The 11th International Symposium on Wireless Personal Multimedia Communications (WPMC 2008)

Development of THz Transistors & (300-3000 GHz) Sub-mm-Wave ICs

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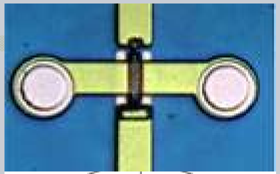
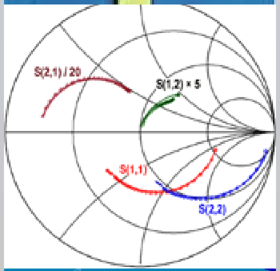
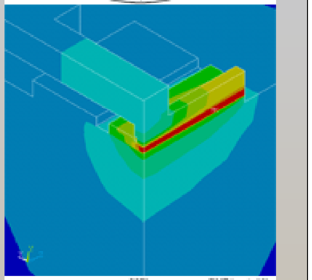
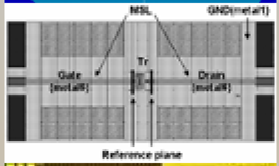
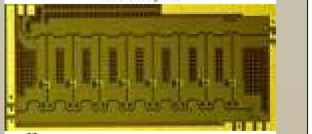
UCSB High-Frequency Electronics Group

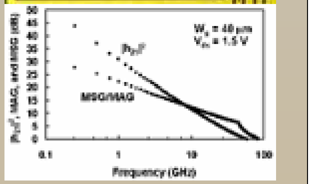


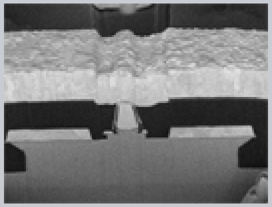




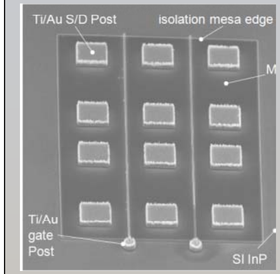






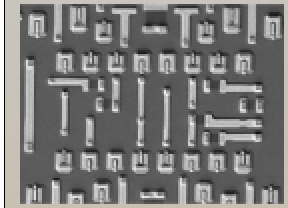


THz InP Bipolar Transistors.



III-V CMOS for Si VLSI

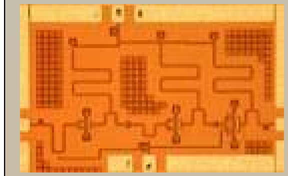
InGaAs-channel MOSFETs for sub-22-nm scaling



Ultra high frequency III-V ICs

sub-mm-wave ICs

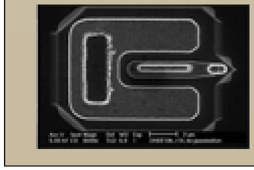
100-500 GHz digital logic

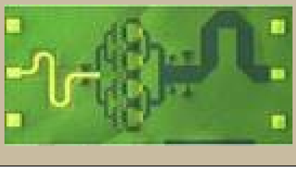


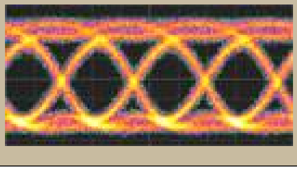
50-200 GHz Silicon ICs

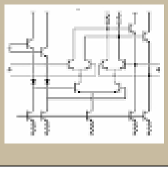
mm-waves: MIMO links, arrays, sensor networks

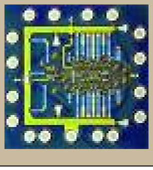
fiber optics

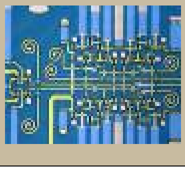






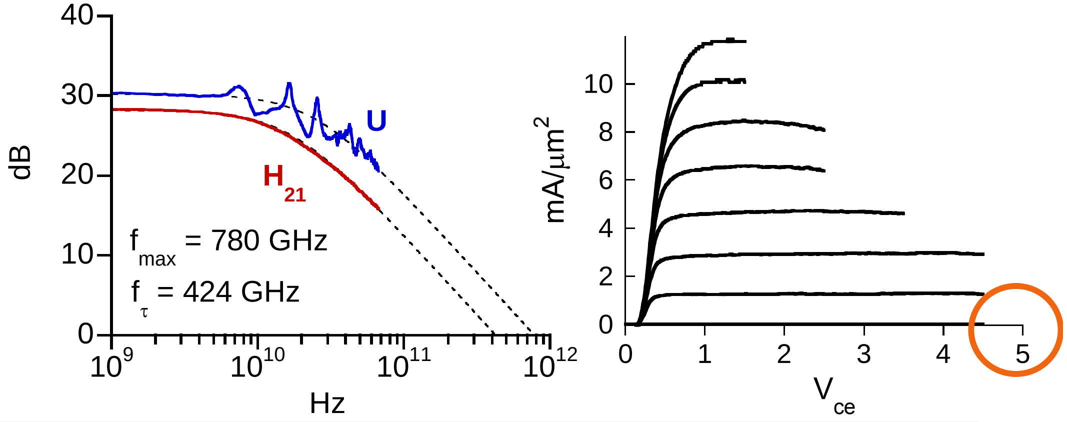






Multi-THz Transistors Are Coming

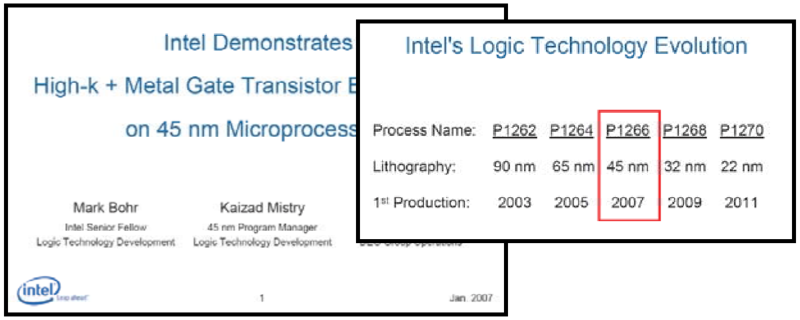
InP Bipolars: 250 nm generation: → 780 GHz f_{max}, 400 GHz f_{τ}, 5 V BV_{CEO}



125 nm & 62 nm nodes
→ ~THz devices

IBM IEDM '06: 65 nm SOI CMOS → 450 GHz f_{max}, ~1 V operation

Intel June '07: 45 nm / high-K / metal gate production 65 nm: ~250 GHz f_{max}



Intel Demonstrates
High-k + Metal Gate Transistor B
on 45 nm Microprocess

Mark Bohr
Intel Senior Fellow
Logic Technology Development

Kaizad Mistry
45 nm Program Manager
Logic Technology Development

Jan. 2007

Intel's Logic Technology Evolution

Process Name:	P1262	P1264	P1266	P1268	P1270
Lithography:	90 nm	65 nm	45 nm	32 nm	22 nm
1st Production:	2003	2005	2007	2009	2011

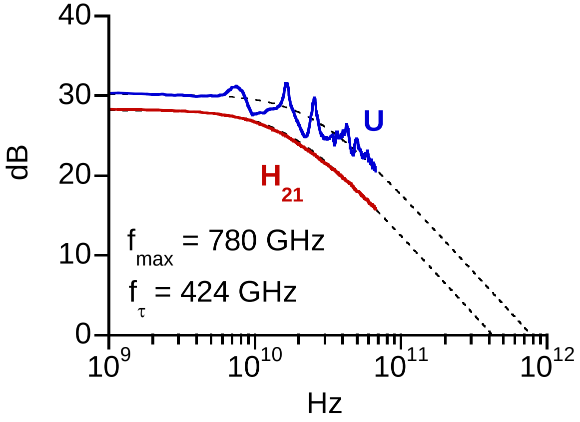
→ continued rapid progress

What applications for III-V bipolars ?

What applications for mm-wave CMOS ?

