Chapter 11

Millimeter-Wave Flip-Chip Transitions

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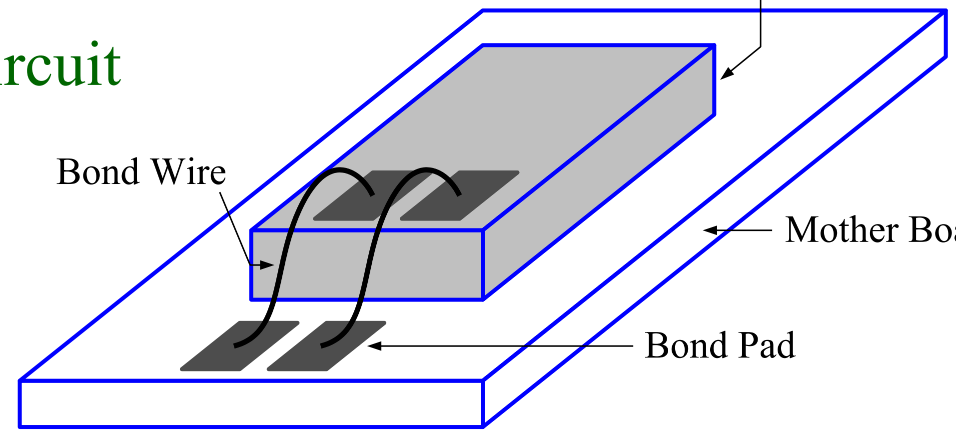
Outline

- Introduction
- Conventional Flip-chip Transition
- Resonant Flip-chip Transition
- Inductive Compensation Flip-chip Transition
- Locally Matching Flip-chip Transition
- On Chip Design and Measurement Correction
- Conclusions

Introduction

- Bonding Wire → Inductive
  - Multiple Bonding Wires [1]
  - Ribbon Wire [1]-[2]
    - Up to 40 GHz
  - Capacitive Matching Circuit [3]-[4]
    - Sacrifice of chip areas
    - Requirement of precise fabrication



[1] J. Y. Kim et al., IEEE APMC'00, pp. 1265-1268.
[2] A. Sutono et al., IEEE Advanced Packaging-24, pp. 595-603, 2001.
[3] U. Goebel, IEEE EPEP'94, pp. 182-185.
[4] T. P. Budka, IEEE MTT-49, pp. 715-718, 2001.

Introduction

- Why Flip-chip over Bonding Wire
  - Short and Stable Electrical Interconnection [5]
    - Lower insertion loss
  - Good Power Distribution Fidelity [6]
  - Good Heat Sinking Ability [7]
  - Good Surface Wave Immunity [8]
  - Available Fabrication in Millimeter-wave Frequencies [9]

[5] T. Krems et al., IEEE MTT-S'96, pp. 247-250.
[6] H. Hashemi et al., IEEE EPEP'96, pp. 24-26.
[7] E. Wolf, Proc. Semiconductor Packaging Symposium, 2000.
[8] T. Krems et al., IEEE MTT-S'97, pp. 987-990.
[9] Y. Arai et al., IEEE MTT-45, pp. 2261-2266, 1997.

Introduction

- Flip-chip → Capacitive
  - Geometry of the Bumps

    e.g. Bump pad and height [10]

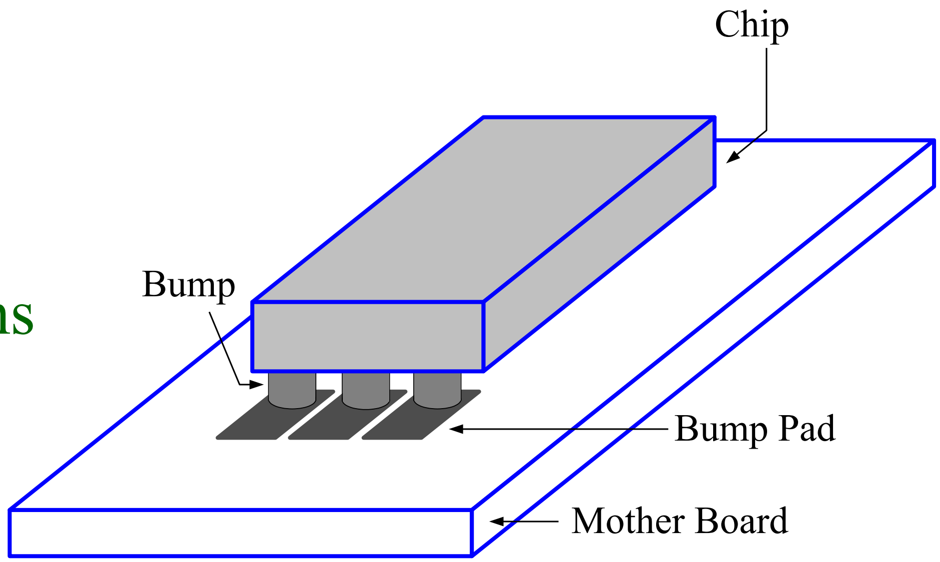
    Bump cross section [11]
  - Structure of the Transitions

    e.g. Staggered structure [12]

    Resonant structure [13]
  - Impedance Matching

    e.g. Compensated structure [11]

    Locally matching structure [14]



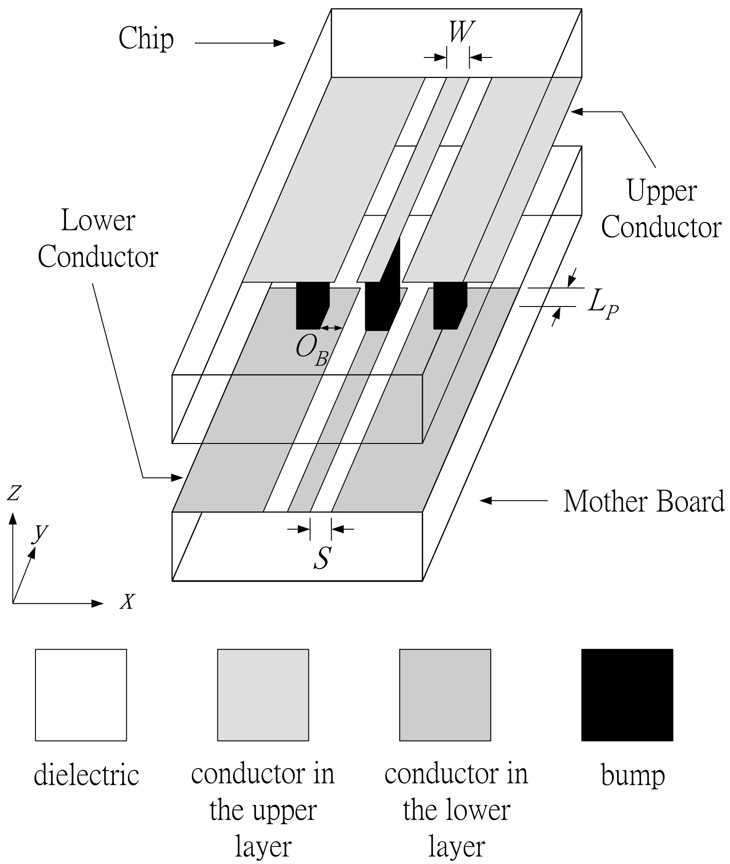
[10] W. Heinrich et al., IEEE MTT-S'98, p. 1083.
[11] A. Jentzsch et al., IEEE MTT-S'99, pp. 637-640.
[12] H. H. M. Ghouz et al., IEEE MTT-44, p. 2550, 1996.
[13] C. L. Wang et al., IEEE MTT-S'99, pp. 1423-1426.
[14] C. L. Wang et al., IEEE MTT-S'02, pp. 1397-1400.

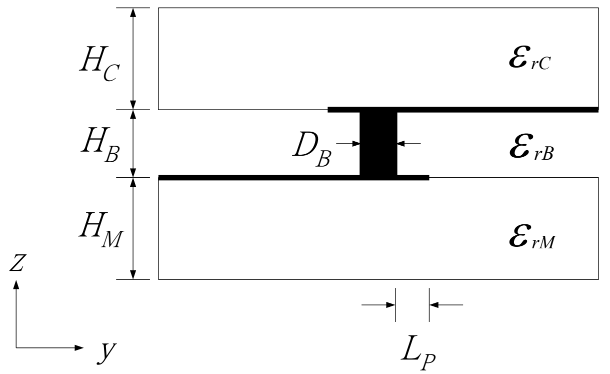
Introduction

- Various Structure Achievement
  - Two Resonant Designs
    - Control of the large return loss region
    - Optimization up to millimeter-wave frequencies
  - Inductive Compensation Design
    - A systematic design rule for implementing the inductive circuit
  - Locally Matching Technique
    - Enhancement of the frequencies above millimeter-wave
  - On Real Chip Design
    - Consideration of the conductor thickness.
    - A procedure for acquiring the correct return loss level

Conventional Flip-chip Transition

- Configuration
  - Use Rectangular Bump Cross Section [10]

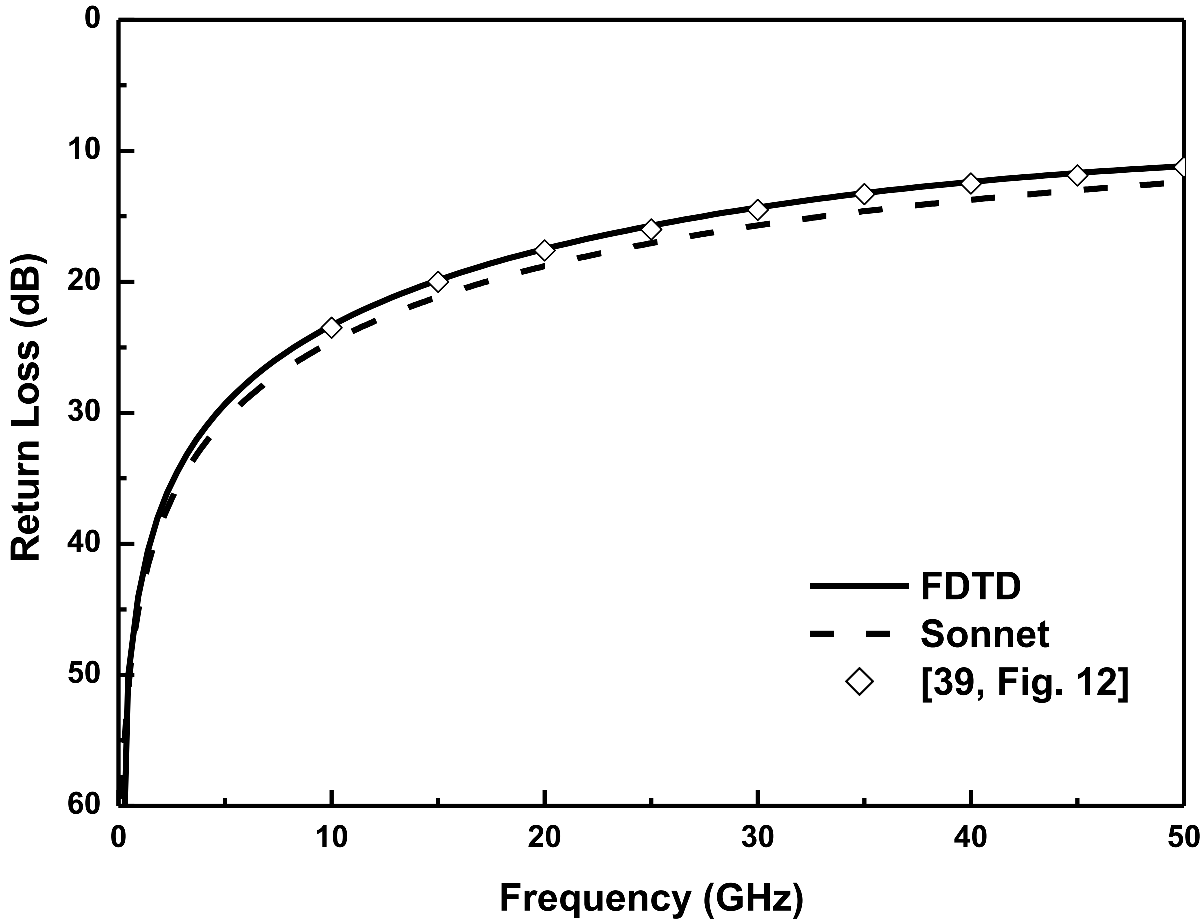




H_C=H_M=0.36mm, W=S=0.12mm, H_B=D_B=0.12mm, L_P=O_B=0mm , ε_{rM}=12.9, ε_{rB}=1, ε_{rC}=12.9.

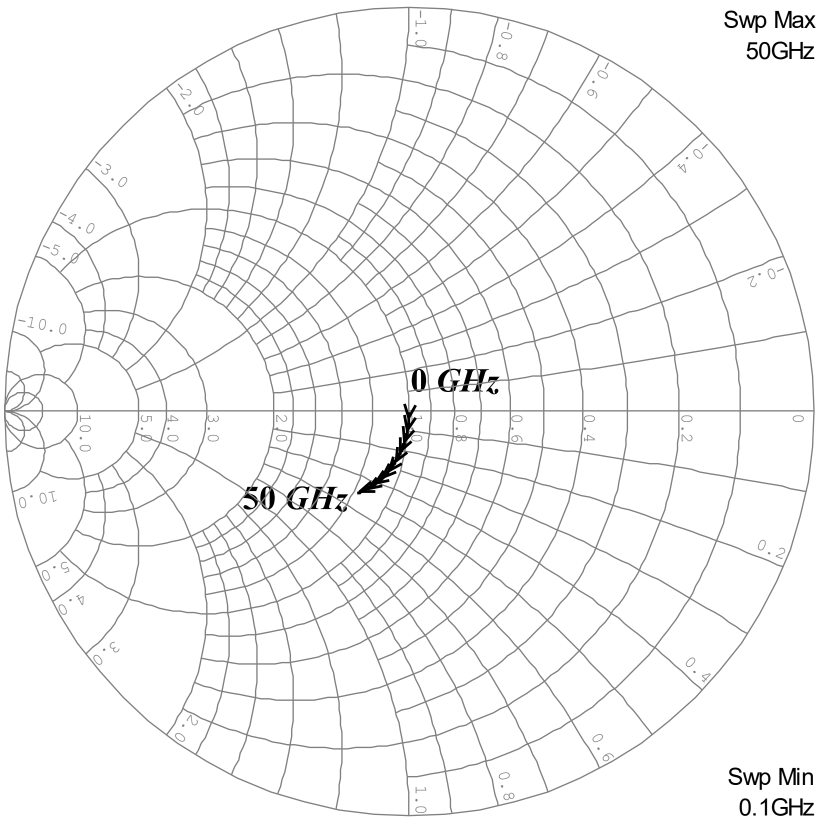
Conventional Flip-chip Transition

- Comparison between Different Methods



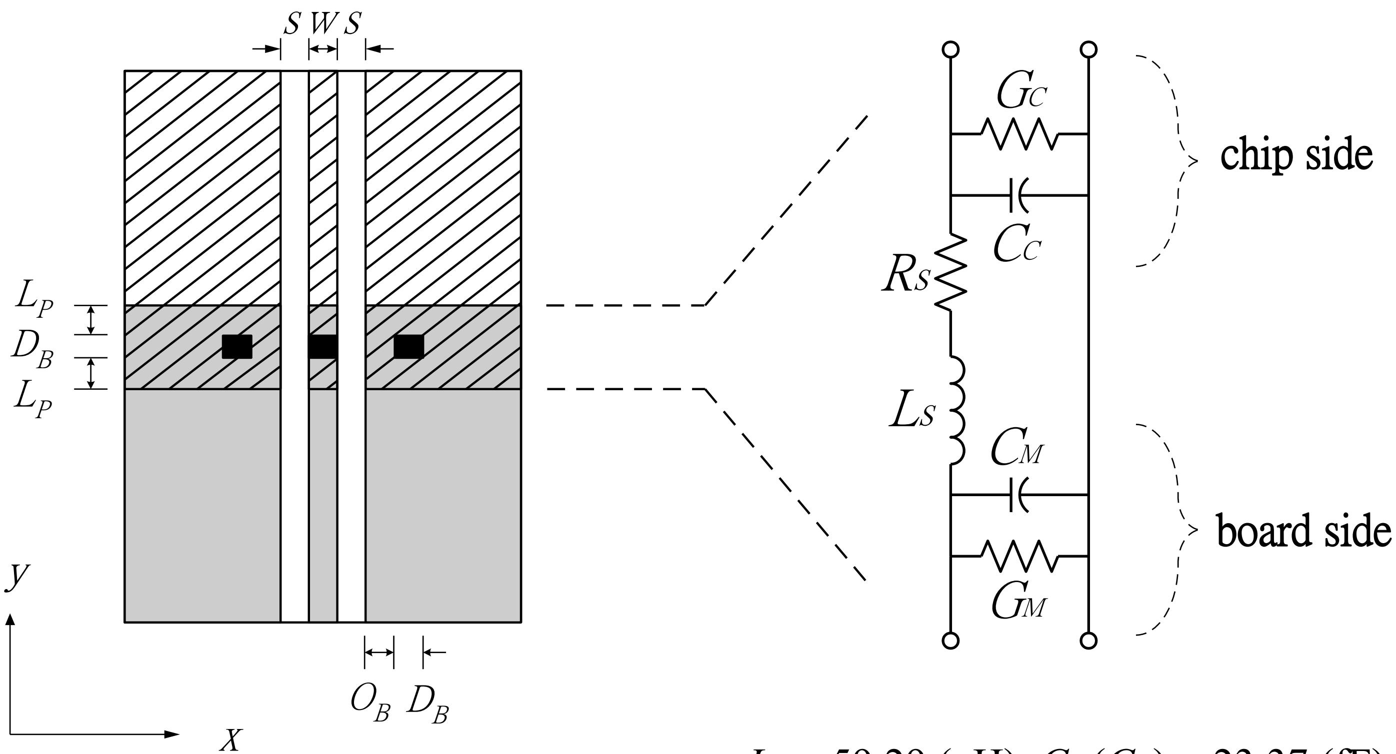
Conventional Flip-chip Transition

- S_{11} Plotted on the Admittance Smith Chart



Conventional Flip-chip Transition

- Equivalent Circuit Model [12]
  - Extracted Using ABCD Matrix by Least Square Method



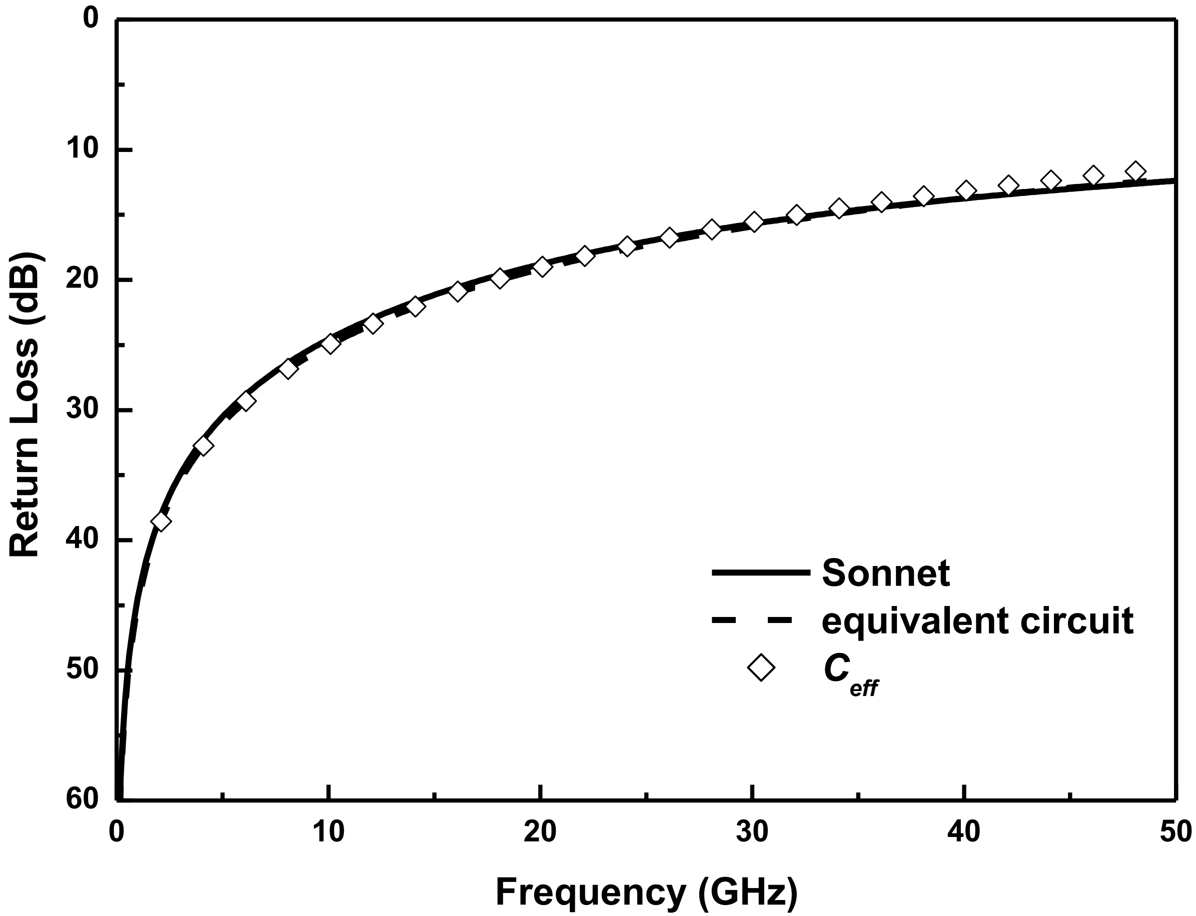
L_S = 59.29 (pH), $C_M(C_C)$ = 23.37 (fF)

[12] H. H. M. Ghouz et al., IEEE MTT-44, p. 2550, 1996.

