 0.85 mm
die: 2.42 x 1.22 mm

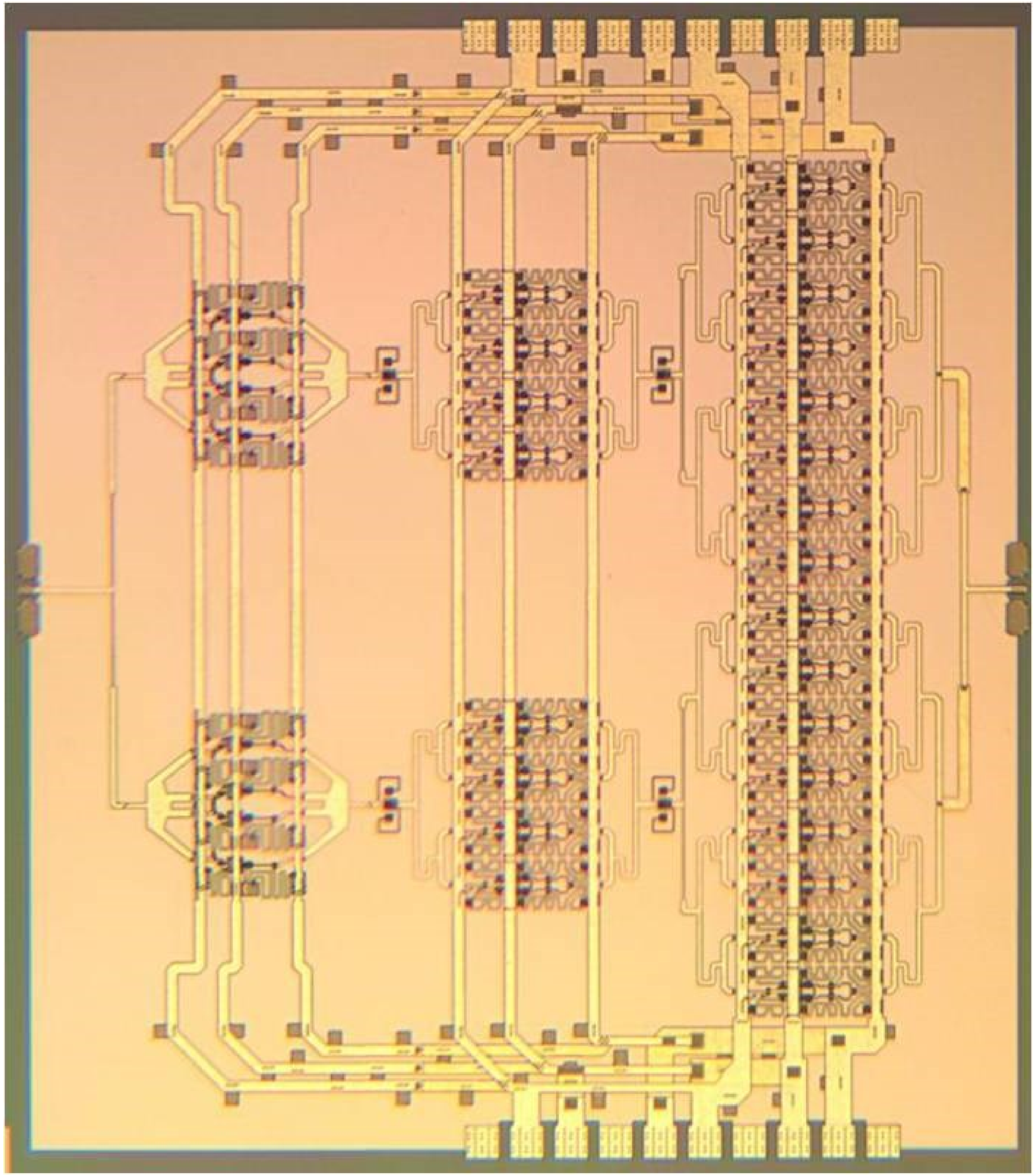


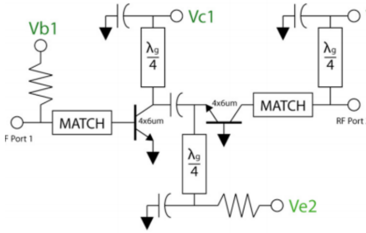


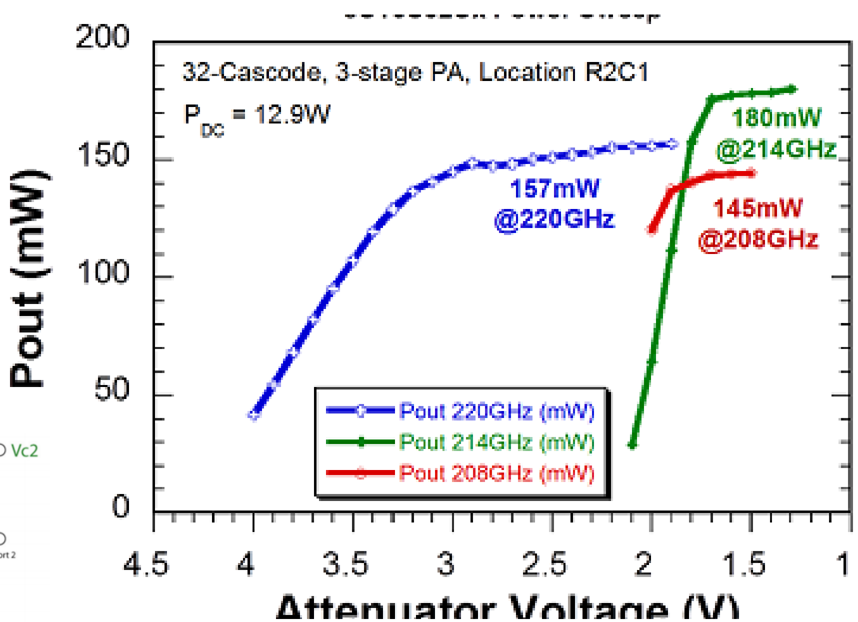


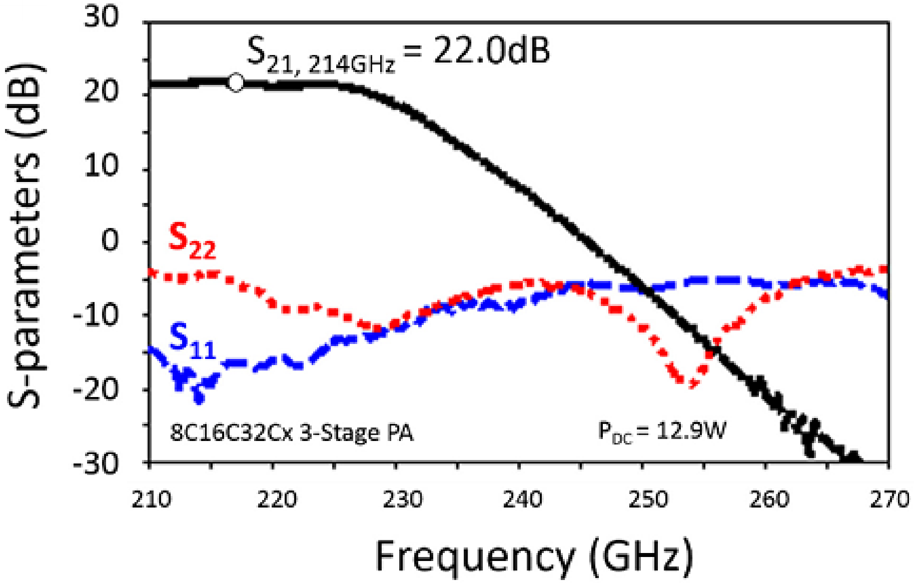
Reed (UCSB) and Griffith (Teledyne): CSIC 2012. Teledyne 250 nm InP HBT

