Millimeter-Wave and Terahertz CMOS Design

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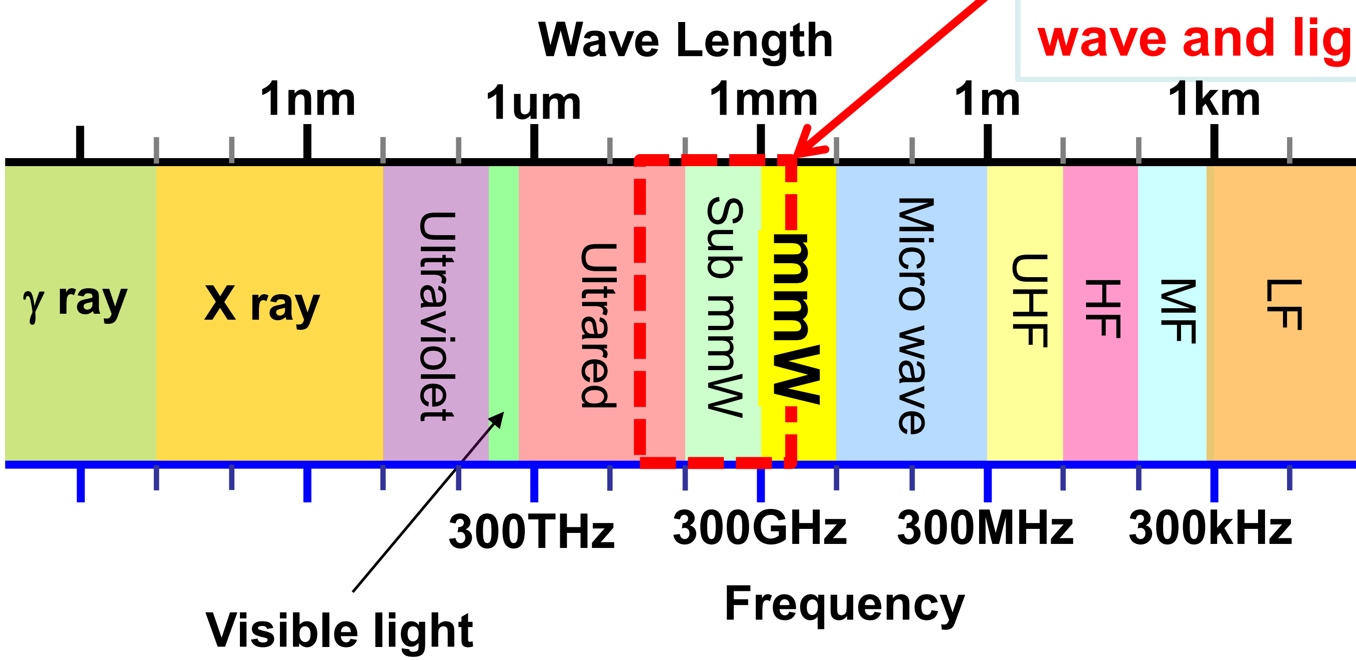
What is mmW & THz?

- 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)

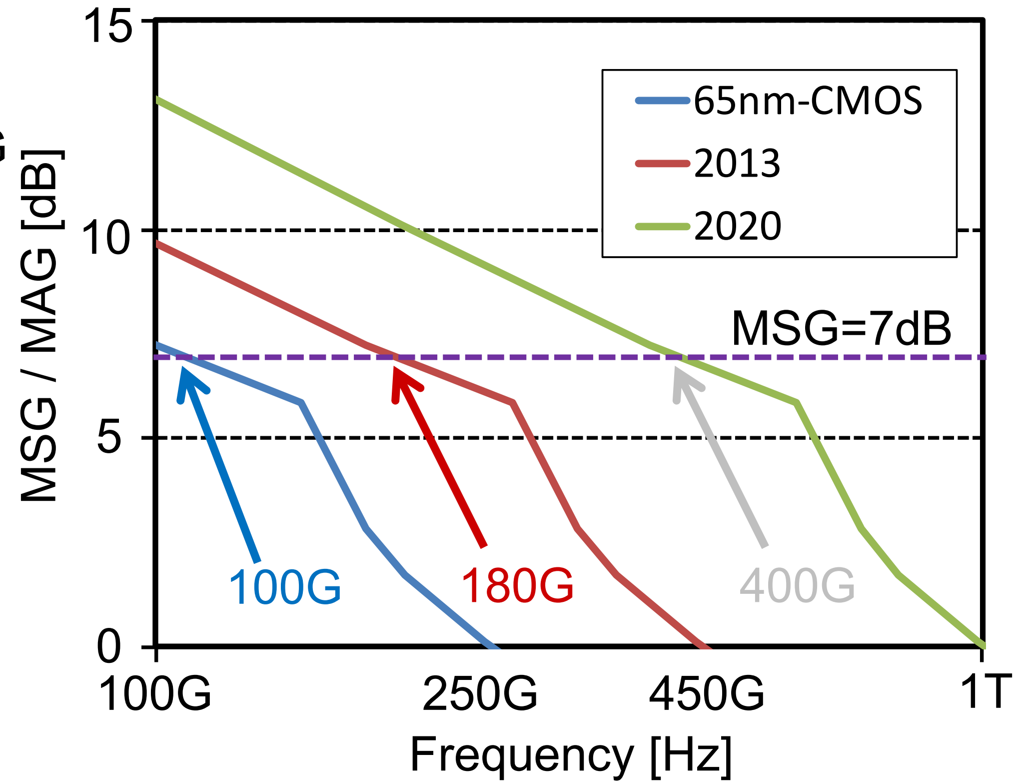
THz wave: Intermediate of radio wave and light

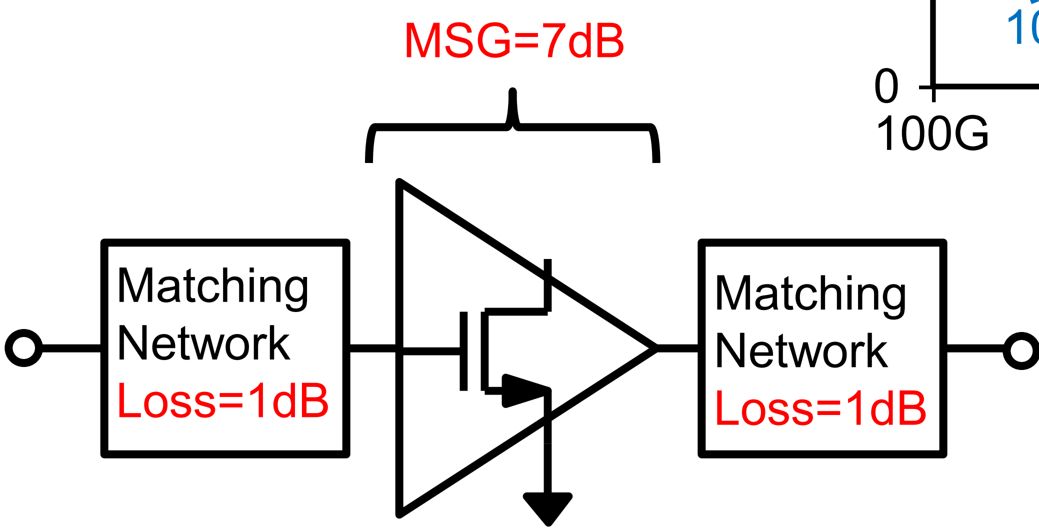


MOSFET Performance in THz Region

ITRS 2010
fmax= 450GHz (2013)
= 990GHz (2020)

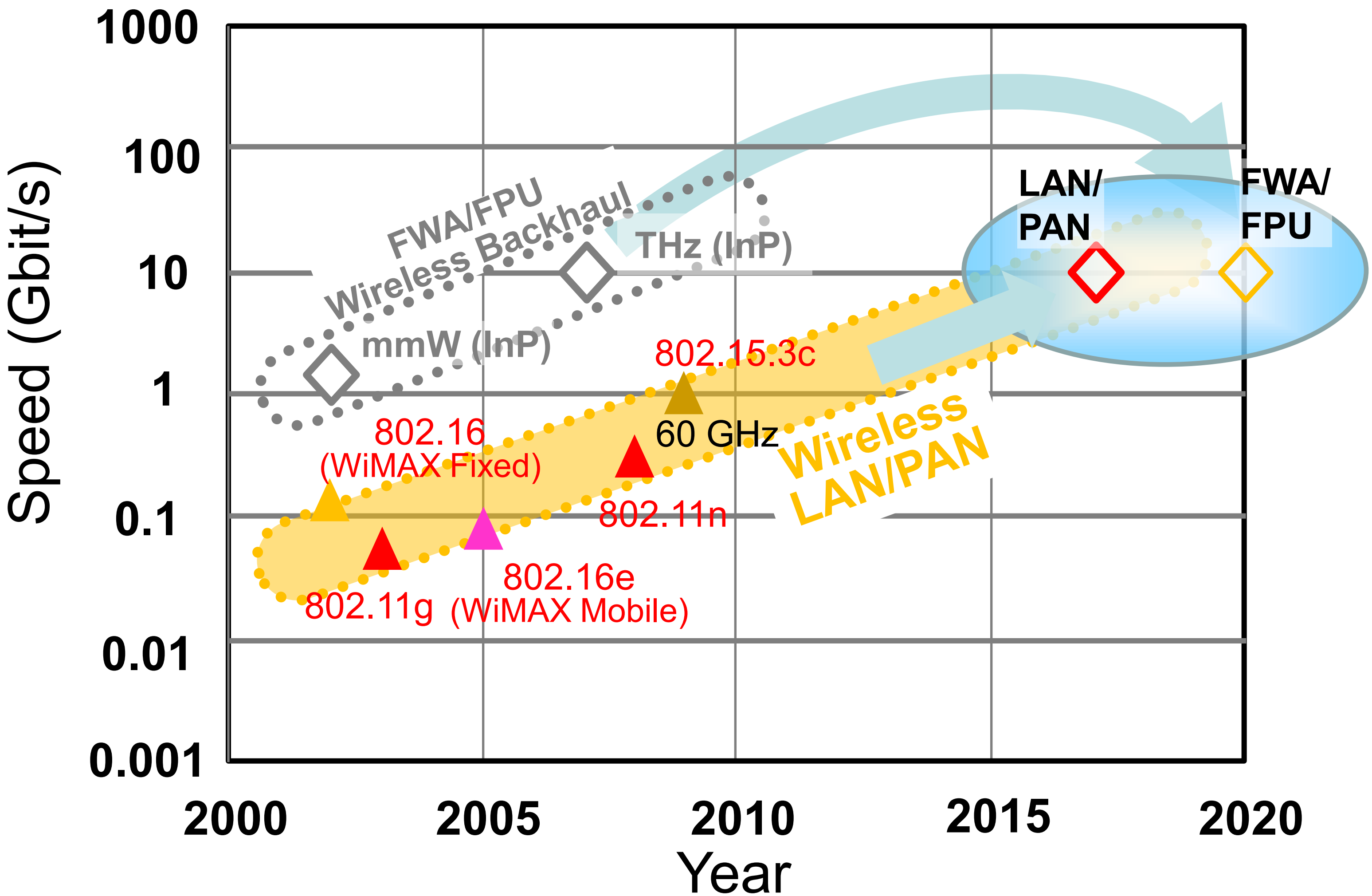
MSG / MAG estimation





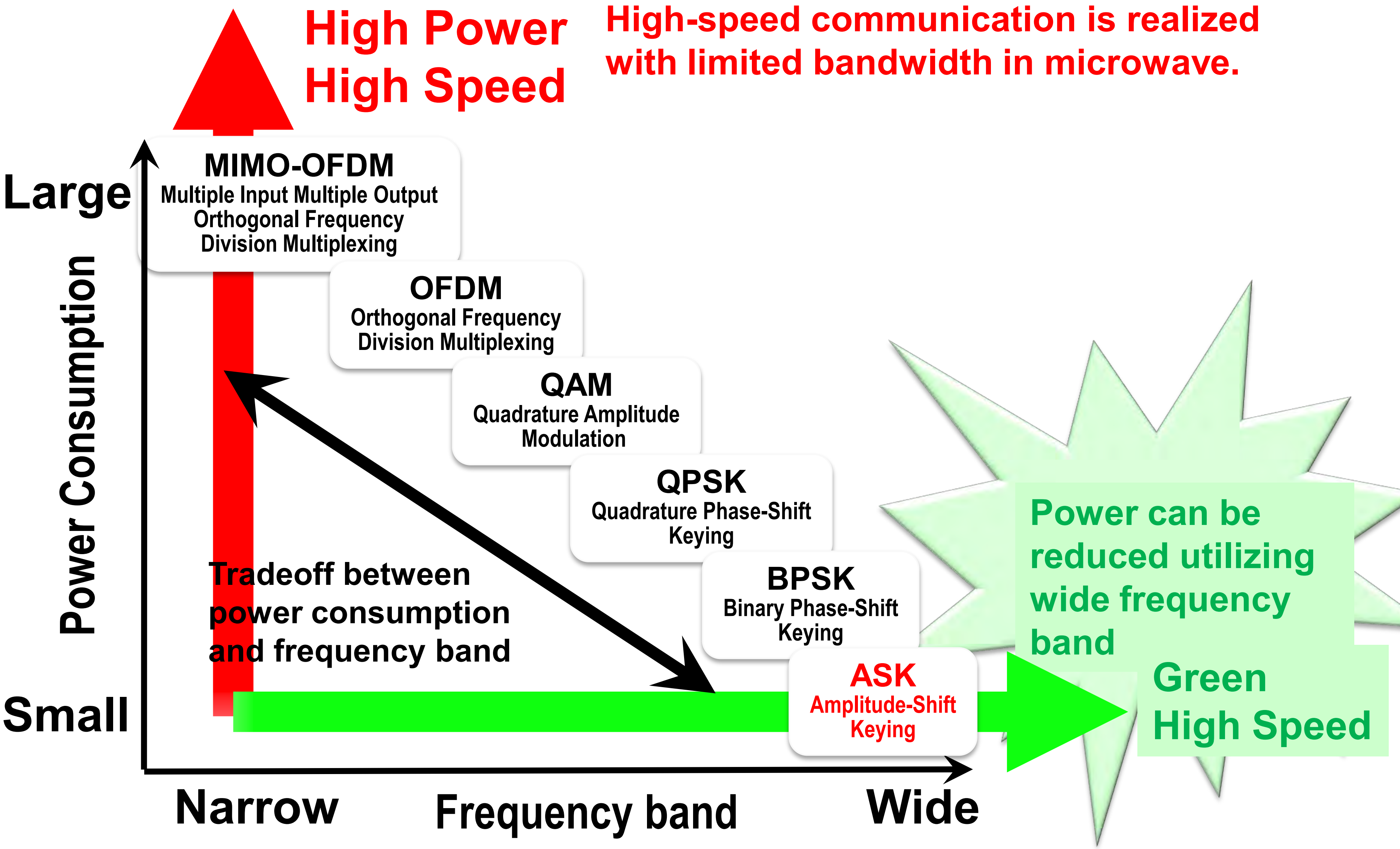
Estimated Gain of Amplifier
Gain= 5dB @ **100GHz (65nm)**
= 5dB @ **180GHz (2013)**
= 5dB @ **400GHz (2020)**

Wireless Communication Trend



After T. Nagatsuma (Osaka Univ), Doc.: IEEE 802.15-10-0149-01-0thz

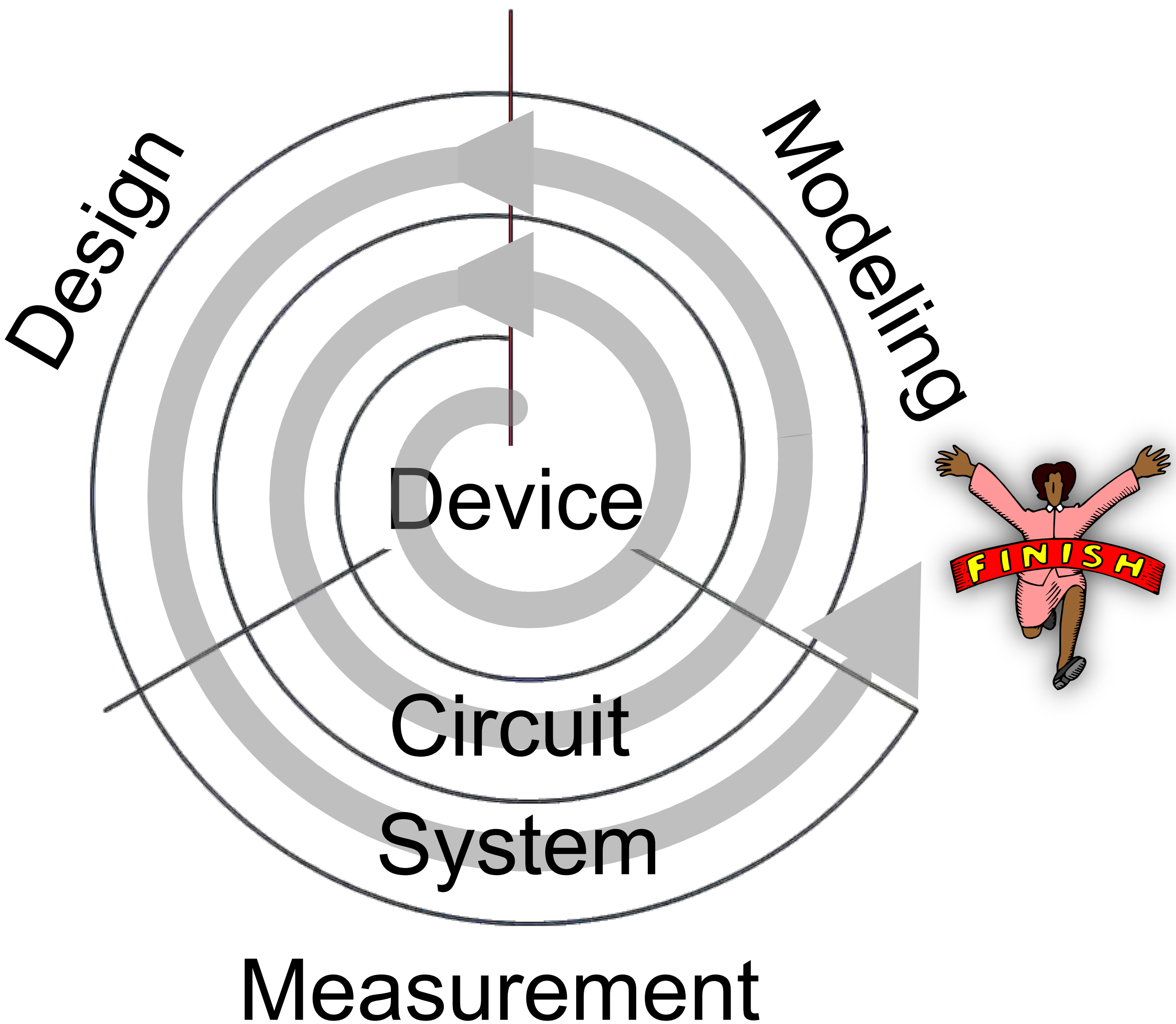
Strategies for Ultrahigh-Speed Wireless Communication



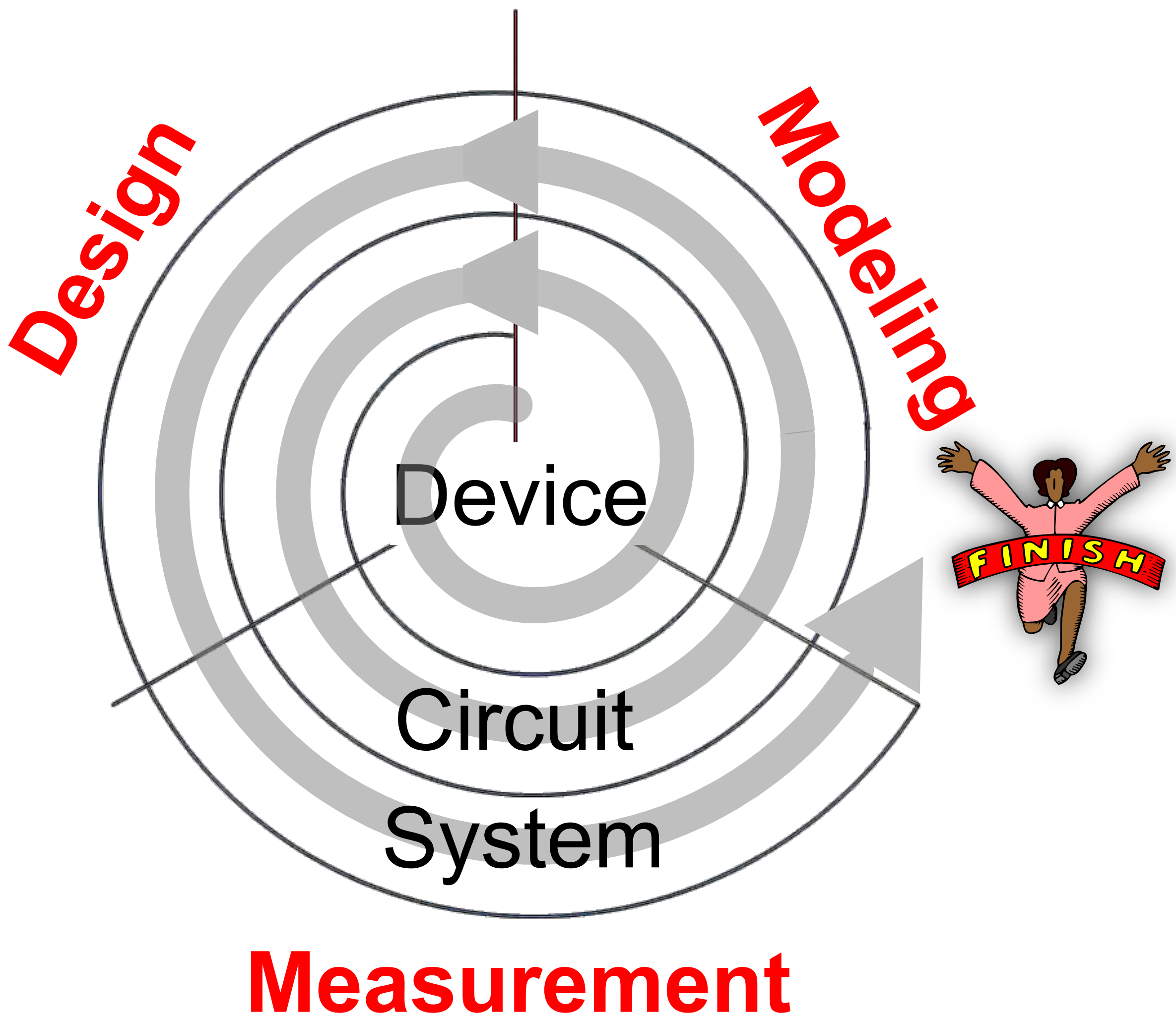
Contents

- mmW / THz CMOS Design
- 60GHz HDMI Transceiver
- 120 / 140GHz Dual Channel Receiver

