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

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Center for Converged Communications & Sensing at THz.

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

Funding:
about $36 million total.

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

Sponsors:
SRC, DARPA

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

Wireless networks: exploding demand.

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

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

DOD applications: Imaging/sensing/radar, comms.
140-340GHz Wireless

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

TV-resolution wireless imaging:
See, fly, drive perfectly in any conditions.
**Benefits of Short Wavelengths**

**Communications:** Massive spatial multiplexing, massive # of parallel channels

- Spatially-multiplexed mm-wave base stations
- mm-wave backhaul
- MIMO arrays on each face

\[ N \propto \frac{L}{\lambda} \]

**Imaging:** very fine angular resolution

- Range/Doppler
- Imaging radar

\[ \Delta \theta \propto \frac{\lambda}{L} \]

**But:**
- High losses in foul or humid weather.
- High \( \frac{\lambda^2}{R^2} \) path losses.
- ICs: poorer PAs & LNAs.
- Beams easily blocked.

**100-340GHz wireless:**
- Terabit capacity,
- Short range,
- Highly intermittent
mm-waves: benefits & challenges

Large available spectrum

Massive # parallel channels

Need phased arrays (overcome high attenuation)

Need mesh networks

Torklinson : 2006 Allerton Conference
Sheldon : 2010 IEEE APS-URSI
140-340 GHz: Applications
140 GHz spatially multiplexed base station

1 Tb/s spatially-multiplexed base station
256 users/face, 4 faces
1024 total users @ 1 user/beam, 1 Gb/s/beam;
225 m range

Link budget is feasible, but...
Required component dynamic range?
Required complexity of back-end beamformer?
140 GHz spatially multiplexed base station

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

225 meters range in 50 mm/hr rain

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

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

LNAs: 3 dB noise figure
75 GHz spatially multiplexed base station

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

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

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

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

*The hub array is now 9mm×655mm (vs. 5mm×350mm)
340 GHz (or even 650 GHz) backhaul

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

1.6m MIMO array: 8-elements, each 80 Gb/s QPSK; 640Gb/s total

4 × 4 sub-arrays → 8 degree beamsteering

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

Realistic packaging loss, operating & design margins

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

LNAs: 4 dB noise figure
340 GHz 5 Tb/s MIMO backhaul

500m range in 50mm/hr. rain.

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

**8-element 5Tb/s square array:**
same link assumptions
requires 10mW power/element
...10W total radiated power
requires 1.6m square array
140 GHz, 640 Gb/s MIMO backhaul

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

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

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

Proposed demo: 220GHz frequency-scanned system
- 64×512 pixels, 60Hz refresh
- 35cm × 35cm aperture
- 64-element linear array

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

System:
- \( F=6\text{dB}, P_{\text{element}}=10\text{dBm} \) (10% duty cycle)

DOD-relevant: 140GHz close-range system
- 256×256 pixels, 10ms image acquisition time
- 27 cm linear arrays, 256 elements

Target (large bullet):
- 2cm diameter, 10% reflectivity, 100m
  detect with 10dB SNR in 20dB/km rain.

System
- \( F=6\text{dB}, \rightarrow \text{Need 0.4W PAs (10% duty cycle)} \)
  (reasonable margins)
Systems
Beamforming for massive spatial multiplexing

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

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

Digital beamforming

- **ADCs/DACs**: only 3-4 bit ADC/DACs required (Madhow, Studer, Rodwell)
- **Linearity**: Amplifier $P_{1dB}$ need be only 3dB above average power (Madhow).
- **Phase noise**: Requirements same as for SISO (Alon, Madhow, Niknejad, Rodwell)

**Efficient digital beamforming**: beamspace algorithm=complexity $\sim N \times \log(N)$ (Madhow)

**Efficient digital beamforming**: low-resolution matrix (Studer)

**Efficient channel estimation**: fast beamspace algorithm (Studer)

**Efficiently addressing true-time-delay problem**: "rainbow" FFT algorithm (Madhow)

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

In progress...

