mm-wave “Wafer Scale” Phased Array ICs for High Data-Rate Links

Sanjay Raman, Professor of ECE and Assoc. Vice President, NCR
NEMO Future Networks Workshop 2018
Overview of MICS Group

5 core faculty, ~30 graduate students

Dong Ha (Director)
Analog/RF ICs, Energy Harvesting, High-Temp. Circuits

Paul Ampadu
Digital VLSI, Multicore/Networks-on-Chip

Luke Lester
Optoelectronics/OEICs, Semiconductor Lasers, Photovoltaics

Sanjay Raman
RF/mm-wave ICs, Antennas, Mixed-Signal, 3D, RF MEMS

Yang (Cindy) Yi
AI/ML, Neuromorphic Computing, 3D IC

Analog/Mixed-signal

Digital SoCs/NoCs

Optoelectronics

RF/mm-wave ICs

Neuromorphic Computing
MICS Lab Capabilities

- Full RF/analog/mixed-signal/microsystems CAD capability – AMS/digital VLSI/EM simulation, layout, verification, etc.
- Foundry fabrication in advanced CMOS, SiGe BiCMOS, GaAs FET/HBT, GaN HEMT, etc. – GF, Jazz, TI, TSMC, Win, etc.
- In-house device fabrication/packaging – MicrON labs
- Well-equipped RF/microwave/millimeter-wave, analog/mixed-signal measurement lab – 4-port network/spectrum analysis, high-power, signal generation, noise/phase-noise, time domain, on-wafer measurement capability to >67GHz
RF/mixed-signal ICs (Raman)

Tunable Microwave IC Filters

Analog Signal Processing

Transmit/Receive Components

Mm-wave 3D/Wafer Scale Arrays
Why mm-waves?
Why mm-waves?

- BW ↑
  - Datarate ↑
  - Range Resolution ↓
- Antenna Gain (for given aperture) ↑
  - EIRP ↑
  - Angular resolution ↓
- Sparser interference environment
- Propagation thru fog, smoke, dust, etc.
New FCC Rulemaking for 5G (July 2016)

- ~11 GHz of mm-wave spectrum made available → 3.85 GHz licensed, 7 GHz unlicensed
- Upper Microwave Flexible Use service:
  - 28 GHz (27.5-28.35)
  - 37 GHz (37-38.6)
  - 39 GHz (38.6-40)
- New unlicensed band:
  - 64-71 GHz
### Current/Emerging mmWave Applications

<table>
<thead>
<tr>
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<tbody>
<tr>
<td><strong>Ka (26.5-40)</strong></td>
<td></td>
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<td></td>
</tr>
<tr>
<td></td>
<td>28, 37, 39</td>
<td>Mobile communications for 5G Cellular networks (emerging)</td>
<td>Under development</td>
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<tr>
<td></td>
<td>27.5-30</td>
<td>SATCOM uplinks (e.g., Inmarsat Global Xpress: 27.5-30, Iridium: 29.1-29.3)</td>
<td>MIL-STD-188-164, ITU-R S.524-9, FCC 25.138, ETSI EN 303 978</td>
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<tr>
<td></td>
<td>24.25-30</td>
<td>L-3 ProVision imaging scanners at airports</td>
<td>IEEE C95.1</td>
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<tr>
<td></td>
<td>35</td>
<td>Munitions and missiles seekers and sensors</td>
<td>Unknown</td>
</tr>
<tr>
<td><strong>V (40-75)</strong></td>
<td>43.5-45.5</td>
<td>U.S. AEHF military SATCOM system uplinks*</td>
<td>MIL-STD-3015</td>
</tr>
<tr>
<td></td>
<td>57-66</td>
<td>“Last inch”, short range wireless communications</td>
<td>IEEE 802.11ad, IEEE 802.11aj, IEEE 802.15c</td>
</tr>
<tr>
<td></td>
<td>64-71</td>
<td>Mobile communications for 5G Cellular networks (emerging)</td>
<td>Under development</td>
</tr>
<tr>
<td><strong>E-band (75-110)</strong></td>
<td>71-75, 75-76, 81-86, 92-95</td>
<td>“Last mile”, point-to-point backhaul wireless communications</td>
<td>ETSI TS 102 524</td>
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<tr>
<td></td>
<td>76-77</td>
<td>Autonomous cruise control (ACC) “long range” automotive radar</td>
<td>ETSI EN 301 091 parts 1 &amp; 2</td>
</tr>
<tr>
<td></td>
<td>77-81</td>
<td>Short range “stop &amp; go” automotive radar</td>
<td>ETSI TR 102 263</td>
</tr>
<tr>
<td></td>
<td>94</td>
<td>Missile seekers, collision avoidance radars</td>
<td>Unknown</td>
</tr>
<tr>
<td></td>
<td>85-110</td>
<td>Imaging for medicine, biology, and security</td>
<td>IEEE C95.1</td>
</tr>
<tr>
<td><strong>W (75-110)</strong></td>
<td>110-120</td>
<td>Imaging for medicine, biology, and security</td>
<td>IEEE C95.1</td>
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<tr>
<td></td>
<td>220-240</td>
<td>Long range wireless communications, atmospheric research radar</td>
<td>None yet available</td>
</tr>
<tr>
<td></td>
<td>120, 183, 325</td>
<td>Short range wireless communications (emerging)</td>
<td>None yet available</td>
</tr>
</tbody>
</table>

* U.S. AEHF system downlink frequencies are located at 20.2 GHz – 21.2 GHz (IEEE K band).
Millimeter Wave Hotspots: Enabling the Path to 5G

The Technology Solution for 5G Small Cell Access and Backhaul

- Abundant Millimeter Wave Spectrum can provide fiber-like capacity
- Growth beyond what emerging Small Cell and Spectrum Sharing solutions can provide (100x – 1000x growth!)