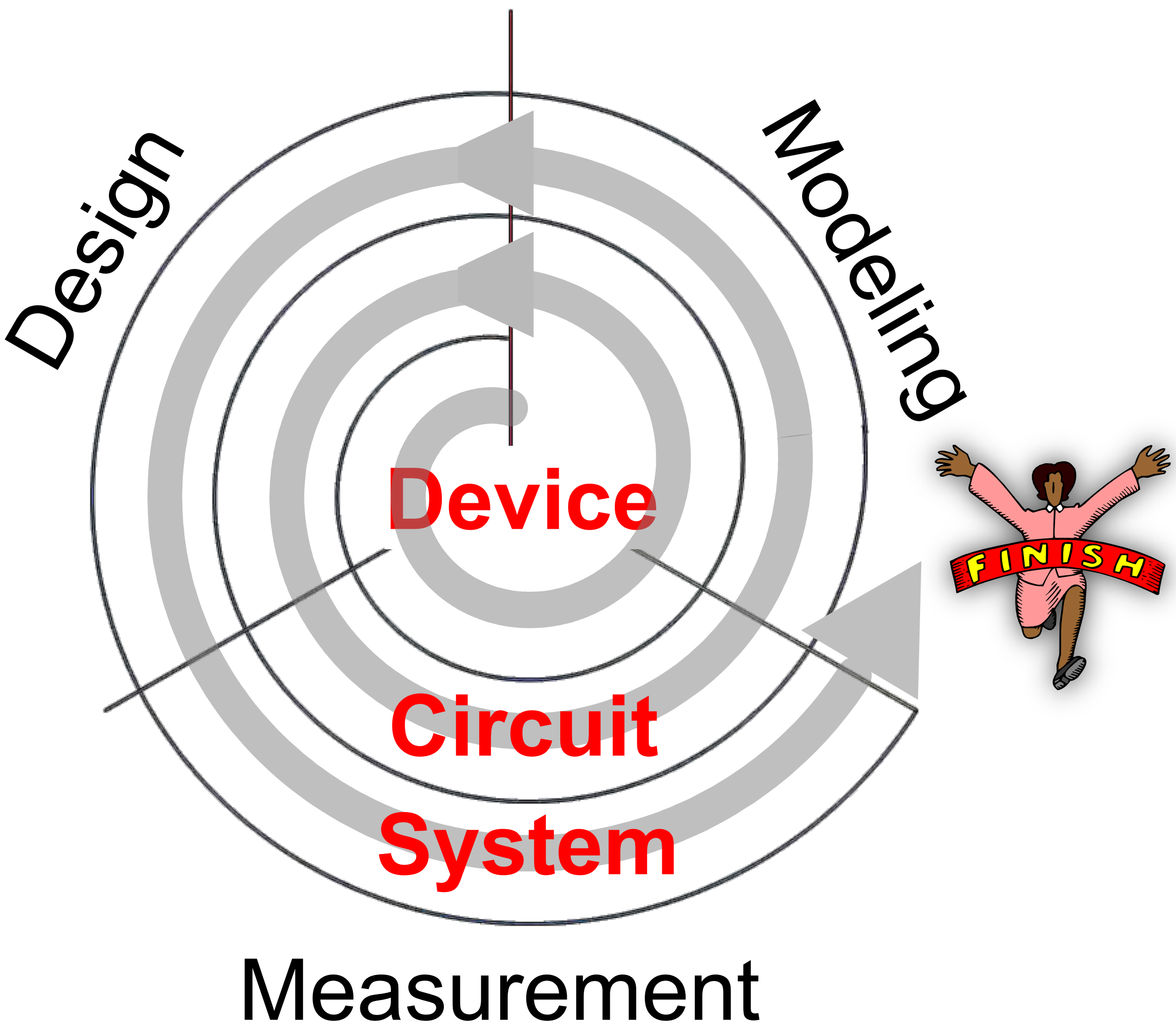
Chip Development Process



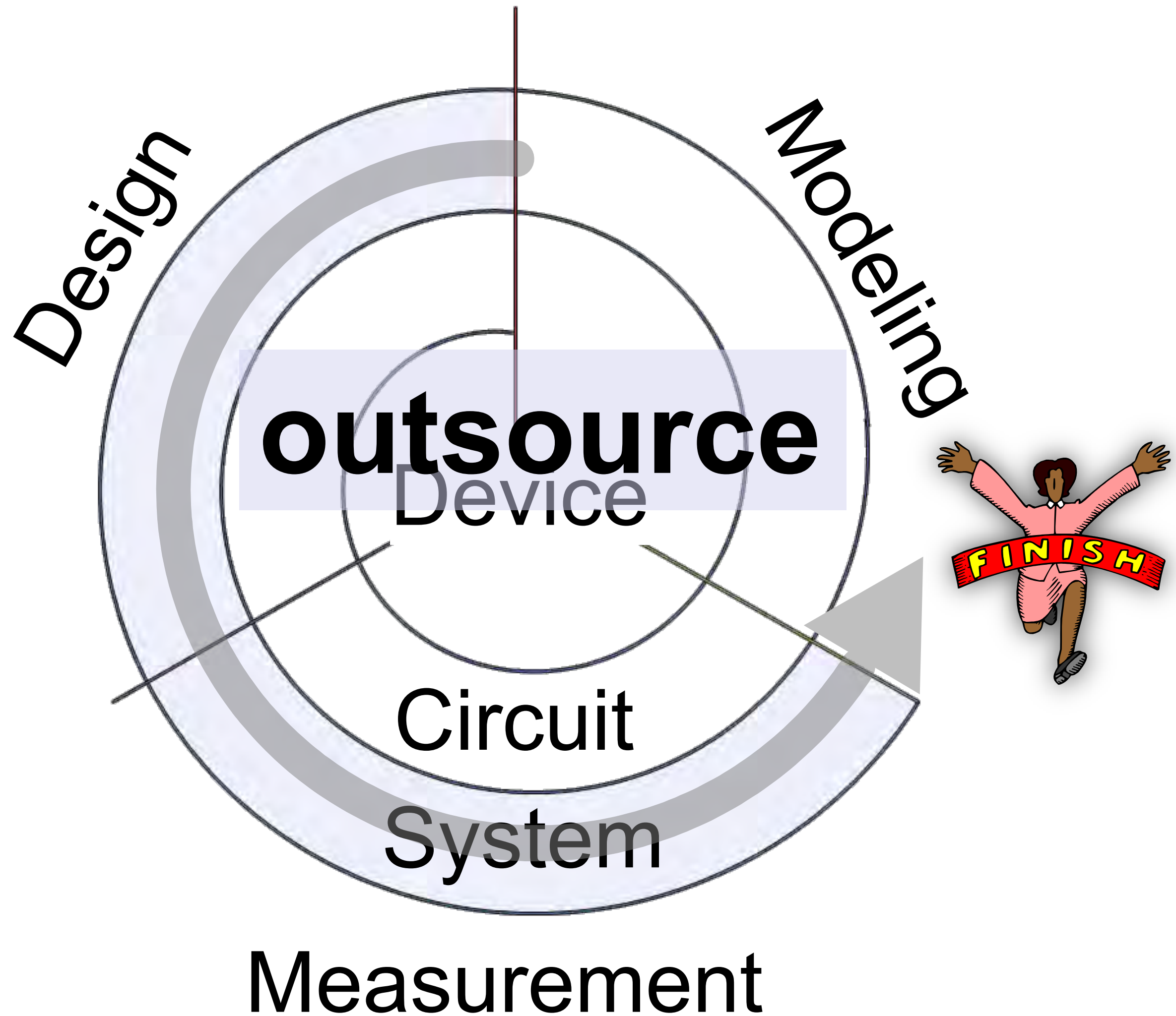
Three Development Tasks



Three Development Layers

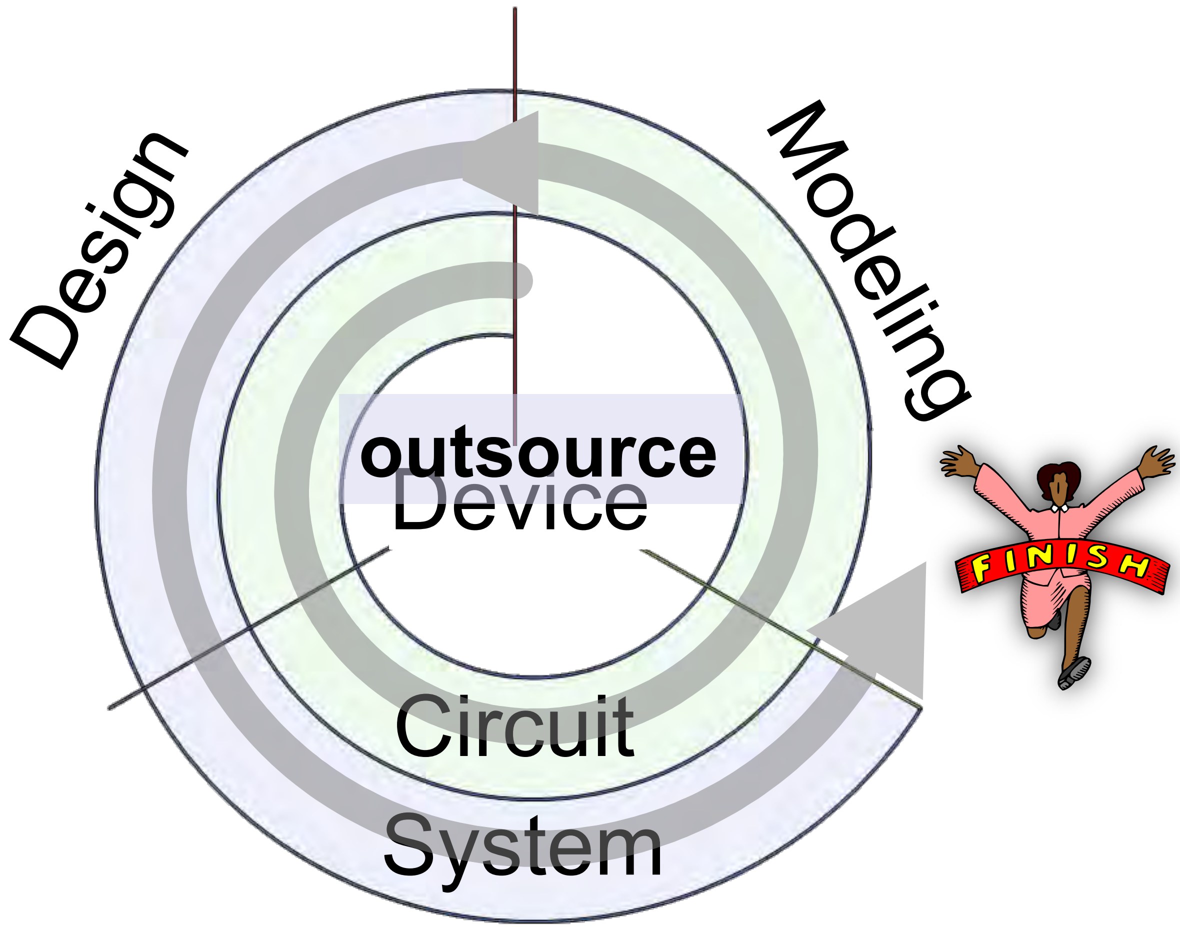


SoC Design



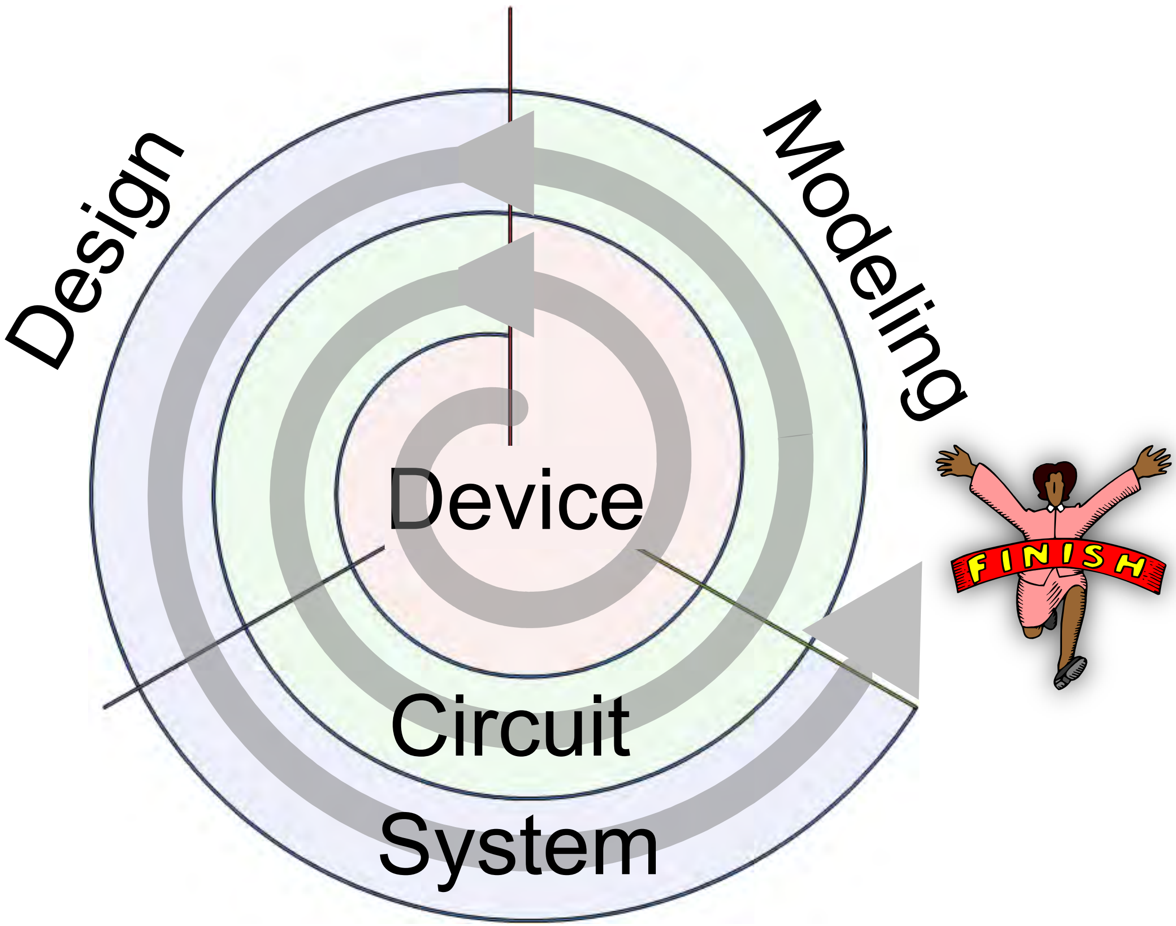
Design
Modeling
outsource
Device
Circuit
System
Measurement
FINISH