THz InP vs. near-THz CMOS: different opportunities

InP HBT: THz bandwidths, good breakdown, analog precision



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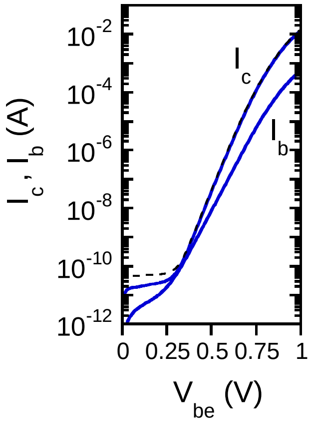
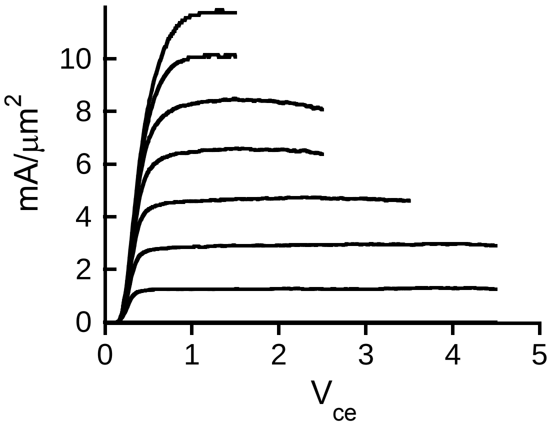
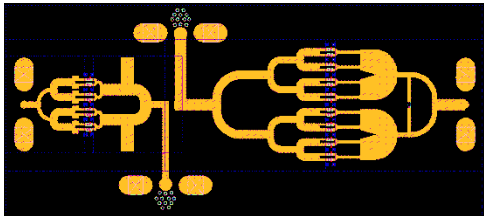


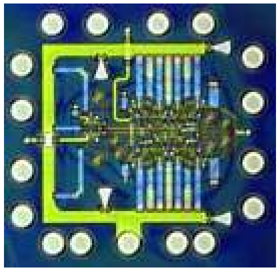




J. Hacker (Teledyne) M. Jones (UCSB)

***340 GHz, 70 mW amplifiers** (design)*

In future: 700 or 1000 GHz amplifiers ?

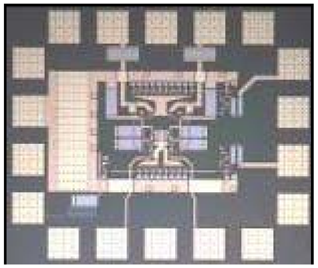


Z. Griffith

***200 GHz digital logic** (design)*

In future: 450 GHz clock rate ?

→ *fast blocks for microwave mixed-signal*



Z. Griffith

M. Urteaga (Teledyne)

25-40 GHz gain-bandwidth op-amps→ low IM3 @ 2 GHz

In future: 200 GHz op-amps for low-IM3 10 GHz amplifiers?

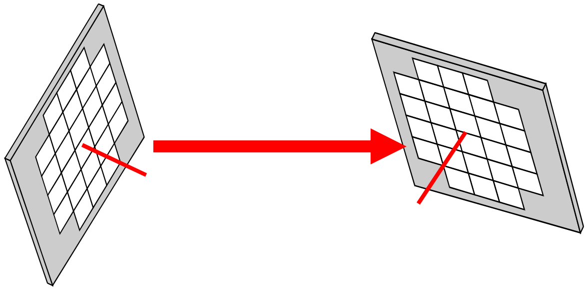
THz InP vs. near-THz CMOS: different opportunities

65 / 45 / 33 / 22 ... nm CMOS

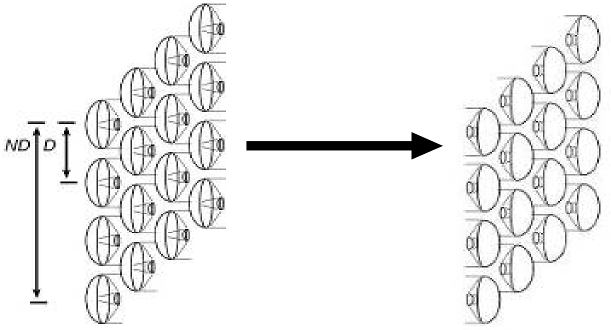
vast #s of very fast transistors

... having low breakdown, high output conductance

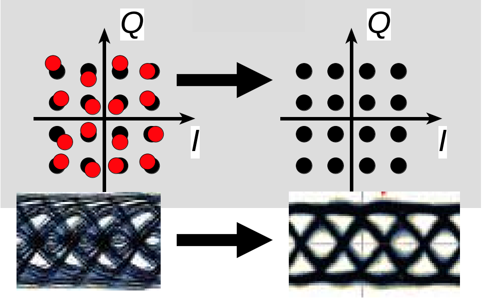
what NEW mm-wave applications will this enable ?



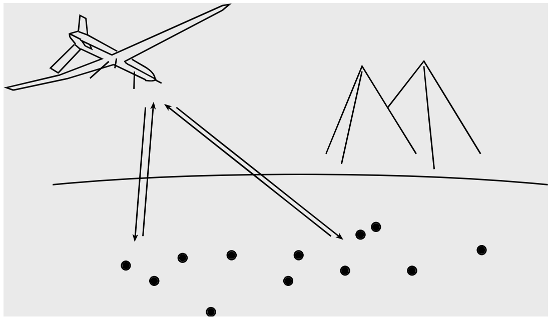
massive monolithic mm-wave arrays
→ 1 Gb/s over ~1 km



mm-wave MIMO

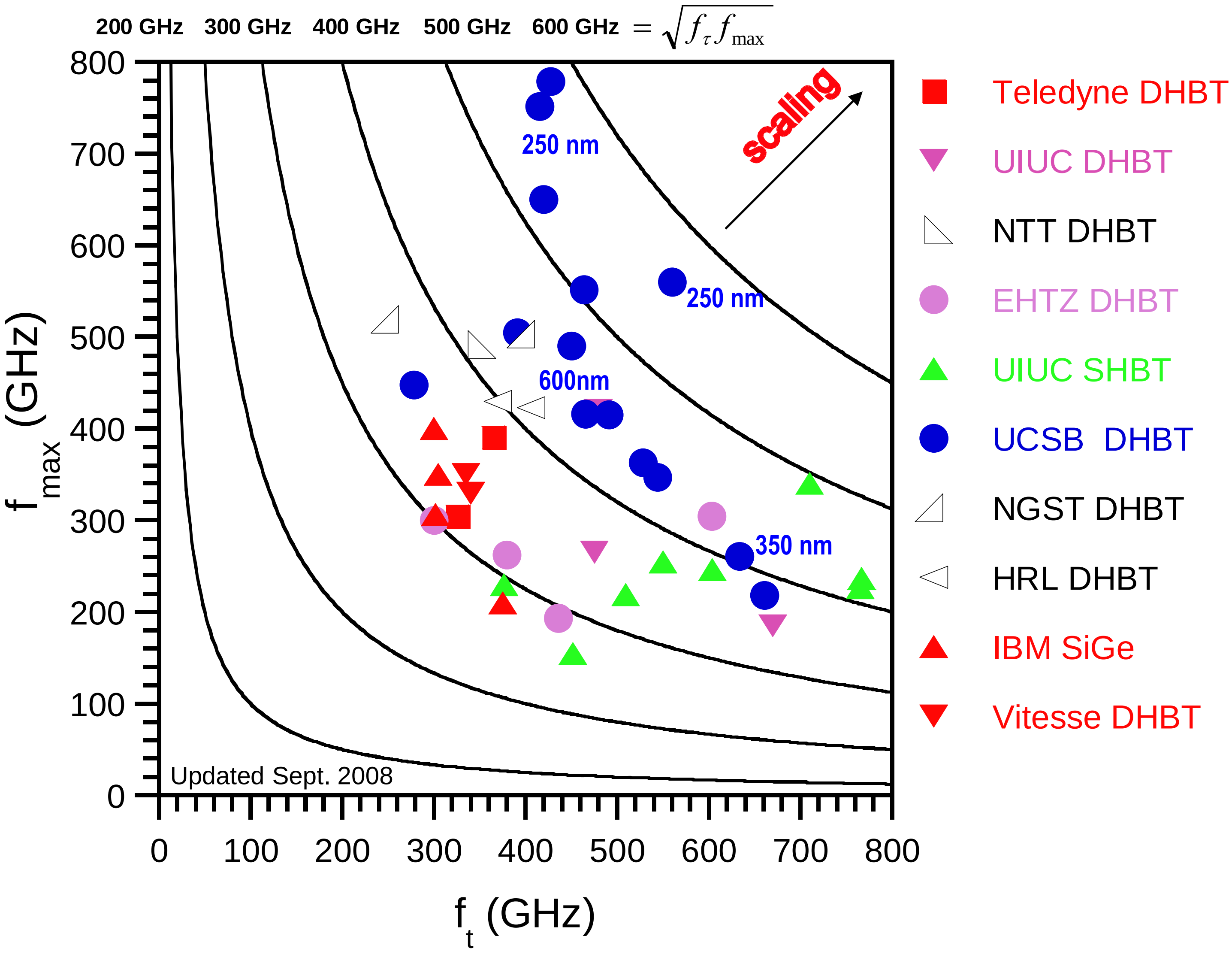


comprehensive equalization of
~100 Gb/s wireless, wireline, optical links



mm-wave imaging
sensor networks

InP DHBTs: September 2008



popular metrics :