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

220GHz PA Design; in development

Technology: 250nm InP HBT

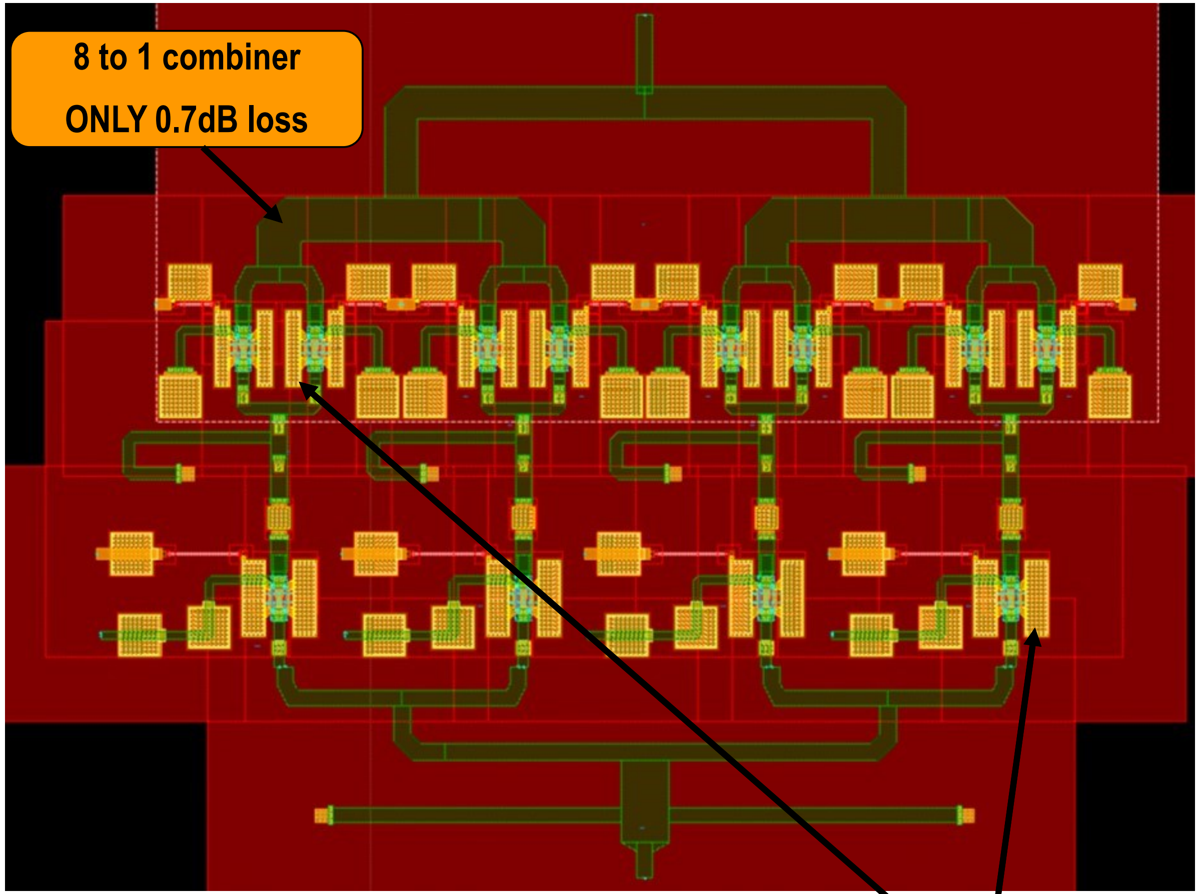
Combining techniques investigated:

- **Series, Balun, Wilkinson**
- **Branched λ/4 network ✓**

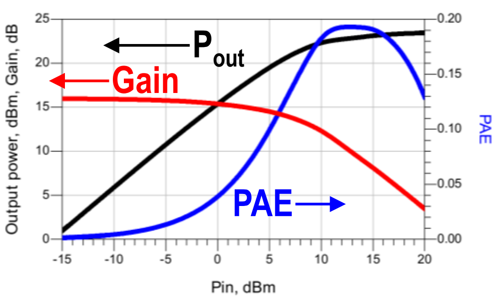
Unit cells investigated

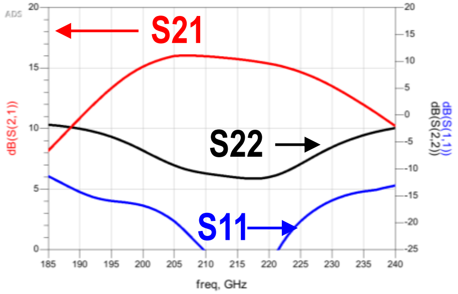
- **CE, Cascode**
- **CB with grounded base**
- **CB with optimized base impedance**

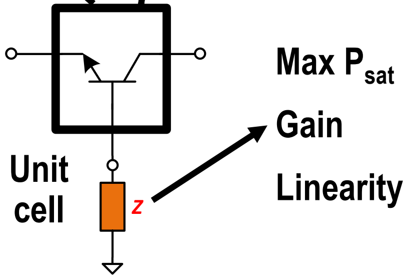
Technology	250-nm InP HBT
Freq, GHz	205
#cells	8
VCC, V	2.25
J_{bias},mA/um	1.33
S21, dB	15.9
P_{out},dB_m	17.8*, 20.7**
PAE %	6.8*,12.9**
BW_{3dB}, GHz	35
area, μm×μm	750×717
*at 1dB compression, **at 2dB	