Analog/RF Design



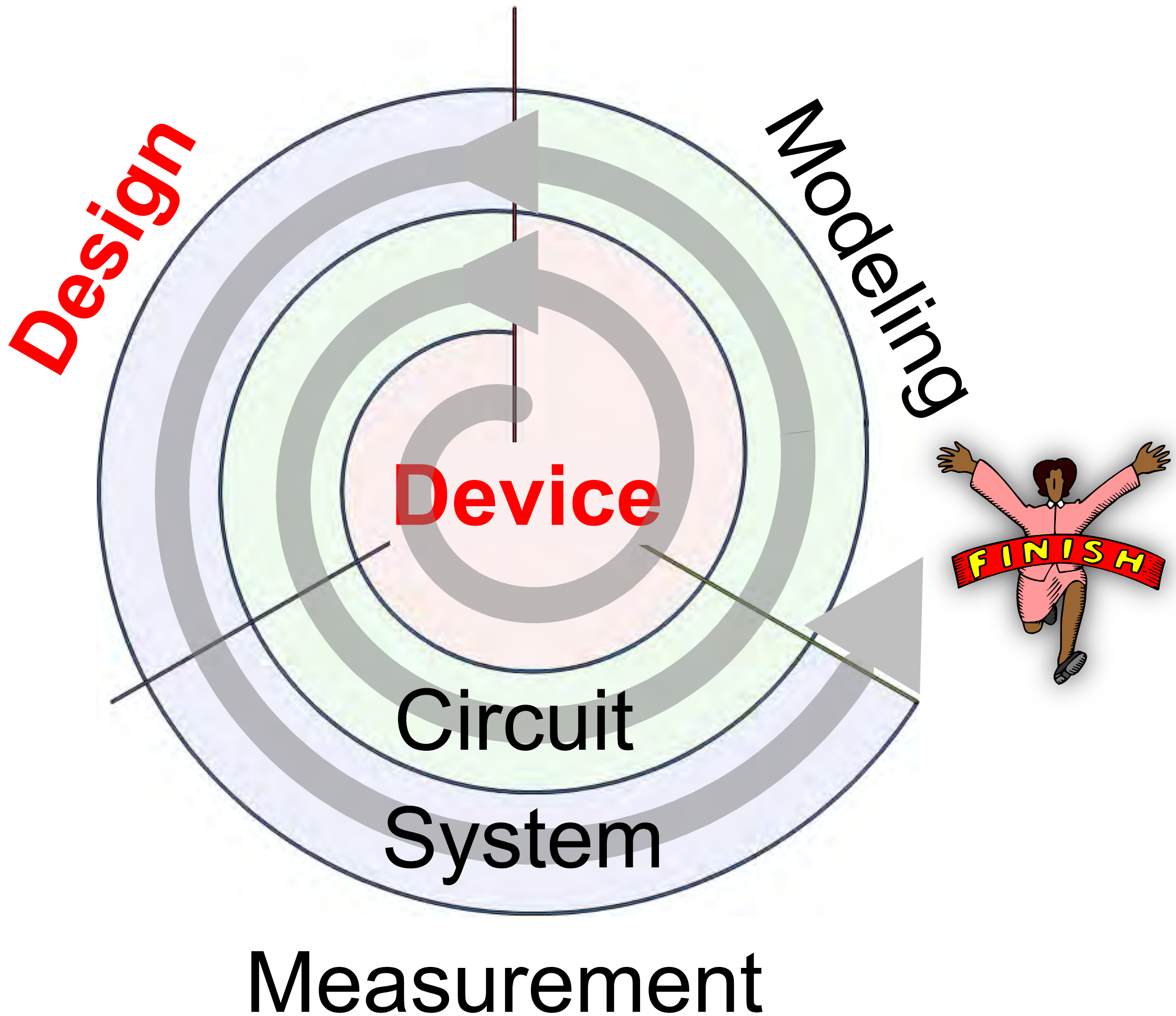
Measurement

Millimeter-Wave Design



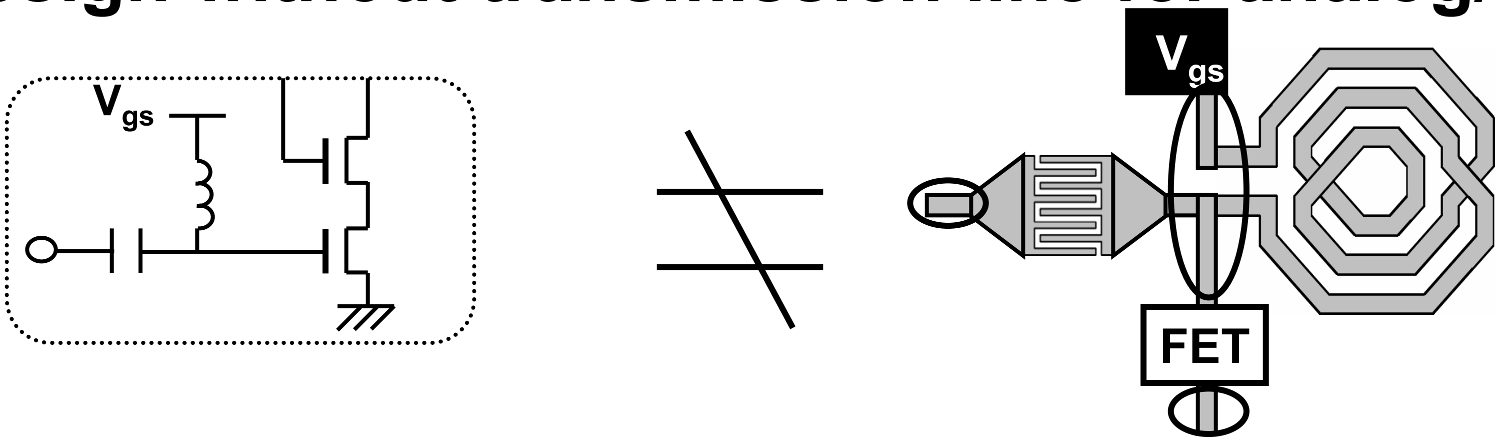
Measurement

Millimeter-Wave Design

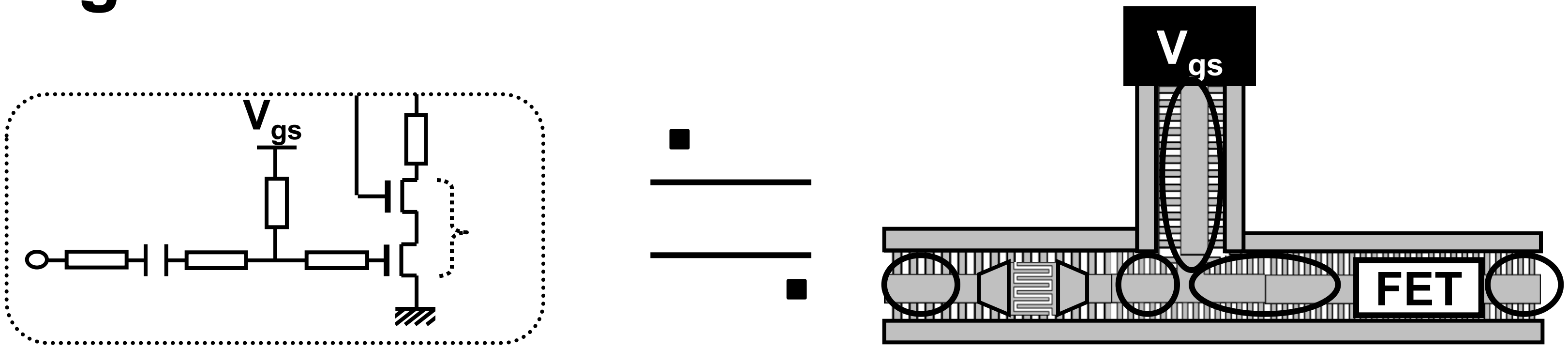


mmW Layout Issue

- ✓ **Design without transmission line for analog/RF**

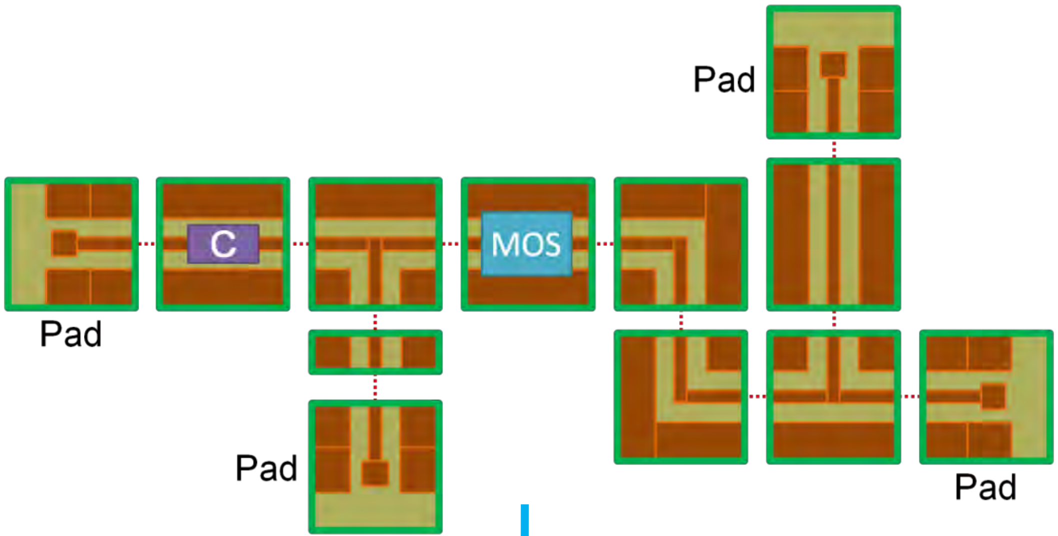


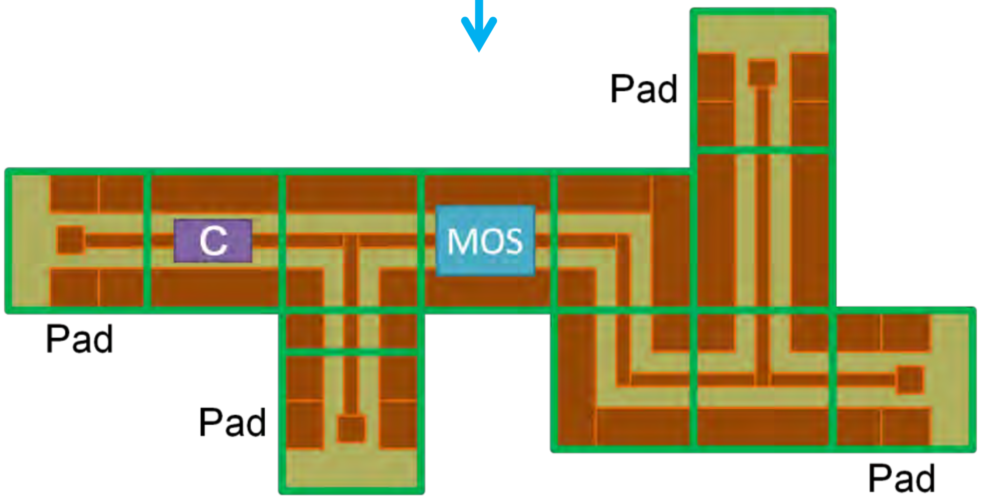
- ✓ **Design with transmission line for millimeter wave**



Modeled transmission line is used for interconnect.

Bond-Based Design



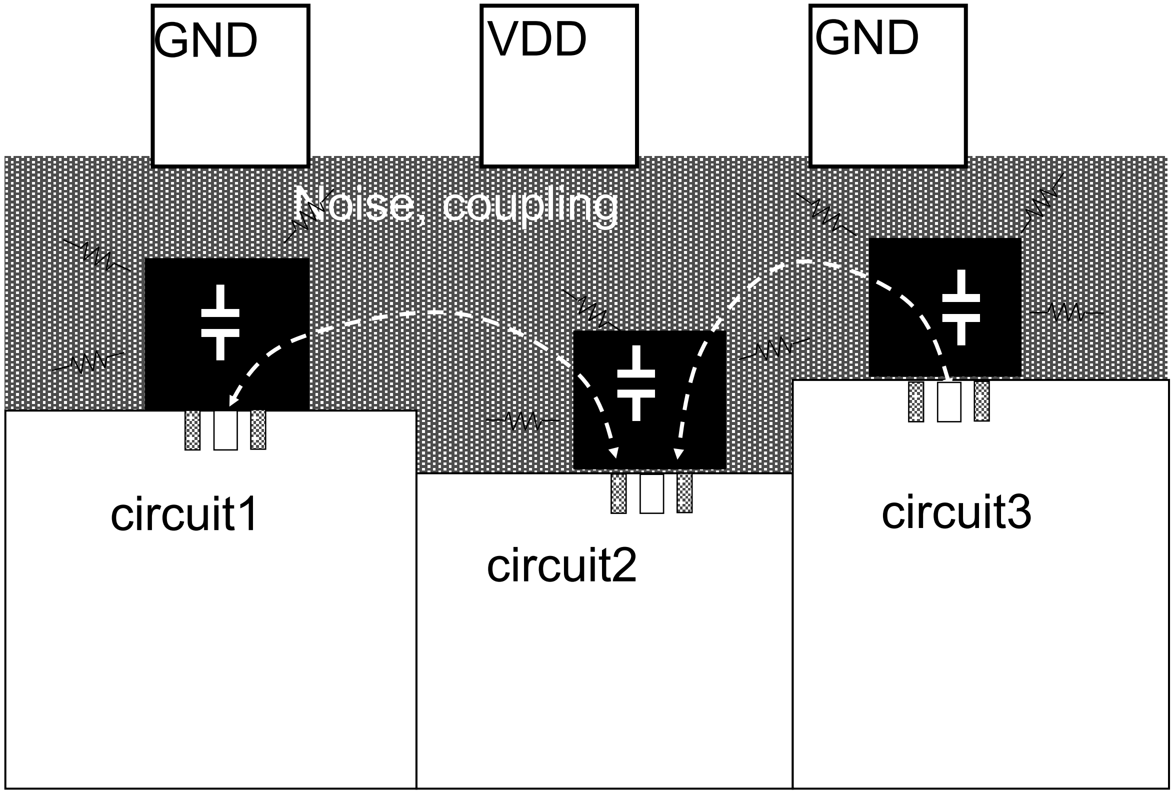


- Use Device Tiles
  - MOSFET
  - Transmission Line
  - Pad
  - etc.
- Interface for tiles
  - Transmission Line

- No Parasitic Wire Connect
- No LPE is required

Device model including transmission line interface is necessary.

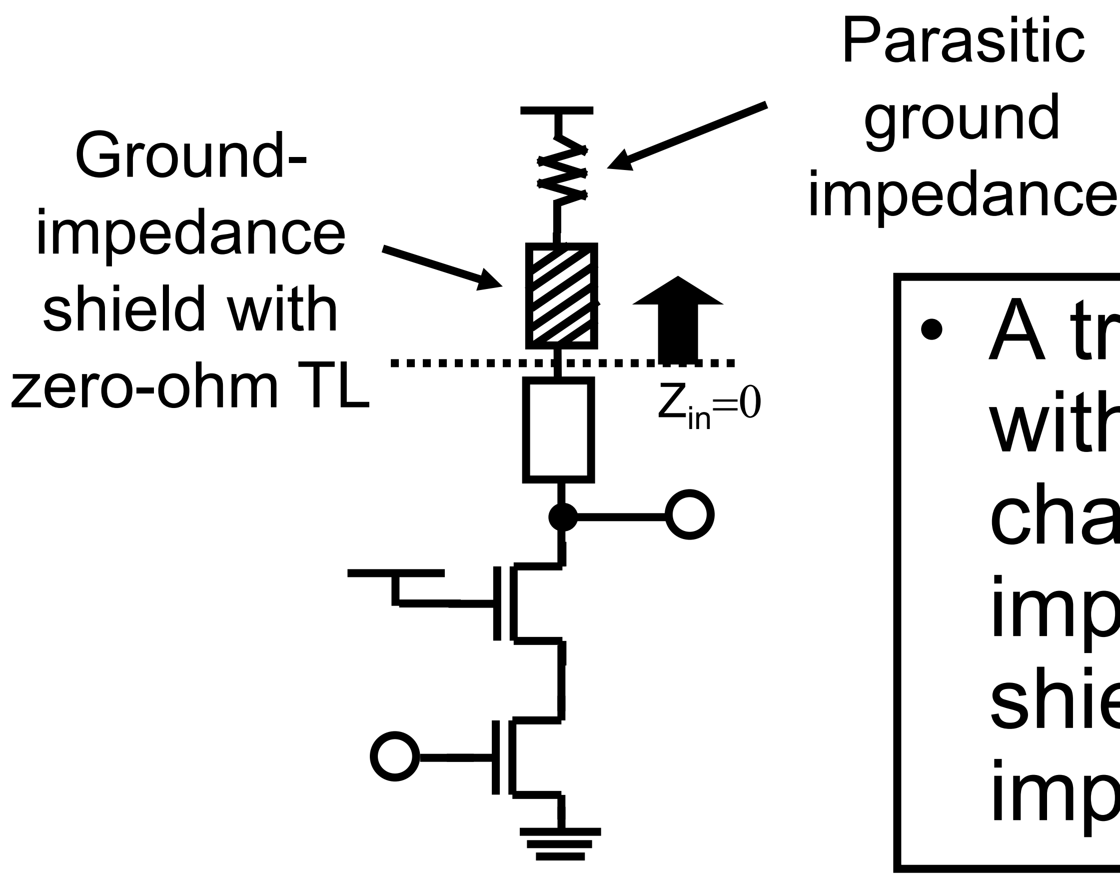
mmW Decoupling Issue



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.

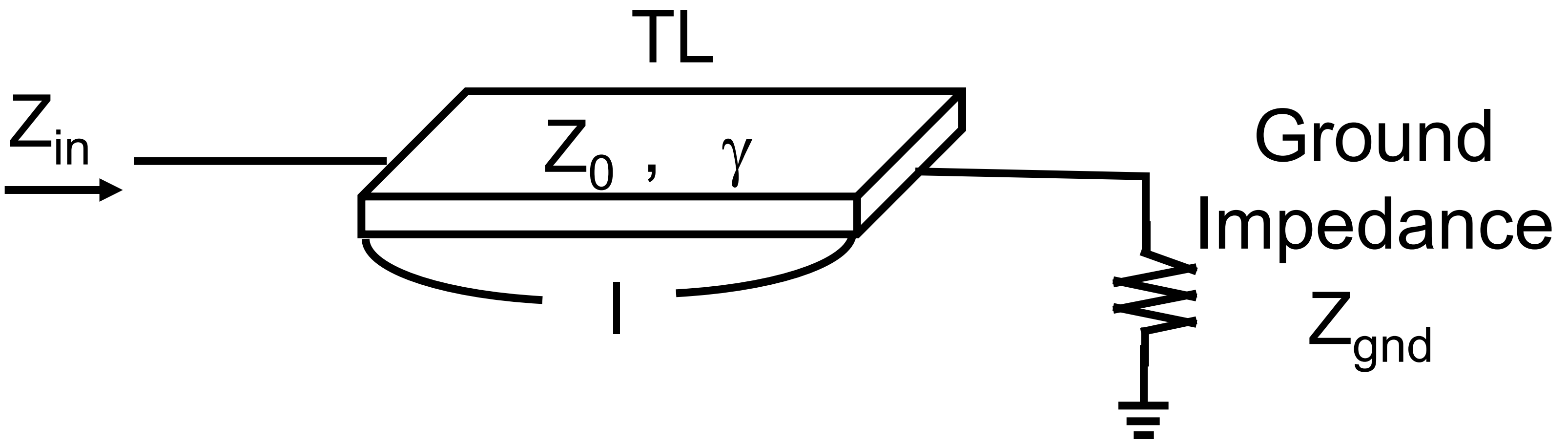
Millimeter-Wave Decoupling



Single-ended amplifier with zero-ohm TL

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

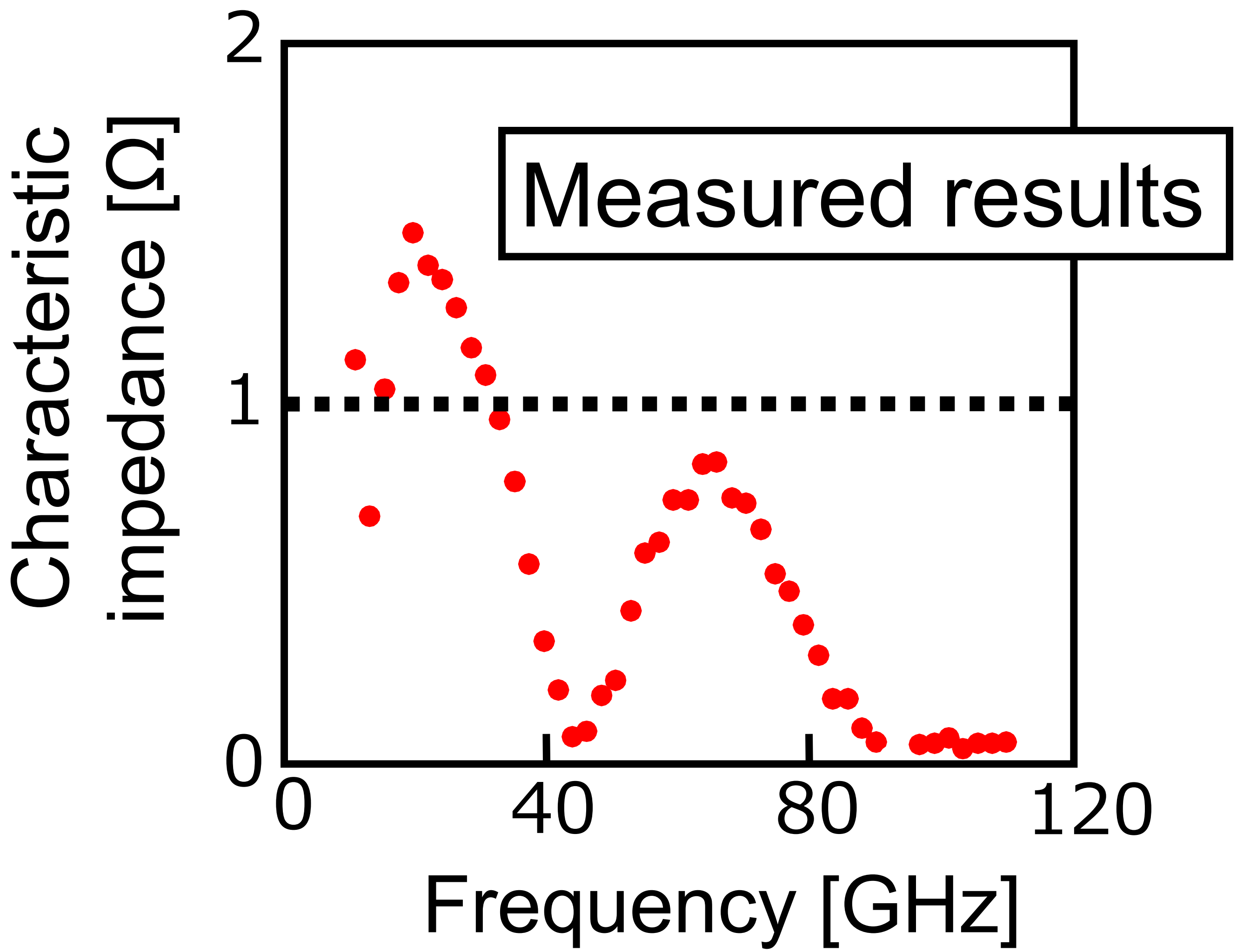
Impedance of Short Stub



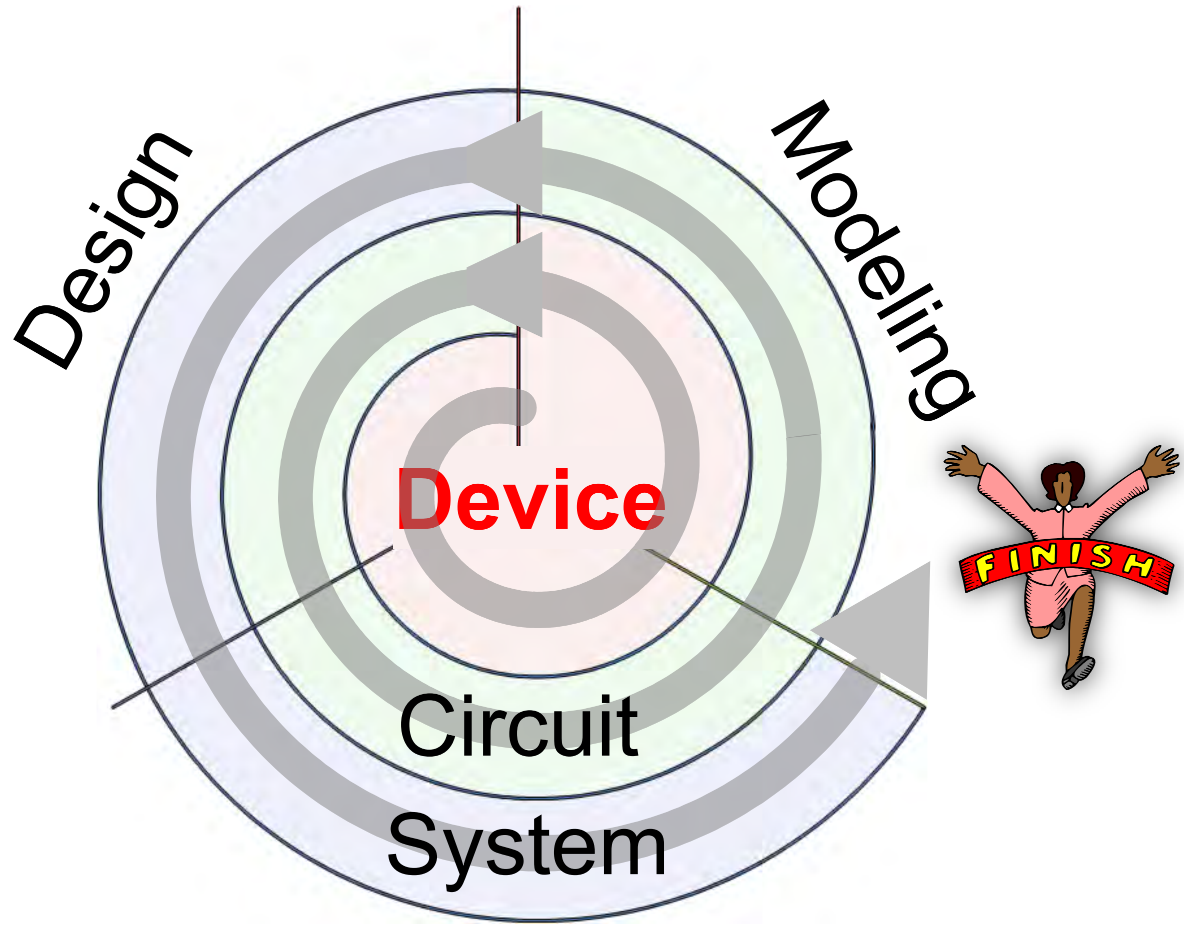
$$Z_{in} = Z_0 \frac{(Z_{gnd}+Z_0)+(Z_{gnd}-Z_0)e^{-2\gamma l}}{(Z_{gnd}+Z_0)-(Z_{gnd}-Z_0)e^{-2\gamma l}}$$

$\rightarrow 0$ if $Z_0 \rightarrow 0$ (0ΩTL)

Characteristic Impedance of 0ΩTL

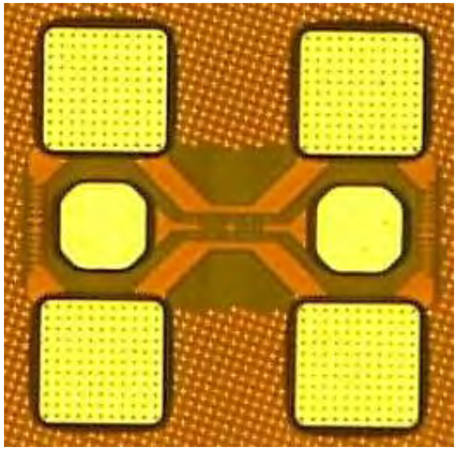


Millimeter-Wave Design

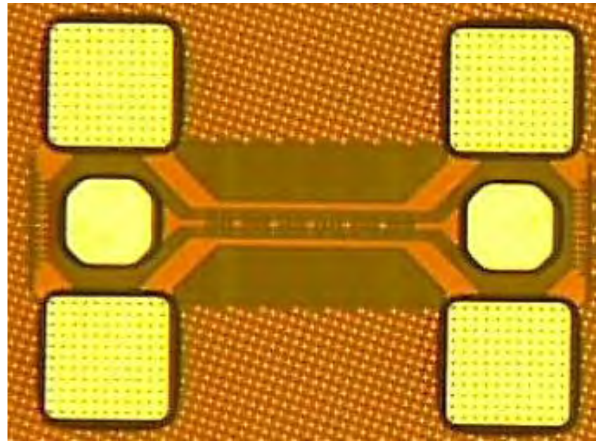


Measurement

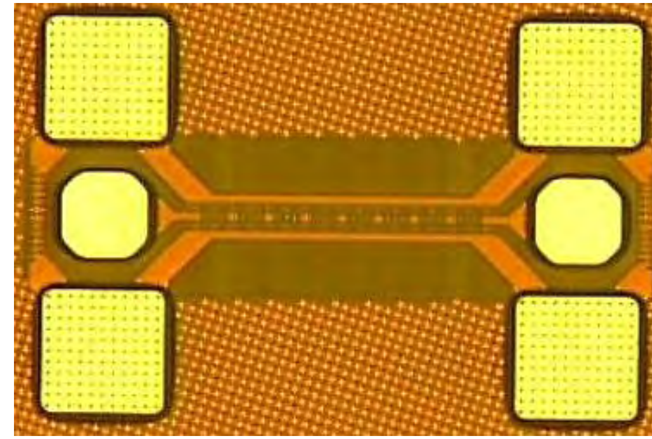
Transmission Line Evaluation



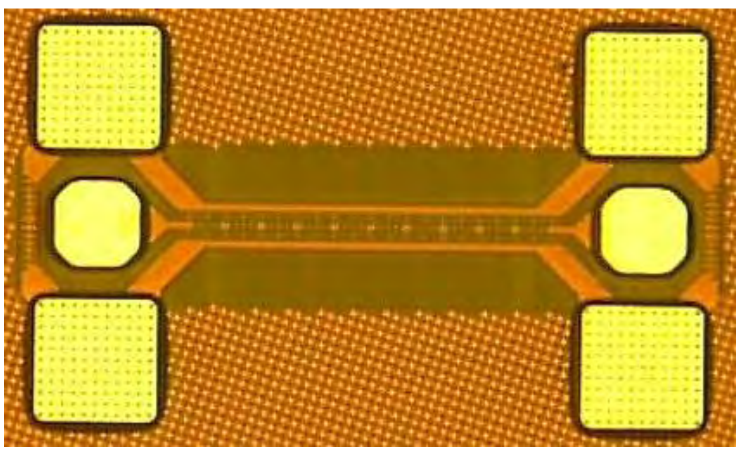
THRU
(0μm)