f_τ or $f_{\max}$ alone

$(f_\tau + f_{\max})/2$

$\sqrt{f_\tau f_{\max}}$

$(1/f_\tau + 1/f_{\max})^{-1}$

much better metrics :

power amplifiers:

PAE, associated gain,

mW/μm

low noise amplifiers:

$F_{\min}$, associated gain,

digital:

f_{clock}, hence

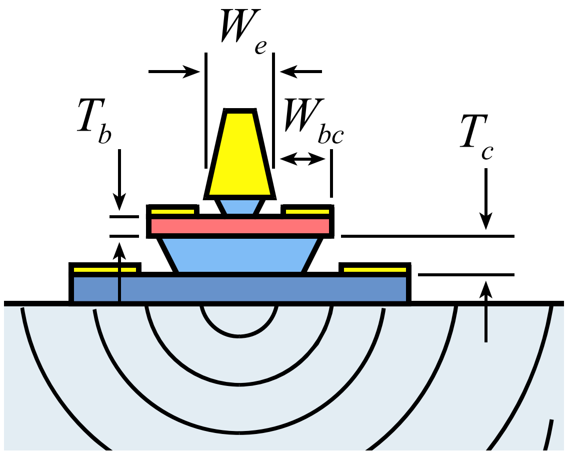
$(C_{cb}\Delta V / I_c)$,

$(R_{ex} I_c / \Delta V)$,

$(R_{bb} I_c / \Delta V)$,

$(\tau_b + \tau_c)$

Bipolar Transistor Design



(emitter length L_E)

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

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

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

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

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

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

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

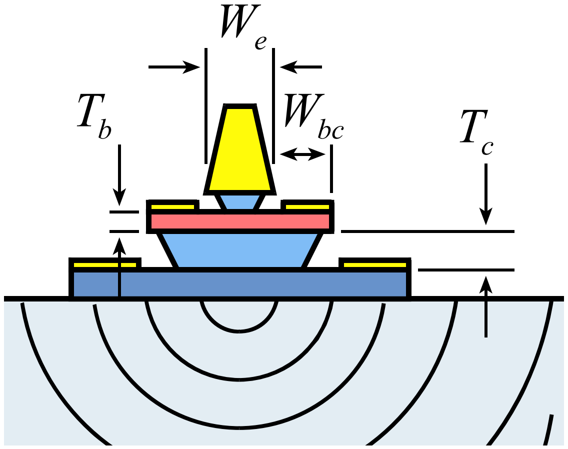
Bipolar Transistor Design: Scaling

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

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

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

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



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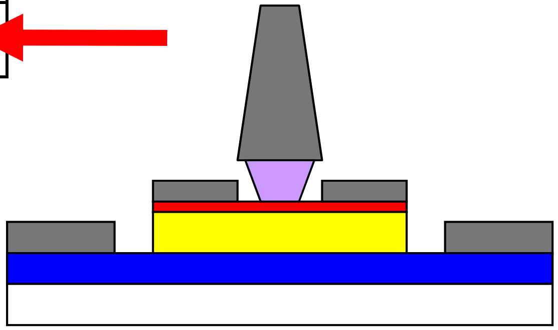
Bipolar Transistor Scaling Laws

Changes required to double transistor bandwidth:

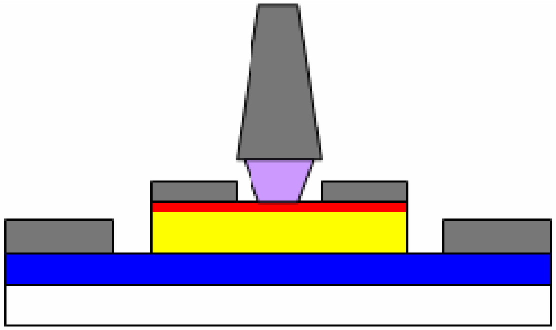
parameter	change
collector depletion layer thickness	decrease 2:1
base thickness	decrease 1.414:1
emitter junction width	decrease 4:1
collector junction width	decrease 4:1
emitter contact resistance	decrease 4:1
current density	increase 4:1
base contact resistivity	decrease 4:1



Linewidths scale as the inverse square of bandwidth because thermal constraints dominate.

InP Bipolar Transistor Scaling Roadmap

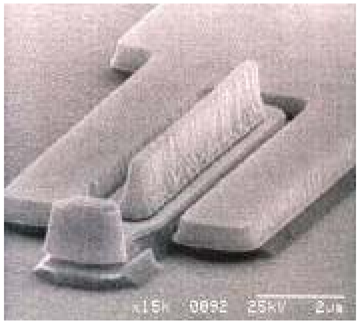
	industry	**university →industry**	**university 2007-8**	**appears feasible**	**maybe**
emitter	512	256	128	64	**32** nm width
	16	8	4	2	**1** $\Omega\cdot\mu m^2$ access ρ
base	300	175	120	60	**30** nm contact width,
	20	10	5	2.5	**1.25** $\Omega\cdot\mu m^2$ contact ρ
collector	150	106	75	53	**37.5** nm thick,
	4.5	9	18	36	**72** $mA/\mu m^2$ current density
	4.9	4	3.3	2.75	**2-2.5** V, breakdown
f_τ	370	520	730	1000	**1400** GHz
f_{max}	490	850	1300	2000	**2800** GHz
power amplifiers	245	430	660	1000	**1400** GHz
digital 2:1 divider	150	240	330	480	**660** GHz



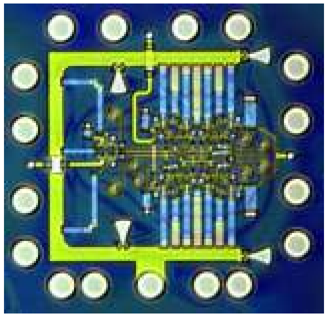
512 nm InP DHBT

Laboratory Technology

500 nm mesa HBT

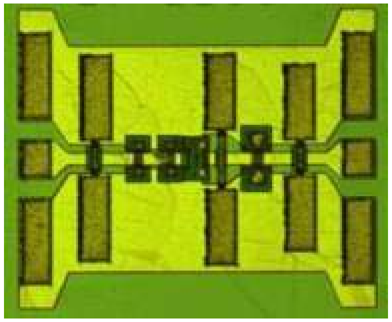


150 GHz M/S latches



UCSB / Teledyne / GCS

175 GHz amplifiers

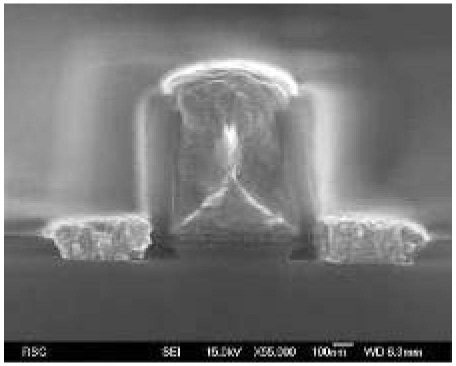


UCSB

Production

(Teledyne)

