Cross-Line Characterization for Capacitive Cross Coupling in Differential Millimeter-Wave CMOS Amplifiers

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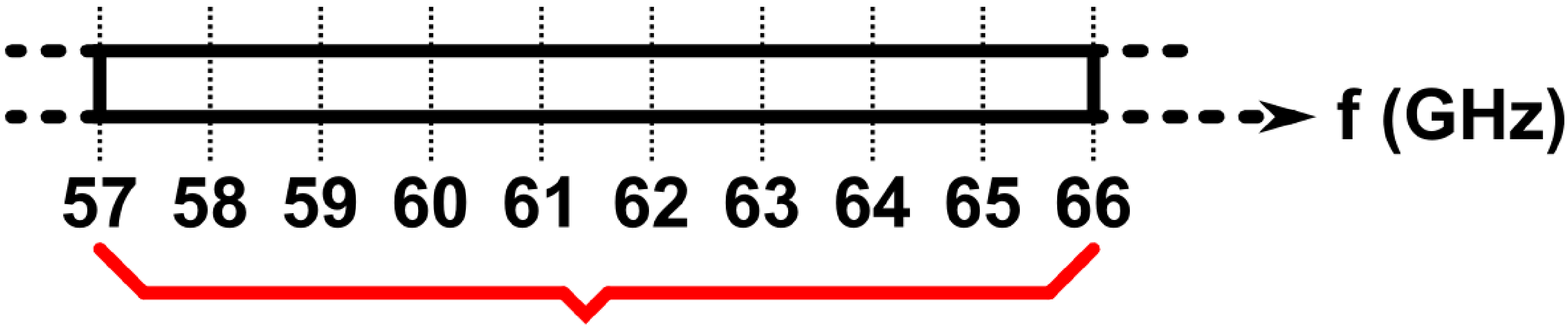
Outline

- Background & Motivation
- Cross-Line for Capacitive Cross Coupling
  - Characterization Structures
  - Method
- GSSG De-embedding Using Virtual-Thru
  - Results for De-embedding
- Results for Characterization
- Application Example on a Differential Amplifier

Millimeter-Wave Band: 60 GHz



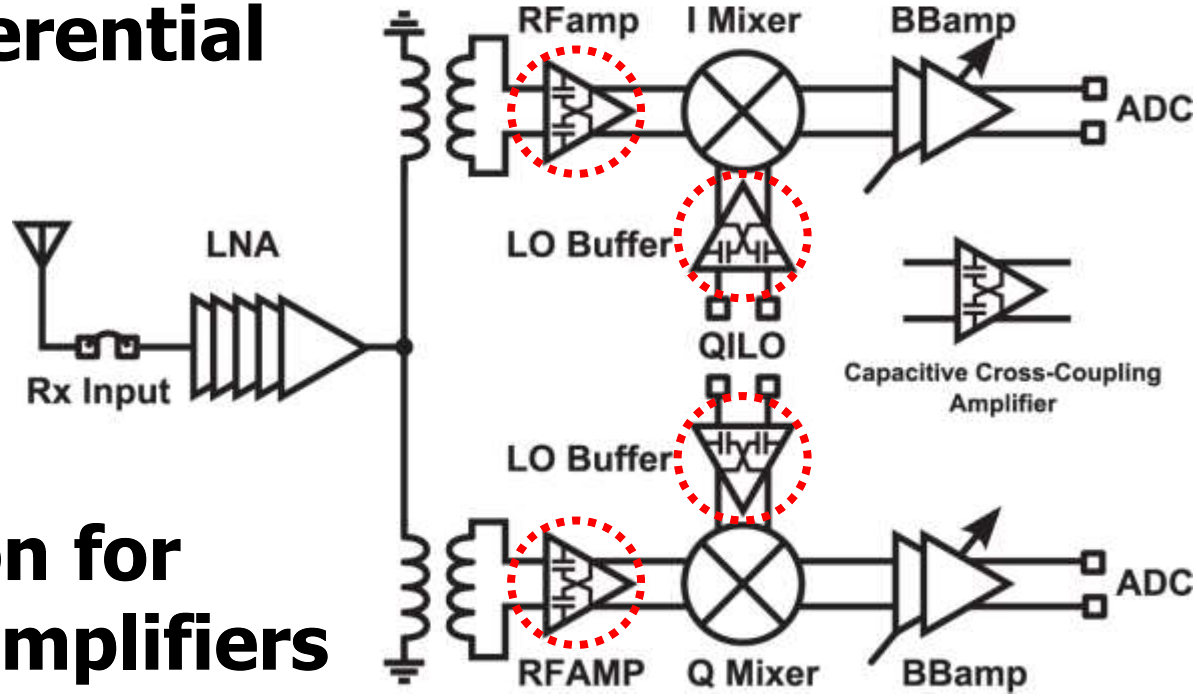
***57-66 GHz Unlicensed Frequency Band**