Conventional Flip-chip Transition

- Return Loss of Equivalent Circuit Model [11]

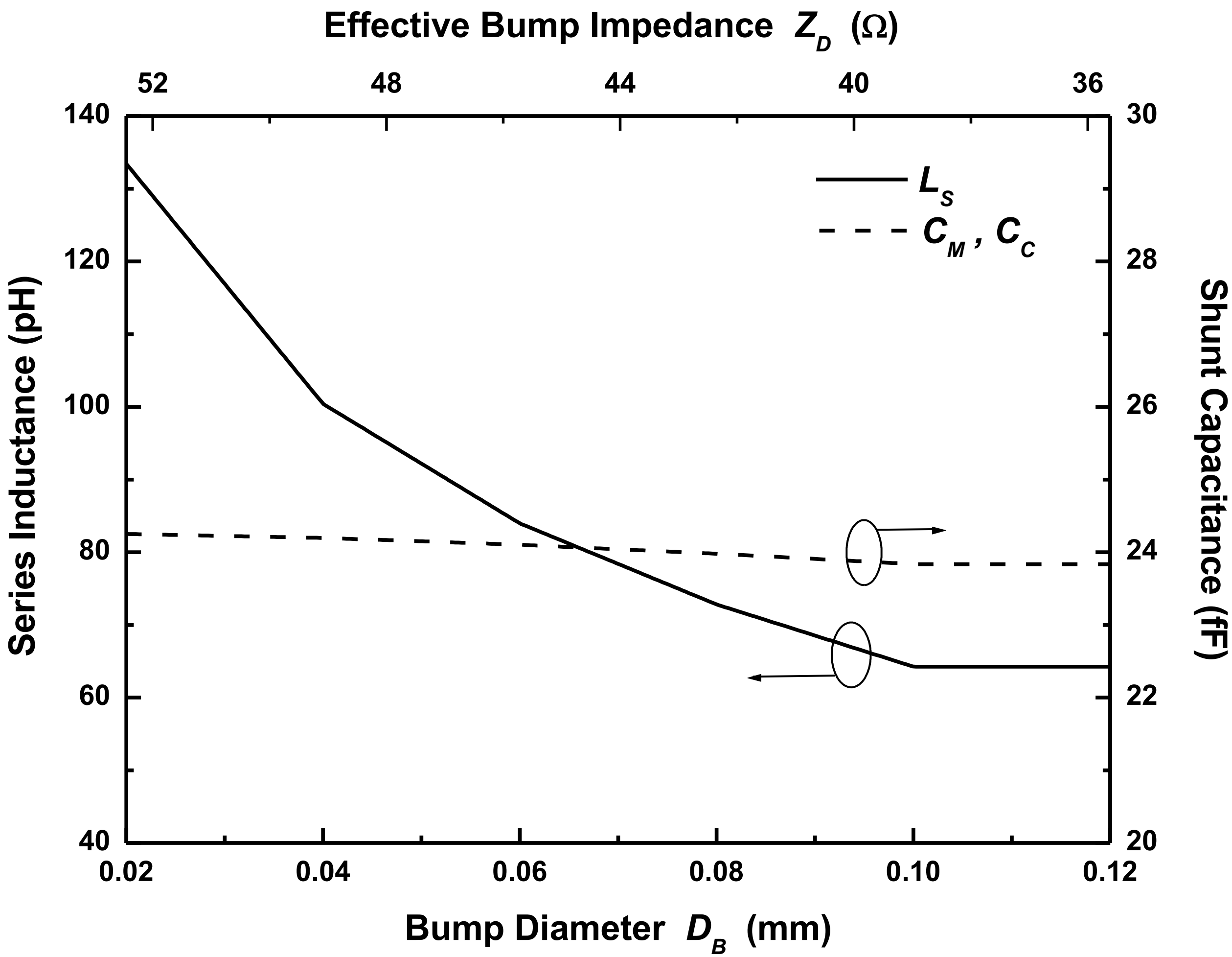
$$C_{eff} = (C_M + C_C) - \frac{L_S}{Z_0^2} = 29.11\,(\text{fF})$$

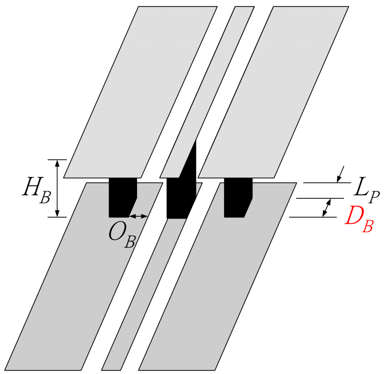


[11] A. Jentzscsch et al., IEEE MTT-S'99, pp.637-640

Conventional Flip-chip Transition

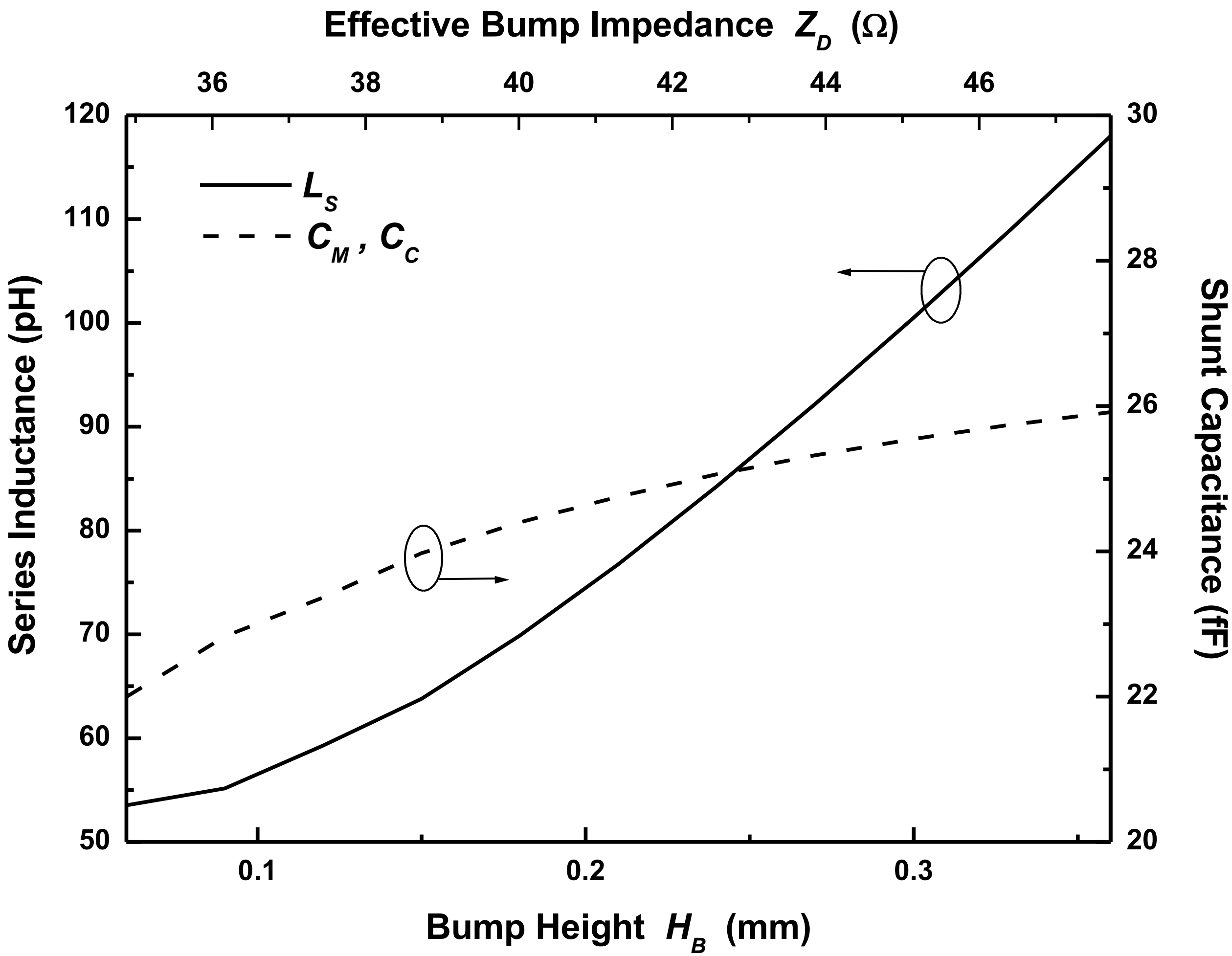
- The Influence of Bump Diameter D_B on L_S and $C_M(C_C)$
  - H_B=0.12mm, L_P=O_B=0mm $Z_D = \sqrt{L_S/(C_M + C_C)}$

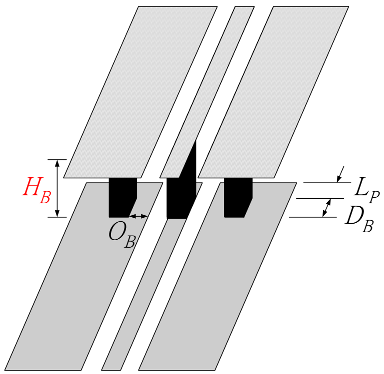




Conventional Flip-chip Transition

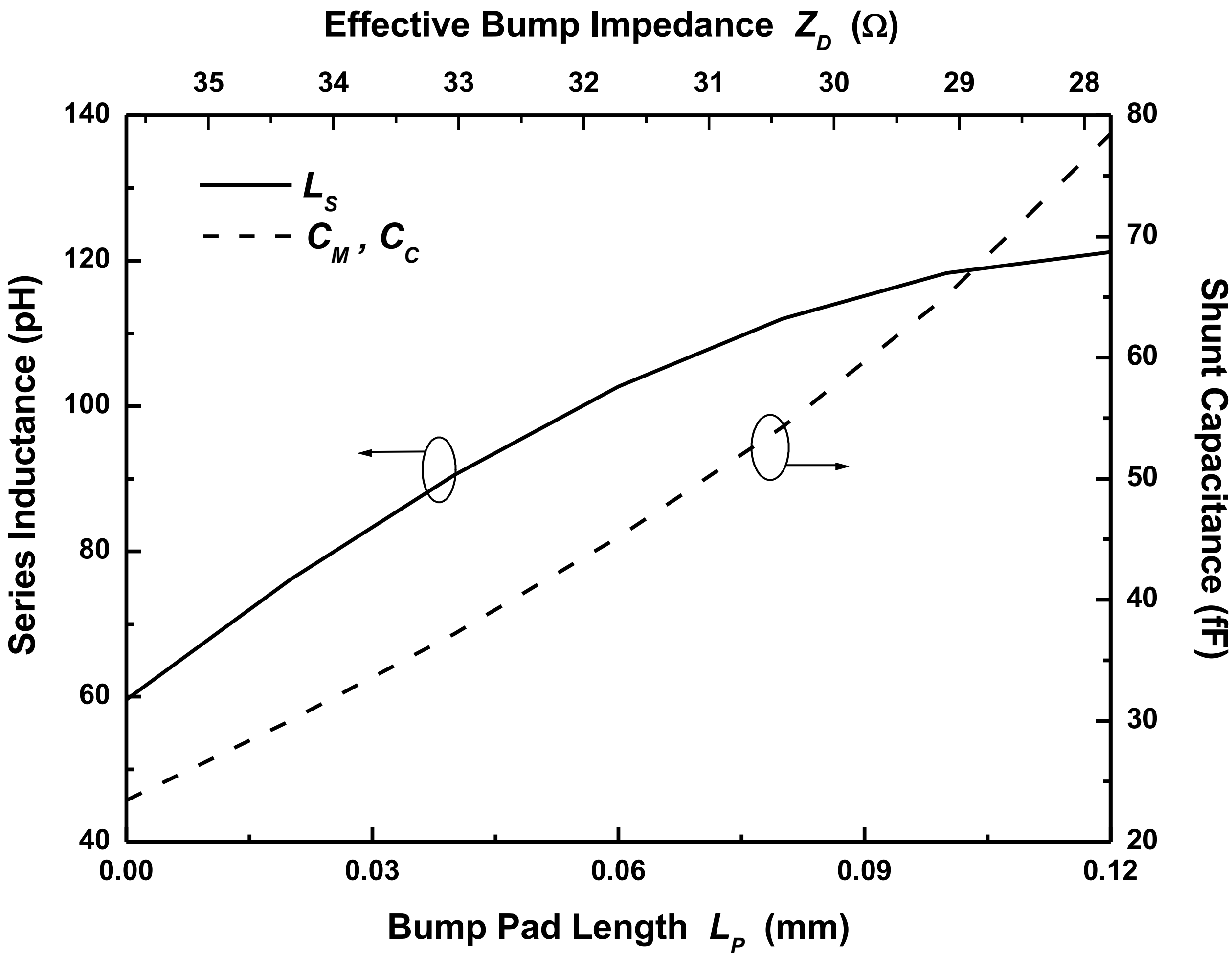
- The Influence of Bump Height H_B on L_S and $C_M(C_C)$
  - D_B=0.12mm, L_P=O_B=0mm

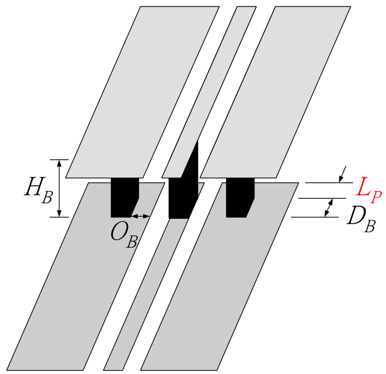




Conventional Flip-chip Transition

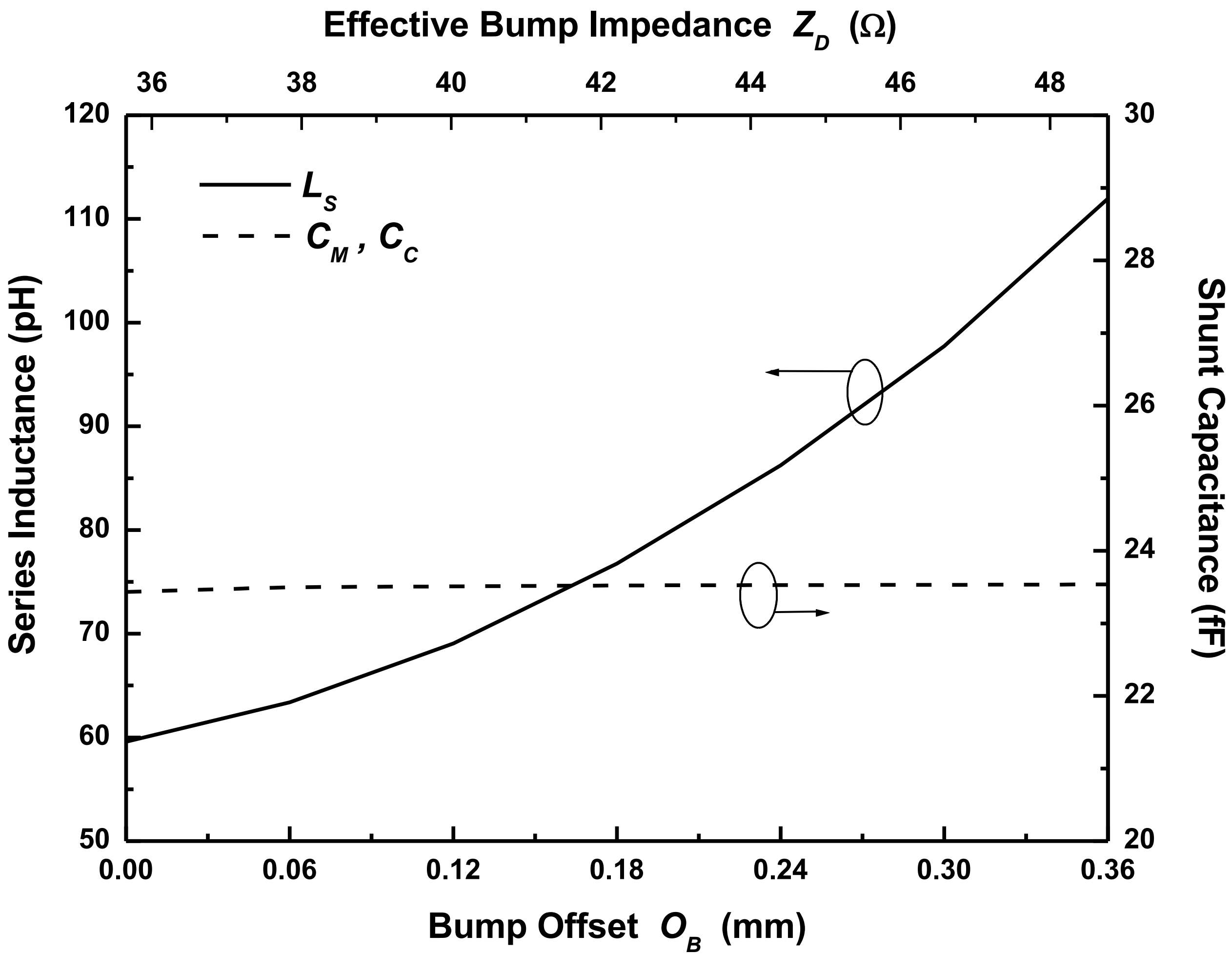
- The Influence of Bump Pad Length L_P on L_S and $C_M(C_C)$
  - $H_B=D_B=0.12$mm, $O_B=0$mm

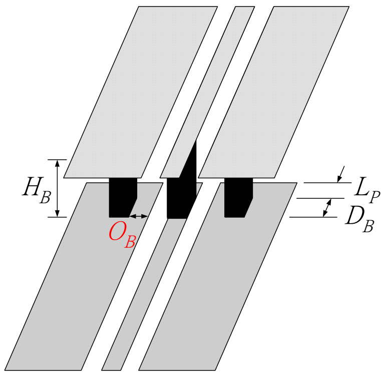




Conventional Flip-chip Transition

- The Influence of Bump Offset O_B on L_S and $C_M(C_C)$
  - – H_B=D_B=0.12mm, L_P=0mm





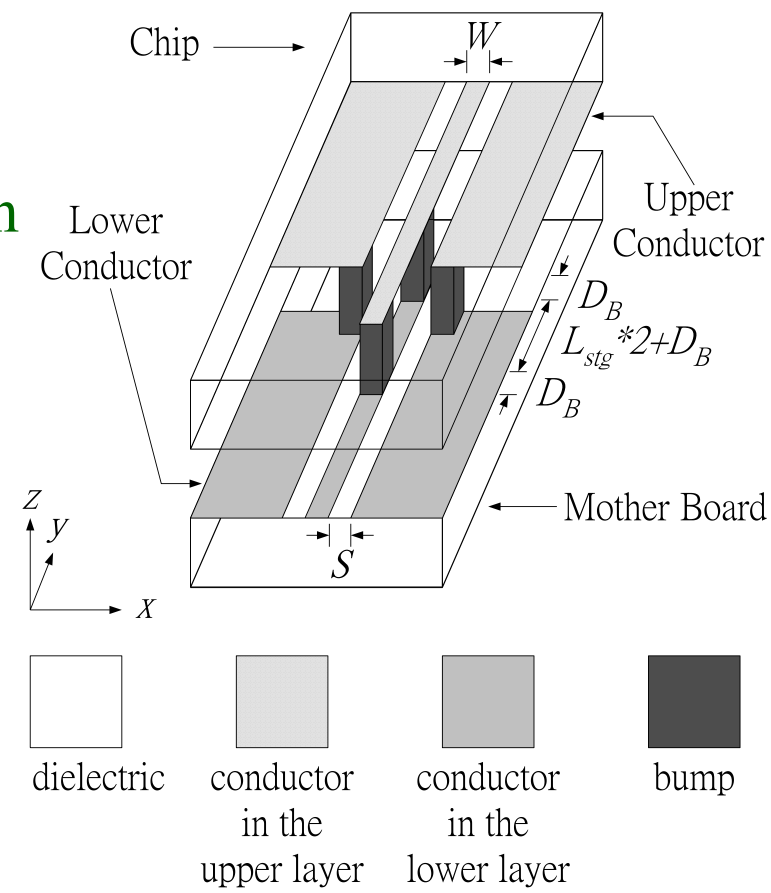
Conventional Flip-chip Transition

- Summary
  - Three methods are in a good agreement.
  - The equivalent circuit resembles a low pass prototype
  - The conventional flip-chip possesses a capacitive effect
  - Ways to lower down the capacitive effect:
    - Reduce the Bump Diameter
    - Lengthen the Bump Height
    - Minimize the Bump Pad Length
    - Maximize the Bump Offset

Resonant Flip-chip Transition

- Single Resonance Design
  - Simulated via FDTD
  - Control of Resonant Length (L_{stg}*2+D_B)
  - Sacrifice of Chip Areas

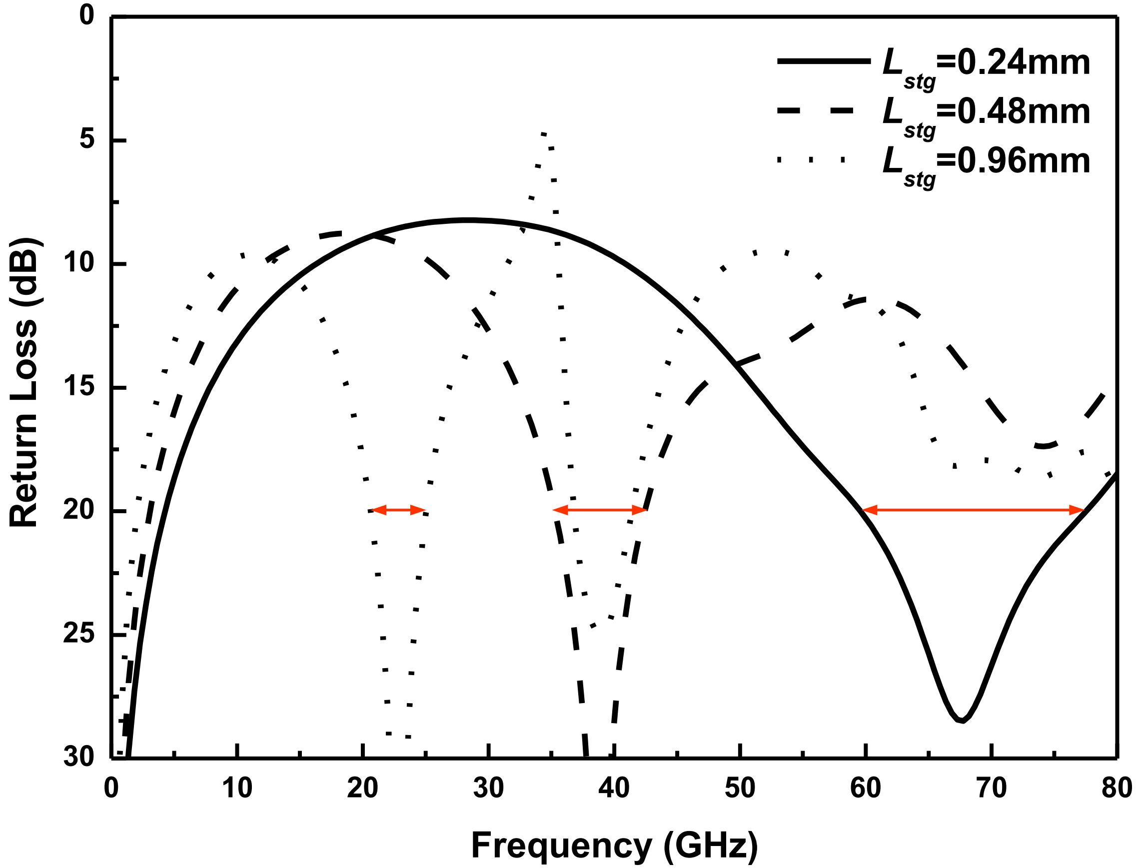
W=S=D_B=0.12mm, other parameters are the same as conventional



Resonant Flip-chip Transition

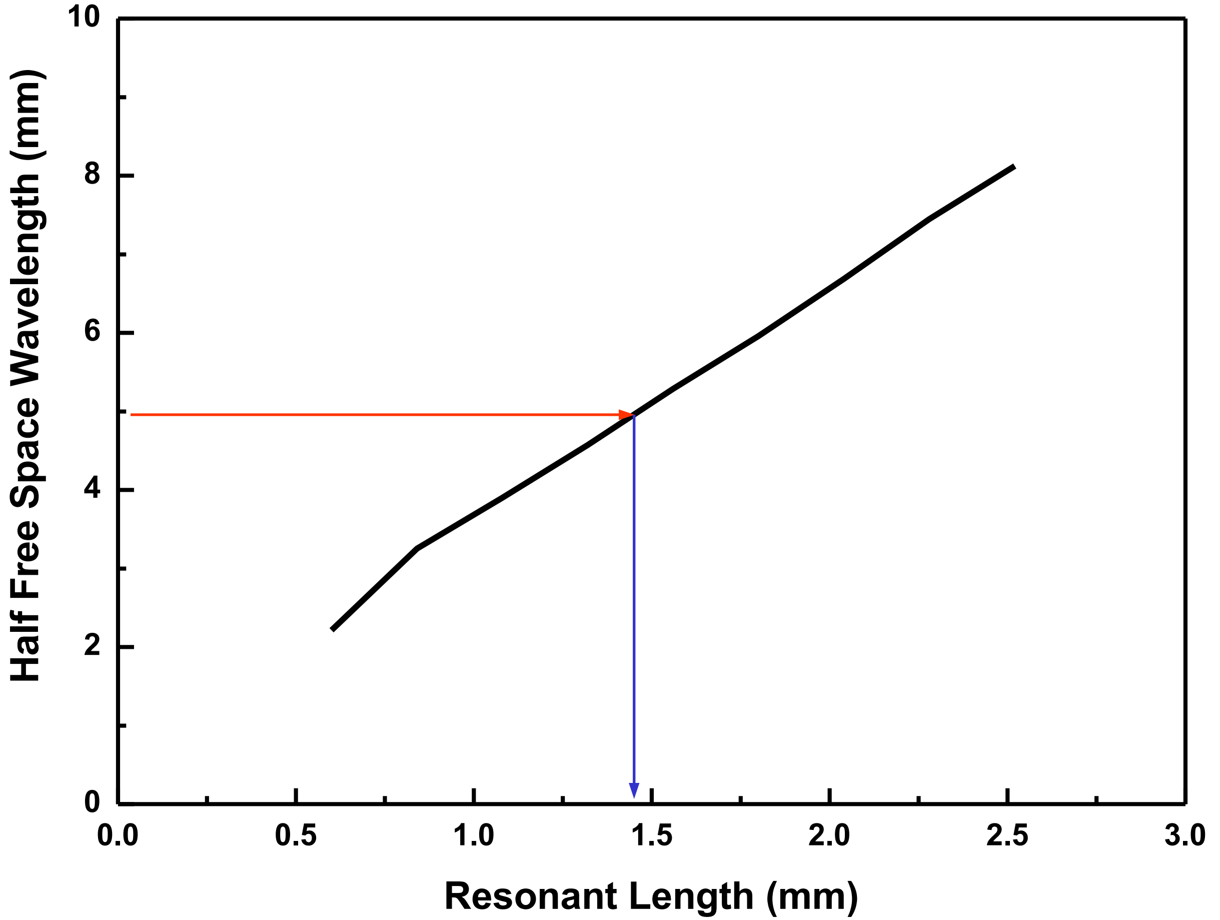
- Return Loss

	f_0 (GHz)	20dB BW (%)
L_{stg}=0.24 mm	68.21	26.17
L_{stg}=0.48 mm	38.91	17.65
L_{stg}=0.96 mm	22.89	18.67