500 nm sidewall HBT



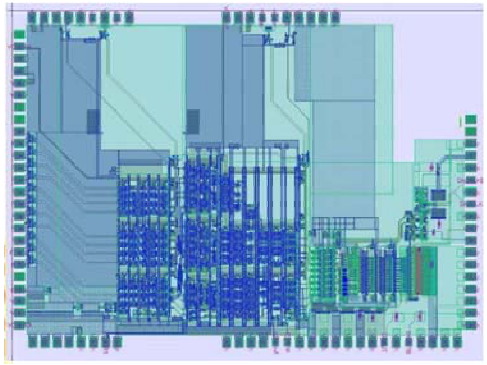
Teledyne

f_τ = 405 GHz

f_{max} = 392 GHz

$V_{br,\,ceo}$ = 4 V

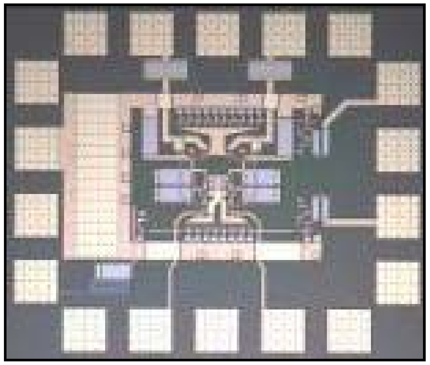
DDS IC: 4500 HBTs



Teledyne / BAE

20 GHz clock

20-40 GHz op-amps

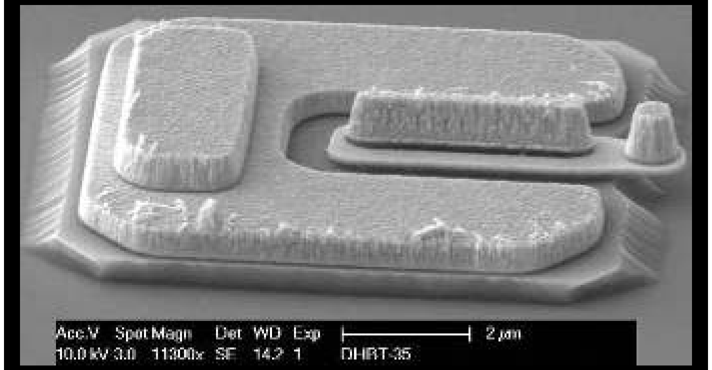


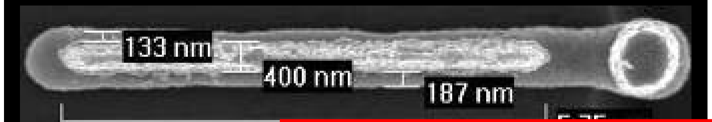
Teledyne / UCSB

53 dBm OIP3 @ 2 GHz
with 1 W dissipation

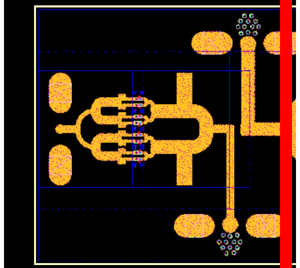
Z. Griffith
M. Urteaga
P. Rowell
D. Pierson
B. Brar
V. Paidi

256 nm Generation InP DHBT

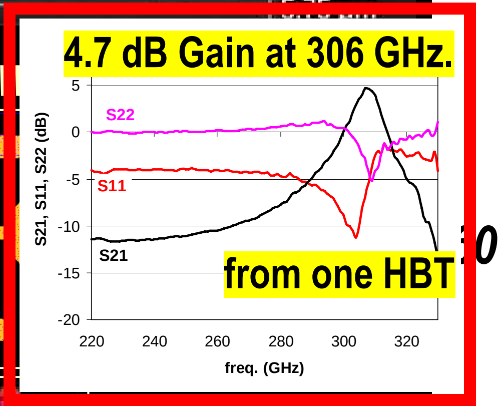




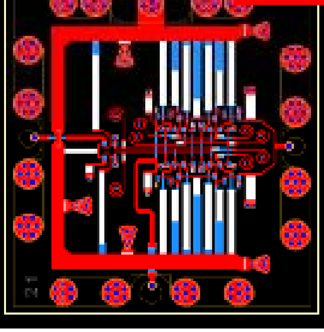
340 GHz, 70 m



4.7 dB Gain at 306 GHz.



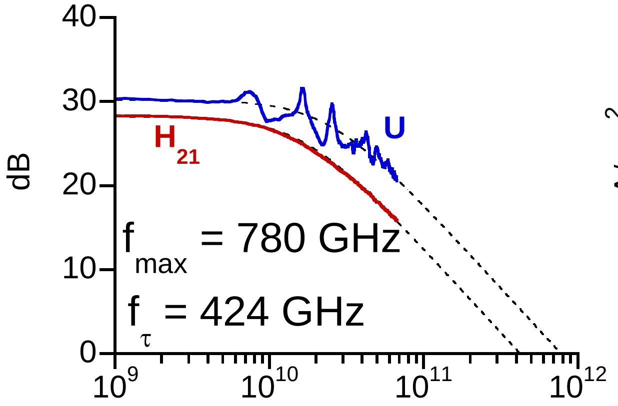
from one HBT



200 GHz master-slave latch design

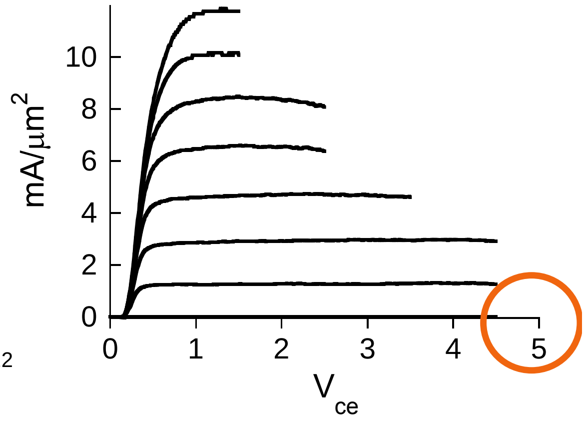
Z. Griffith, E. Lind, J. Hacker, M. Jones

