Test Structures for Millimeter-Wave CMOS Circuit Design

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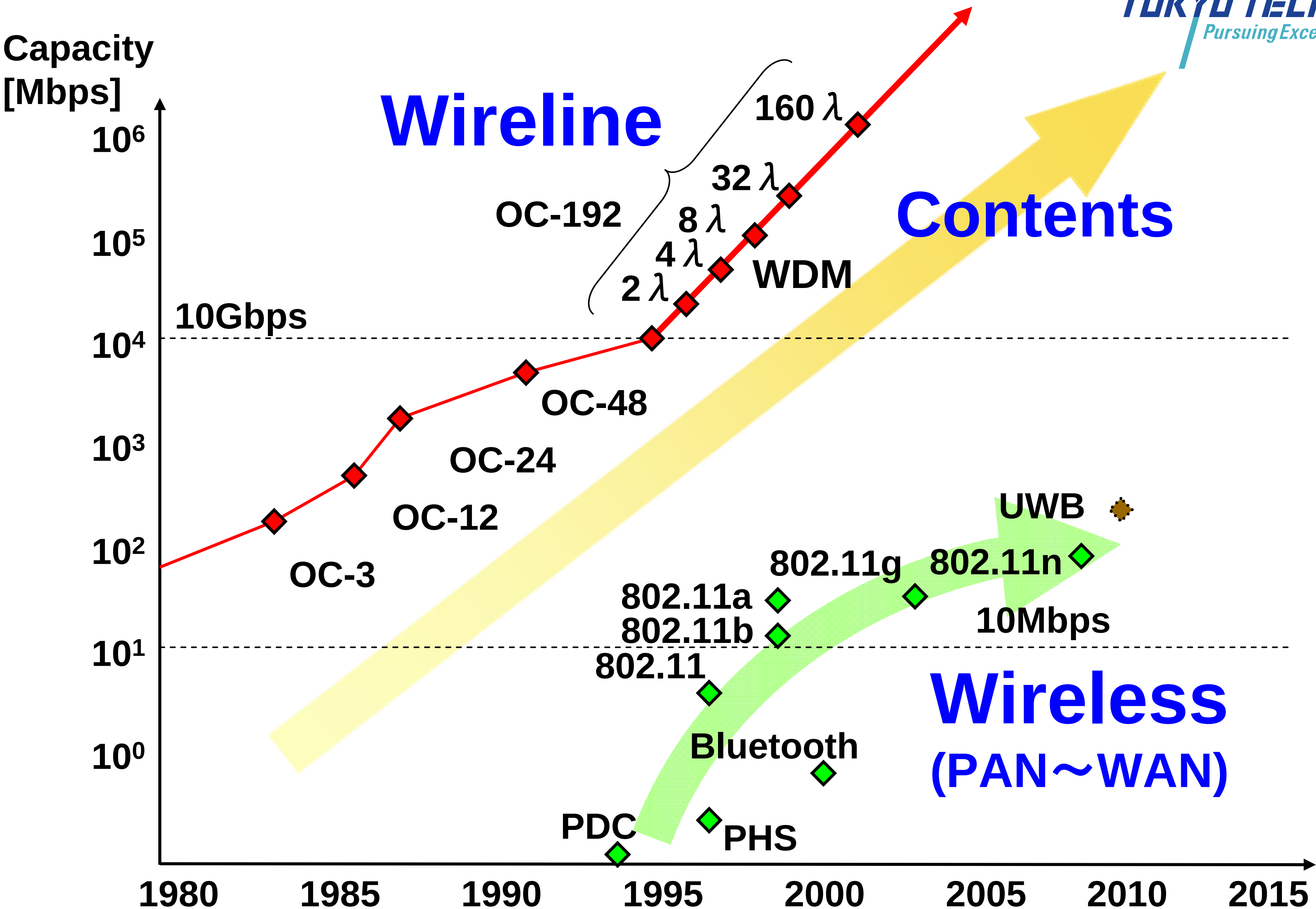
Outline

- Motivation
- Issues for mmW CMOS Circuits
- Device Characterization
- De-embedding
- Conclusion

Motivation



Capacity [Mbps]
10^6
10^5
10^4
10^3
10^2
10^1
10^0
Wireline
Contents
160 λ
32 λ
8 λ
4 λ
2 λ
WDM
OC-192
10Gbps
OC-48
OC-24
OC-12
OC-3
UWB
802.11g
802.11n
802.11a
802.11b
10Mbps
802.11
Wireless
(PAN～WAN)
Bluetooth
PDC
PHS
1980
1985
1990
1995
2000
2005
2010
2015

Motivation

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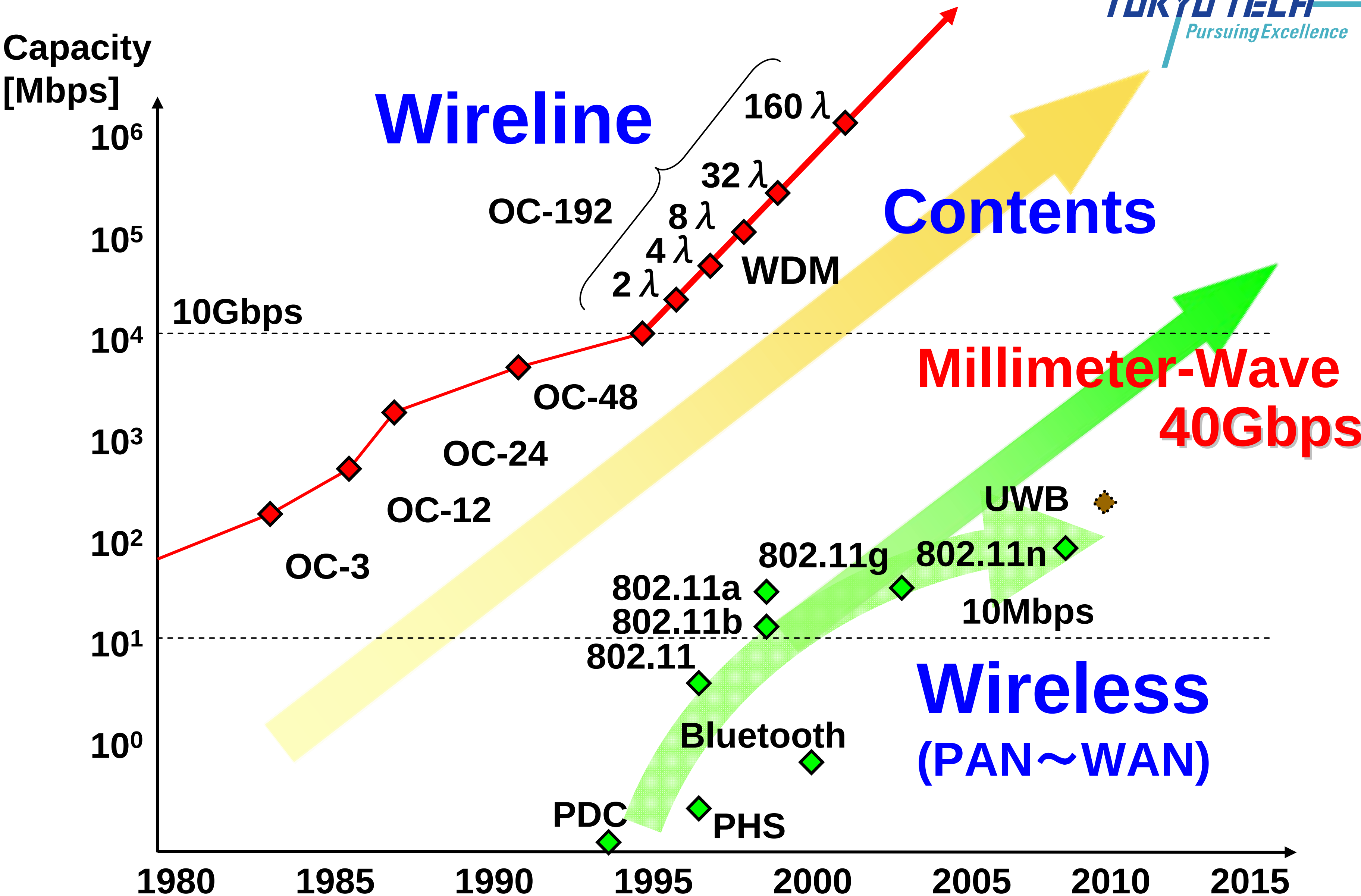

Matsuzawa & Okada Lab.

Applications

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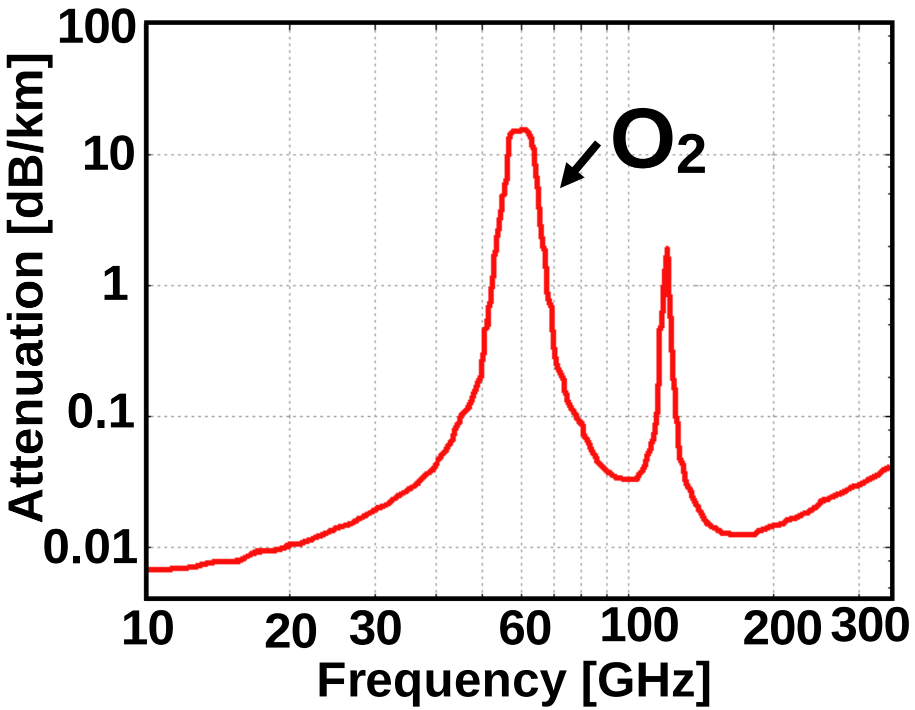
24GHz: Automotive radar

60GHz: IEEE 802.15.3c, WirelessHD, etc.

77-79GHz: Automotive radar

94GHz: Imaging

Ultra high speed
Wireless communication
By CMOS



*Rec. ITU-R P.676-2, Feb. 1997

60GHz ISM band

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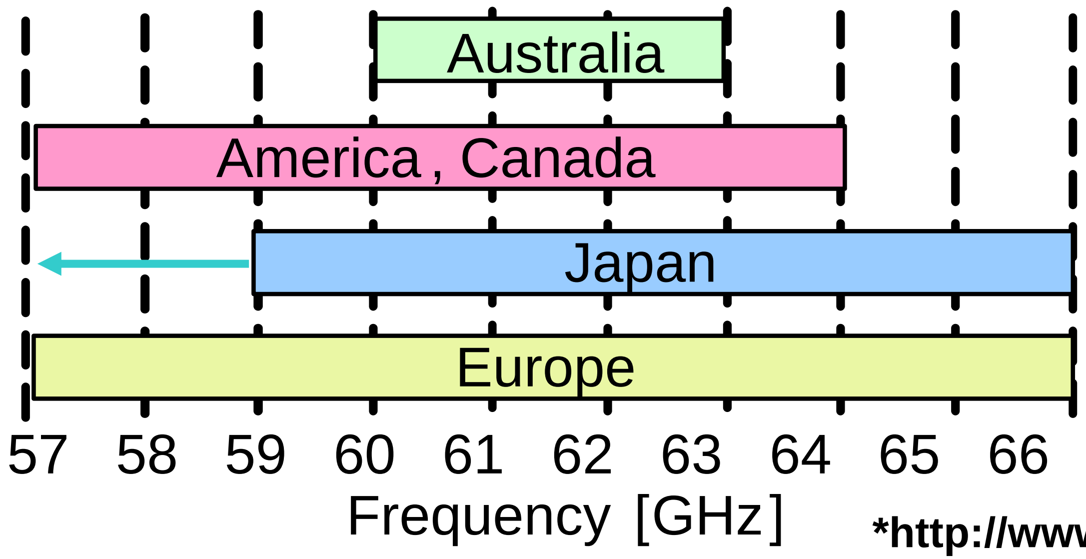
60GHz unlicensed band



*http://www.tele.soumu.go.jp

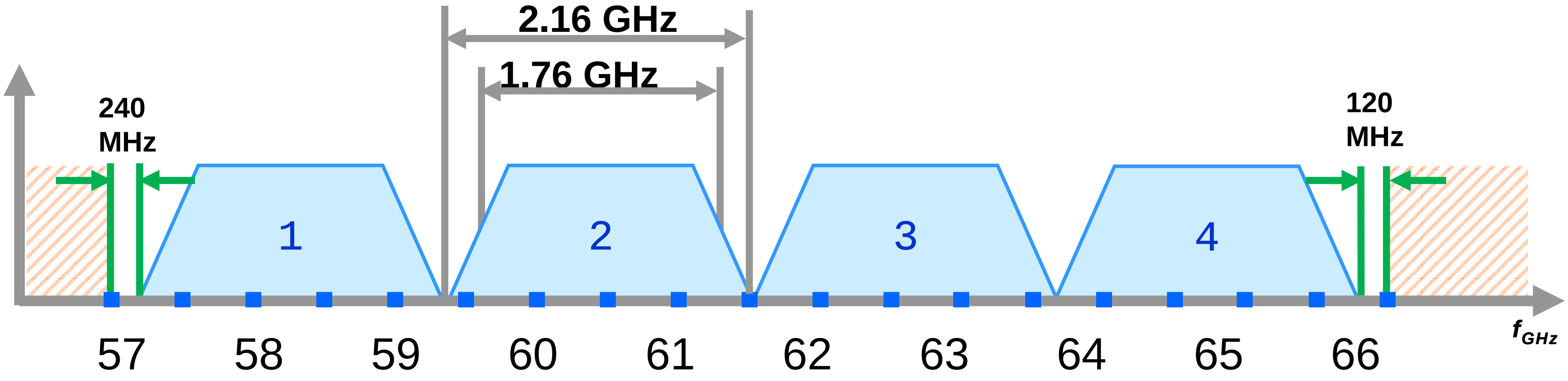
- **9GHz-BW around 60GHz**
  ➡ **Several-Gbps wireless communication**
- **Use of CMOS process**
  ➡ **Fab. cost is very important to generalize it. RF&BB mixed chip can be realized.**

60GHz channel plan

IEEE802.15.3c

Ref: IEEE 802.15-09-192-003c with draft doc.

Channel Number	Low Freq. (GHz)	Center Freq. (GHz)	High Freq. (GHz)	Nyquist BW (GHz)	Roll-Off Factor
A1	57.24	58.32	59.40	1.76	0.227
A2	59.40	60.48	61.56	1.76	0.227
A3	61.56	62.64	63.72	1.76	0.227
A4	63.72	64.80	65.88	1.76	0.227



4 channel of 2.16GHz-BW

Overview on TG3c System Design

- **One unified MAC**
- **Three PHYs optimized for respective and specific market segments**
  - **Single carrier (SC) PHY**
    - **low complexity, low power consumption and low cost**
    - **handheld mobile applications**
  - **High speed interface (HSI) PHY - OFDM**
    - **low latency bi-directional data communications**
    - **PC peripherals**
  - **AV PHY - OFDM**
    - **optimized for high speed uncompressed video transmission**
    - **Audio/visual consumer electronics (CE) applications**

Ref: IEEE 802.15-09-192-003c

***e.g.*, 3Gbps(QPSK), 6Gbps(16QAM), 9Gbps(64QAM) x4ch**

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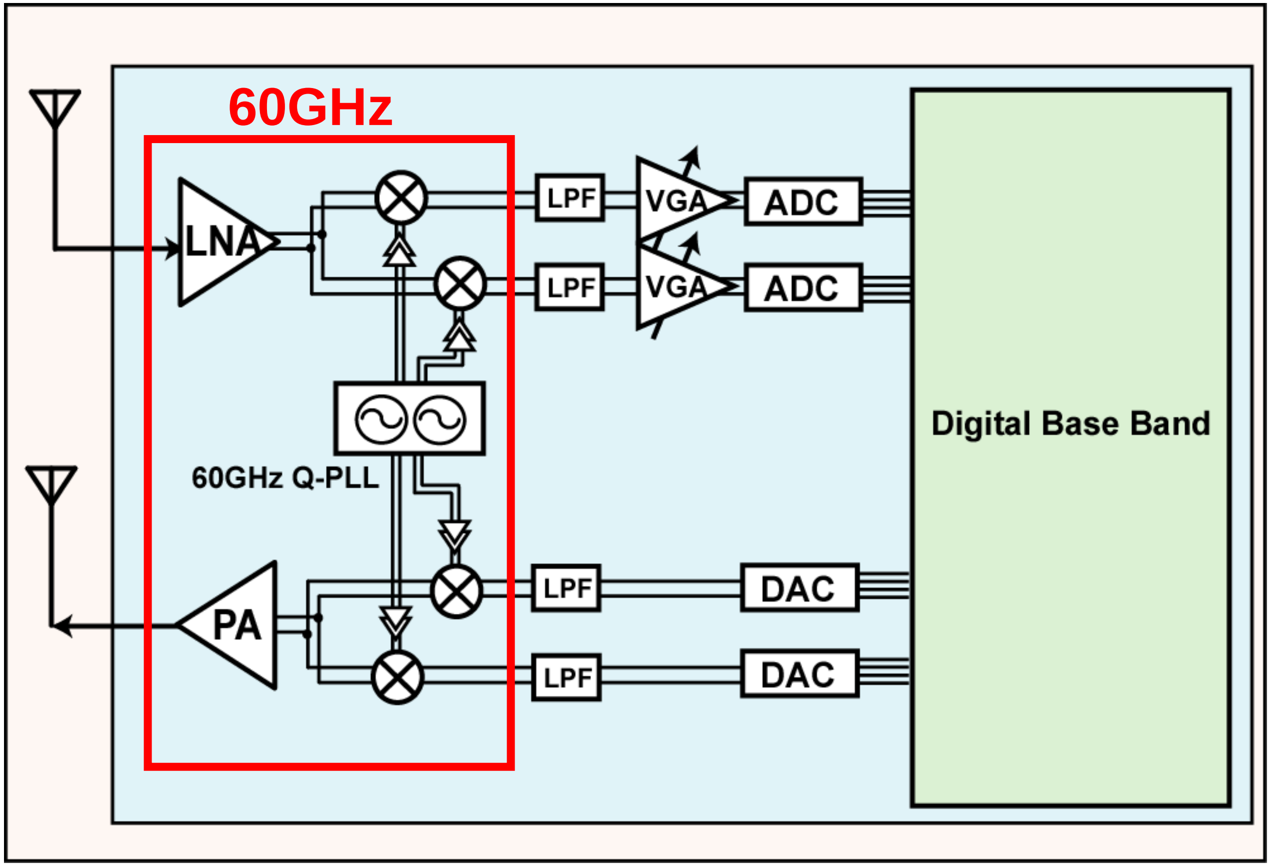
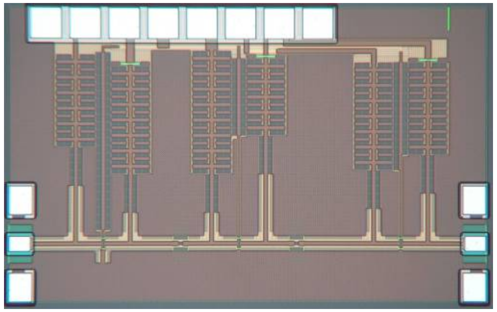
60GHz Direct-conversion transceiver

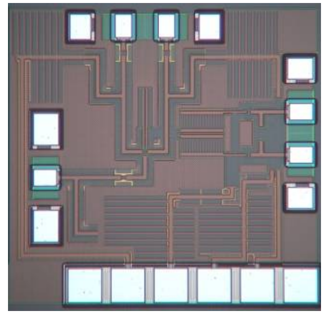


60GHz 2.16GHz-full 4ch direct-conversion by CMOS Tr
QPSK 3Gbps & 16QAM 6Gbps & 64QAM 9Gbps
IEEE 802.15.3c conformance
Dynamic power management: <300mW for RF front-end

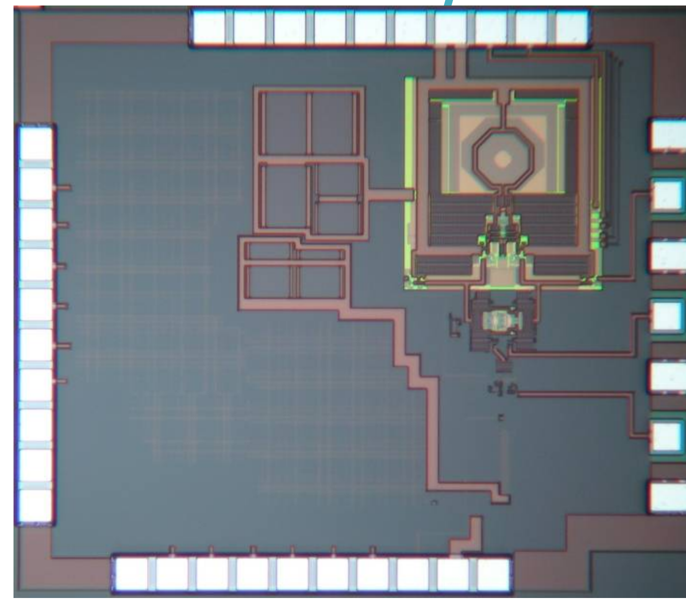
Circuit blocks of 60GHz transceiver



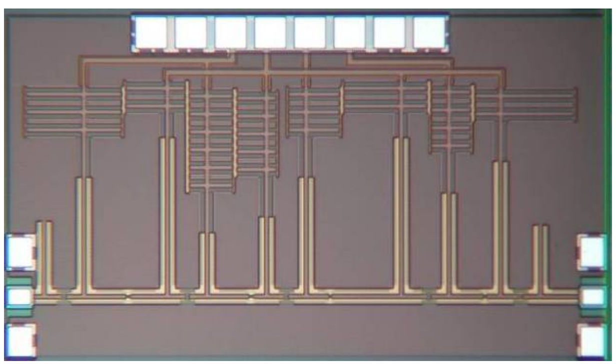
60GHz LNA



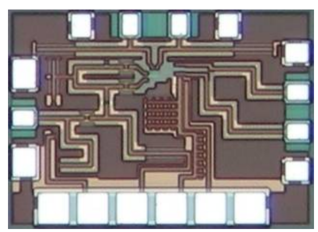
Down-Mixer



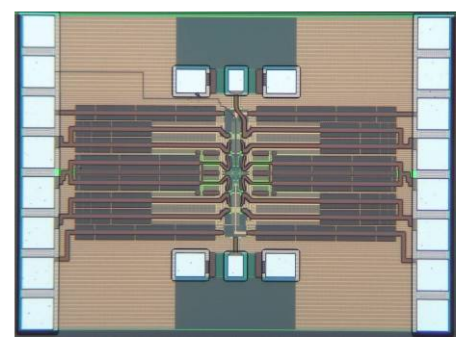
20GHz PLL



60GHz PA



Up-Mixer



I/Q Tripler

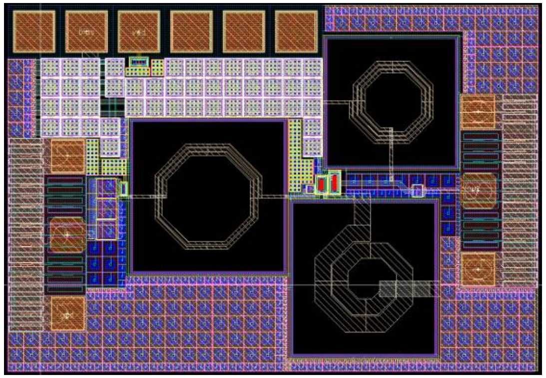
FUJITSU(Eshuttle) CMOS 65nm

mmW CMOS circuit design

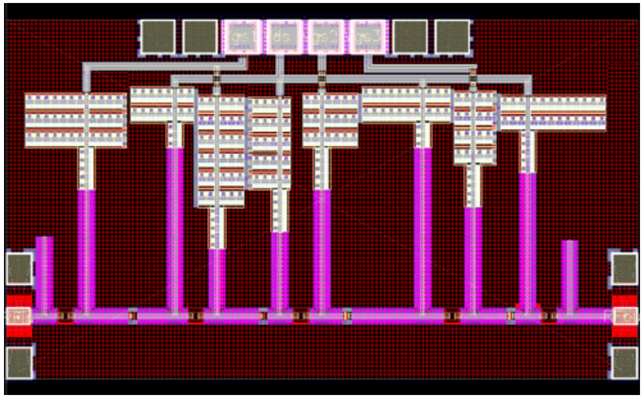
Layout parasitics become critical for mmW circuit design.