Wireless Mesh Backhaul

mmW Phase Array Radio and Antenna

2016

MWC 2015

5G Access

Earliest Commercialization Timeline

Full mmH Architecture 2023

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• Recent renaissance of interest in deploying high-data-rate networks based on constellations of 1000’s of **LEO small satellites**, and/or other suborbital platforms (**UAVs, airships, etc.**) with modest investments in ground infrastructure.

• Provide **high-speed connectivity to those 60% of the world’s population** that lives in underserved regions of the world.

• Serve as a **critical backbone for 5G systems and the IoT.**

**Critical need for low-cost electronically steered arrays**
State-of-the-Art in mm-wave Phased Arrays

- Small silicon chip → fan out to antennas
- 2+ dB loss from chip to BGA (laminate interposer)
- 2+ dB loss from BGA to antennas (PCB)
- 4-5 dB one-way loss (8-10 dB system loss)

- SOLUTION: Wafer-scale!!!
- USE silicon as interposer
- Use silicon as PCB/antennas
- 1.5 dB loss
- Scalable to 2D easily
Wafer-Scale Phased-Array Concept

- Direct attachment of EM-coupled antenna layer
- Front-end loss does not scale with the number of elements
- First developed at UCSD with W-band 3x3 amplifier array on silicon
- High yield achieved on 64 elements. Acceptable yields on 256 elements.

Why Wafer-Scale?

• Wafer-scale approach eliminates all the transitions between the phased-array elements and the antennas (less loss at mm-wave frequencies). Antennas are integrated directly on top of the silicon substrate.

• Wafer-scale results in lower cost since there is no dicing, handling, and packaging cost. At mm-waves, the phased-array cost is dominated by packaging cost and not by the silicon (for low power T/R modules).

• Wafer-scale is highly scalable, from 1x1” to an entire 8” wafer.

• Today, microprocessors and FPGA chips have chip areas of 250-500 mm$^2$, hundreds of millions of gates, and 50-100 W power consumption. Phased arrays have 10,000x less transistor density and much less power consumption than complex digital chips in the same core area (500mm$^2$).

• Yield is high and wafer-scale imaging arrays (IR, Visible) have been done. Therefore, it is time to investigate this technology for mm-wave phased arrays.
TowerJazz SBCH3 Process

- 0.18 μm SiGe BiCMOS process
- SiGe HBT with 0.13μm emitter width
- $F_T/F_{MAX}$ of 240/270 GHz
- 6 metal layers
- Excellent SiGe BiCMOS technology for mm-wave transceivers/phased arrays
Sub-reticle Stitching Technique

- **Block A**: 4x4 radiating element (main block)
- **Blocks E1/E2/F1/F2/G/H**: Distribution elements for H-tree
- **Blocks B1/B2/C1/C2**: Pads and digital control
- **Blocks D1/D2/D3/D4**: Digital control and filling
Sub-reticle Stitching Technique

Array Size | 8x8 (22x22mm) | 16x16 (42x42mm)  
# of Blocks used | 8 of 10 | 10 of 10  
# of Lithography steps | 17 | 65

Scribe lines
Possible Array Configurations from Mask

- 4x4 Array
- 4x8 Array
- 8x16 Array
- 8x8 Array
- 16x16 Array
- 32x32 Array
8x8 and 16x16 Wafer-Scale Arrays

- 8x8 phased array: 21.4 mm x 22 mm
- 16x16 phased array: 41.4 mm x 42 mm
Detail of 8x8 (64-element) Array

- Branchline couplers and Wilkinson dividers are used as power dividers
- Redundant line amplifiers are used to compensate line ohmic loss and division loss
- Differential circuits are used for stability
Distribution loss for 8x8 Array

Distribution Statement
SPI Control

- Every 4x4 blocks has its own SPI
- Master/Slave with entire chip
Redundant Amplifier Design

- Two-way amplifier is designed what is decently matched in either mode (01/10/11)
- Both amplifiers are activated for high output power requirements! (+6 dBm)
Transmit Phased-Array Module

- 4-bit Phase Control, 10 dB (3-bit) VGA
- 20 dB Gain, 3 dBm PA
On-Wafer Differential Dipole Antenna

- Differential feed in top metal
- EM-coupled feed: No vias
Efficiency is 50% at 60.5 GHz
D = 6.3 dB, Gain = 3 dB at 60.5 GHz
BW = 3 GHz (G > 0 dB)
S11 BW = 5 GHz
Complete 64-Element (8x8) Phased Array

20 mm (8 x $\lambda_0/2$)

3.4 A at 2.5 V

Cost: $64/array ($1/element!)