150 nm thick collector

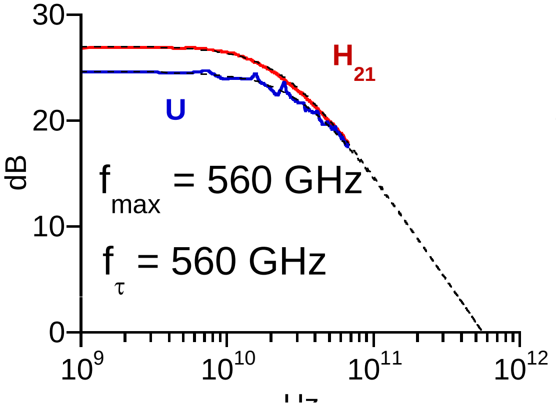


f_{max} = 780 GHz

f_τ = 424 GHz

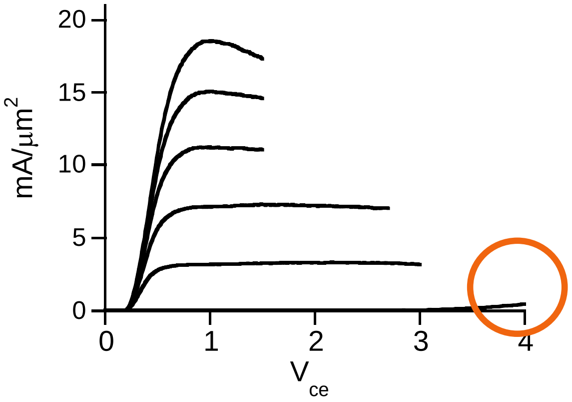


70 nm thick collector

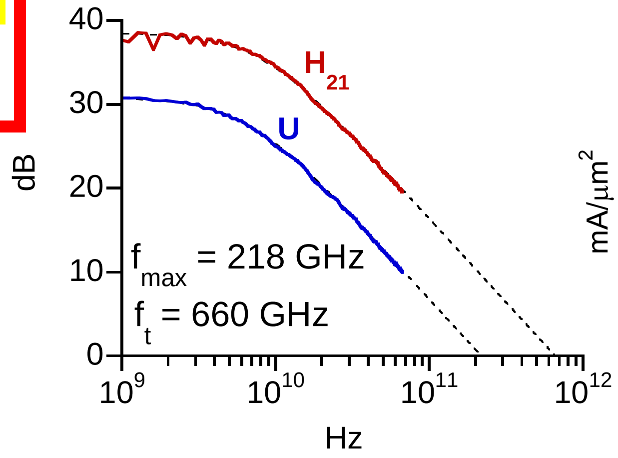


f_{max} = 560 GHz

f_τ = 560 GHz

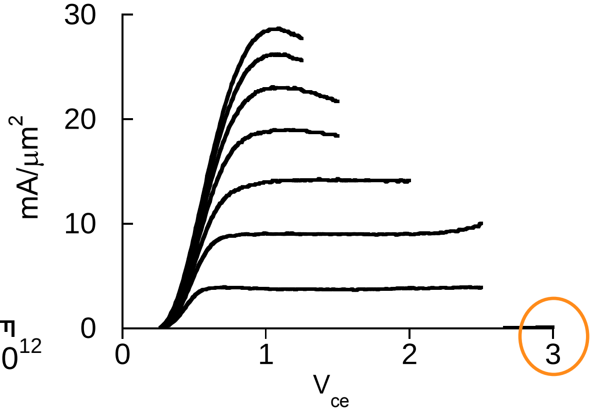


0 nm thick collector



f_{max} = 218 GHz

f_t = 660 GHz



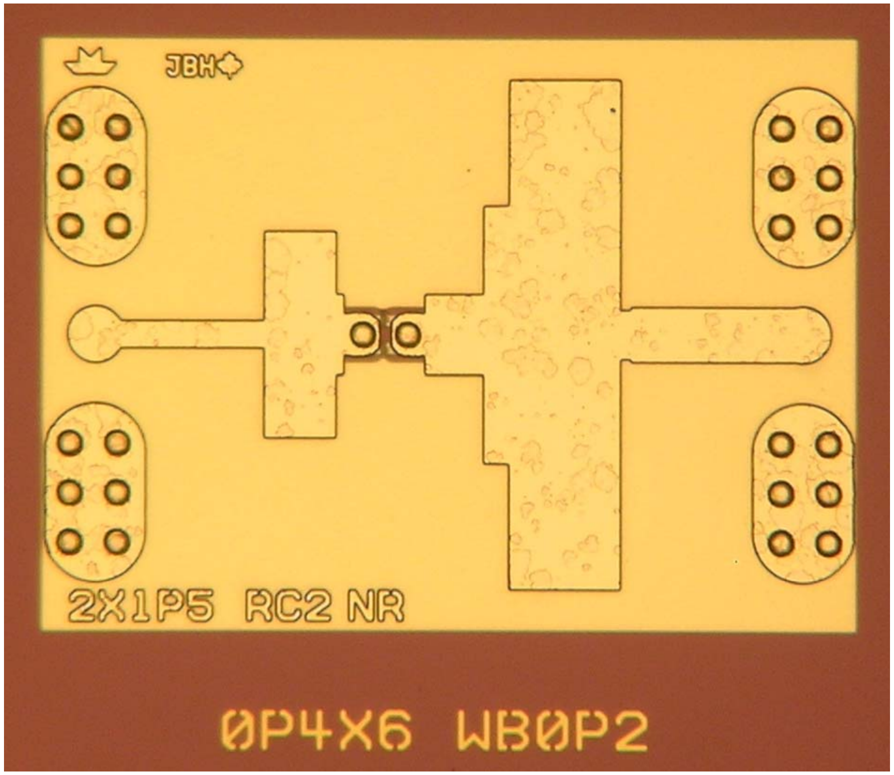
324 GHz Medium Power Amplifiers in 256 nm HBT

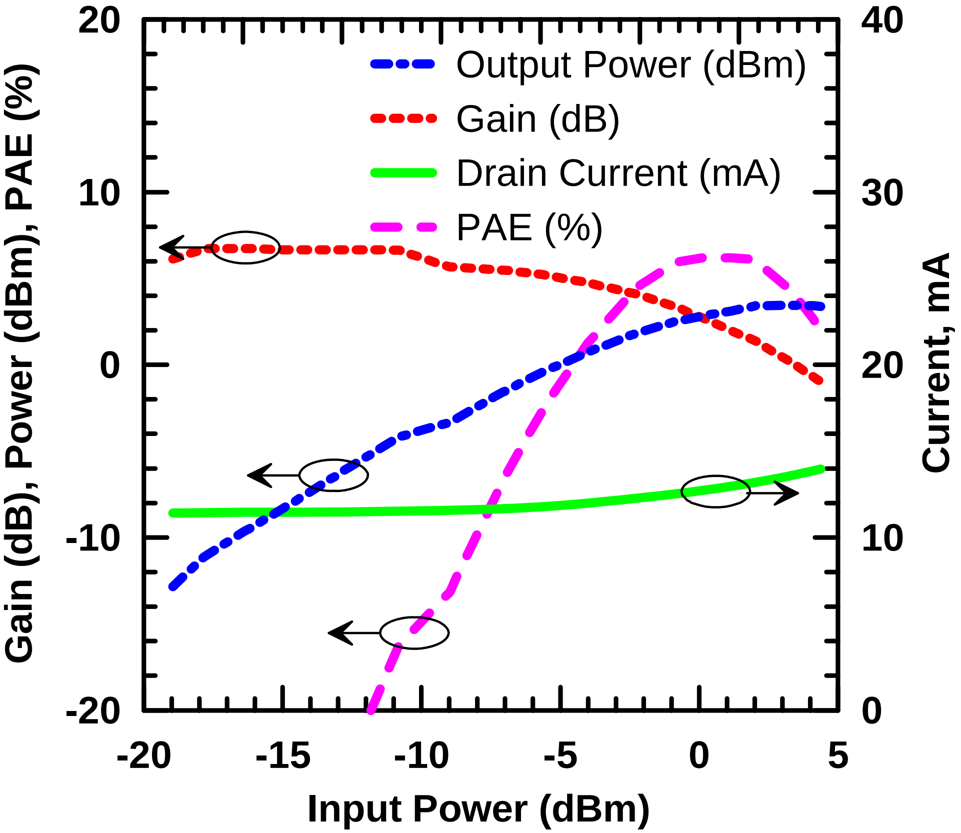
ICs designed by Jon Hacker / Teledyne

Teledyne 256 nm process flow-

Hacker et al, 2008 IEEE MTT-S

~2 mW saturated output power





Can we make a 1 THz SiGe Bipolar Transistor ?

Simple physics clearly drives scaling

transit times, C_{cb}/I_c → thinner layers, higher current density

high power density → narrow junctions

small junctions→ low resistance contacts

Key challenge: Breakdown

15 nm collector → very low breakdown

(also need better Ohmic contacts)

Solutions

Eliminating excess collector area would partly ease scaling

emitter	18	nm width
	1.2	$\Omega\cdot\mu m^2$ access ρ
base	56	nm contact width,
	1.4	$\Omega\cdot\mu m^2$ contact ρ
collector	**15**	nm thick
	125	$mA/\mu m^2$ current density
	???	V, breakdown
f_τ	1000	GHz
f_{max}	2000	GHz
PAs	1000	GHz
digital	480	GHz

(2:1 static divider metric)

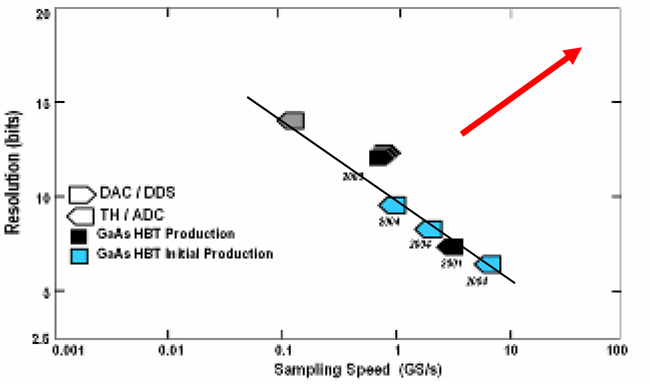
Assumes collector junction 3:1 wider than emitter.