8 to 1 combiner

ONLY 0.7dB loss





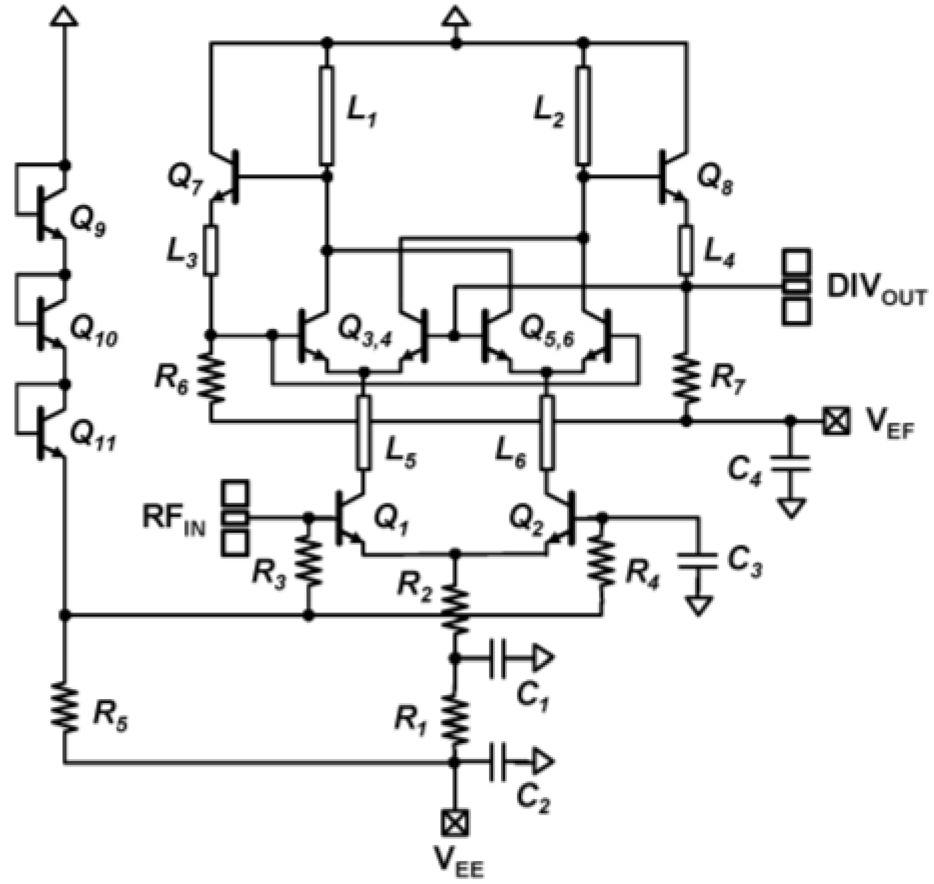


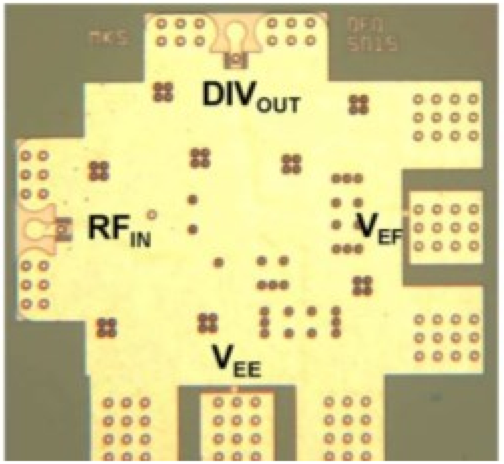
Max P_{sat}

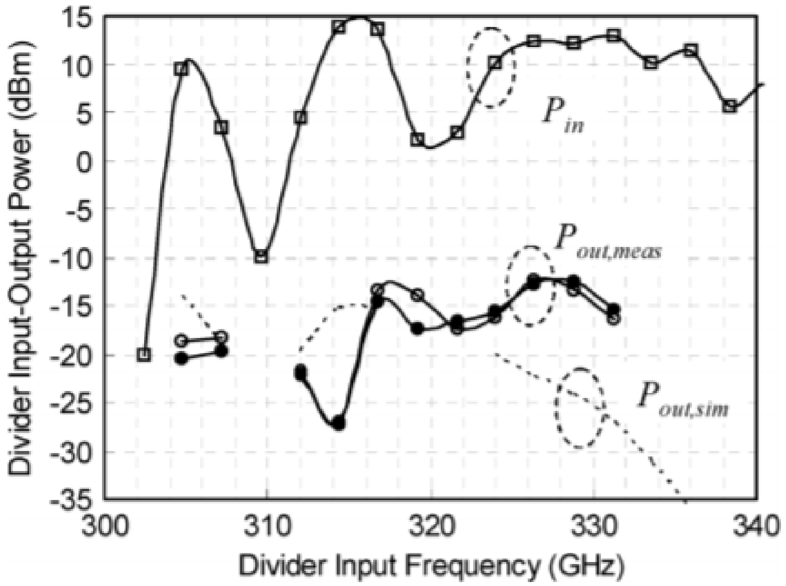
Gain

Linearity

370 GHz dynamic divider





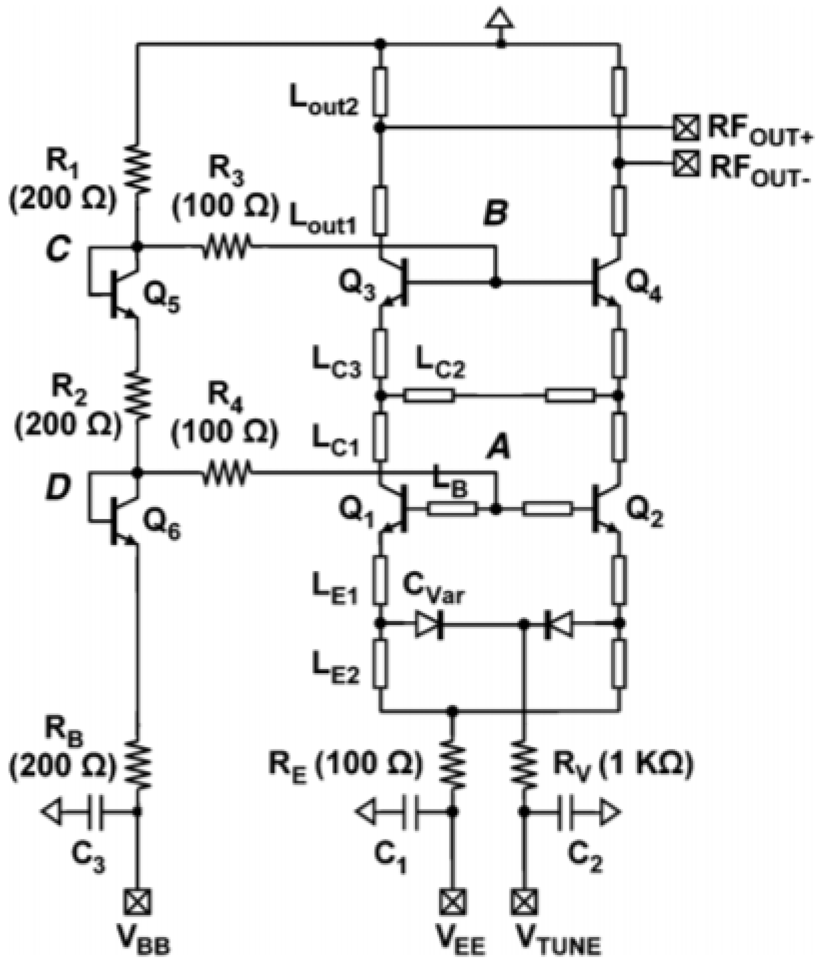


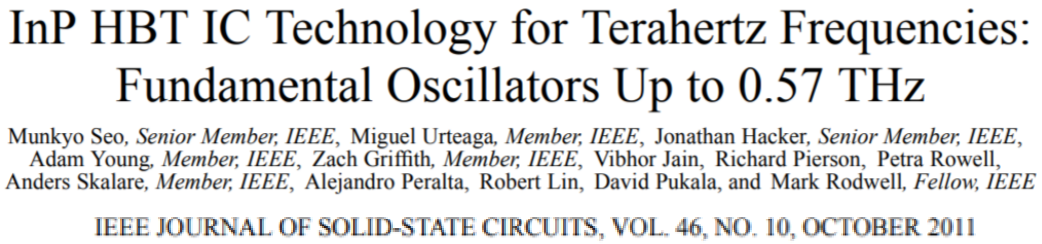
A 305–330+ GHz 2:1 Dynamic Frequency Divider Using InP HBTs

Munkyo Seo, *Member, IEEE*, Miguel Urteaga, Adam Young, and Mark Rodwell, *Fellow, IEEE*

IEEE MICROWAVE AND WIRELESS COMPONENTS LETTERS, VOL. 20, NO. 8, AUGUST 2010

570 GHz oscillator

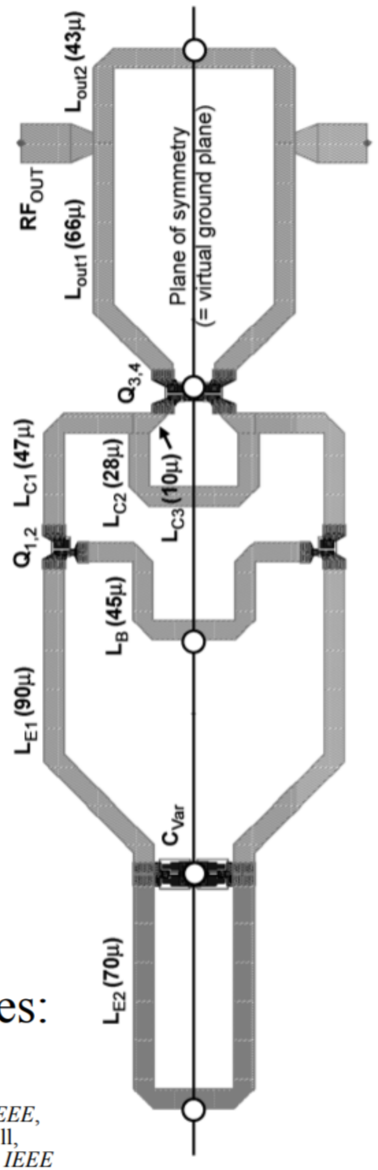


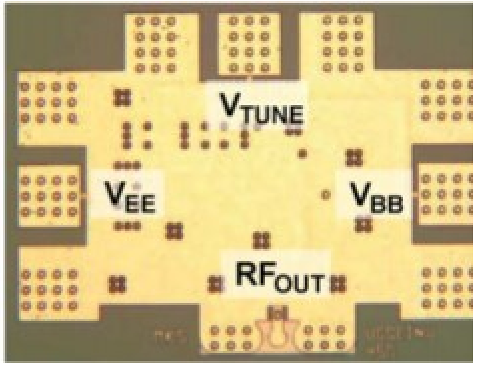


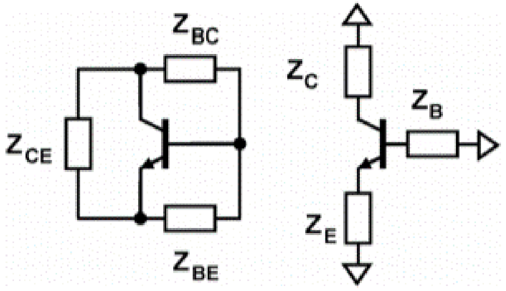
InP HBT IC Technology for Terahertz Frequencies: Fundamental Oscillators Up to 0.57 THz