# Chips | 45
---|---
Yield | >90%

8” Wafer

8” Wafer
Complete 256-Element Phased Array

40 mm (16 x \(\lambda_0/2\))

14 A at 2.5 V

Active radiating area
Complete 256-Element (16x16) Phased-Array

8” Wafer
9 Phased Arrays

Yield = 2-3/9 (we will improve yield in Phase II)

1740 mm², largest RF chip ever produced!
Pattern Measurement Set-up for 8x8 Array

- WR-15 antenna and detector receive the radiated signal
- Detected signal is measured using a lock-in amplifier
- Far-Field measurements

\[
R \approx \frac{2D^2}{\lambda} = 32 \text{ cm}
\]
Measured Patterns at Broadside (no calibration)

@61 GHz

H-Plane

E-Plane

16x16

H-Plane

E-Plane

8x8

H-Plane

E-Plane
Scanned Patterns: 64-Element (8x8) Array

- HPBW: 12°
- D: 23 dB
- EIRP: 37-38 dBm
- Side lobe levels < -13 dB
- Simple packaging (FR-4)!!
64-Element (8x8) EIRP Measurements

- $T = 95^\circ C$ operation
- Additional 1.5 dB antenna loss due to air gap

**Graph:**
- Measured vs. Simulated EIRP
- Frequency range: 56 to 68 GHz
- Peak EIRP: 41 dBm
- Additional Ant. Eff.: -1.5 dB
- Soft Comp.: -1.5 dB
- Measured Peak EIRP: ~38 dBm

**Dimensions:**
- $L_1 = 1.25$ mm
- $L_2 = 1.34$ mm
256-Element (16x16) Pattern Measurements

- HPBW: 6°
- D: 29 dB
- EIRP: 45 dBm
- Side lobe levels < -11 dB
- Simple packaging (FR-4)!!
256-Element (16x16) EIRP Measurements

- $T = 95^\circ$C operation
- Additional 1.5 dB antenna loss due to air gap

![Graph showing EIRP vs. Frequency](image)

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sim. Peak EIRP</td>
<td>50 dBm</td>
</tr>
<tr>
<td>Add. Ant. Eff.</td>
<td>-1.5 dB</td>
</tr>
<tr>
<td>Soft Comp.</td>
<td>-1.5 dB</td>
</tr>
<tr>
<td>Power variation due to Quartz</td>
<td>-2 dB</td>
</tr>
<tr>
<td>Meas. Peak EIRP</td>
<td>~45 dBm</td>
</tr>
</tbody>
</table>
Communication System Test

Link (distance): 4, 30, 100 meters

- 4 meters
  - 2-4 Gbps
  - +/-45° scan
  - EVM (9.5%)

- 30 meters
  - 1.5 Gbps
  - +/-45° scan
  - EVM (20%)

- 100 meters
  - 2-4 Gbps
  - +/-45° scan
  - EVM (9.5%)
More Measurements at 100 meters

Given below different modulation schemes @ 58.25 GHz

<table>
<thead>
<tr>
<th>Constellation</th>
<th>QPSK (1 GBps)</th>
<th>QPSK (1.5 GBps)</th>
<th>16-QAM (0.4 GBps)</th>
<th>16-QAM (1 GBps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulation</td>
<td>16.7 %</td>
<td>21.2 %</td>
<td>11.4 %</td>
<td>12.5 %</td>
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<tr>
<td>EVM</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Given below different channels for MCS6 (1.54 GBps)

<table>
<thead>
<tr>
<th>Constellation</th>
<th>Frequency</th>
<th>57 GHz</th>
<th>58 GHz</th>
<th>59 GHz</th>
<th>Broadsided</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>EVM</td>
<td>25 %</td>
<td>34.9 %</td>
<td>33.9 %</td>
<td>30.9 %</td>
</tr>
</tbody>
</table>

Given below different scanning angles for QPSK (1.5 GBps) @ 58.25 GHz

<table>
<thead>
<tr>
<th>Constellation</th>
<th>Scanning</th>
<th>Broadside</th>
<th>-45° (V)</th>
<th>+45° (V)</th>
<th>+45° (H)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>EVM</td>
<td>21.2 %</td>
<td>23.4 %</td>
<td>25 %</td>
<td>25 %</td>
</tr>
</tbody>
</table>
Takeaways...

- Advanced silicon technologies can be leveraged for large-scale mm-wave electronically-scanned phased-arrays with 100’s of elements, at low cost (in volume!), for high data-rate comms architectures.

- **Applications**
  - Mm-wave front-haul and back-haul
  - ESAs for LEO Sat constellations, airborne nodes, customer equipment...

- **Challenges include:**
  - Link budgets as frequencies scale up through E-band → smaller cells or larger arrays
  - Digital beamforming for multiple simultaneous beams, but need ADCs at each element/subarray → increased power consumption and complexity
  - Power efficiency/thermal management, particularly for user equipment
  - 5G mm-wave standards definitions needed