Assumes contacts 2:1 wider than junctions

What Would You Do With a THz Transistor ?

microwave ADCs and DACs

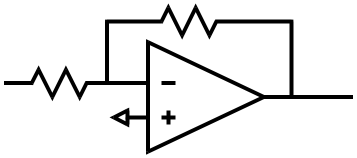
more resolution & more bandwidth



High-Performance 2-20 GHz Microwave Systems

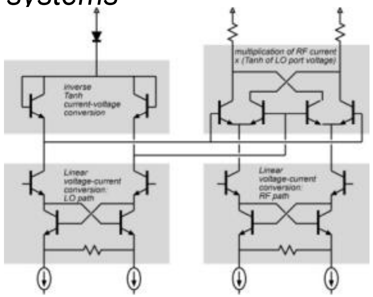
high excess transistor bandwidth + precision design

--> high linear, highly precise microwave systems



microwave op-amps

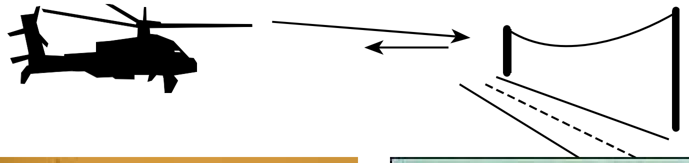
high IP3 at low DC power



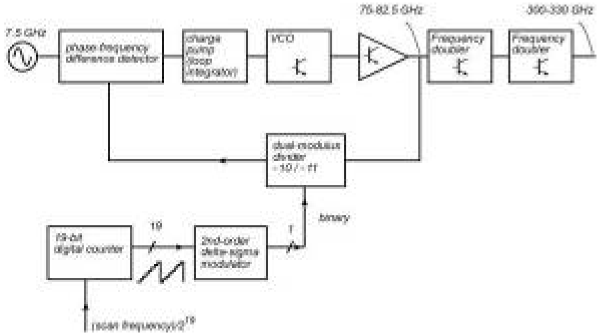
translinear mixers

high IP3 at low DC power

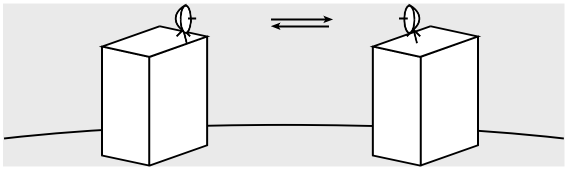
670-1000 GHz imaging systems



single-chip 300-600 GHz spectrometers (gas detection)



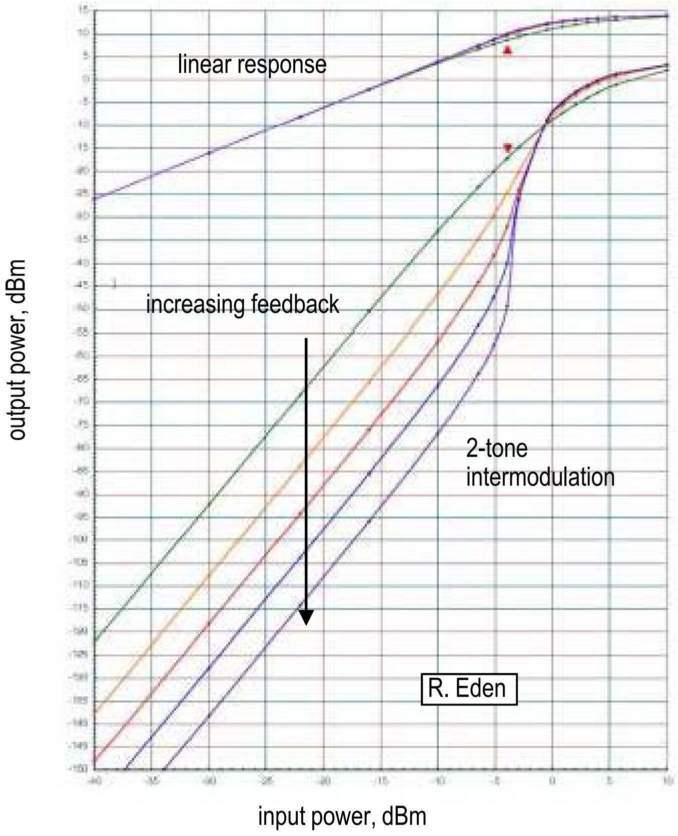
sub-mm-wave communications

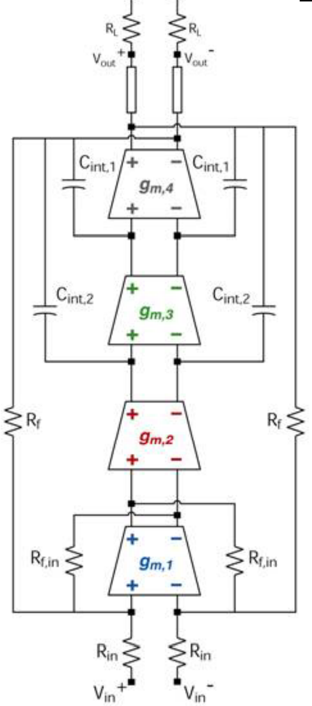


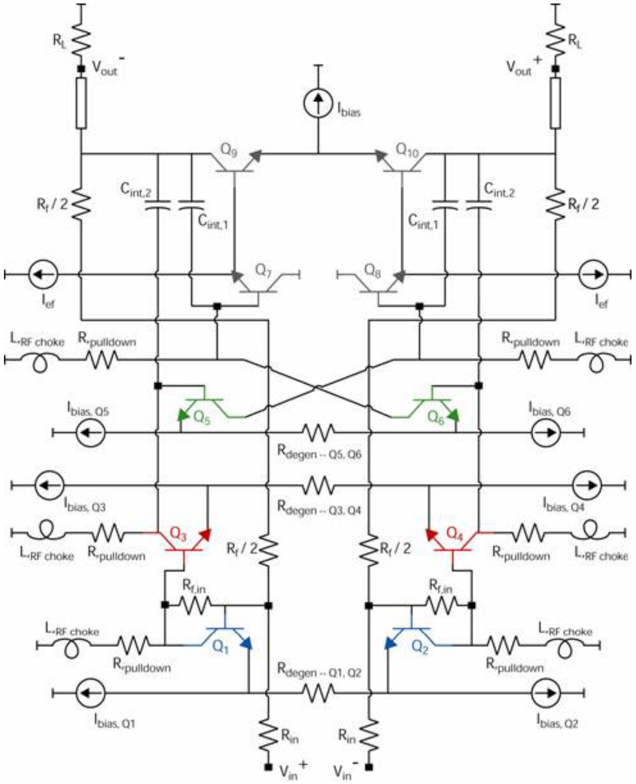
mm-wave Op-Amps for Linear Microwave Amplification

DARPA / UCSB / Teledyne FLARE: Griffith & Urteaga

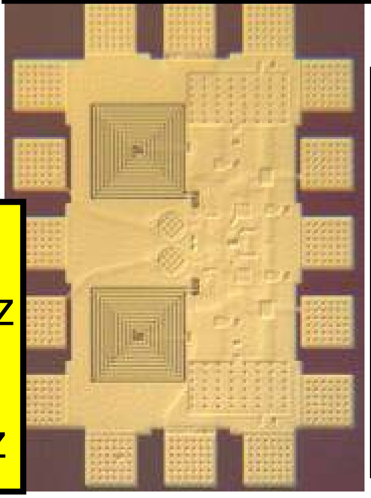
Reduce distortion with strong negative feedback

