A Multi-Line De-Embedding Technique for mm-Wave CMOS Circuits

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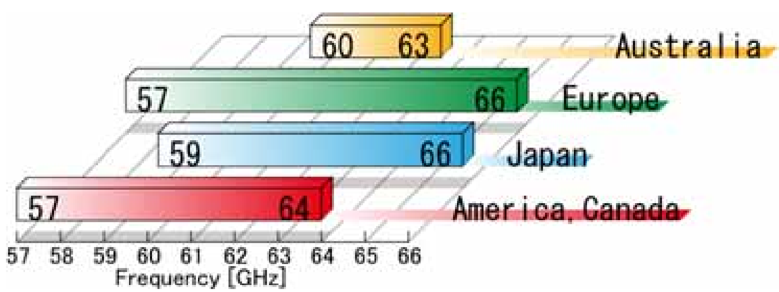
Outline

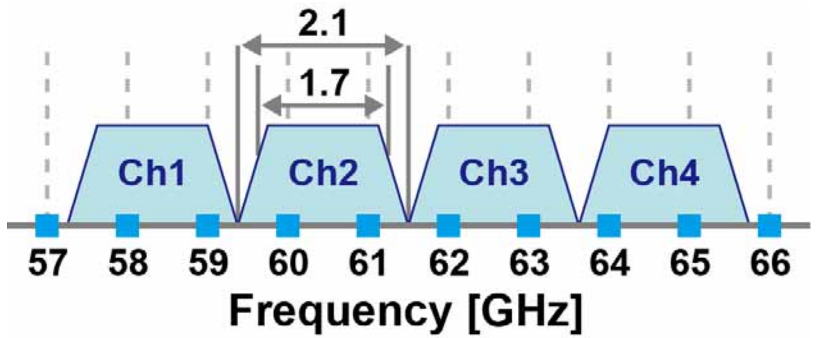
- Background
- De-embedding
  - Conventional Methods
  - Proposed Method
  - Experimental Results
- Conclusion

Background

- **CMOS 60GHz RF Circuits**
  - Available wide frequency range without licensees
  - High data rate wireless communication
  - IEEE 802.15.3c
    - 1.7 GHz × 4 ch
    - QPSK ⇒ 14 Gbps, 16QAM ⇒ 28 Gbps



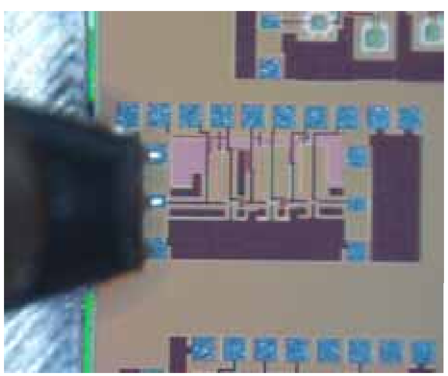
Available frequency range



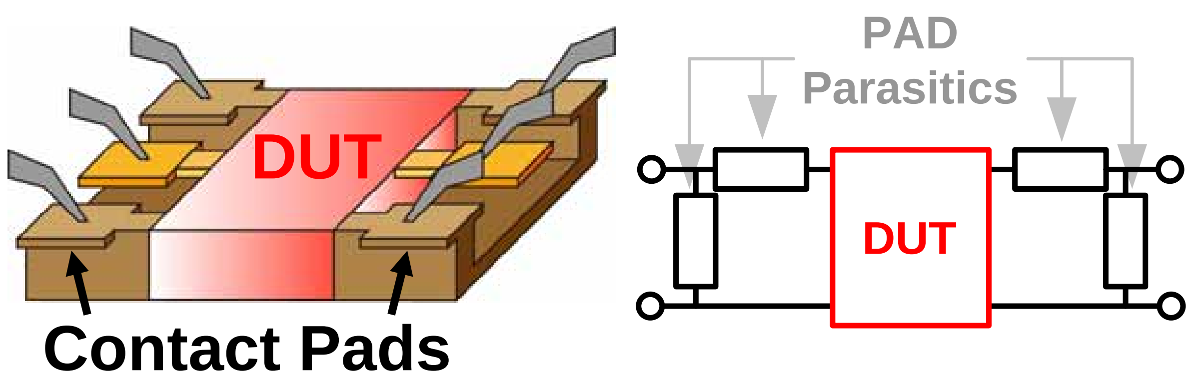
IEEE 802.15.3c

De-Embedding

- **On-wafer probing measurement**
  - Contact pads are needed.
  - Measurement data include the parasitics of pads.
  - At high frequency, parasitic elements becomes problematic.
- **De-Embedding**
  - Remove parasitic elements from measurement data