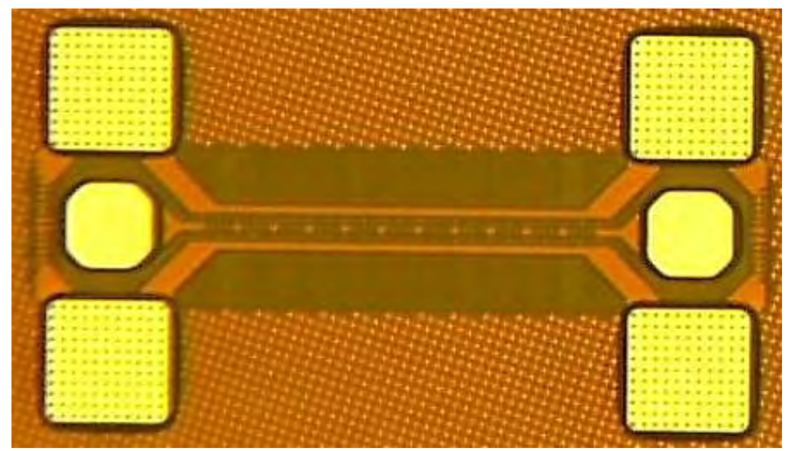
TL4
(80μm)



TL6
(120μm)

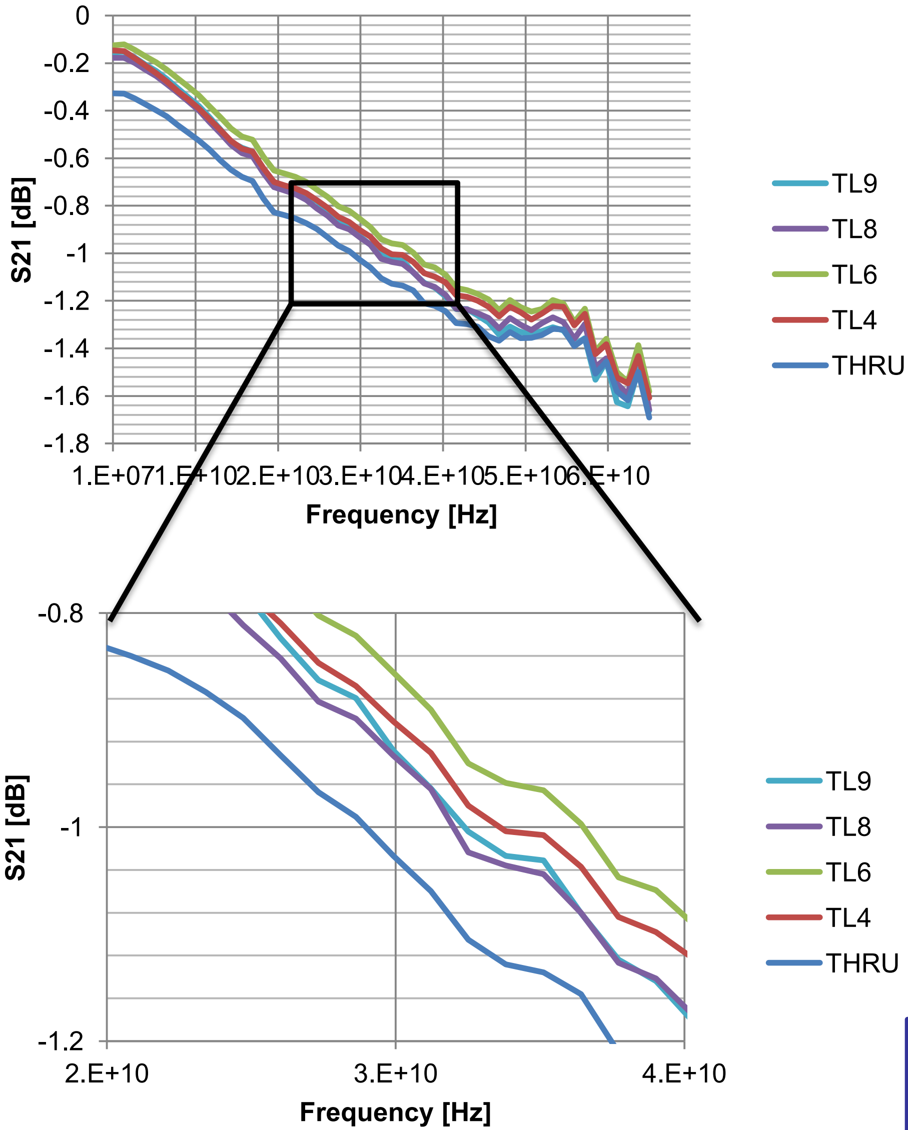


TL8
(160μm)



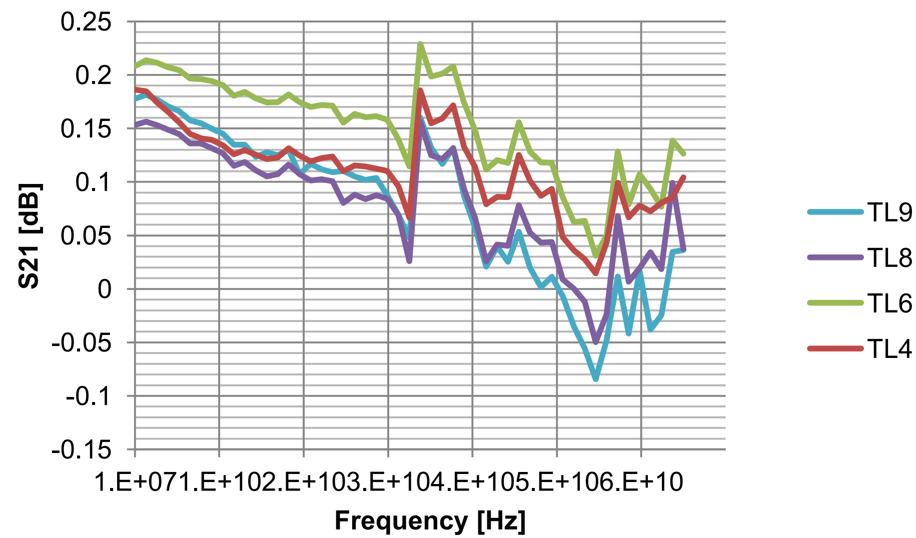
TL9
(180μm)

Measurement Issues



The S21 should be…
THRU > TL4 > TL6 > TL8 > TL9
However, in this case…
TL6 > TL4 > TL9 > TL8 > THRU

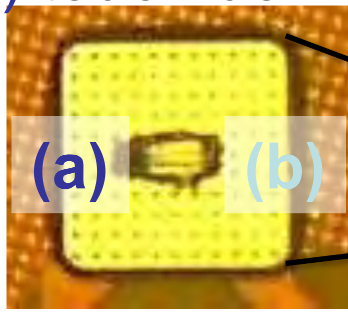
After de-embedding…



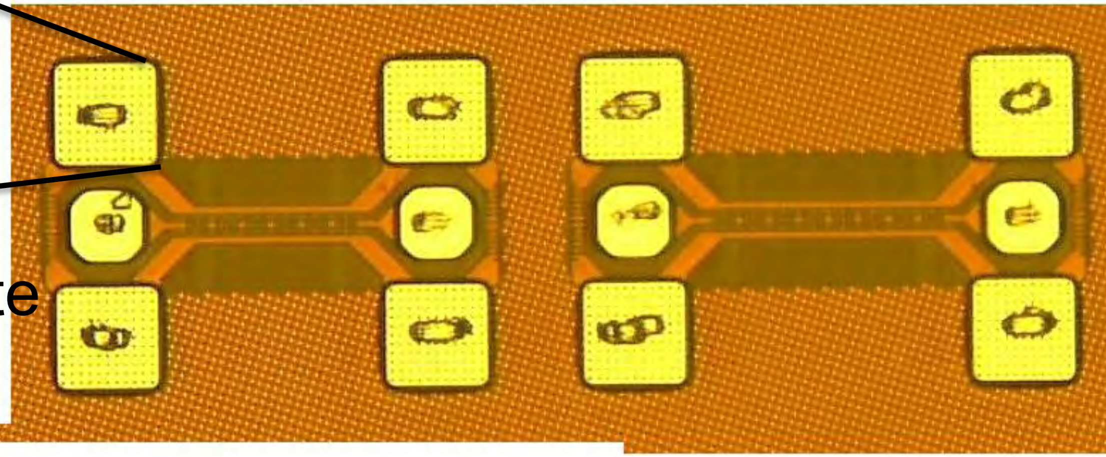
S21 become positive !!

Caused by irreproducible probing!

(a) touch down

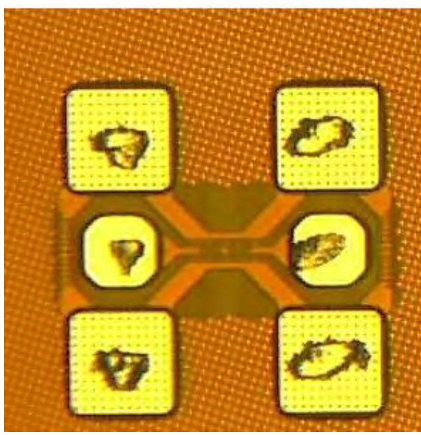


(b) skate



TL4

TL6



THRU

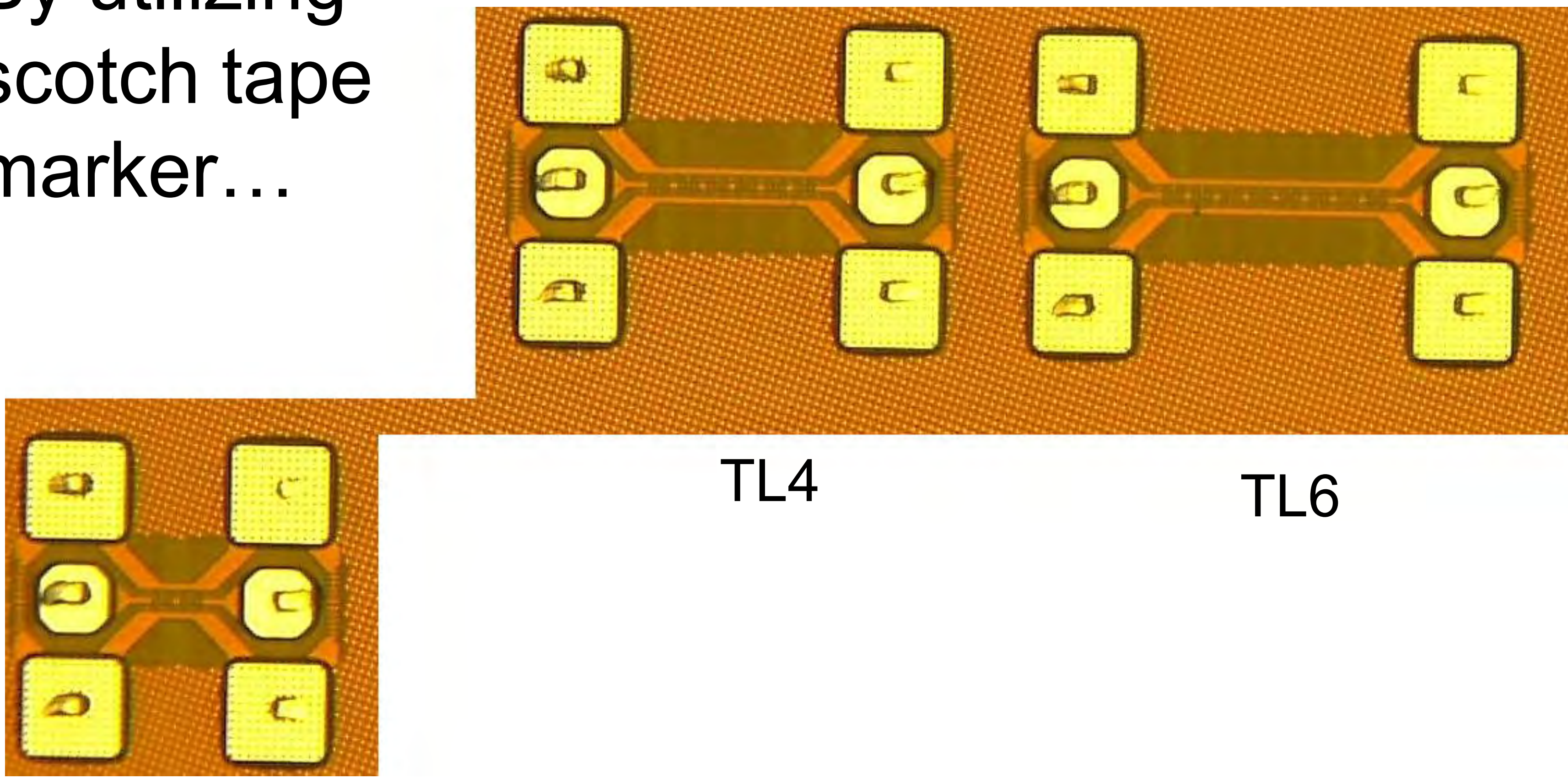
Probe positions were irreproducible.

⇩

Length & contact resistance are fluctuating.

Accurate Probing

By utilizing scotch tape marker…

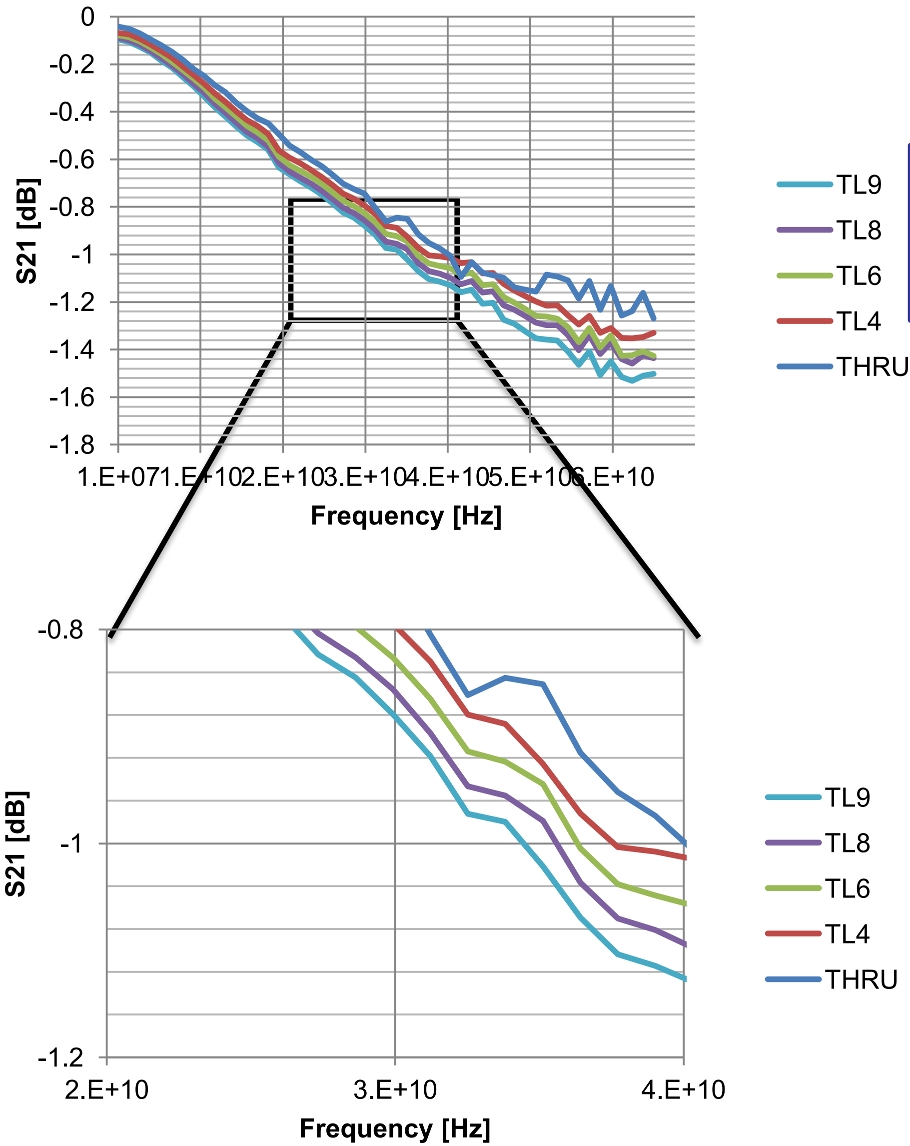


TL4

TL6

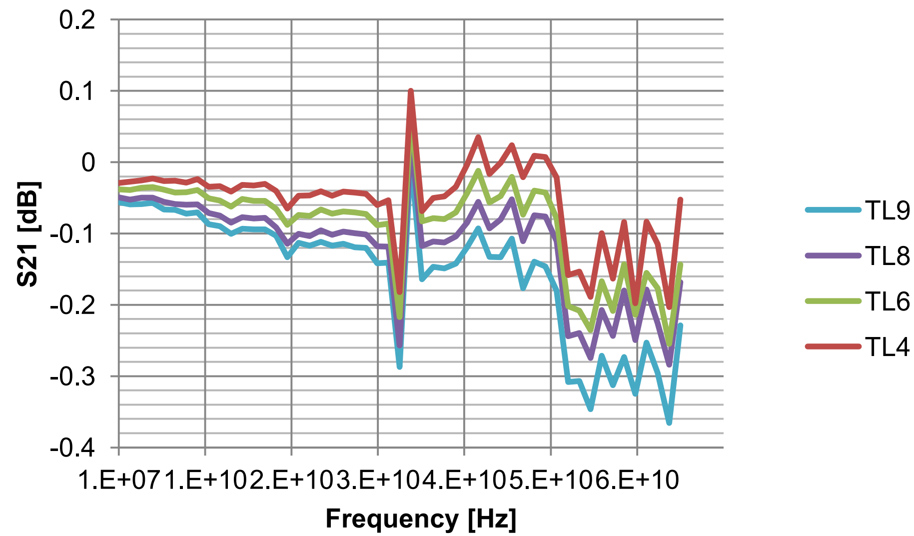
THRU

Measured Results



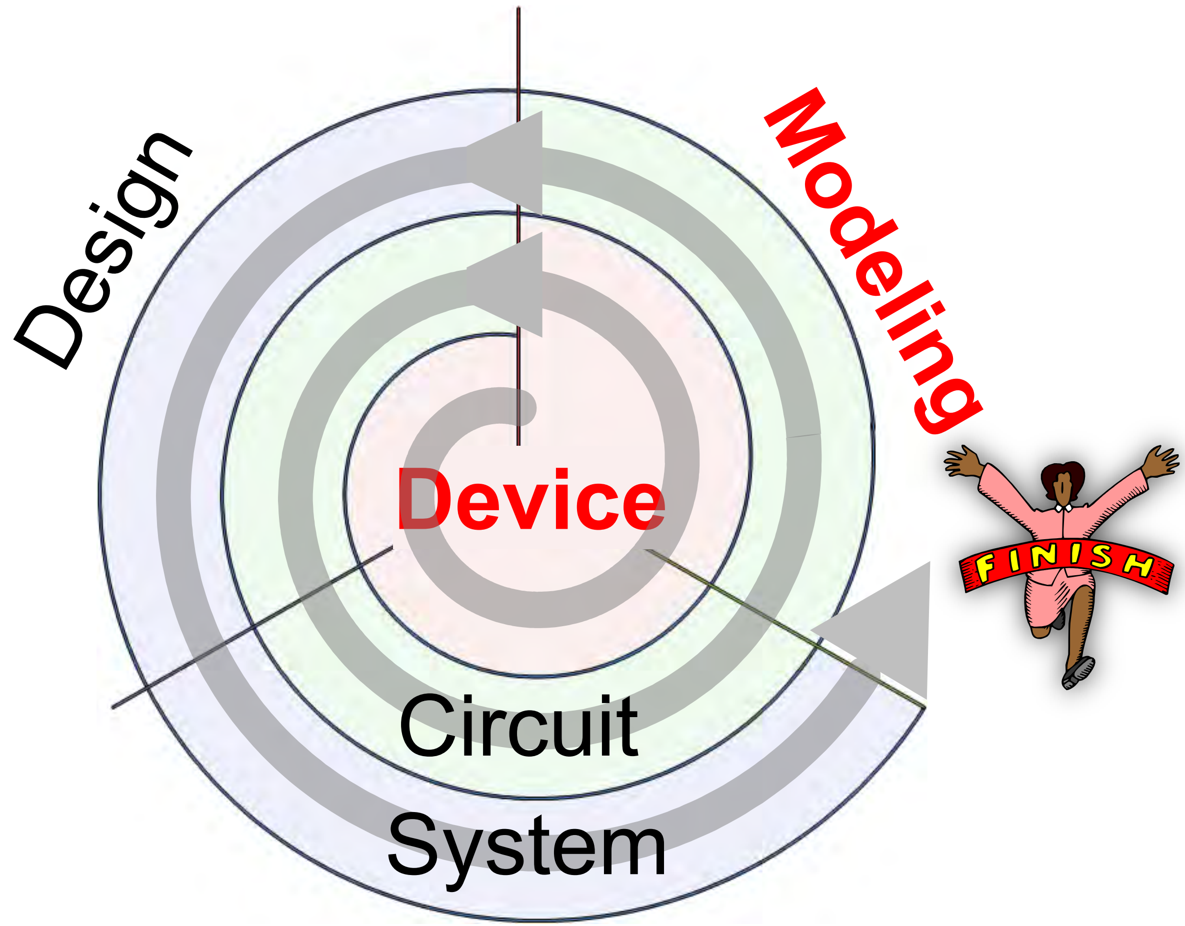
The S21 is expected order
THRU > TL4 > TL6 > TL8 > TL9