- **9 GHz Unlicensed band**
  - **Data rates up to 40 Gbps**
- **Large atmospheric attenuation**
  - ☺ **Secure Communication**
  - ☹ **Limited Communication Range**

*http://www.tele.soumu.go.jp/resource/e/search/share/2008/t3.pdf

Direct Conversion RX on CMOS

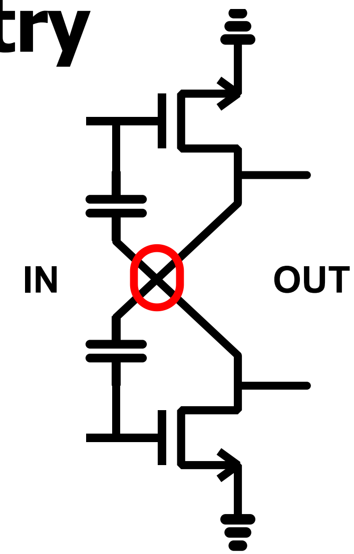
- Single & differential amplifiers

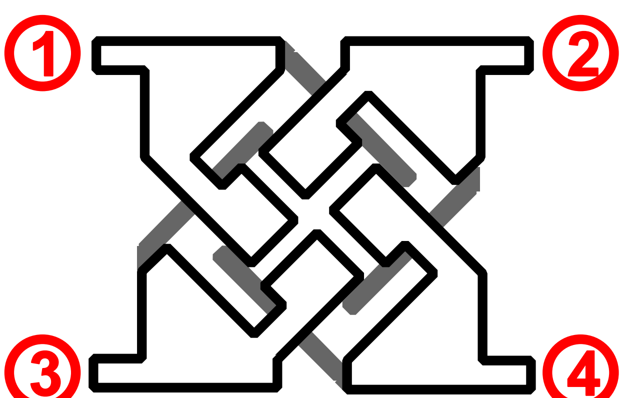


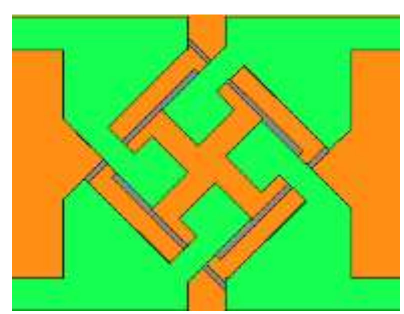
- Neutralization for differential amplifiers
  - High gain
  - Lower power consumption
  - Less Area
- Capacitive cross coupling amplifiers

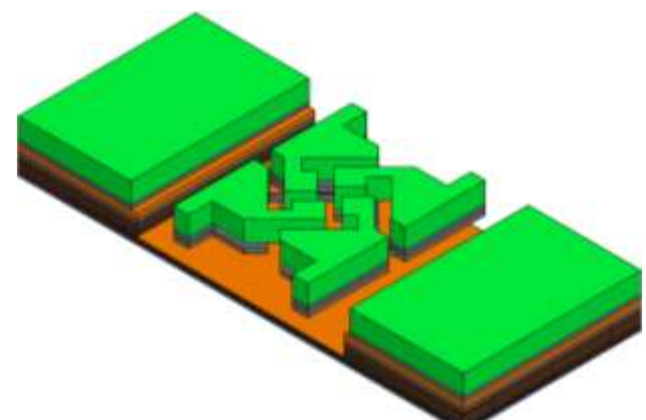
Capacitive Cross Coupling Amp.

