Bringing THz communication to the mass market: no longer an illusion?

Piet Wambacq, imec Fellow and professor at VUB, Brussels

with thanks to many imec colleagues
THz communication comes in the spotlight

But how close are we to products?
D-band integrated circuits coming to maturity

Transceiver functionality, efficient power amplifiers, ...

A 140GHz power amplifier with 20.5dBm output power and 20.8% PAE in 250-nm InP HBT technology


*Department of Electrical and Computer Engineering, University of California, Santa Barbara, USA

130nm BiCMOS

Imec, 140GHz BiCMOS PA, ESSCIRC 2019

34 dB gain, Psat of 17 dBm with 13% PAE

Nokia, European 5G Conference 2021

Can we make mass markets 6G systems with these circuits?

A Broadband Direct Conversion Transmitter/Receiver at D-band Using CMOS 22nm FDSOI

ECE Department, University of California Santa Barbara, CA 93106
afarid@ece.ucsb.edu, rodwell@ece.ucsb.edu

imec, 40GHz radar transceiver 28nm CMOS

1X4 MIMO module

16 GHz FMCW PLL

6.5mm² SISO TRx chip

public
Convergence of
- Communication
- Sensing
- Localization
Outline

- The application level
- The challenge level
  - Active circuits
  - Antennas and packaging
  - Getting rid of the heat
- Conclusions
New radio spectrum to meet the 6G capacity demands

Towards THz frequencies for TBPS wireless connectivity

- Large aggregated bandwidth available at higher frequencies
  - V-band: > 7GHz
  - E-band: >10GHz
  - W-band: >17GHz
  - D-band: > 30GHz
  - 802.15.3d: > 50GHz

- FCC opens up the higher frequencies
  - FCC TAKES STEPS TO OPEN SPECTRUM HORIZONS FOR NEW SERVICES AND TECHNOLOGIES
  
  WASHINGTON, March 15, 2019—The Federal Communications Commission adopted new rules to encourage the development of new communications technologies and expedite the deployment of new services in the spectrum above 95 GHz. This spectrum has long been considered the outermost horizon of the usable spectrum range, but rapid advancements in

- WRC-19 extends mobile spectrum, aggregated bandwidth of 137GHz available from 275GHz–450GHz
Beyond 5G and 6G: extreme capacity communication applications
Towards >100GHz frequencies for >100Gbps wireless connectivity

- **Wireless connectors & meshes**
  - Short range ad-hoc point-to-point for D2D, kiosk, automotive

- **Mobile hotspot, Multi-User Mixed Reality**
  - Fixed Point-to-Mobile multipoint for next-gen mobile indoor & outdoor

- **Fixed wireless Access**
  - Fixed point-to-multipoint links as fiber substitute

- **Wireless Backhaul/Fronthaul**
  - Fixed point-to-point links for cellular networks

- **50Gb/s | <5m**
- **>10Gb/s per user | 10-100m**
- **>20Gb/s per user | 100m**
- **>500Gb/s | >100m**
Sensing and communication: not so far apart

Fig. 1 — Schematic diagram of a general communication system.

In sensing the channel is the message

Fig. 1 — Schematic diagram of a general sensing system.

Sensing while communicating (or vice-versa)

Potential items of interest for a 6G system

- Range
  - RSS
  - ToF
  - Phase difference
- Angle
  - Arrival/Departure
  - Azimuth/Elevation
- Location
- Speed / velocity
  - Doppler
- Users vs. Nonusers
- User density
- Orientation
- Pose
- Body blocking
- Context
- ...
WiFi-based passive bistatic radars
Opportunistic use of known preambles

Need for clutter removal, extensive to 160MHz
6G PHY design
Taking into account sensing requirements from the start

- Non Uniform Multiband OFDM THz
  - Combine distance and sensing accuracy, using multiple OFDM waveforms
  - Non-uniform subcarrier spacing parameters
    - long detectable distance from the small subcarrier spacing
    - high sensing accuracy from the large subcarrier spacing.
  - 100 Gbps and sub-mm ranging

- SI-DFT-s-OFDM
  - Sensing integrated joint design allows for mm scale ranging and x10 better velocity accuracy.
  - Delay spread of sensing channel >> communication channel due to beamforming: different CPs are needed

Yongzhi Wu, Filip Lemic, Chong Han, Zhi Chen, "A Non-Uniform Multi-Wideband OFDM System for Terahertz Joint Communication and Sensing", submitted for publication, 2020

Beamforming used to overcome large path loss

**low-gain antenna**
- lots of wasted energy
- captured energy

**directional antenna array**
- much less wasted energy
- captured energy

**Beamforming circuitry:**
- Phase shift $\Delta \phi$
- Combiner $+\quad$ splitter in transmit

**Optimum antenna pitch:**
- half wavelength $\lambda/2$
Beamforming is here to stay
To overcome free space path loss and atmospheric attenuation

- TX side with $N_{TX}$ antennas:

$$E_{IRP} = P_{1TX} + 20 \log_{10} N_{TX} + G_{antenna}$$

- RX side with $N_{RX}$ antennas:

$$\text{Sensitivity} = -174 \text{dBm/Hz} + NF + \text{loss margin} + 10 \log_{10} \text{BW} + \text{SNR}_{min} - 10 \log_{10} N_{RX}$$

- For $N_{TX} = N_{RX} = N$: link budget improves with $30 \log_{10} N$

... and antenna area for a given gain $\sim \lambda^2$
Larger the antenna array $\rightarrow$ less power per power amplifier needed

![Graph showing TX power needed vs. number of antennas](image)