1. **Interconnects between circuit components become close to the wave length.**
2. **Dummy metal for CMP**
3. **Tr gain is very small, and TL is lossy.**

Matching blocks



Inductor@5GHz

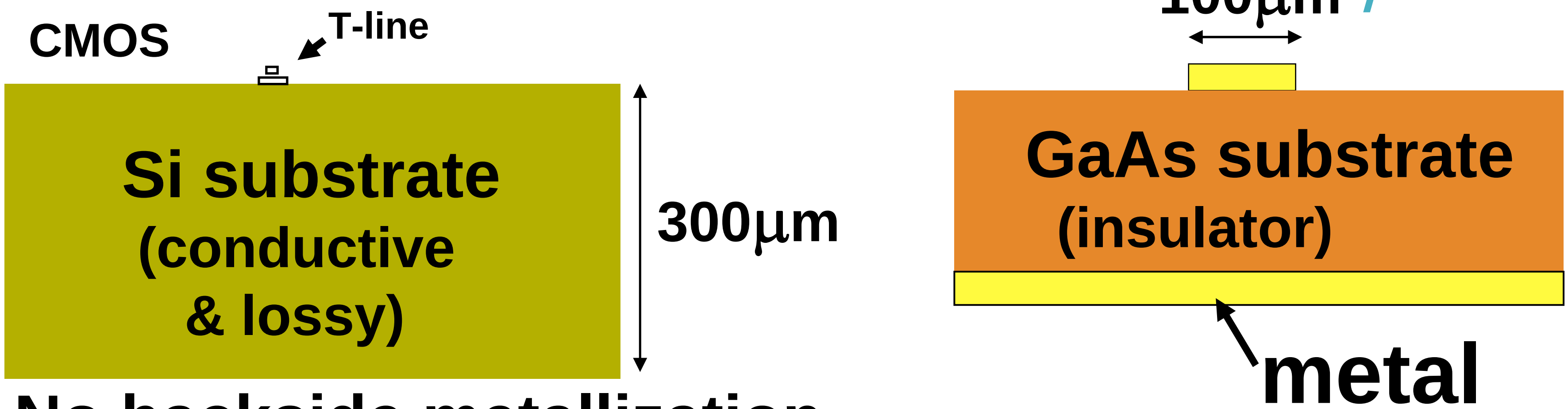


Transmission line@60GHz

At 60GHz, every interconnects should be dealt with as a distributed component.

➡ **The accurate characterization is required.**

Loss of passive devices



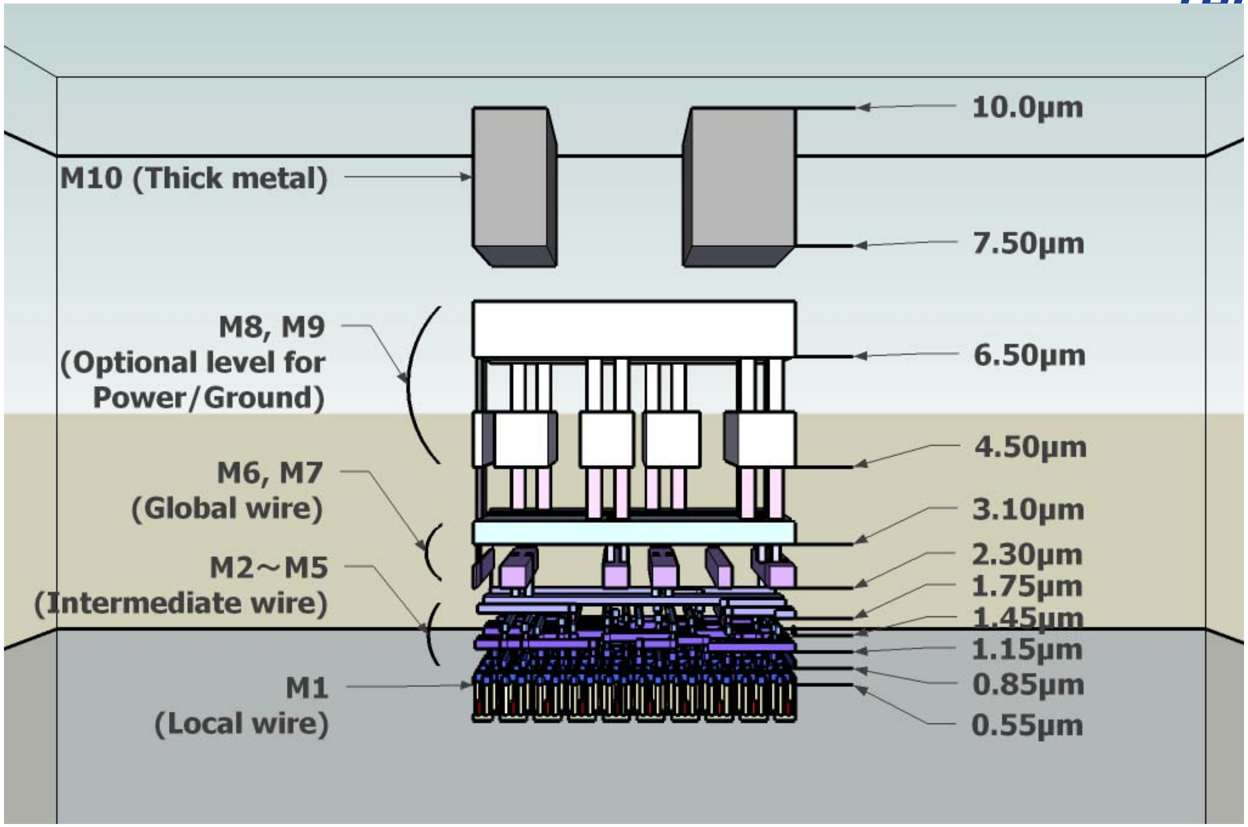
No backside metallization

Conductor loss + Substrate eddy-current loss

50Ω T-line loss: 0.5 – 1.5dB/mm @60GHz

	Si CMOS	GaAs
Wire width	10µm	100µm
Wire thickness	1 – 2µm	10µm
Dielectric thickness	< 5µm	100µm

Multi-level interconnects(65nm CMOS)

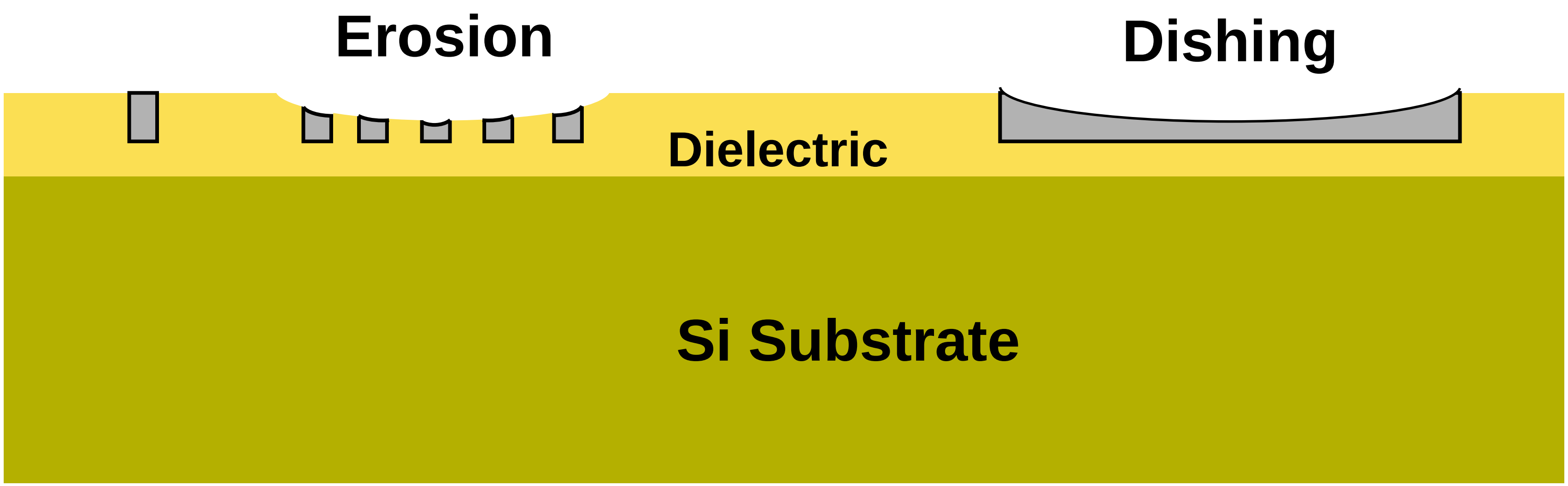


http://www.tamaru.kuee.kyoto-u.ac.jp/~tsuchiya/LSI-3D-CG.html

- **Every tiers have a different cross-sectional structure with different dielectric constant.**
- **EM simulation becomes considerably difficult.**
- **Cu wire needs high-resistance barrier metal.**

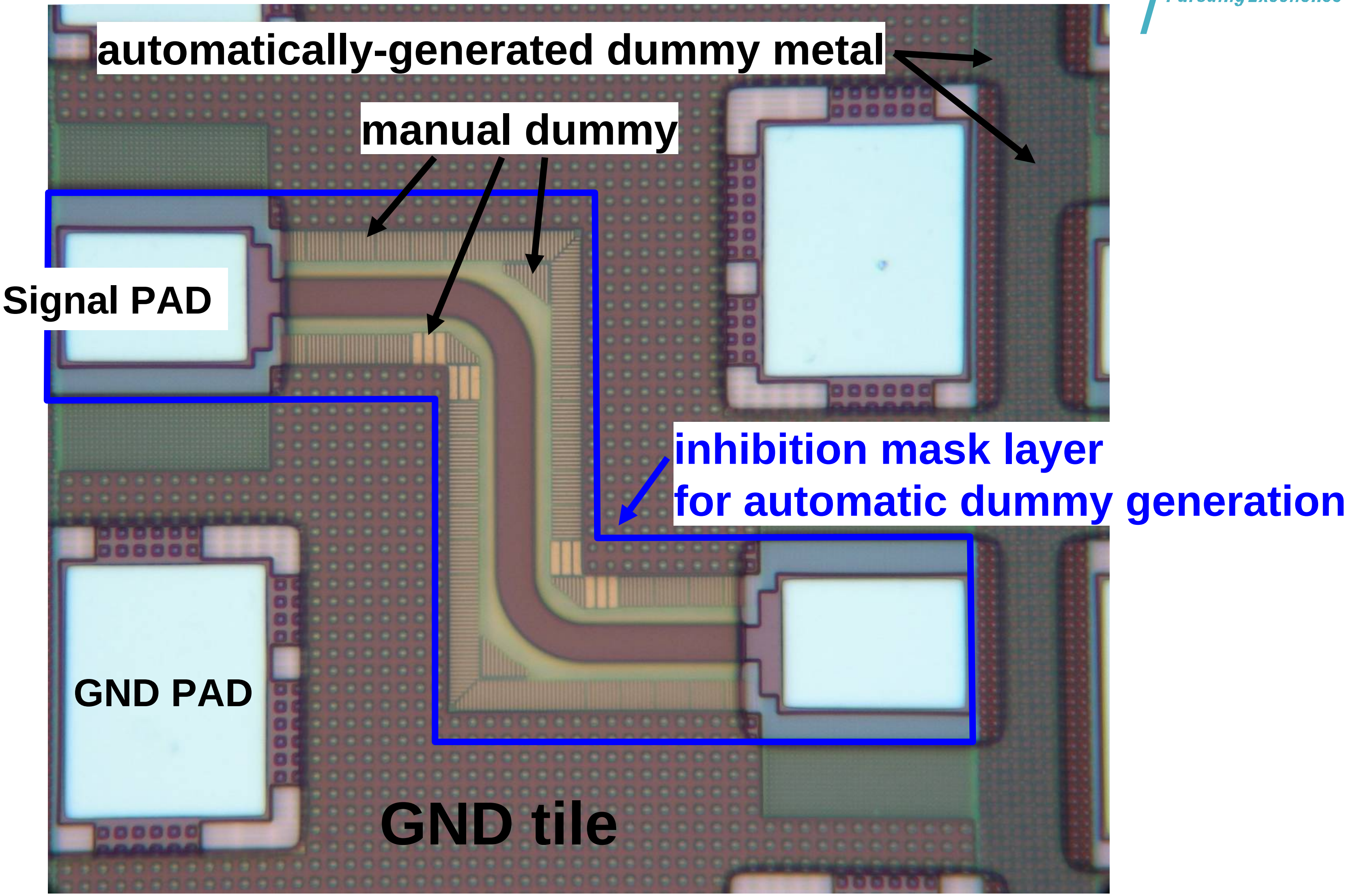
Density rule for CMP

CMP (Chemical Mechanical Polishing/Planarization) every metal layers are polished.



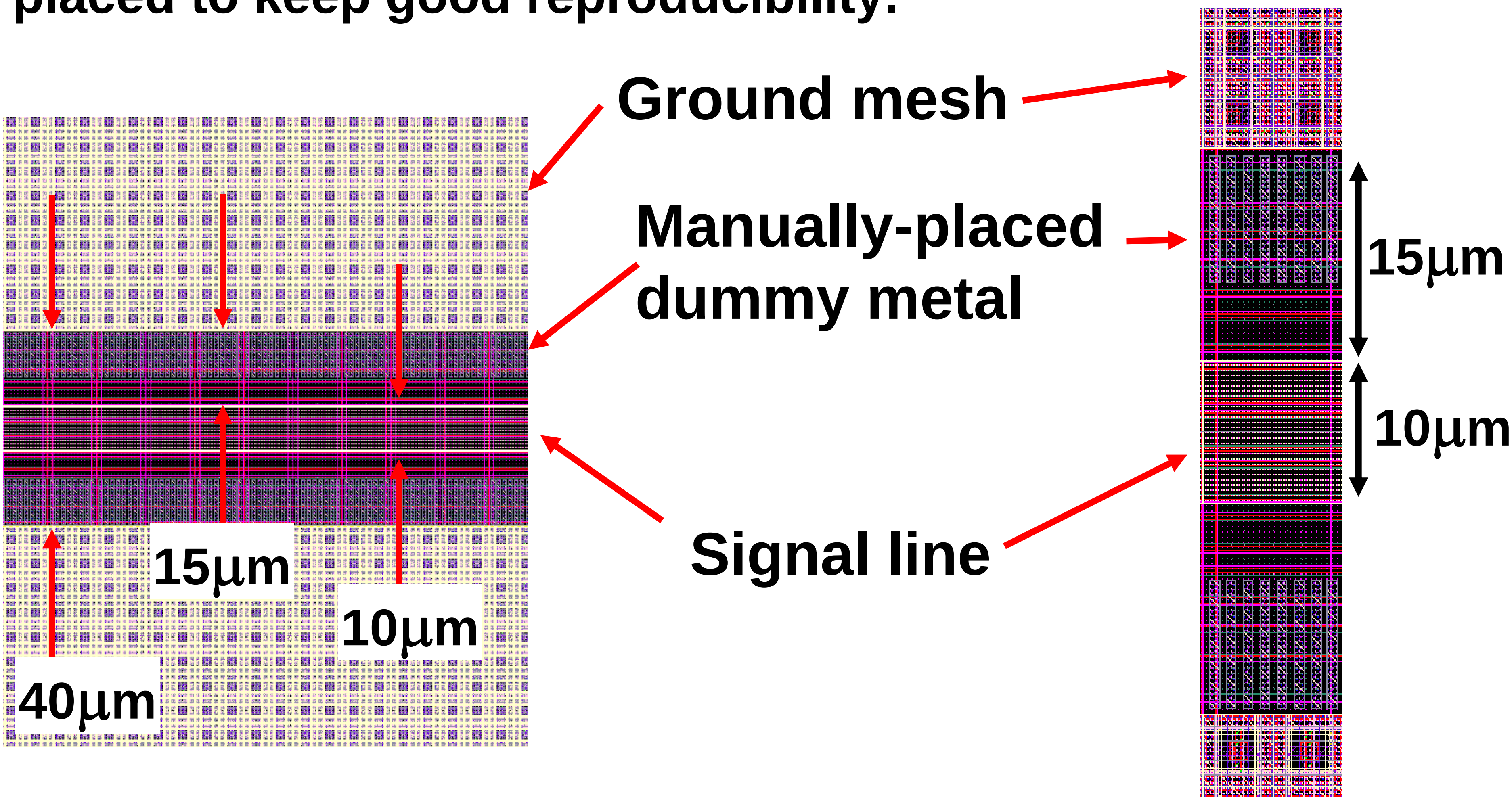
- **Uneven metal density causes nonuniform metal thickness.**
- **Dummy metals are required to keep a constant metal thickness.**

Dummy metal

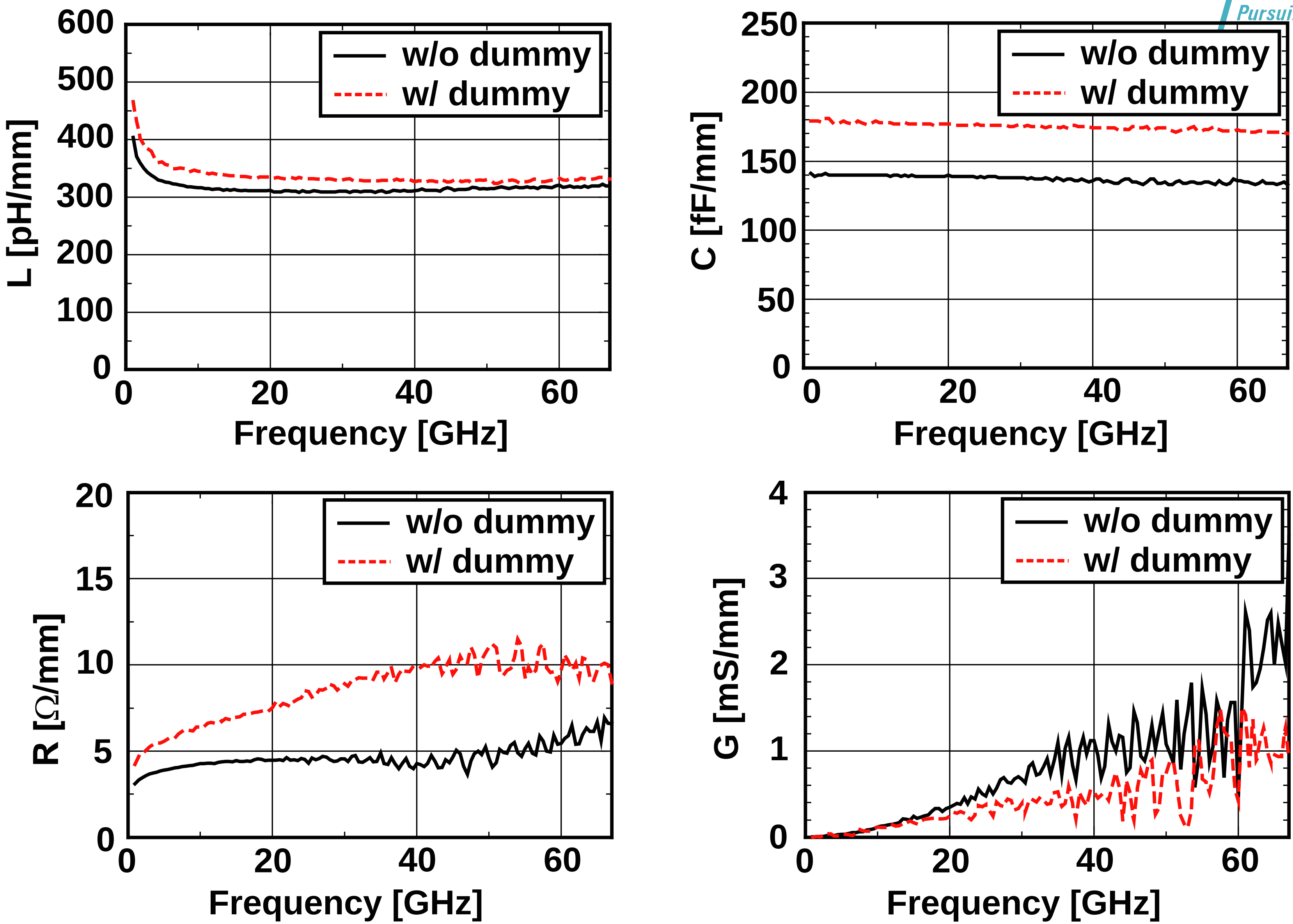

automatically-generated dummy metal
manual dummy
Signal PAD
inhibition mask layer
for automatic dummy generation
GND PAD
GND tile

Dummy metal in TL

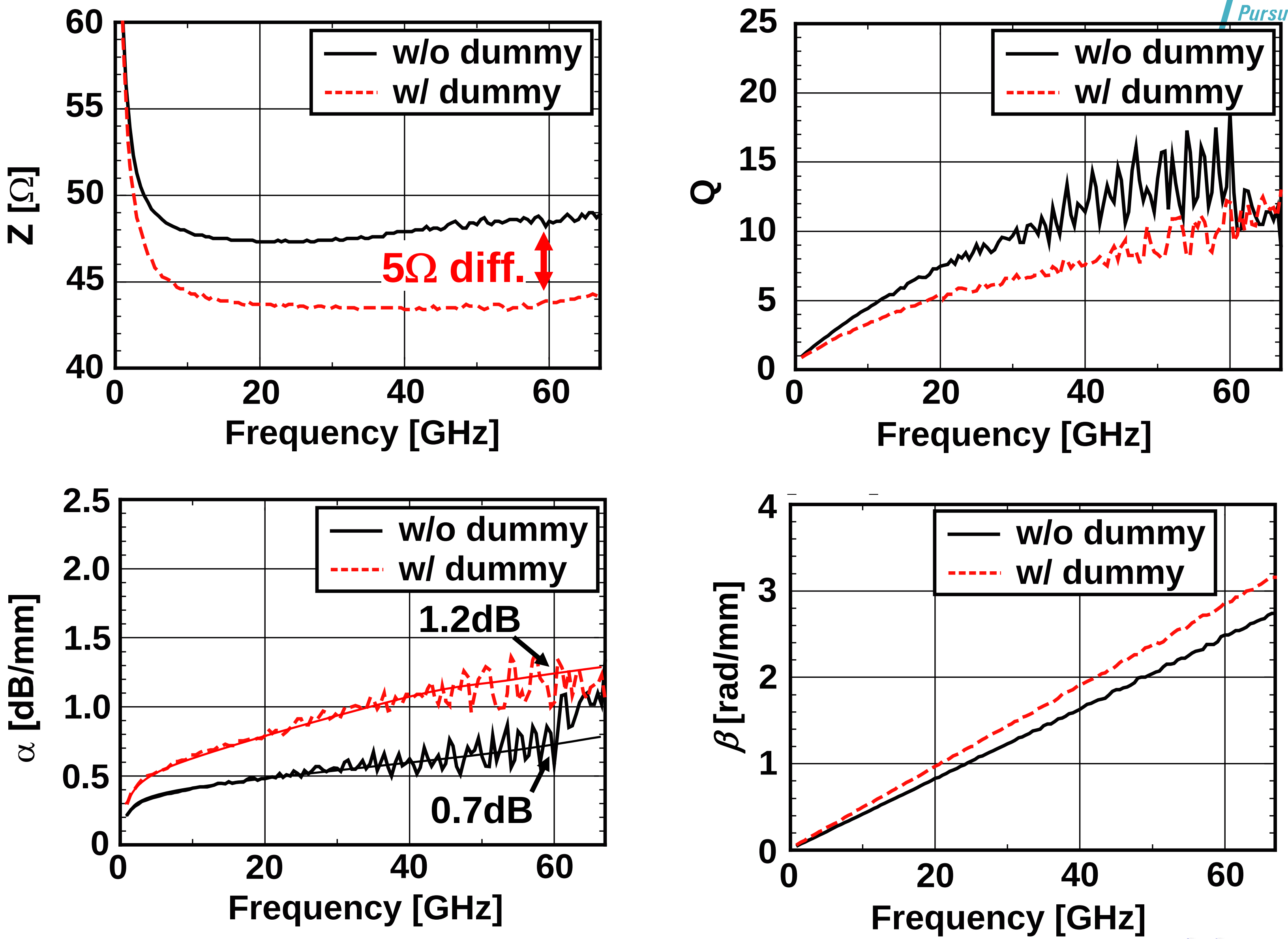
To avoid random production of dummy metal, it is manually placed to keep good reproducibility.