After de-embedding…



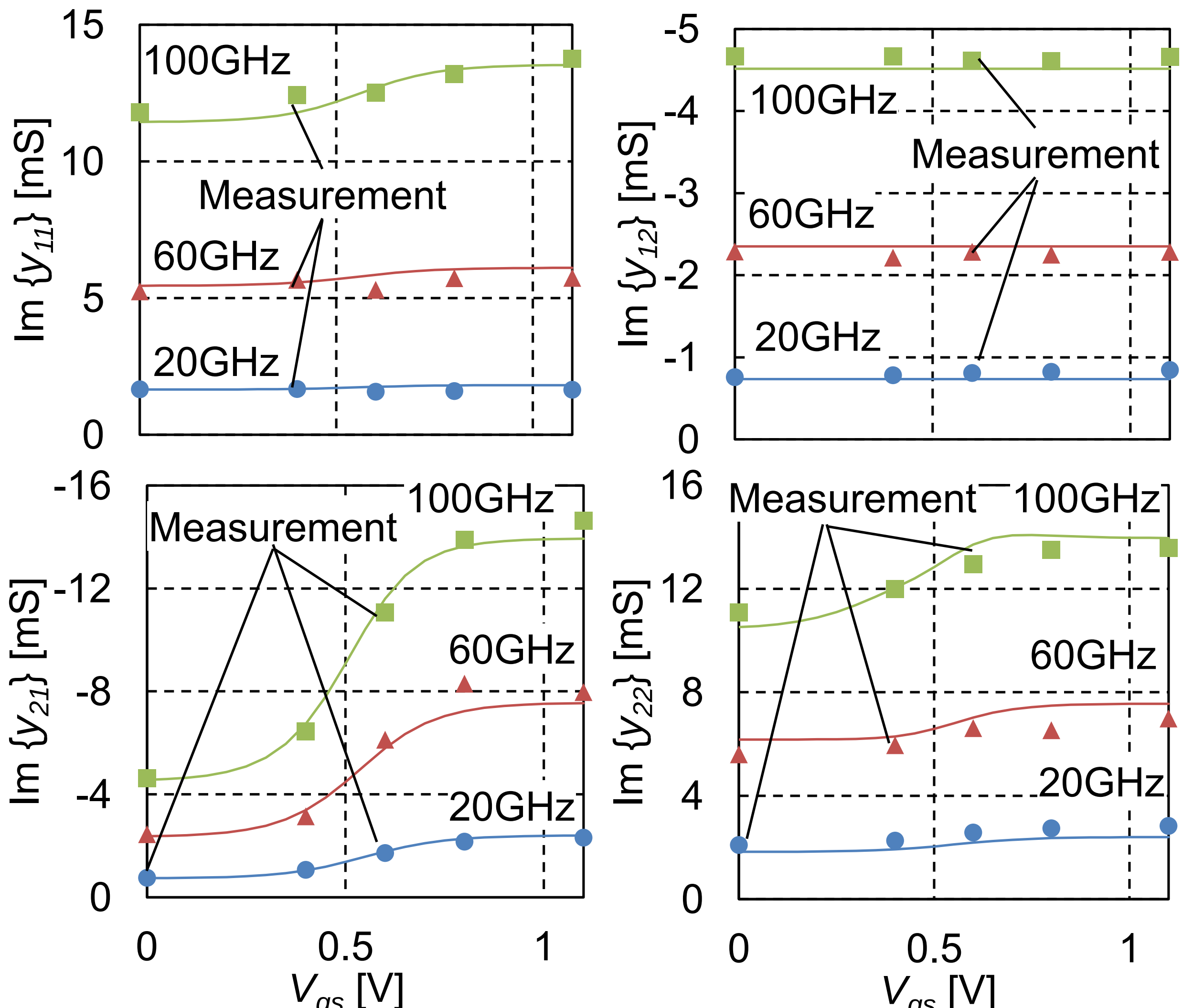
S21 become normal

Millimeter-Wave Design



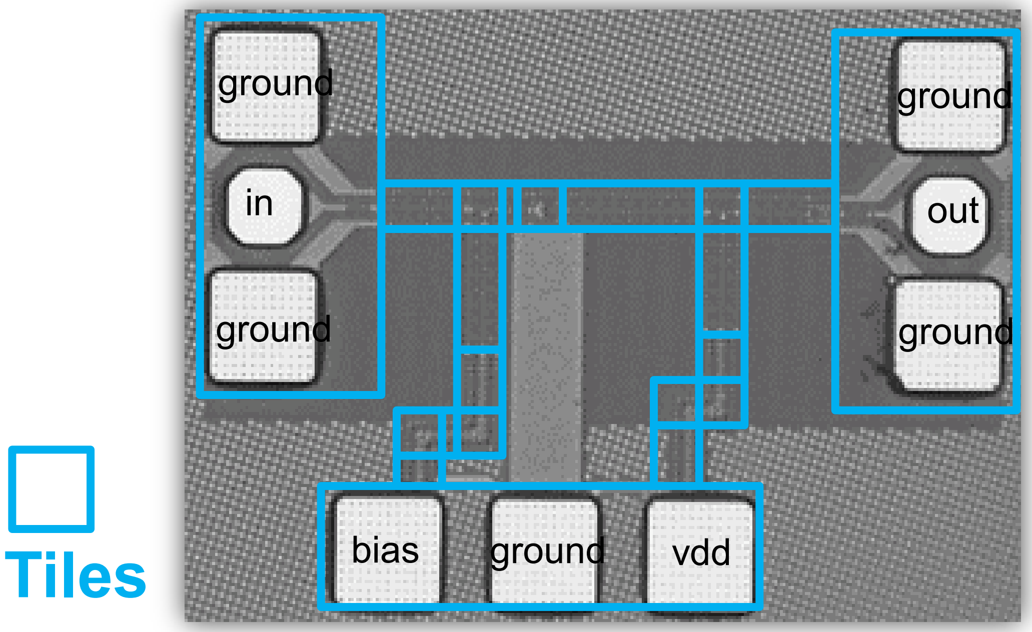
Measurement

Admittance Comparison

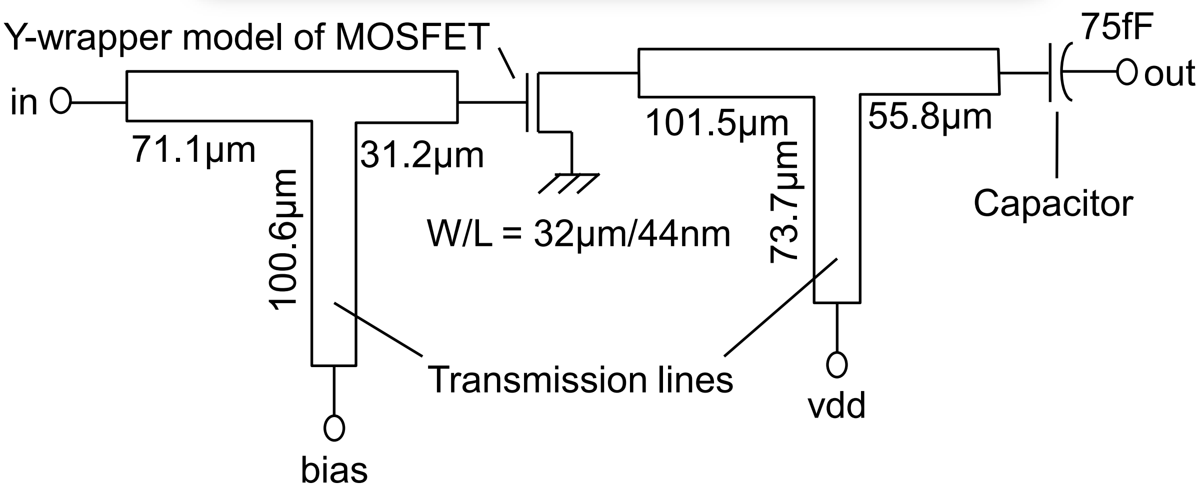


Verification using Amplifier

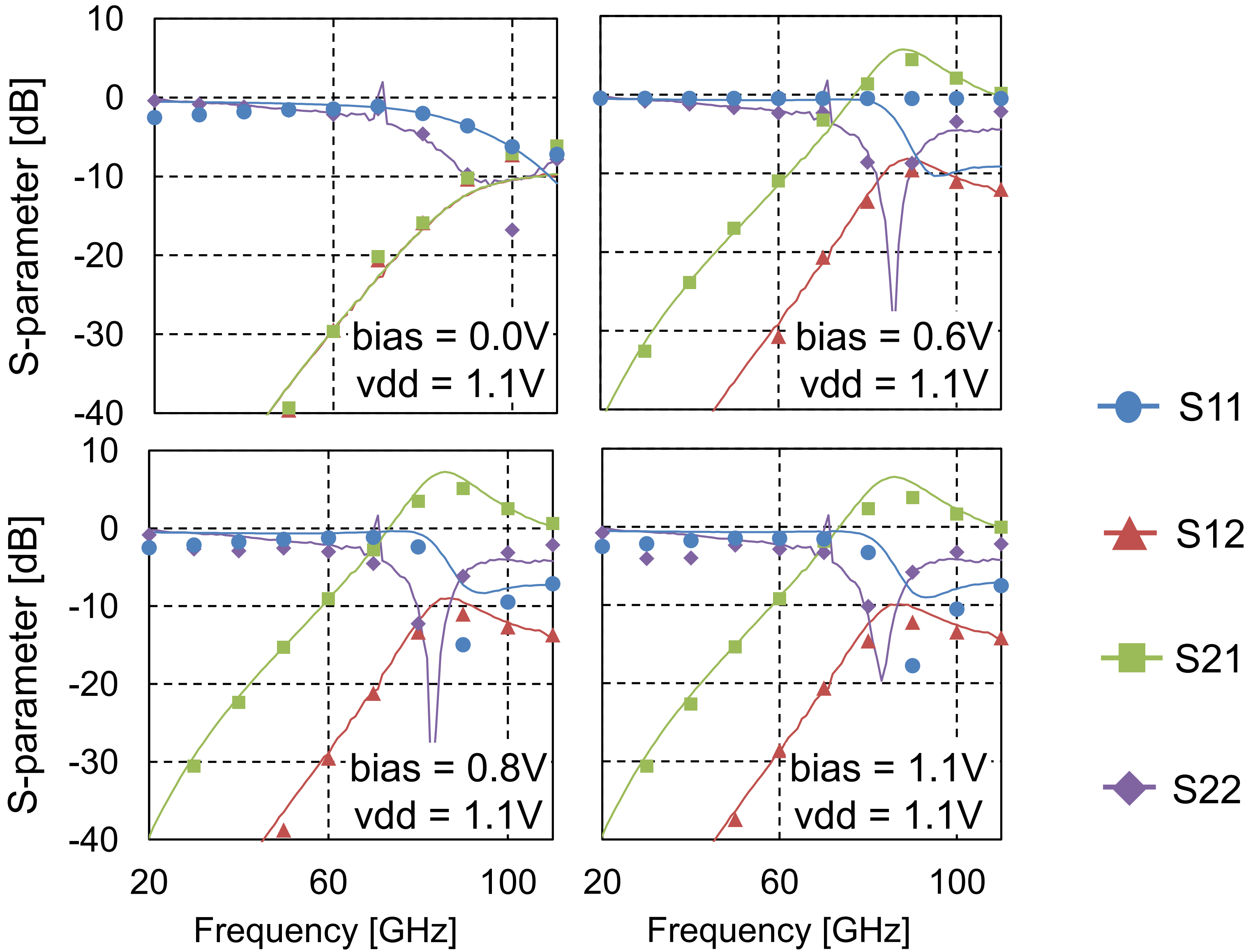
65nm-CMOS Technology



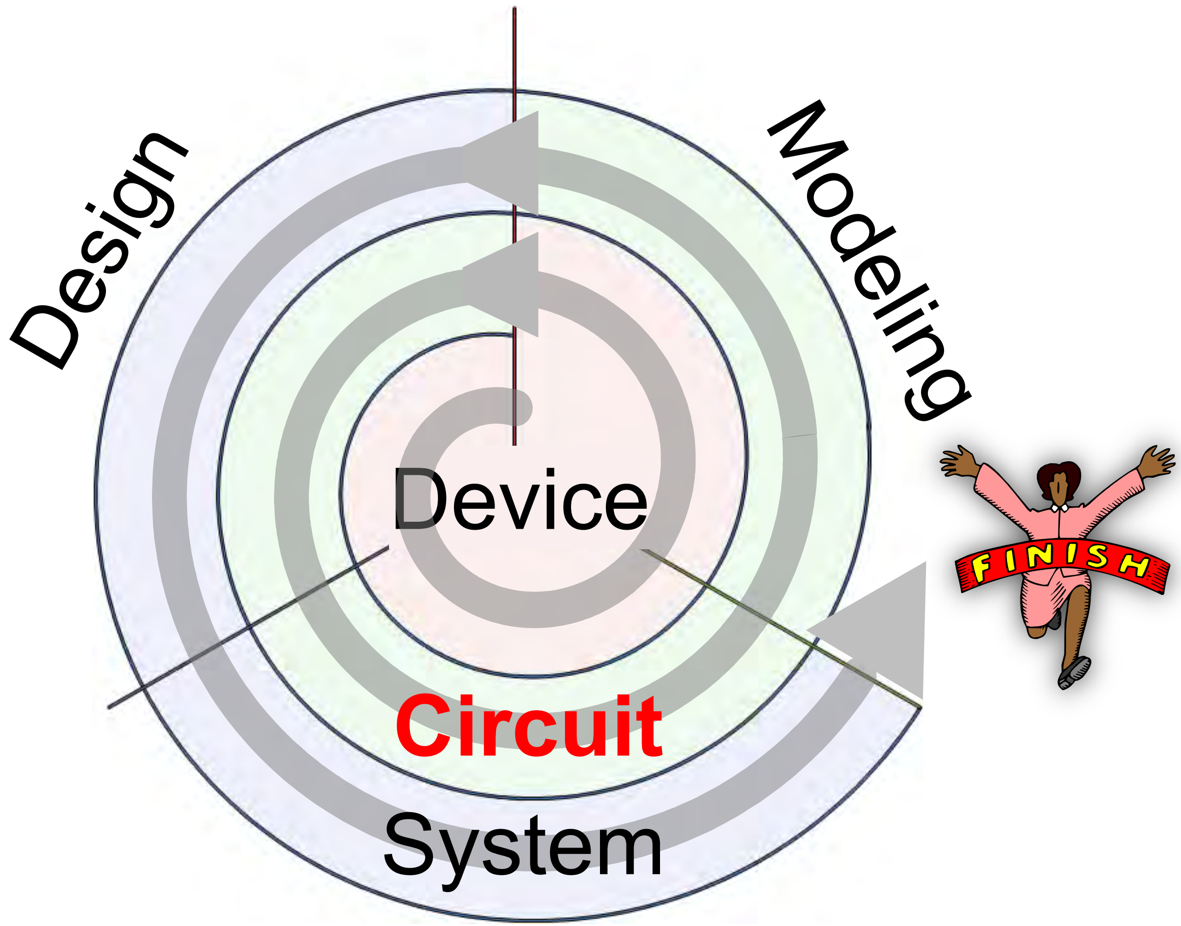
Simplified Circuit Diagram



Measured and Simulated Results

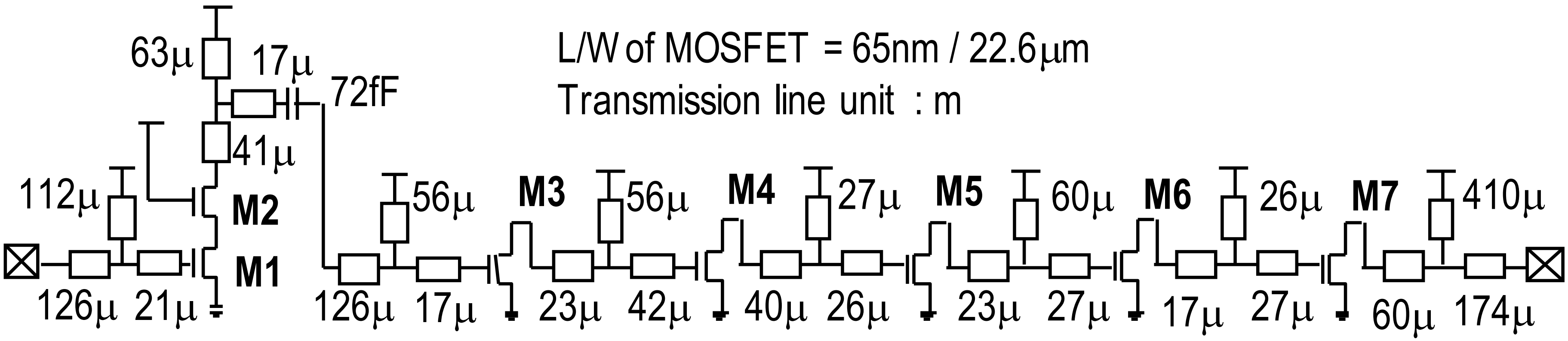


Millimeter-Wave Design

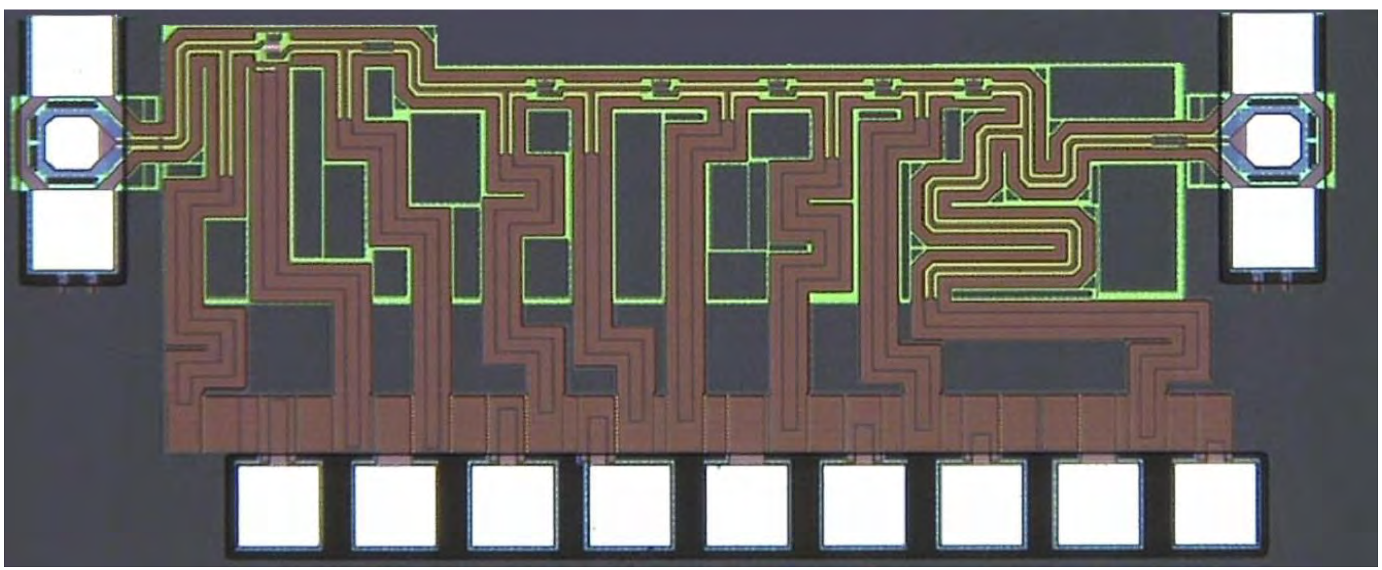


Measurement

Wideband 140GHz CMOS Amp.