**Propagation models and measurements**: (Molisch)

**Blockage probability, mesh networks, network protocols**: (Rangan, Cabric)

**MIMO system power analysis**: (Rangan, Cabric, Buckwalter)
Transistors

[Image of transistor structures with labels: HBT64J, High-k, Au, Ni, InGaAs, InP, TiW, Pt/Ru/Pt, Link, Channel, Buffer, 64nm HBT]
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: $F = 4 \text{dB}$, $P_{\text{avg}} = 17.5 \text{dBm}$, $P_{\text{sat}} \approx 21.5 \text{dBm}$
- 220GHz: $F = 4 \text{dB}$, $P_{\text{avg}} = 21 \text{dBm}$, $P_{\text{sat}} \approx 25 \text{dBm}$

**Point-point MIMO:**
- 340GHz: $F = 4 \text{dB}$, $P_{\text{avg}} = 9.9 \text{dBm}$, $P_{\text{sat}} \approx 13.9 \text{dBm}$
- 650GHz: $F = 4 \text{dB}$, $P_{\text{avg}} = 14.5 \text{dBm}$, $P_{\text{sat}} \approx 18.5 \text{dBm}$
mm-wave CMOS (UCSB examples)

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

145 GHz amplifier
GF 45 nm SOI CMOS, 6.3 dB gain per stage Kim, Simseck, 2017 BCICTS
mm-Wave CMOS won't scale much further

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

Inac et al, CSICS 2011

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

Tungsten via resistances reduce the gain

Present finFETs have yet larger end capacitances
III-V high-power transmitters, low-noise receivers

Cell phones & WiFi: GaAs PAs, LNAs

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

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

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

1.9mW @585GHz
M Seo, TSC, IMS 2013
Gallium Nitride Power Technologies

GaN is the leading high-frequency power technology

N-polar GaN: Mishra
130nm / 1.1THz InP HBT Technology

Teledyne: M. Urteaga et al: 2011 DRC

Rode (UCSB), IEEE TED, 2015

3.5 V breakdown

$J_c (mA/mm^2)$

$V_{CE} (V)$

$J_E (mA/mm^2)$

$R_{ode} (UCSB), IEEE TED, 2015$

$3.5 V$ breakdown

$J_c = 6.9 mA$

$V_{CE} = 1.6 V$

$f_{max} = 1.15\mathrm{THz}$

$f = 521\mathrm{GHz}$

$\Lambda_e = 0.2 \cdot 2.9 \, \mu m^2$

$V_{ce} = 2.0 V$

$I_s = 18 mA/\mu m^2$

$f_i = 480 \, \mathrm{GHz}$

$f_{max} = 1070 \, \mathrm{GHz}$
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

but, only ~1 mW output power
Transistor scaling laws: \((V, I, R, C, \tau)\) vs. geometry

**Depletion Layers**

\[ C = \varepsilon \cdot \frac{A}{T} \]

\[ \tau = \frac{T}{2v} \]

**Bulk and Contact Resistances**

\[ R \approx \frac{\rho_{\text{contact}}}{A} \]

**Fringing Capacitances**

\[ C_{\text{finging}} / L \sim \varepsilon \]

1) FET fringing capacitances
2) IC interconnection capacitances

**Thermal Resistance**

\[ \Delta T_{\text{IC}} \propto \frac{P_{\text{IC}}}{K_{\text{th}} L} \]

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

**Available quantum states to carry current**

\[ I_{\text{max}} = \frac{4\varepsilon V_{\text{sat}} (V_{\text{appl}} + \phi)}{T^2} \]

contact terms dominate

\[ \Delta k = \pi / L \]

\[ \Delta k = \pi / L \]

\[ \rightarrow \text{capacitance, transconductance contact resistance} \]
Frequency Limits and Scaling Laws of (most) Electron Devices

\[ \tau \propto \text{thickness} \]
\[ C \propto \frac{\text{area}}{\text{thickness}} \]
\[ R_{\text{top}} \propto \frac{\rho_{\text{contact}}}{\text{area}} \]
\[ R_{\text{bottom}} \propto \frac{\rho_{\text{contact}}}{\text{area}} + \frac{\rho_{\text{sheet}}}{4} \frac{\text{width}}{\text{length}} \]
\[ I_{\text{max, space-charge-limit}} \propto \frac{\text{area}}{\left(\text{thickness}\right)^2} \]
\[ \Delta T \propto \frac{\text{power}}{\text{length}} \times \log\left(\frac{\text{length}}{\text{width}}\right) \]

