Millimeter-Wave and Terahertz CMOS Design

Minoru Fujishima
What is mmW & THz?

- **Definition of millimeter wave (mmW)**
  - 30GHz ~ 300GHz (wave length: 1mm ~ 10mm)

- **Definition of Terahertz (THz)**
  - 100GHz ~ 10THz (wave length: 30μm ~ 3mm)
  - sometimes 300GHz ~ 3THz (=submmW)

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### Wave Length

- γ ray
- X ray
- Ultraviolet
- Ultrared
- Sub mmW
- Micro wave
- UHF
- HF
- MF
- LF

### Frequency

- 300THz
- 300GHz
- 300MHz
- 300kHz

### THz wave: Intermediate of radio wave and light
MOSFET Performance in THz Region

ITRS 2010
f_{max} = 450GHz (2013)
= 990GHz (2020)

MSG / MAG estimation

Matching Network
Loss=1dB

Matching Network
Loss=1dB

Estimated Gain of Amplifier
Gain= 5dB @ 100GHz (65nm)
= 5dB @ 180GHz (2013)
= 5dB @ 400GHz (2020)
Wireless Communication Trend

After T. Nagatsuma (Osaka Univ), Doc.: IEEE 802.15-10-0149-01-0thz
Strategies for Ultrahigh-Speed Wireless Communication

High-speed communication is realized with limited bandwidth in microwave.

Power consumption

- High Power
- High Speed

Tradeoff between power consumption and frequency band

- MIMO-OFDM
  Multiple Input Multiple Output
  Orthogonal Frequency Division Multiplexing

- OFDM
  Orthogonal Frequency Division Multiplexing

- QAM
  Quadrature Amplitude Modulation

- QPSK
  Quadrature Phase-Shift Keying

- BPSK
  Binary Phase-Shift Keying

- ASK
  Amplitude-Shift Keying

Frequency band

- Narrow
- Wide

Power can be reduced utilizing wide frequency band

Green

High Speed
Contents

• mmW / THz CMOS Design

• 60GHz HDMI Transceiver

• 120 / 140GHz Dual Channel Receiver
Chip Development Process

Design → Modeling → Device → Circuit → System → Measurement
Three Development Tasks

Design

Device

Modeling

Circuit

Measurement

System
Three Development Layers

- Measurement
- Device
- Circuit
- System

Design
Modeling
Measurement

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SoC Design
Analog/RF Design

Diagram showing a cycle with labels: Design, Modeling, Device, Circuit, System, Measurement, with "outsource" at the center.
Millimeter-Wave Design

Design → Modeling → Device → Circuit → System → Measurement
Millimeter-Wave Design

Design → Modeling → Device → Circuit → System → Measurement

FINISH
mmW Layout Issue

- Design without transmission line for analog/RF

- Design with transmission line for millimeter wave

Modeled transmission line is used for interconnect.
Bond-Based Design

- Use Device Tiles
  - MOSFET
  - Transmission Line
  - Pad
  - etc.

- Interface for tiles
  - Transmission Line

- No Parasitic Wire Connect
- No LPE is required

Device model including transmission line interface is necessary.
mmW Decoupling Issue

Decoupling capacitors have own parasitic impedance. Large C does not always work as a decoupling in millimeter wave.

Dedicated decoupling device for millimeter wave is required.
Millimeter-Wave Decoupling

- A transmission line with ultralow characteristic impedance (0Ω TL) shields the ground impedance.