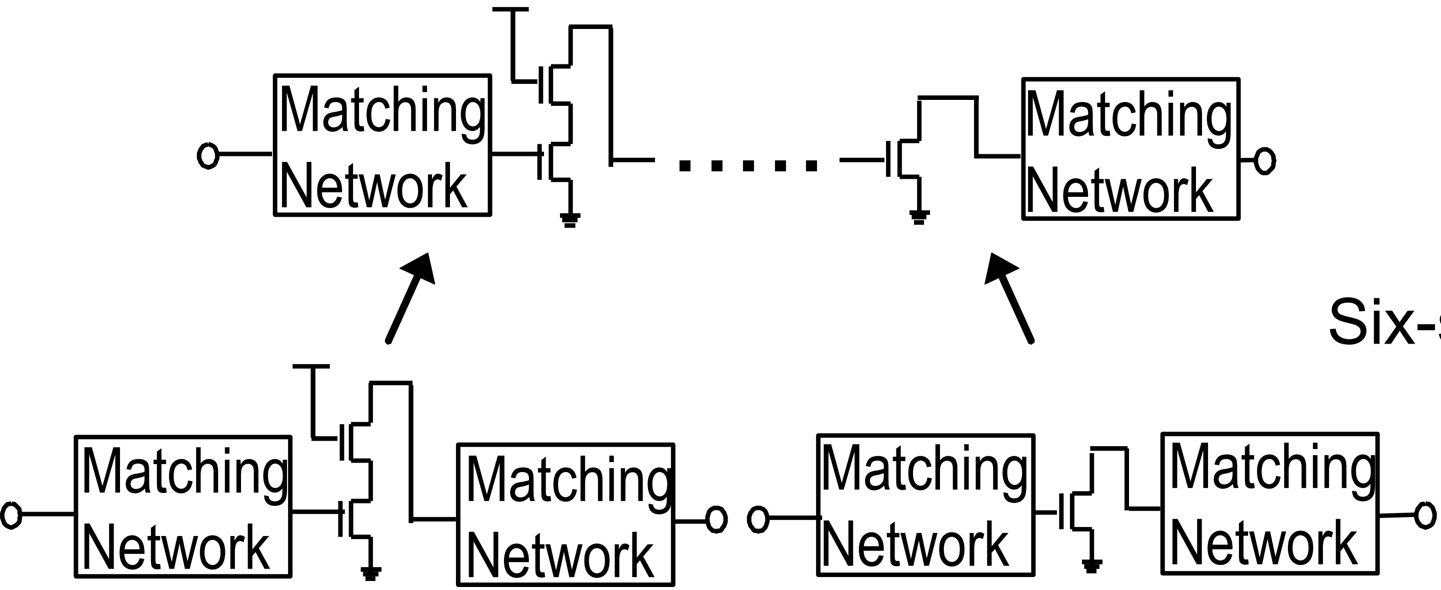


Input

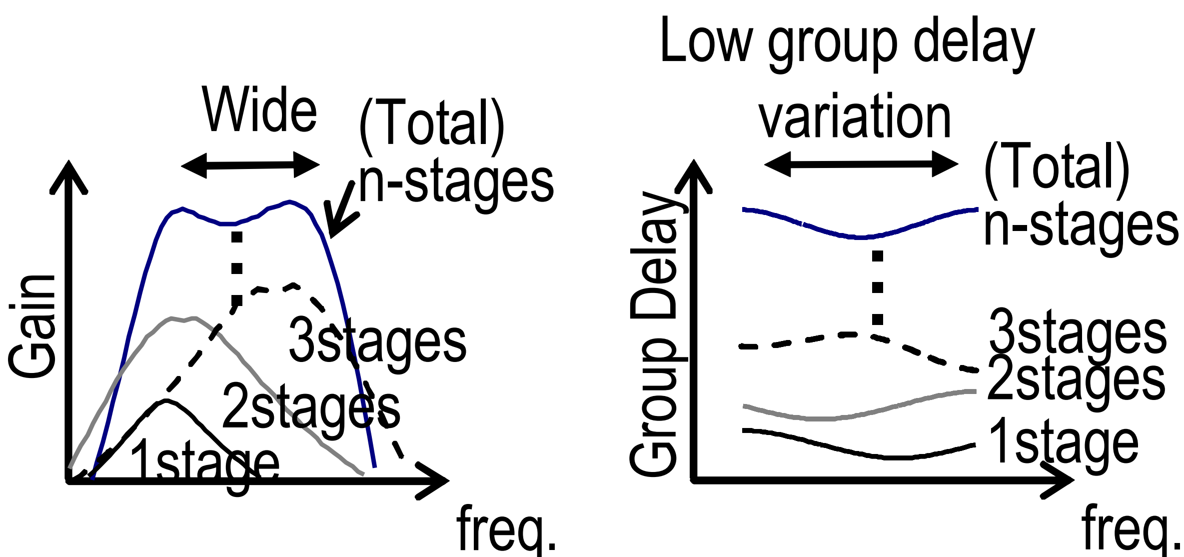


Output

Wideband LNA



Six-stage amplifier



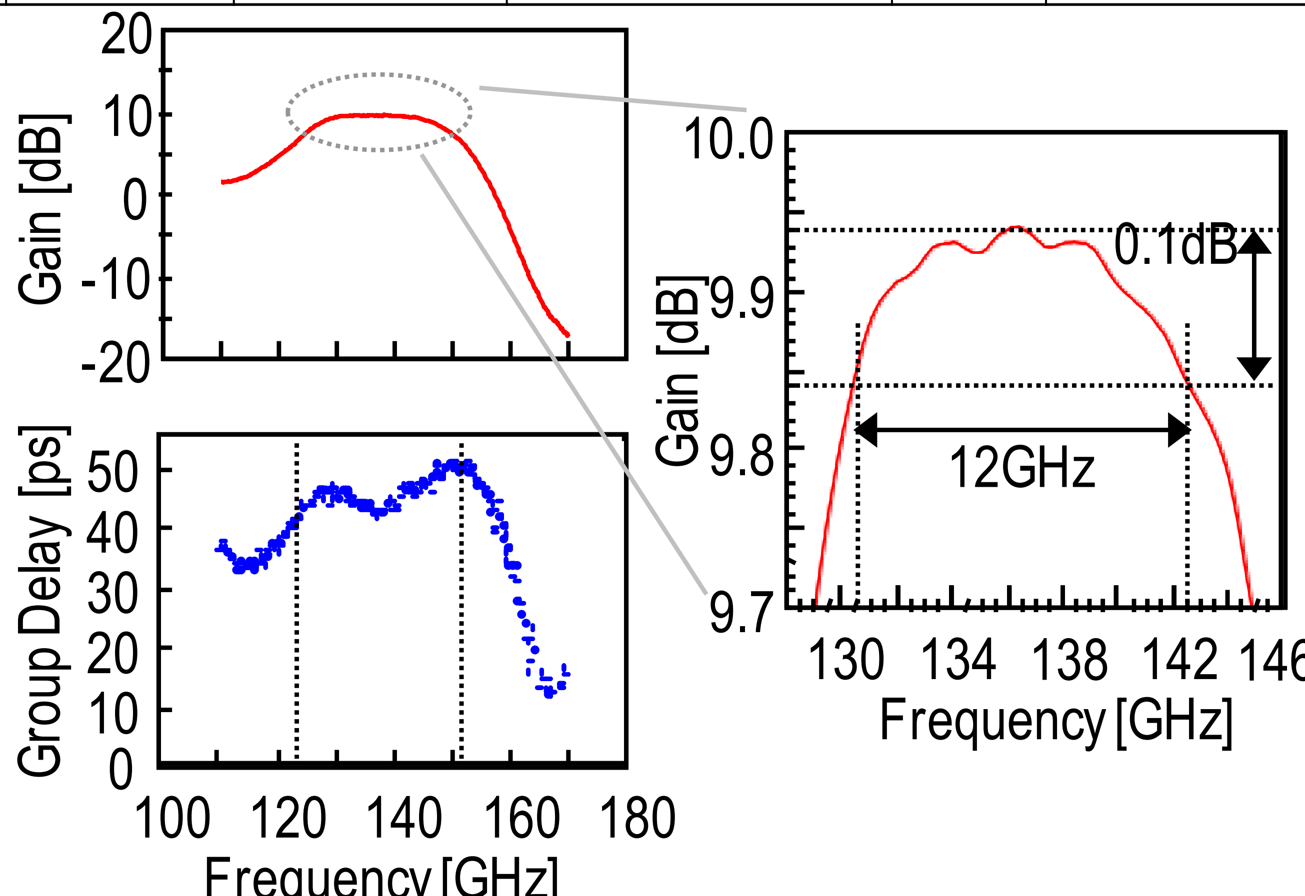
Center frequencies in matching networks are distributed to flatten frequency responses of power gain and group delay.

Measurement Results

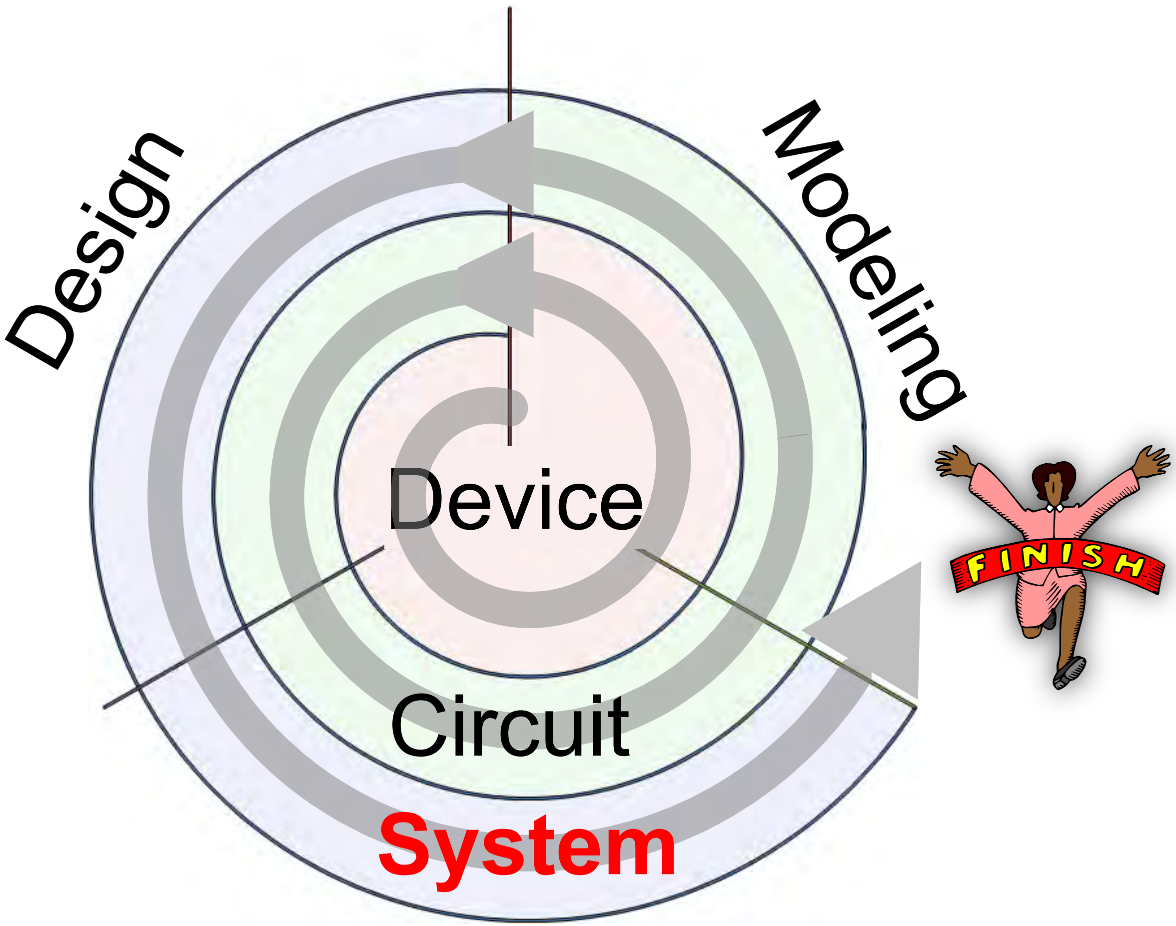
Freq. [GHz]	0.1dB-BW [GHz]	3dB-BW [GHz]	Peak Gain [dB]	GD @3dB-BW [ps]	P_{DC} [mW]	Technology [nm]
136.1	12	27.6	9.9	46.2±13.1	57.1	65

Specification Summary

Frequency Characteristics



Millimeter-Wave Design



Measurement

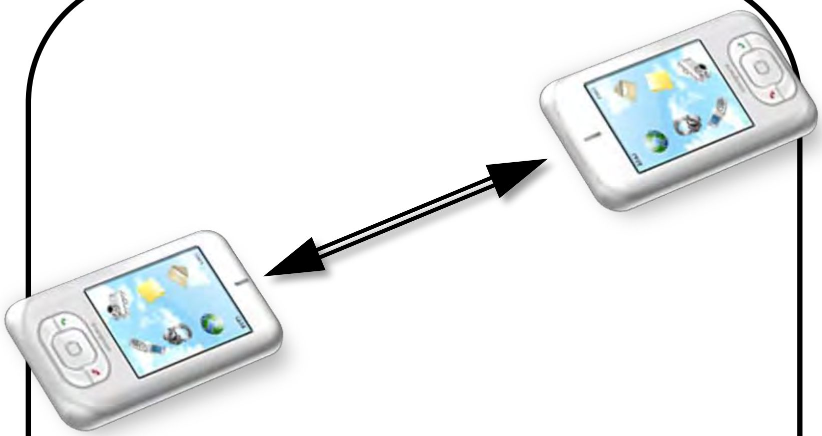
Promising Application: Indoor PAN

Rick Roberts (Intel), 802.15 THz IG

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.

So what might make a winning solution?



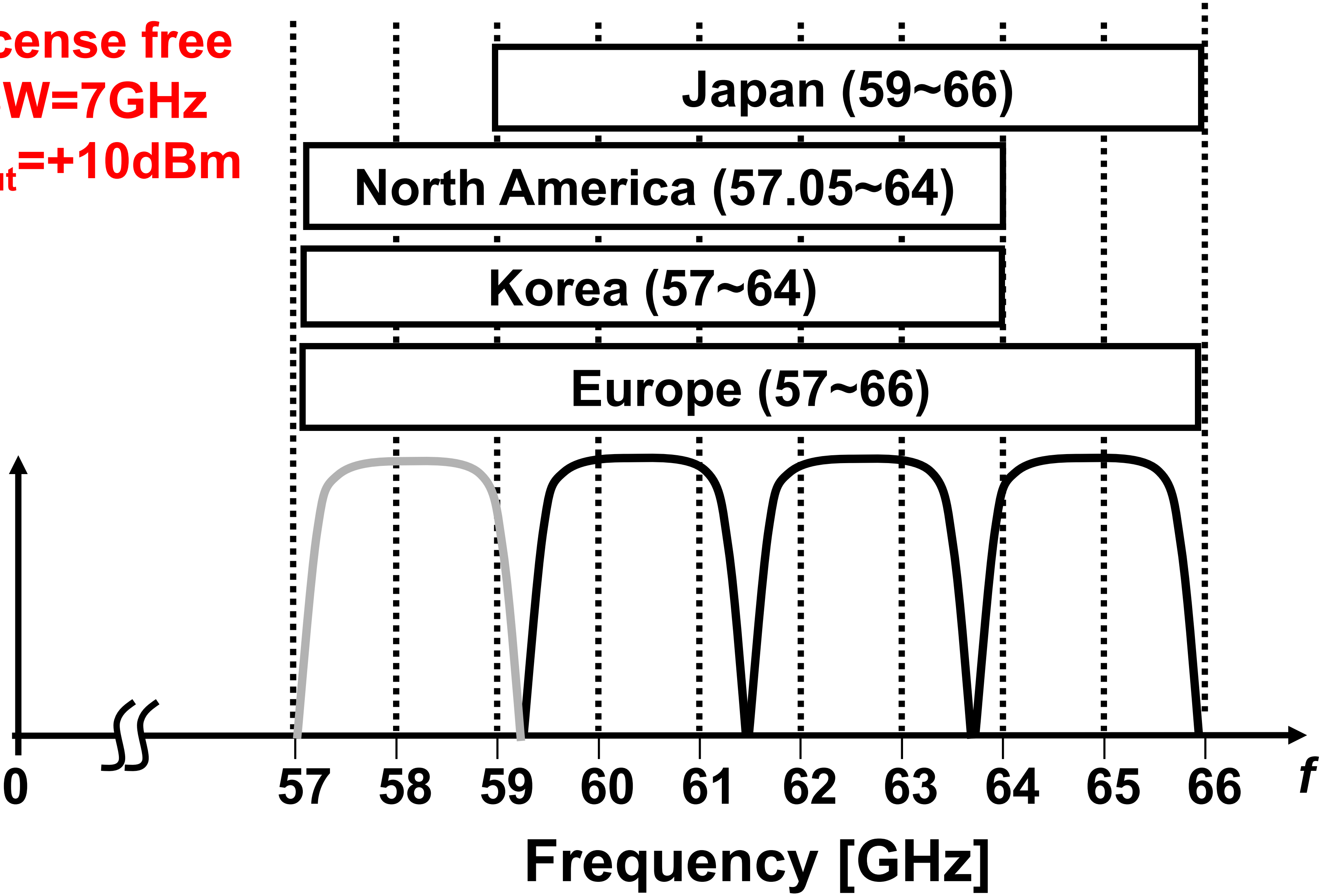
Distance: LOS ~1 meter
Bit Rates: 20 to 50+ Gbps
Cost: comparable to Bluetooth
Power consumption: comparable to Bluetooth

Contents

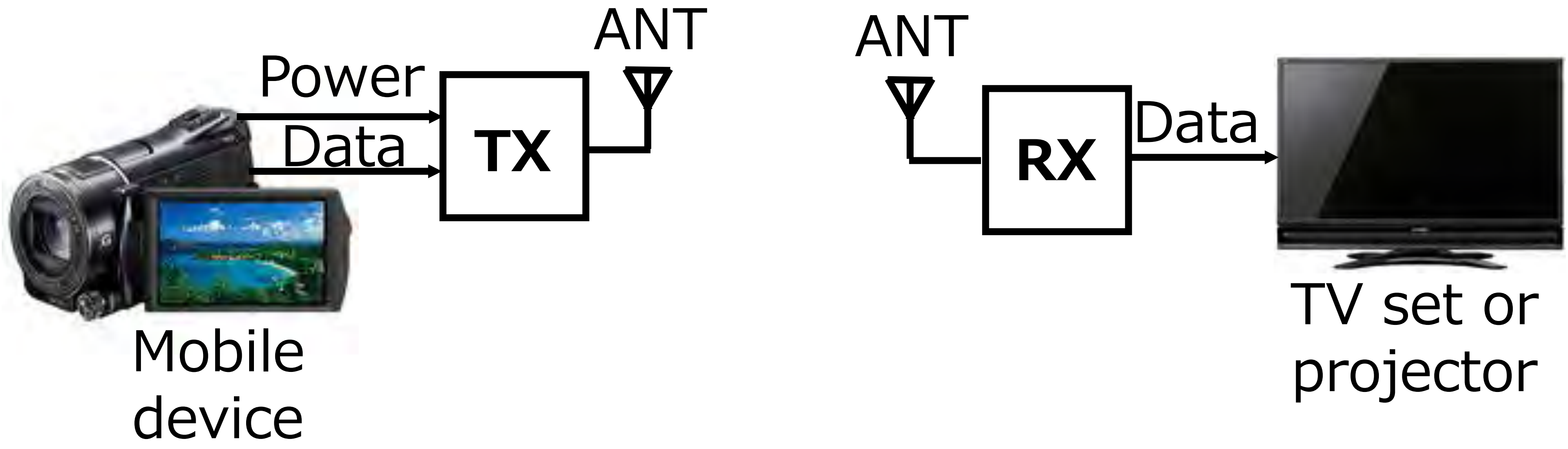
- mmW / THz CMOS Design
- 60GHz HDMI Transceiver
- 120 / 140GHz Dual Channel Receiver

Wideband 60GHz Regulations

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



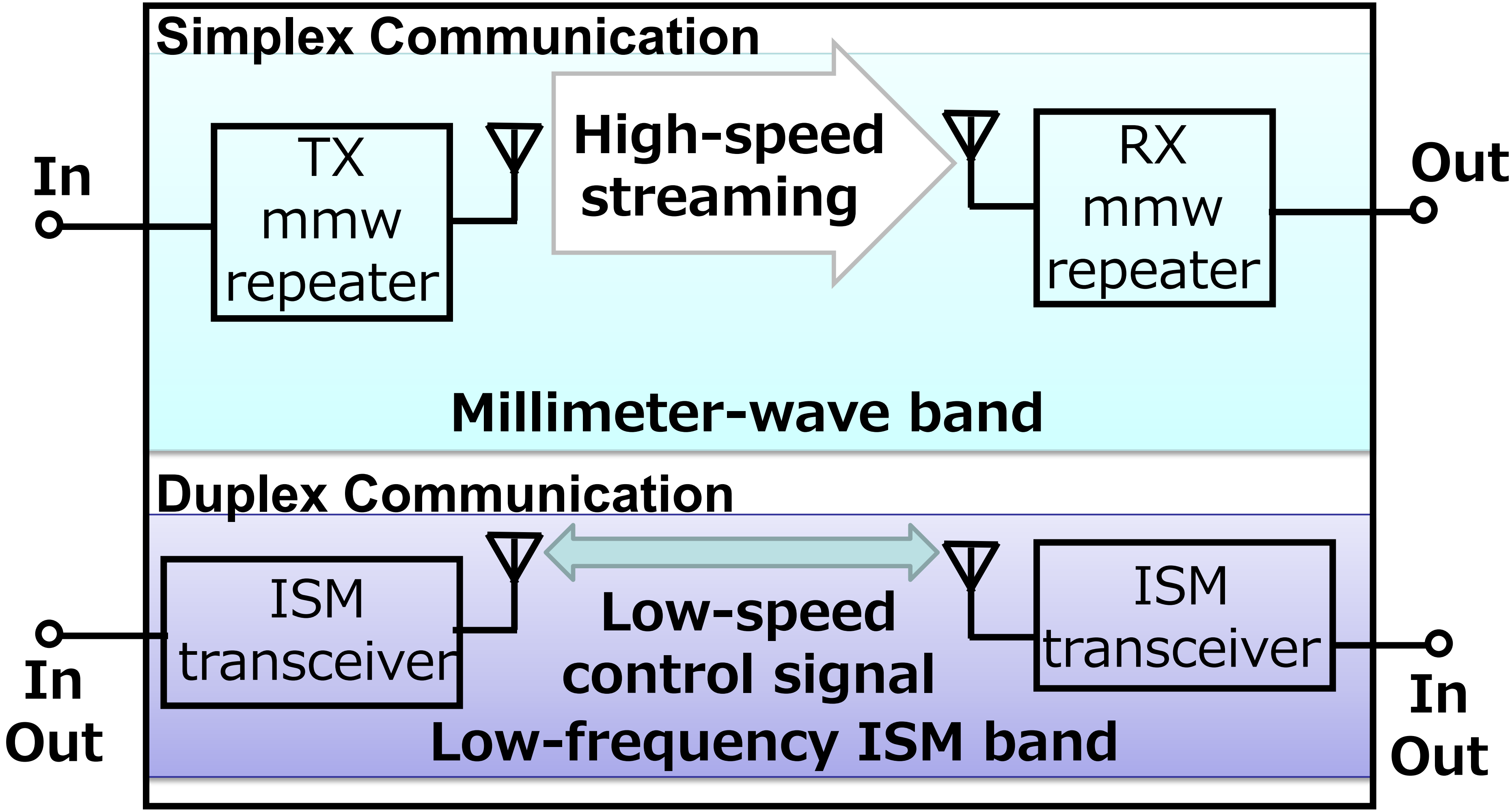
Target Application: Mobile Streaming



Mobile streaming application for mmw.

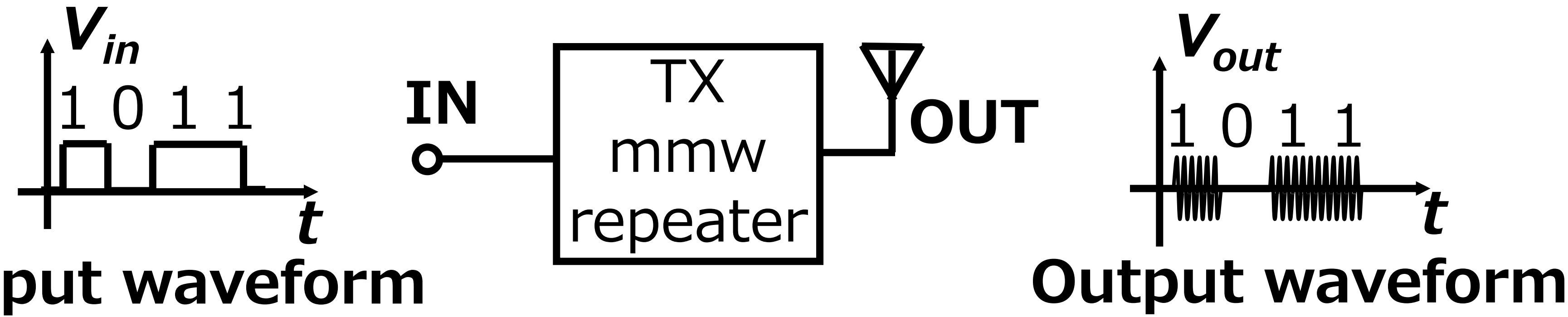
TX Power consumption should be reduced for mobile streaming applications.

mmWave Simplex Communication



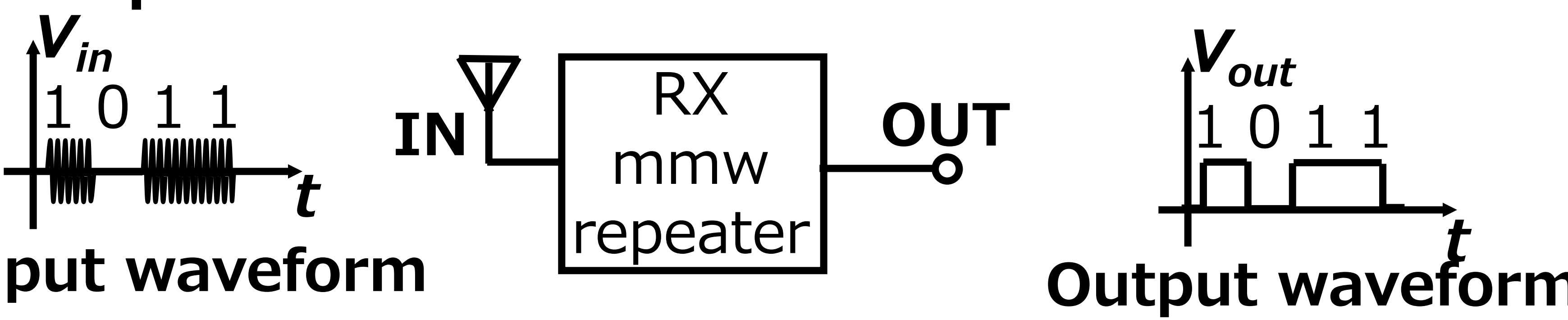
Repeater for Low Power

Tx "Repeater"



Digital data transfered from baseband to mmWave.