- Important characteristic: Symmetry
- Asymmetrical crossing part
  - Amplitude imbalance
  - Phase imbalance
  - Unwanted mode conversions
- SNDR and EVM degradation
- Electrically symmetric Cross-Line





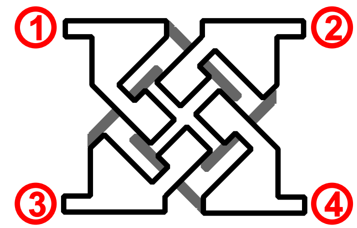




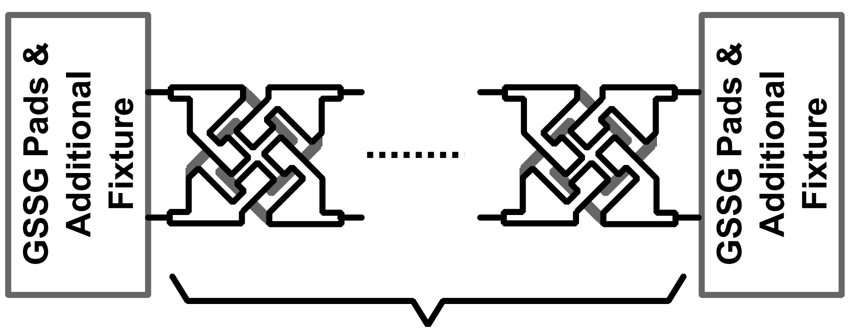
Structures for Characterization

- **Assuming symmetry and reciprocity**

$$S_{CCC} = \begin{bmatrix} S_{11} & S_{12} & S_{13} & S_{14} \\ S_{12} & S_{11} & S_{14} & S_{13} \\ S_{13} & S_{14} & S_{11} & S_{12} \\ S_{14} & S_{13} & S_{12} & S_{11} \end{bmatrix}$$



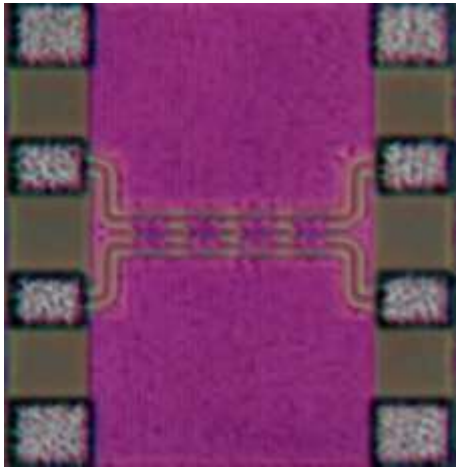
- **Four unknowns for full characterization**
  - **Two four-port characterization structures**



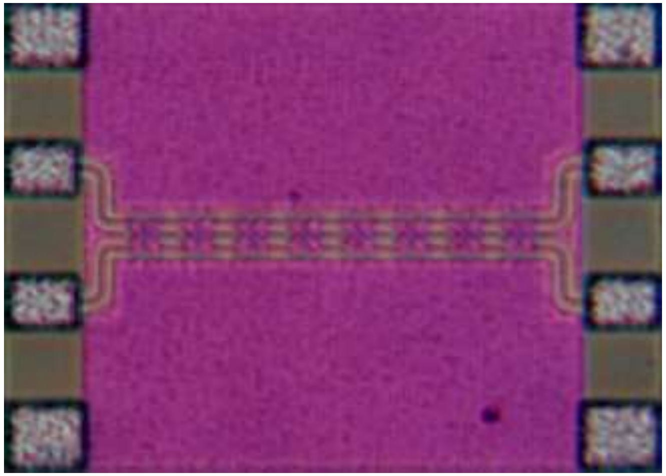
Two Structures:
1) 4 Repeated CCC
2) 8 Repeated CCC

Structures for Characterization

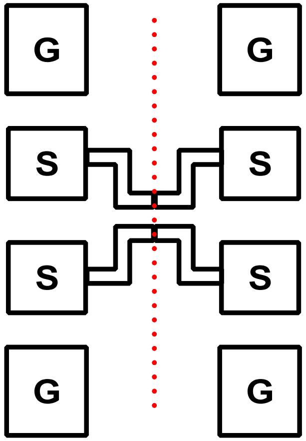
- 4 repeated



- 8 repeated



- 4 and 8 repeated structure selected
  - Easy calculation for fixture effects
- Mixed-mode S-parameters
  - Avoiding four-port T-parameters