Dummy influence on T-line



Dummy influence on T-line



Summary of dummy issues

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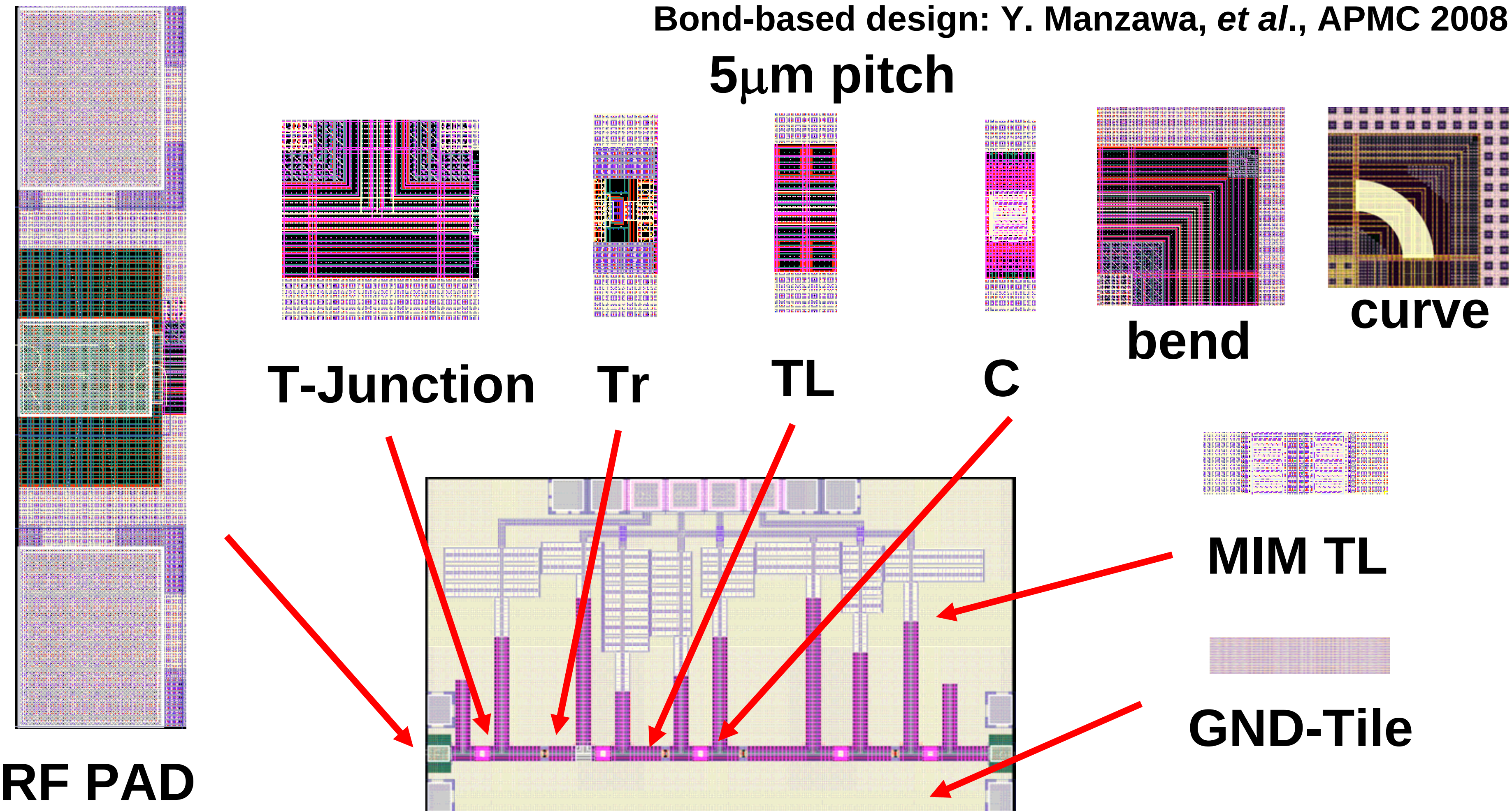
Dummy metals are required for CMP.

- Loss (mainly caused by eddy current)
  - Too-close dummy causes loss in T-lines.
- Parasitic capacitance
- Layout complexity
  - The common MS model cannot be used.
  - EM simulation is also difficult.

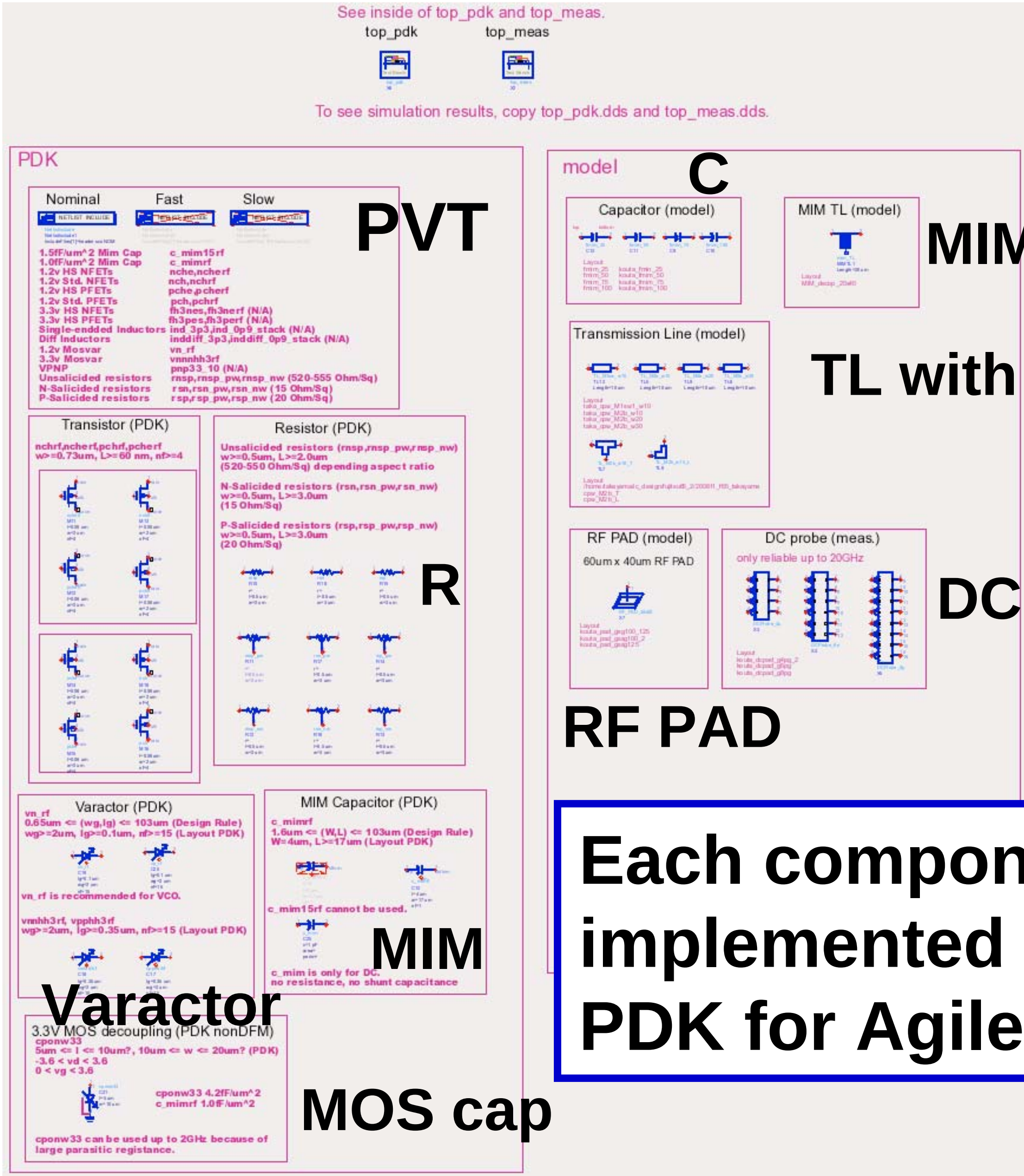
Tile-based layout

Each component is previously measured and modeled.
The same layout is utilized to maintain modeling accuracy.

Bond-based design: Y. Manzawa, *et al.*, APMC 2008



In-house PDK



Each component is implemented as an in-house PDK for Agilent ADS.

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Remaining issues

- **Tile-based layout**
  - **Layout and circuit model are strictly corresponded, which contributes to avoid uncertainty caused by dummy metals and interconnections between circuit components.**
- **Measurement**
  - **mmW measurement is still challenging**
  - **Accuracy of de-embedding becomes a considerably sensitive at mmW frequencies.**
- **Characterization**
  - **No fab-provided PDK for mmW circuit design**
  - **Measurement is not so accurate**
  - **TEG is very important.**

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  - Decoupling capacitor
  - 1-stage amplifier
  - DC probe
- De-embedding
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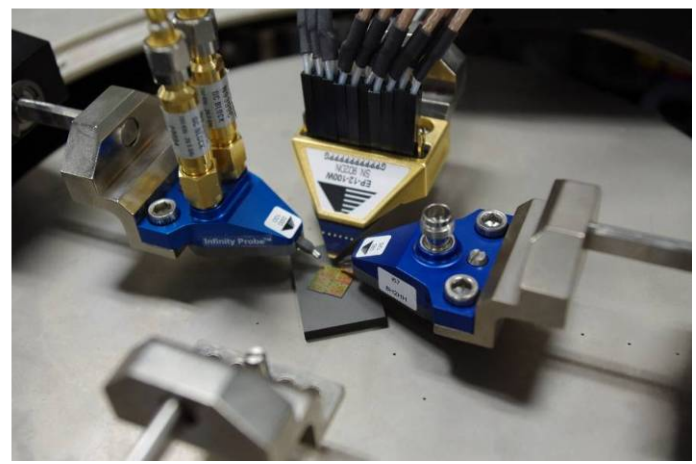
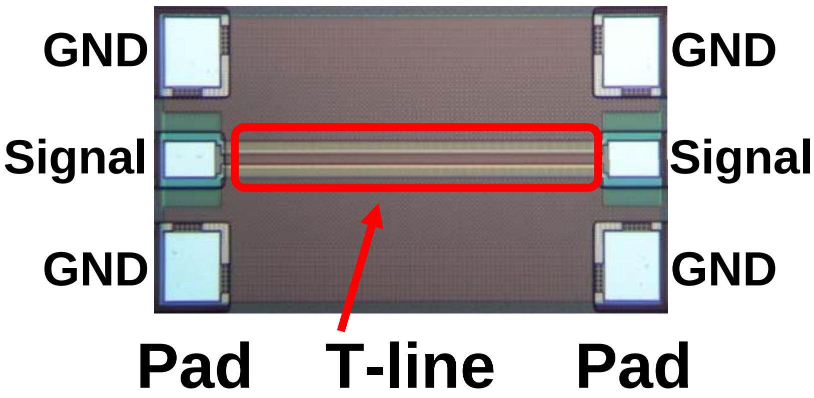
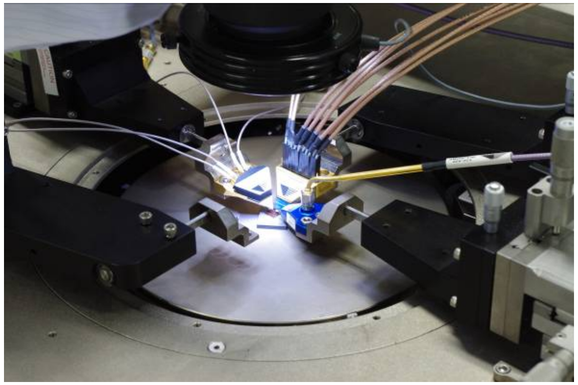
mmW measurement

- **Network analyzer**
  - **S-parameter measurement**
- **RF probe**



mmW device characterization





- Transistors
- Transmission line
- Branch & bend line
- Spiral inductor
- Balun
- Series capacitor
- Decoupling capacitor

- DC pad
- RF pad
- Bonding wire

Overview of device characterization

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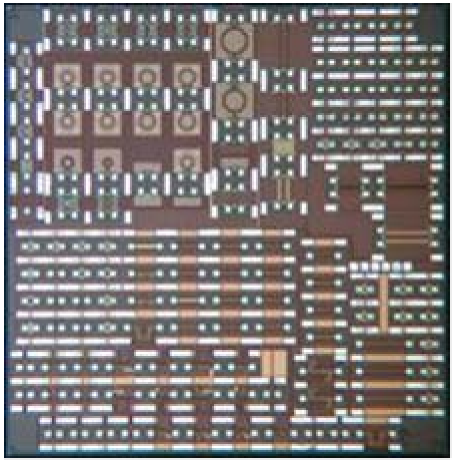
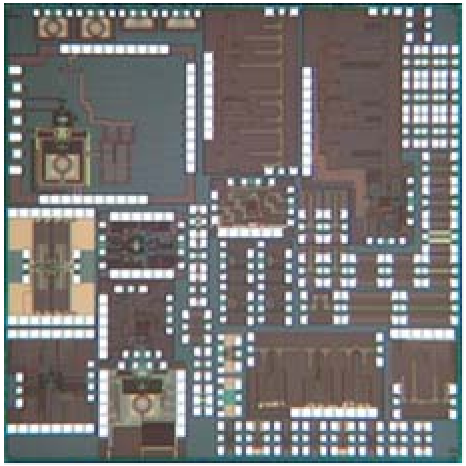


Initial T.O.



Second T.O.

Initial T.O. for Modeling

- Transistors (CS, CG with various layouts)
- Transmission line (various length & Z_0)
- Branch & bend line
- Spiral inductor
- Balun
- Series capacitor
- Decoupling capacitor
- De-embedding patterns
- 1-stage amplifier for the model evaluation
- DC probe

Second T.O.

- Circuit building blocks
- Whole system

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  - 1-stage amplifier
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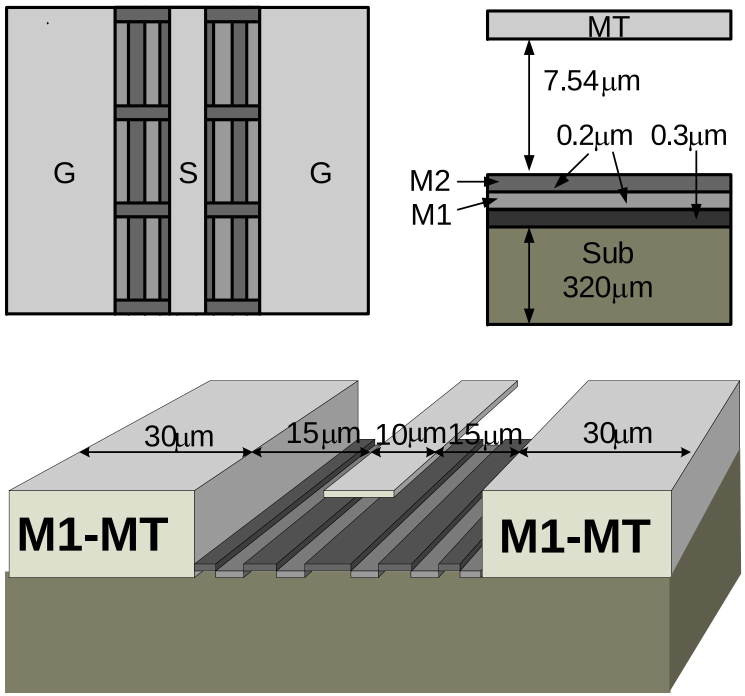
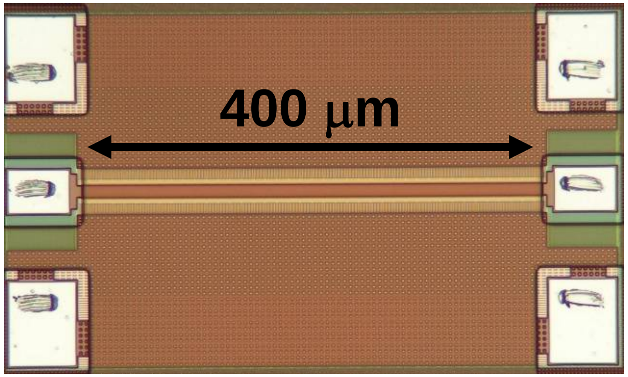
On-chip Transmission Line



Structure

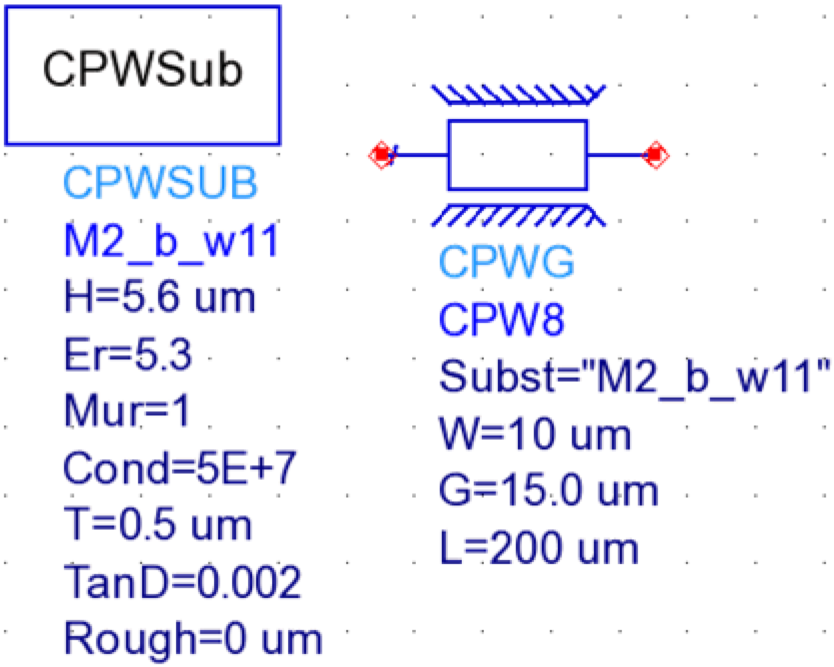


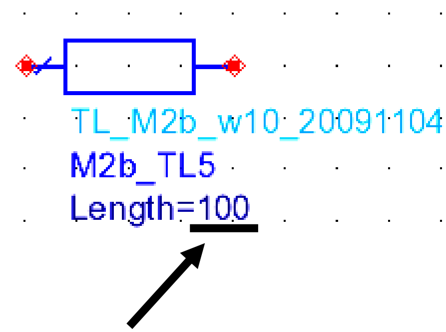
Microphoto

- **Guided Micro-Strip (GMS)**
- **M1-MT ground wall (for density)**
- **Totally shielding the substrate from the signal line by using M1-M2 grounded-strips**

Model of transmission line

CPW model (ADS)





configurable

- **To meet measured α, β, Q and Z_0, substrate model is individually extracted for each structure.**
- **RLGC is not good, and S-parameters should also be checked.**

Calculation of Z, α, β, and Q

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Z, α, β, and Q can be calculated from S-parameters.

$$e^{-\gamma\ell} = \left\{ \frac{1 - S_{11}{}^2 + S_{21}{}^2}{2S_{21}} \pm K \right\}^{-1} \qquad K = \left\{ \frac{(S_{11}{}^2 + S_{21}{}^2 + 1)^2 - (2S_{11})^2}{(2S_{21})^2} \right\}^{\frac{1}{2}}$$

therefore

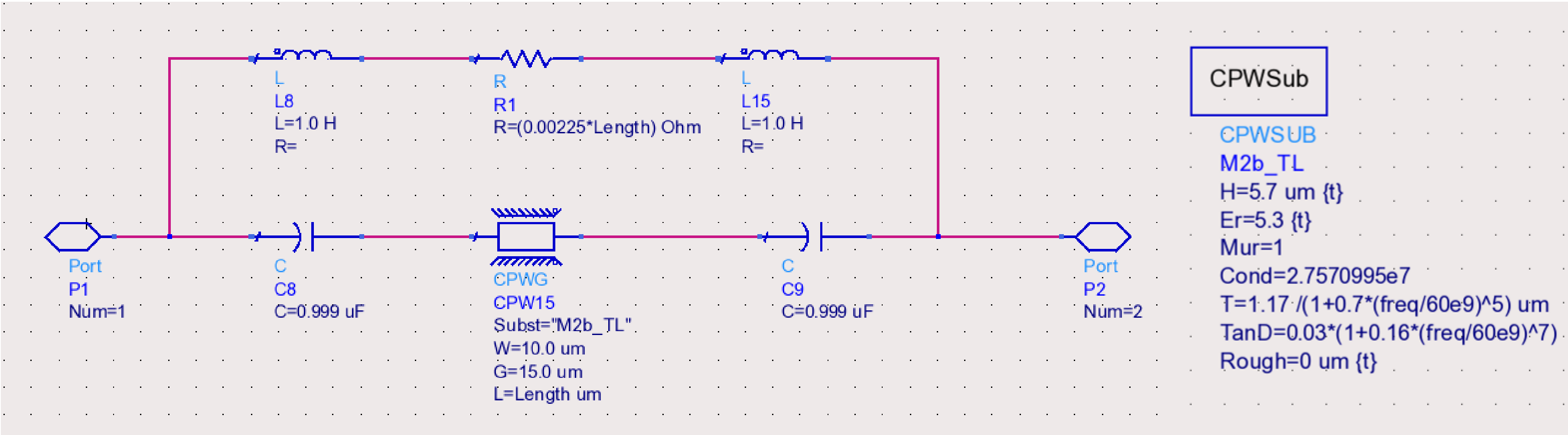
$$Z_0{}^2 = Z_{\mathrm{ref}}{}^2 \frac{(1 + S_{11})^2 - S_{21}{}^2}{(1 - S_{11})^2 - S_{21}{}^2} \qquad Q = \frac{\beta}{2\alpha}$$

$$\gamma = \alpha + j\beta$$

W. R. Eisenstadt and Y. Eo, IEEE T-MTT 1992.

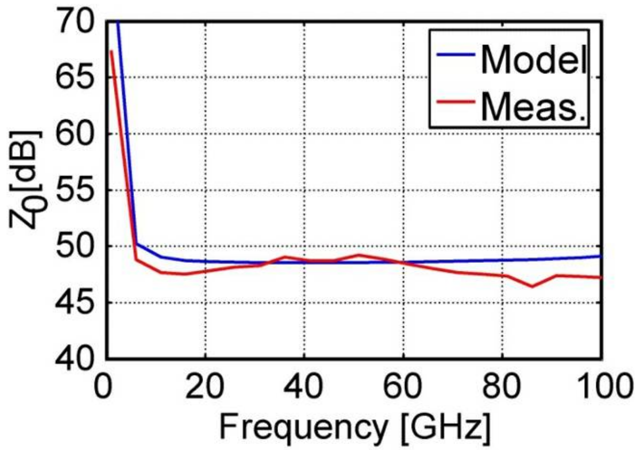
Model of transmission line

T-Line model (detail)

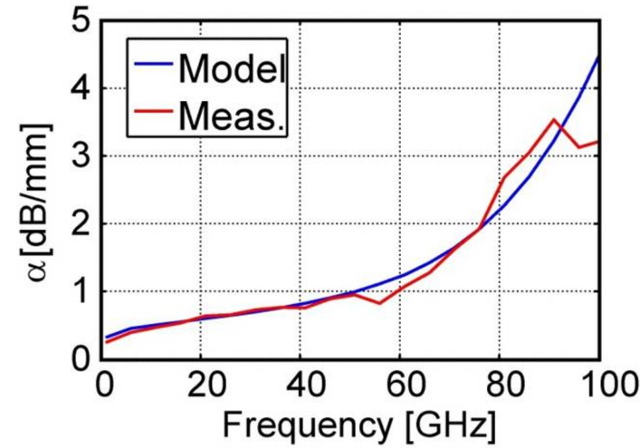


- **DC characteristic is separately characterized.**
- **tanδ and dielectric thickness are frequency-dependent.**