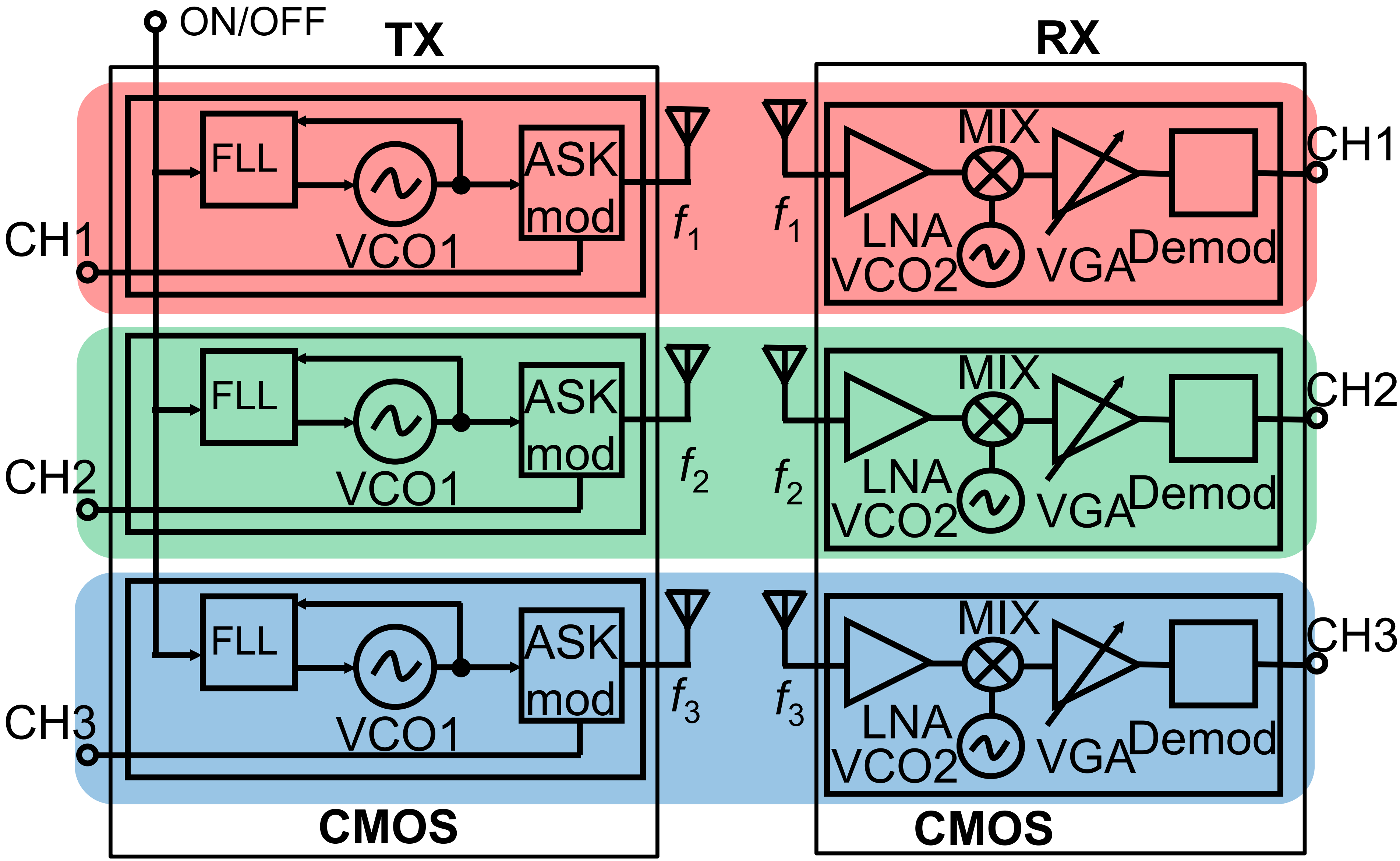
Rx "Repeater"



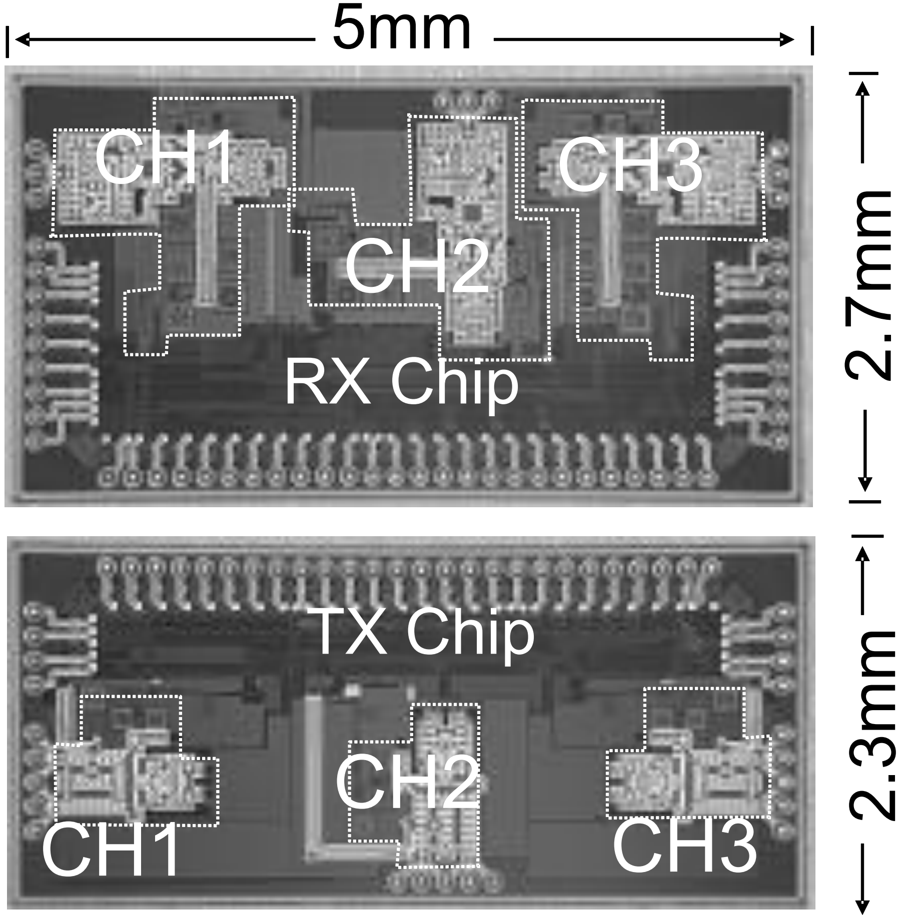
Digital data transfered from mmWave to baseband.

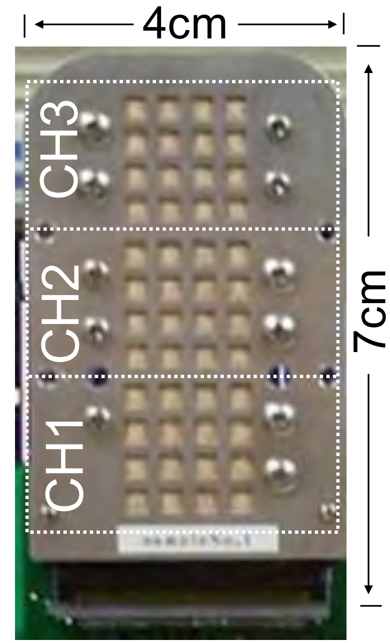
Simple architecture Realizes lower power.

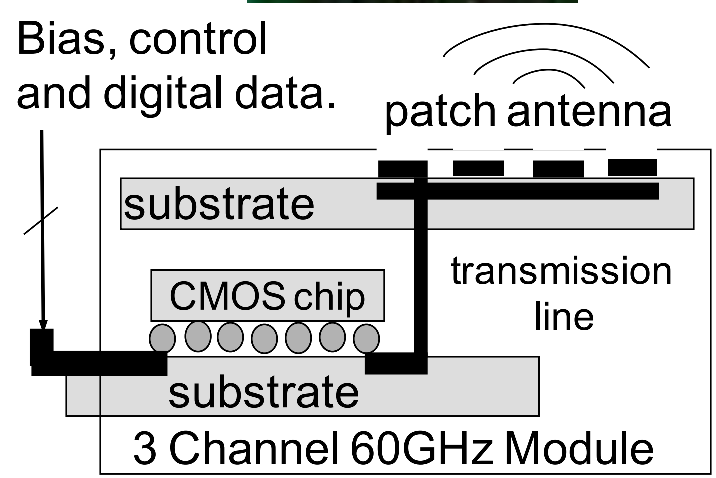
Low-Power 3CH TX and RX Repeaters



Chip and Module Photographs







Wireless Communication Measurement

System Spec.	Technology	Data Rate	TX RF Power [dBm]	RX Sensitivity or Noise Figure	Power Consumption (TX / RX) [mW]	Core area TX, RX [mm^2]
This Work	**90nm CMOS**	**1Gbps**	**5**	**-52dBm**	**51 / 116**	**0.85, 1.92**
[5]	90nm					

Contents

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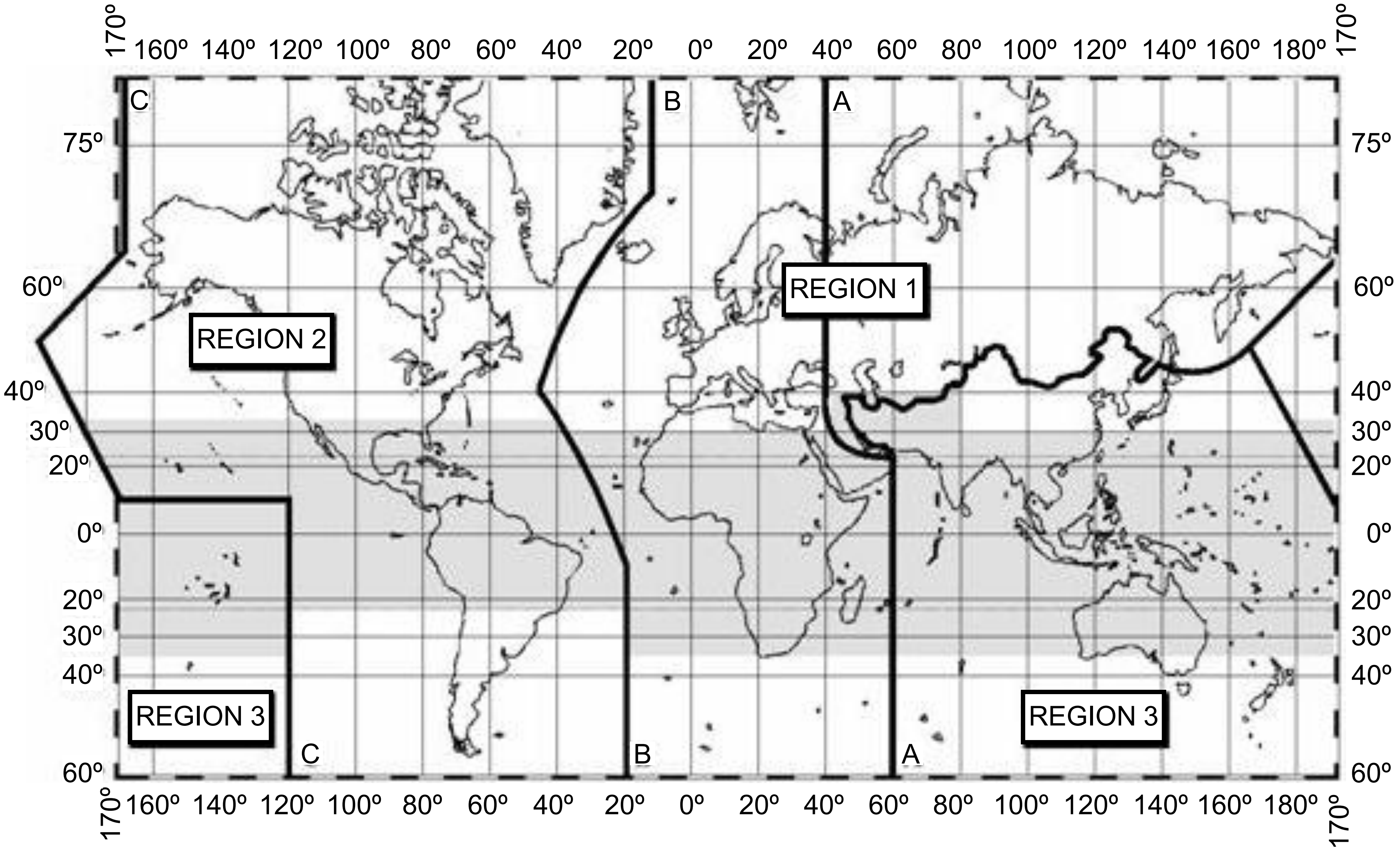
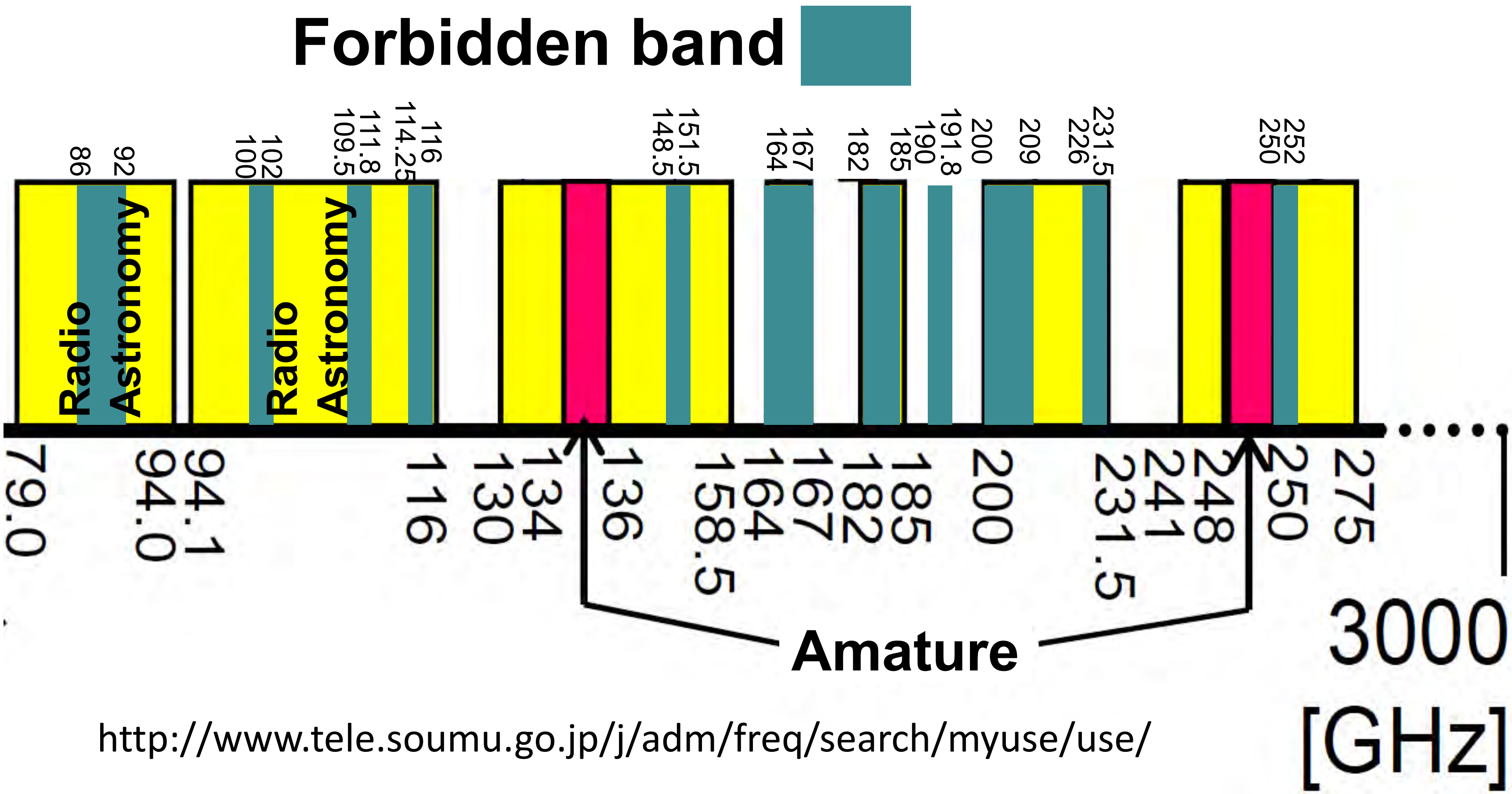
- mmW / THz CMOS Design
- 60GHz HDMI Transceiver
- 120 / 140GHz Dual Channel Receiver

Worldwide Radio Wave Allocation



Frequency Allocation in Japan (region 3)



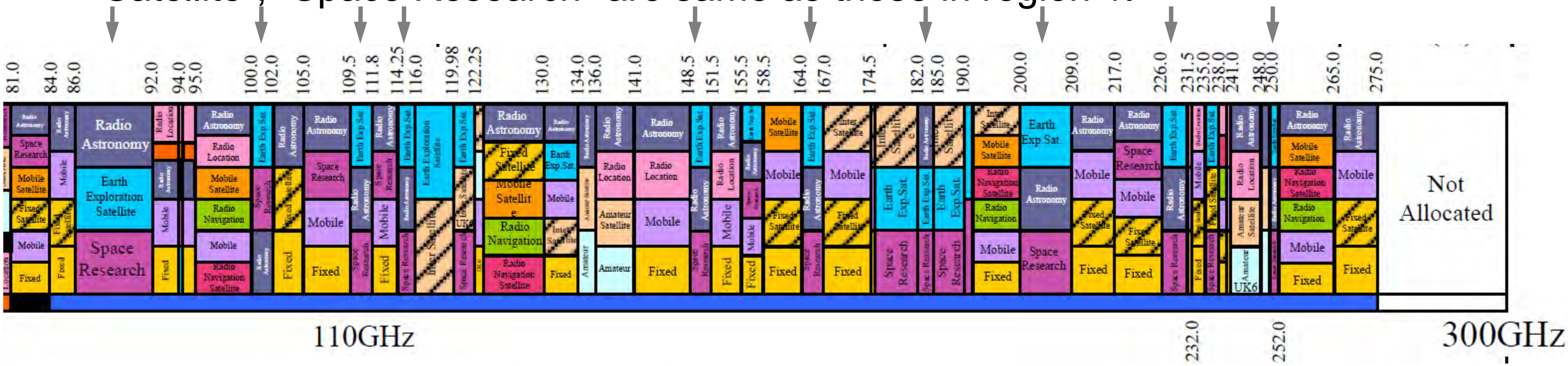
http://www.tele.soumu.go.jp/j/adm/freq/search/myuse/use/

Wireless communication may be available when the forbidden bands are avoided.

Frequency Allocation in Region 1 & 2

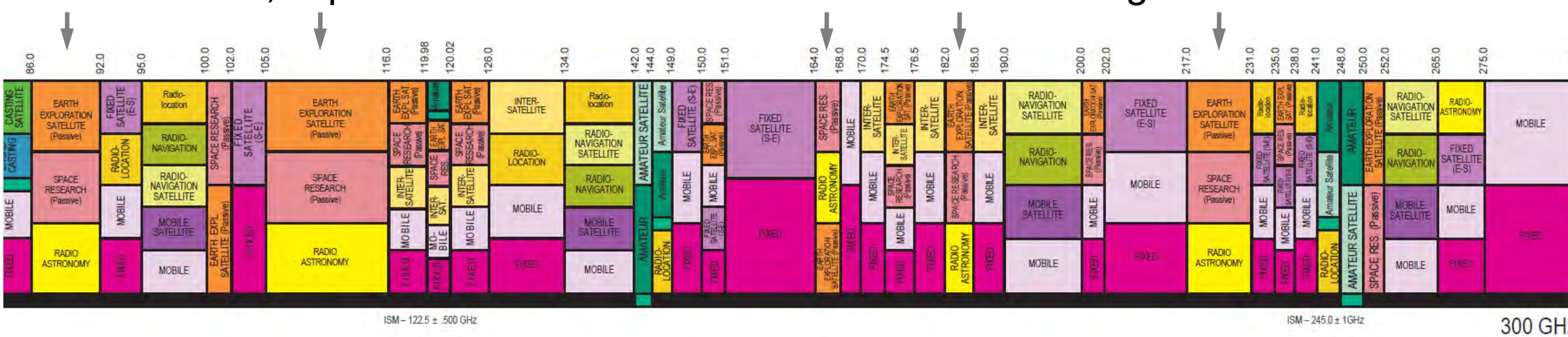
Frequency allocation in UK (region 1)

Forbidden bands exclusively used by “Radio Astronomy”, “Earth Exploration Satellite”, “Space Research” are same as those in region 1.