Method for Characterization

- **Single-ended four-port S-parameters to mixed-mode S-parameters**

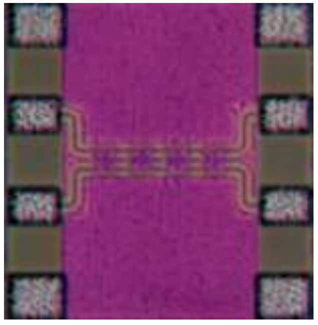
$$[S_{MM}] = [M][S][M]^{-1} = \begin{bmatrix} S_{DD} & S_{DC} \\ S_{CD} & S_{CC} \end{bmatrix}$$

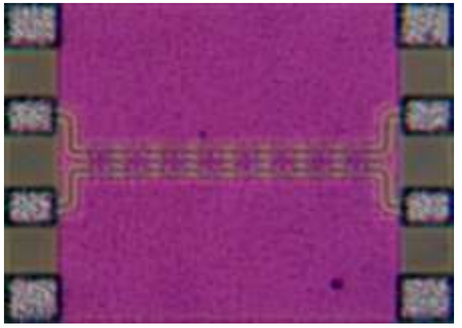
where; $[M] = \frac{1}{\sqrt{2}} \begin{bmatrix} I & -I \\ I & I \end{bmatrix}$

- **Symmetrical and reciprocal:**
  - **No mode conversion**
- **Two pure modes: two two-port networks**
  - **Differential and common**

Method of Characterization

- **Differential and common mode S-parameters → T-parameters**

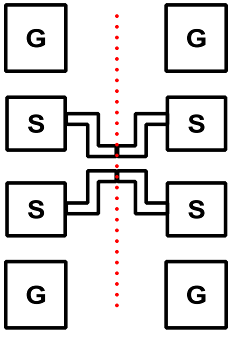




$$[T]_{4U,DD} = [T]_{LP,DD}[T]_{F,DD}[T]_{C,DD}{}^{4}[T]_{F,DD}[T]_{RP,DD}$$

$$[T]_{8U,DD} = [T]_{LP,DD}[T]_{F,DD}[T]_{C,DD}{}^{8}[T]_{F,DD}[T]_{RP,DD}$$

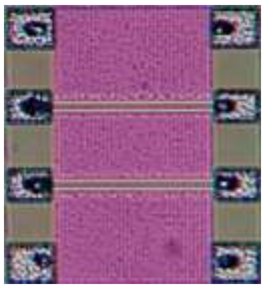
$$[T]_{PF,DD} = [T]_{4U,DD}[T]_{8U,DD}{}^{-1}[T]_{4U,DD}$$

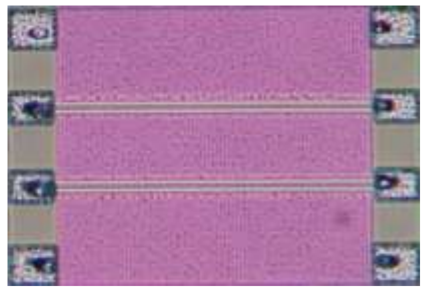


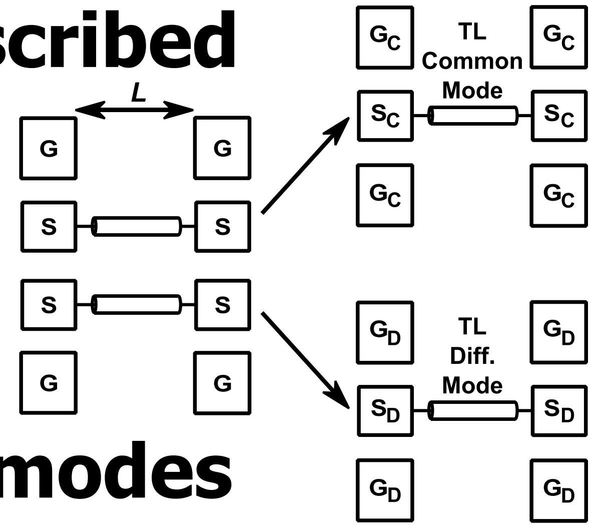
- **Similarly for common mode**
- **Pads has to be de-embedded**