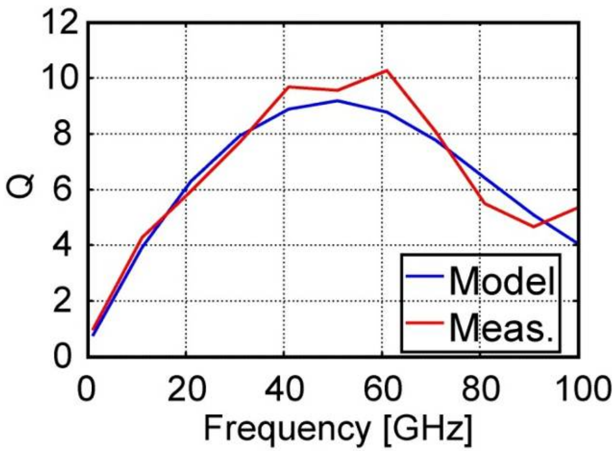
Transmission line (400μm)



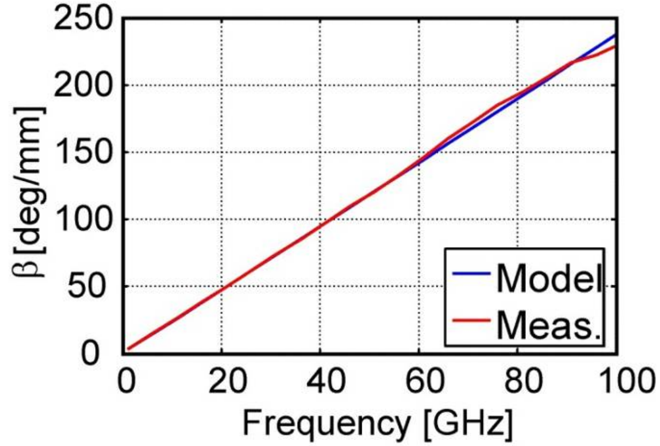
Characteristic impedance



Attenuation constant



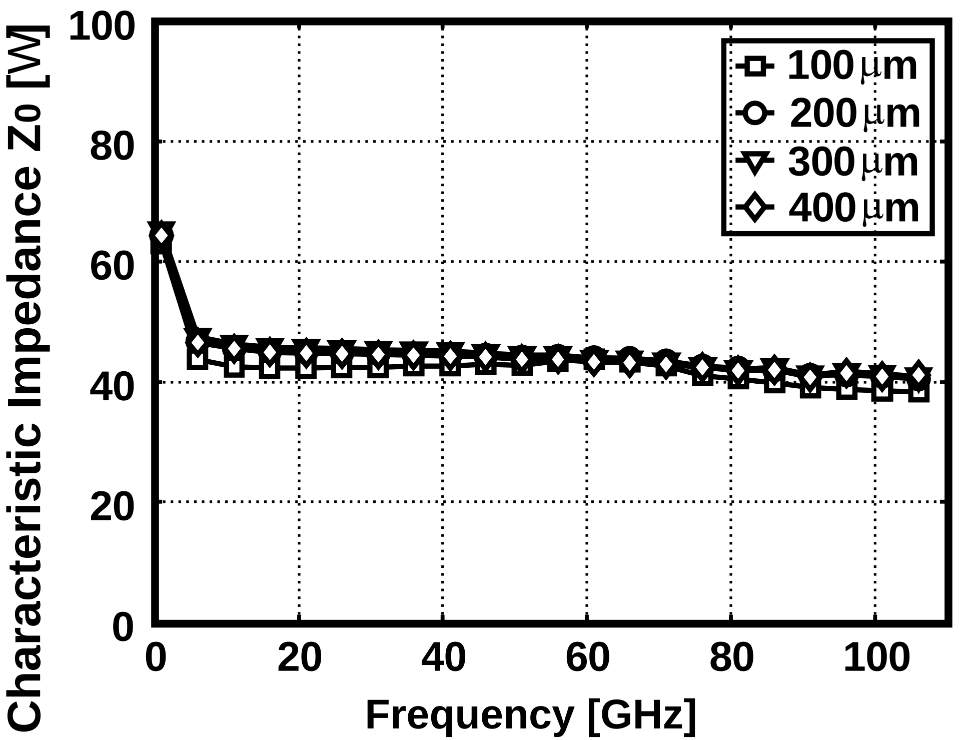
Quality factor



Phase constant

Verification of T-Line model

1. **PAD model is built by measurement results of 200µm and 400µm T-lines.**
2. **Measurement results of 100µm, 200µm, 300µm, and 400µm T-lines are de-embedded by using the PAD model.**



***different TL from the previous one**

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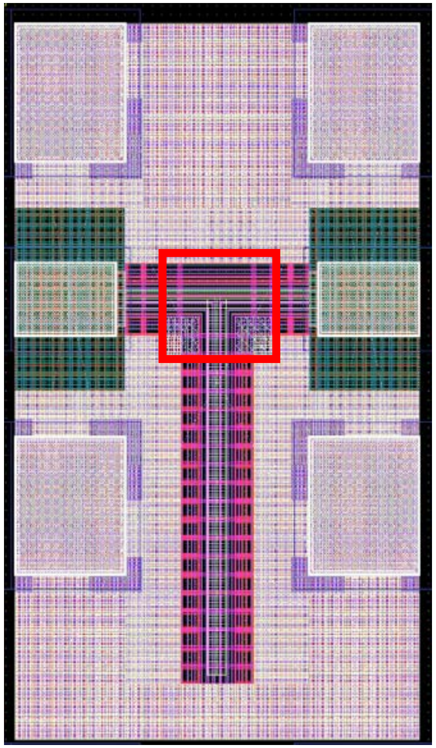
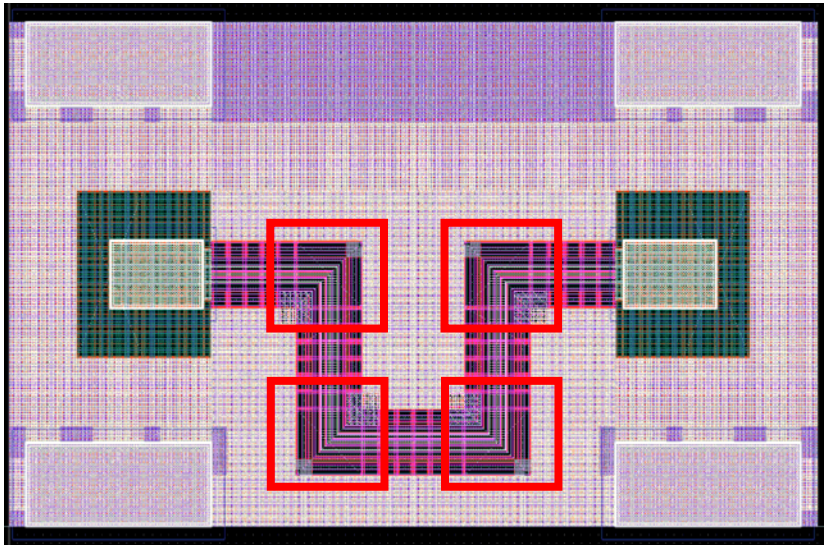
Branch & bend modeling



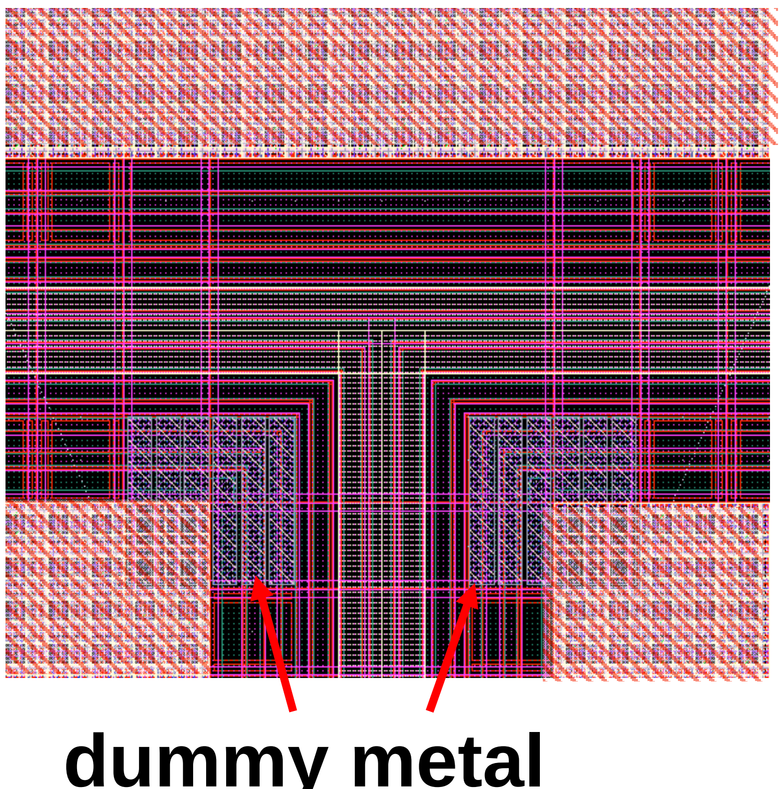
with 200μm shunt TL

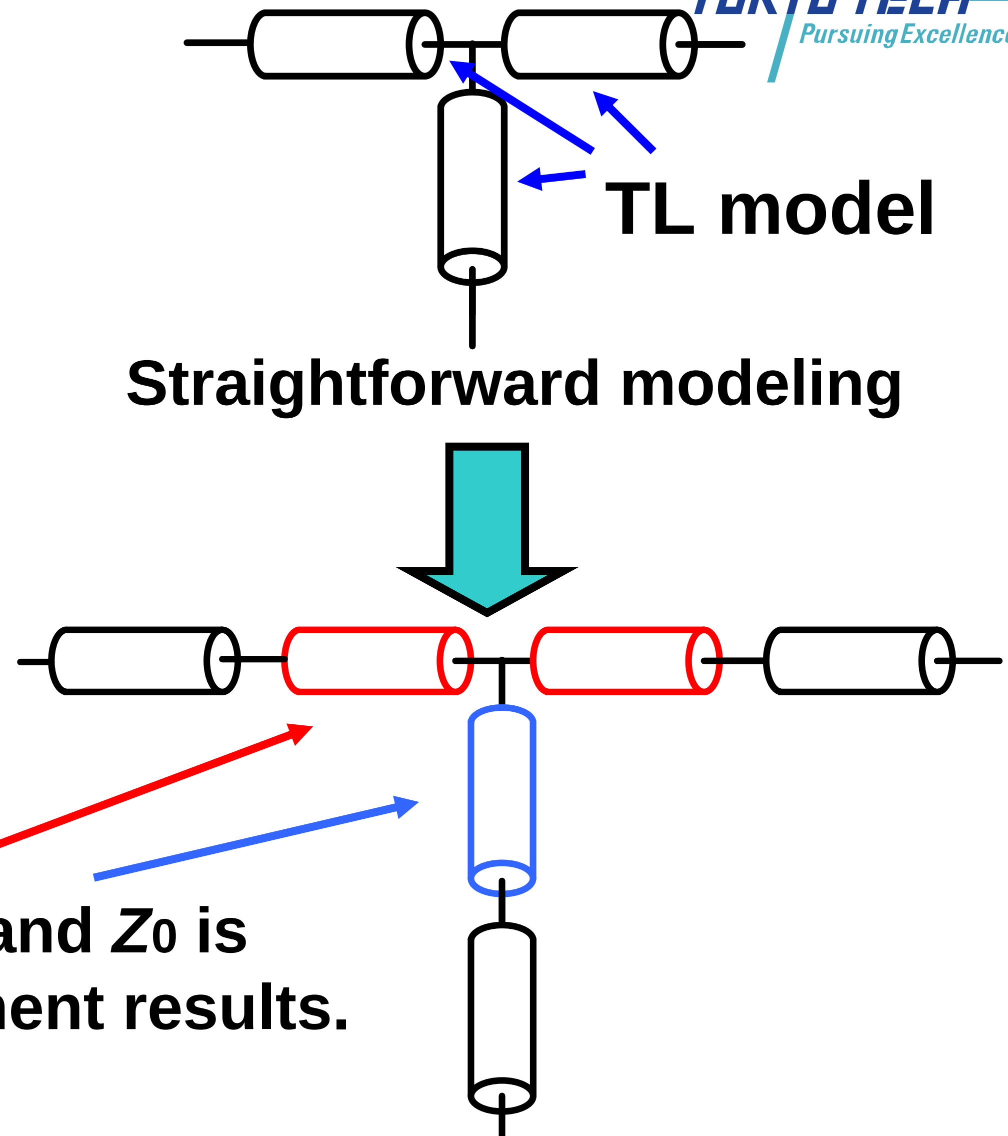


with 4 bending parts

Each red-box part is characterized as a combination of optimized transmission lines.

T-junction modeling

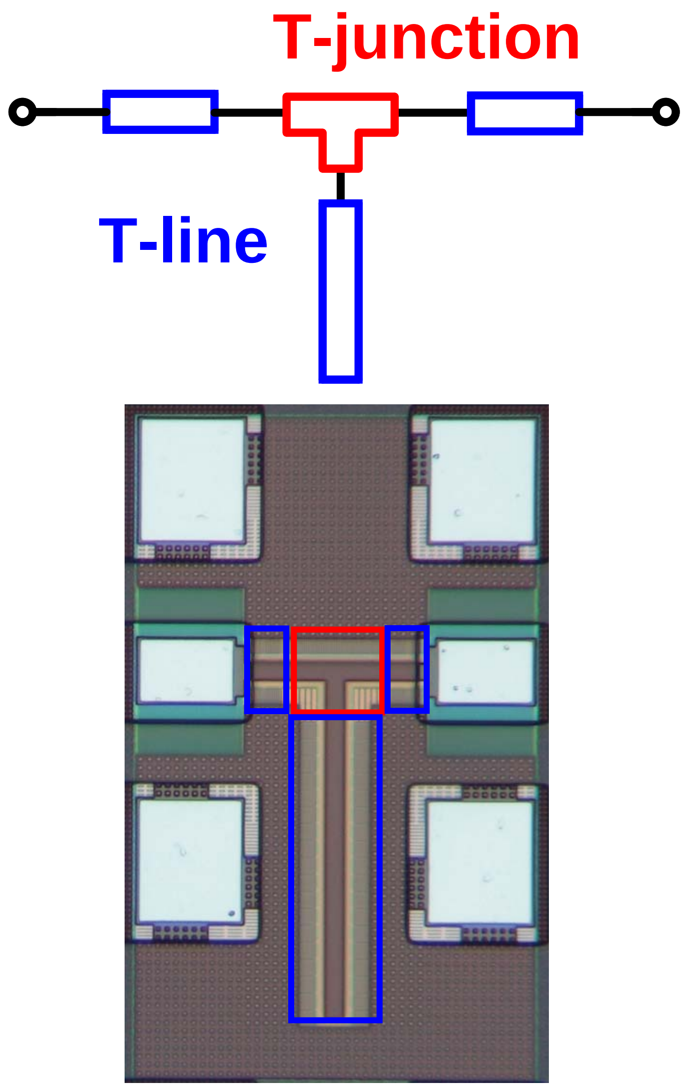


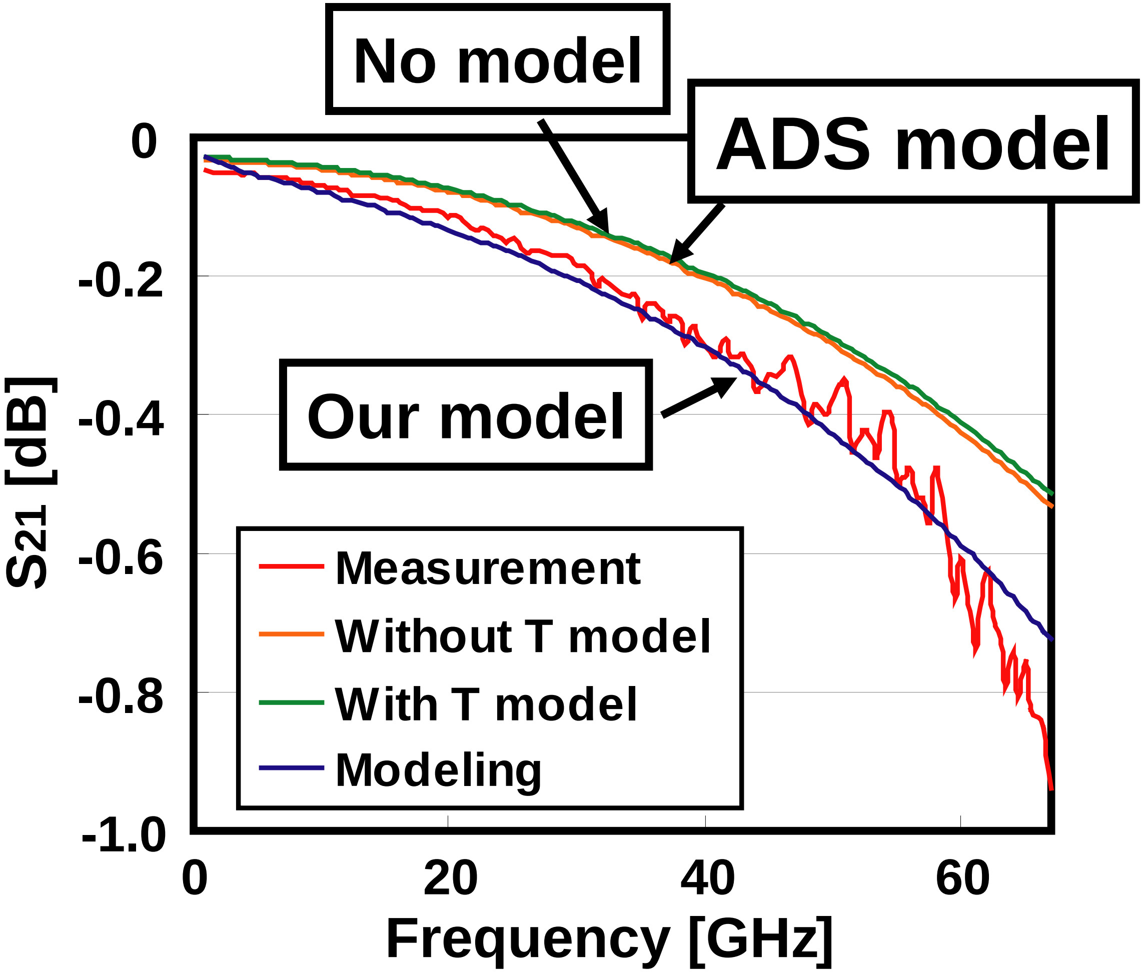


Lower *Z*0 TLs are utilized, and *Z*0 is adjusted for the measurement results.

Dummy metal causes unexpected response.

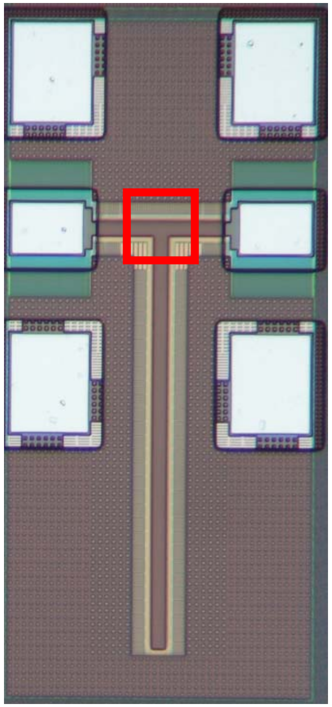
Extracted results of T-junction





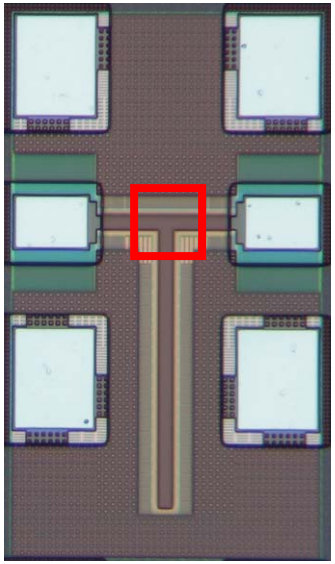
A simple analytical model cannot be used.