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

\[ \tau_b \approx \frac{T_b^2}{2D_n} \]

\[ \tau_c = \frac{T_c}{2v_{sat}} \]

\[ C_{cb} = \frac{\varepsilon A_e}{T_c} \]

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

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

\[ R_{ex} = \frac{\rho_{\text{contact}}}{A_e} \]

\[ R_{bb} = \rho_{\text{sheet}} \left( \frac{W_e}{12L_e} + \frac{W_{bc}}{6L_e} \right) + \frac{\rho_{\text{contact}}}{A_{\text{contacts}}} \]
Bipolar Transistor Design: Scaling

\[ \tau_b \approx \frac{T_b^2}{2D_n} \]

\[ \tau_c = \frac{T_c}{2v_{sat}} \]

\[ C_{cb} = \frac{\varepsilon A_c}{T_c} \]

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

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

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\[ R_{bb} = \rho_{\text{sheet}} \left( \frac{W_e}{12L_e} + \frac{W_{bc}}{6L_e} \right) + \frac{\rho_{\text{contact}}}{A_{\text{contacts}}} \]
Making faster bipolar transistors

Narrow junctions.
Thin layers
High current density
Ultra low resistivity contacts

to double the bandwidth:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>emitter &amp; collector junction widths</td>
<td>decrease 4:1</td>
</tr>
<tr>
<td>current density (mA/μm²)</td>
<td>increase 4:1</td>
</tr>
<tr>
<td>current density (mA/μm)</td>
<td>constant</td>
</tr>
<tr>
<td>collector depletion thickness</td>
<td>decrease 2:1</td>
</tr>
<tr>
<td>base thickness</td>
<td>decrease 1.4:1</td>
</tr>
<tr>
<td>emitter &amp; base contact resistivities</td>
<td>decrease 4:1</td>
</tr>
</tbody>
</table>

Teledyne: M. Urteaga et al: 2011 DRC
InP HBTs: 1.07 THz @200nm, ?? @ 130nm

Rode et al., IEEE TED, Aug. 2015
THz HBTs: The key challenges

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

RC parasitics along finger length
metal resistance, excess junction areas

Towards a 2 THz SiGe Bipolar Transistor

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

Key distinction: Breakdown
InP has:
  thicker collector at same $f_t$
  wider collector bandgap

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

<table>
<thead>
<tr>
<th></th>
<th>InP</th>
<th>SiGe</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>emitter</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>junction width</td>
<td>64</td>
<td>18</td>
</tr>
<tr>
<td>access resistivity</td>
<td>2</td>
<td>0.6</td>
</tr>
<tr>
<td><strong>base</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>contact width</td>
<td>64</td>
<td>18</td>
</tr>
<tr>
<td>contact resistivity</td>
<td>2.5</td>
<td>0.7</td>
</tr>
<tr>
<td><strong>collector</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>thickness</td>
<td>53</td>
<td>15</td>
</tr>
<tr>
<td>current density</td>
<td>36</td>
<td>125</td>
</tr>
<tr>
<td>breakdown</td>
<td>2.75</td>
<td>1.3?</td>
</tr>
<tr>
<td>$f_t$</td>
<td>1000</td>
<td>1000</td>
</tr>
<tr>
<td>$f_{\text{max}}$</td>
<td>2000</td>
<td>2000</td>
</tr>
</tbody>
</table>

Assumes collector junction 3:1 wider than emitter.
Assumes SiGe contacts no wider than junctions
FETs (HEMTs): key for low noise

2:1 to 4:1 increase in $f_\tau$: improved noise less required transmit power smaller PAs, less DC power or higher-frequency systems

Noise figure, dB

Frequency, Hz

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

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

$\Gamma \approx 1$
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)