Resonant Flip-chip Transition

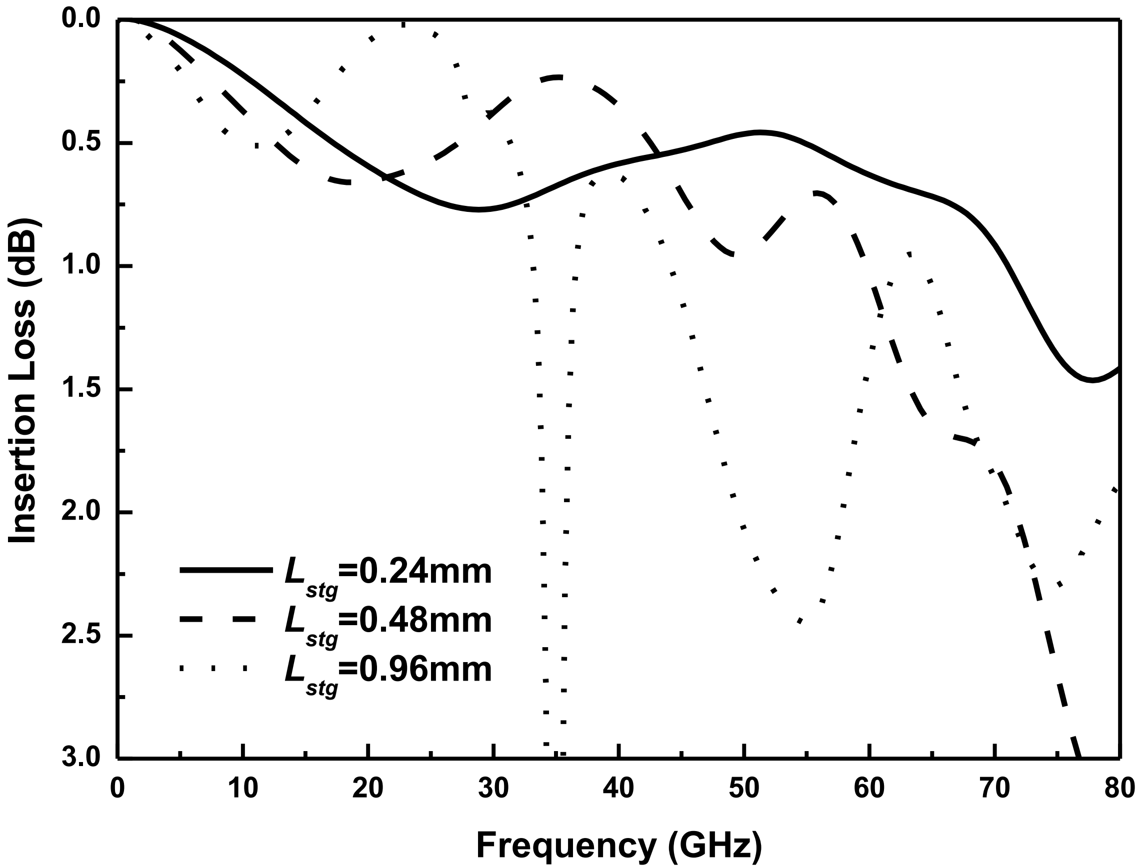
- Design Chart
  - $\lambda_0/2$ versus Resonance Length (L_{stg}*2+D_B)



Resonant Flip-chip Transition

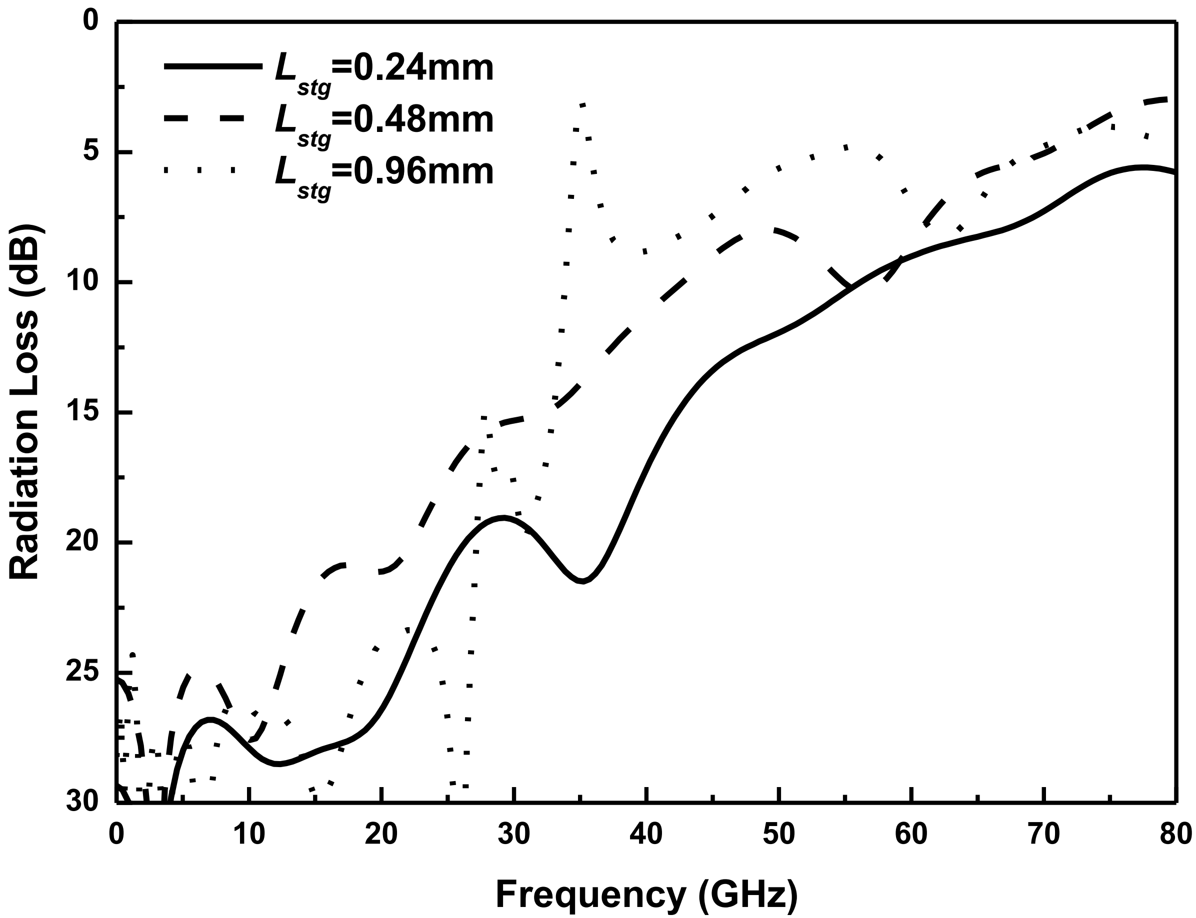
- Insertion Loss

	IL at f_0 (dB)	IL in 20dB BW (dB)
L_{stg}=0.24 mm	0.81	<1.46
L_{stg}=0.48 mm	0.30	<0.47
L_{stg}=0.96 mm	0.02	<0.06



Resonant Flip-chip Transition

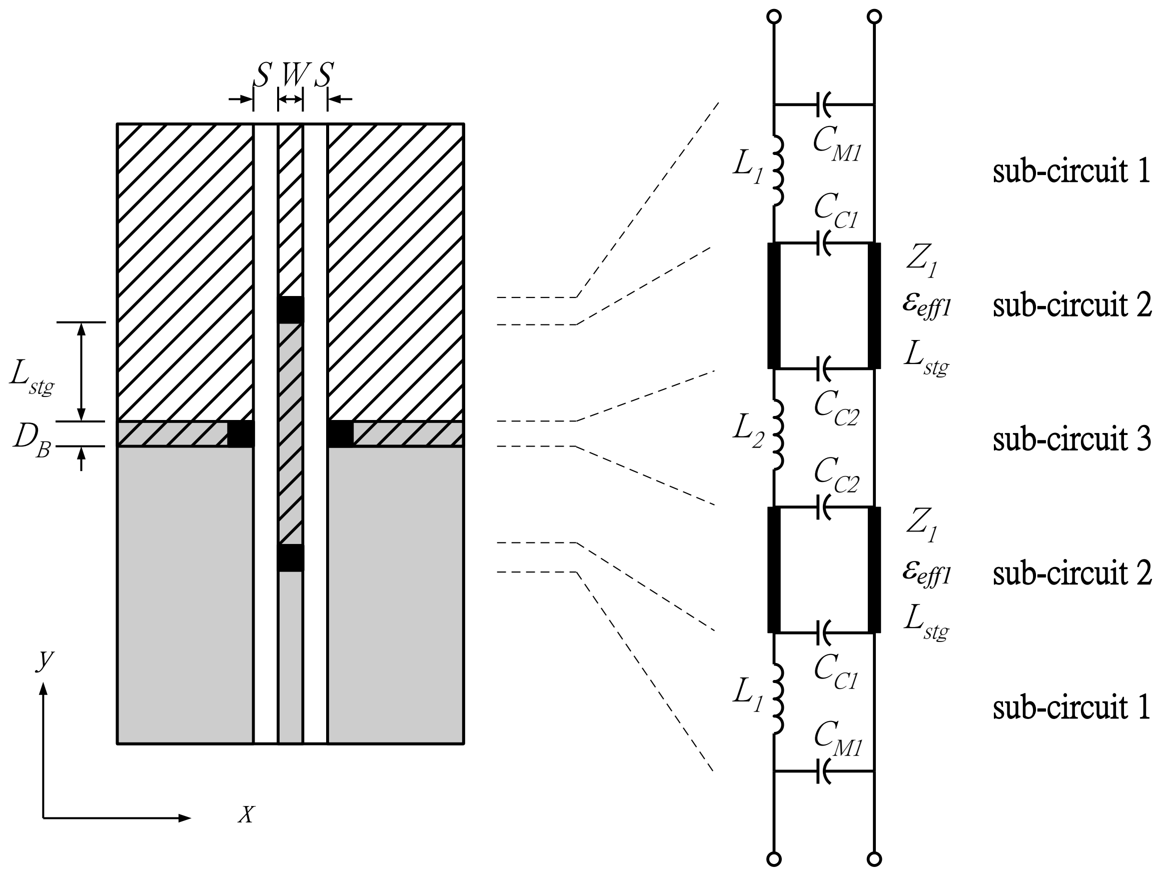
- Radiation Loss
  - Severe above Millimeter-wave Frequencies



Resonant Flip-chip Transition

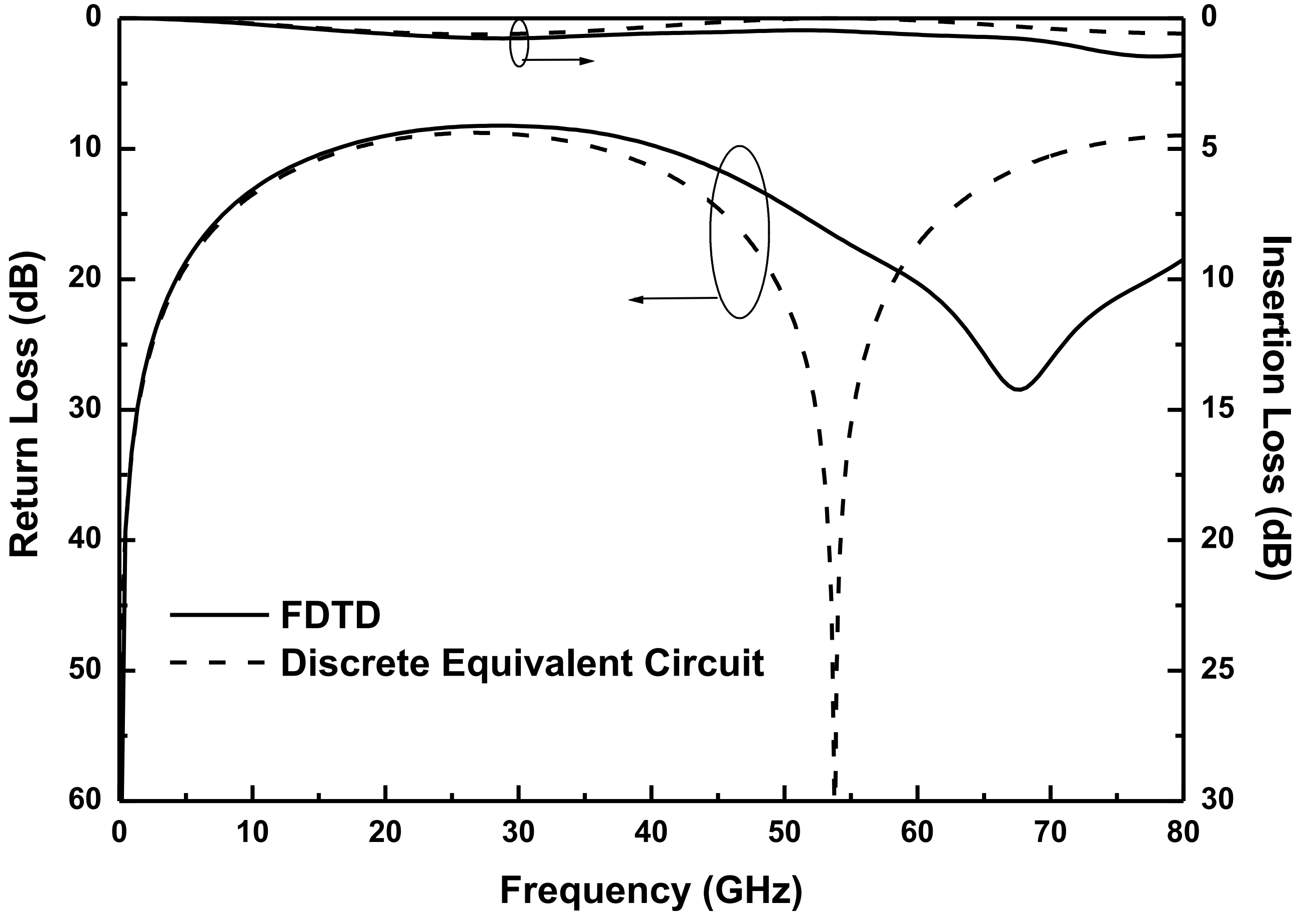
- Discrete Equivalent Circuit
  - Simulated by Sonnet and Extracted via LSM

C_{M1} (fF)	L_1 (pH)	C_{C1} (fF)	Z_1 (Ω)	ε_{eff1}	C_{C2} (fF)	L_2 (pH)
21.01	48.04	14.42	40.07	7.70	22.83	65.17



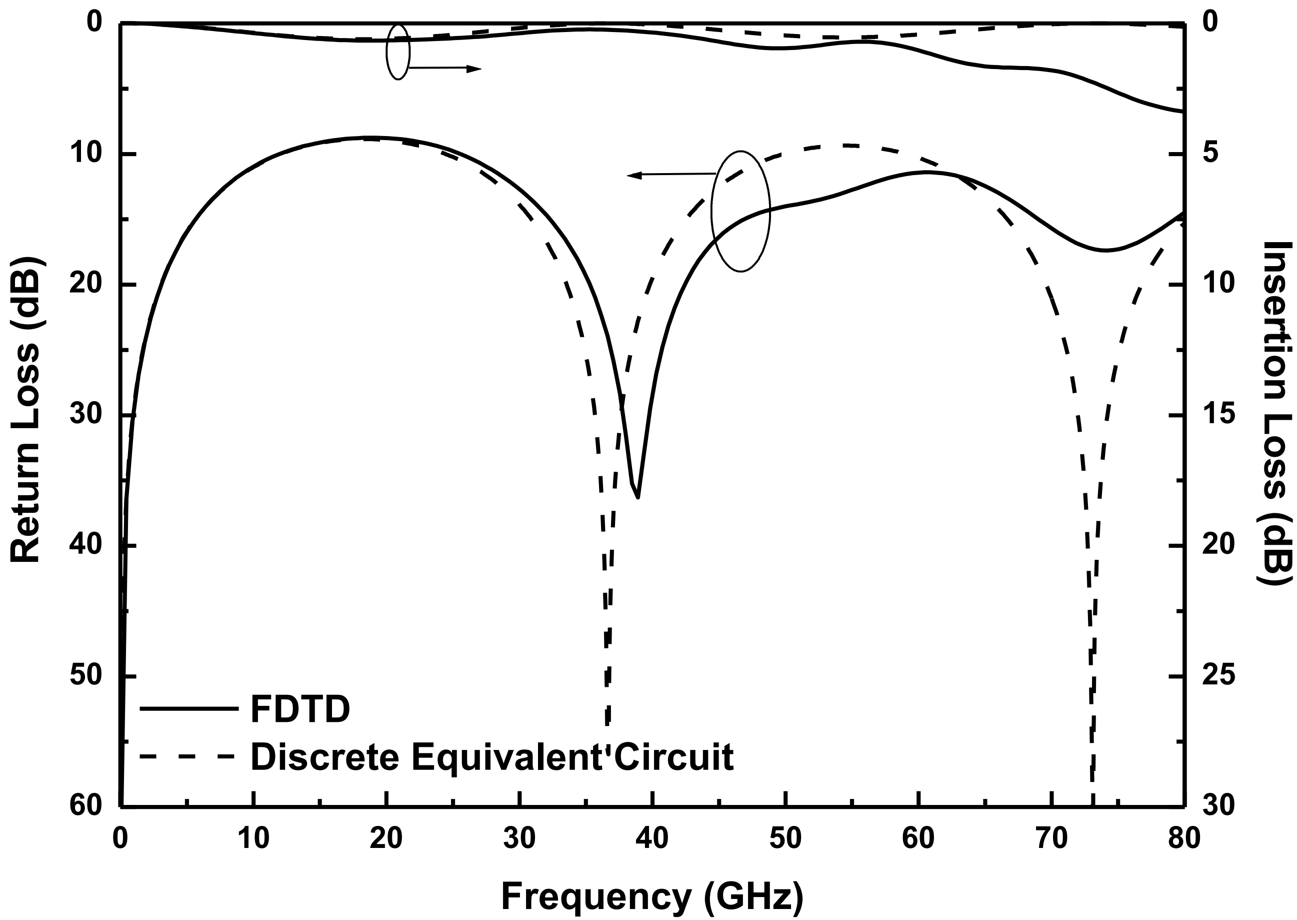
Resonant Flip-chip Transition

- Comparison for L_{stg}=0.24mm



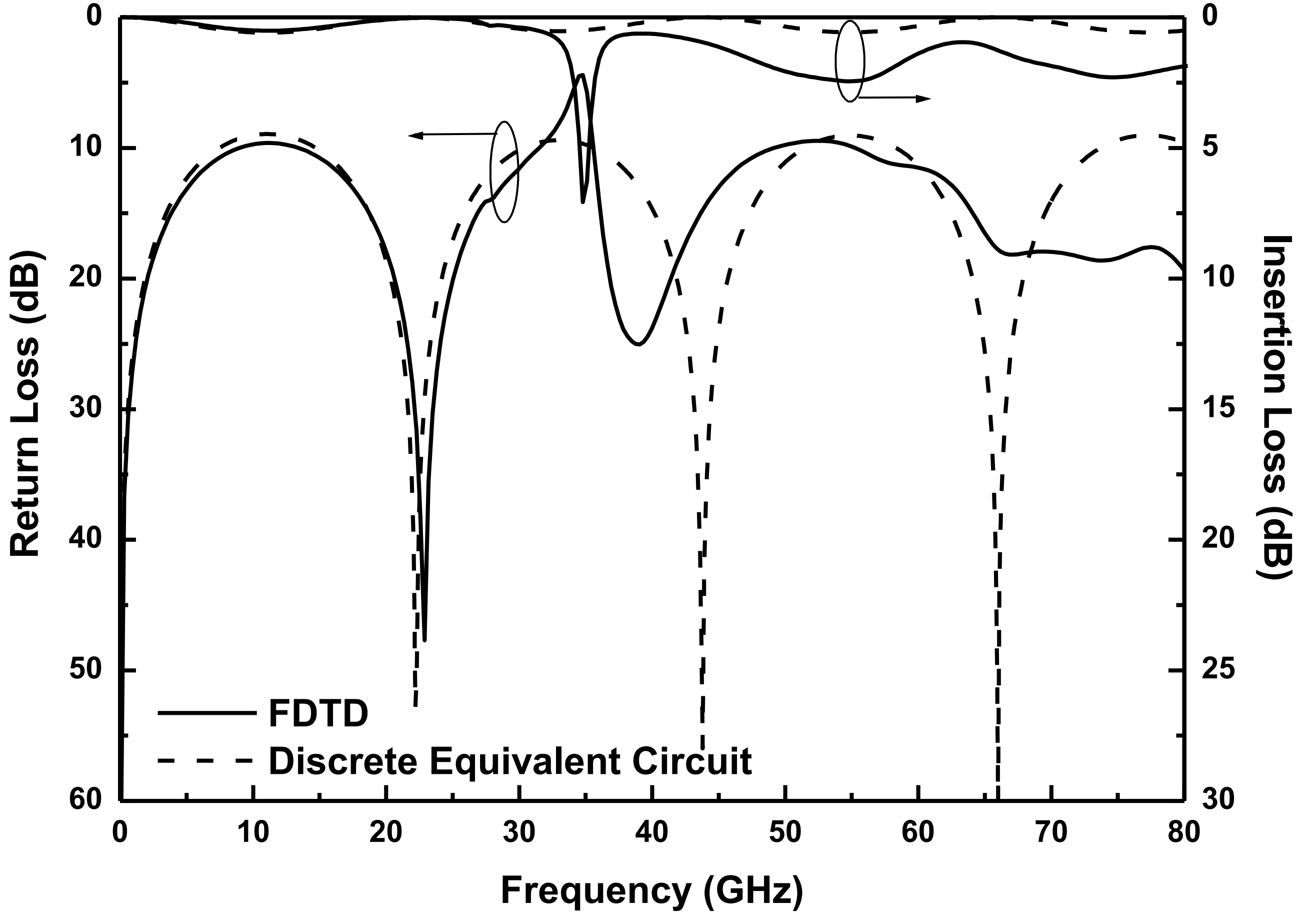
Resonant Flip-chip Transition

- Comparison for L_{stg}=0.48mm



Resonant Flip-chip Transition

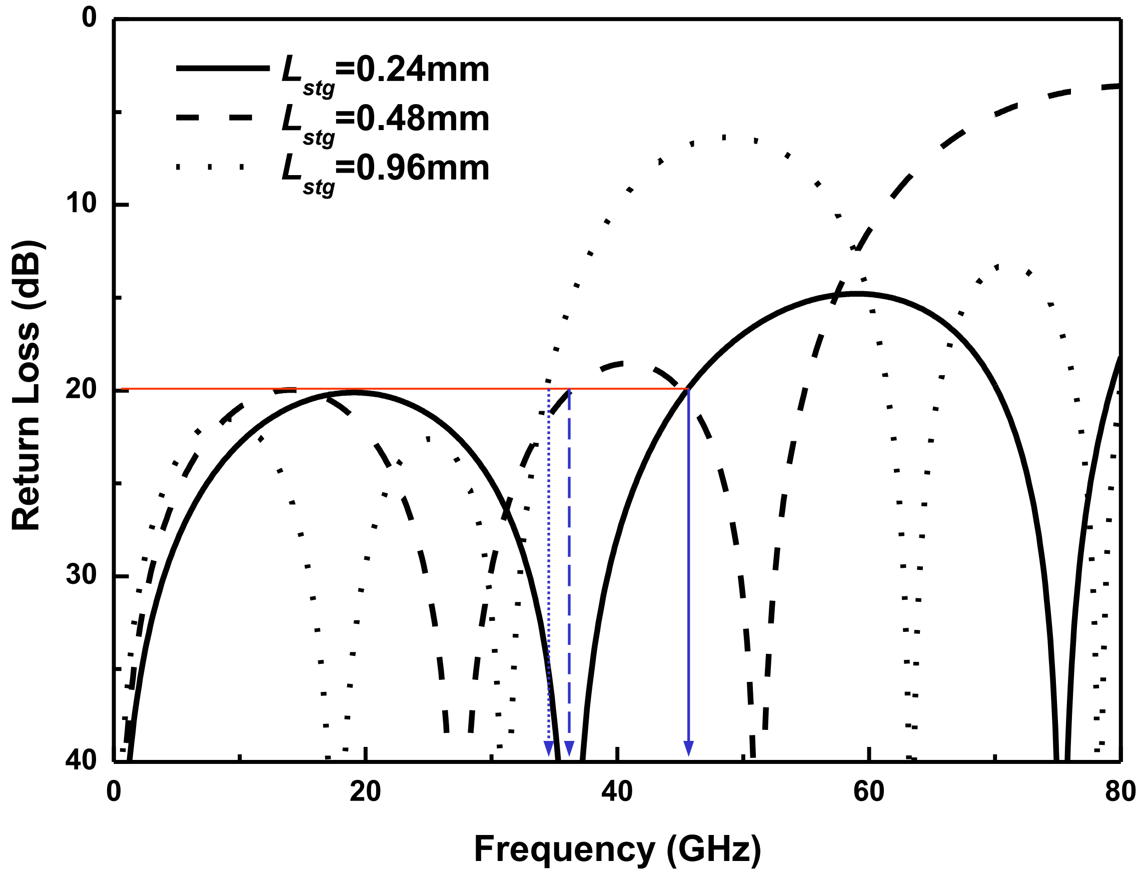
- Comparison for L_{stg}=0.96mm



Resonant Flip-chip Transition

- Optimum Results

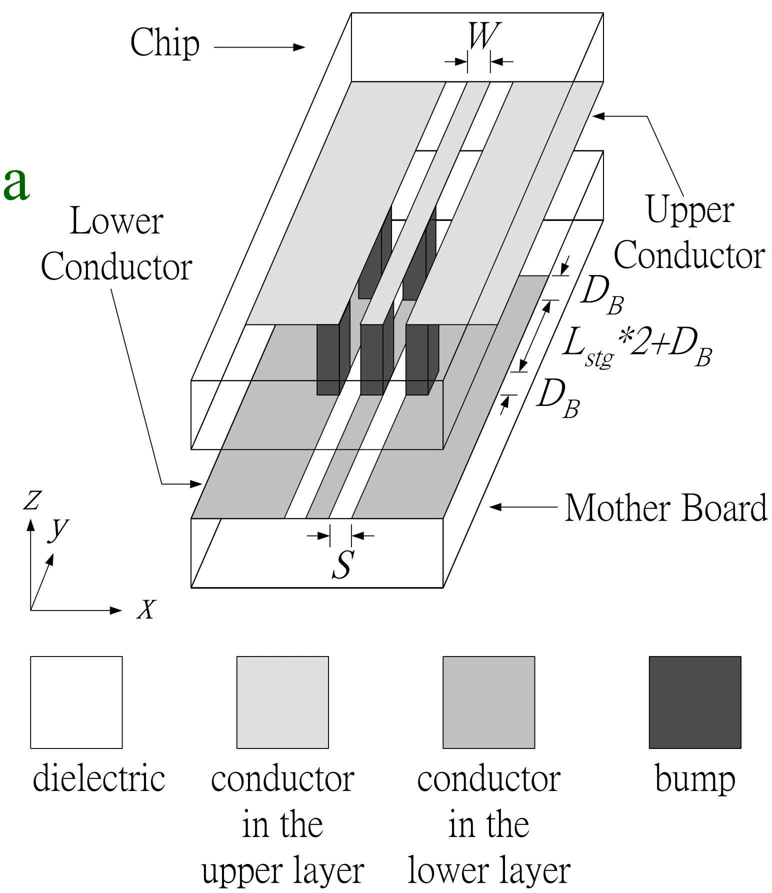
	L_{stg}=0.24 mm	L_{stg}=0.48 mm	L_{stg}=0.96 mm
Z_1 (Ω)	67.50	59.10	56.60
20dB Bound (GHz)	45.50	36.30	34.30