Single-ended amplifier with zero-ohm TL

Parasitic ground impedance

Ground-impedance shield with zero-ohm TL

Z_{in}=0
Impedance of Short Stub

\[ Z_{\text{in}} = Z_0 \frac{(Z_{\text{gnd}} + Z_0) + (Z_{\text{gnd}} - Z_0)e^{-2\gamma l}}{(Z_{\text{gnd}} + Z_0) - (Z_{\text{gnd}} - Z_0)e^{-2\gamma l}} \]

\[ \rightarrow 0 \text{ if } Z_0 \rightarrow 0 \text{ (0}\Omega\text{TL)} \]
Characteristic impedance of 0ΩTL

**Measured results**

Characteristic impedance [Ω] vs. Frequency [GHz]

- Frequency range: 0 to 120 GHz
- Characteristic impedance range: 0 to 2 Ω

The graph shows the measured results for characteristic impedance as a function of frequency.
Millimeter-Wave Design
Transmission Line Evaluation

THRU (0µm)  TL4 (80µm)  TL6 (120µm)

TL8 (160µm)  TL9 (180µm)
Measurement Issues

The S21 should be…

THRU > TL4 > TL6 > TL8 > TL9

However, in this case…

TL6 > TL4 > TL9 > TL8 > THRU

After de-embedding…

S21 become positive !!
Caused by irreproducible probing!

Probe positions were irreproducible.

Length & contact resistance are fluctuating.
Accurate Probing

By utilizing scotch tape marker…
Measured Results

The S21 is expected order
THRU > TL4 > TL6 > TL8 > TL9

After de-embedding...

S21 become normal
Millimeter-Wave Design

Design → Modeling → Device → Circuit → System → Measurement
Admittance Comparison

\[ \text{Im} \{ y_{11} \} \text{ [mS]} \]

- 100GHz
- 60GHz
- 20GHz

\[ \text{Im} \{ y_{21} \} \text{ [mS]} \]

- Measurement

\[ \text{Im} \{ y_{12} \} \text{ [mS]} \]

- 100GHz
- 60GHz
- 20GHz

\[ \text{Im} \{ y_{22} \} \text{ [mS]} \]

- Measurement

\( V_{gs} \text{ [V]} \)

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Verification using Amplifier

65nm-CMOS Technology

Simplified Circuit Diagram
Measured and Simulated Results

- **S-parameter [dB]**
  - **S11**
  - **S12**
  - **S21**
  - **S22**

**Bias and VDD Values**
- **Bias = 0.0V, VDD = 1.1V**
- **Bias = 0.6V, VDD = 1.1V**
- **Bias = 0.8V, VDD = 1.1V**
- **Bias = 1.1V, VDD = 1.1V**

**Graphs**
- **Frequency [GHz]**: 20, 60, 100
- **S-parameter [dB]**: -40, -30, -20, -10, 0, 10, 20
Millimeter-Wave Design

Design → Device → Circuit → System → Measurement → Modeling
Wideband 140GHz CMOS Amp.

L/W of MOSFET = 65nm / 22.6μm
Transmission line unit : m

Input

Output
Wideband LNA

Center frequencies in matching networks are distributed to flatten frequency responses of power gain and group delay.

Six-stage amplifier

Gain

Wide (Total) n-stages

Group Delay

Low group delay variation (Total) n-stages

 freq.

1 stage

2 stages

3 stages
Measurement Results

<table>
<thead>
<tr>
<th>Freq. [GHz]</th>
<th>0.1dB-BW [GHz]</th>
<th>3dB-BW [GHz]</th>
<th>Peak Gain [dB]</th>
<th>GD @3dB-BW [ps]</th>
<th>P_{DC} [mW]</th>
<th>Technology [nm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>136.1</td>
<td>12</td>
<td>27.6</td>
<td>9.9</td>
<td>46.2 ± 13.1</td>
<td>57.1</td>
<td>65</td>
</tr>
</tbody>
</table>

Specification Summary

Frequency Characteristics

- Frequency: 136.1 GHz
- Gain: 9.9 dB
- Group Delay: 46.2 ± 13.1 ps
- Power DC: 57.1 mW
- Technology: 65 nm
Millimeter-Wave Design

Diagram:
- Design
- Modeling
- Device
- Circuit
- System
- Measurement

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Promising Application: Indoor PAN

THz will be exciting if and when …

1. Bit rates unmatched by any other wireless technologies are offered.
   • Historically, wireless technology that offers more throughput (even at short ranges) is interested.
2. Costs are comparable to existing technologies
   • The market wants more for the same cost. Going 10x faster captures the market, but charging 10x more is not allowed.
3. Power/bit is less than existing technology
   • Going 10x faster is done with the same battery used by the same technology.