<table>
<thead>
<tr>
<th>FET parameter</th>
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<tbody>
<tr>
<td>gate length</td>
<td>decrease 2:1</td>
</tr>
<tr>
<td>current density (mA/mm)</td>
<td>increase 2:1</td>
</tr>
<tr>
<td>specific transconductance (mS/mm)</td>
<td>increase 2:1</td>
</tr>
<tr>
<td>transport mass</td>
<td>constant</td>
</tr>
<tr>
<td>2DEG electron density</td>
<td>increase 2:1</td>
</tr>
<tr>
<td>gate-channel capacitance density</td>
<td>increase 2:1</td>
</tr>
<tr>
<td>dielectric equivalent thickness</td>
<td>decrease 2:1</td>
</tr>
<tr>
<td>channel thickness</td>
<td>decrease 2:1</td>
</tr>
<tr>
<td>channel state density</td>
<td>increase 2:1</td>
</tr>
<tr>
<td>contact resistivities</td>
<td>decrease 4:1</td>
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</tbody>
</table>

- vertical S/D spacer
- low-K dielectric spacer
- high-K gate dielectric
### FET Scaling Laws (these now broken)

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<tr>
<td>contact resistivities</td>
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</tr>
</tbody>
</table>

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

\[
g_m/W_g \text{ (mS/\mu m)} \text{ hard to increase} \rightarrow C_{end}/g_m \text{ prevents } f_T \text{ scaling.}
\]

*Shorter gate lengths degrade electrostatics} \rightarrow \text{ reduced } g_m/G_{ds} \rightarrow \text{ reduced } f_{\text{max}}, f_T*
Towards faster HEMTs: MOS-HEMTs

Scaling limit: gate insulator thickness
HEMT: InAlAs barrier: tunneling, thermionic leakage
solution: replace InAlAs with high-K dielectric
2nm ZrO$_2$ ($\varepsilon_r=25$): 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 $f_t$.

Jun Wu, UCSB, IEEE EDL, 2018
ICs
mm-Wave IC design: the challenges

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

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

Transmission-line losses are high  
low Q in VCO resonators and filters  
high combining losses in PAs: low power, low efficiency  
several dB added noise in LNAs.
Thin-film microstrip: inverted or right-side-up

S.I. Substrate

Inverted microstrip line

Low $\varepsilon_r$

Via

Ground Plane

S.I. Substrate
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

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

220 GHz 180 mW power amplifier
T. Reed, UCSB CSICS 2013
214 GHz, 180mW Power Amplifier (330 mW design)

2.3 mm x 2.5 mm

205GHz Logic in Thin-Film Inverted Microstrip

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

205 GHz divider, Griffith et al, IEEE CSICS, Oct. 2010
140GHz Transceivers: GF 22nm SOI CMOS

A. Farid UCSB, 2019 RFIC symposium
RX Characterization
TX Characterization

- Chart 1: LO Frequency (GHz) vs. Output Power (dBm)
  - BB Freq. Fixed @ 1 GHz
  - BB Freq. Fixed @ 2 GHz
  - BB Freq. Fixed @ 5 GHz

- Chart 2: Input Power (dBm) vs. Output Power (dBm)
  - Sim. LO@135 GHz
  - LO@135 GHz
  - LO@134 GHz
  - LO@133 GHz

- Chart 3: Modulation Frequency (GHz) vs. Relative Sideband Power (dBm)
  - LO @ 133 GHz
  - LO @ 134 GHz
  - Sim. LO @ 135 GHz
**Class-A mm-Wave Power Amplifiers**