Resonant Flip-chip Transition

- Transformer Design
  - Simulated via FDTD
  - Impedance Transformer Idea
  - Sacrifice of Chip Areas
  - Better Field Confinement

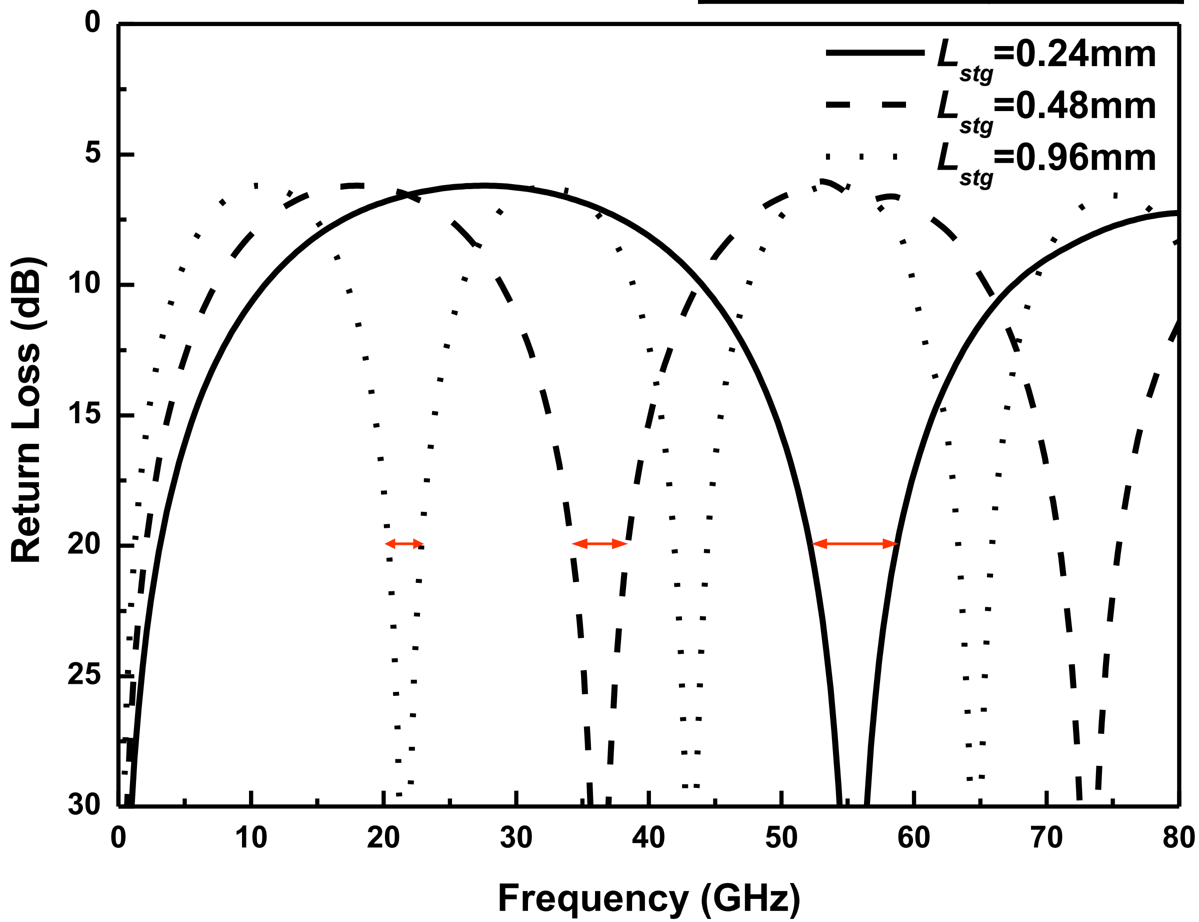
$W=S=D_B=0.12$mm, other parameters are the same as conventional



Resonant Flip-chip Transition

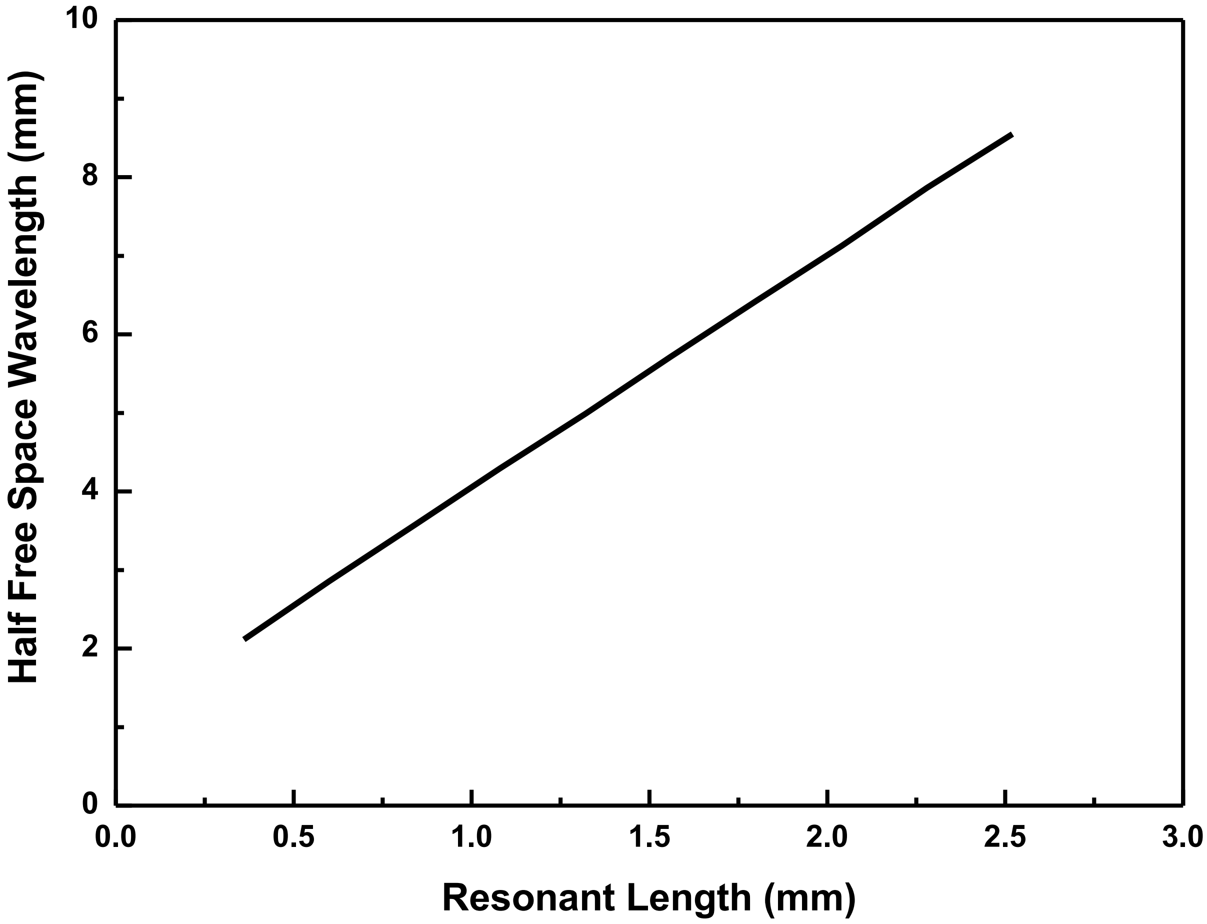
- Return Loss
  - 20 dB Bandwidth: 11.5%

	f_0 (GHz)
L_{stg}=0.24 mm	55.54
L_{stg}=0.48 mm	36.32
L_{stg}=0.96 mm	21.67



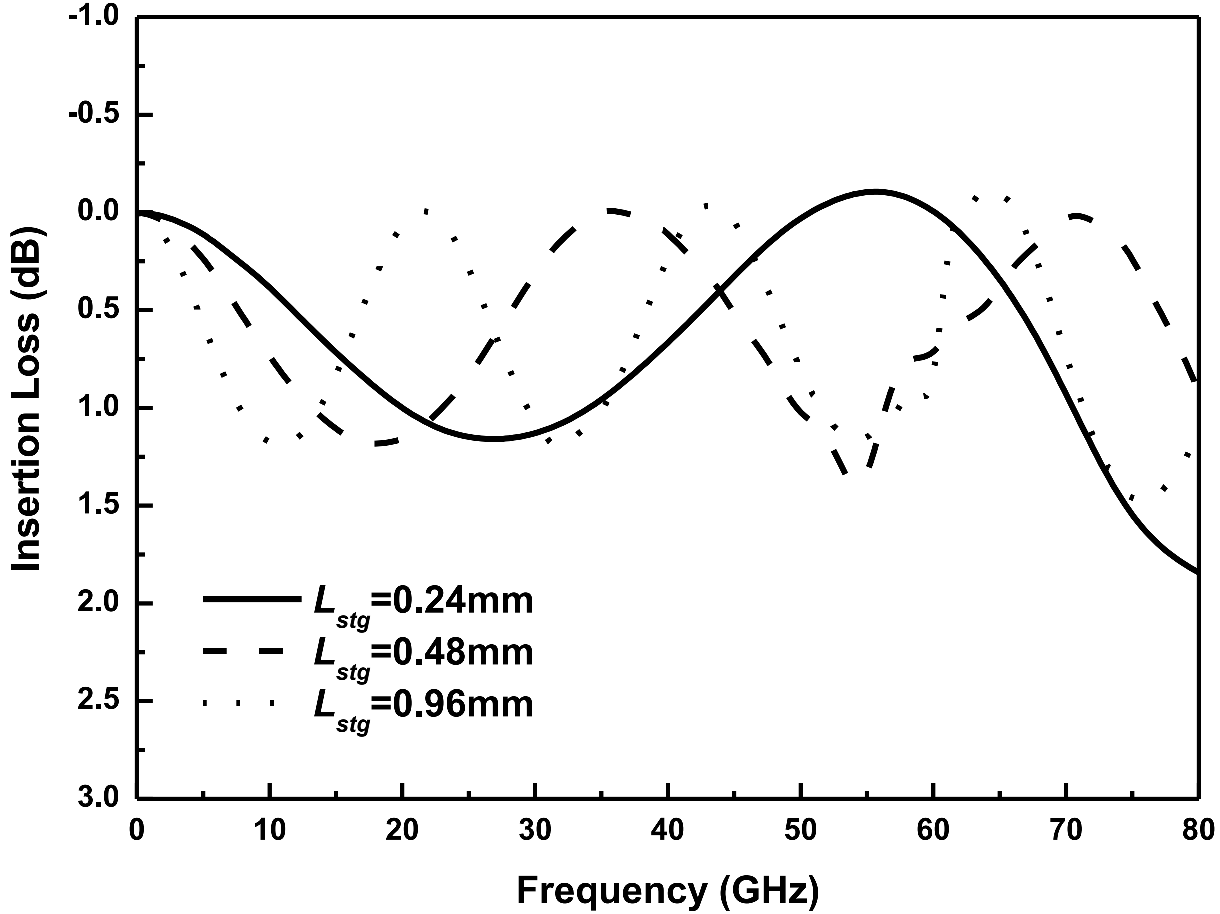
Resonant Flip-chip Transition

- Design Chart
  - $\lambda_0/2$ versus Resonance Length (L_{stg}*2+D_B)



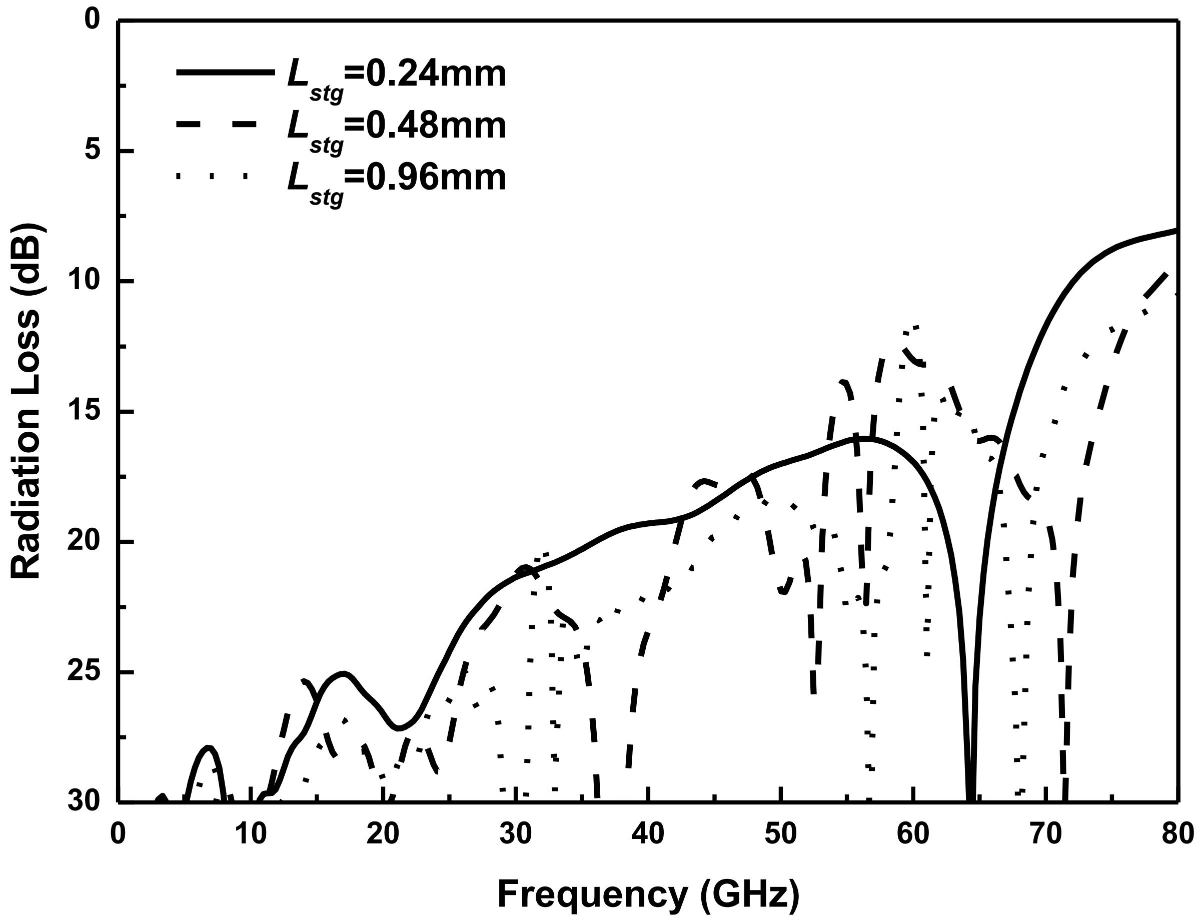
Resonant Flip-chip Transition

- Insertion Loss
  - IL in 20 dB Bandwidth > 0.05 dB



Resonant Flip-chip Transition

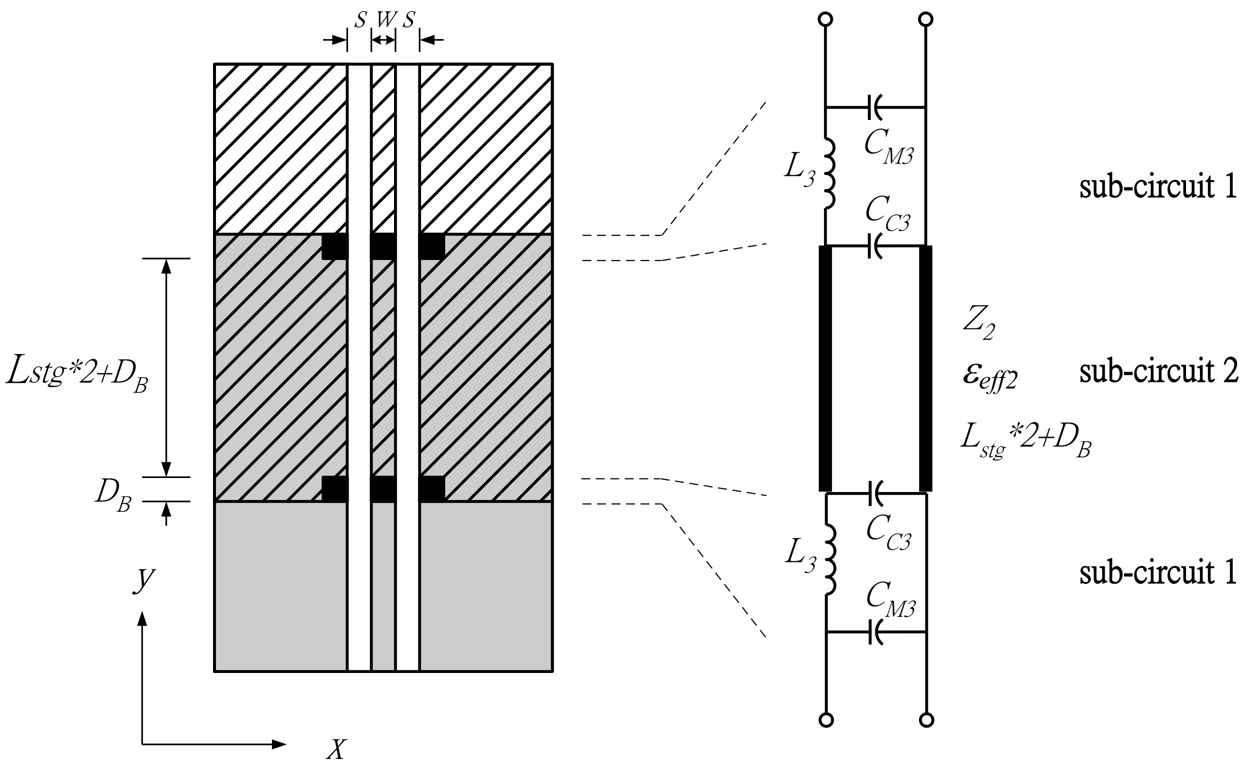
- Radiation Loss
  - Severe above 60 GHz



Resonant Flip-chip Transition

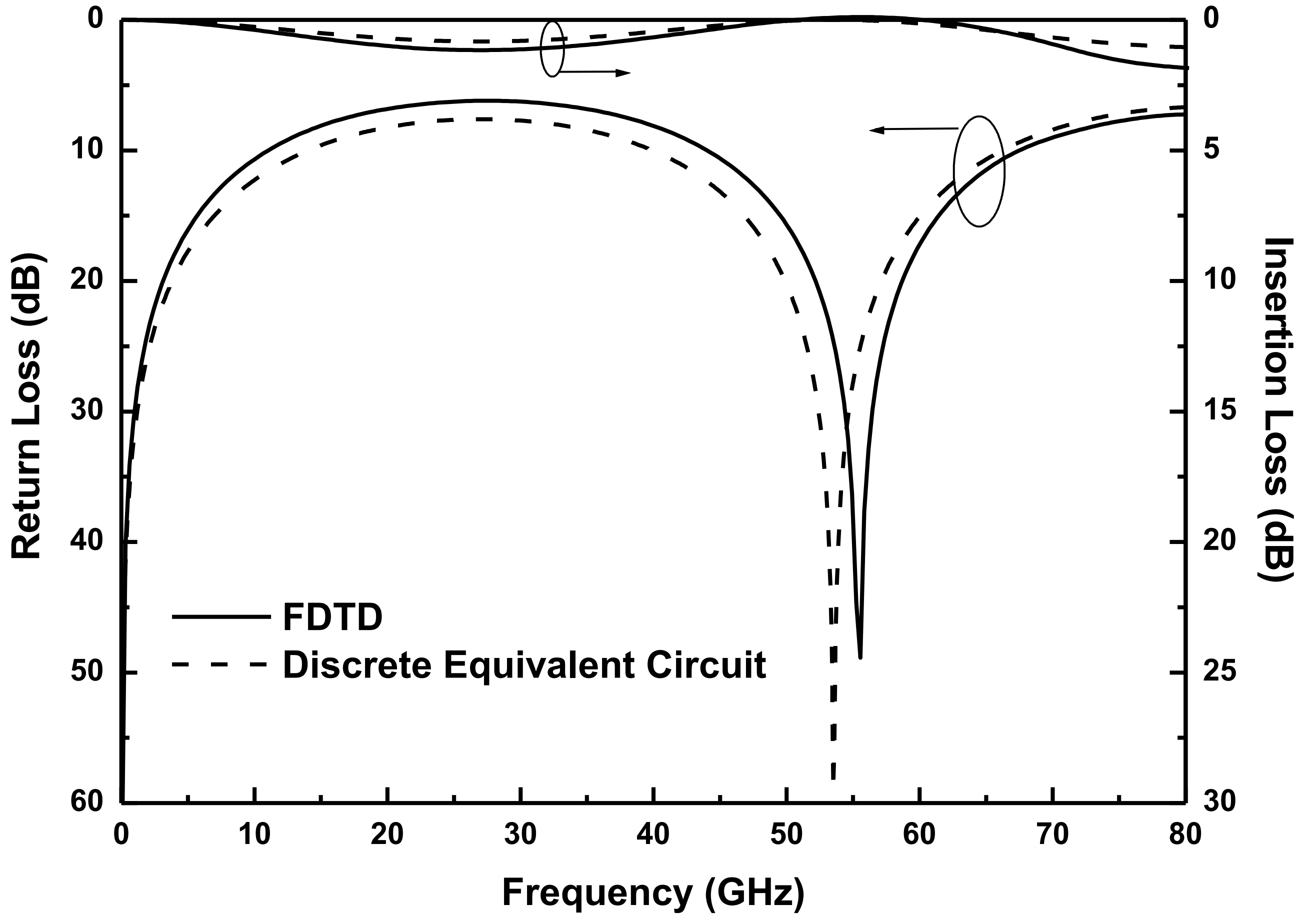
- Discrete Equivalent Circuit
  - Simulated by Sonnet and Extracted via LSM