- **EIRP=60dBm (base station)**
- **40dBm EIRP (user)**

<table>
<thead>
<tr>
<th>#antennas</th>
<th>Array Size (λ/2 pitch at 140GHz) [mm x mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^1$</td>
<td>3.5x3.5</td>
</tr>
<tr>
<td>$10^2$</td>
<td>11x11</td>
</tr>
<tr>
<td>$10^3$</td>
<td>35x35</td>
</tr>
</tbody>
</table>
THz hardware: pressure on COST, power consumption and size

- Photonics ruled out (for the time being)
- High degree of integration needed → CMOS, as usual?
  “if it can be done in CMOS, it will be in CMOS”
Beamforming radio architecture for >100GHz connectivity
Challenges from the antenna down to baseband

Transmitter (TX)
- Upconversion
- PLL
- CMOS Power & efficiency
- Small

Receiver (RX)
- Down conversion
- Complex high-speed DSP
- ADC
- DSP
- Sample rate of tens of GHz

Beamforming control & calibration
- PLL: phase-locked loop
- LNA: low-noise amplifier
- PA: power amplifier
- ADC: analog-to-digital converter
- DSP: digital signal processing

Package, interconnect, passives
The BIG challenge: power generation above 100 GHz

InP PAs: higher power + higher efficiency

InP offers power advantages for medium to long ranges

Example: 140 GHz transmission of user equipment (UE) to hotspot

16 antenna array: 15dBm_{RMS} per antenna  
Area: 0.43 x 0.43cm^2

64 antenna array: 3dBm_{RMS} per antenna  
Area: 0.86 x 0.86cm^2
INP ADVANTAGE REMAINS WHEN BASEBAND IS INCLUDED

- Scenario of transmission from **UE to hotspot, 32 antennas** in UE (9dB_{rms})
- Power estimates with digital downscaled to 2nm
  - assuming power reduction of 35% per new logic generation
- Total power consumption heavily PA-dominated

![Power Consumption Diagram](image)

**Link (Tx+Rx) efficiency:** factor 2.5 difference between full CMOS and CMOS + InP

*Grows with frequency, distance and smaller form factor.*
GaN: a game changer above 100 GHz?
Mobility similar to Si but much wider bandgap...

4-stage PA, 107-148 GHz
100nm GaN on SiC,
$f_T/f_{MAX} = 100/300$ GHz
$VDD = 15V$, Gain $> 25$ dB
$P_{out} = 26.4$ dBm, $PAE_{max} = 16.5$

Cwiklinski et al., T-MTT 2019
Is InP ready for the mass market?

Today it is a niche process...
Can we combine CMOS high integration degree with III-V assets?

Bonding III-V wafer on Si wafer

different wafer sizes!

W. Heinrich et. al., Connecting Chips With More Than 100 GHz Bandwidth, IEEE Journal of Microwaves 2021

M. Urteaga et. al., THz Bandwidth InP HBT Technologies and Heterogeneous Integration with Si CMOS, IEEE BCTM 2016
Can we grow III-V on a 300 mm Si wafer?

Lattice mismatch → dislocations → disfunctional devices

InP lattice

Si lattice
GaN and InP on 300 mm Si wafer

Fig. 8: Loadpull results show industry’s best (a) peak PAE=65% with saturated power of 19.5dBm at 28GHz, (b) 20.7dBm of saturated power with peak PAE=55%.

Then et al., IEDM 2020

RF GaN on 200/300 mm wafers, processed with Si tools, Au free

U. Peralagu et al., IEDM 2019

InP on 300mm Si wafers

imec, 2018
Above 100 GHz: antenna pitch < front-end circuit pitch

- Area of antenna array scales with $\lambda^2$
- Area of mm-wave chip hardly scales

- Solution: exploit the third dimension
# 2D IC TECHNOLOGY VERSUS 3D: DIFFERENCE IN FOOTPRINT

<table>
<thead>
<tr>
<th></th>
<th>2D footprint</th>
<th>3D footprint</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>2D</strong></td>
<td>memory/control</td>
<td>beamformer</td>
</tr>
<tr>
<td><strong>3D</strong></td>
<td>PA</td>
<td>LNA</td>
</tr>
</tbody>
</table>

### Example:

**InP on 300mm**

- **Wafer-level 3D stacking**
### Connection to the antennas

**Example: CMOS + Antenna array**

- **Wafer to Wafer bonding**
  - CMOS: Circuits + Antenna feed
  - Quartz superstrate antenna substrate

- **Active circuits highly constrained by antenna feed**
  - Reduced amplifier stages

---

**Example Image**

- **Silicon wafer**
- **Antenna layer (Quartz dielectric)**
- **Phased array unit element with on-chip antenna feed**
- **Heat sink**

---

**Reference**


**UC San Diego**
Packaging design with heat sinks

**HRL LABORATORIES, USA**

- **Metal Embedded Chip Assembly (MECA)**
- Embedding different chips in a copper carrier
  - Wirebond interconnects between different chips
  - Bandwidth issues: wirebonds

J. A. Estrada et al., *Metal-Embedded Chip Assembly Processing for Enhanced RF Circuit Performance*, IEEE TMTT 2019

**Ferdinand Braun Institute, Berlin**

- Thin-film Amorphous diamond heat sink layer connected to HBT device using vias
  - Best thermal material
  - Cost may be high
  - Power amplifier at 90 GHz
    - Pout: 20 dBm, PAE: 22%

Conclusions

- The lower part of the THz gap can be filled with a full electronic approach
  - IC technologies provide a cheaper path to products than optical approaches

- 6G convergence of communication and sensing
  - Sensing with communication hardware is feasible

- Low-cost D-band transceivers for user equipment: CMOS + III-V most energy efficient
  - Cost effective processing technologies being explored

- Packaging strategy challenged by half-wavelength antenna pitch and by heat removal strategy

- Non-addressed challenges: testability, EDA tools for co-design of electrical, thermal, package, IC, antenna