120, 140, 220, 300GHz designs  
Power: 50-100-200mW  
140GHz efficiencies: 17%

**Class-B mm-Wave Power Amplifiers**

120GHz designs  
Power: 30 mW  
140GHz efficiencies: 28%

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

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<table>
<thead>
<tr>
<th>#</th>
<th>Description</th>
<th>Area(mm×mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>140GHz, $P_{out}=19.3$dB, PAE=13%, Gain=23.2dB</td>
<td>0.63×1.08</td>
</tr>
<tr>
<td>2</td>
<td>140GHz, $P_{out}=21.8$dB, PAE=13.5%, Gain=23.2dB</td>
<td>1.2×1.09</td>
</tr>
<tr>
<td>3</td>
<td>140GHz, $P_{out}=19.9$dB, PAE=6.6%, Gain=24.8dB</td>
<td>0.95×1.07</td>
</tr>
<tr>
<td>4</td>
<td>140GHz, $P_{out}=19.5$dB, PAE=17.9%, Gain=14.5dB</td>
<td>0.63×0.86</td>
</tr>
<tr>
<td>5</td>
<td>220GHz, $P_{out}=20.2$dB, PAE=7.8%, Gain=19.7dB</td>
<td>1.09×0.78</td>
</tr>
<tr>
<td>6</td>
<td>140GHz, $P_{out}=19.1$dB, PAE=17.1%, Gain=14.4dB</td>
<td>0.6×0.79</td>
</tr>
<tr>
<td>7</td>
<td>220GHz, $P_{out}=15.9$dB, PAE=10.2%, Gain=19.9dB</td>
<td>0.56×0.79</td>
</tr>
<tr>
<td>8</td>
<td>300GHz, $P_{out}=13.5$dB, PAE=4.2%, Gain=13.5dB</td>
<td>0.63×0.8</td>
</tr>
<tr>
<td>9</td>
<td>300GHz, $P_{out}=17.8$dB, PAE=3.5%, Gain=15.8dB</td>
<td>1.1×0.94</td>
</tr>
<tr>
<td>10</td>
<td>140GHz, $P_{out}=19.7$dB, PAE=8.1%, Gain=17.7dB</td>
<td>0.95×0.9</td>
</tr>
<tr>
<td>11</td>
<td>140GHz, $P_{out}=21.7$dB, PAE=10.4%, Gain=30.7dB</td>
<td>1.2×1.3</td>
</tr>
<tr>
<td>12</td>
<td>120GHz, $P_{out}=20.4$dB, PAE=9.2%, Gain=20.4dB</td>
<td>0.95×0.98</td>
</tr>
<tr>
<td>13</td>
<td>140GHz, $P_{out}=17.3$dB, PAE=7.5%, Gain=25.3dB</td>
<td>1.07×0.54</td>
</tr>
<tr>
<td>14</td>
<td>140GHz, $P_{out}=15$dB, PAE=28%, Gain=16dB</td>
<td></td>
</tr>
</tbody>
</table>

James Buckwalter, Mark Rodwell: UCSB
140GHz PA: power and S-parameter simulations

<table>
<thead>
<tr>
<th>Technology</th>
<th>250-nm InP HBT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freq, GHz</td>
<td>140</td>
</tr>
<tr>
<td>VCC, V</td>
<td>2.5</td>
</tr>
<tr>
<td>J_{bias}, mA/um</td>
<td>1.3</td>
</tr>
<tr>
<td>S21, dB</td>
<td>25</td>
</tr>
<tr>
<td>P_{out}, dB_m, 2dB</td>
<td>19.1</td>
</tr>
<tr>
<td>PAE %, 2dB</td>
<td>12.6</td>
</tr>
<tr>
<td>P_{sat}, dB_m</td>
<td>20.9</td>
</tr>
<tr>
<td>PAE_{sat} %</td>
<td>18.3</td>
</tr>
<tr>
<td>BW_{3dB}, GHz</td>
<td>43</td>
</tr>
<tr>
<td>P_{DC}, W</td>
<td>0.65</td>
</tr>
</tbody>
</table>
220GHz PA (CB version)

Power cell:
Smaller base capacitor,
SRF=679GHz
Decrease the shunt inductor

Two stage drivers:
Similar to power cell with higher cap
SRF=512GHz

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

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

Two stage drivers:
- Similar to power cell with higher cap
  SRF=512GHz

Area=1.09 mm × 0.78 mm
300GHz PA (CB version)

power cell and driver:

Decrease base cap and inductor

SRF=714GHz

Three driver stages

<table>
<thead>
<tr>
<th>Technology</th>
<th>250-nm InP HBT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freq, GHz</td>
<td>300</td>
</tr>
<tr>
<td>VCC, V</td>
<td>2.5</td>
</tr>
<tr>
<td>$J_{bias}$, mA/um</td>
<td>1.3</td>
</tr>
<tr>
<td>S21, dB</td>
<td>17.6</td>
</tr>
<tr>
<td>$P_{out, dB_{m/2dB}}$</td>
<td>17.8</td>
</tr>
<tr>
<td>PAE %, 2dB</td>
<td>3.5</td>
</tr>
<tr>
<td>$P_{sat, dB_{m}}$</td>
<td>19.4</td>
</tr>
<tr>
<td>PAE$_{sat}$ %</td>
<td>5</td>
</tr>
<tr>
<td>BW$_{3dB}$, GHz</td>
<td>43</td>
</tr>
<tr>
<td>$P_{DC}$, W</td>
<td>1.65</td>
</tr>
</tbody>
</table>