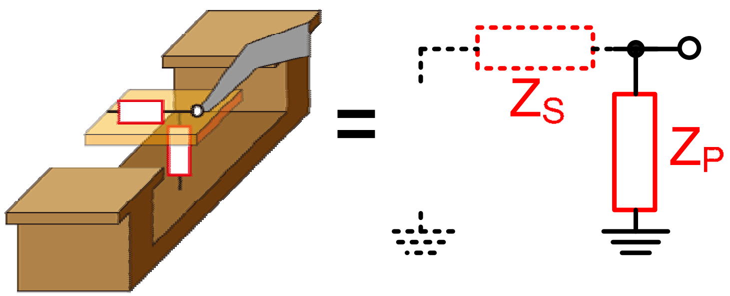
Measurement



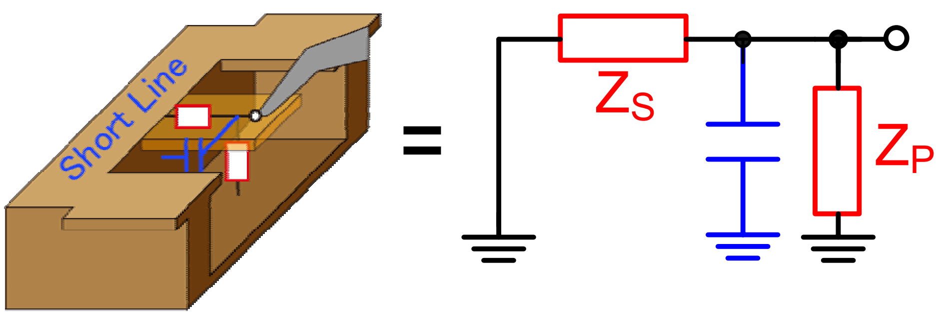
Parasitic elements of contact pads

Open-Short Method (Conventional 1)

- **Open-Structure and Short-Structure**
  - Z_P : Parallel element of contact pad
  - Z_S : Series element of contact pad
- **Problem at high frequency**
  - Nonideality of short cannot be neglected.