GSSG Pad De-embedding

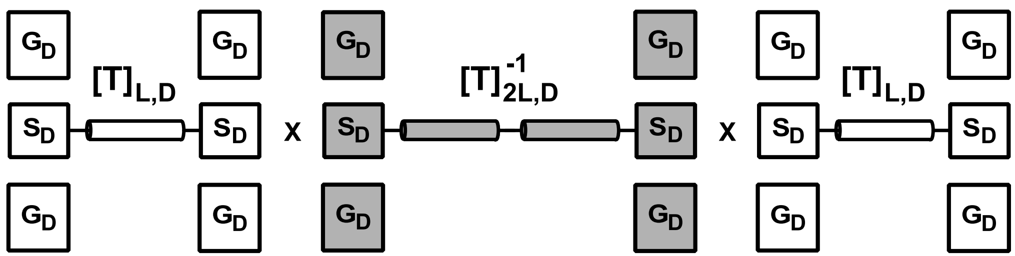
- **Mixed-mode is used as described**







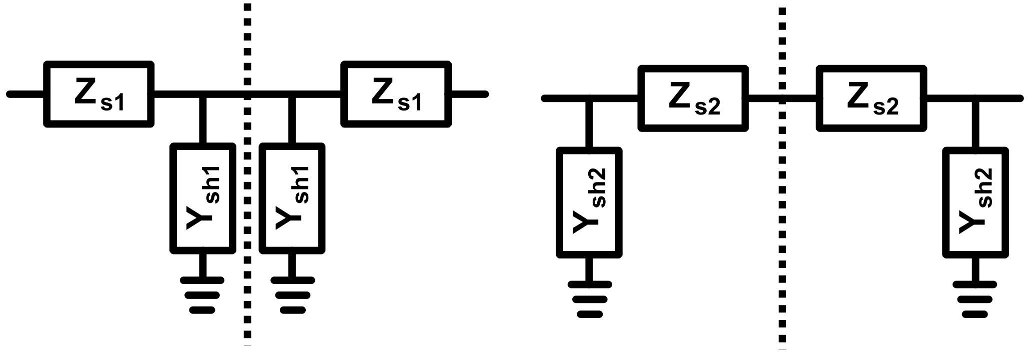
- **Apply virtual-thru for two modes**

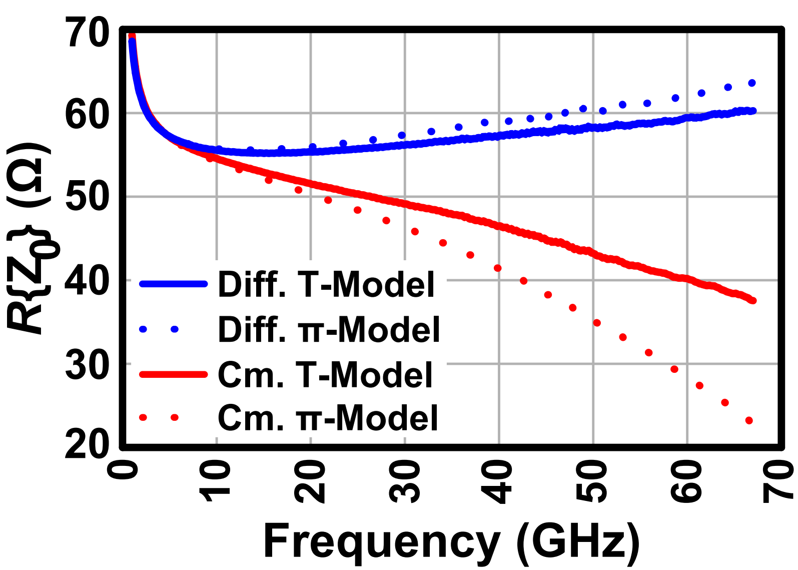


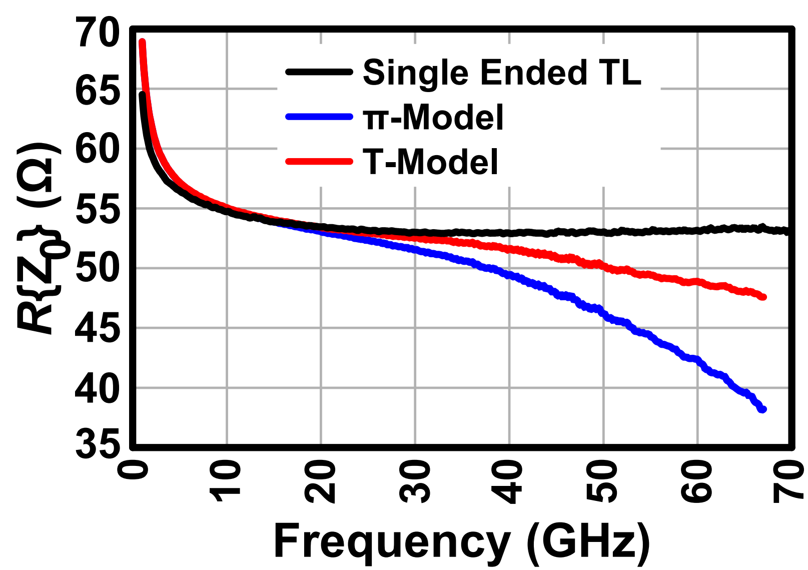
- **Solve for T-, and Π-model for two modes of pads**

Results for De-embedding