Area=1.1 mm × 0.94mm

Four fingers, LE =6um.
Packages
The mm-wave module design problem

**How to make the IC electronics fit?**

100+ GHz arrays: $\frac{\lambda_0}{2}$ element spacing is very small.
Antennas on or above IC $\rightarrow$ IC channel spacing = antenna spacing
$\rightarrow$ **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 $\rightarrow$ very long wires between beam former and antenna
$\rightarrow$ **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 $\lambda/2$.
→ Array packaging then greatly simplified.
Concept: Tile for linear arrays

Terrestrial system: horizontal steering only → linear array.
Space at edges of linear array: room for III-V PAs, LNAs.
Alternating-sides feed: 2mm pitch → room for large GaN PAs.
Mounting directly on metal carrier → heatsinking.
140GHz array module design

Simulations good: working with Kyocera. June tapeout?
140GHz Indoor Gigabit Network Demonstration
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
\(\lambda/2\)-spaced 2-D Arrays

**Tray design**
Vertical spacings become very small
difficult to remove heat

**Split-block / waveguide design**
heatsinking maintained
difficult to manufacture
Wireless above 100GHz
Wireless above 100 GHz

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

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

IC Technology
All-silicon for short ranges below 250 GHz.
III-V LNAs and PAs for longer-range links. Just like cell phones today
III-V frequency extenders for 340GHz and beyond