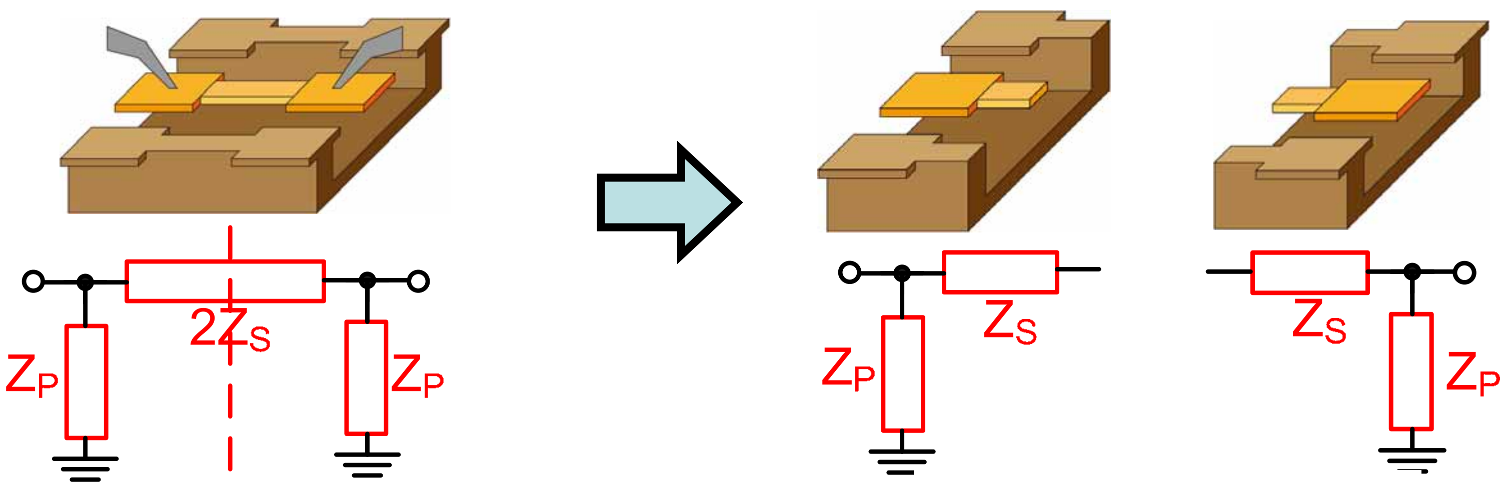
Open-Structure



Short-Structure

Thru-only Method (Conventional 2)

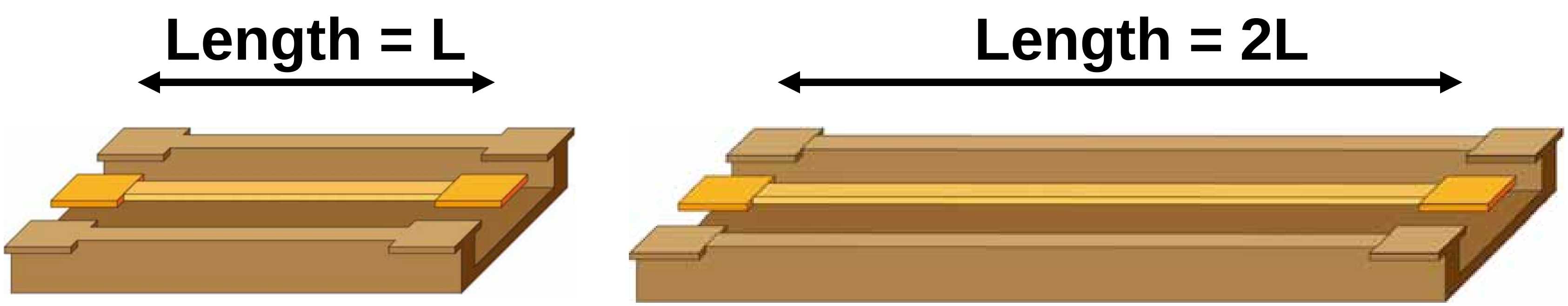
- **Short-Line-Structure**
  - Replace the measurement result with the "π"-Model
  - Separate in two symmetric parts
- **Issue of this method at high frequency**
  - Lumped components
  - The line length must be short.
  - The measurement error has large influence.



Short-Line-Structure **Models of Pads**

Proposed Method

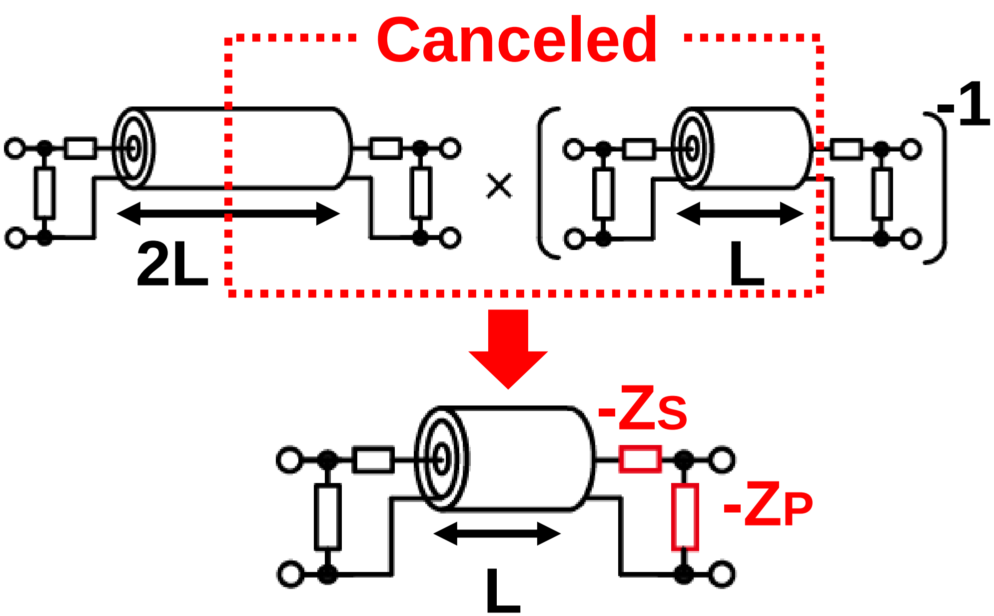
- **Multi-Lines De-embedding**
  - The Length of the lines are L and 2L
    - Not need “Short” or “Short-Line”
  - De-embed transmission lines from the measurement data
  - Build the model of the contact pad
  - Remove the pad from other TEG