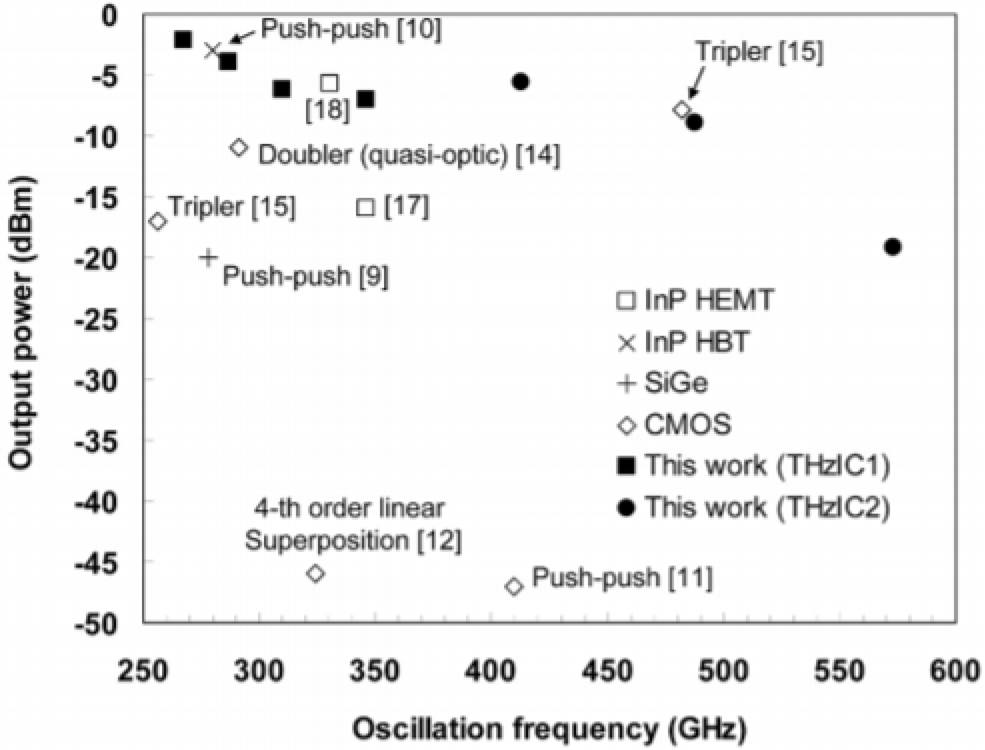
Munkyo Seo, *Senior Member, IEEE*, Miguel Urteaga, *Member, IEEE*, Jonathan Hacker, *Senior Member, IEEE*,
Adam Young, *Member, IEEE*, Zach Griffith, *Member, IEEE*, Vibhor Jain, Richard Pierson, Petra Rowell,
Anders Skalare, *Member, IEEE*, Alejandro Peralta, Robert Lin, David Pukala, and Mark Rodwell, *Fellow, IEEE*