Verification



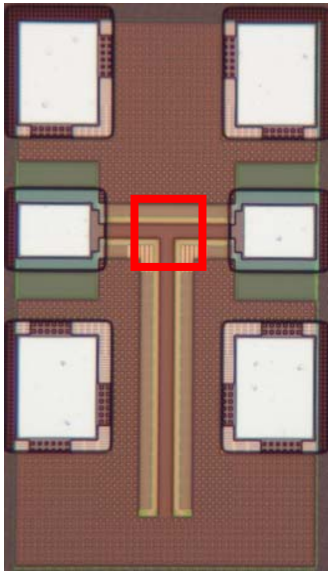
300μm open-stub

used for verification



200μm open-stub

used for modeling



200μm short-stub

used for verification

Verification with 200μm and 300μm open-stub

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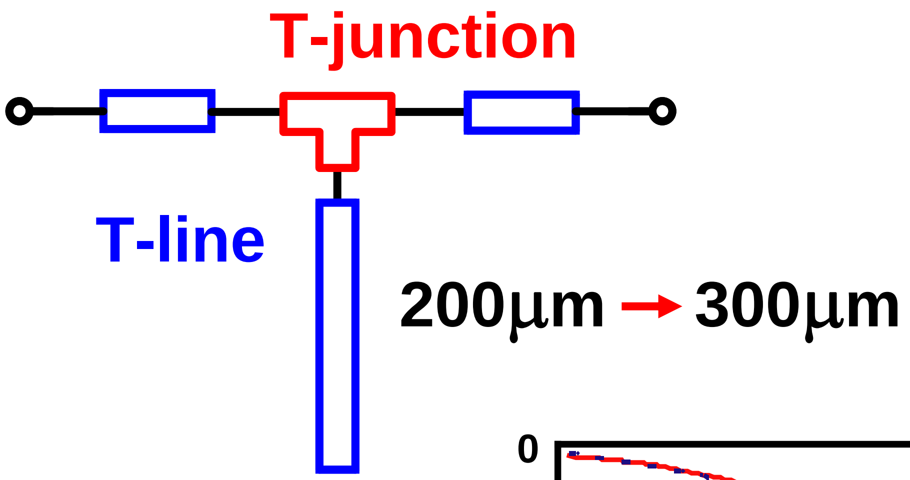
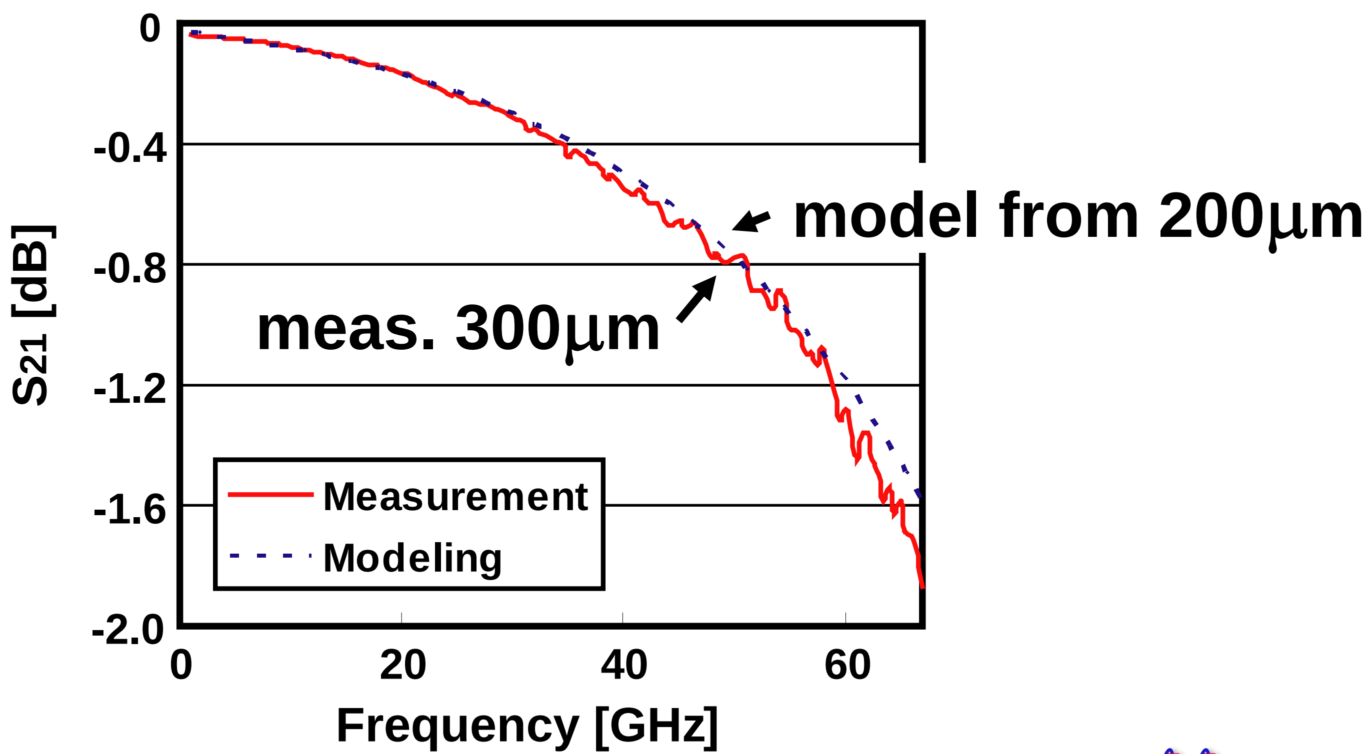
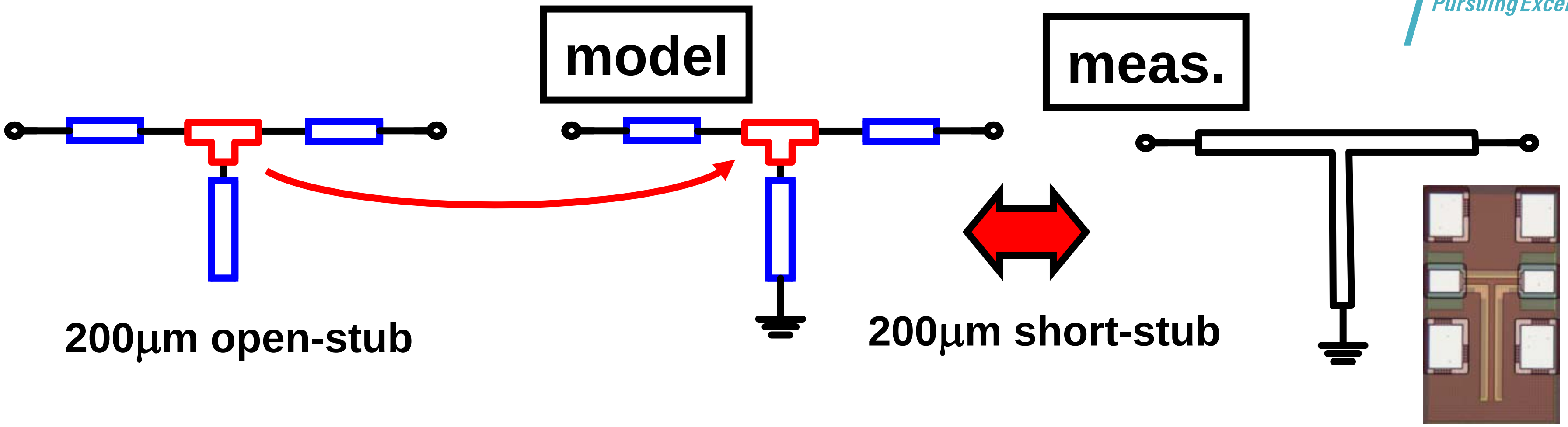
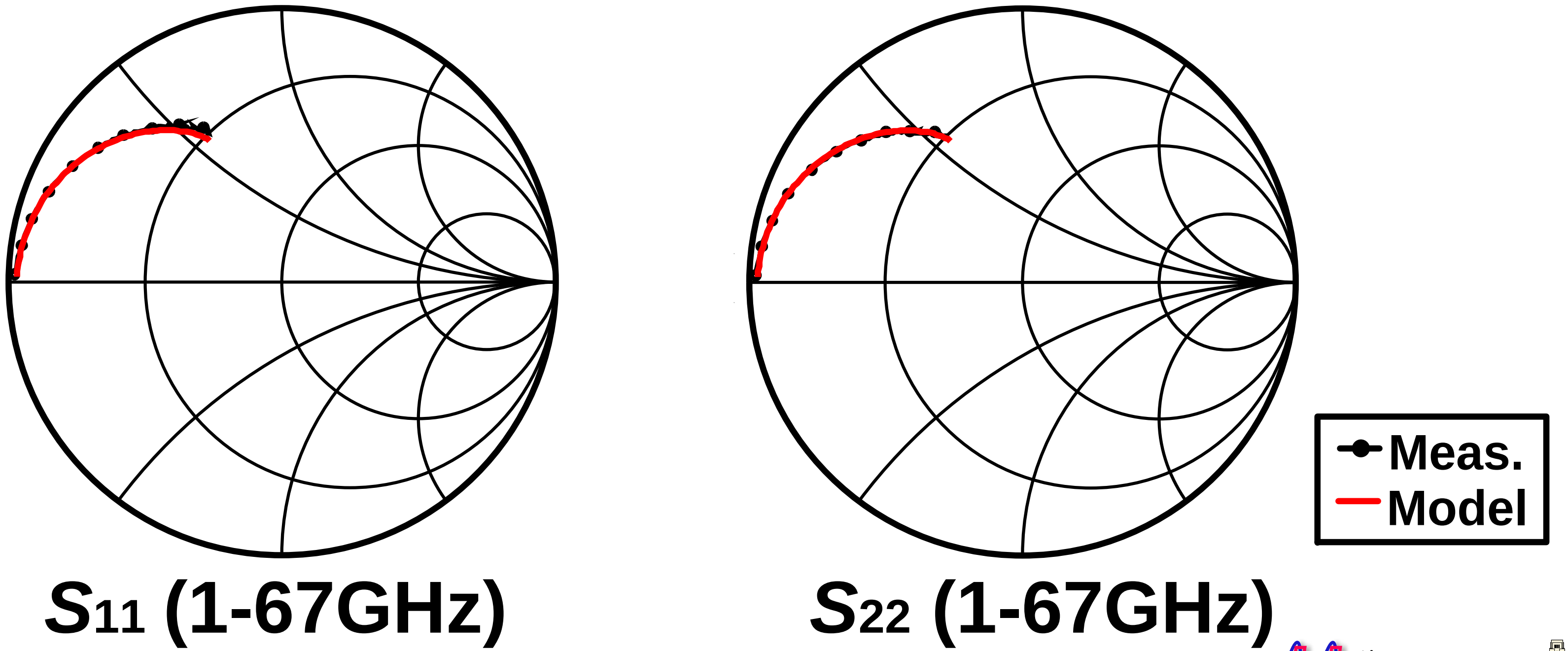


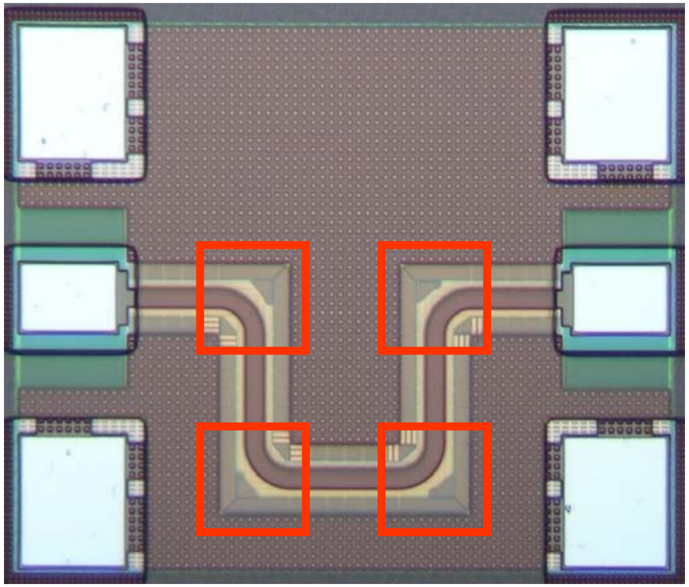


Verification with short stub

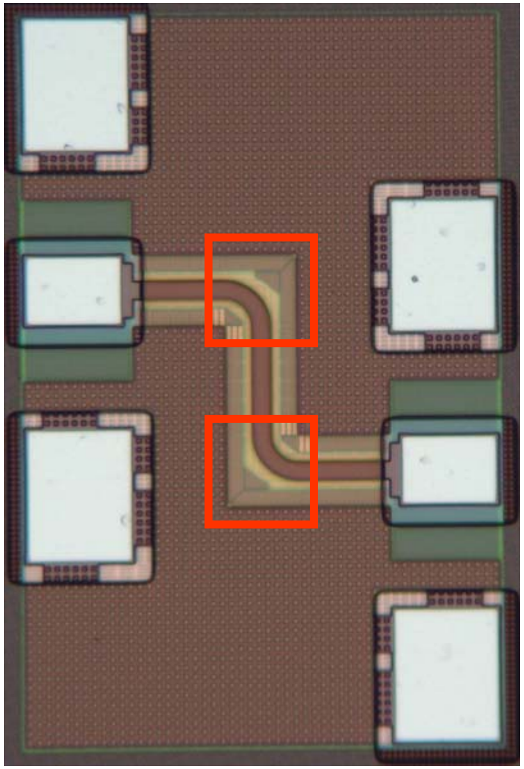




L-Curve modeling

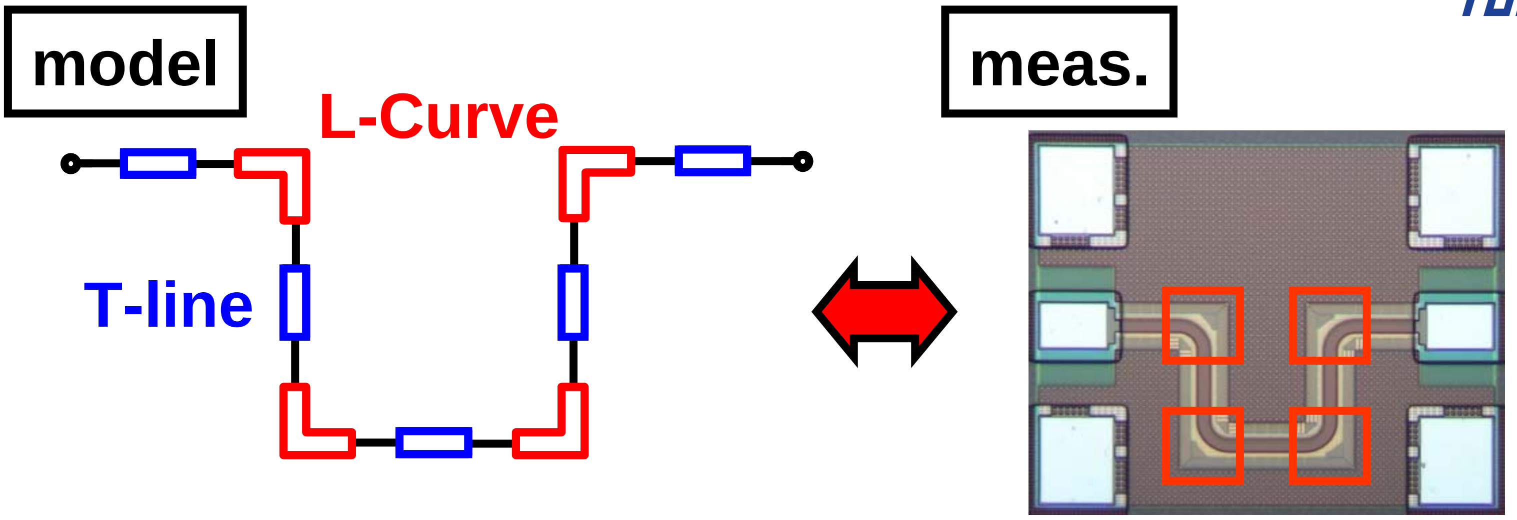


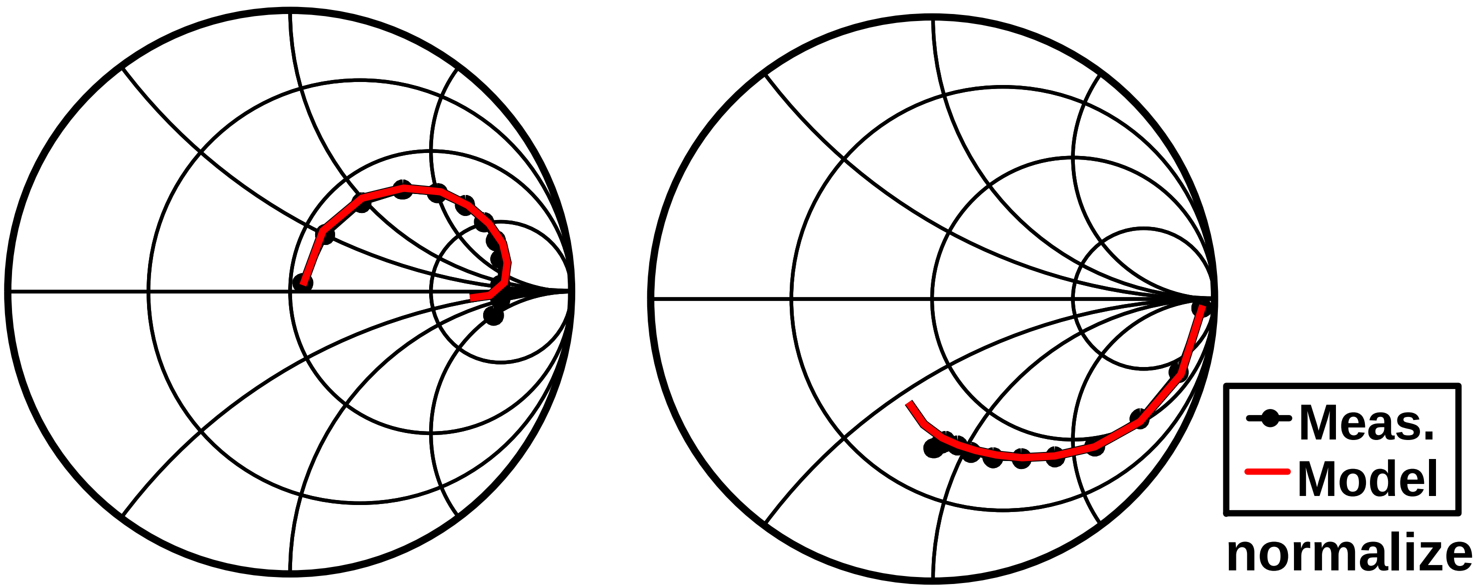
4-L-curve



2-L-curve

Extracted result





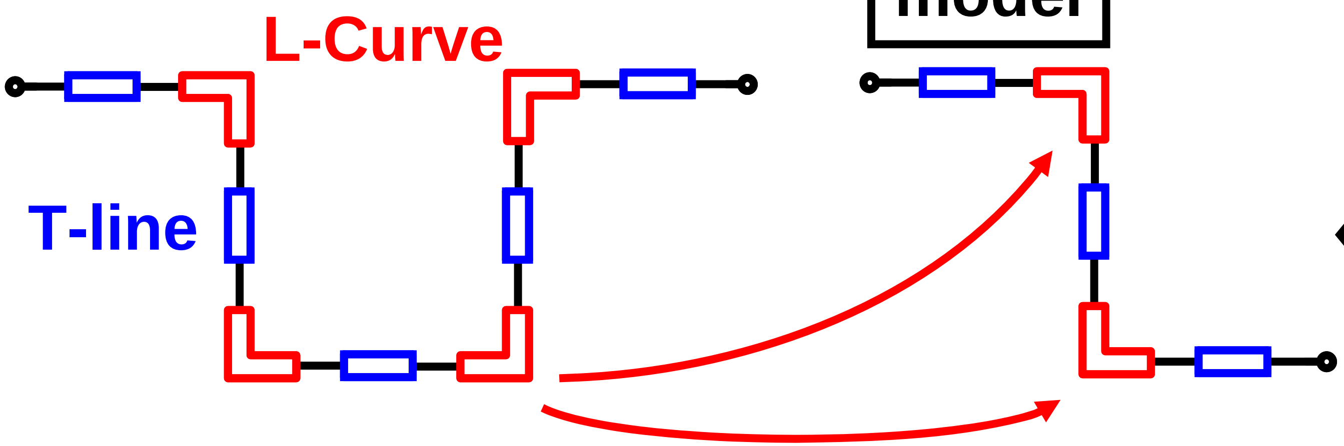
normalized by 20Ω

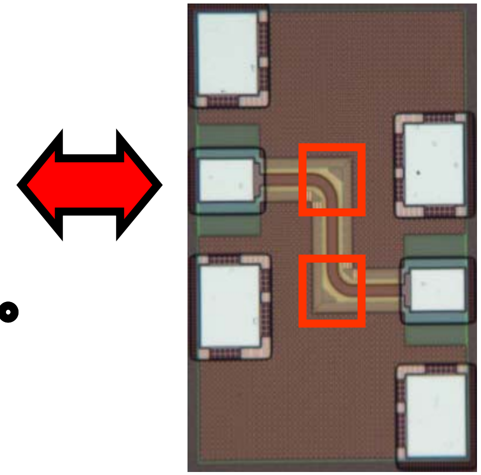
S_{11} (1-67GHz) S_{21} (1-67GHz)

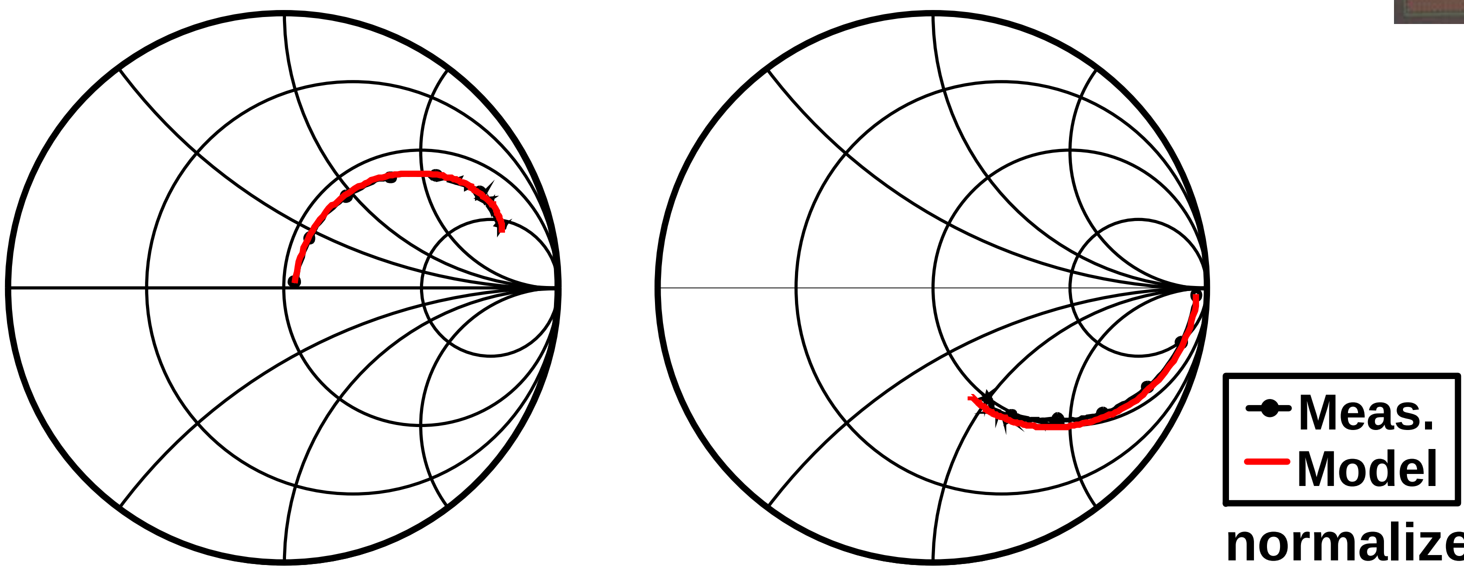
Verification with 2-bend

model

meas.







normalized by 20Ω

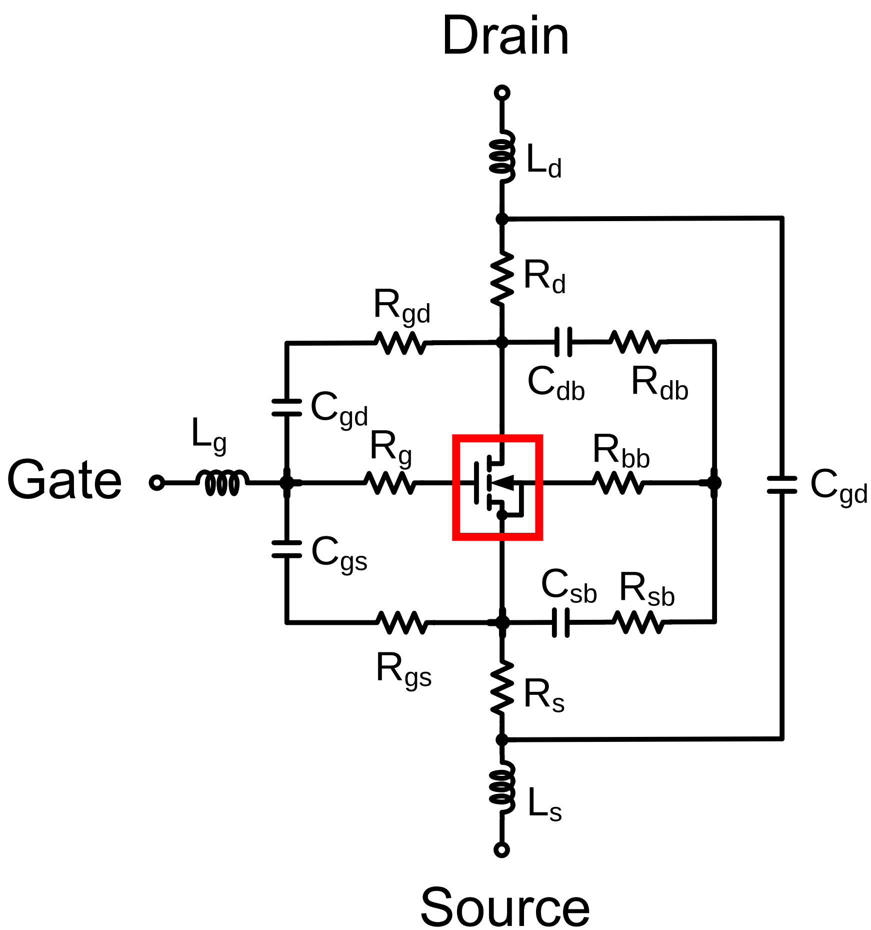
S_{11} (1-67GHz) S_{21} (1-67GHz)

Outline

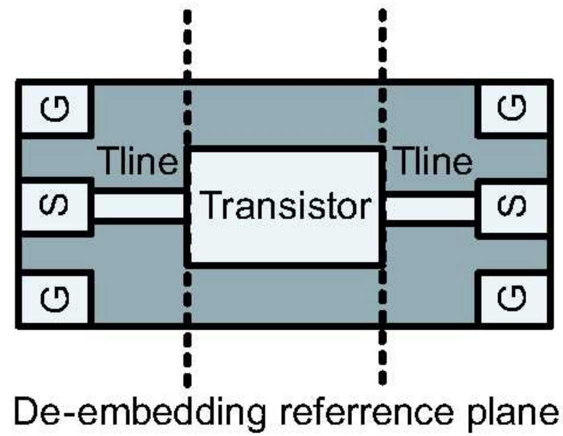
- Motivation
- Issues for mmW CMOS Circuits
- Device Characterization
  - Transmission line
  - Branch & bend line
  - Transistor
  - Decoupling capacitor
  - 1-stage amplifier
  - DC probe
- De-embedding
- Conclusion

Transistor model

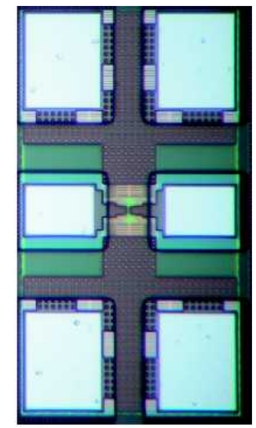
- **Tr. is modeled from two-port measured results**