C_{M3} (fF)	L_3 (pH)	C_{C3} (fF)	Z_2 (Ω)	ε_{eff2}
23.05	41.42	18.32	37.78	8.45



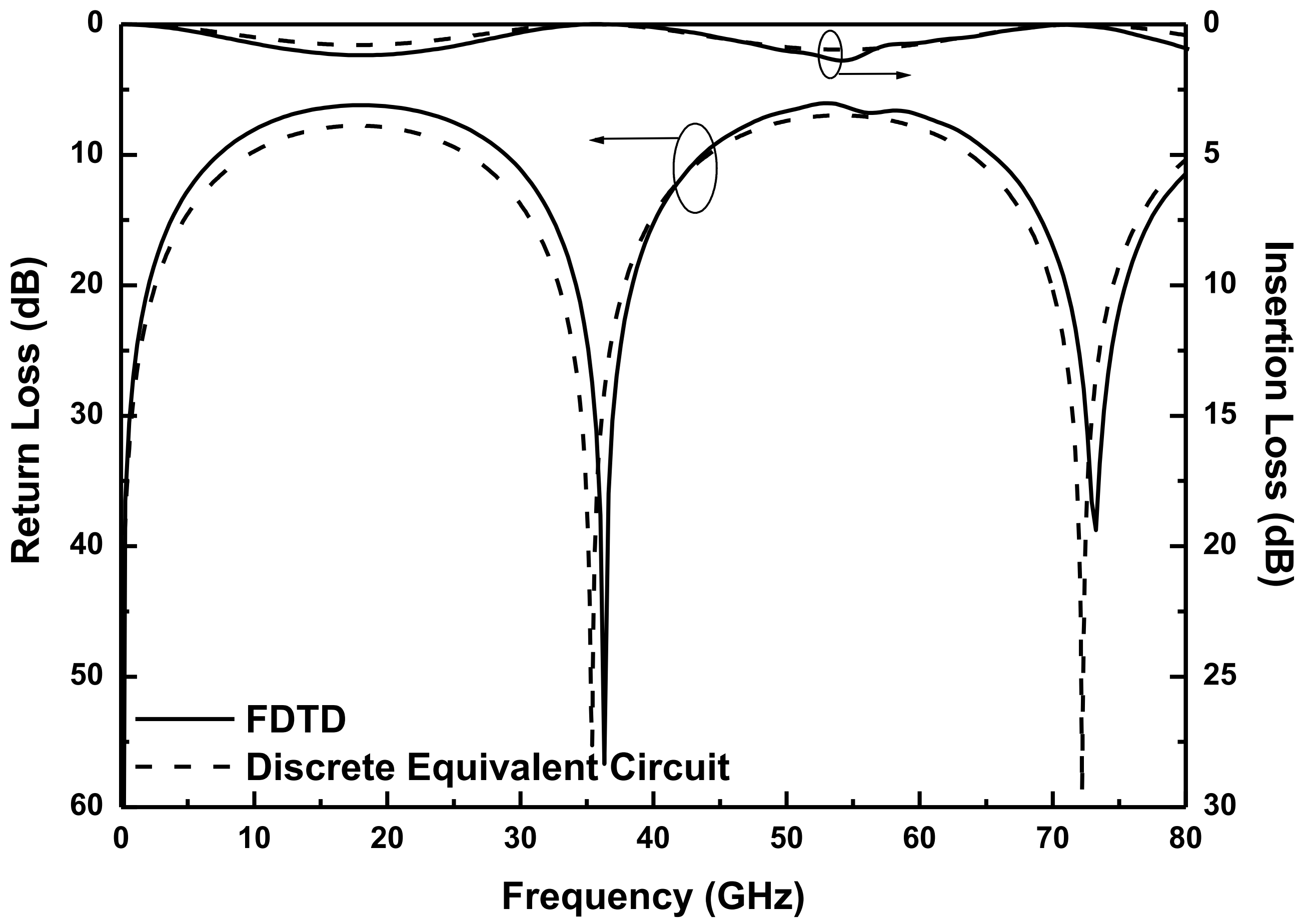
Resonant Flip-chip Transition

- Comparison for L_{stg}=0.24mm



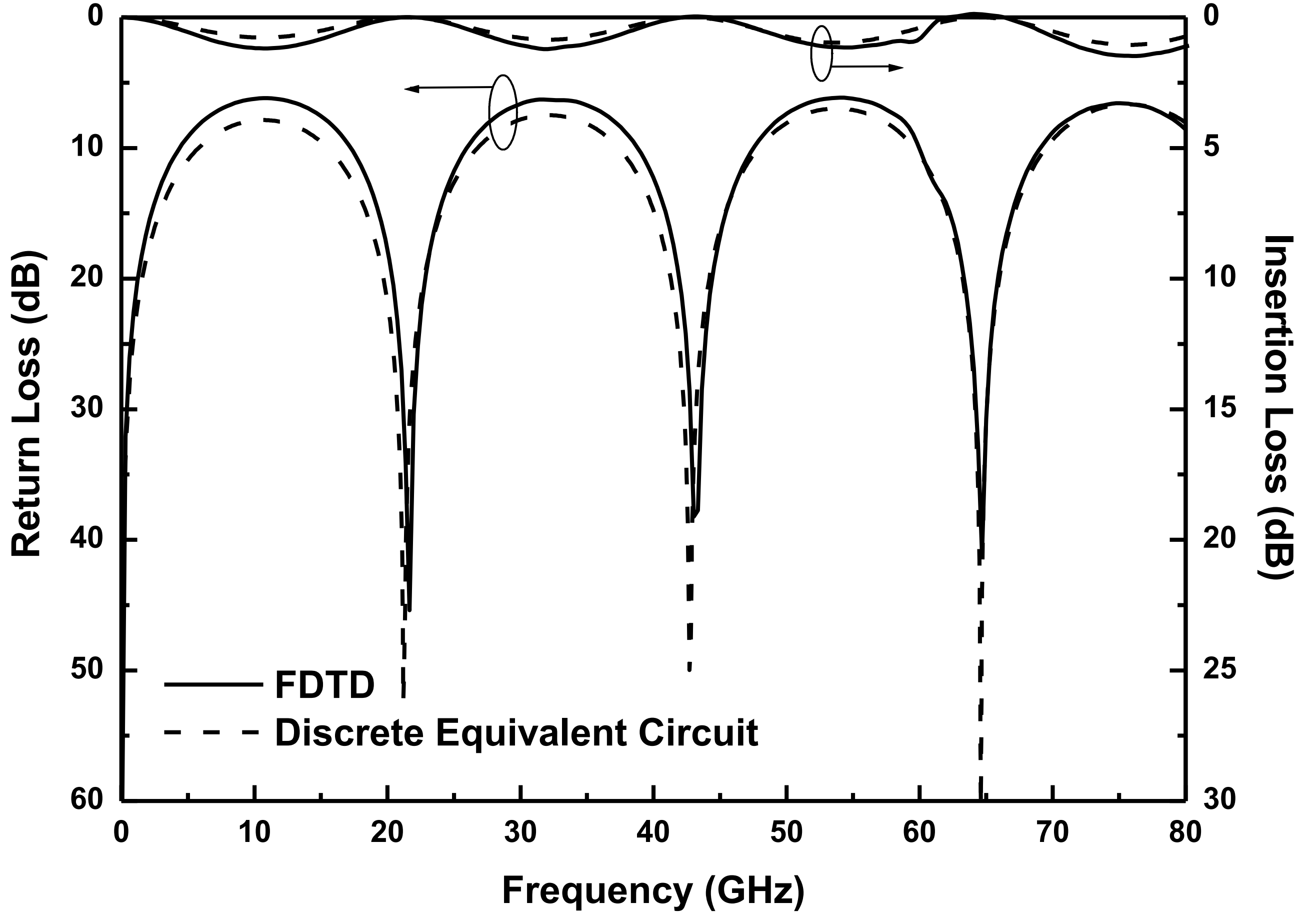
Resonant Flip-chip Transition

- Comparison for L_{stg}=0.48mm



Resonant Flip-chip Transition

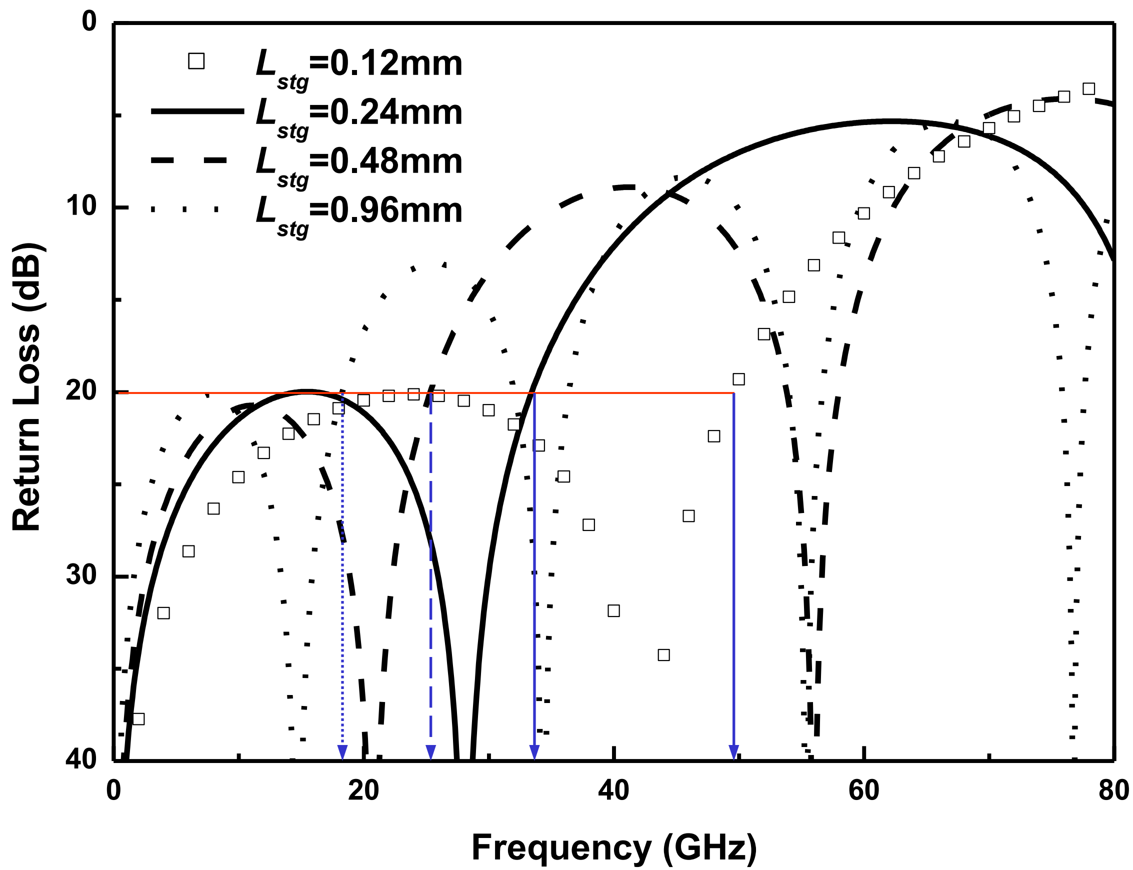
- Comparison for L_{stg}=0.96mm



Resonant Flip-chip Transition

- Optimum Results

	L_{stg}=0.12 mm	L_{stg}=0.24 mm	L_{stg}=0.48 mm	L_{stg}=0.96 mm
Z_1 (Ω)	96.80	58.00	55.60	53.50
20dB Bound (GHz)	49.60	33.40	25.30	18.20



Resonant Flip-chip Transition

- Summary
  - Single Resonance Design
    - 20 dB Bandwidth: 17.5 ~ 26 %
    - Insertion Loss in 20 dB BW: 1.5 dB
    - Optimum Design

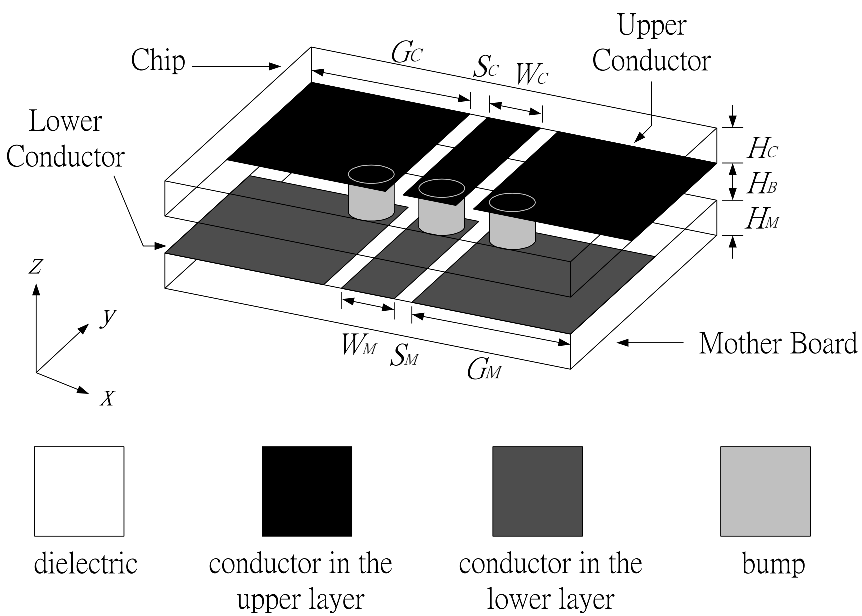
	L_{stg}=0.24 mm	L_{stg}=0.48 mm	L_{stg}=0.96 mm
20dB Bound (GHz)	45.50	36.30	34.30

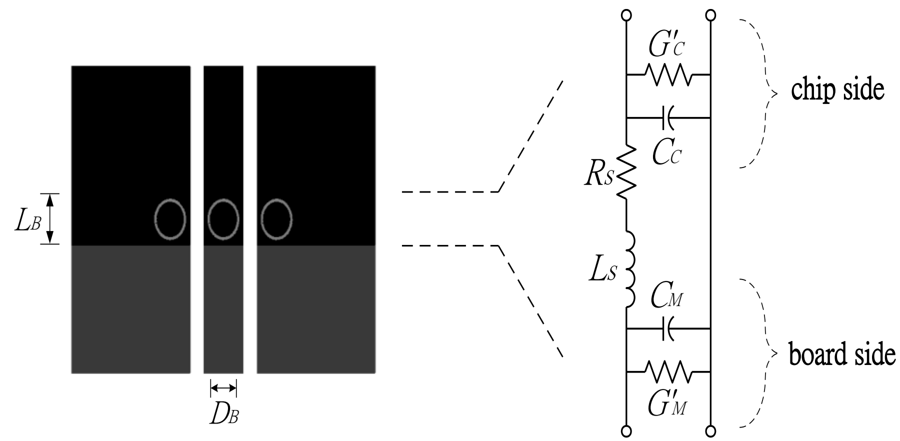
  - Transformer Design
    - 20 dB Bandwidth: 11.5 %
    - Insertion Loss in 20 dB BW: 0.05 dB
    - Optimum Design

	L_{stg}=0.12 mm	L_{stg}=0.24 mm	L_{stg}=0.48 mm	L_{stg}=0.96 mm
20dB Bound (GHz)	49.60	33.40	25.30	18.20

Inductive Compensation Flip-chip Transition

- Structure Parameters
  - Introduce an Inductive Element to Compensate the Capacitive Effect





L_S=68.67pH, C_M=C_C=34.91fF

W_C=W_M=200μm, S_C=S_M=70μm, G_C=G_M=600μm, H_C=H_B=H_M=127μm, ε_r=10.2.

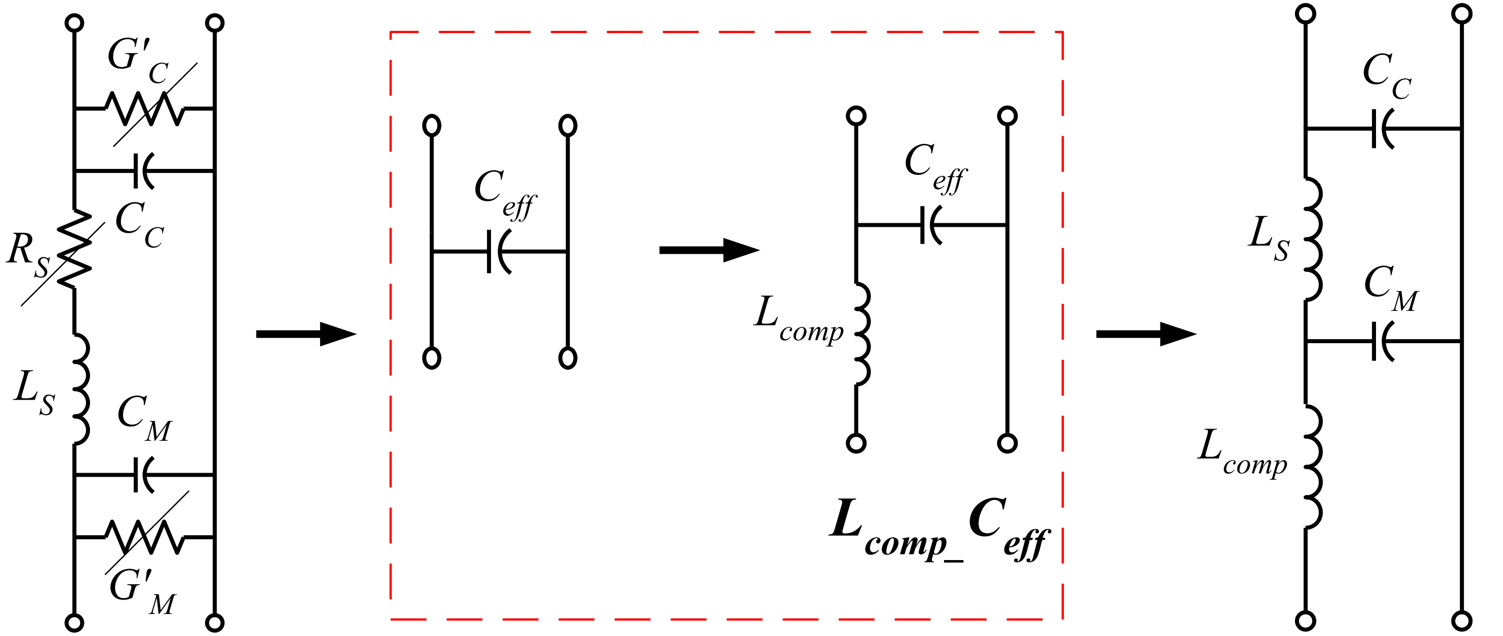
Inductive Compensation Flip-chip Transition

- Lumped Element Compensation

Low pass filter of order N=3

Approximation procedures

Low pass filter of order N=4



Inductor compensation

$C_{eff}=C_M+C_C-L_S/Z_0^2$

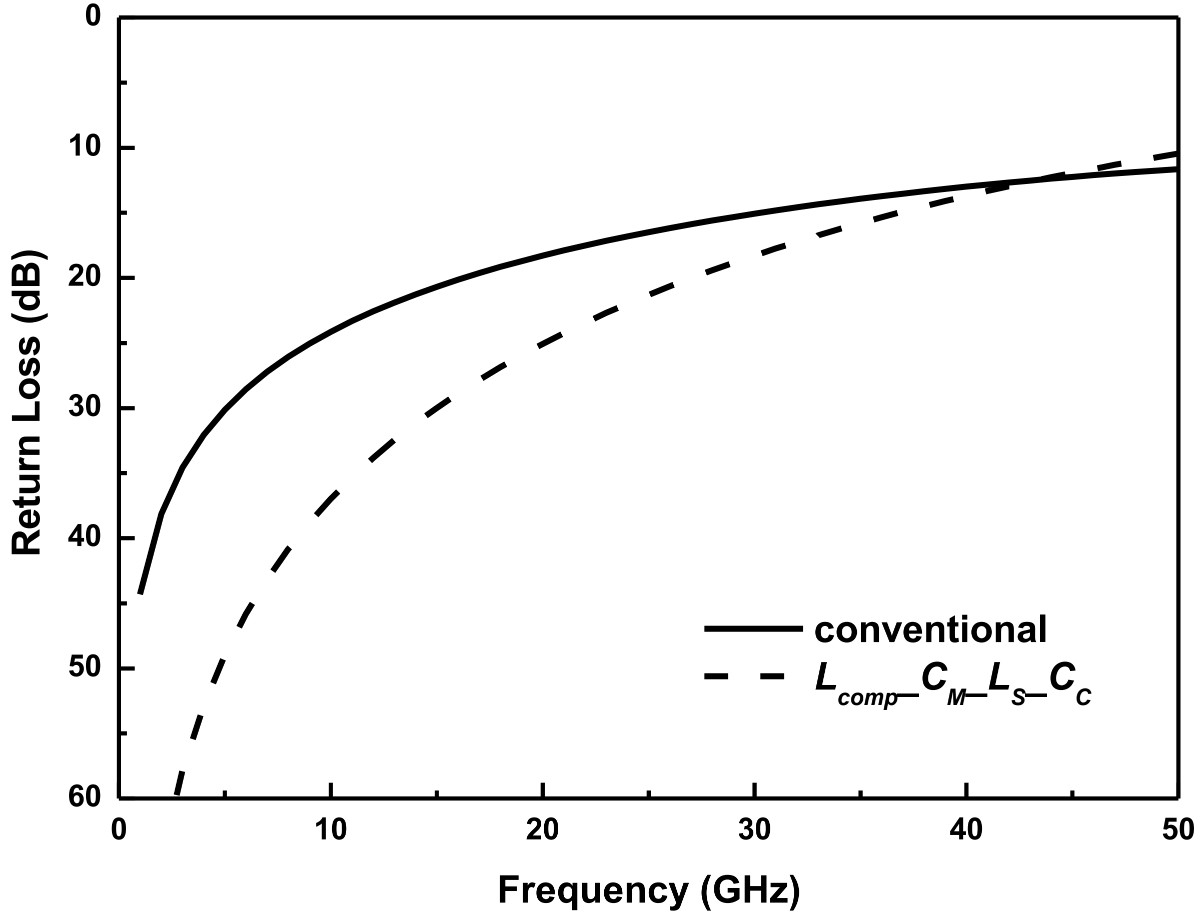
= 41.8fF

$L_{comp}=C_{eff}*Z_0^2$

= 104.5pH

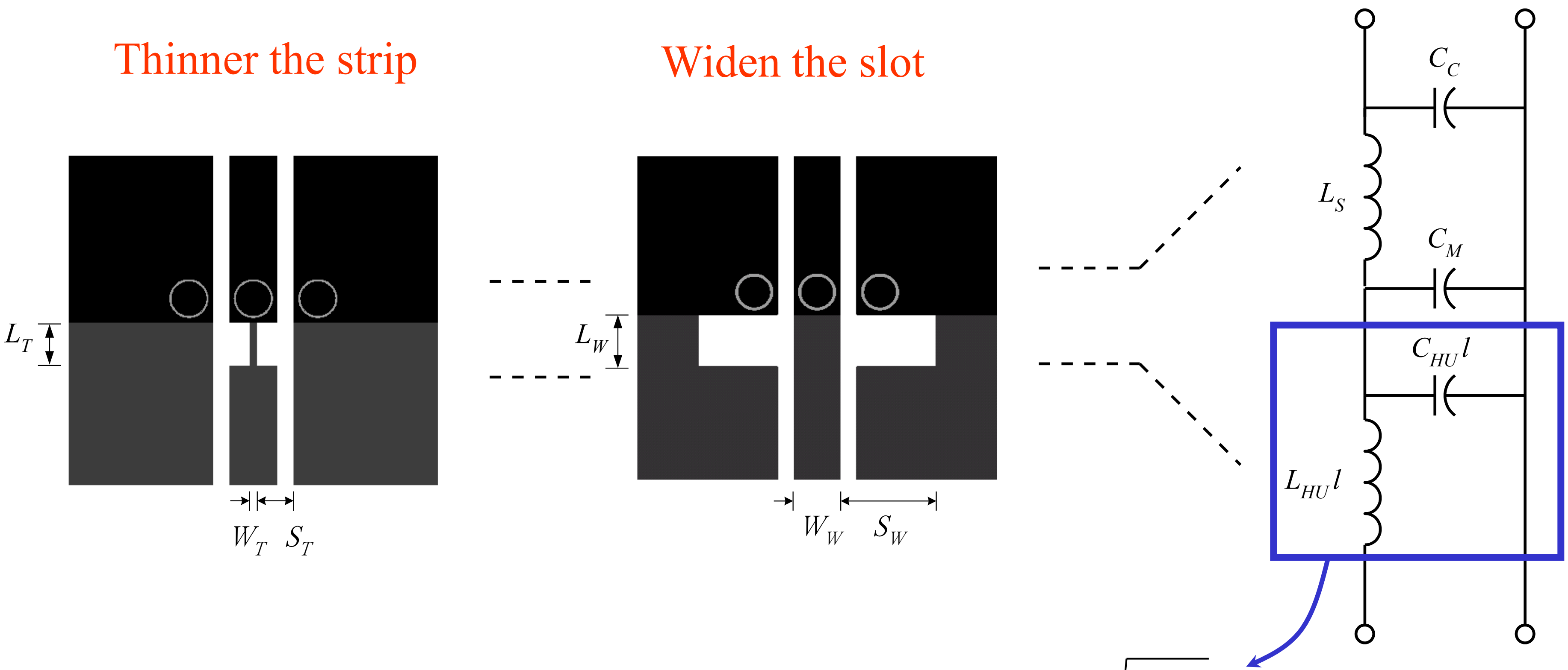
Inductive Compensation Flip-chip Transition

- Comparison between Inductance Compensation and Conventional Transition



Inductive Compensation Flip-chip Transition

- High Impedance Transmission Line Compensation [11]



$$Z_H = \sqrt{\frac{L_{HU}}{C_{HU}}}$$

[11] A. Jentzscsch et al., IEEE MTT-S'99, pp.637-640

Inductive Compensation Flip-chip Transition

- High Impedance Transmission Line Compensation
  - Matching Condition

$$\sqrt{\frac{L_{HU}l}{C_{HU}l + C_{eff}}} = Z_0 \quad \longrightarrow \quad l = \left(\frac{\omega_H}{\beta_H}\right)\left(\frac{Z_H Z_0^2 C_{eff}}{Z_H^2 - Z_0^2}\right)$$