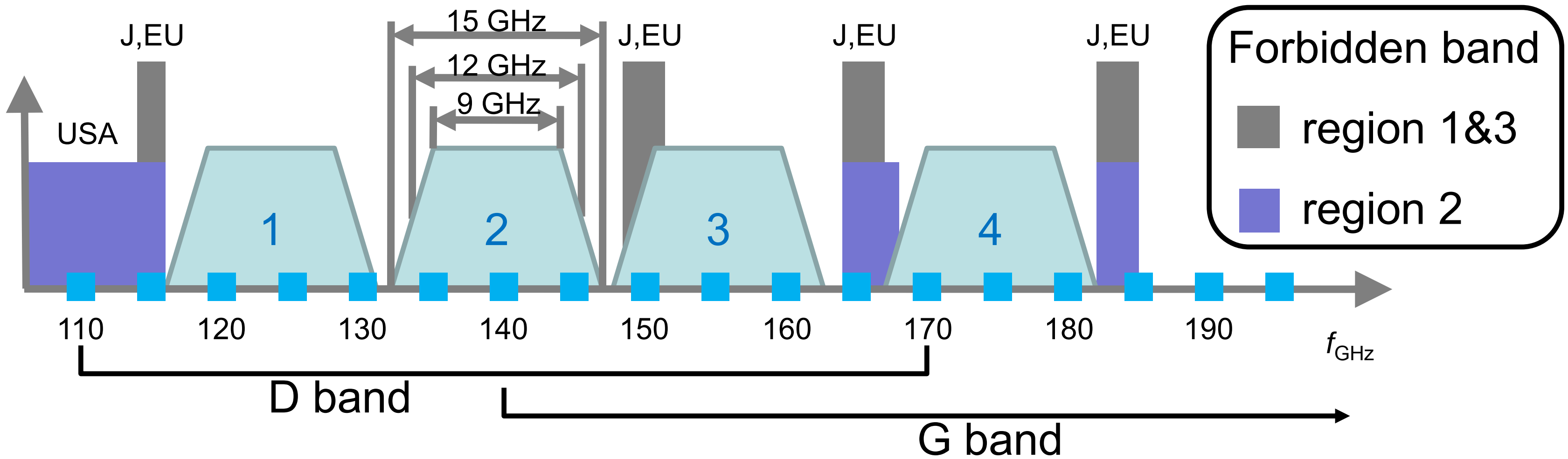
Frequency allocation in USA(region 2)

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



Channelization Plan for THz

Channel Number	Low Freq. (GHz)	Center Freq. (GHz)	High Freq. (GHz)	3dB BW (GHz)	Roll-Off Factor
1	116.589	124.089	131.589	12	0.25
2	132.100	139.600	147.100	12	0.25
3	147.611	155.111	162.611	12	0.25
4	167.000	174.500	182.000	12	0.25



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

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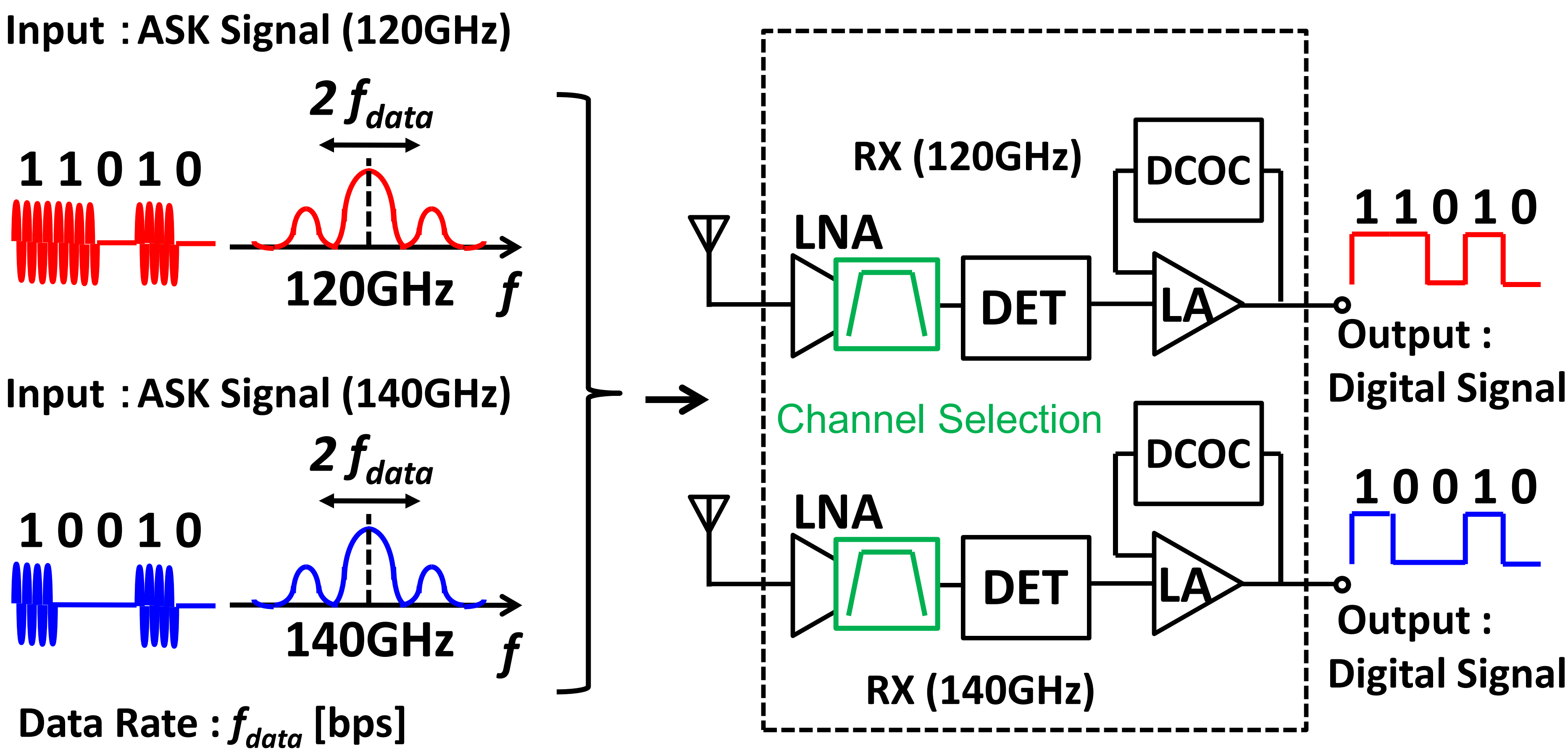
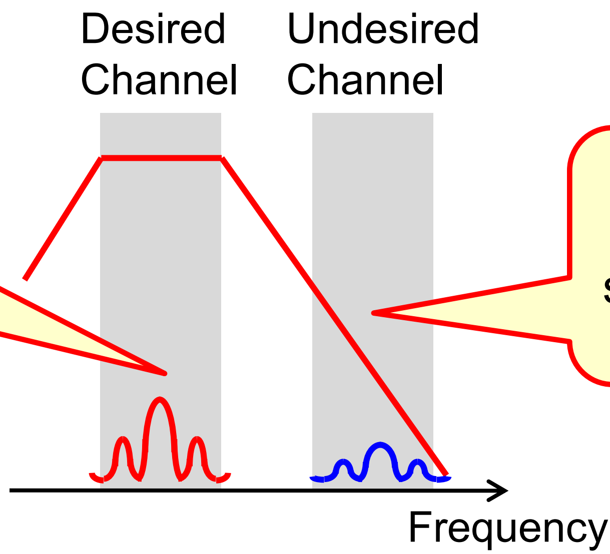


Channel Selection is required for receivers.

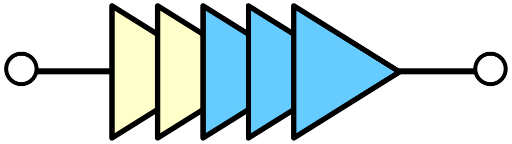
Channel Selection using LNA

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

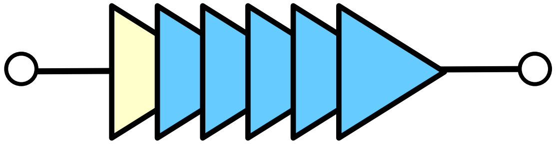


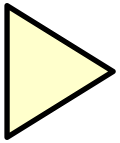
Low-gain property is required for channel selection in undesired channel.

120-GHz LNA
5 stage cascaded amplifier

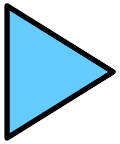


140-GHz LNA
6 stage cascaded amplifier





Cascode amplifier



Common source amplifier

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

Chip micrograph

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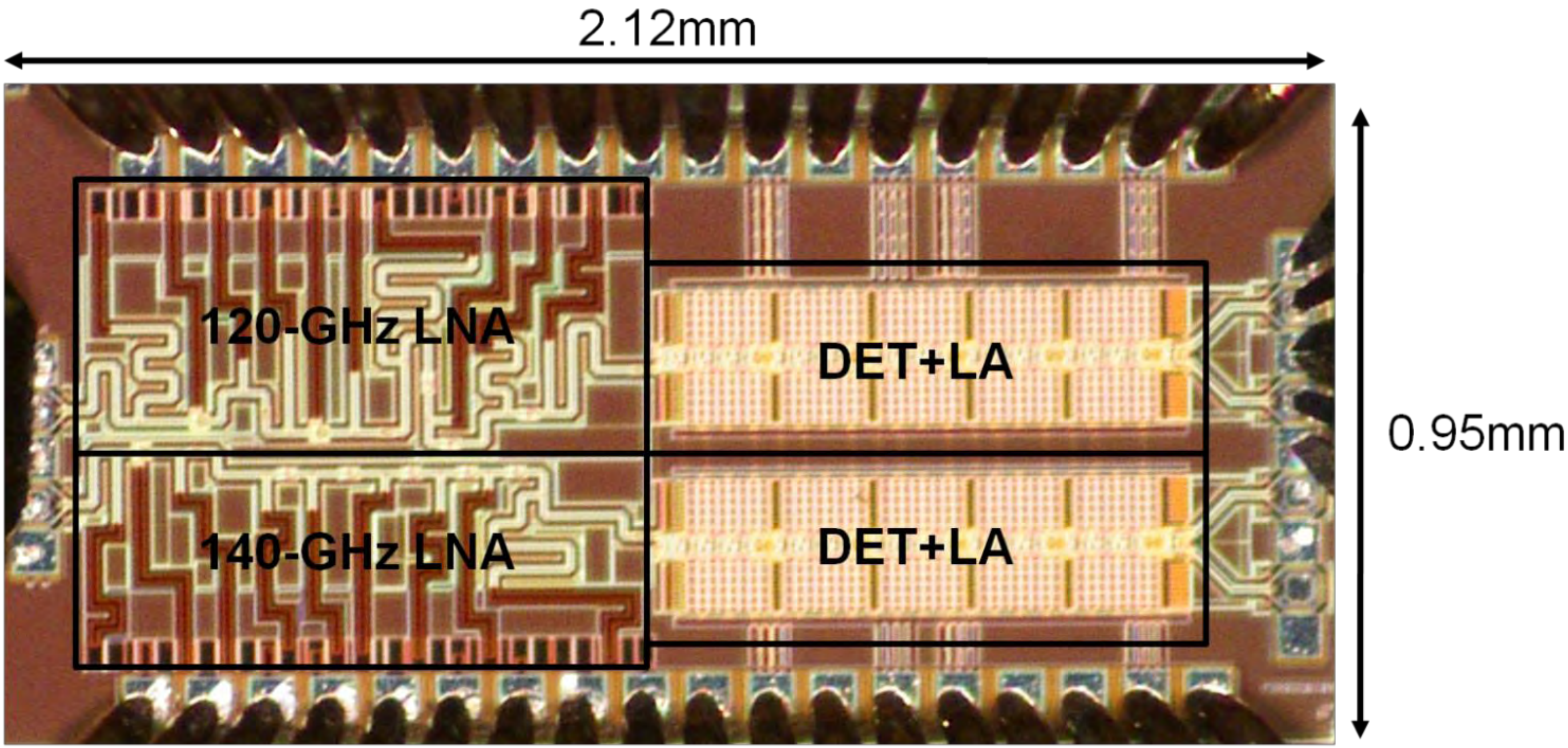
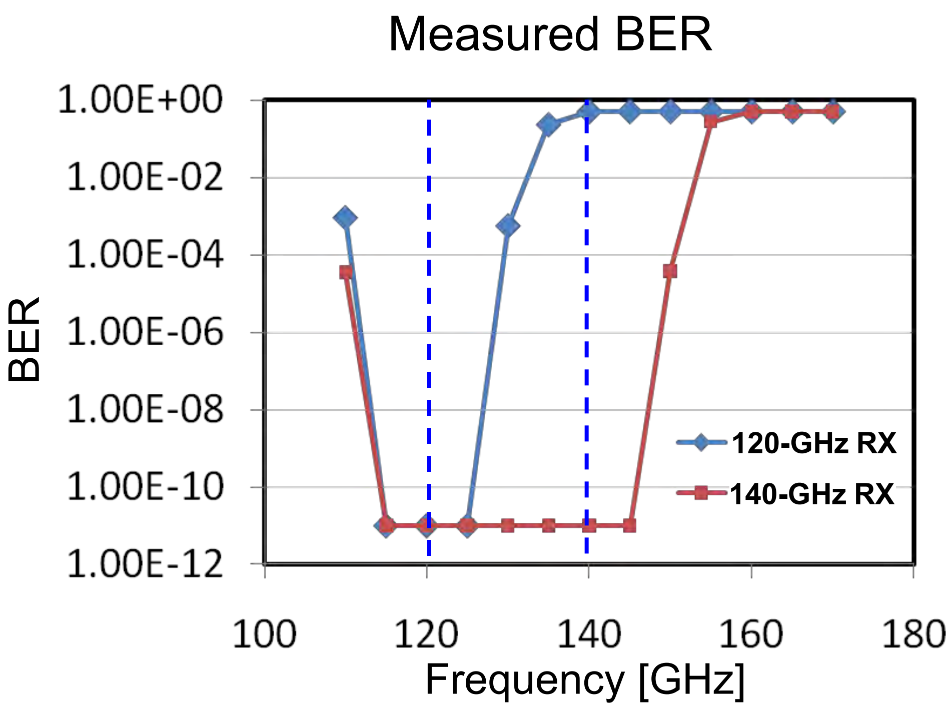
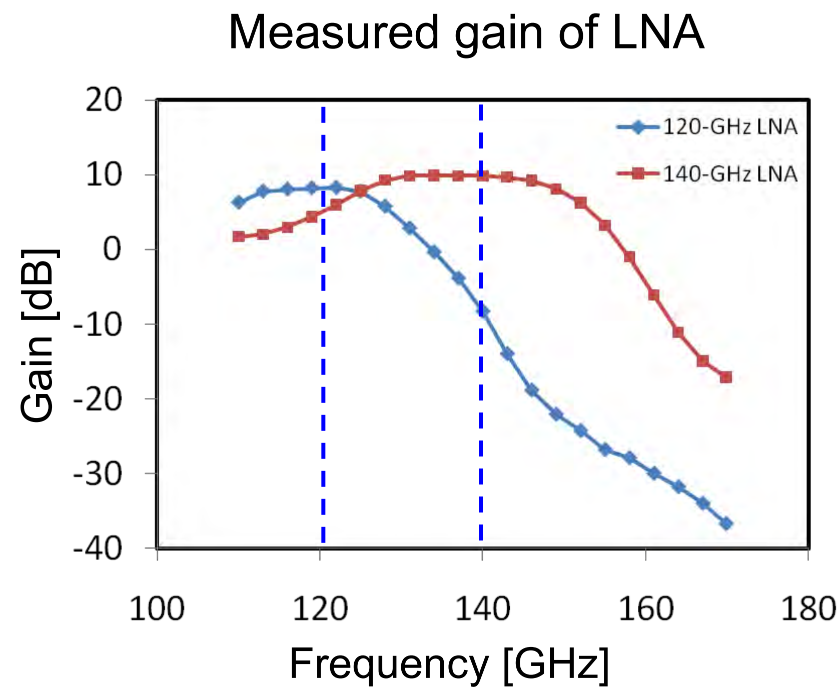


65nm CMOS Technology
Supply Voltage: 1.2V
Power Consumption: 85.7mW (120GHz-RX)
111.7 mW (140GHz-RX)

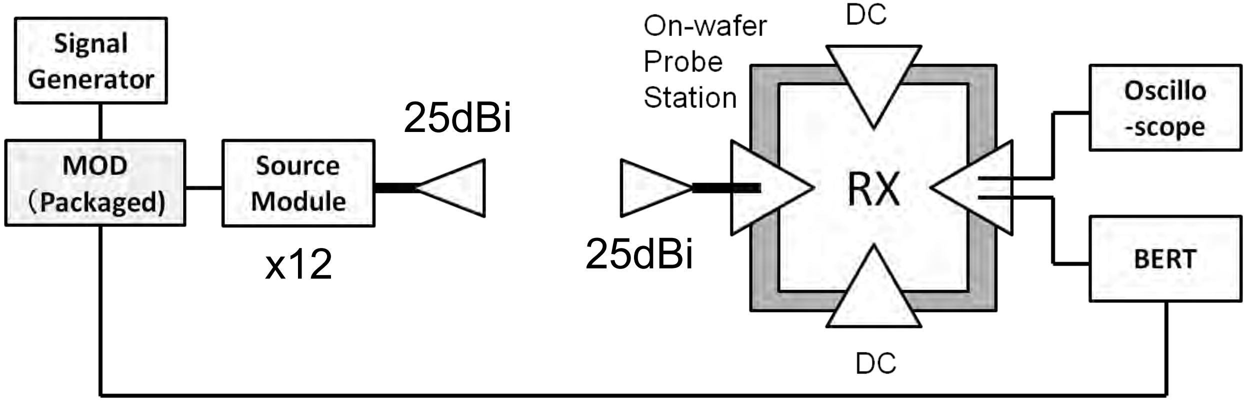
Frequency Response of LNA



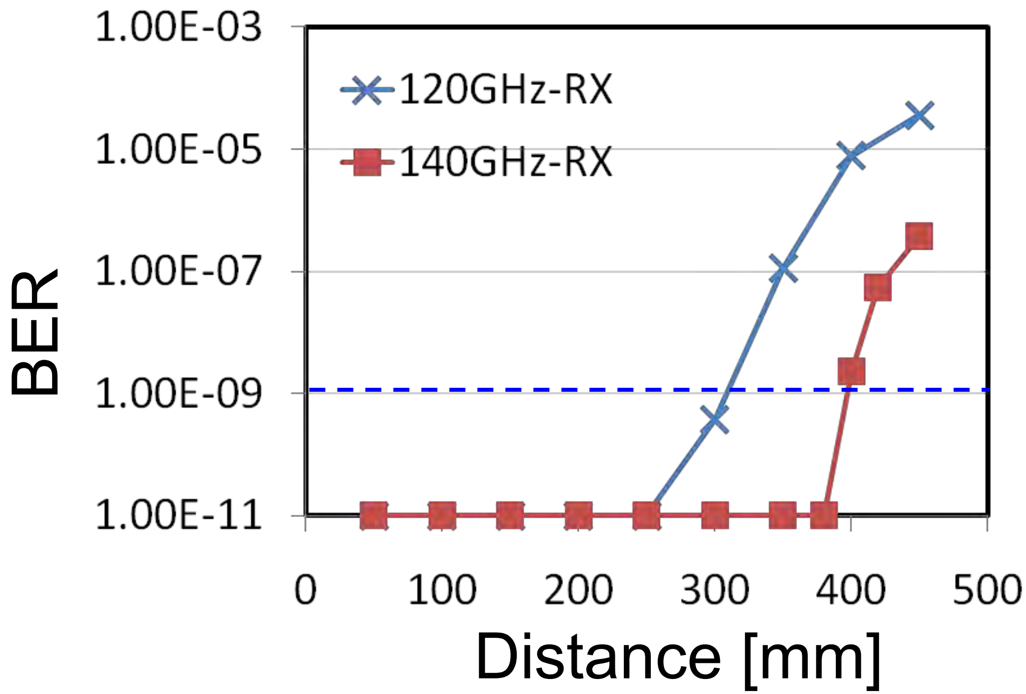


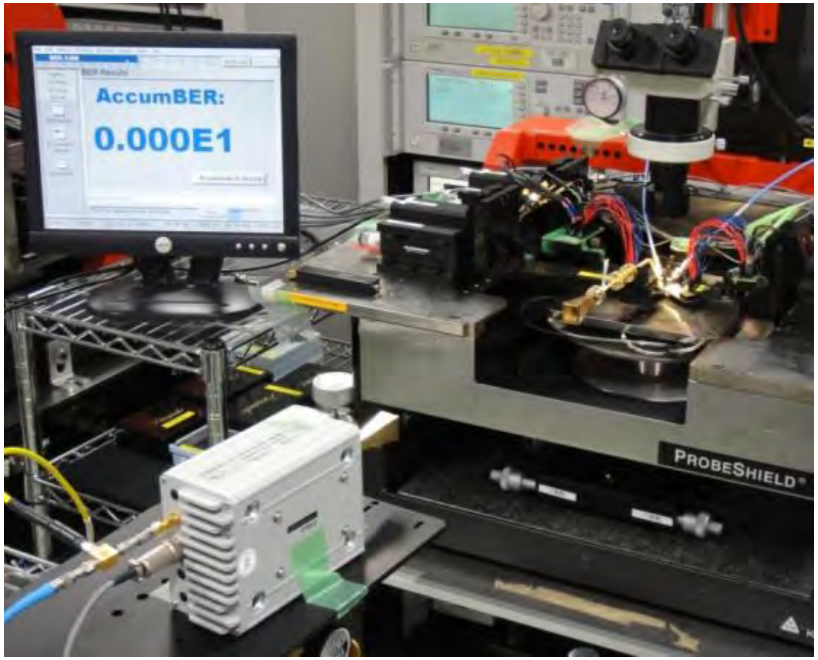
Gain bandwidth of 140-GHz LNA is too wide.
Channel selection is degraded.

Wireless Measurement



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





Benchmark Result

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

(*) 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

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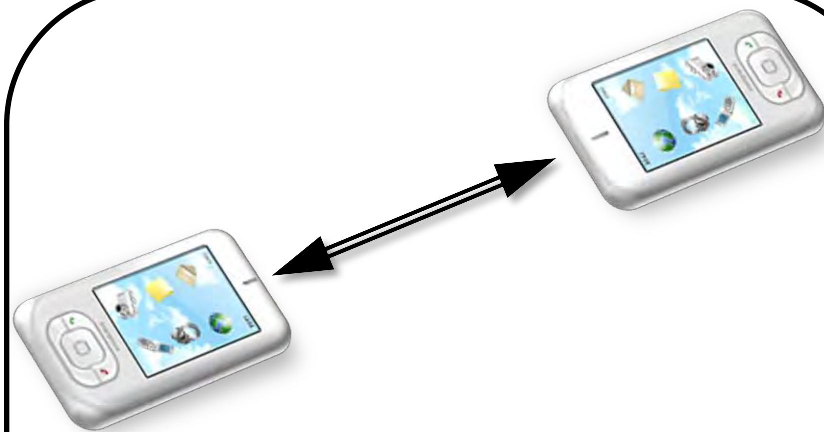
Winning Solution

Rick Roberts (Intel)



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

- This study was partially supported by The Semiconductor Technology Academic Research Center (STARC), the Core Research for Evolutional Science and Technology (CREST) of the Japan Science and Technology Agency (JST), Extremely Low Power (ELP) project supported by the Ministry of Economy, Trade and Industry (METI) and the New Energy and Industrial Technology Development Organization (NEDO).