Transistor model



Test structure



Microphoto

- **Based on BSIM4 model**
- **Small signal**
- **With external ind., cap., res.**

Extracted results of Tr model

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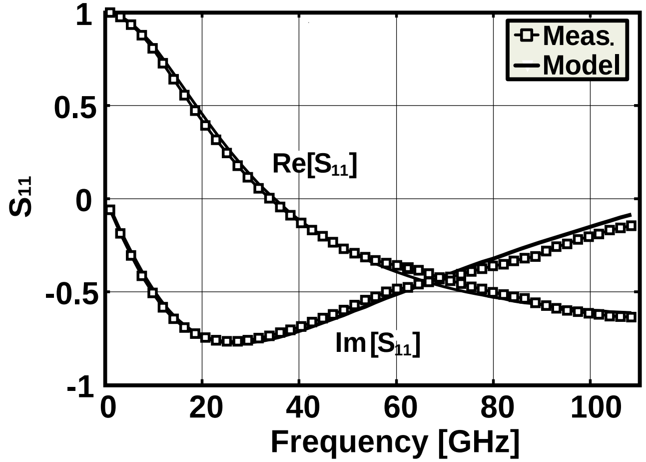
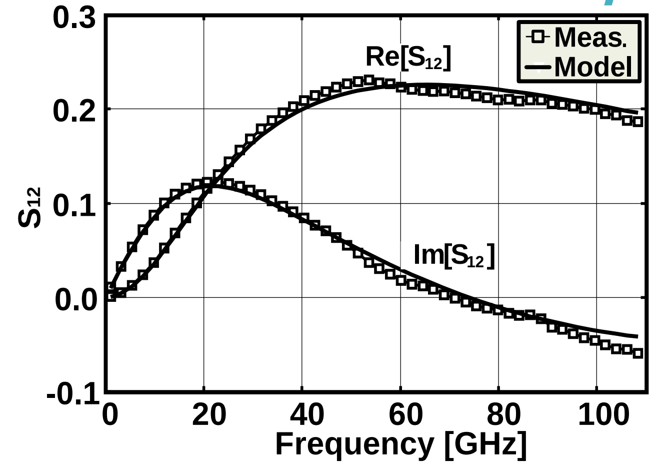
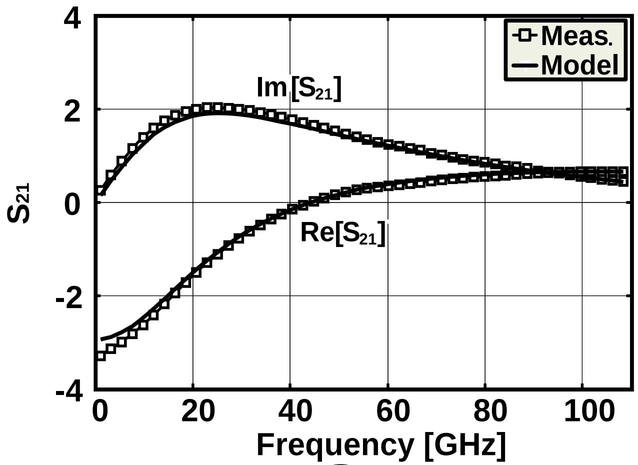


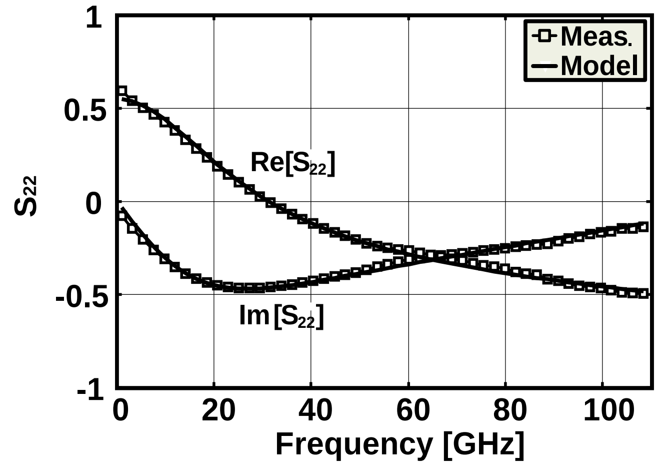
S_{11}



S_{12}



S_{21}



S_{22}

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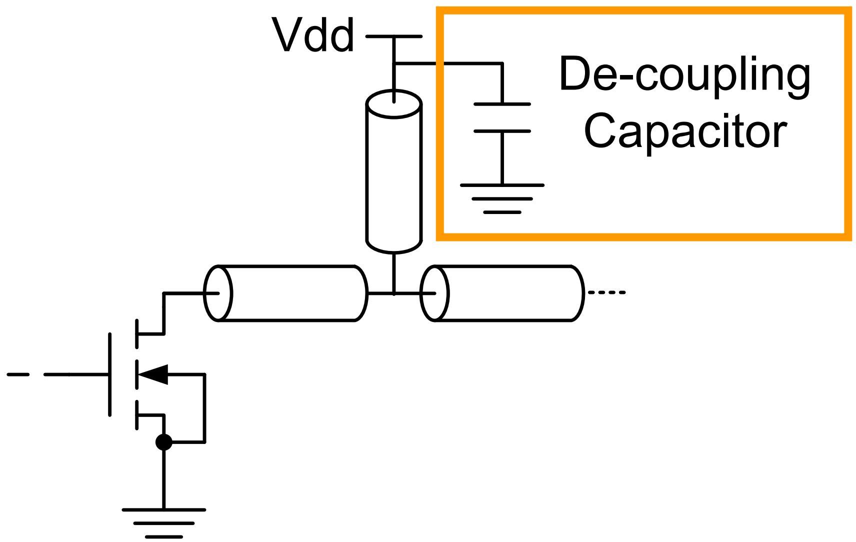
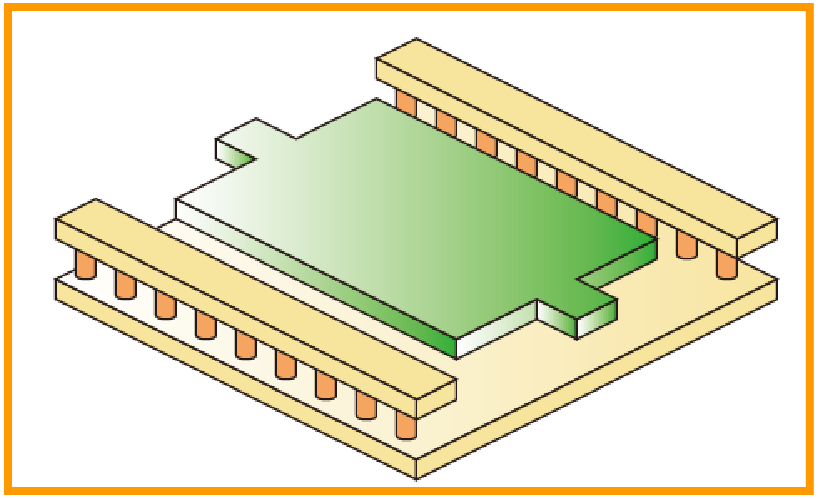
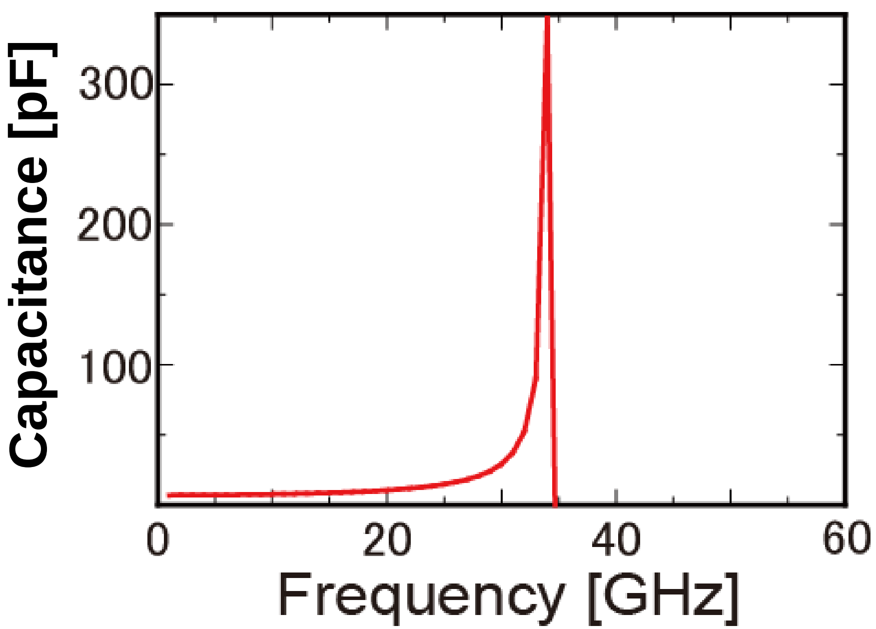
MIM capacitor for de-coupling







Area efficiency is large, but the self-resonance freq. is low.

The regular layout of MIM cap. cannot be used at 60GHz.

TL-shape MIM capacitor

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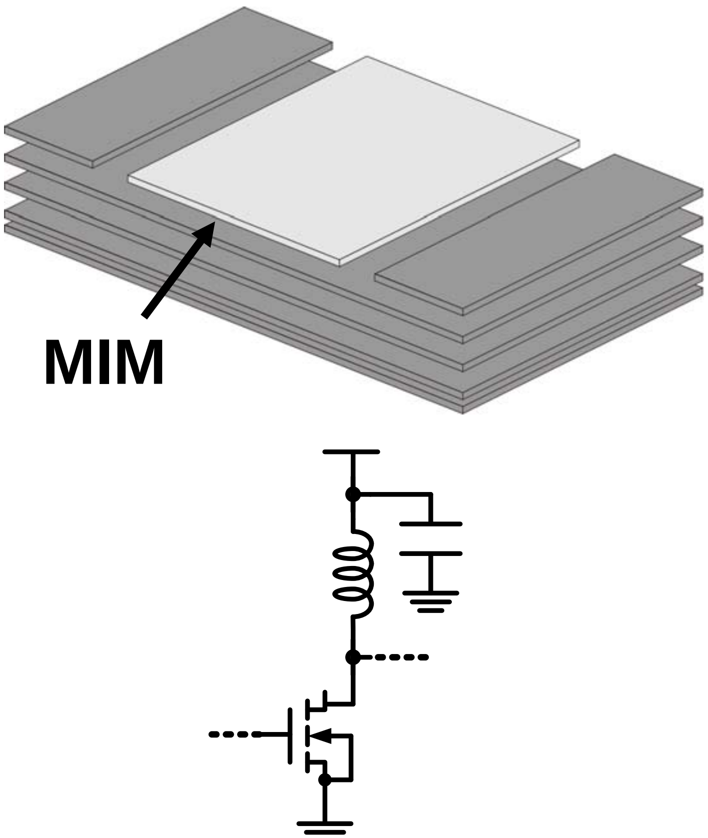
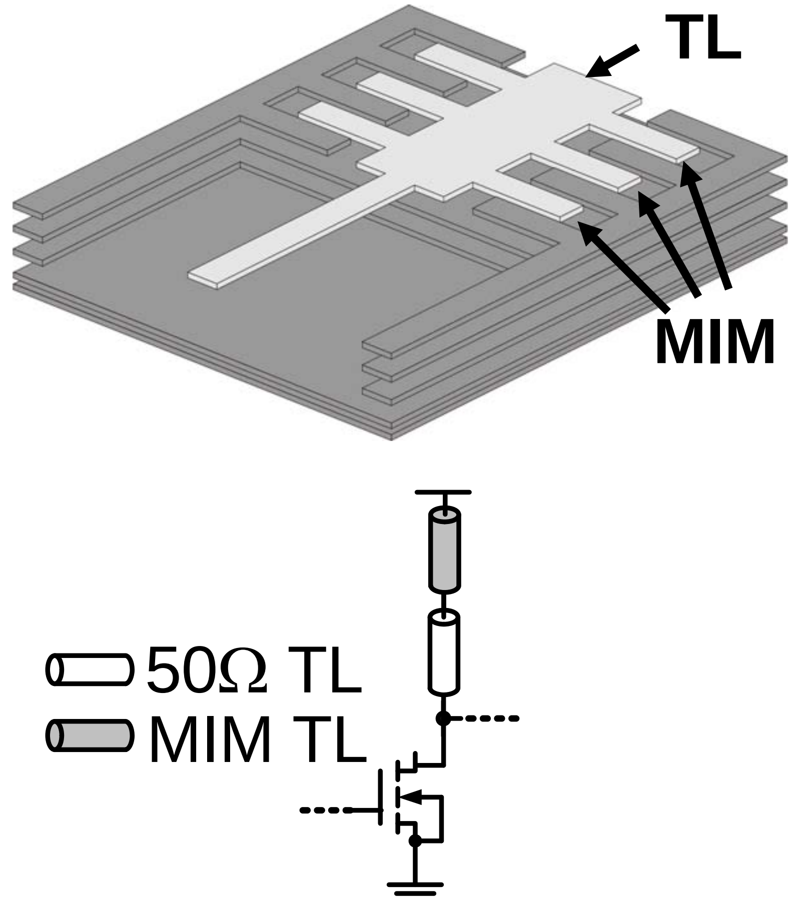
parallel plate MIM cap.



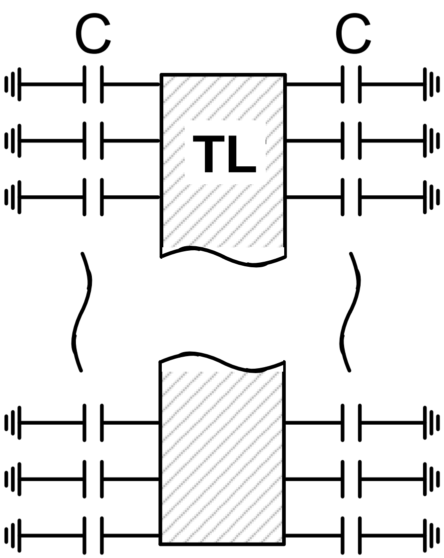
TL arranged MIM cap.[1]



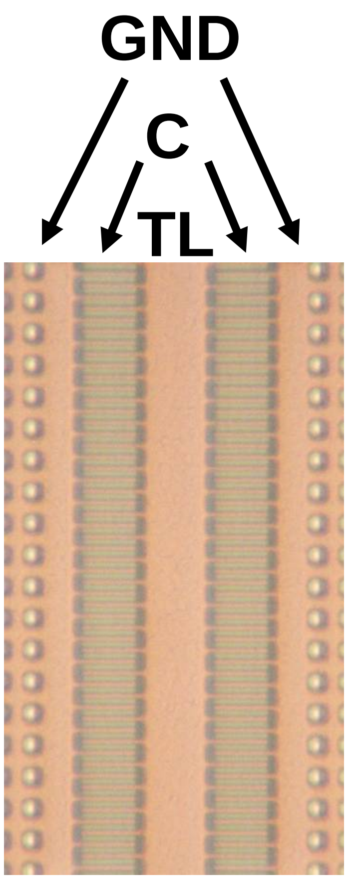
[1] T.Suzuki, *et al*., ISSCC 2008.
[2] Y.Natsukari, *et al*., VLSI Circuits 2009.

Layout of MIM-TLine

Extendable for length

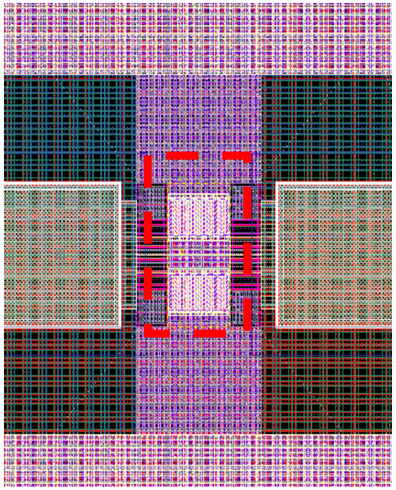


MIM TLine structure



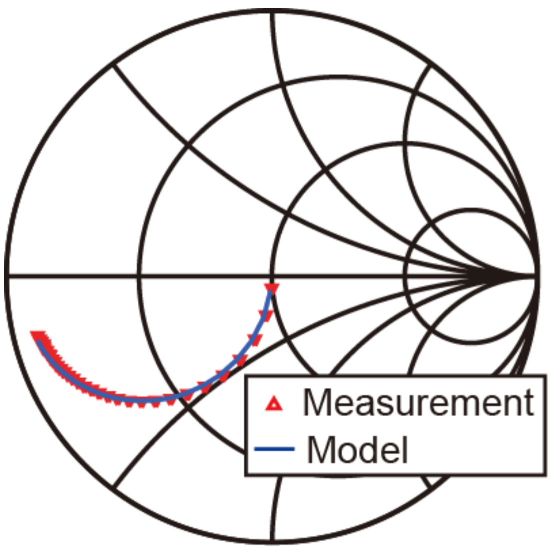
Microphoto

Extracted result of MIM-TLine

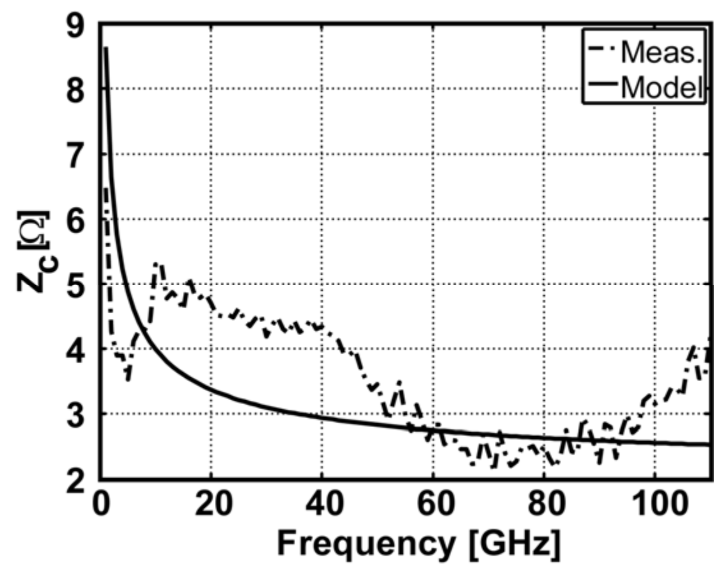


TLINP
TL6
Z=2.8 Ohm
L=20 um
K=205
A=70000
F=60 GHz
TanD=0.02
Mur=1
TanM=1.8
Sigma=0

Characterized as a transmission line



S_{11} (1-67GHz)



Z_0

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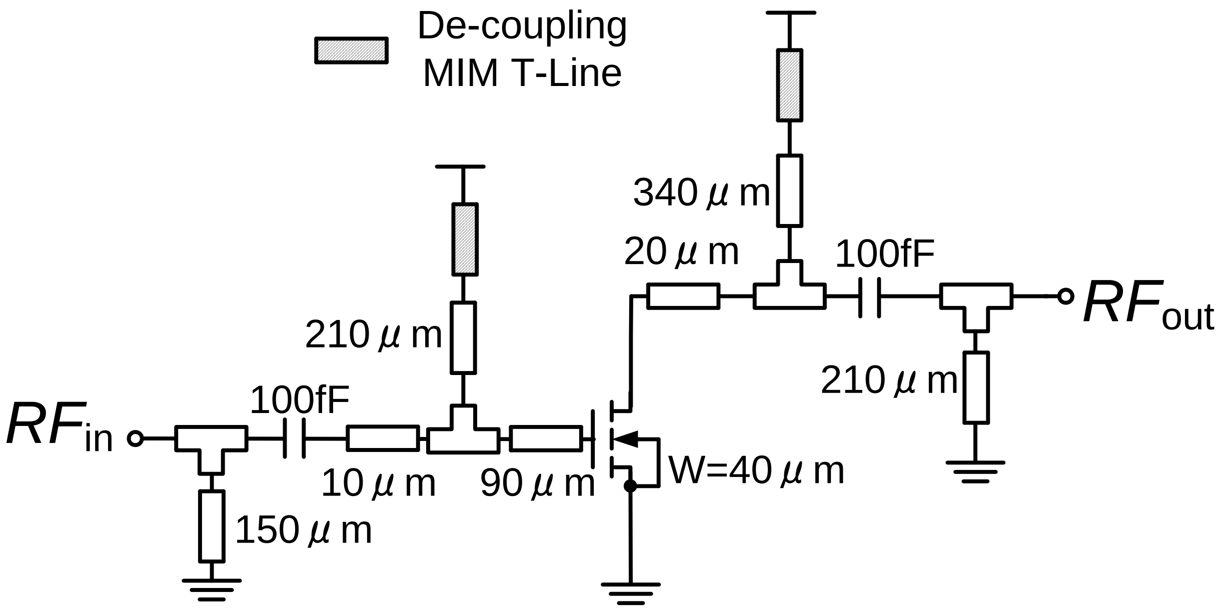
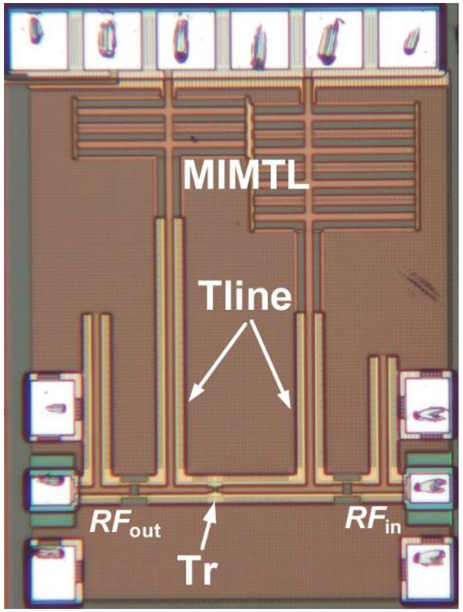
An evaluation using a 1-stage amplifier

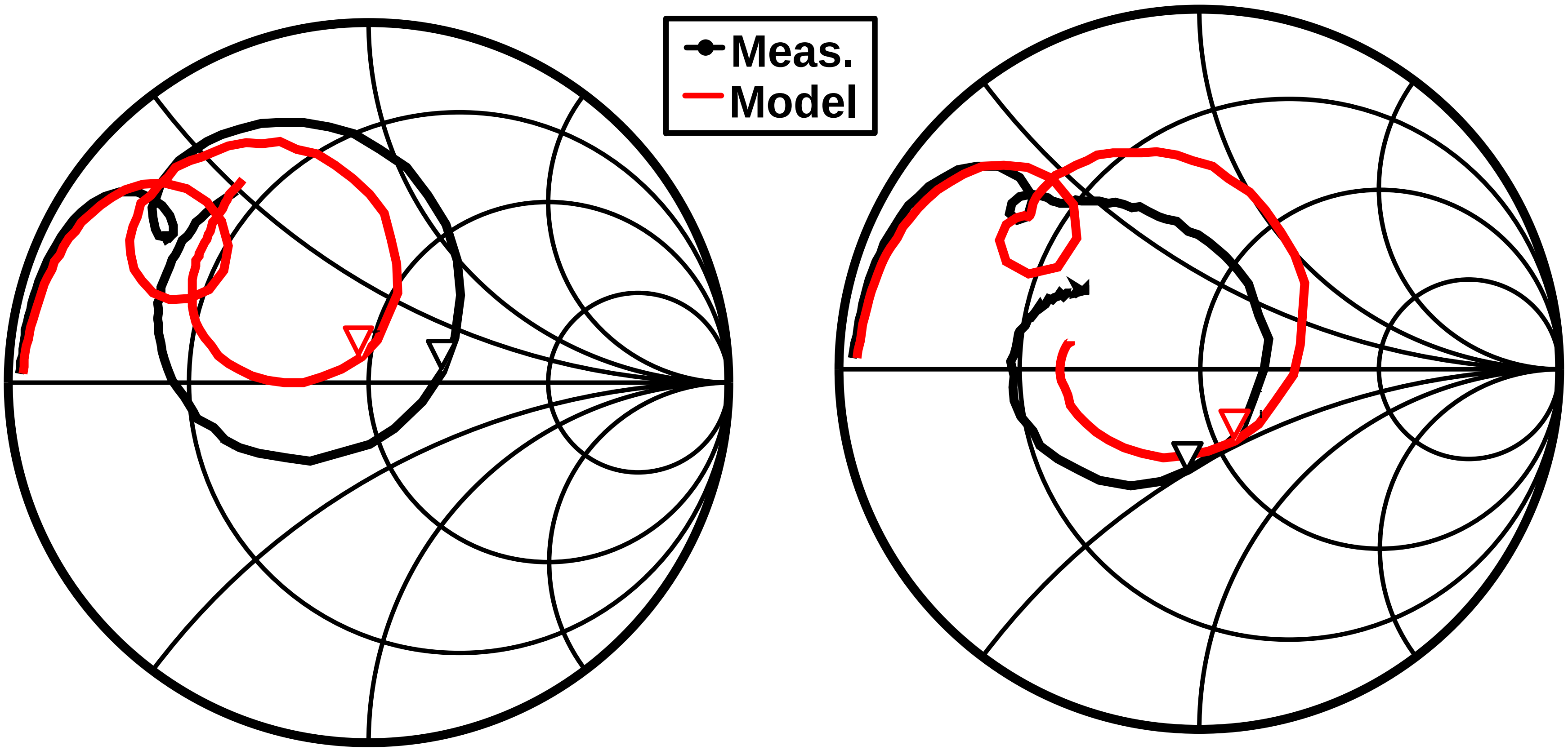
A 1-stage amplifier is also used for a verification.