•Z_H=100Ω

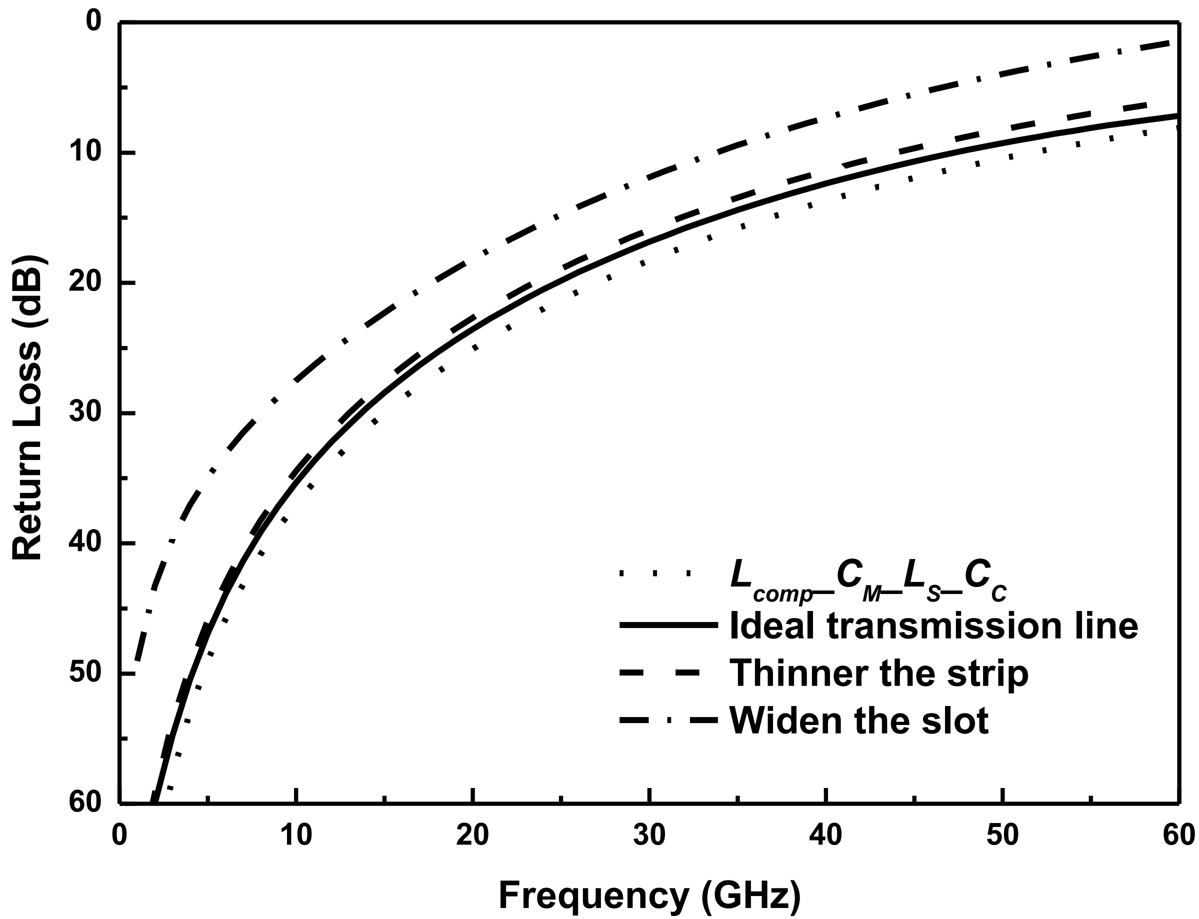
$\beta l\|_{30GHz}$(°)	W_T (μm)	S_T (μm)	L_T (μm)	W_W (μm)	S_W (μm)	L_W (μm)
15.048	30	155	185	200	410	230

•Z_H=76Ω

$\beta l\|_{30GHz}$(°)	W_T (μm)	S_T (μm)	L_T (μm)	W_W (μm)	S_W (μm)	L_W (μm)
25.554	30	130	315	200	240	340

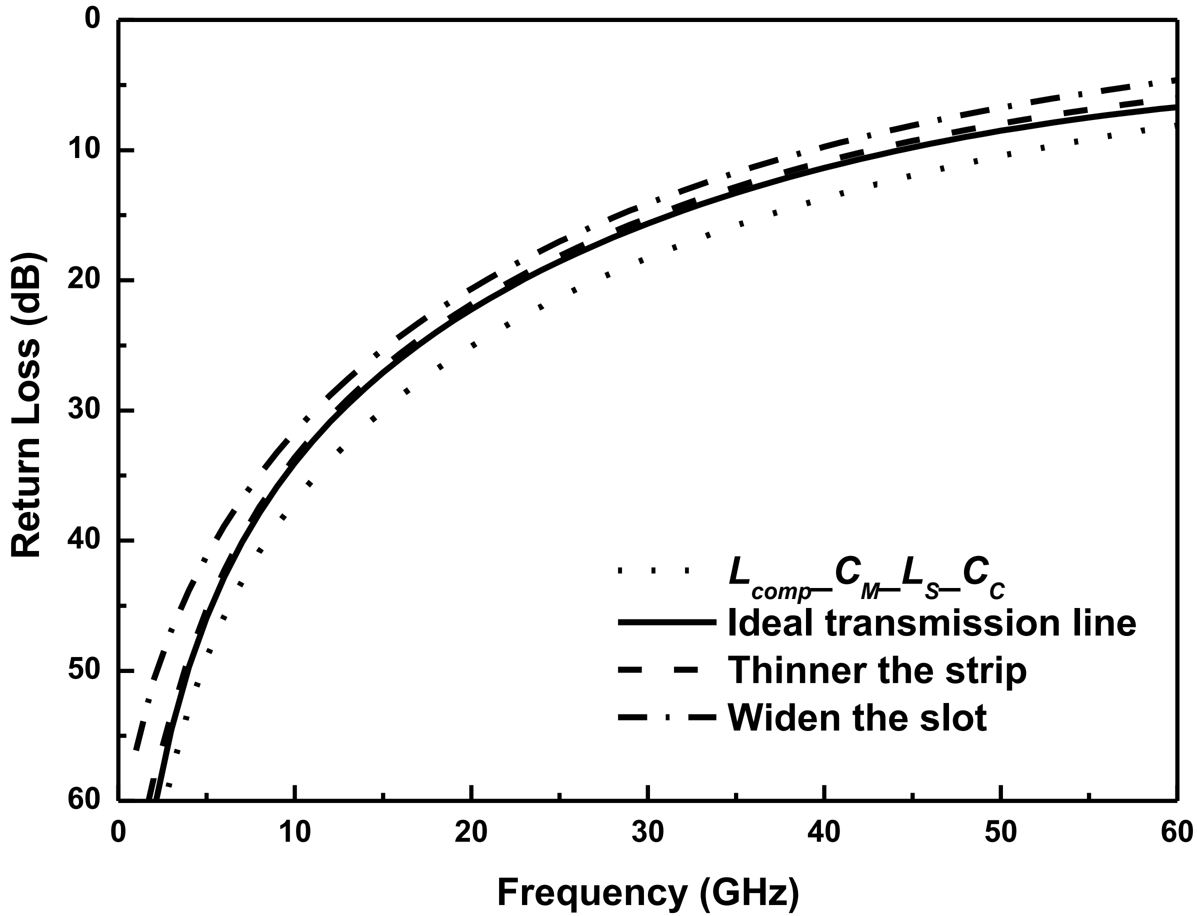
Inductive Compensation Flip-chip Transition

- $Z_H = 100\Omega$



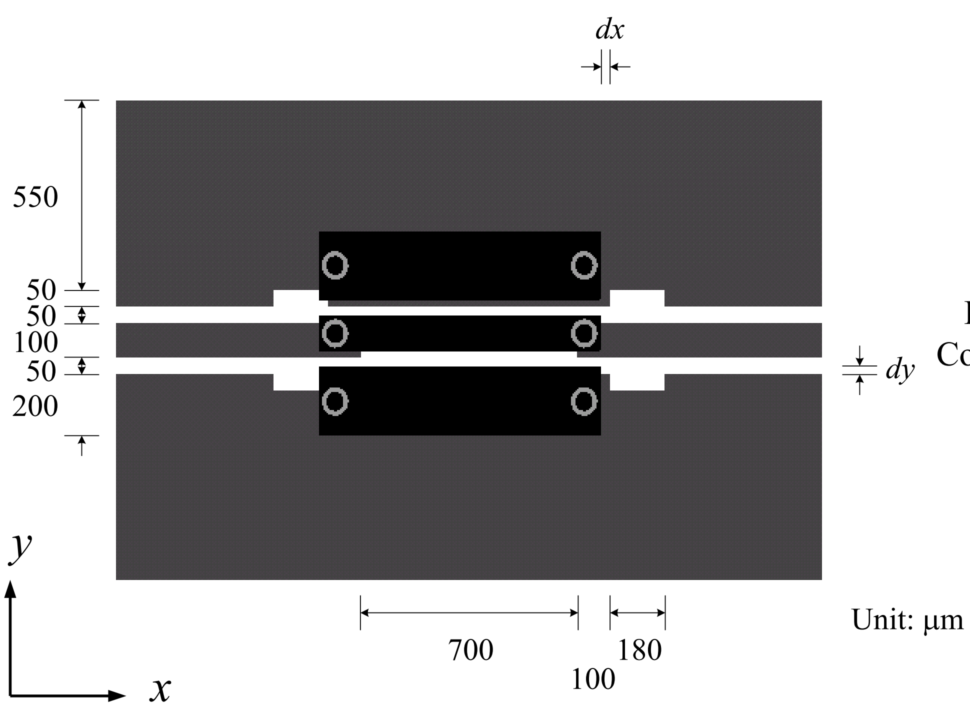
Inductive Compensation Flip-chip Transition

- Z_H=76Ω

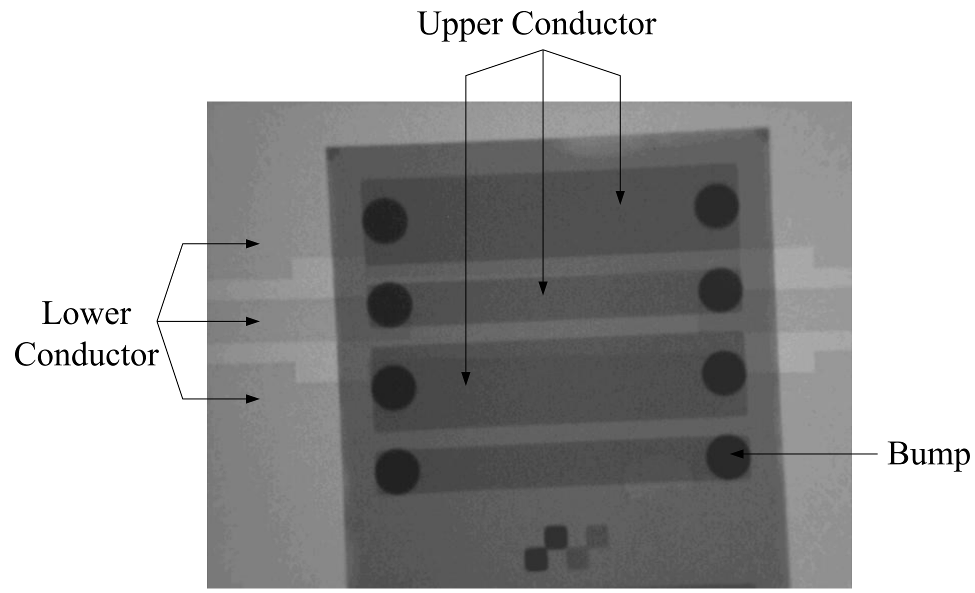


Inductive Compensation Flip-chip Transition

- Experiment



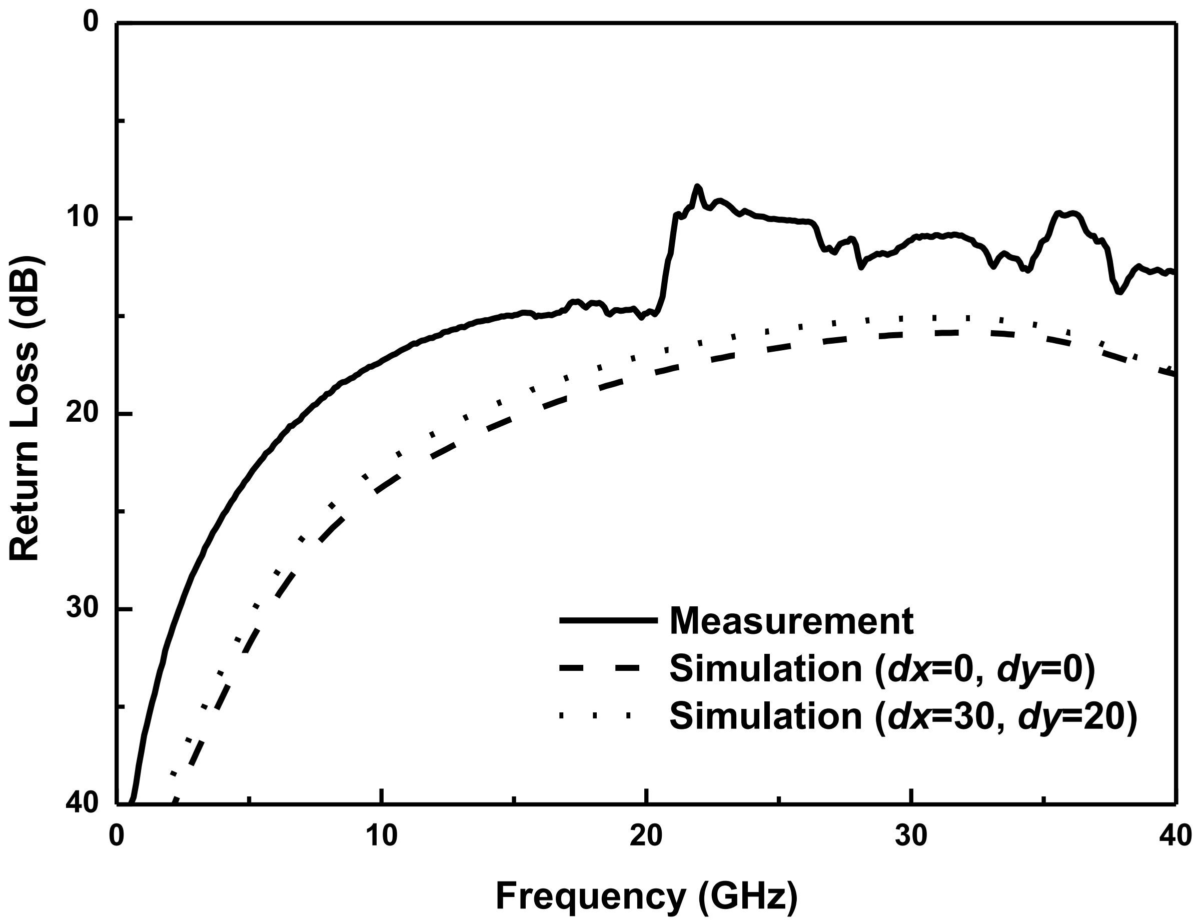
Simulation Size



Chip Photo

Inductive Compensation Flip-chip Transition

- Comparison between Simulation and Measurement

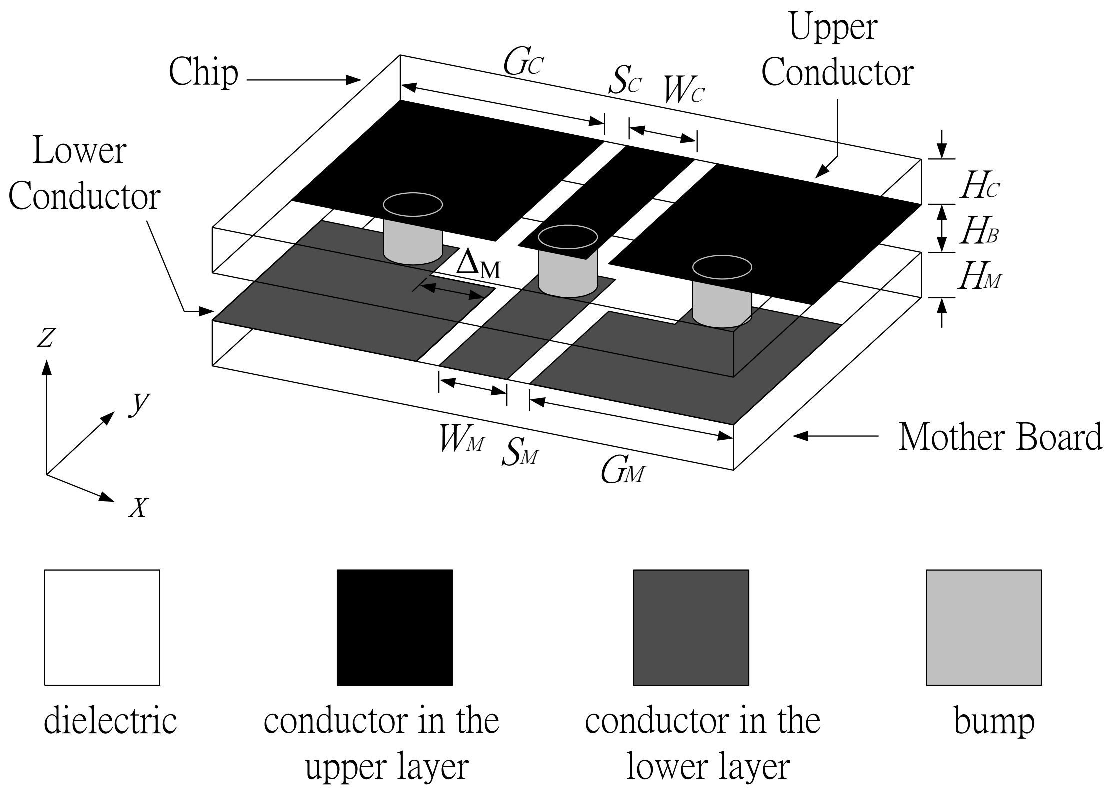


Inductive Compensation Flip-chip Transition

- Summary
  - Lumped Inductance
    - This can well compensate the capacitive effect at low frequencies
  - Ideal High Impedance Transmission Line
    - Higher impedance results in smaller length
    - Higher impedance can better represent the inductance
  - High Impedance Compensation
    - Thin strip has little discontinuity effect than wide slot
  - The Best Choice is to Adopt
    - higher impedance implemented with thin strip
  - Experiment
    - Return Loss is better than 15dB up to 20 GHz

Locally Matching Flip-chip Transition

- Ground Retreat on Mother Board [15]
  - Make $Z_D = \sqrt{L_S/(C_M + C_C)}$ Close to 50 Ω

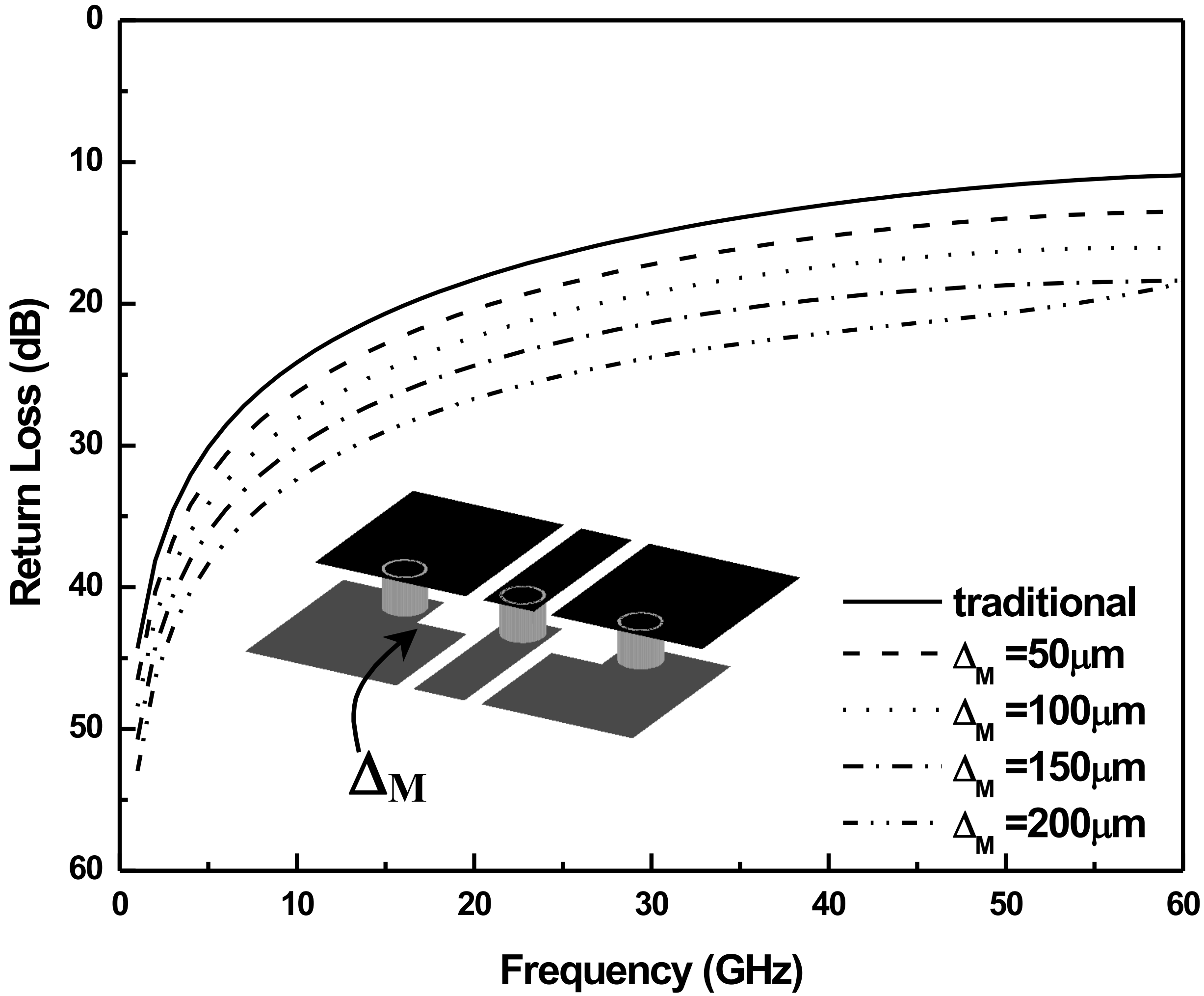


W_C=W_M=200μm, S_C=S_M=70μm, G_C=G_M=600μm, H_C=H_B=H_M=127μm, ε_r=10.2.

[15] N. Iwasaki et al., IEEE EPEP'96, pp. 207-209.