IEEE JOURNAL OF SOLID-STATE CIRCUITS, VOL. 46, NO. 10, OCTOBER 2011

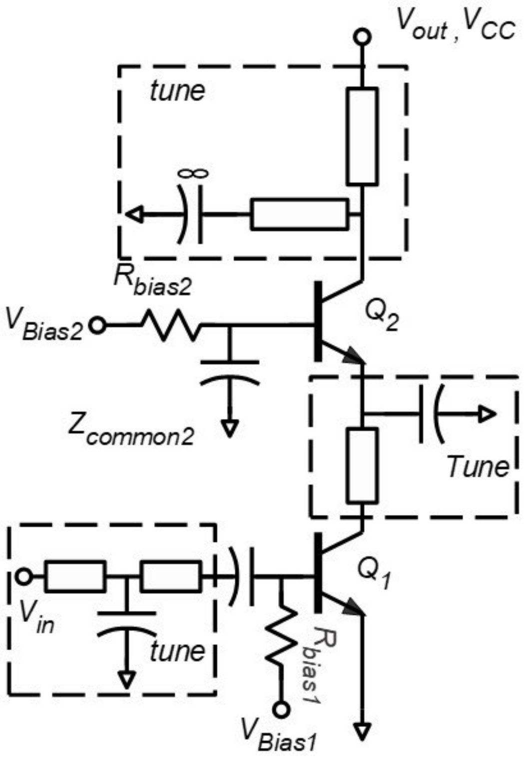


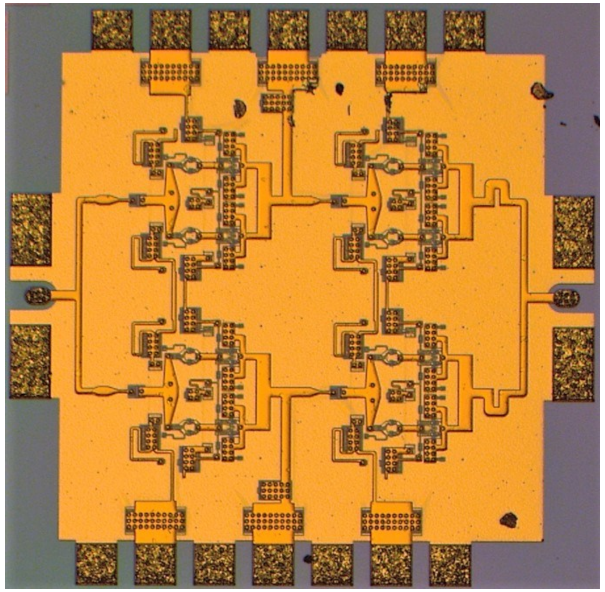


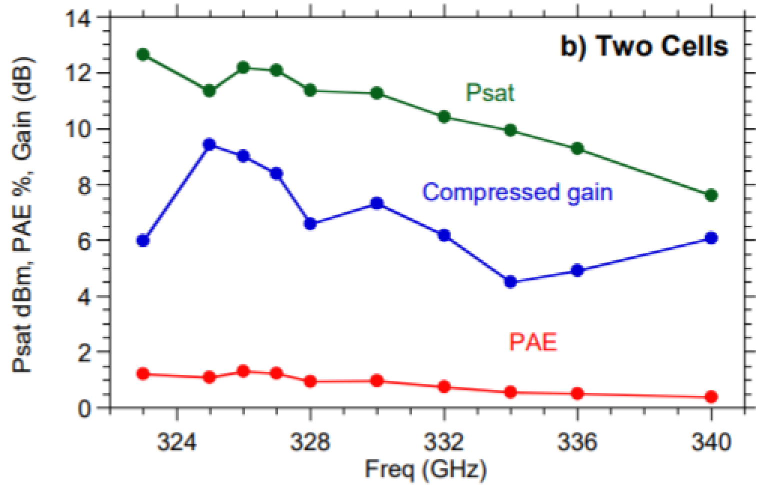


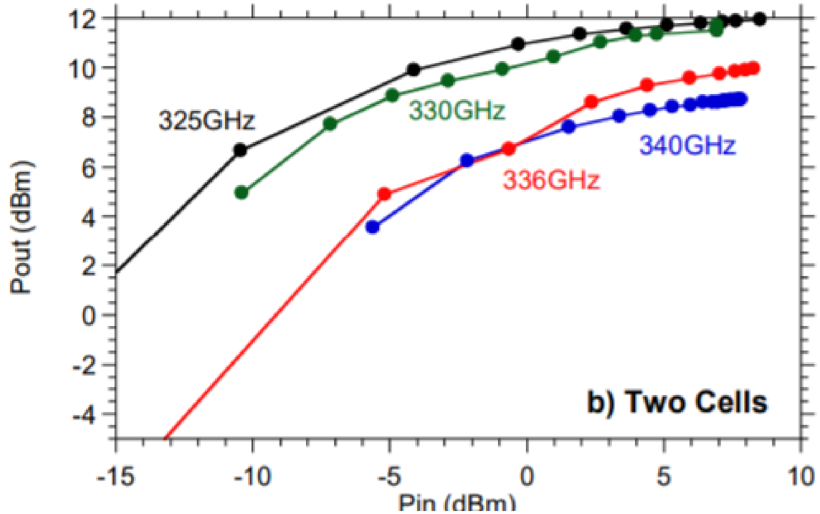


326 GHz series-connected PA





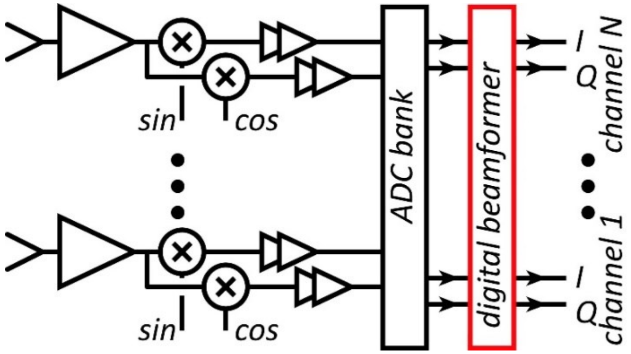


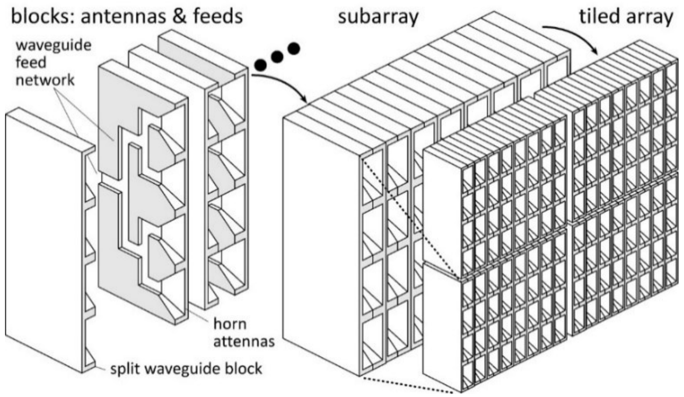


16mW Psat; 1.3% PAE, 16.6dB gain

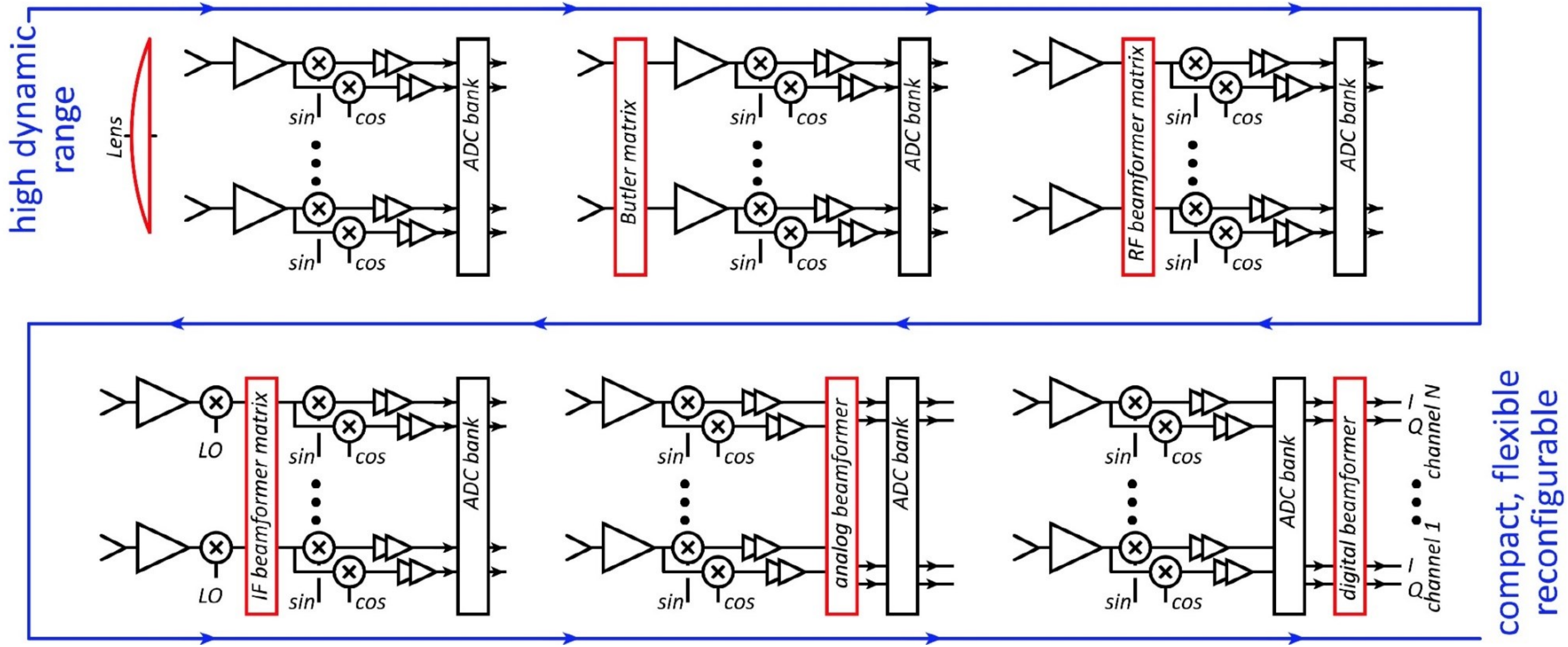
A. Ahmed, 2018 BCICTS

Systems & Packages





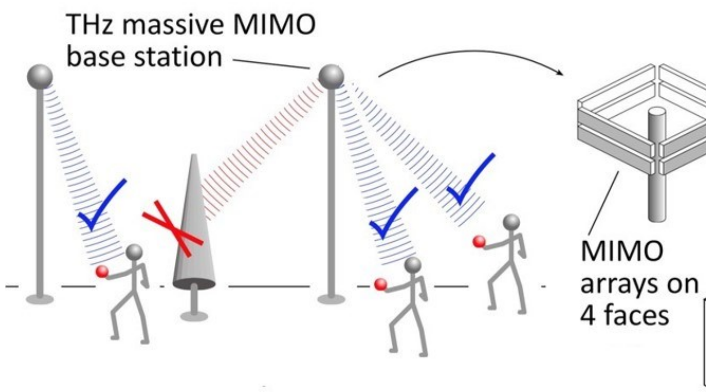
Beamforming for massive spatial multiplexing

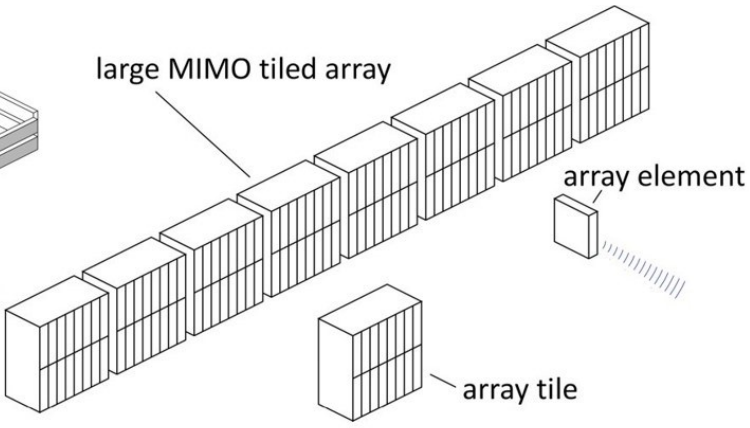


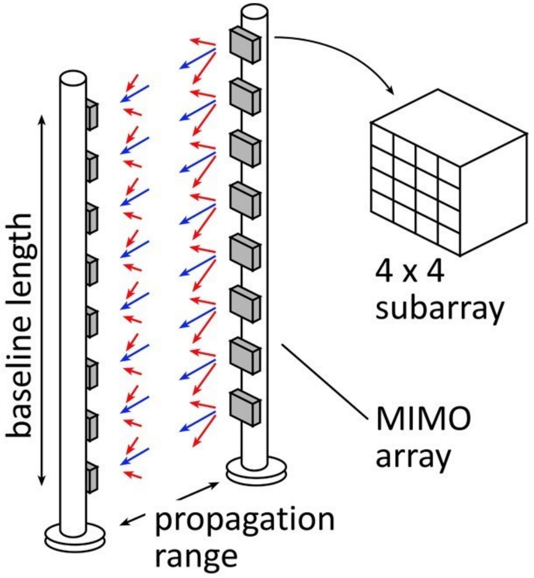
Pure digital beamforming:
dynamic range & phase noise requirements: both appear to be manageable ✓✓✓
Digital back-end processing requirements (die area, DC power): being investigated ???

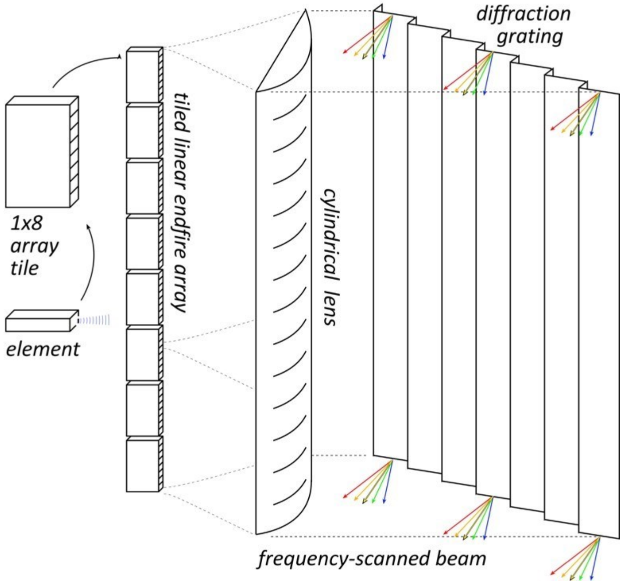
Pure RF beamforming: (focal plane, Butler matrixes, RF beamforming)
Established approach in DOD systems (high dynamic range). Issues of array tiling.

Large arrays formed from small tile models









Point-point MIMO, MIMO hub, imaging
all require relative large arrays

Modular assembly
large array formed from many small tiles

The mm-wave module design problem

How to make the IC electronics fit ?