- **Pad models: T-model and Π-model**

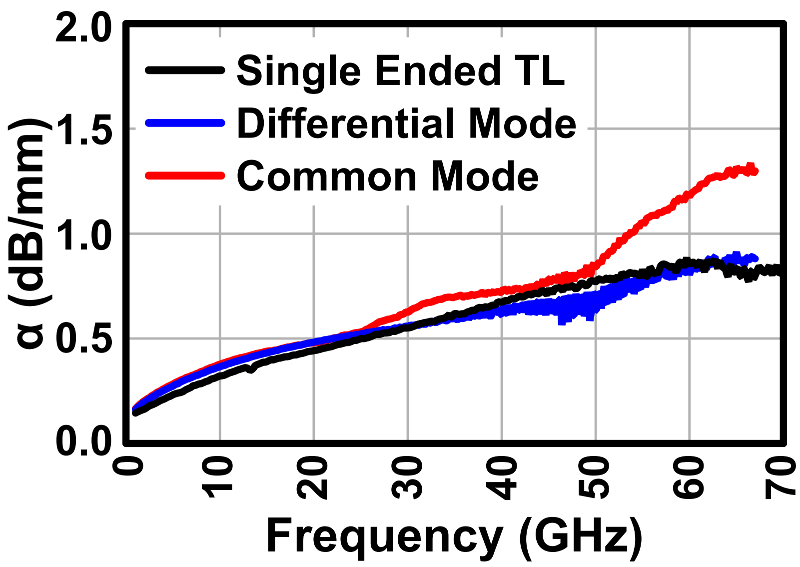


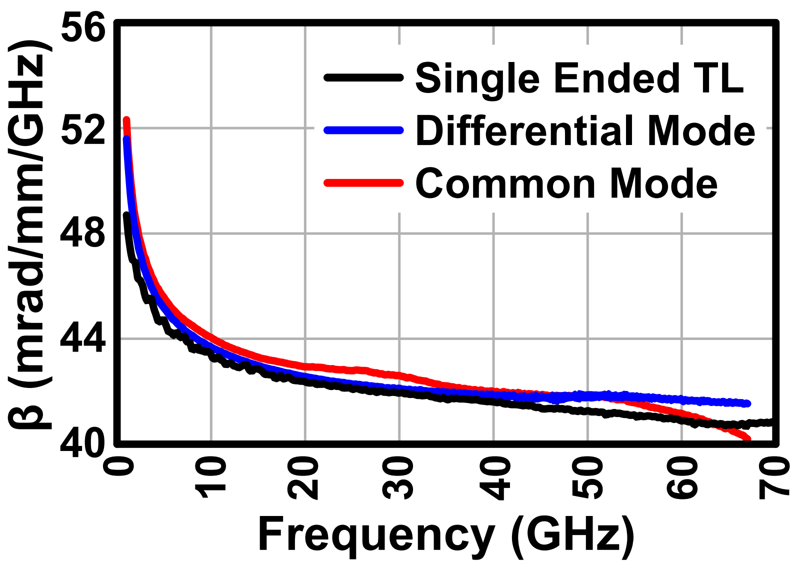




Results for De-embedding

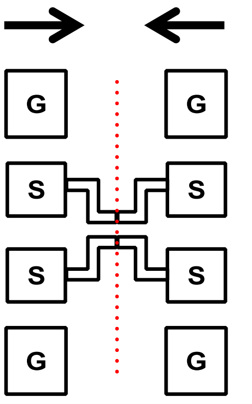
- **Loss component and propagation constant independent of model**
- **Compared with single-ended transmission line results**
  - **Nearly the same (expected)**