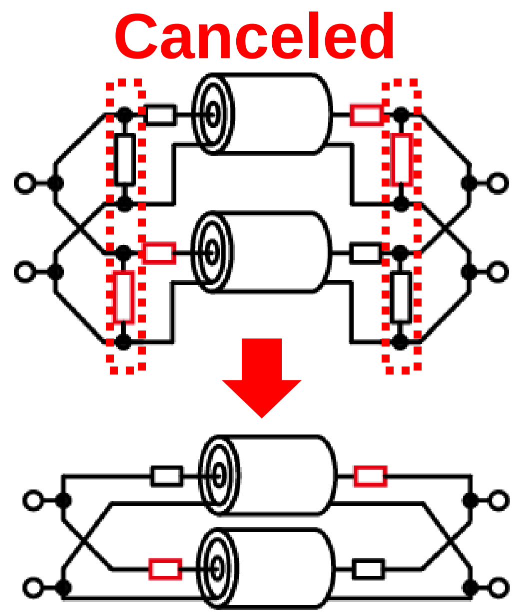


Two transmission lines

Canceling Parallel Elements

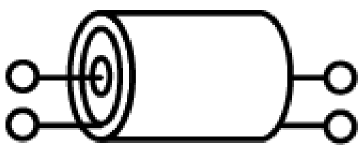
- **Use T-parameters**
  - $T_{2L} \times (T_{L})^{-1} = T_{X1}$
  - T-para ➡ Y para : T_{X1} ➡ Y_{X1}
  - Y_{X1} + Swap (Y_{X1}) = Y_{X2}
    - The parallel components are canceled





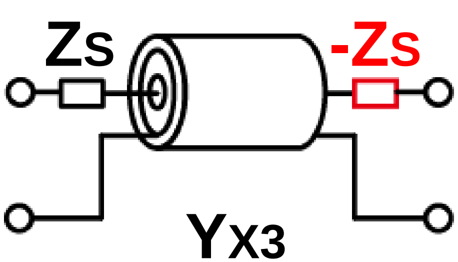
Intrinsic Transmission Line

- **Intrinsic Transmission Line : Y_{TL}**
  - **Symmetrical matrix**
- **$Y_{X3} = Y_{TL}$ with Z_S and $-Z_S$**
- **$Y_{X2} = Y_{X3} + \mathrm{Swap}(Y_{X3})$**
  - **$Y_{X2} = 2Y_{TL}$**



Y_{TL}

$$Y_{TL} = \begin{bmatrix} Y_{TL\_1} & Y_{TL\_2} \\ Y_{TL\_2} & Y_{TL\_1} \end{bmatrix}$$