Rick Roberts (Intel), 802.15 THz IG

Distance: LOS ~1 meter
Bit Rates: 20 to 50+ Gbps
Cost: comparable to Bluetooth
Power consumption: comparable to Bluetooth

So what might make a winning solution?
Contents

• mmW / THz CMOS Design

• 60GHz HDMI Transceiver

• 120 / 140GHz Dual Channel Receiver
Wideband 60GHz Regulations

License free
BW=7GHz
$P_{\text{out}} = +10\text{dBm}$

- Japan (59~66)
- North America (57.05~64)
- Korea (57~64)
- Europe (57~66)
Target Application: Mobile Streaming

TX Power consumption should be reduced for mobile streaming applications.
mmWave Simplex Communication

Simplex Communication

- TX mmw repeater
- RX mmw repeater
- High-speed streaming

Millimeter-wave band

Duplex Communication

- ISM transceiver
- Low-speed control signal
- ISM transceiver

Low-frequency ISM band
Repeater for Low Power

Tx “Repeater”

Input waveform
Digital data transferred from baseband to mmWave.

Rx “Repeater”

Input waveform
Digital data transferred from mmWave to baseband.

Simple architecture Realizes lower power.
Low-Power 3CH TX and RX Repeaters

ON/OFF

TX

CH1

FLL

VCO1

ASK mod

f1

CH2

FLL

VCO1

ASK mod

f2

CH3

FLL

VCO1

ASK mod

f3

CMOS

RX

CH1

MIX

LNA

VCO2

VGA Demod

f1

CH2

MIX

LNA

VCO2

VGA Demod

f2

CH3

MIX

LNA

VCO2

VGA Demod

f3

CMOS
Chip and Module Photographs

- **CMOS chip**
- **Patch antenna**
- **Substrate**

Bias, control, and digital data.

3 Channel 60GHz Module

Transmission line

4cm

7cm

2.7mm

2.3mm

CH1 CH2 CH3

5mm

RX Chip

TX Chip

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<table>
<thead>
<tr>
<th>System Spec.</th>
<th>Technology</th>
<th>Data Rate</th>
<th>TX RF Power [dBm]</th>
<th>RX Sensitivity or Noise Figure</th>
<th>Power Consumption (TX / RX) [mW]</th>
<th>Core area TX, RX [mm(^2)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>This Work</td>
<td>90nm CMOS</td>
<td>1Gbps</td>
<td>5</td>
<td>-52dBm</td>
<td>51 / 116</td>
<td>0.85, 1.92</td>
</tr>
<tr>
<td>2011/11/21</td>
<td>90nm CMOS</td>
<td>51Gbps</td>
<td></td>
<td></td>
<td>162 / 292</td>
<td>43</td>
</tr>
</tbody>
</table>

This Work: Present work takes a different approach to wireless communication measurement.
Contents

• mmW / THz CMOS Design

• 60GHz HDMI Transceiver

• 120 / 140GHz Dual Channel Receiver
Worldwide Radio Wave Allocation

Region 1

Region 2

Region 3

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Wireless communication may be available when the forbidden bands are avoided.
Forbidden bands exclusively used by “Radio Astronomy”, “Earth Exploration Satellite”, “Space Research” are same as those in region 1.