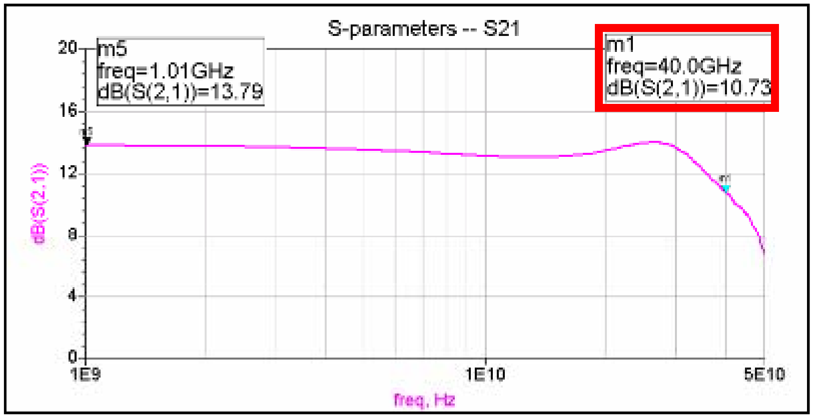






300 GHz / 4 V InP HBT





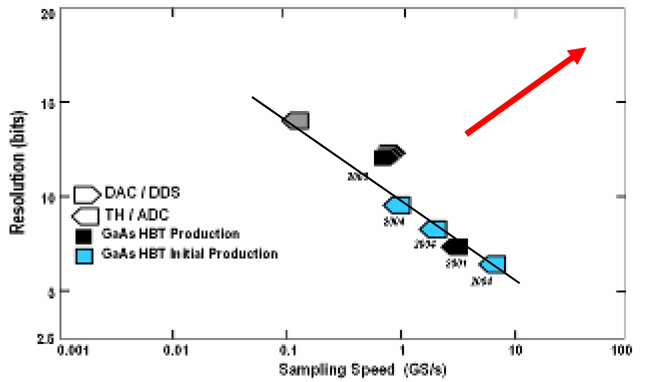
measured 20-40 GHz bandwidth
measured **54 dBm OIP3** @ 2 GHz

new designs in fabrication
simulated **56 dBm OIP3** @ 2 GHz

What Would You Do With a THz Transistor ?

microwave ADCs and DACs

more resolution & more bandwidth



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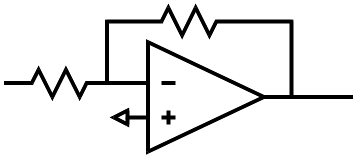

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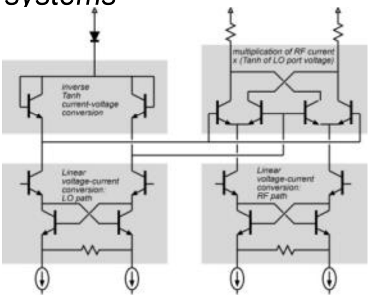

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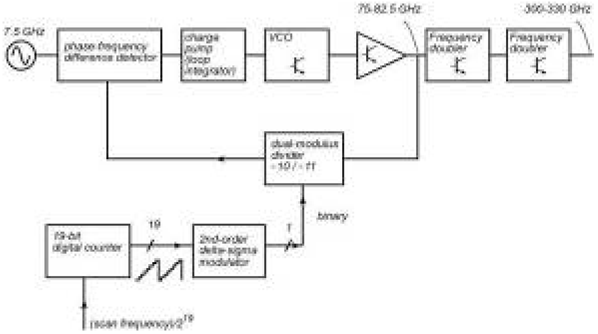
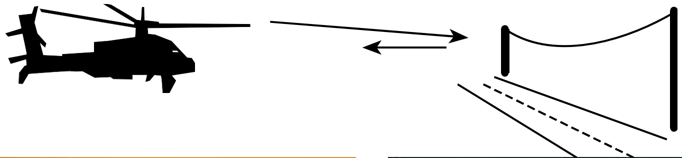
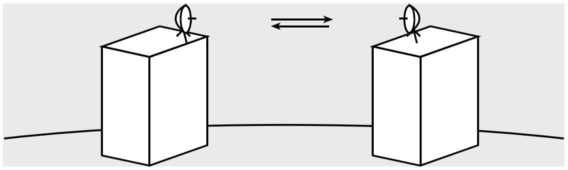


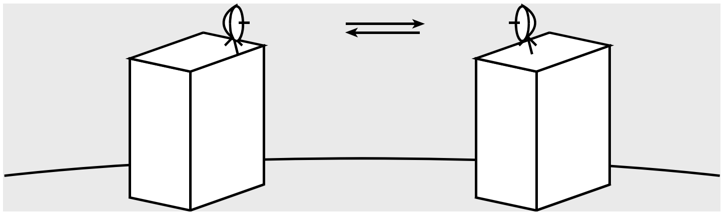
670-1000 GHz imaging systems



sub-mm-wave communications



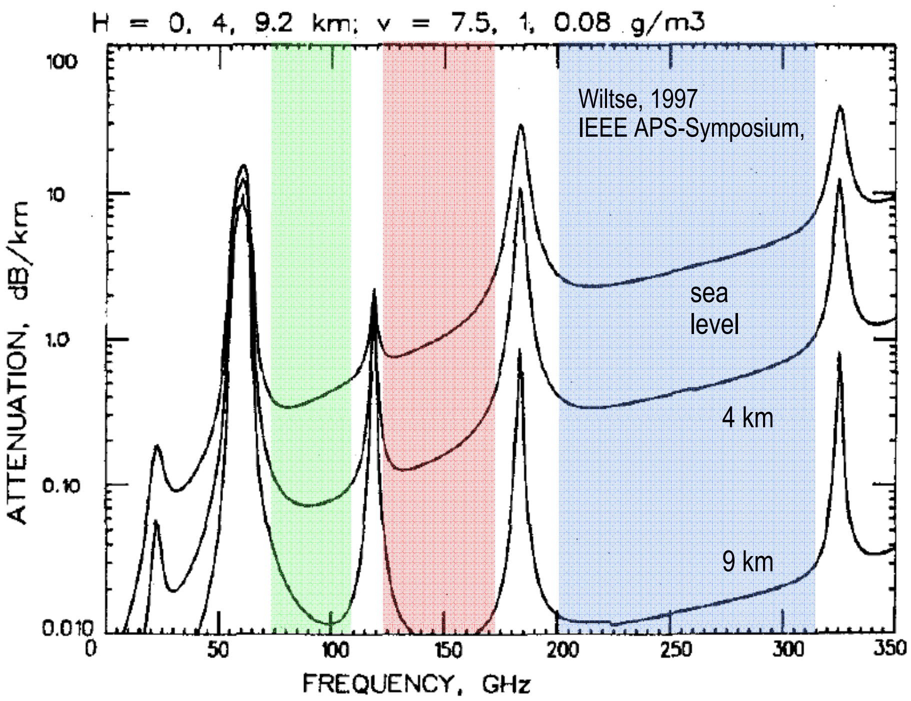
150 & 250 GHz Bands for 100 Gb/s Radio ?