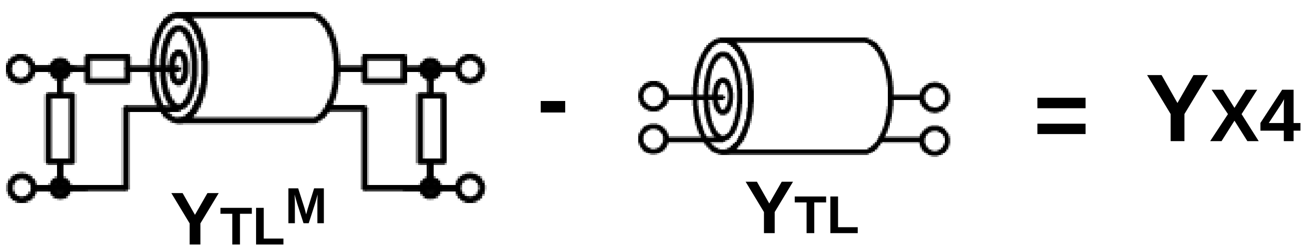


$$Y_{X3} \cong \begin{bmatrix} Y_{TL\_1} - X & Y_{TL\_2} \\ Y_{TL\_2} & Y_{TL\_1} + X \end{bmatrix}$$

$$X = Z_S (Y_{TL\_1}{}^2 - Y_{TL\_2}{}^2)$$

Parallel Element

- **Parallel element of pad : Z_P**
  - **Measurement data of TL : Y_{TL}^M**
  - **$Y_{TL}^M - Y_{TL} = Y_{X4}$**
  - **$Y_{X4}(1,1) + Y_{X4}(1,2) = 1 / Z_P$**
    - **Using approximation**