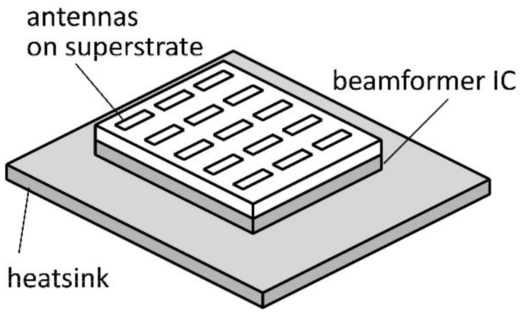
100+ GHz arrays: $\lambda_0/2$ element spacing is very small.
Antennas on or above IC → IC channel spacing = antenna spacing
→ ***limited IC area to place circuits***

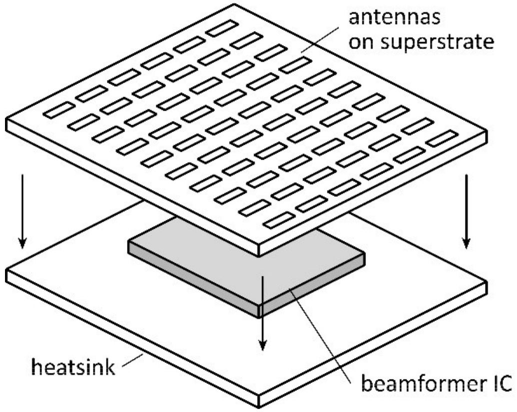
How to avoid catastrophic signal distribution losses ?

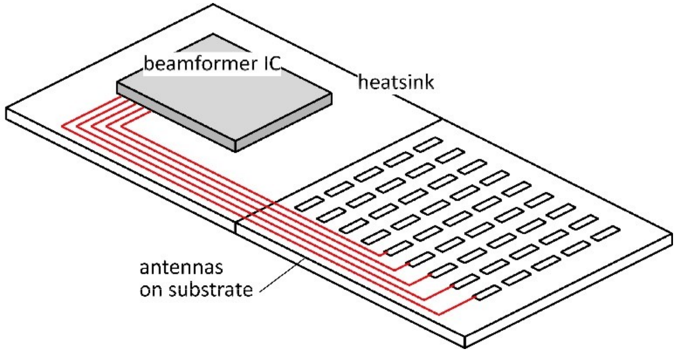
long-range, high-gain arrays: array size can be large.
ICs beside array → very long wires between beam former and antenna
→ ***potential for very high signal distribution losses***

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



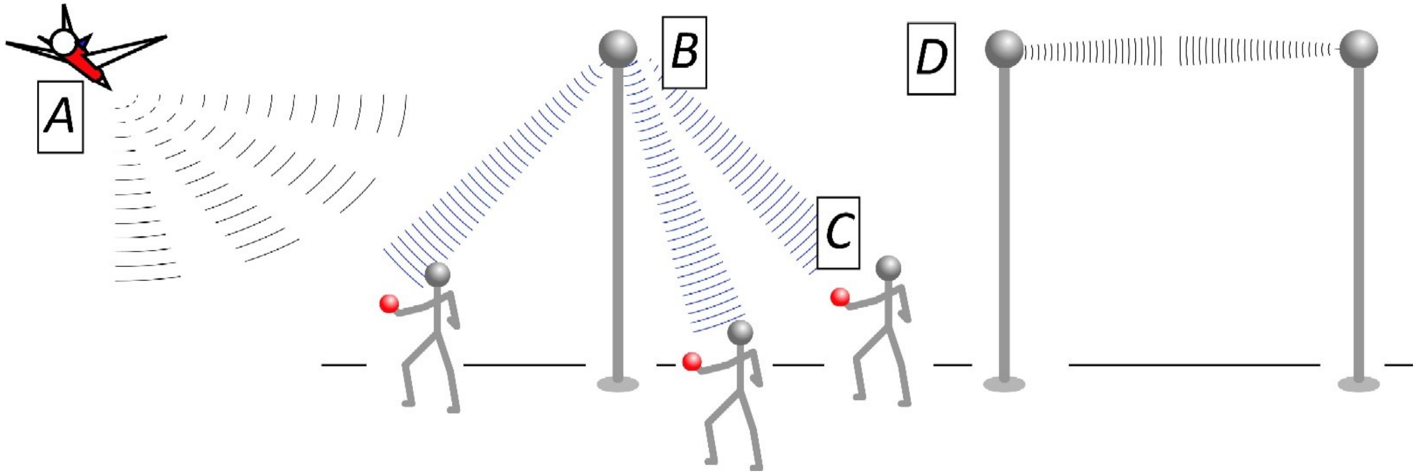




mm-wave/sub-mm-wave packaging

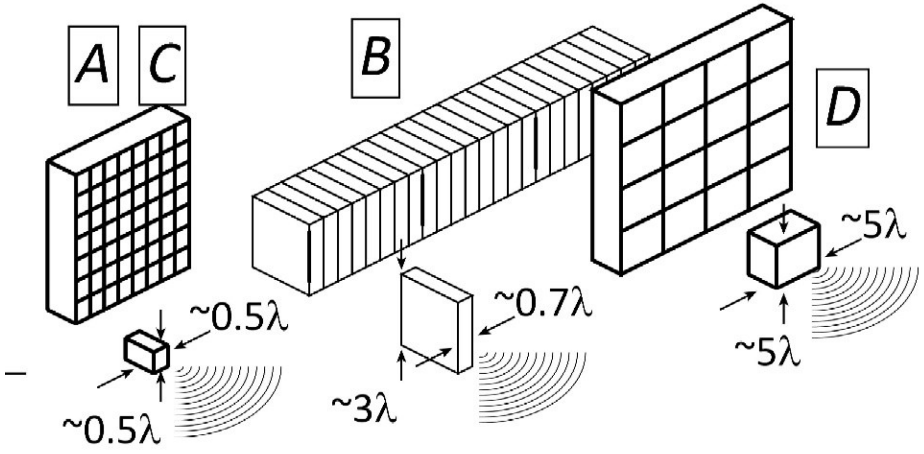
Not all systems steer in two planes...
...some steer in only one.

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

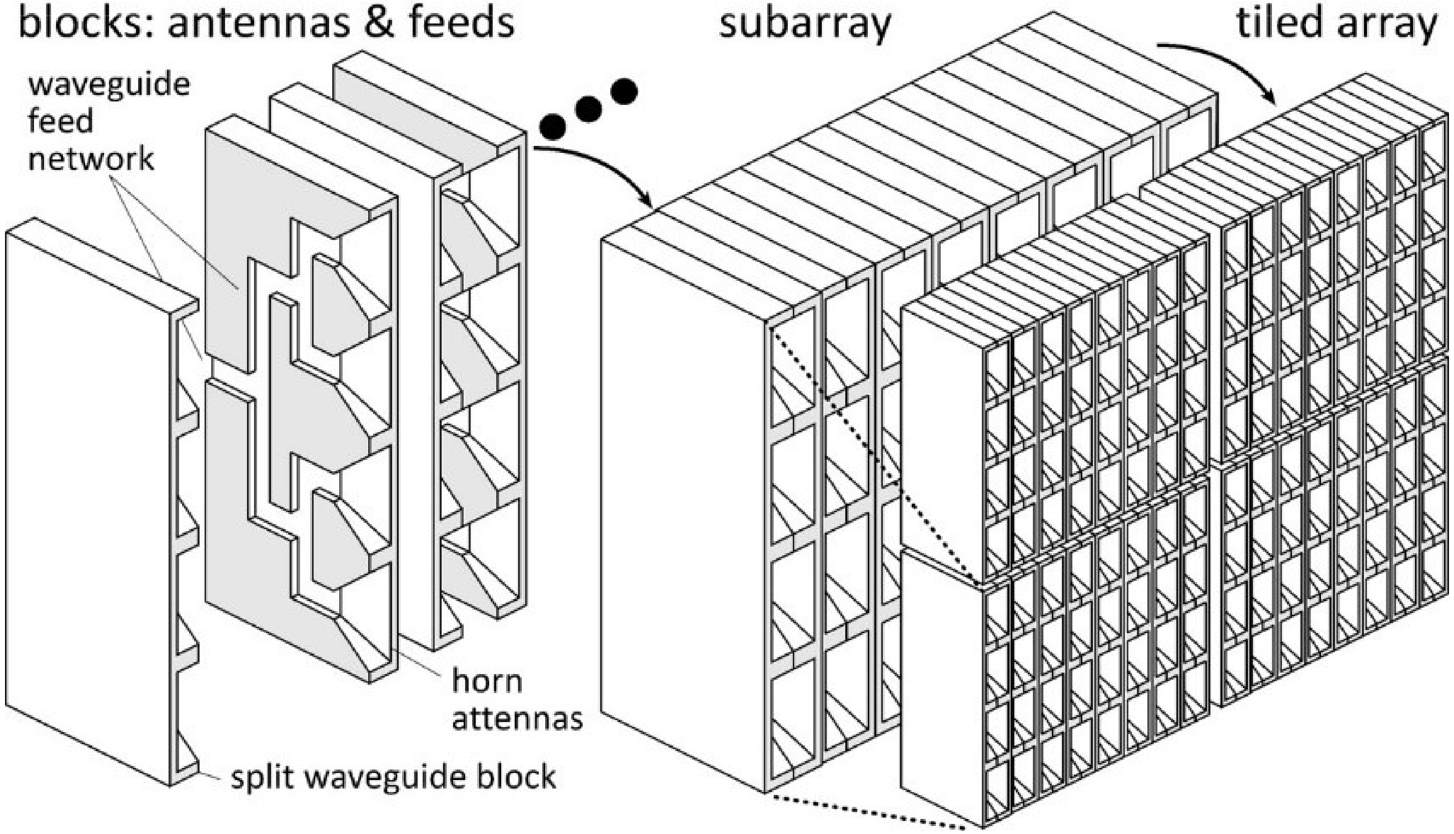


Arrays can often be linear (1D), instead of rectangular (2D)
Element spacing can often be greater than λ/2.