$$P_{received} / P_{trans} = (D_t D_r / 16\pi^2)(\lambda / R)^2$$

$$P_{received\,(4QPSK)} = Q^2 \cdot kTFB\,; \quad Q \cong 6$$

$$D = 4\pi A_{eff} \big/ \lambda^2$$



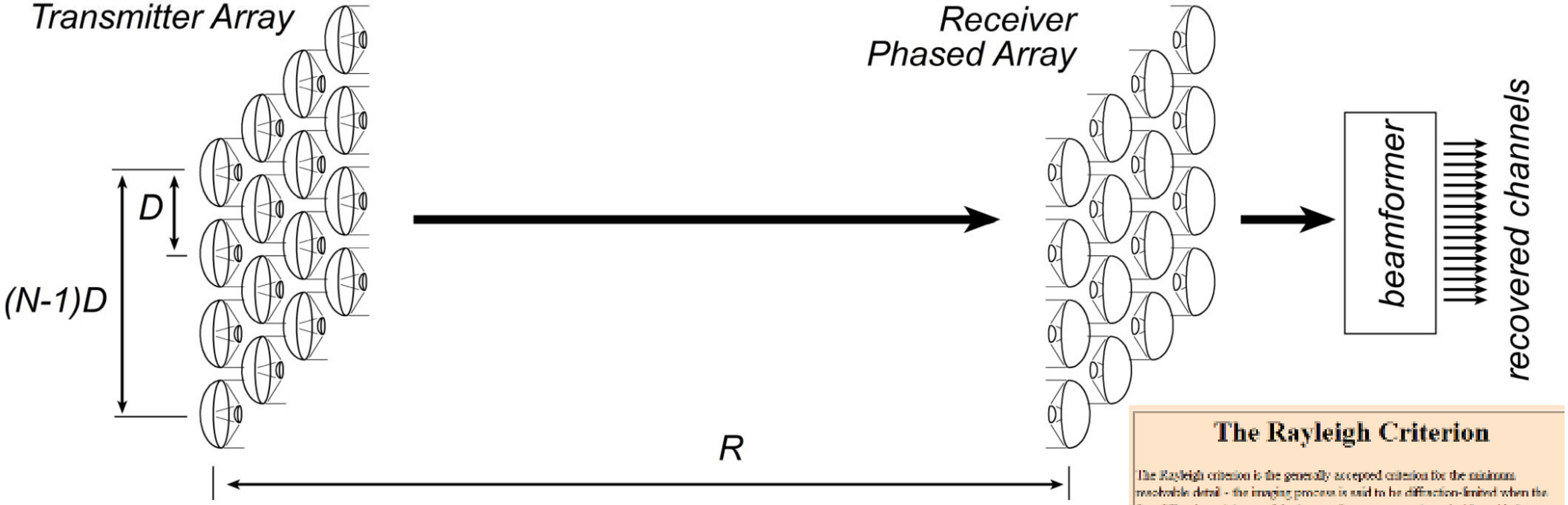
Wiltse, 1997
IEEE APS-Symposium,

125-150 GHz, 200-300 GHz:
enough bandwidth for 100 Gb/s QPSK

150 GHz carrier, 100 Gbs/s QPSK radio:
30 cm antennas, 10 dBm power, fair weather→ 1 km range

150 GHz band: Expect ~10-20 dB/km attenuation for rain
But, for > 300 GHz : expect >30 db/km from 90% humidity

mm-wave (60-80 GHz) MIMO → wireless at 40+ Gb/s rates ?

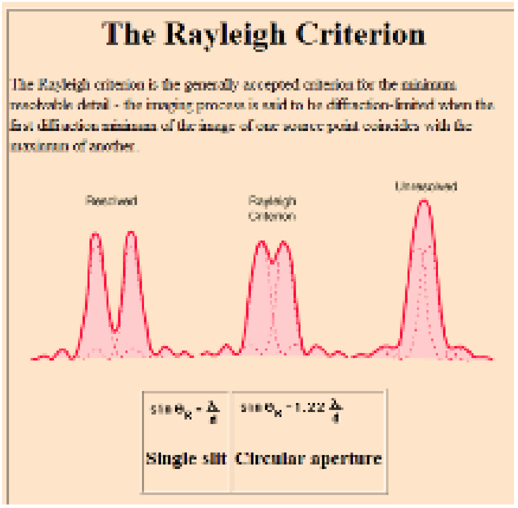


Rayleigh Criterion:

Spatial angular separation of adjacent transmitters: $\delta\theta_t = D / R$

Receive array angular resolution: $\delta\theta_r = \lambda / (N-1)D$

To resolve adjacent channels, $\delta\theta_r \le \delta\theta_r \Rightarrow (N-1)D = \sqrt{\lambda R(N-1)}$



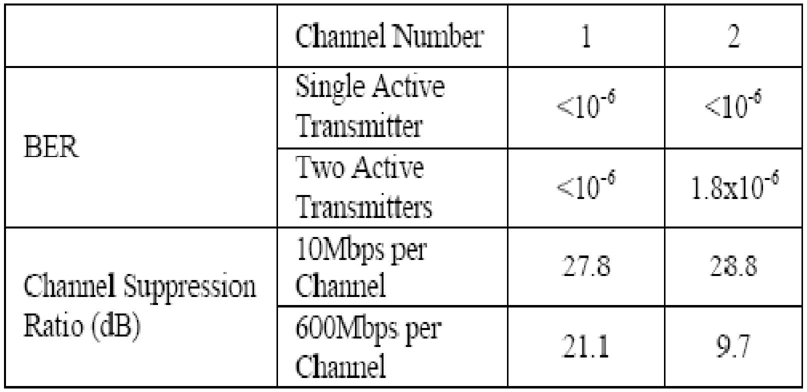
The Rayleigh Criterion

The Rayleigh criterion is the generally accepted criterion for the minimum resolvable detail - the imaging process is said to be diffraction-limited when the first diffraction minimum of the image of one source point coincides with the maximum of another.

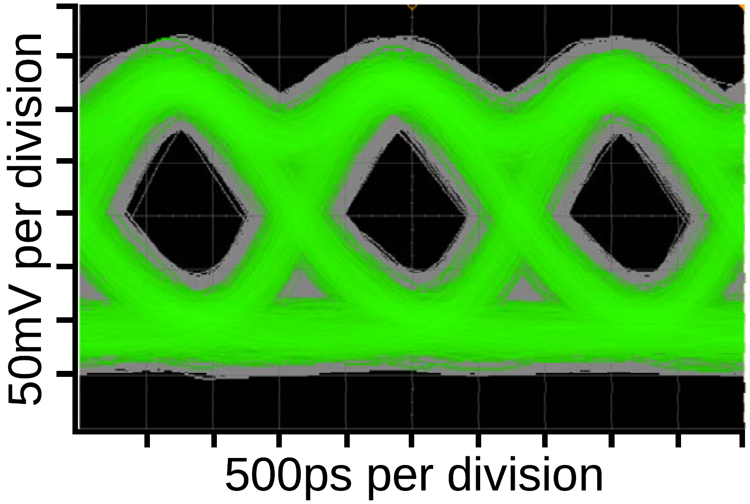
$\sin\theta_R = \frac{\lambda}{d}$	$\sin\theta_R = 1.22\frac{\lambda}{d}$
Single slit	**Circular aperture**

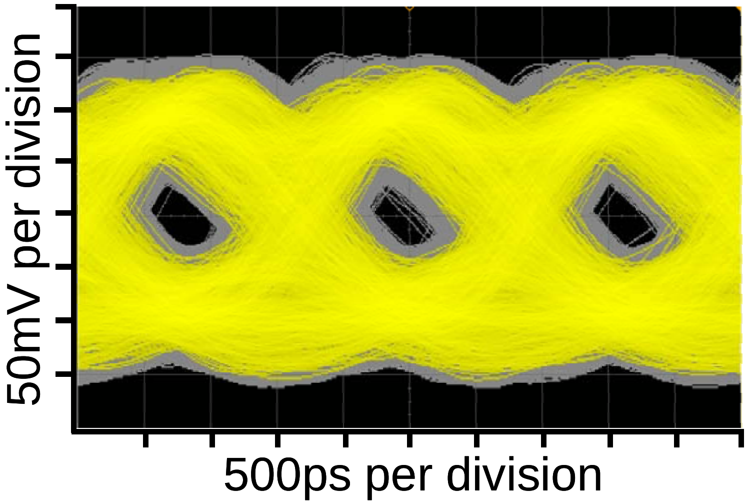
70 GHz, 1 km, 16 elements, 2 polarizations, 3.6 x 3.6 meter array, 2.5 GBaud QPSK
→ <u>160 Gb/s digital radio ?</u>

mm-wave MIMO: 2-channel prototype, 60 GHz, 40 meters



	Channel Number	1	2
BER	Single Active Transmitter	$<10^{-6}$	$<10^{-6}$
	Two Active Transmitters	$<10^{-6}$	$1.8\text{x}10^{-6}$
Channel Suppression Ratio (dB)	10Mbps per Channel	27.8	28.8
	600Mbps per Channel	21.1	9.7





mm-Wave & Sub-mm-Wave Wireless Links

The ICs will soon make this possible

SiGe BiCMOS: up to 150 GHz now,
future uncertain

Si CMOS: up to 150 GHz now, 200-300 GHz soon,
low output power

InP HBT: up to 500 GHz now, up to 1000 GHz soon
moderate to high power, moderate noise

Propagation characteristics will determine applications

Foul-Weather Attenuation, Highly Directional (LOS only) propagation

Massive mm-wave IC complexity in future
→ aggressive system adaptations / corrections