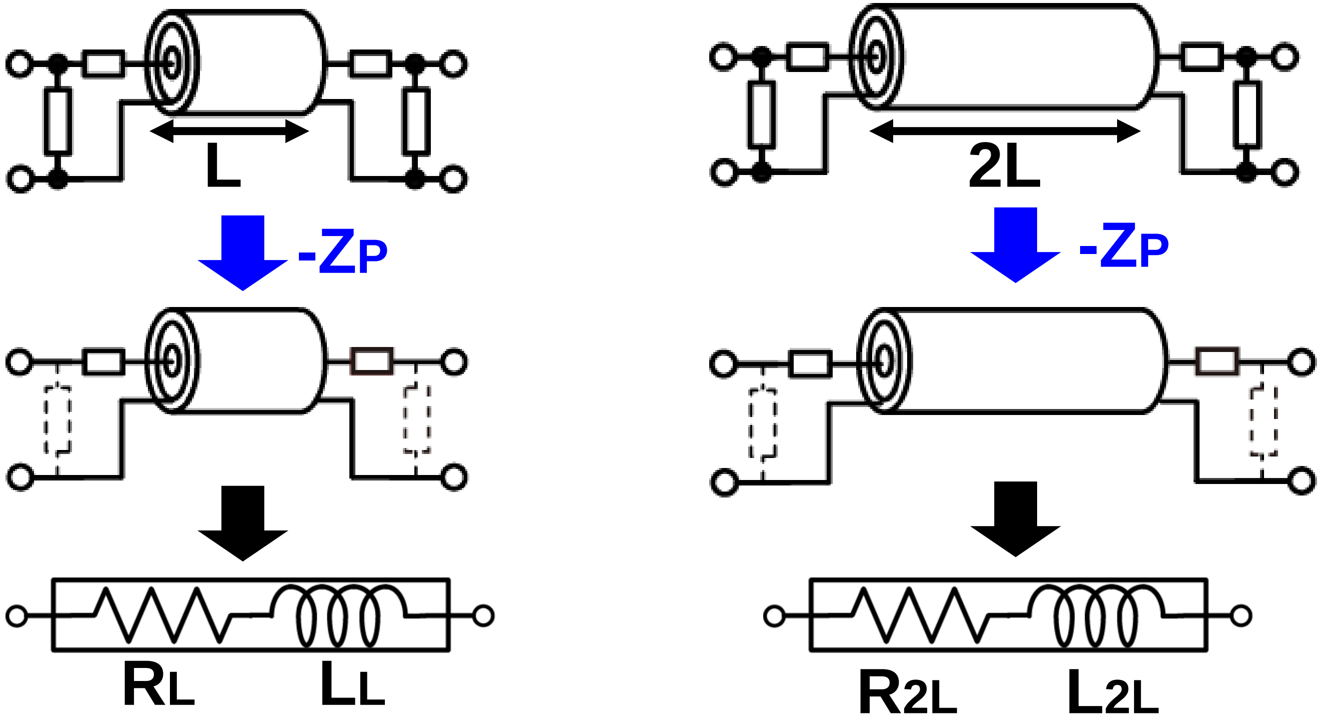


Requirement of the approximation

$$\frac{(Y_{TL\_1}+Y_{TL\_2})^2 \cdot Z_S \cdot Z_P}{1+(Y_{TL\_1}+Y_{TL\_2})\cdot Z_S} << 1$$

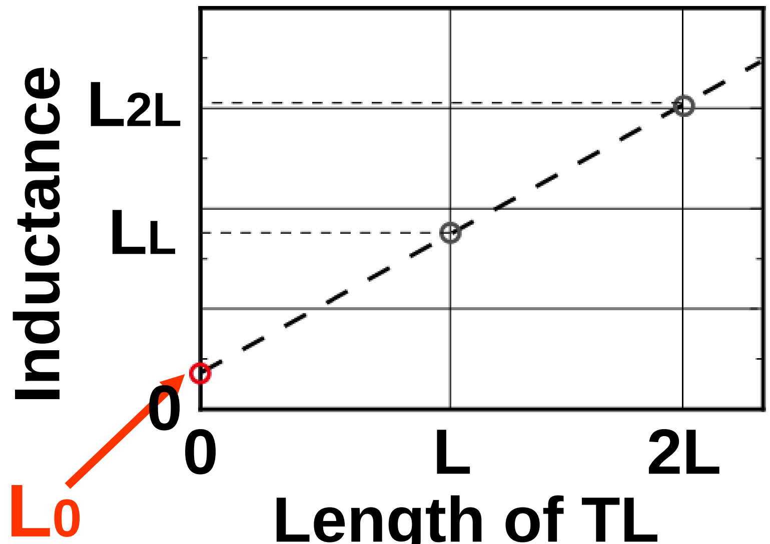
Lumped Components

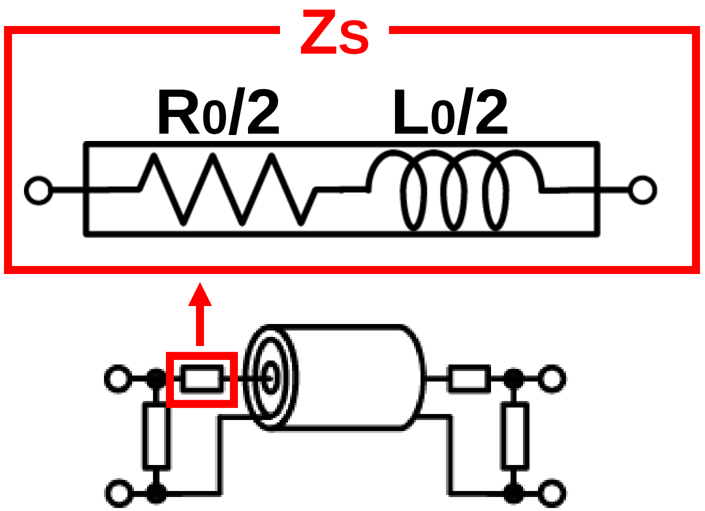
- Series element of pad : Zs
  - Subtract Z_P from Y_{TL}^M
  - Approximate by Lumped Components
    - Inductance and Resistance



Series Element

- **Plot the calculated Inductances**
  - **L_0 : Offset of Inductance**
- **Perform the Same Process about R**
- **Z_S : $L_0/2$ and $R_0/2$**





Experimental Results

- **CMOS 65nm process**
- **TL structure**
  - **CPW with bottom ground metal**
  - **W = 10 [μm], H = 8 [μm], G = 15 [μm]**
  - **Length of TLs : 200, 400 [μm]**
- **Pad structure**
  - **Signal pad : 40x60 [μm^2]**