→ Array packaging then greatly simplified.



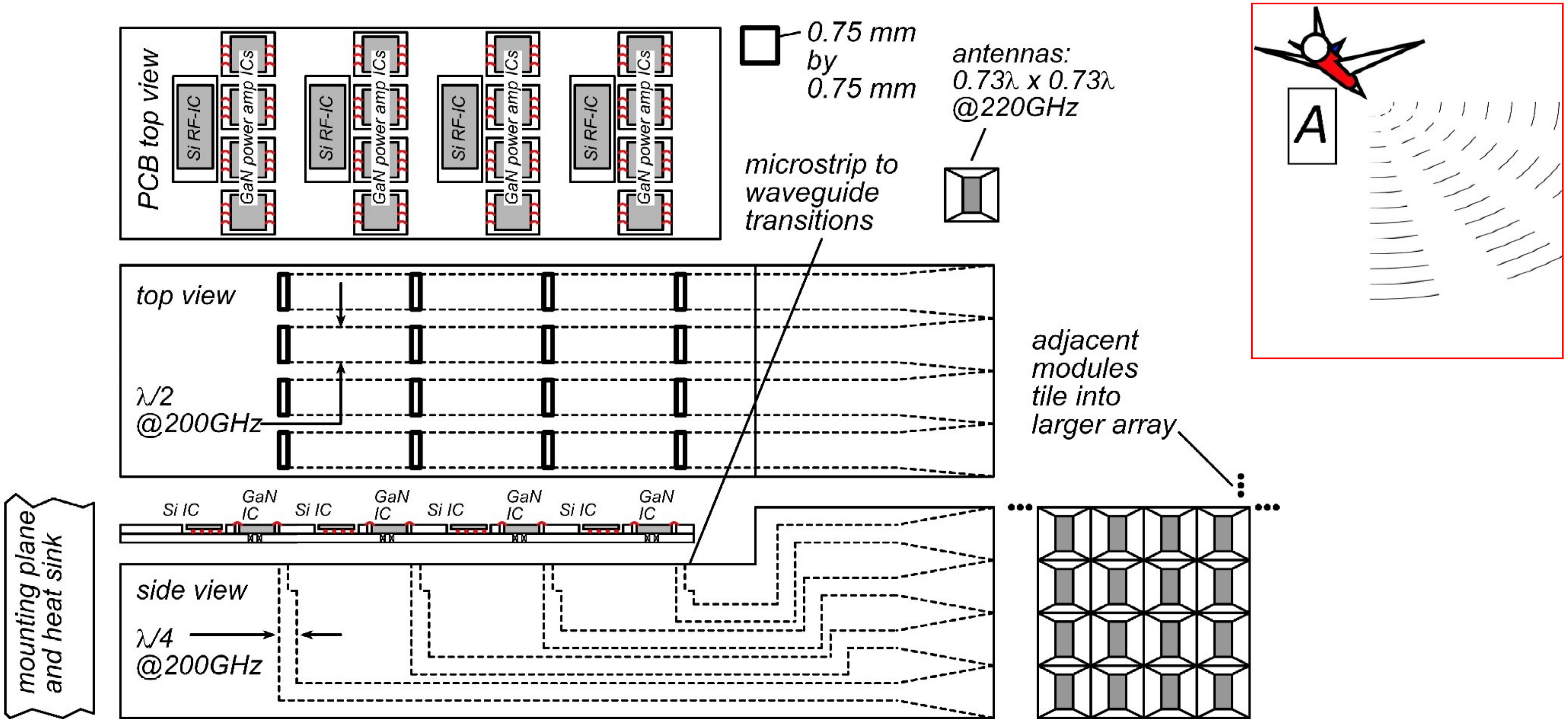
Background: split-block waveguides



Waveguides are manufactured (milled or die cast) from a set of pieces

Precision pins aid alignment

Concept: Tile for mm-wave arrays



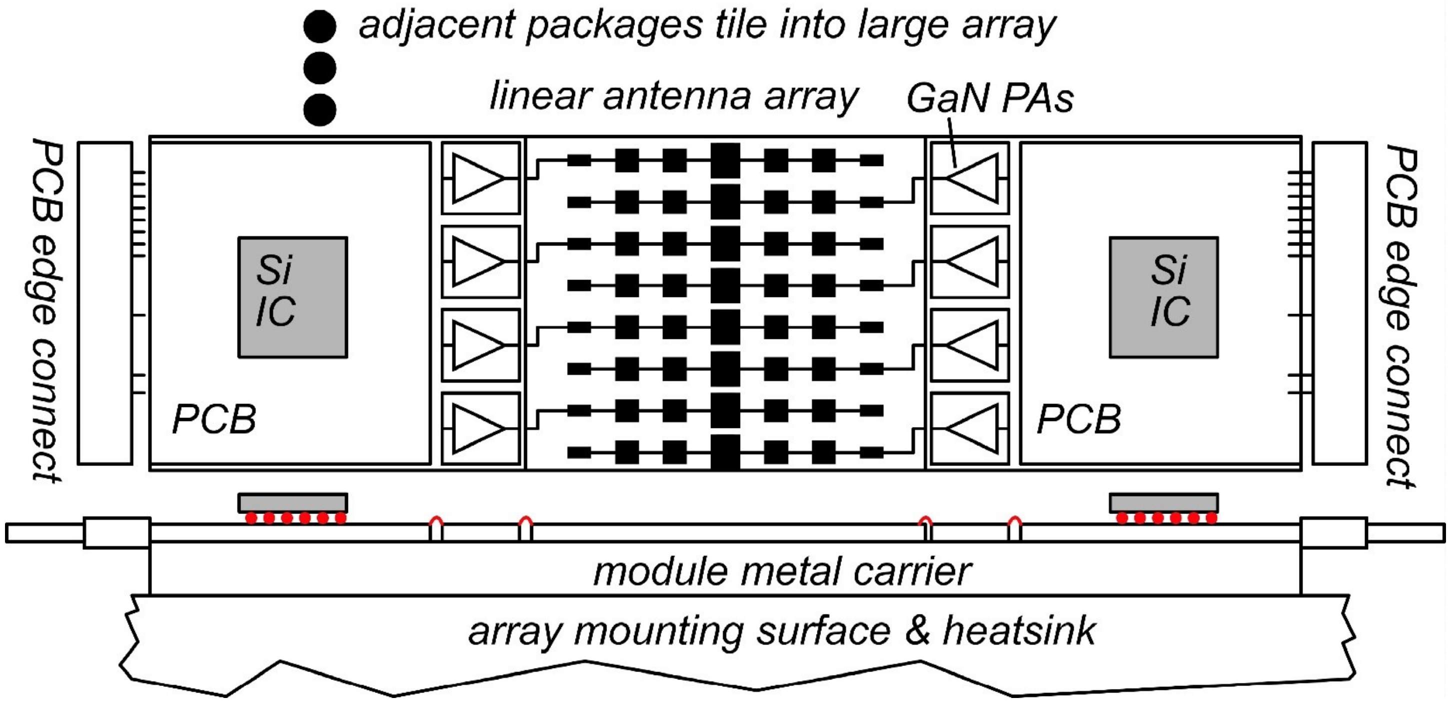
Split-block assembly. Modules tile into larger array