Forbidden bands exclusively used by “Radio Astronomy”, “Earth Exploration Satellite”, “Space Research” are different from those in region 1.
## Channelization Plan for THz

<table>
<thead>
<tr>
<th>Channel Number</th>
<th>Low Freq. (GHz)</th>
<th>Center Freq. (GHz)</th>
<th>High Freq. (GHz)</th>
<th>3dB BW (GHz)</th>
<th>Roll-Off Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>116.589</td>
<td>124.089</td>
<td>131.589</td>
<td>12</td>
<td>0.25</td>
</tr>
<tr>
<td>2</td>
<td>132.100</td>
<td>139.600</td>
<td>147.100</td>
<td>12</td>
<td>0.25</td>
</tr>
<tr>
<td>3</td>
<td>147.611</td>
<td>155.111</td>
<td>162.611</td>
<td>12</td>
<td>0.25</td>
</tr>
<tr>
<td>4</td>
<td>167.000</td>
<td>174.500</td>
<td>182.000</td>
<td>12</td>
<td>0.25</td>
</tr>
</tbody>
</table>

When channels are allocated in D and G bands, three channels are available in worldwide as in 60GHz bands (IEEE 802.15.3c).

cf: 60GHz-band 2GHz/ch  
D-band+ 15GHz/ch
Dual-Channel ASK Receiver

Input: ASK Signal (120GHz)

1 1 0 1 0

2f_{data}

120GHz

Data Rate: f_{data} [bps]

Input: ASK Signal (140GHz)

1 0 0 1 0

2f_{data}

140GHz

Output: Digital Signal

Channel Selection is required for receivers.
Channel Selection using LNA

Wideband and high-gain properties are required in desired channel.

Low-gain property is required for channel selection in undesired channel.

120-GHz LNA
5 stage cascaded amplifier

140-GHz LNA
6 stage cascaded amplifier

Cascode amplifier: Stability
Common-source amplifier: High gain
Matching frequencies are different: Wideband Gain Flatness

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Chip micrograph

65nm CMOS Technology
Supply Voltage: 1.2V
Power Consumption: 85.7mW (120GHz-RX)
111.7 mW (140GHz-RX)
Gain bandwidth of 140-GHz LNA is too wide. Channel selection is degraded.
Wireless Measurement

Pout@TX-ANT:
-7.8 dBm (120GHz)
-7.2 dBm (140 GHz)
1Gbps $2^7$-1 PRBS
### Benchmark Result

<table>
<thead>
<tr>
<th>Technology</th>
<th>Frequency [GHz]</th>
<th># of Channel</th>
<th>Power Consumption [mW]</th>
<th>BER</th>
<th>Maximum Data Rate [Gbps]</th>
<th>Communication Distance [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>[2] InP-HEMT</td>
<td>120</td>
<td>Single</td>
<td>750</td>
<td>1.00E-12</td>
<td>10</td>
<td>200</td>
</tr>
<tr>
<td>[3] SiGe BiCMOS</td>
<td>140</td>
<td>Single</td>
<td>1500 (*)</td>
<td>N/A</td>
<td>N/A</td>
<td>1.15</td>
</tr>
<tr>
<td>[4] 65nm CMOS</td>
<td>140</td>
<td>Single</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>[5] SiGe BiCMOS</td>
<td>160</td>
<td>Single</td>
<td>1473</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>[6] 65nm CMOS</td>
<td>120</td>
<td>Single</td>
<td>80.9 (**)</td>
<td>1.00E-09</td>
<td>9</td>
<td>N/A</td>
</tr>
<tr>
<td>This work</td>
<td>65nm CMOS</td>
<td>Dual</td>
<td>85.7 (120GHz)&lt;br&gt;111.7 (140GHz)</td>
<td>1.00E-11</td>
<td>3.0 (120GHz)&lt;br&gt;3.6 (140GHz)</td>
<td>0.3 (120GHz)&lt;br&gt;0.4 (140GHz)</td>
</tr>
</tbody>
</table>

(*) Power consumption of transmitter is included  
(**) Low-noise amplifier is not included

**Required energy per bit**: 29pJ/bit (120GHz-RX), 31pJ/bit (140GHz-RX)
Promising Application: Indoor PAN

Winning Solution

Distance: LOS ~1 meter **OK**
Bit Rates: Towards **10Gbps**
Cost: will become Bluetooth
Power consumption: will become Bluetooth

**CMOS possibility for THz is infinite.**
Acknowledgements

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