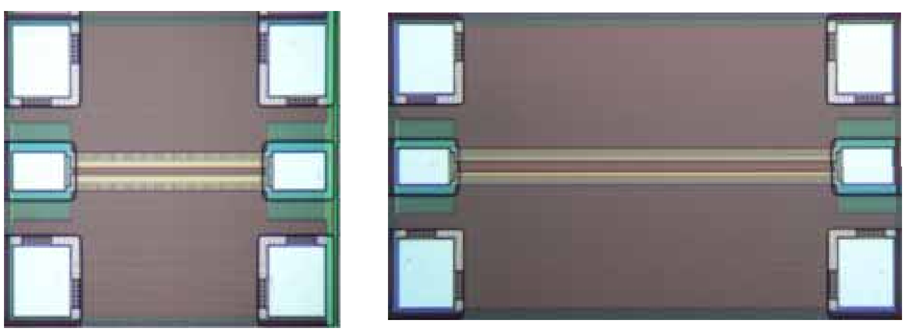
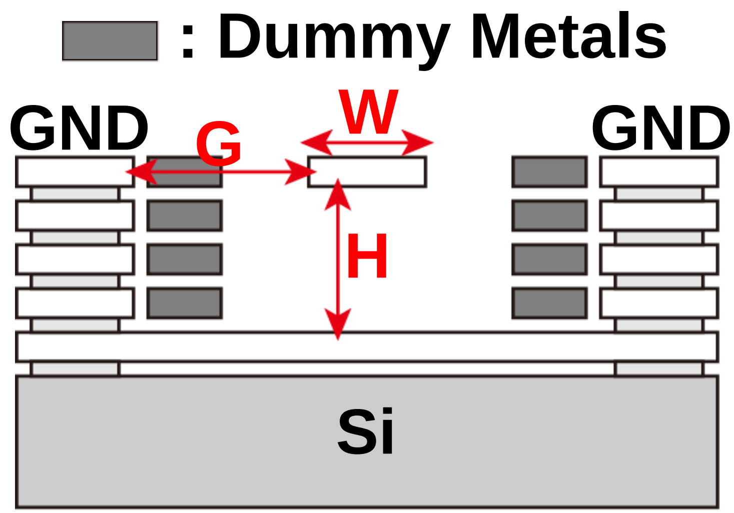