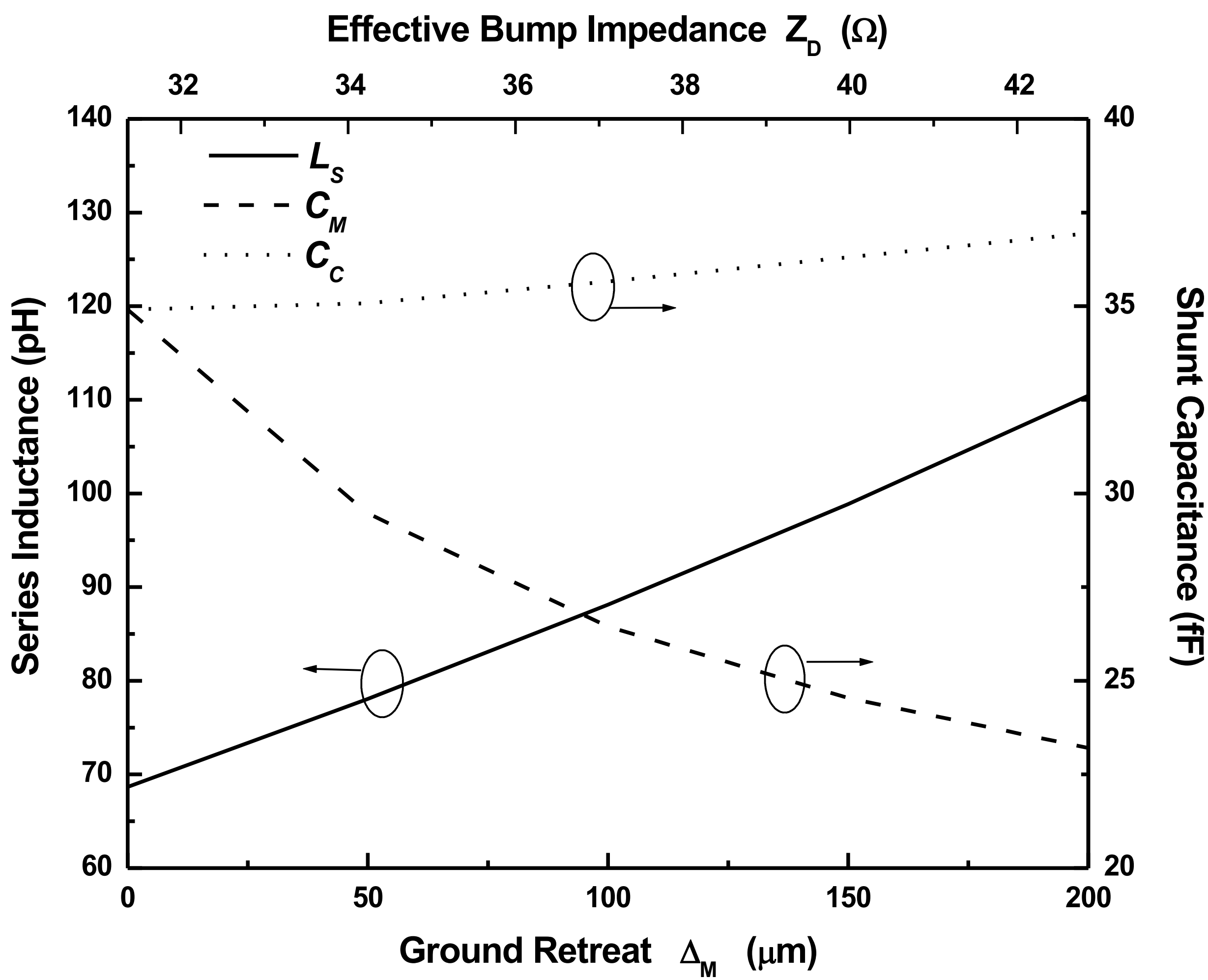
Locally Matching Flip-chip Transition

- Return Loss



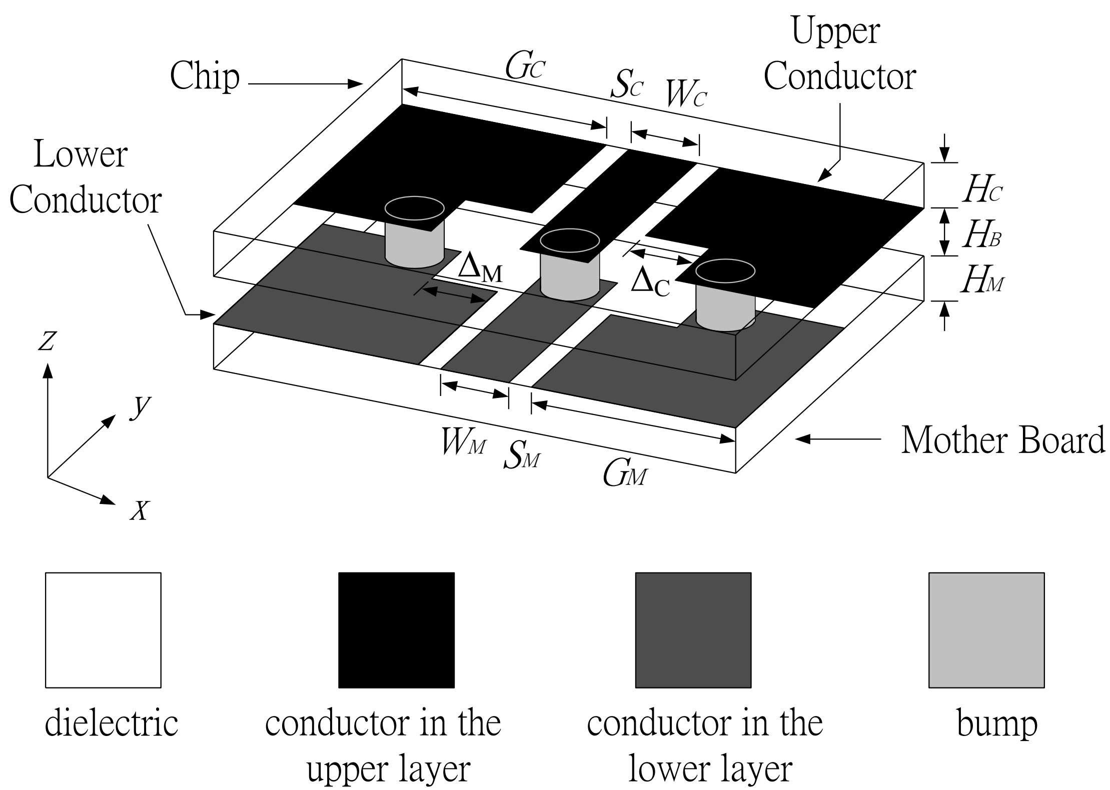
Locally Matching Flip-chip Transition

- Equivalent Circuit Values versus Δ_M



Locally Matching Flip-chip Transition

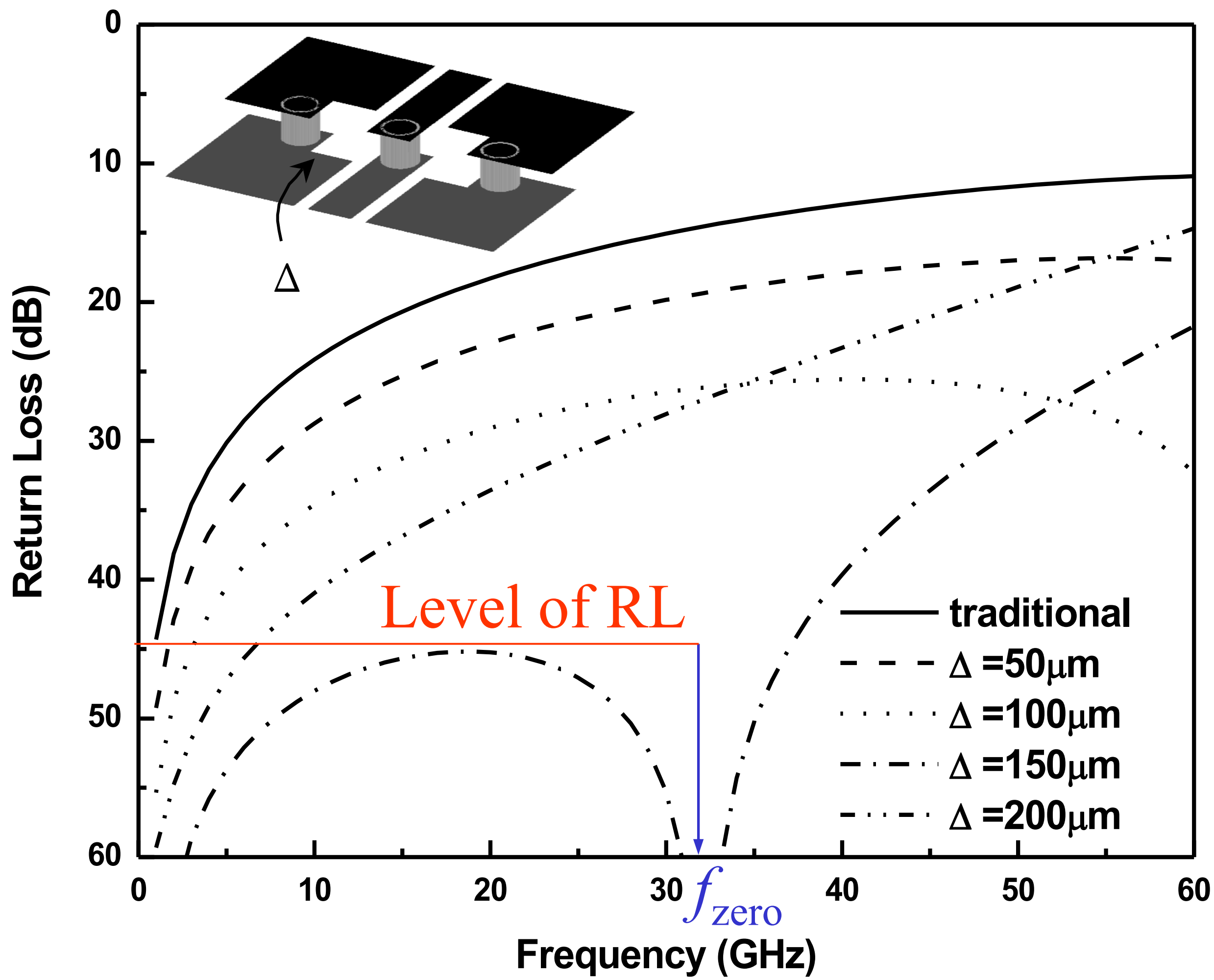
- Ground Retreats Both on Mother Board and Chip



$W_C = W_M = 200\mu m$, $S_C = S_M = 70\mu m$, $G_C = G_M = 600\mu m$, $H_C = H_B = H_M = 127\mu m$, $\varepsilon_r = 10.2$.

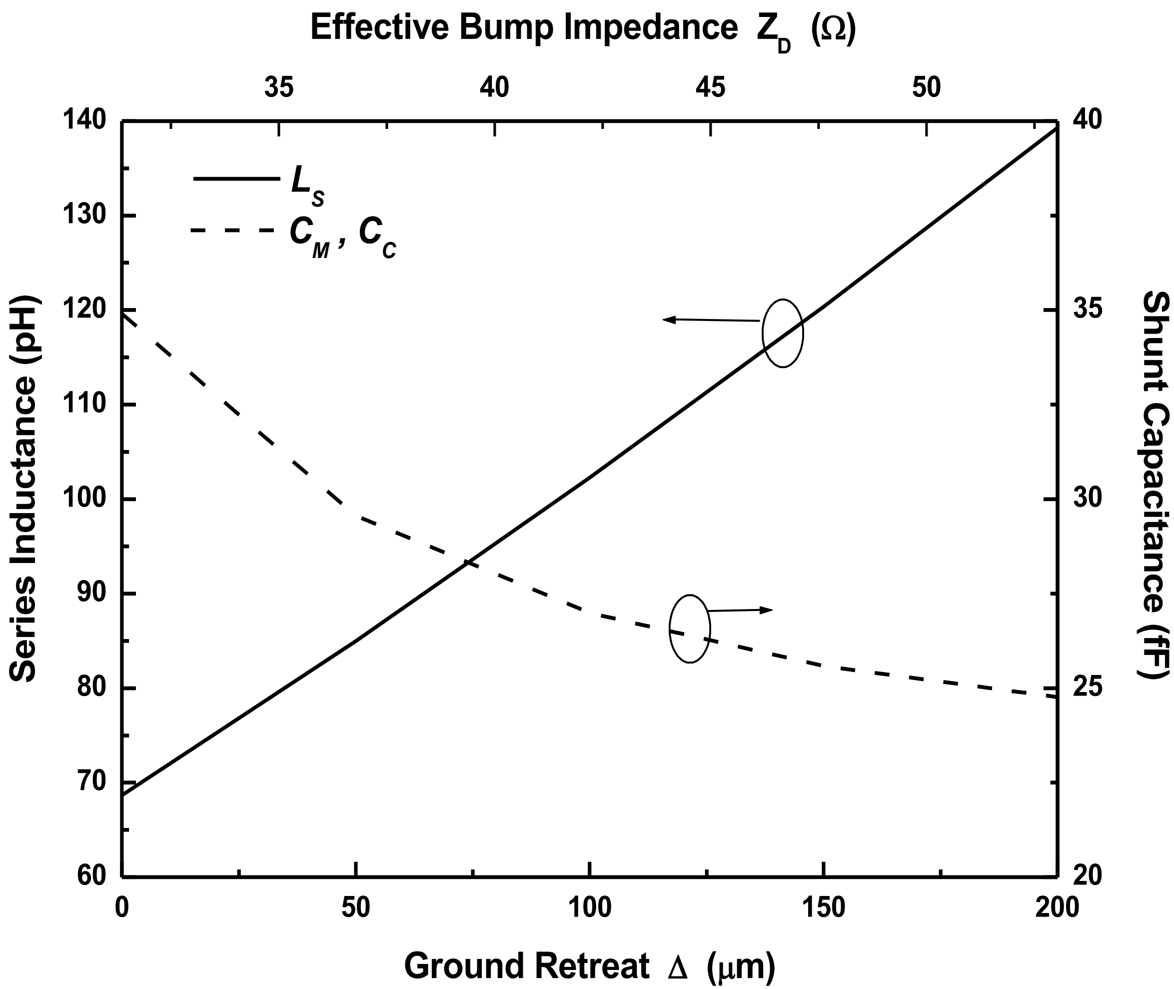
Locally Matching Flip-chip Transition

- Return Loss



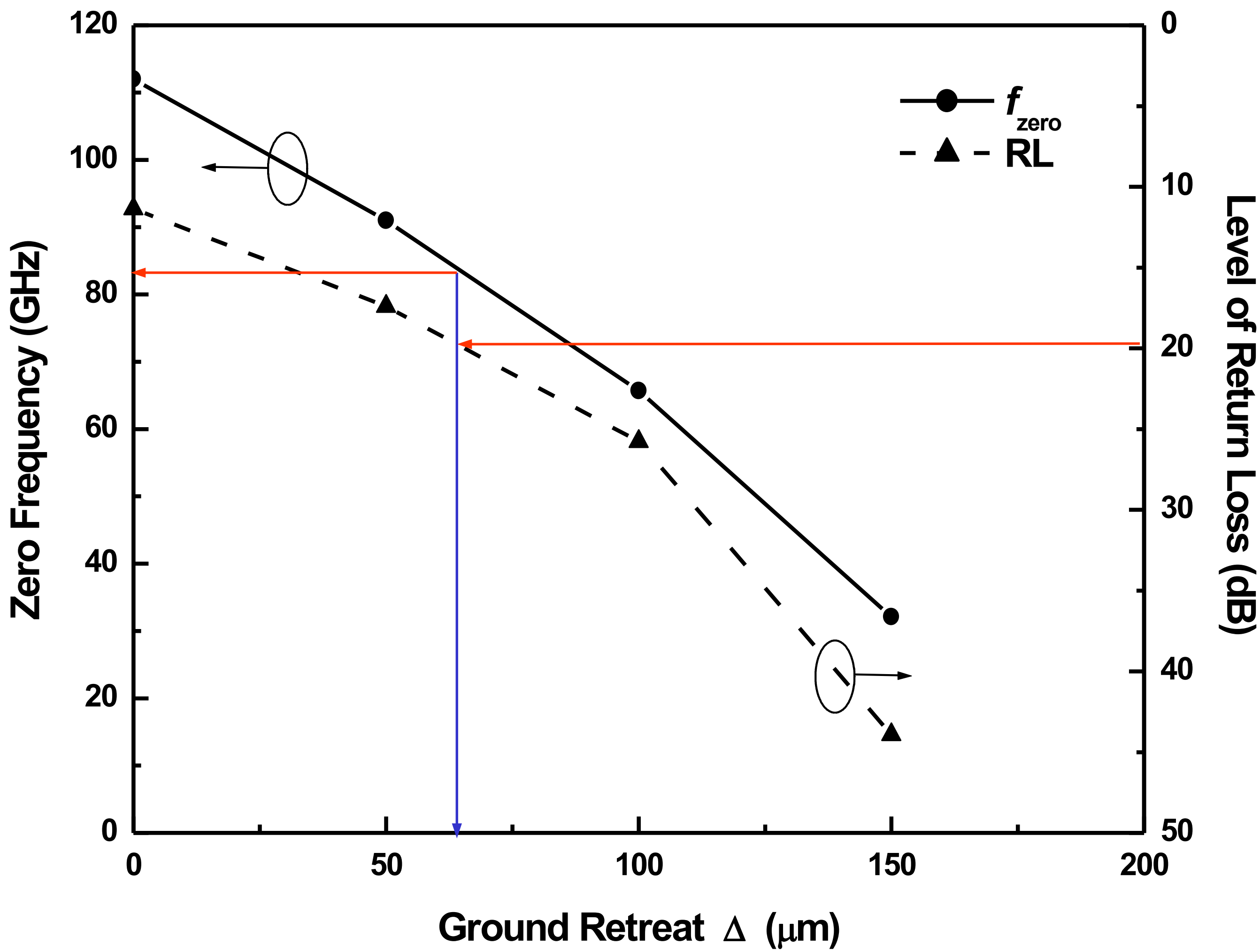
Locally Matching Flip-chip Transition

- Equivalent Circuit Values versus Δ_M



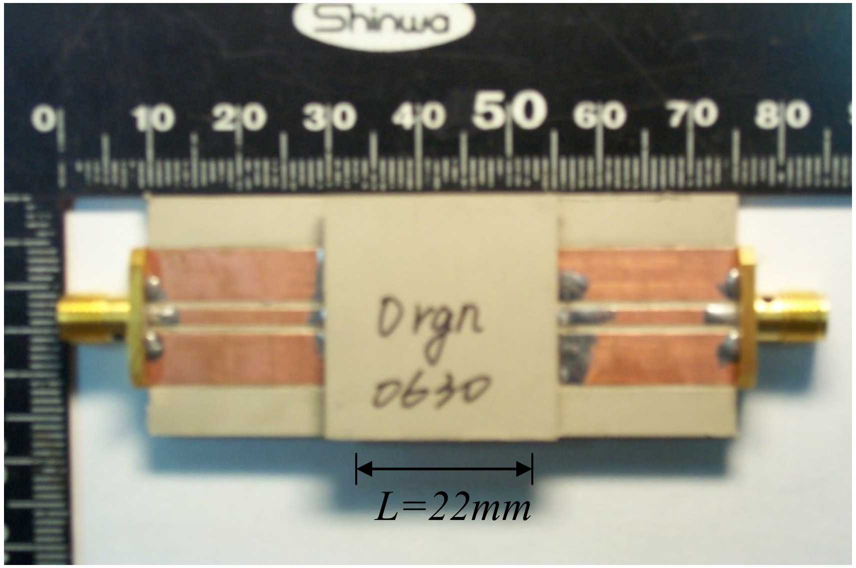
Locally Matching Flip-chip Transition

- Design Chart $f_{zero} = \dfrac{1}{2\pi}\sqrt{\dfrac{1}{L_S C_C^2}(2C_C - \dfrac{L_S}{Z_o^2})}$

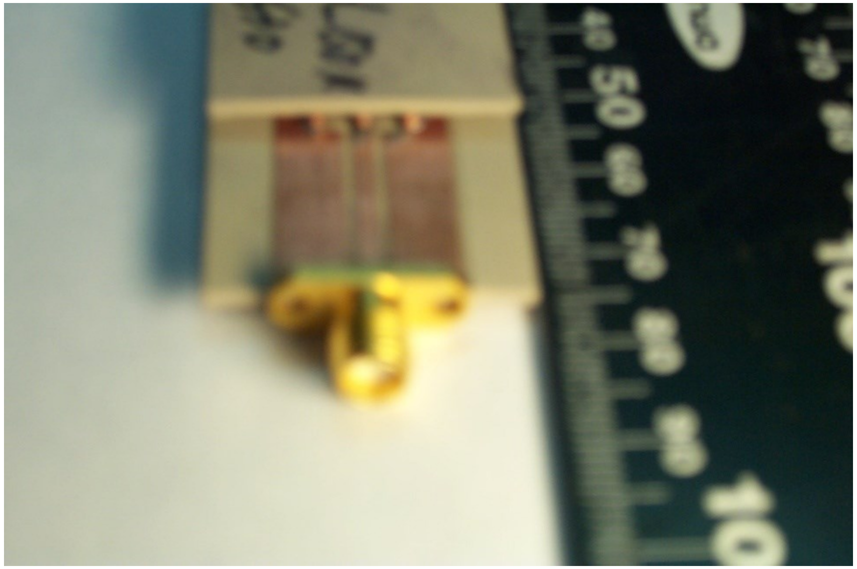


Locally Matching Flip-chip Transition

- 10 times Scaled up Circuit
  - Fabricated on RT/Duroid6010 of ε_r=10.2, and Measured with TRL Calibration.



Top view of the whole circuit

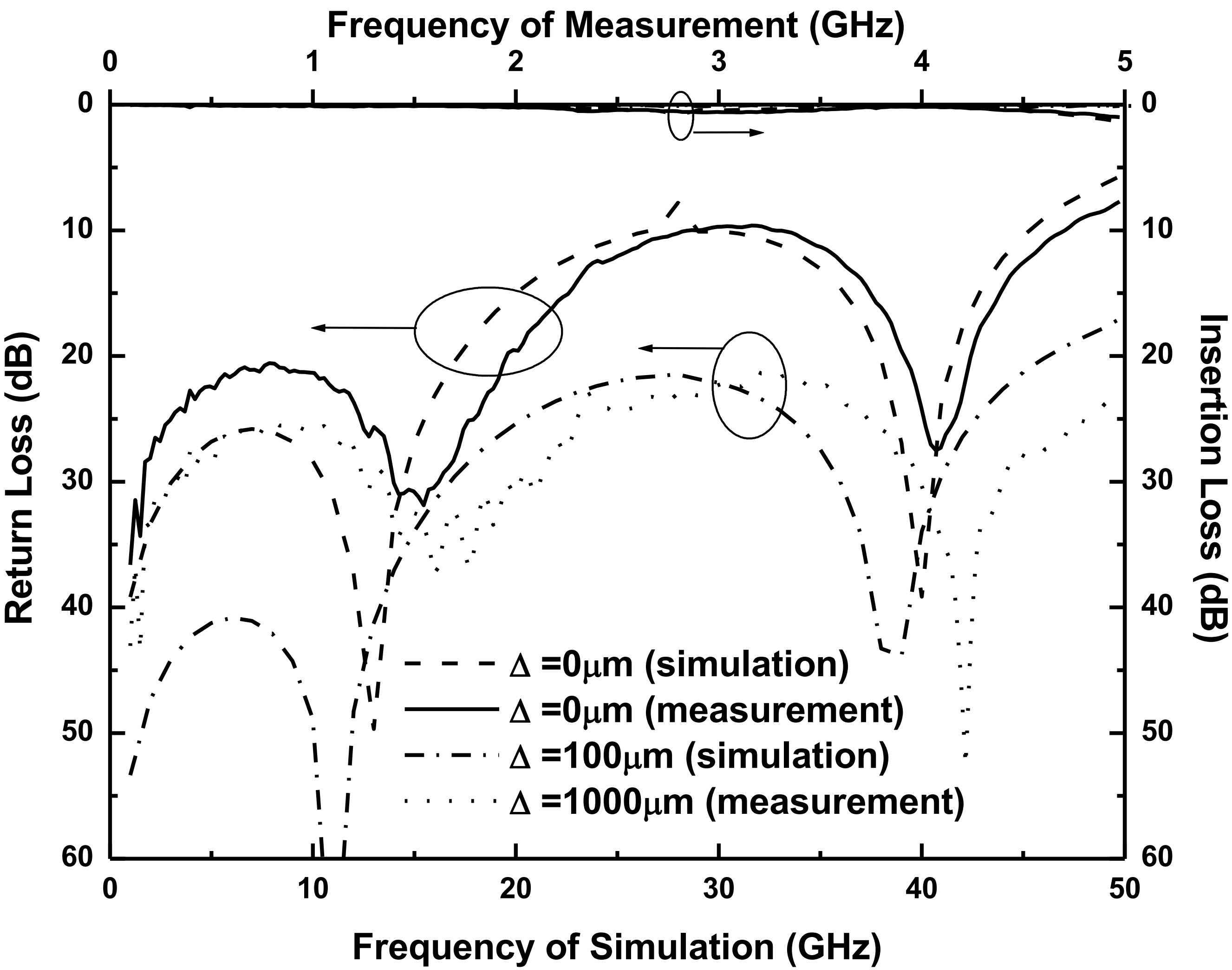


Local view of the bump area

Many thanks to Mr. Shih-Chieh Yen and Shih-Je Yang for helps on the fabrication.
Many thanks to Mr. Wen-Hua Tu for the suggestions in the measurement.

Locally Matching Flip-chip Transition

- Comparison between Simulation and Measurement

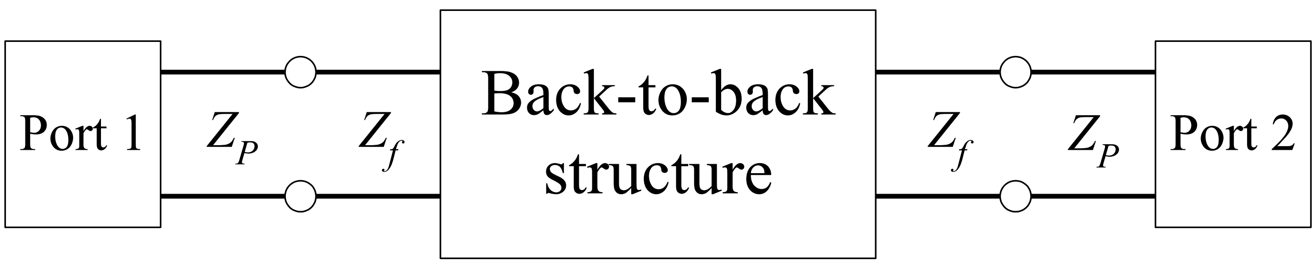


Locally Matching Flip-chip Transition

- Summary
  - Ground Retreat on Mother Board
    - The response of return loss does not change severely with Δ_M
    - The performance is still restricted by C_C on the chip side
  - Ground Retreats on Mother Board and Chip
    - This structure exhibits good transition when Δ is chosen well to match the impedance.
    - The area occupied is in the transverse direction of propagation and the frequency band is wide.
    - A design graph built with four simulated points can be used to design the return loss level validated up to the resonant frequency.
    - Measurement results of the ten-times scaled up circuit show good agreement with the simulation results.