Schematic

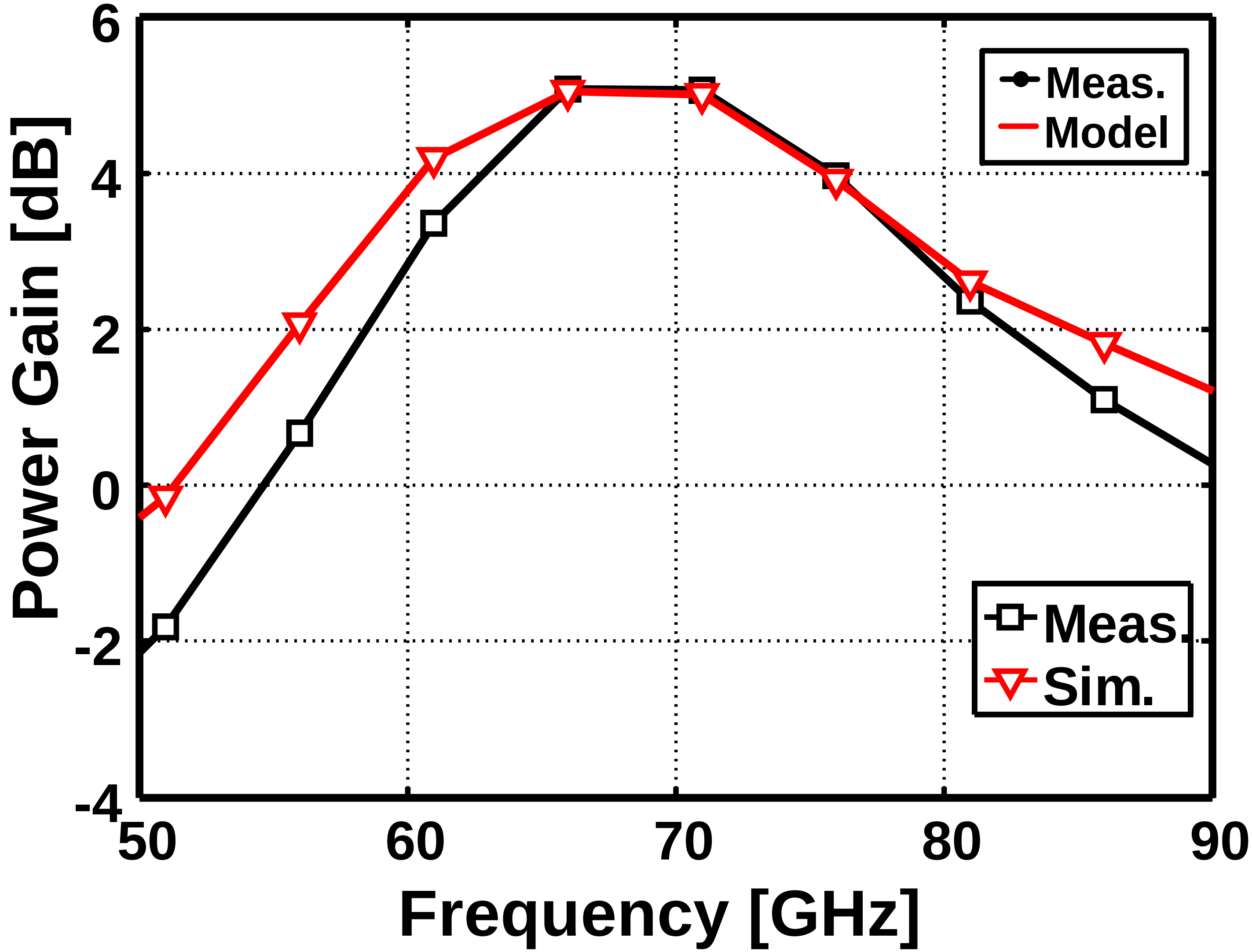


Simulation vs Measurement



S_{11}(gate-side reflection) S_{22}(drain-side reflection)

Simulation vs Measurement



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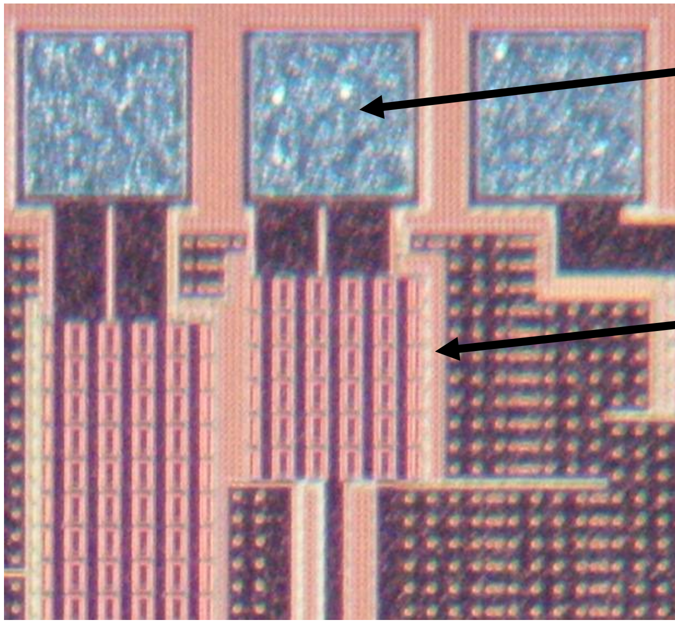
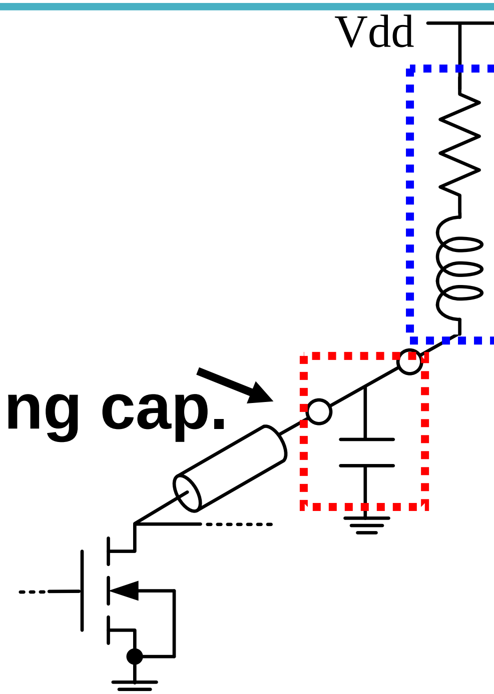
DC probe impedance





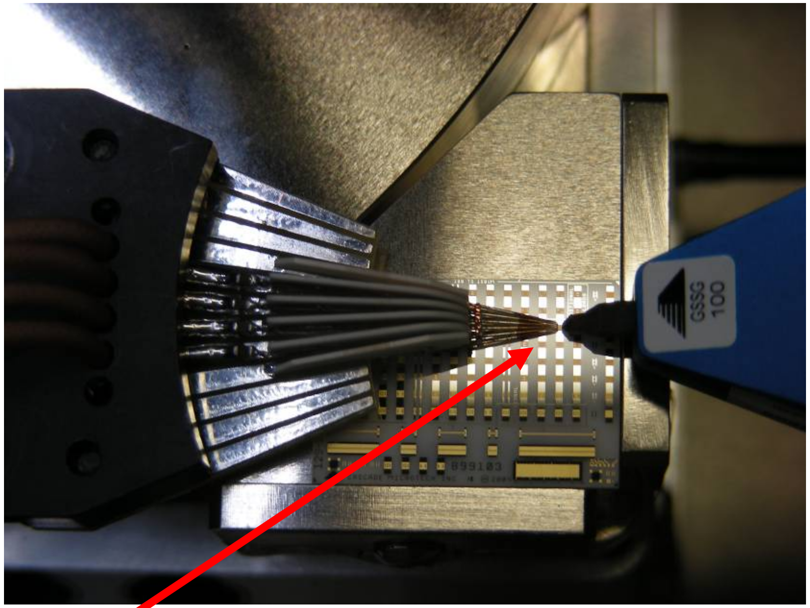
External de-coupling capacitor works well.
***e.g.*, DC probe**

Supply impedance is not stable.
Oscillation

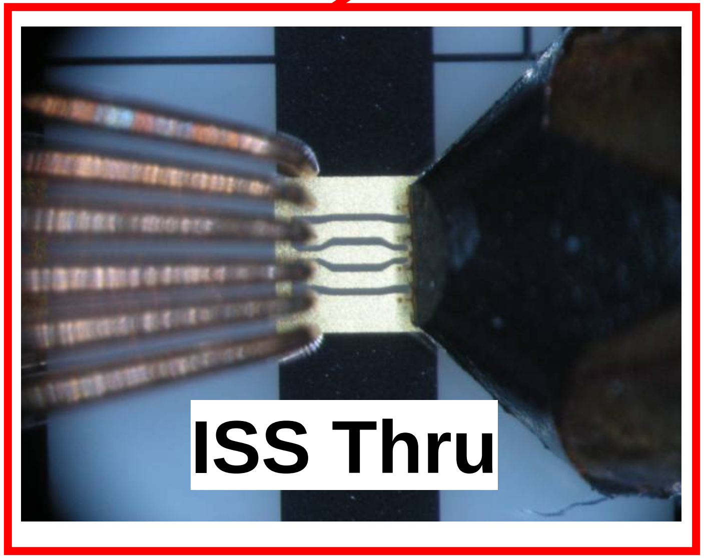
On-chip de-coupling capapacitor works well.

DC probe characterization

DC Probe (DUT)



RF Probe



- DC pad/probe is characterized, and it is taken into account in circuit simulation.
- RF pad is also characterized.

Other modeling issues

- De-embedding
- Transistor layout optimization
- Spiral inductor
- Balun
- RF Pad
- DC probe / bonding wire / bump / filler / PCB

Summary

A modeling approach to design a 60GHz CMOS amplifiers

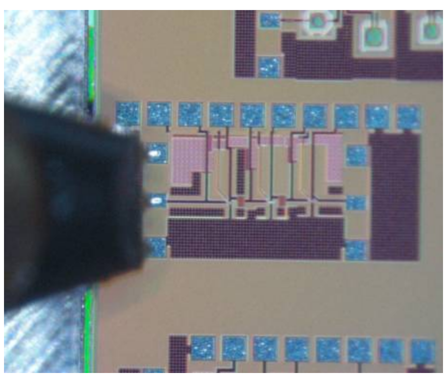
1. **Design issue of TL on CMOS chips is different from that of compound semiconductors.**
   ***e.g.*, dummy metal, lossy substrate, large conductive loss, etc**
2. **Branch modeling**
3. **Distributed modeling of de-couple MIM cap.**
4. **Evaluation using a 1-stage amplifier**

Outline

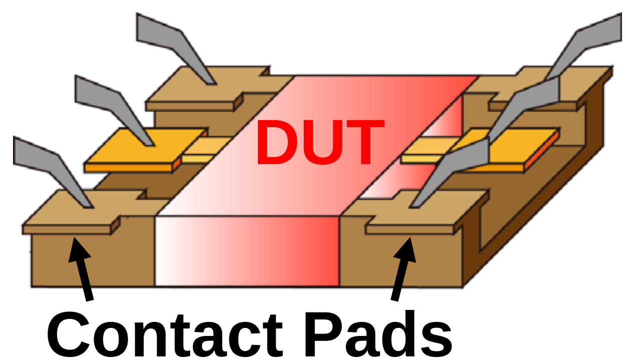
- Motivation
- Issues for mmW CMOS Circuits
- Device Characterization
- ➡ De-embedding
  - Open-Short, Thru-Only method
  - L-2L method
- Conclusion

De-Embedding

- **On-wafer probing measurement**
  - **Contact pads are needed.**
  - **Measurement data includes pad parasitic components.**
  - **At high frequency, parasitic components are not negligible.**
- **De-Embedding**
  - **Remove parasitic components from measurement data**



Measurement

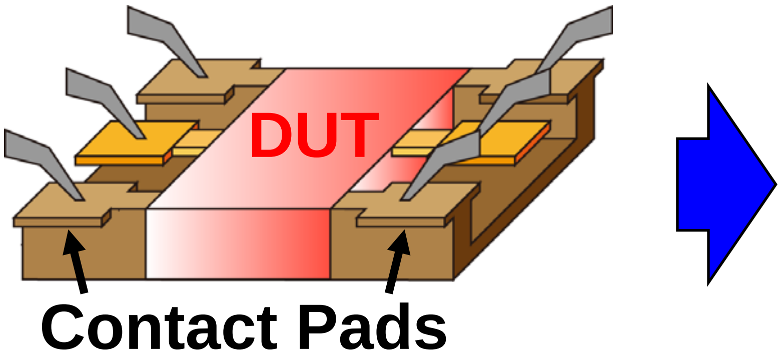


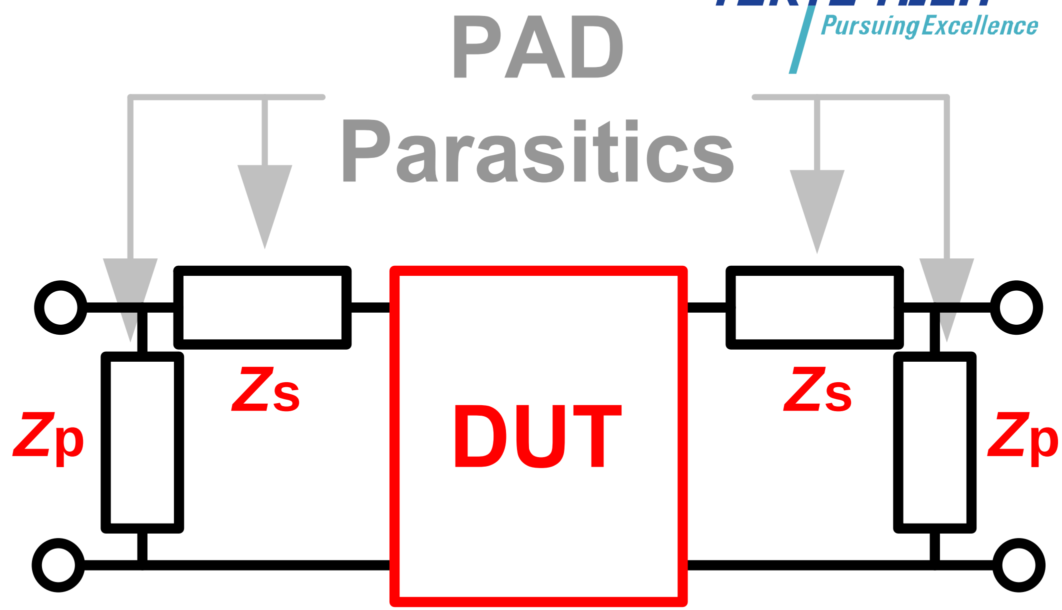
Parasitic elements of contact pads

Classification of de-embedding methods

- Lumped-constant approach
  - Open-Short
  - Open-Short-Thru
  - Thru-only
- Distributed-constant approach
  - L-2L
  - Mangan's method
  - Takayama's method

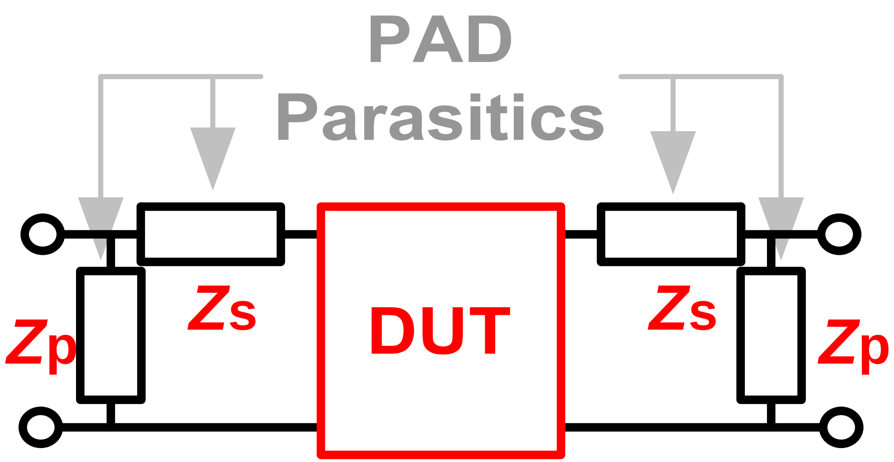
PAD model

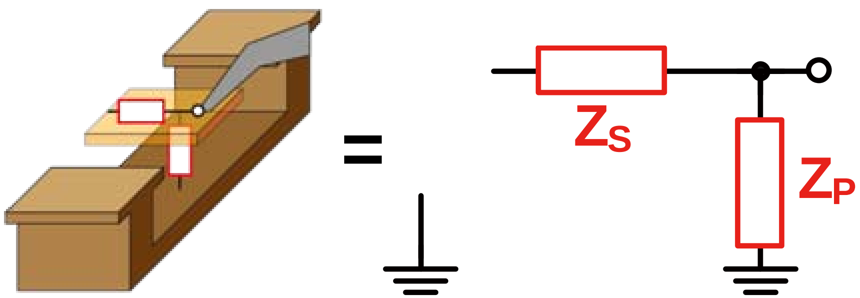




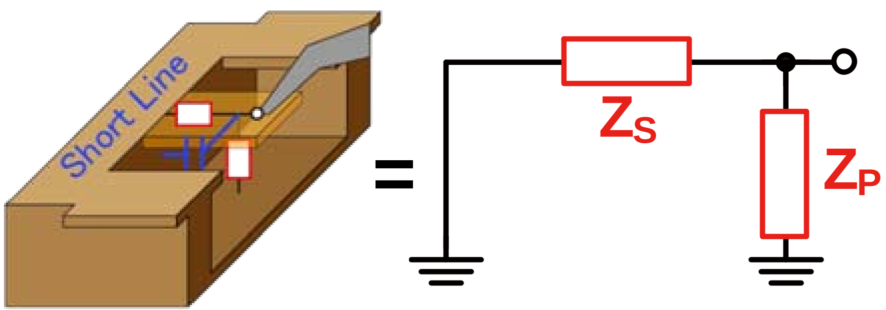
- **Simple Series-and-Shunt model**
  - **Z_P : Shunt parasitic components of contact pad**
  - **Z_S : Series parasitic components of contact pad**
- **T-parameter model**
  - **Characterized by 4 or 3 complex parameters**

Open-Short method





OPEN

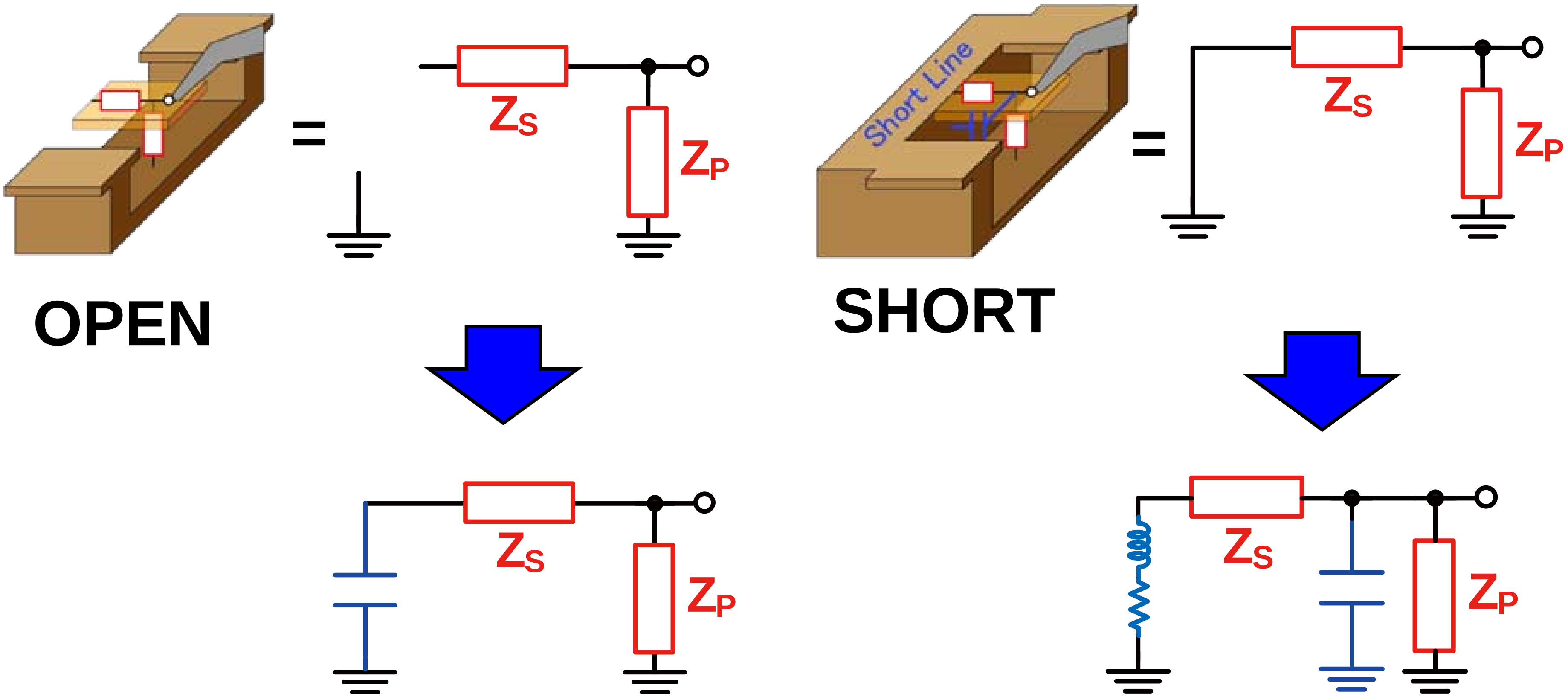


SHORT

Non-ideality of Open-Short structures

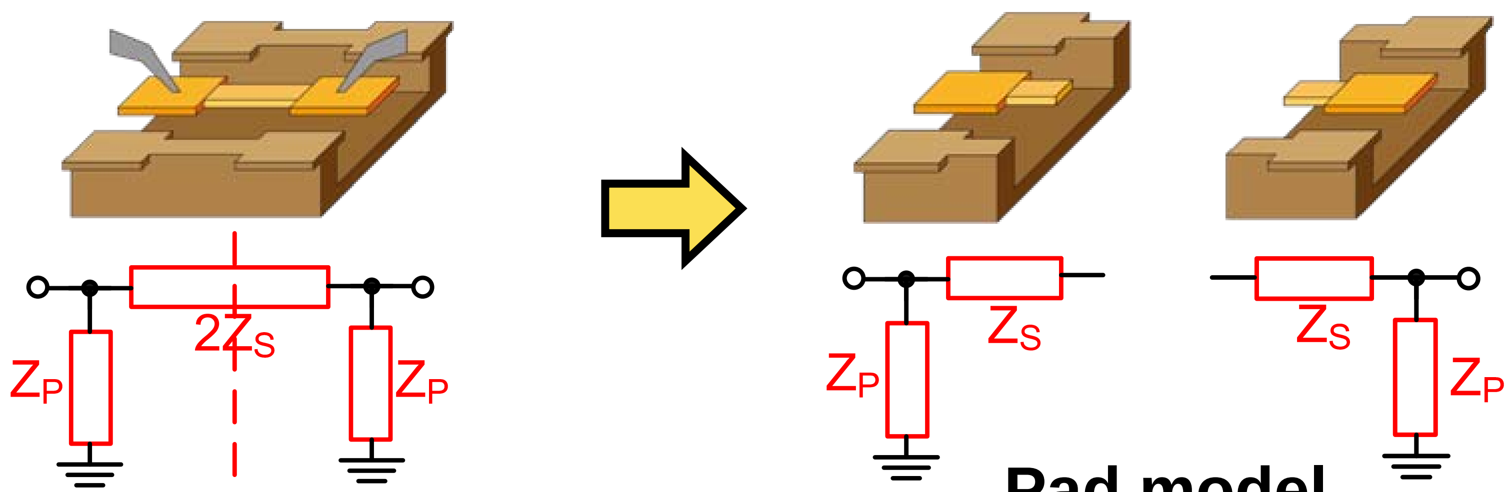
Problem at high frequency

– Ideal short cannot be obtained.