Photo of TLs



Structure of TL

Method of Evaluation

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

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

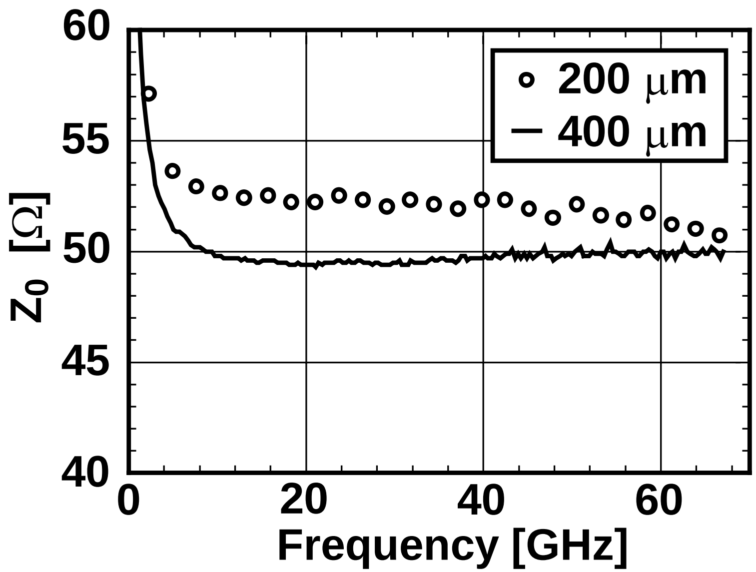
Z_0 : Normalized Impedance

Z : Characteristic Impedance

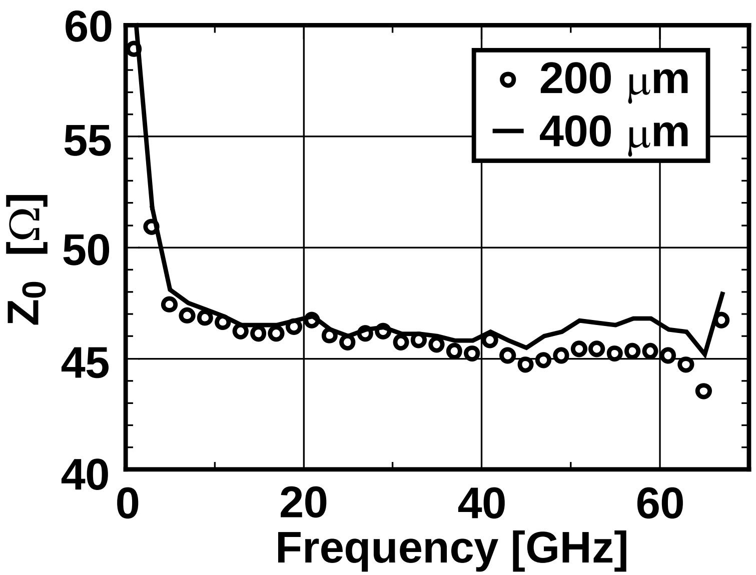
[1] W. R. Eisenstadt, *et.al.*, “S-parameter-Based IC Interconnect Transmission Line Characterization”

Experimental Results (Conventional)

- **Open-Short Method**
  - **Characteristic Impedances of 200μm and 400μm don't agree with each other.**
- **Thru-only Method**
  - **The results are unstable.**



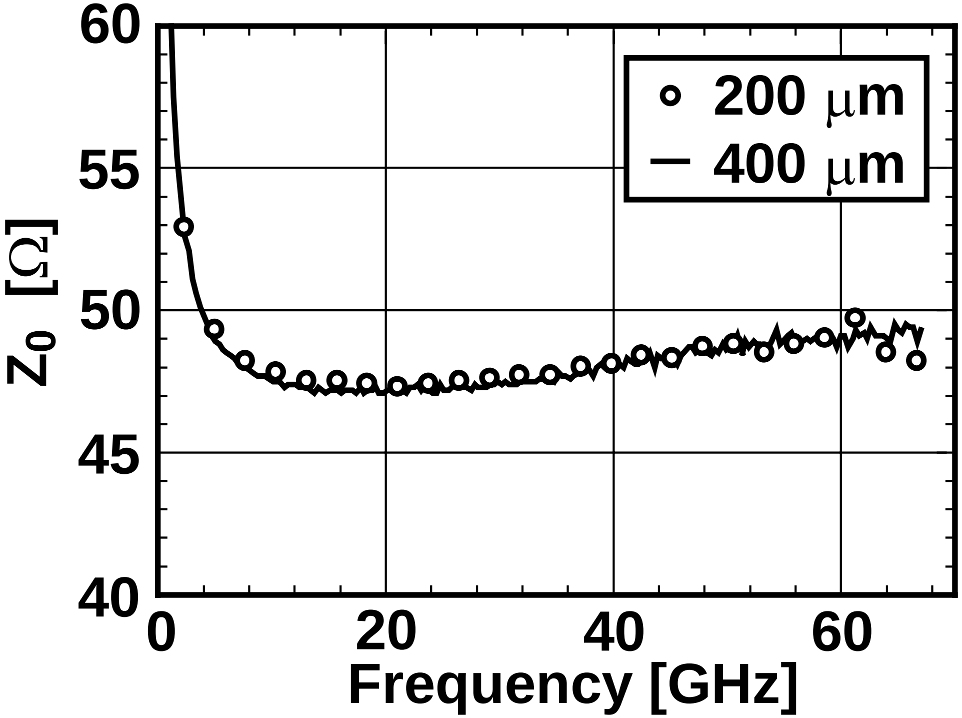
Open-Short Method



Thru-only Method

Experimental Results (Proposed)

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



Conclusion

- **The de-embedding method for designing mm-Wave circuits is proposed.**
- **This method can be applied to not only TLs but also other TEGs.**
- **Using this method, the characteristic impedances of different-length TLs agree with each other and the result are stable compared with conventional methods.**

Thank you for your attention!