On Chip Design and Measurement Correction

- Design Consideration
  - Simulated with Zero Conductor Thickness
    - $Z'_f = Z'_P = 52\Omega$
  - Measured with Real Conductor Thickness
    - $Z_f = Z_P = 50\Omega$

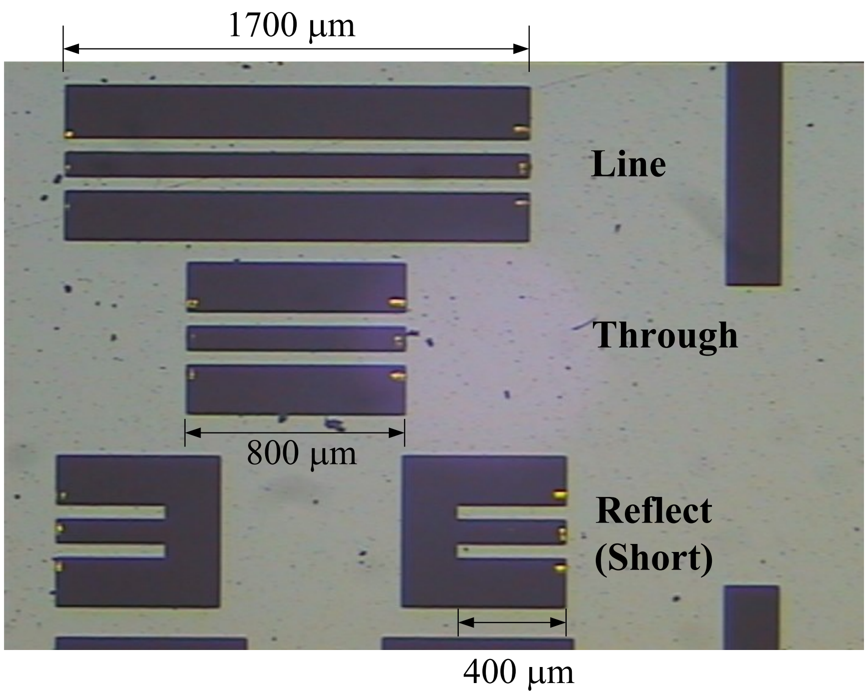


Z_f : characteristic impedance of feed line
Z_P : characteristic impedance of port

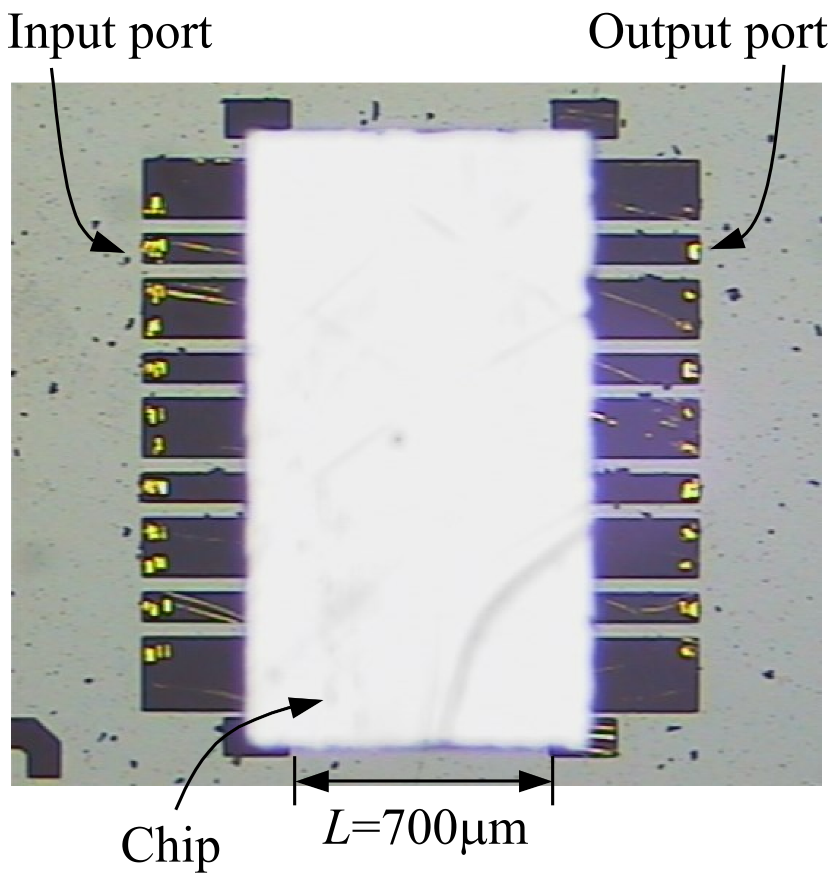
Many thanks to Airwave Inc. for fabricating the real flip-chip circuits, and Mr. Kun-You Lin and Ping-Yu Chen for doing the on wafer measurements.

On Chip Design and Measurement Correction

- Chip Photo



TRL Calibration Kit



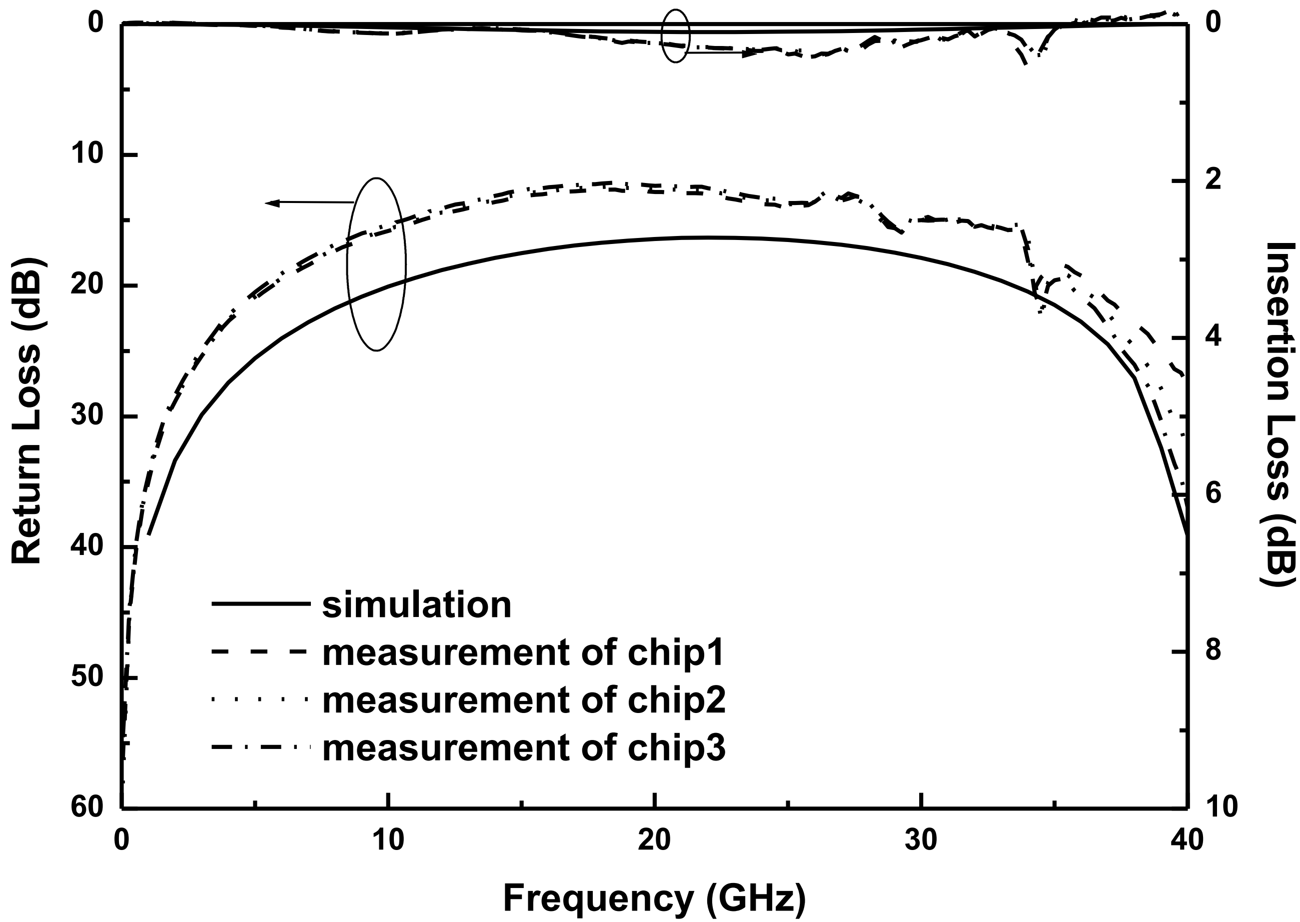
Back to Back Circuit

Bump: H_B=35μm, D_B=80μm

Mother Board (GCPW): H_M=381μm, ε_r=9.9, **Chip (CPW):** H_C=635μm, ε_r=12.9

On Chip Design and Measurement Correction

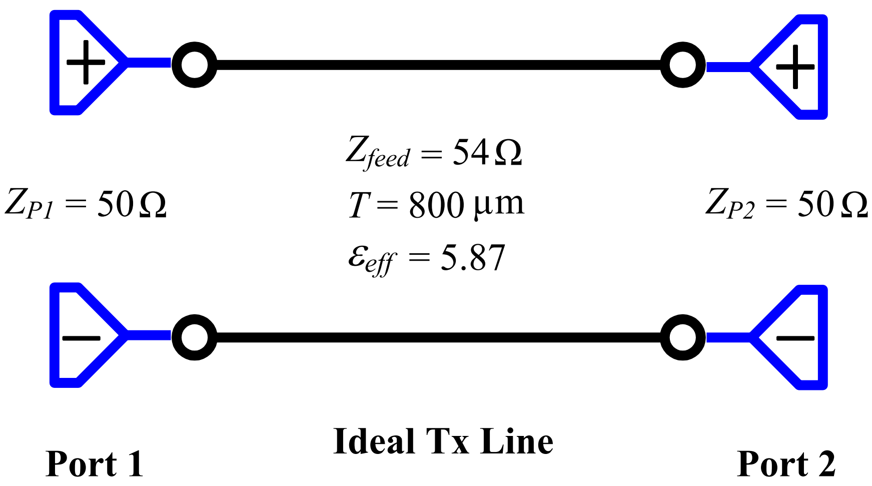
- Ground Retreat on Mother Board Only — Δ_M=50μm
  - Measured Based on Z_f=Z_P=50Ω



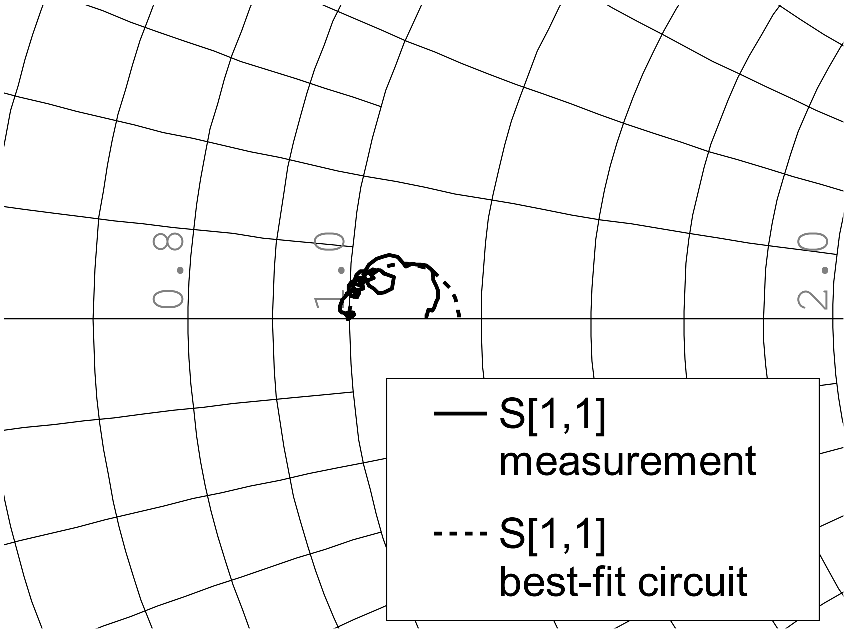
Mother Board: W_M=100μm, S_M=50μm, G_M=200μm. **Chip:** W_C=100μm, S_C=50μm, G_C=200μm.

On Chip Design and Measurement Correction

- Circuit for Acquiring the Correct Feedline Impedance
  - Z_f is Estimated to be 54 Ω



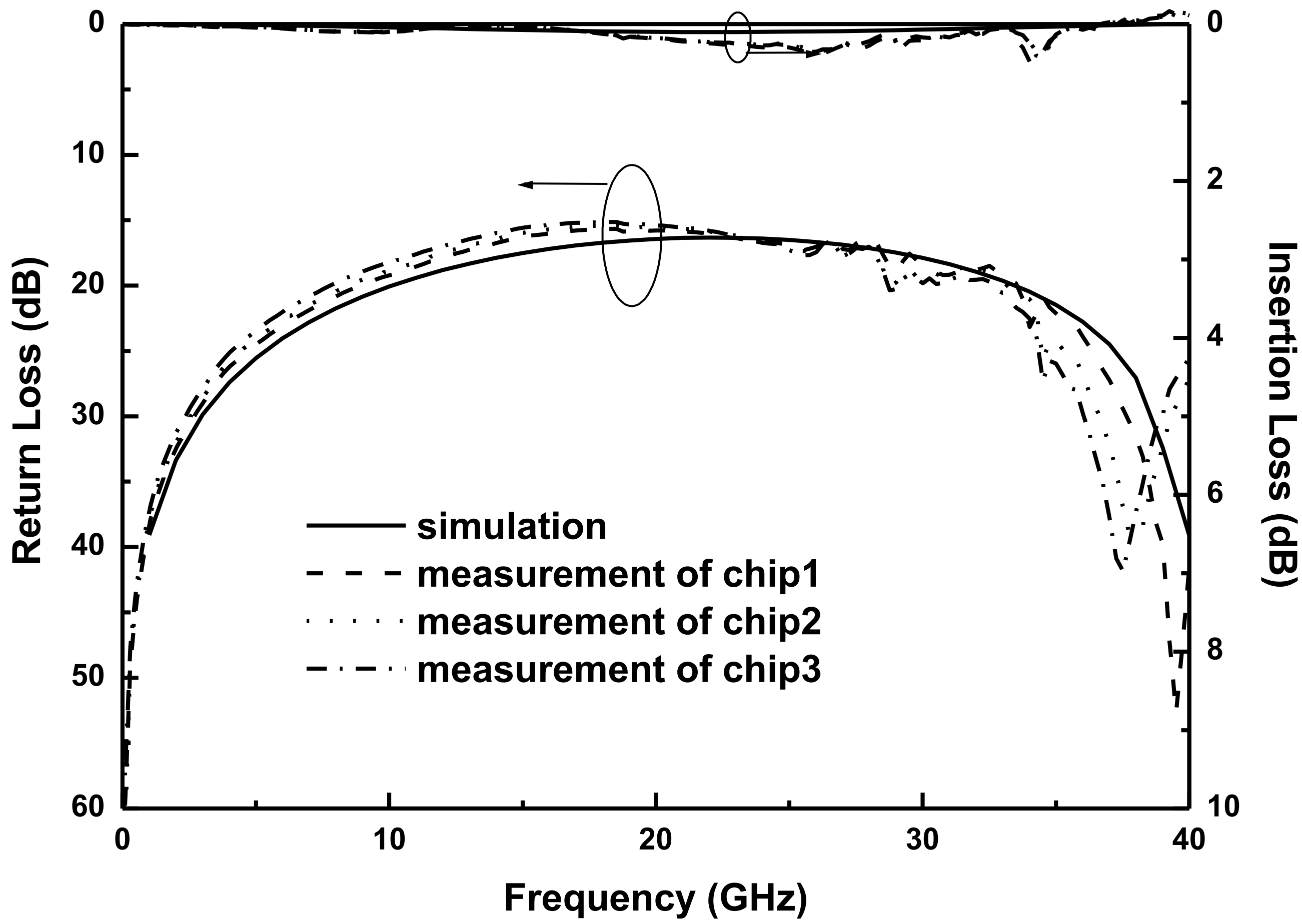
Equivalent Circuit



Comparison Result

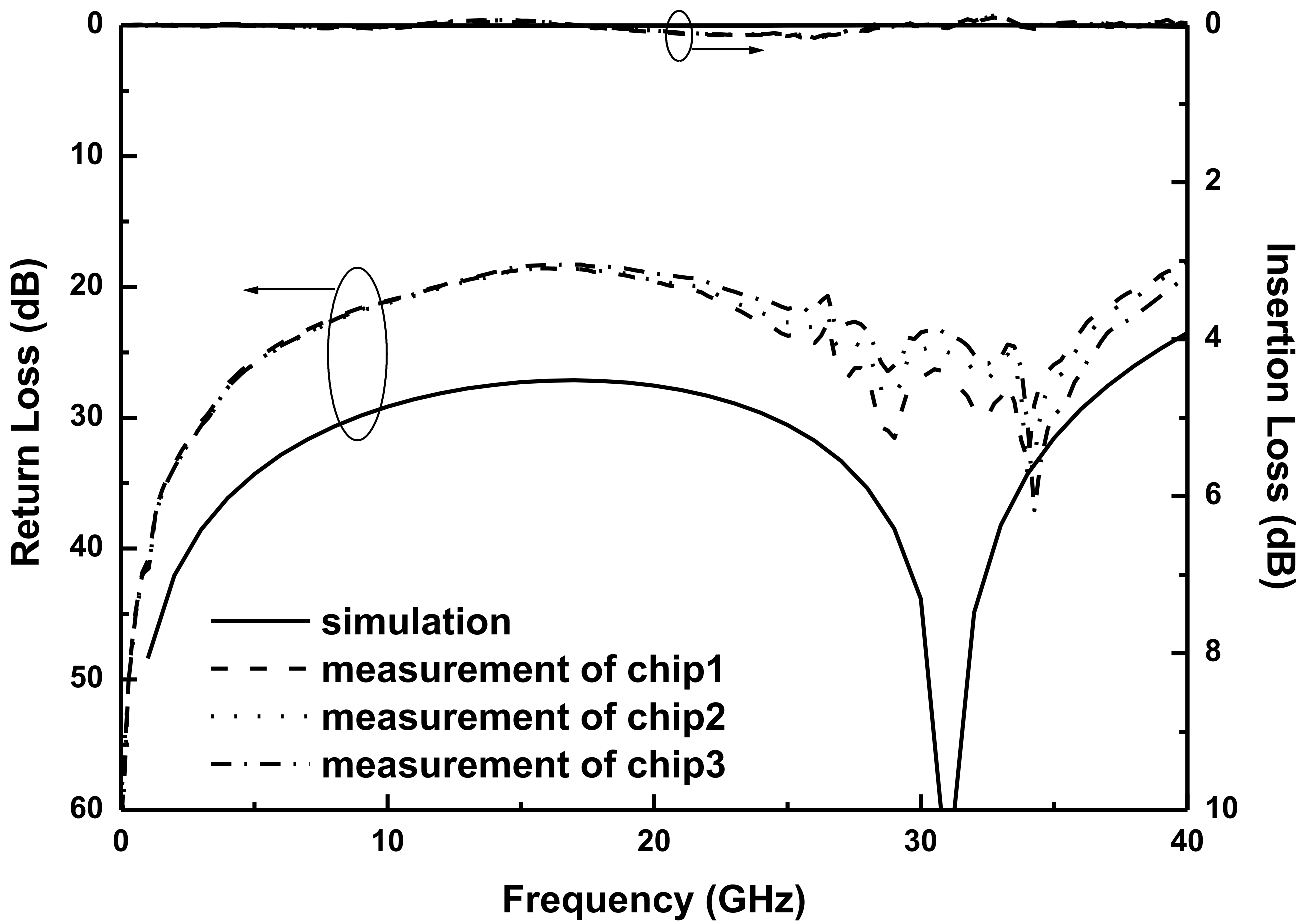
On Chip Design and Measurement Correction

- Ground Retreat on Mother Board Only — Δ_M=50μm
  - Measured Based on Z_f=Z_P=54Ω



On Chip Design and Measurement Correction

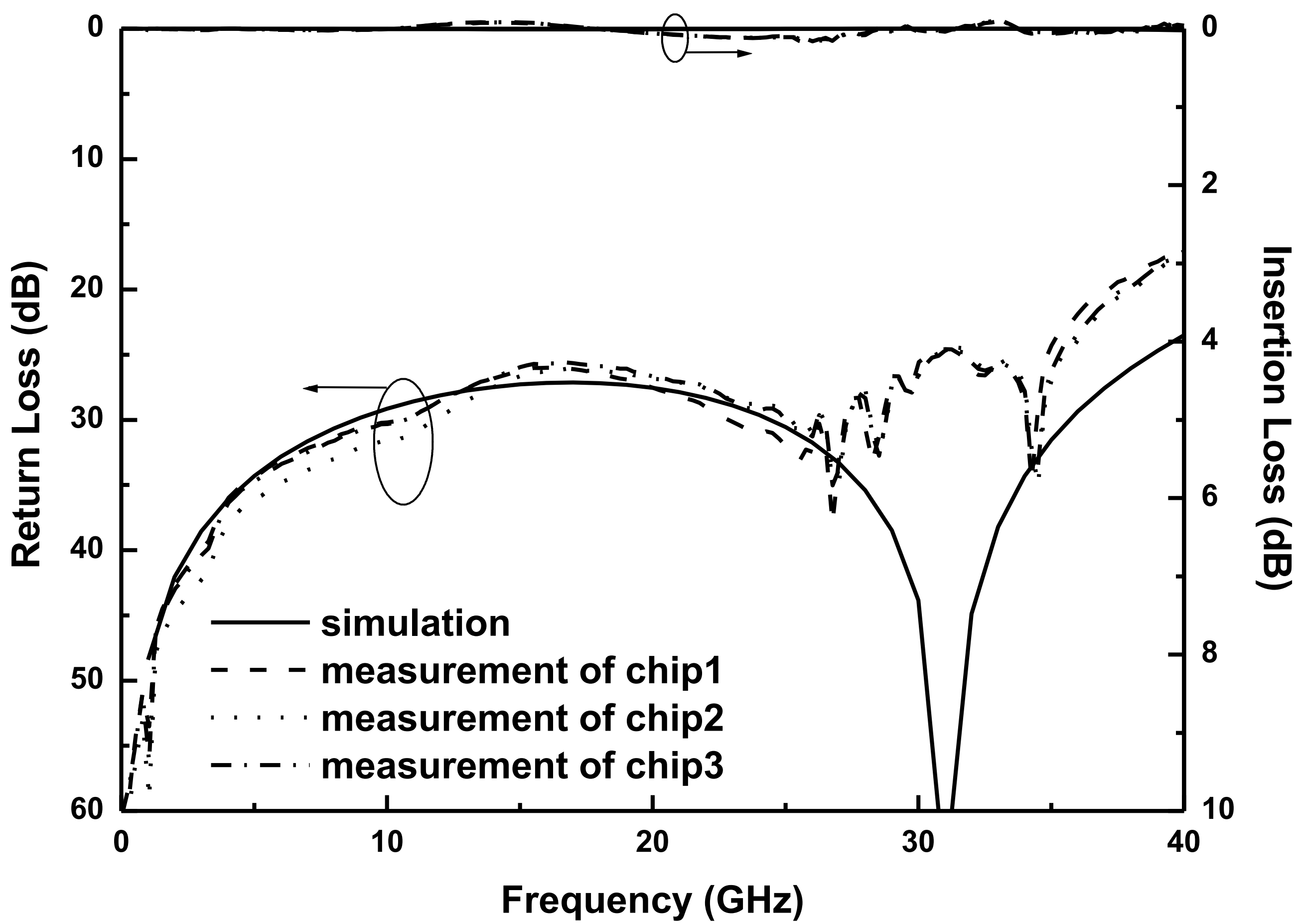
- Ground Retreat on Both Sides — Δ_M=75µm, Δ_C=50µm
  - Measured Based on Z_f=Z_P=50Ω



Mother Board: W_M=100µm, S_M=55µm, G_M=295µm. **Chip:** W_C=100µm, S_C=80µm, G_C=270µm.

On Chip Design and Measurement Correction

- Ground Retreat on Both Sides — Δ_M=75μm, Δ_C=50μm
  - Measured Based on Z_f=Z_P=54Ω



On Chip Design and Measurement Correction

- Summary
  - Simulation
    - zero conductor thickness based on $Z'_f = Z'_P = 52\Omega$ is adopted
  - Measurement
    - Original measurement based on $Z_f = Z_P = 50\Omega$ is calibrated to $Z_f = Z_P = 54\Omega$
    - 4 to 10 dB error in RL is corrected
  - Ground Retreat on Mother Board Only
    - 15 dB RL up to 35 GHz
  - Ground Retreats on Both Sides
    - 25 dB RL up to 35 GHz

Conclusions

- Conclusions
  - Conventional Flip-chip Transition
    - This possesses a capacitive effect
  - Resonant Flip-chip Transition
    - The resonant length is controlled to result in a resonant dip in the desired frequency band
    - Discrete equivalent circuit could be optimized up to millimeter-wave frequencies
    - Chip areas are sacrificed in the longitudinal direction
  - Inductive Compensation Flip-chip Transition
    - Lumped inductance could well compensate the capacitive effect
    - High impedance line with higher impedance and thin strip could result in the best performance and smallest size
    - This saves chip areas
    - This could only enhance the performance up to millimeter-wave frequencies

Conclusions

- Conclusions
  - Locally Matching Flip-chip Transition
    - Ground retreat on mother board could substantially improve the performance
    - Ground retreat on both sides could greatly improve the performance
    - Wide band performance are obtained with chip areas sacrificed in the transverse direction
  - On Chip Design
    - Simulation considering conductor thickness with zero conductor thickness and somewhat higher impedance is adopted
    - Measurement correction procedures are required to calibrate the return loss level due to fabrication error