The challenges
spatial multiplexing: computational complexity
packaging: fitting signal channels in very small areas
In case of questions
<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
<th>I</th>
<th>J</th>
<th>K</th>
<th>L</th>
<th>M</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>B: Bit rate</td>
<td>1.00E+09</td>
<td>1/sec</td>
<td>QPSK required radiated power/beam</td>
<td>17.0</td>
<td>dBm</td>
<td>5.07E-02</td>
<td>W</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>5</td>
<td>carrier frequency</td>
<td>1.40E+11</td>
<td>Hz</td>
<td>PA output power per element / beam</td>
<td>-5.0</td>
<td>dBm</td>
<td>3.14E-04</td>
<td>W</td>
<td></td>
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<tr>
<td>6</td>
<td>λ: wavelength</td>
<td>2.14E+03</td>
<td>m</td>
<td>QPSK total required radiated power</td>
<td>38.1</td>
<td>dBm</td>
<td>6.48E+00</td>
<td>W</td>
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<tr>
<td>7</td>
<td>Required SNR (measured as Eb/No)</td>
<td>9.8</td>
<td>dB</td>
<td>Total PA output power per element</td>
<td>16.0</td>
<td>dBm</td>
<td>4.01E-02</td>
<td>W</td>
<td></td>
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<tr>
<td>8</td>
<td>F: receiver noise figure</td>
<td>8.3</td>
<td>dB</td>
<td>Transmitter: Base station</td>
<td>1.71E-03</td>
<td>meters²</td>
<td>3.72E-02</td>
<td>Wavelengths²</td>
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<tr>
<td>9</td>
<td>R: transmission range</td>
<td>225.0</td>
<td>m</td>
<td>Vertical beam angle, peak-null</td>
<td>25.00</td>
<td>deg</td>
<td>0.4363</td>
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<td>10</td>
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<td>1.93E-02</td>
<td>dB/m</td>
<td>Horizontal beam angle, peak-null</td>
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<td>deg</td>
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<td>total # array elements</td>
<td>256</td>
<td># rows</td>
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<td>vertical angle scanned, total</td>
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<td>0.9679</td>
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<tr>
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<td>λ: bandwidth factor (0.5&lt;λ&lt;1)</td>
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<td>800.0</td>
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<td>2.37</td>
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<tr>
<td>15</td>
<td># beams</td>
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<td>antenna directivity, dB</td>
<td>36.71</td>
<td>dB</td>
<td>36.71</td>
<td>dB</td>
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<tr>
<td>16</td>
<td>KT</td>
<td>-173.39</td>
<td>dBm (1Hz)</td>
<td>array height</td>
<td>2.37</td>
<td>wavelengths</td>
<td>5.07E-03</td>
<td>meters</td>
<td></td>
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<tr>
<td>17</td>
<td>rf power (receiver)</td>
<td>2</td>
<td>dB</td>
<td>array width</td>
<td>163.70</td>
<td>wavelengths</td>
<td>3.51E-01</td>
<td>meters</td>
<td></td>
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<tr>
<td>18</td>
<td>包装功率（发射机）</td>
<td>2</td>
<td>dB</td>
<td>element height</td>
<td>2.37</td>
<td>wavelengths</td>
<td>5.07E-03</td>
<td>meters</td>
<td></td>
<td></td>
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<tr>
<td>19</td>
<td>packaging loss (transmitter)</td>
<td>2</td>
<td>dB</td>
<td>end-of-life hardware degradation</td>
<td>0.04</td>
<td>wavelengths</td>
<td>1.37E-03</td>
<td>meters</td>
<td></td>
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<tr>
<td>20</td>
<td>hardware design margin</td>
<td>2</td>
<td>dB</td>
<td>Antenna directivity, dB</td>
<td>36.71</td>
<td>dB</td>
<td>36.71</td>
<td>dB</td>
<td></td>
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<tr>
<td>21</td>
<td>beam aiming loss (edge of beam)</td>
<td>2</td>
<td>dB</td>
<td>Receiver-handset</td>
<td>3.75E-05</td>
<td>meters²</td>
<td>8.16</td>
<td>Wavelengths²</td>
<td></td>
<td></td>
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<tr>
<td>22</td>
<td>systems operating margin</td>
<td>5</td>
<td>dB</td>
<td>Vertical beam angle, peak-null</td>
<td>20.0</td>
<td>deg</td>
<td>0.3491</td>
<td>radians</td>
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<td>23</td>
<td>prec. received power at 1E-3 BER</td>
<td>-60.03</td>
<td>dBm</td>
<td>Horizontal beam angle, peak-null</td>
<td>20.0</td>
<td>deg</td>
<td>0.3491</td>
<td>radians</td>
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<td>24</td>
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<td>160</td>
<td>deg</td>
<td>160</td>
<td>deg</td>
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<td>26</td>
<td>path obstruction loss (shadowing)</td>
<td>5.00</td>
<td>dB</td>
<td>horizontal angle scanned, total</td>
<td>160</td>
<td>deg</td>
<td>160</td>
<td>deg</td>
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<tr>
<td>27</td>
<td>atmospheric loss</td>
<td>4.48</td>
<td>dB</td>
<td>array height</td>
<td>2.9E+00</td>
<td>wavelengths</td>
<td>6.27E+03</td>
<td>meters</td>
<td></td>
<td></td>
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<tr>
<td>28</td>
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<td>13.93</td>
<td>dB/km</td>
<td>array width</td>
<td>2.9E+00</td>
<td>wavelengths</td>
<td>6.27E+03</td>
<td>meters</td>
<td></td>
<td></td>
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<tr>
<td>29</td>
<td>element height</td>
<td>3.65E-01</td>
<td>wavelengths</td>
<td>7.83E-04</td>
<td>meters</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>30</td>
<td>Antenna directivity, dB</td>
<td>20.11</td>
<td>dB</td>
<td>Antenna directivity, dB</td>
<td>36.71</td>
<td>dB</td>
<td>36.71</td>
<td>dB</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **Boldface** indicates parameters to enter, other parameters are calculated by formula and should be left alone.
- This spreadsheet calculates power levels for QPSK point-point digital microwave radio links along the surface.
- To calculate RANGE, vary the range until the transmit power (cell F9) is at the appropriate level.