Thru-only method

- **Short-Line-Structure**
  - The measurement result is characterized as a "π"-PAD model.
  - Separate in two symmetric parts
- **Issue of this method at high frequency**
  - The line length must be short.
  - The distance between probes is too short.



Thru (short line) structure

***H. Ito, *et al*., IMS 2008**

Outline

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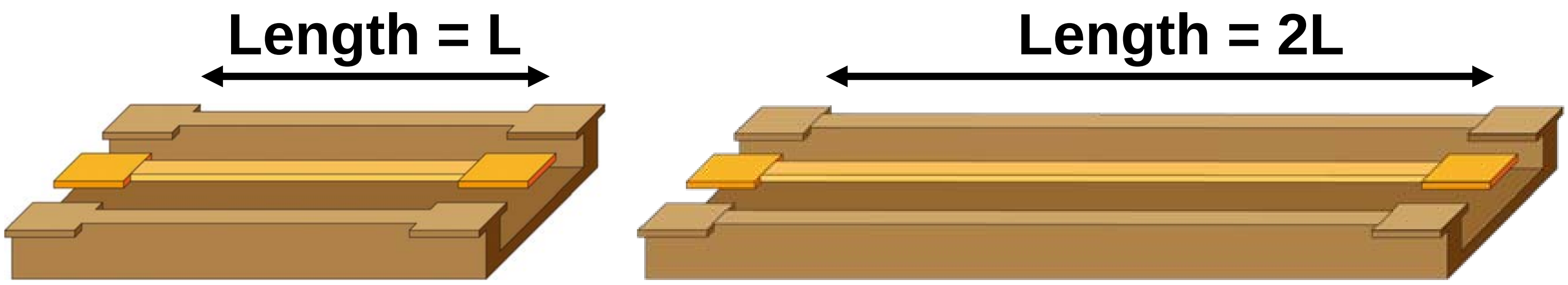
L-2L method

- A kind of multi-line de-embedding methods
  - The line length are L and 2L.
    - Not need "Short" or "Thru (Short-Line)"
- De-embed transmission lines from the measurement data
  - Build a pad model
  - The pad model is used to de-embed the pad components from other TEG.

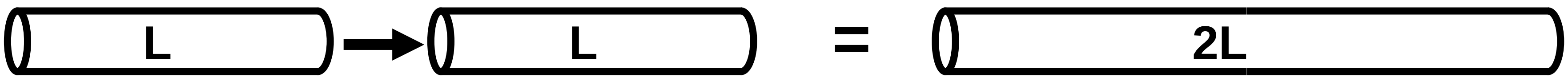


Two transmission lines

*J. Song, *et al.*, EPEP 2001

T-parameters

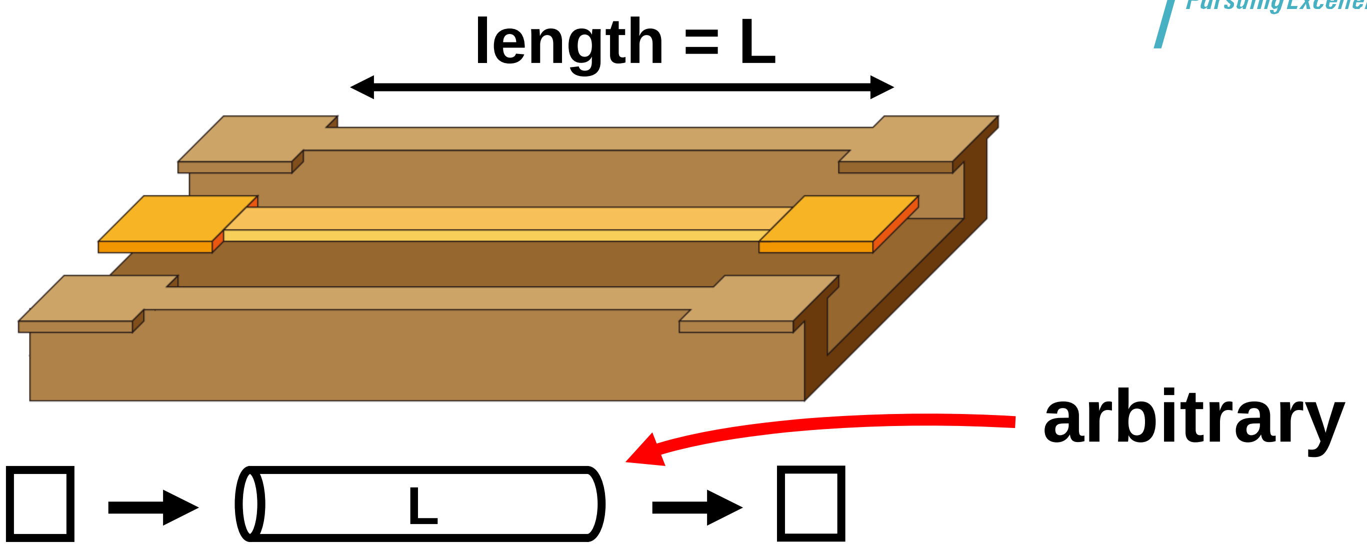
S ⇔ T T-Parameters (Scattering transfer parameters)



$$T_L \times T_L = T_{2L}$$

- **T-parameters can be calculated from S-parameters.**
- **Series connection of T-parameters can be calculated as a product of T-parameters.**
- **T-parameters are not reciprocal.**

De-embedding using T-parameters

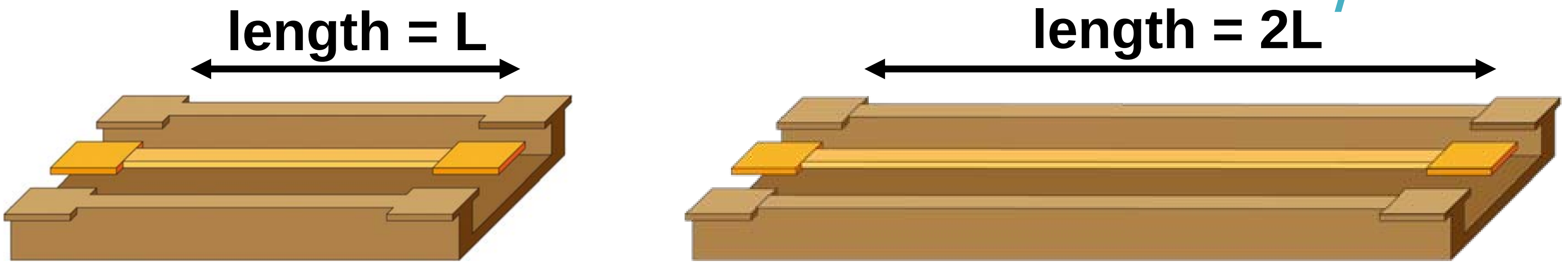


$$T_{L+PAD} = T_{LPAD} \times T_L \times T_{RPAD}$$

If we have T_{LPAD}^{-1} and T_{RPAD}^{-1},

$$T_{LPAD}^{-1}\, T_{L+PAD}\, T_{RPAD}^{-1}$$
$$= T_{LPAD}^{-1}\,(T_{LPAD}\, T_L\, T_{RPAD})\, T_{RPAD}^{-1}$$
$$= T_L$$

L-2L de-embedding method



$T_{L+PAD} = T_{LPAD}\ T_L\ T_{RPAD}$ $T_{2L+PAD} = T_{LPAD}\ T_{2L}\ T_{RPAD}$

$(T_{2L} = T_L^2)$

$T_{L+PAD}\ T_{2L+PAD}^{-1}\ T_{L+PAD}$

$= (T_{LPAD}\ T_L\ T_{RPAD})\,(T_{LPAD}\ T_L^2\ T_{RPAD})^{-1}\,(T_{LPAD}\ T_L\ T_{RPAD})$

$= T_{LPAD}\ T_L\ T_{RPAD}\ T_{RPAD}^{-1}\ T_L^{-2}\ T_{LPAD}^{-1}\ T_{LPAD}\ T_L\ T_{RPAD}$

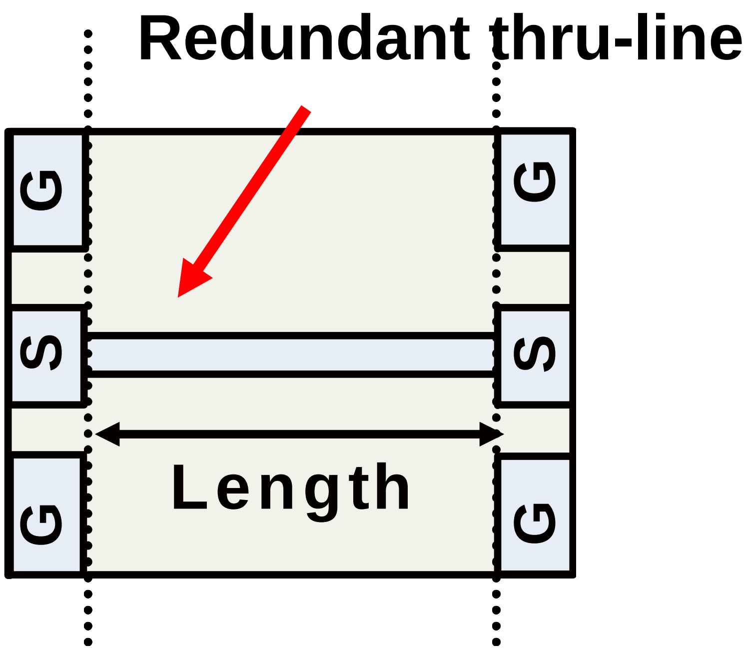
$= T_{LPAD}\ T_L\ T_L^{-2}\ T_L\ T_{RPAD}$

$= T_{LPAD}\ T_{RPAD}$

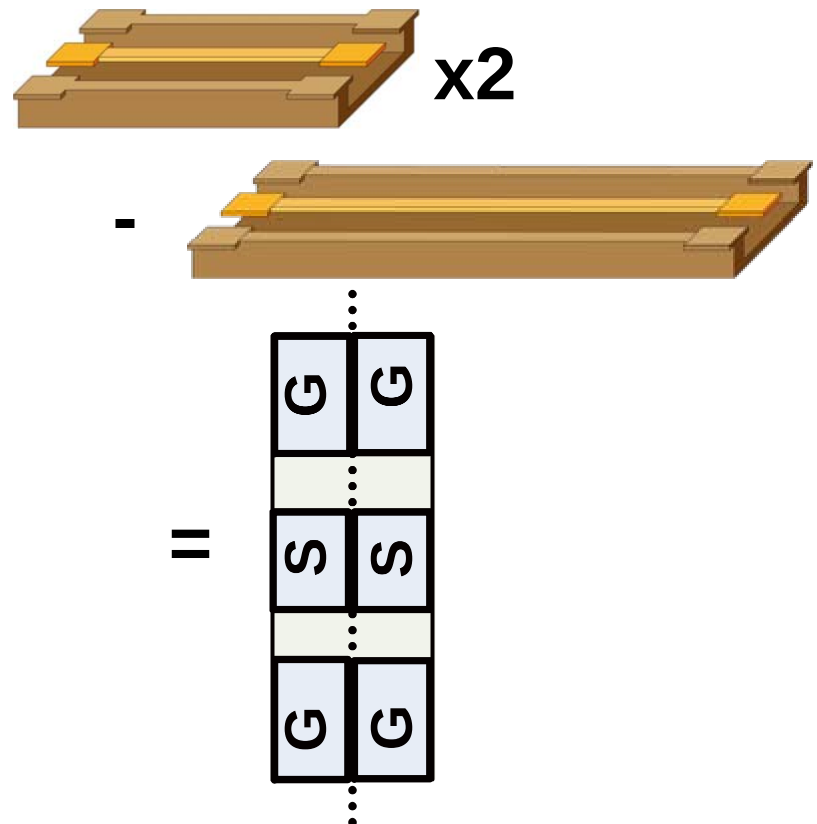
*J. Song, *et al*., EPEP 2001

Thru-only *vs* L-2L methods

Thru-only method



L-2L method



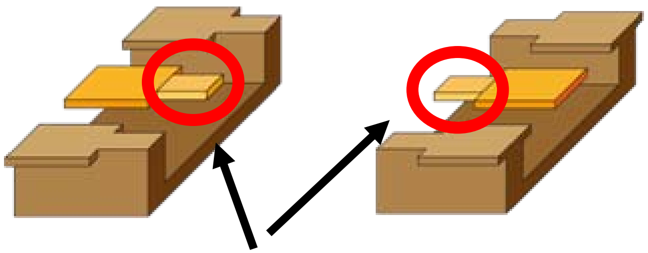
No redundant thru part

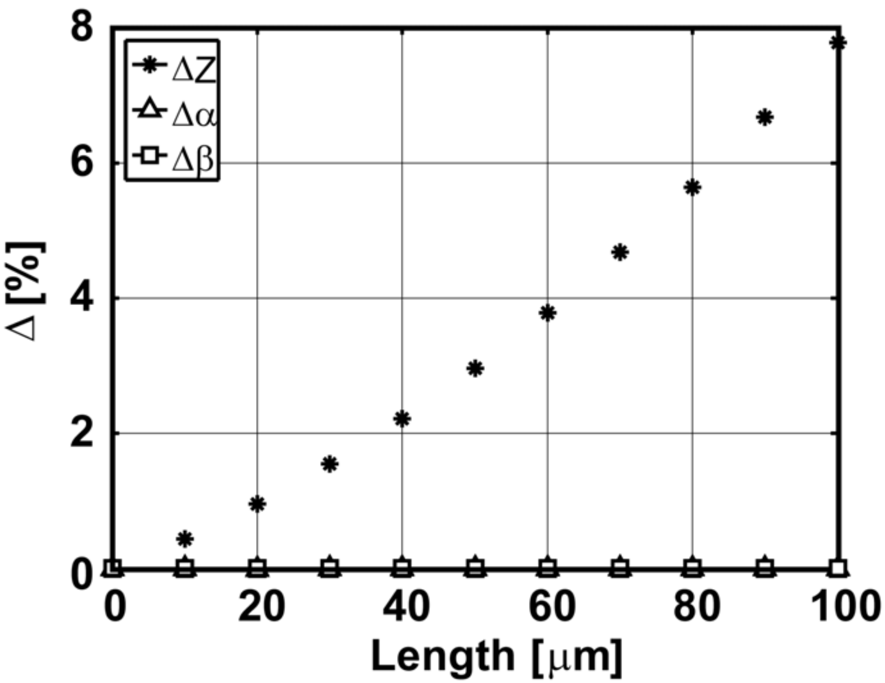
Redundant thru-line causes error at mmW frequencies.

Comparison between L-2L and Thru-only

Thru-only method

PAD model for Thru-only method





Error items vs. thru-line length @60GHz

Z_0 will have more than 2% error.

Experimental results

- **CMOS 65nm process**
- **TL structure**
  - **Guided Micro Strip**
  - **W = 10 [μm], H = 8 [μm], G = 15 [μm]**
  - **Length of TLs : 200, 400 [μm]**
- **Pad structure**
  - **Signal pad : 40x60 [μm²]**

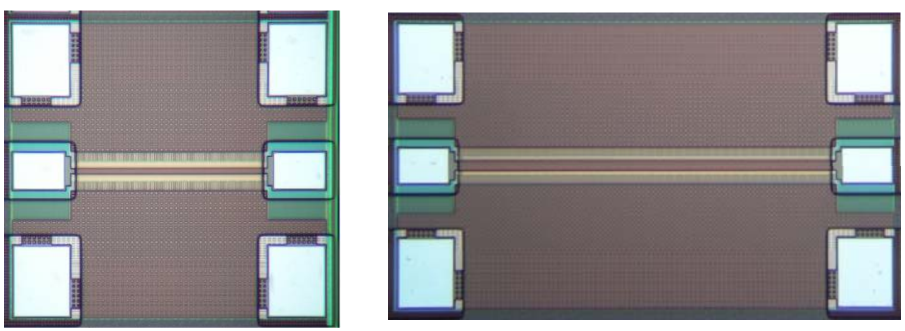
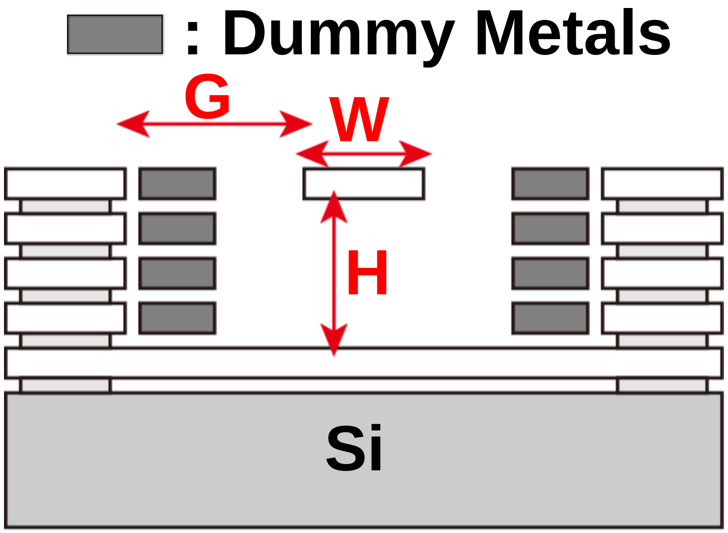


Photo of TLs



Structure of TL

Verification

- **Make pad models by each method**
- **De-embedding of different-length TLs**
- **Calculate Z_0 of TL from S-parameter**
- **Compare Z_0**
  - **Calculated from 200μm-TL**
  - **Calculated from 400μm-TL**

$$Z_0^{\ 2} = Z_{\mathrm{ref}}^{\ 2} \frac{(1+S_{11})^2 - S_{21}^{\ 2}}{(1-S_{11})^2 - S_{21}^{\ 2}}$$

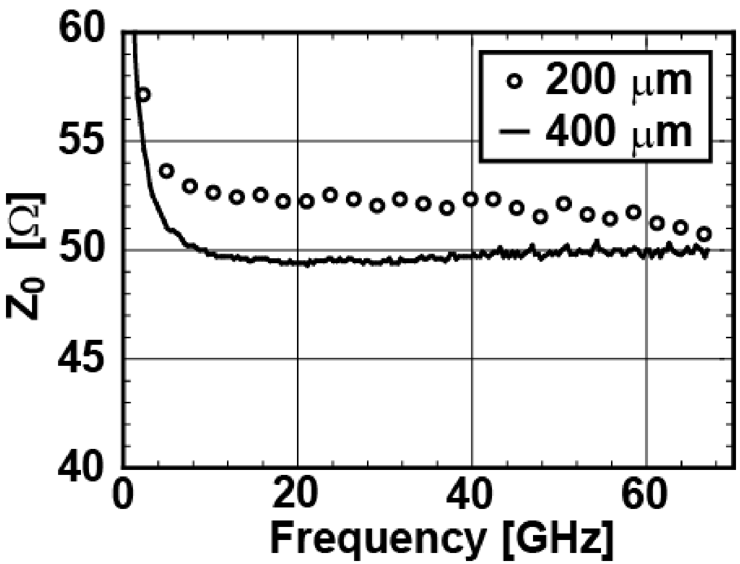
Z_0 **: Characteristic Impedance**

Z_{ref} **: Normalized Impedance**

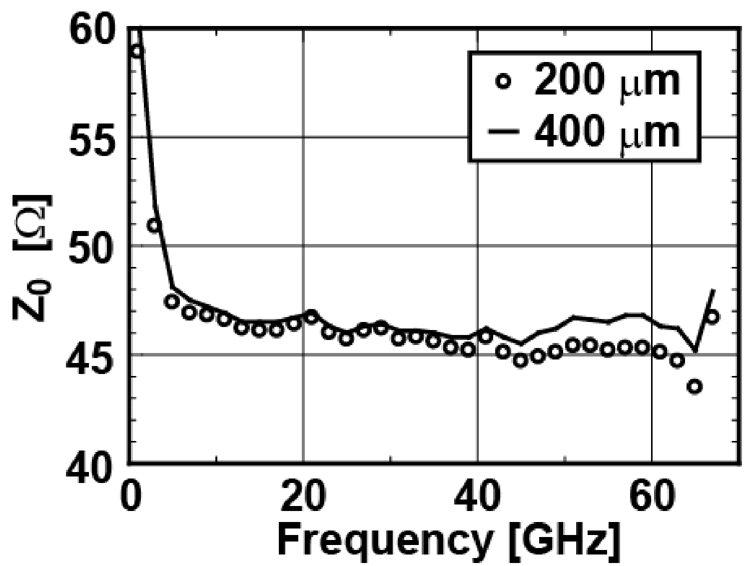
[1] W. R. Eisenstadt, *et.al.*, "S-parameter-Based IC Interconnect Transmission Line Characterization"

Experimental results (Lumped app.)

- **Open-short method**
  - **Characteristic impedances of 200μm and 400μm do not agree with each other.**
- **Thru-only method**
  - **The results are unstable.**



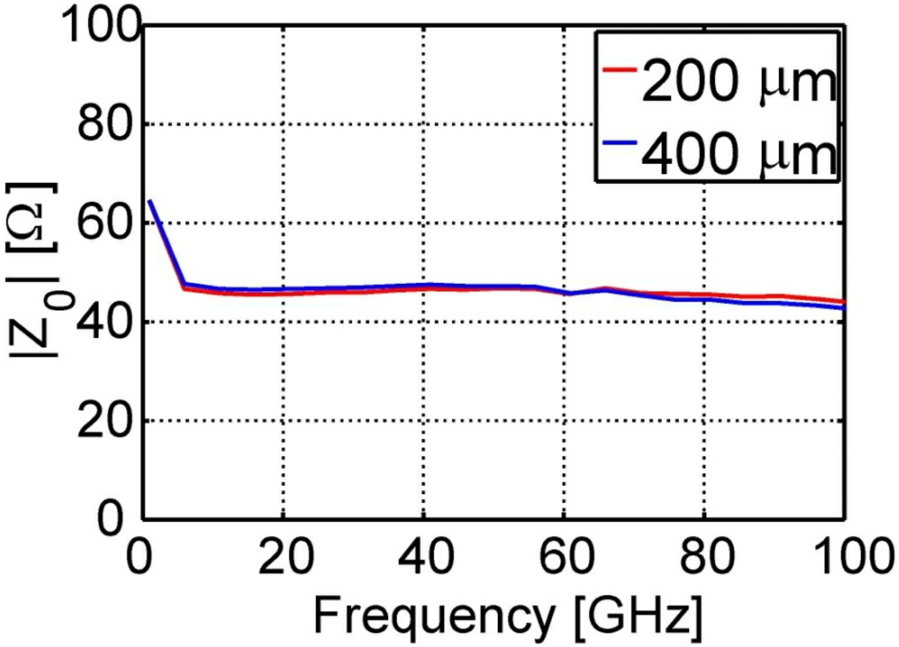
Open-short method



Thru-only method

Experimental results (L-2L)

- **Characteristic impedance of TLs**
  - **The impedances of 200μm and 400μm agree with each other.**
  - **The results are stable.**



Characteristic impedance

Summary

- **Lumped/Distributed de-embedding methods are reviewed.**
- **L-2L method performs very high accuracy at mmW frequency.**
- **The conventional Open-Short fails.**

Outline

- Motivation
- Issues for mmW CMOS Circuits
- Device Characterization
- De-embedding
- ➡ Conclusion

Conclusion

- **This tutorial reviews mmW-frequency measurement and characterization of CMOS passive and active devices for designing mmW circuits.**
- **Tile-based design is required due to dummy metal and parasitic caps.**
- **Branch and bend are individually characterized.**
- **L-2L de-embedding method is practical at mmW frequency.**

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