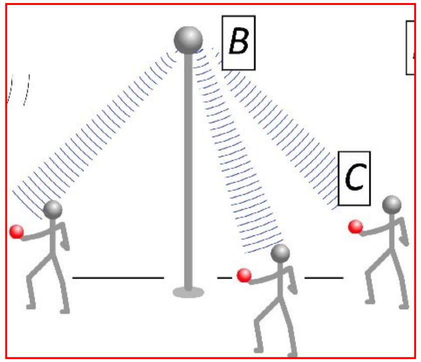
IC area can be much larger than antenna area→ electronics can fit

Low-loss waveguide feeds, efficient waveguide horn antennas

Efficient heat-sinking: permits W-level GaN, InP, SiGe PAs for long range

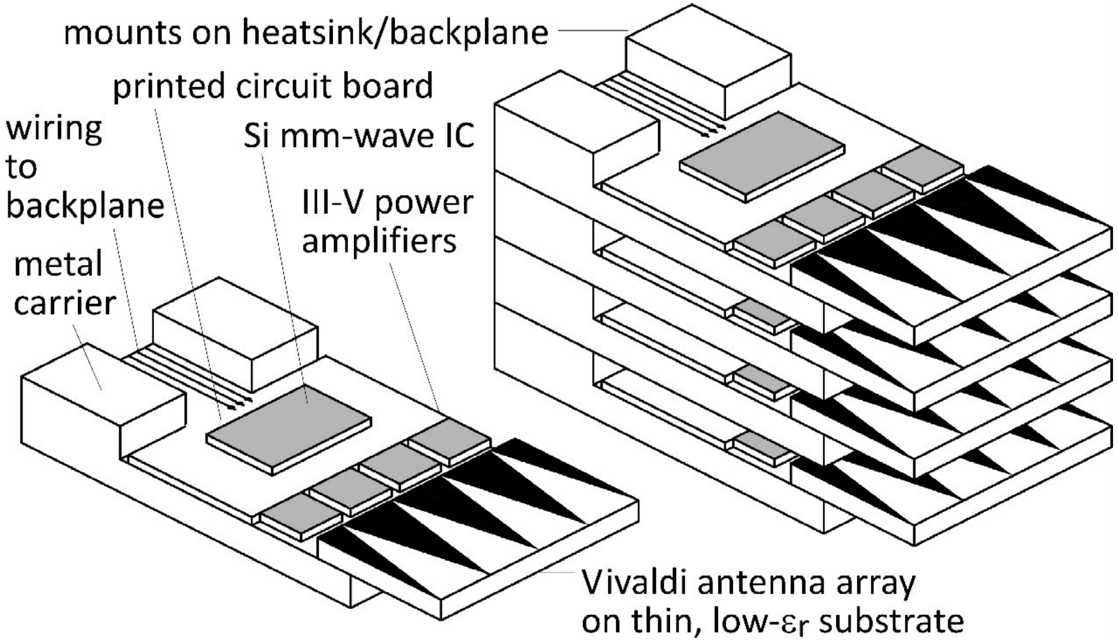
Concept: Tile for linear arrays

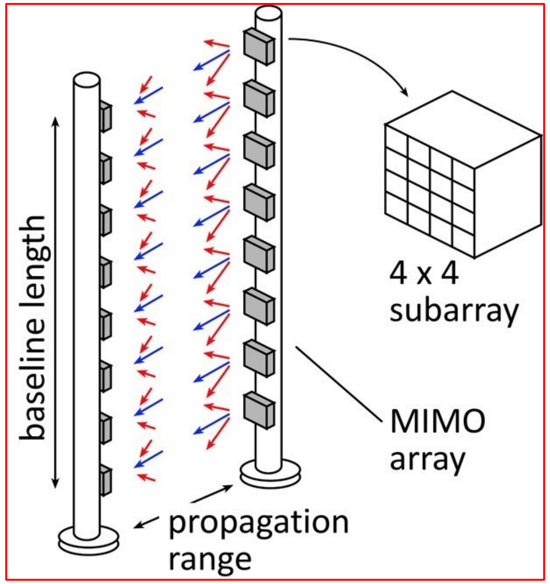




Terrestrial system: horizontal steering only→ linear array.
Space at edges of linear array: room for III-V PAs, LNAs.
Alternating-sides feed: 2mm pitch→ room for large GaN PAs.
Mounting directly on metal carrier→ heatsinking.

Concept: module for small angular scanning

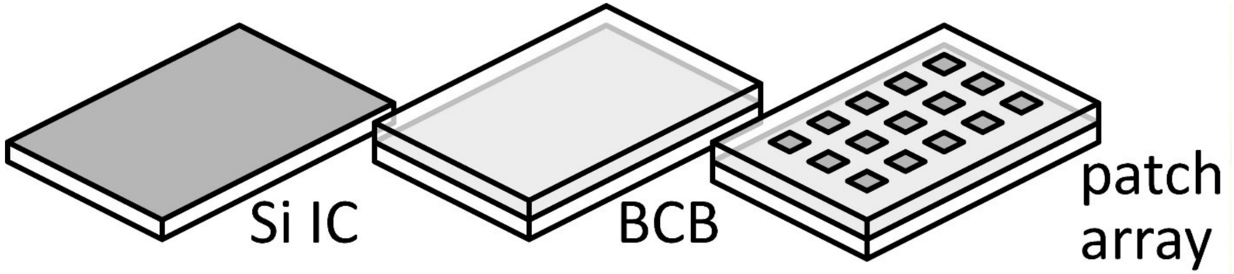


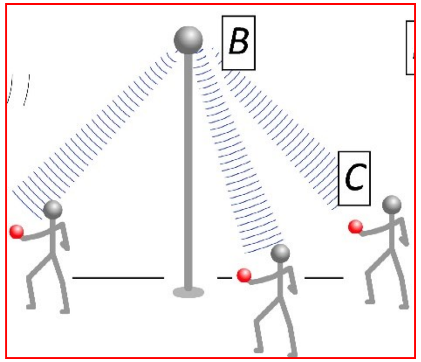


Terrestrial system: horizontal + vertical steering → rectangular array.
Limited angular steering range (installation)→ spacing >> $\lambda/2$
Endfire / edge-card geometry: room for III-V PAs, LNAs.
Mounting directly on metal carrier→ heatsinking.

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

Concept: module for handset



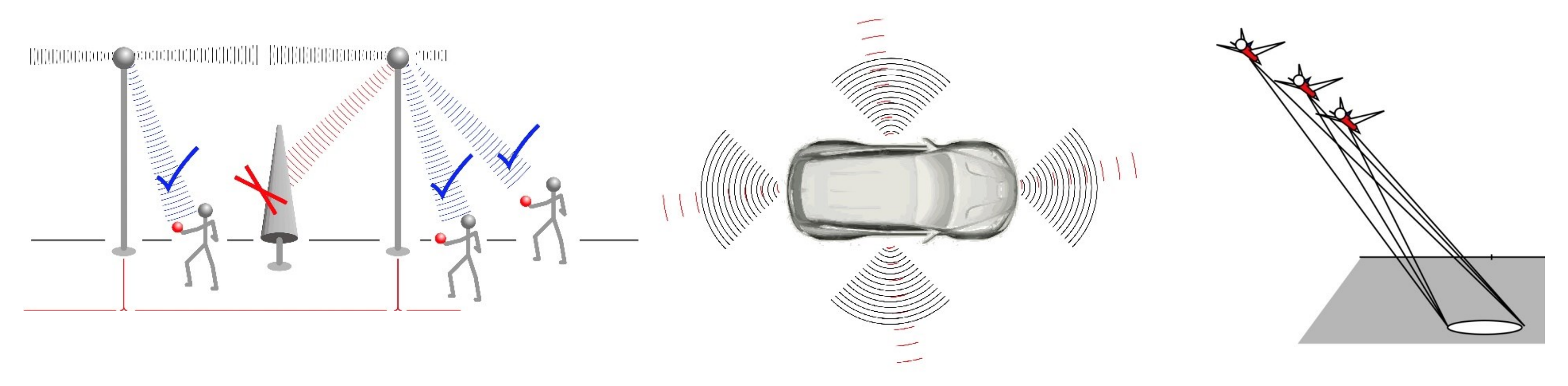


Handset transceiver performance: less challenging.
    No external III-V PAs, LNAs

Handset transceiver is simpler: single-beam, not spatially multiplexed
    Smaller die area→ array pixel fits in $\lambda/2 \times \lambda/2$

Vertical integration of antenna on low-ε_r superstrate.
    fused Silica (Rebeiz)
    possibly also: spin-cast BCB or polyimide, post-process.

Wireless above 100GHz



Wireless above 100 GHz

Massive capacities
large available bandwidths
<u>massive</u> <u>spatial</u> <u>multiplexing</u> 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, ~~dynamic range~~
packaging: fitting signal channels in very small areas