---

**Note:**

- Don't confuse radiated power with PA output power. They differ by cell C22, the transmitter packaging loss, which includes transmit (but not receive) antenna losses.
- "Calculations are a bit off for the handset element spacings because with a wide angular scan range, the angular resolution varies as a function of scan angle."
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

<table>
<thead>
<tr>
<th><strong>Label</strong></th>
<th><strong>B</strong></th>
<th><strong>C</strong></th>
<th><strong>D</strong></th>
<th><strong>E</strong></th>
<th><strong>F</strong></th>
<th><strong>G</strong></th>
<th><strong>H</strong></th>
<th><strong>I</strong></th>
<th><strong>J</strong></th>
<th><strong>K</strong></th>
<th><strong>L</strong></th>
<th><strong>M</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bit rate (per MIMO transmitter)</strong></td>
<td>8.00E+10</td>
<td>sec</td>
<td>1</td>
<td>4QAM required radiated power</td>
<td>29.2</td>
<td>dBi</td>
<td>8.28E-01</td>
<td>W</td>
<td>output power per element</td>
<td>19</td>
<td>W</td>
<td>8.20E-02</td>
</tr>
<tr>
<td><strong>Carrier frequency</strong></td>
<td>3.40E+11</td>
<td>Hz</td>
<td>1</td>
<td>output power per sub-array</td>
<td>3.12</td>
<td>dB</td>
<td>3.12</td>
<td>dB</td>
<td>output power of whole system</td>
<td>40</td>
<td>dB</td>
<td>1.05E+02</td>
</tr>
<tr>
<td><strong>Wavelength</strong></td>
<td>8.82E-04</td>
<td>m</td>
<td>1</td>
<td>output power of whole system</td>
<td>40</td>
<td>dB</td>
<td>1.05E+02</td>
<td>W</td>
<td>output power of whole system</td>
<td>52.34</td>
<td>dB</td>
<td>1.71E+02</td>
</tr>
<tr>
<td><strong>Required SNR (measured as Eb/N0)</strong></td>
<td>9.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Transmitter**

- $A_{\text{effective}} = 6.35E-04$ meters$^2$
- $W_{\text{lens}} = 8.15E-07$ W

**Power levels for 64-QAM, approx**

- $3.75E+00$ W
- $2.57E+00$ W

**Power levels for 16-QAM, approx**

- $3.71E+00$ W
- $5.90E+00$ W

**Array rows and columns**

- $4$ rows
- $4$ columns

### 8-element linear array

- **baseline length**
- **4 x 4 subarray**

### MIMO array

- **propagation range**
340 GHz 5 Tb/s MIMO backhaul

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrier frequency</td>
<td>340 GHz</td>
</tr>
<tr>
<td>Required SNR (measured as Eb/No)</td>
<td>9.8 dB</td>
</tr>
<tr>
<td>Power levels for 64-QAM, approx.</td>
<td></td>
</tr>
<tr>
<td>Transmit power</td>
<td>20.2 dBm</td>
</tr>
<tr>
<td>Output power per element</td>
<td>10.1 dBm</td>
</tr>
<tr>
<td>Output power per sub-array</td>
<td>22.3 dBm</td>
</tr>
<tr>
<td>Output power of whole system</td>
<td>40.2 dBm</td>
</tr>
<tr>
<td>Power levels for 64-QAM, approx.</td>
<td></td>
</tr>
<tr>
<td>Transmit power</td>
<td>6.355 dBm</td>
</tr>
<tr>
<td>Output power of whole system</td>
<td>4.723 dBm</td>
</tr>
</tbody>
</table>

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

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

64-element square array

\[
\text{# channels} \propto \left( \frac{\text{aperture area}}{\text{wavelength} \cdot \text{distance}} \right)
\]

\[
D = (N-1)D
\]

\[
B = \frac{N^2}{\lambda R}
\]

\[
\alpha = 5\alpha \cdot b
\]

\[
\text{rain attenuation fits from Gleiss, Rogers, Hodge, IEEE Trans Ant and Prop, March 1976}
\]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rain rate, mm/hr</td>
<td>50</td>
</tr>
<tr>
<td>Path obstruction loss</td>
<td>0.00 dB</td>
</tr>
<tr>
<td>Atmospheric loss</td>
<td>14.37 dB</td>
</tr>
</tbody>
</table>

\[
D = 1.97 \text{ inch/hr}
\]

\[
\text{Gain of array} = 3.38 \times 10^6 \frac{\text{dB}}{\text{Gb}}
\]

\[
\text{Gain of element} = 1.51 \times 10^6 \frac{\text{dB}}{\text{Gb}}
\]