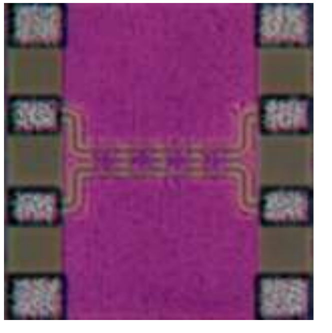


De-embedding from Fixture

- De-embed differential and common mode pad responses
  - From fixture results
- Solve for symmetrical fixture effects
  - For both left and right side
- De-embedding the fixture and pad S-parameters
  - Solve for one cross-line



$$[T]_{F,DD}{}^{-1}[T]_{LP,DD}{}^{-1}[T]_{4U,DD}[T]_{RP,DD}{}^{-1}[T]_{F,DD}{}^{-1} = [T]_{C,DD}{}^{4}$$

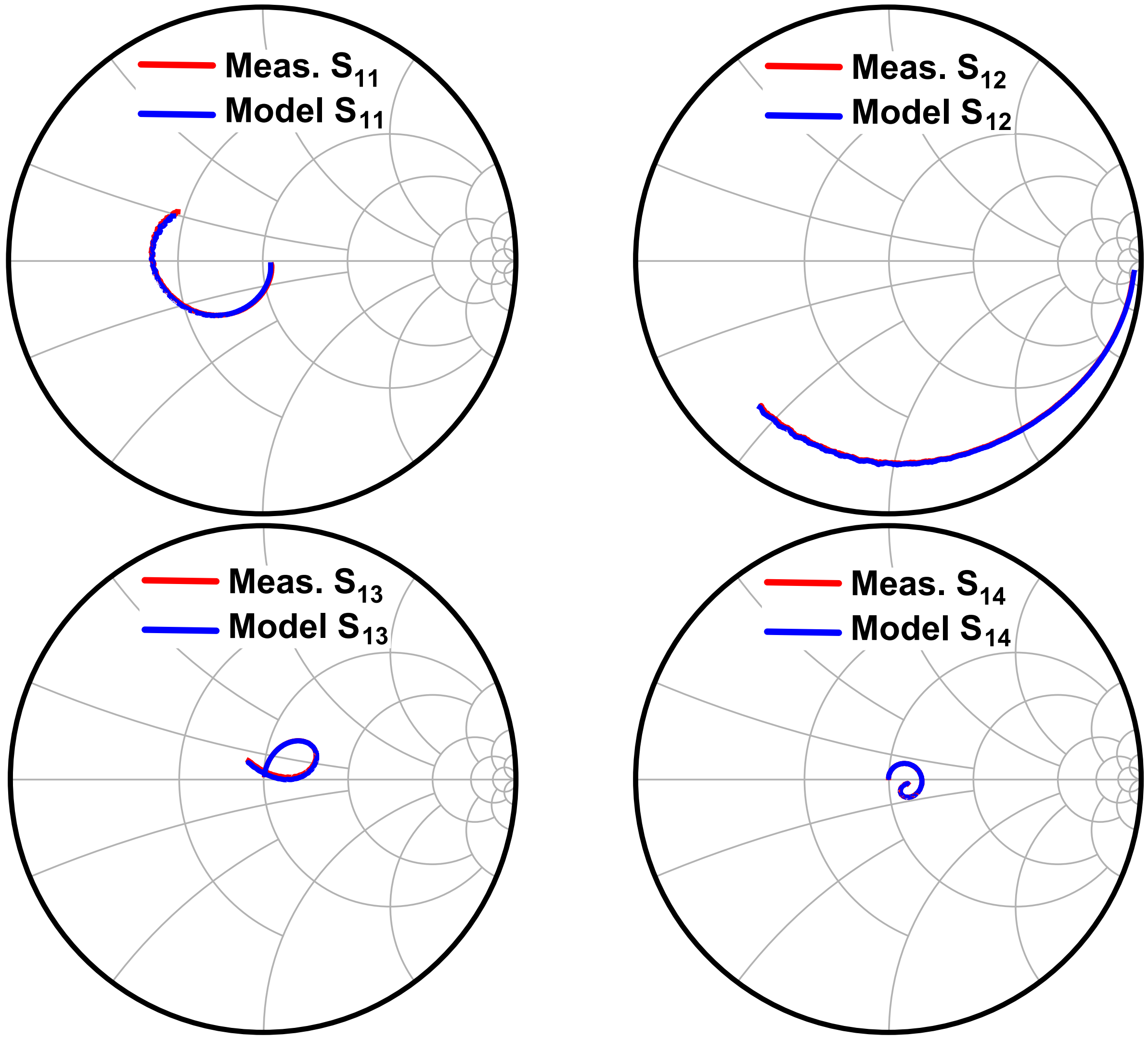


Verification of Cross-Line

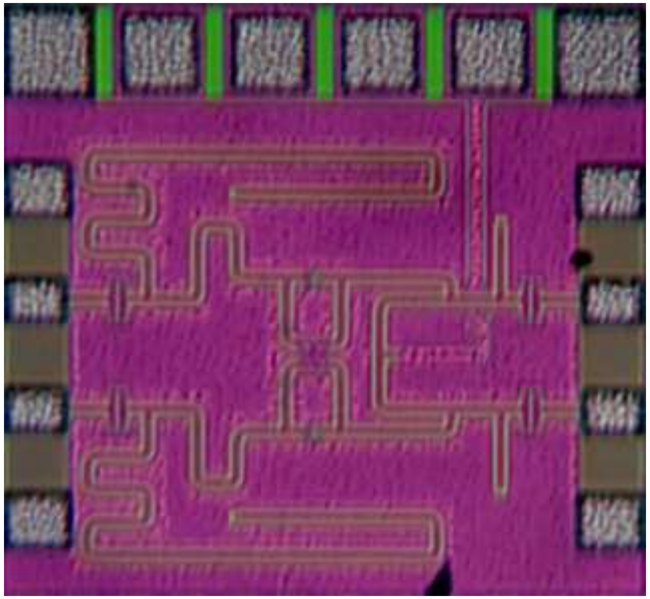
- Reconstruct the response of 8 repeated structure using:
  - Cross-line S-parameters
  - Fixture results
  - Pad results
- Comparison of model and measurement results are presented next

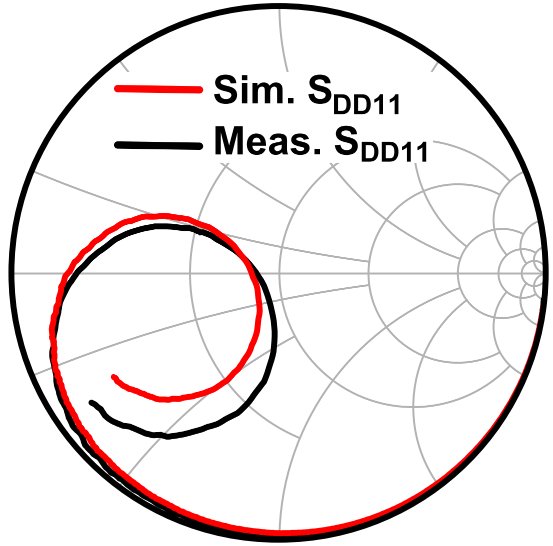
Results

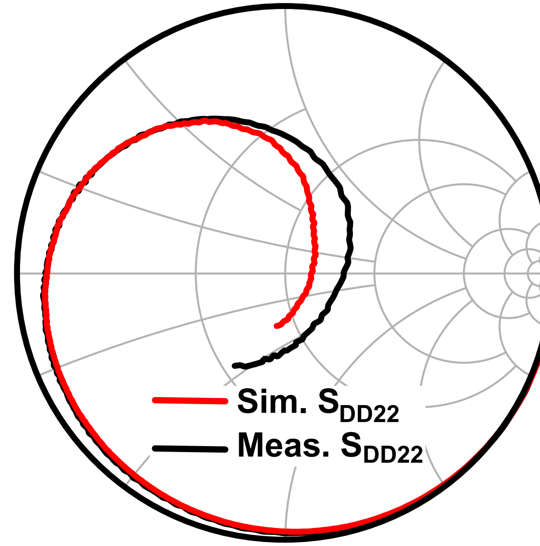
Model and Measurements agree well up to 67 GHz

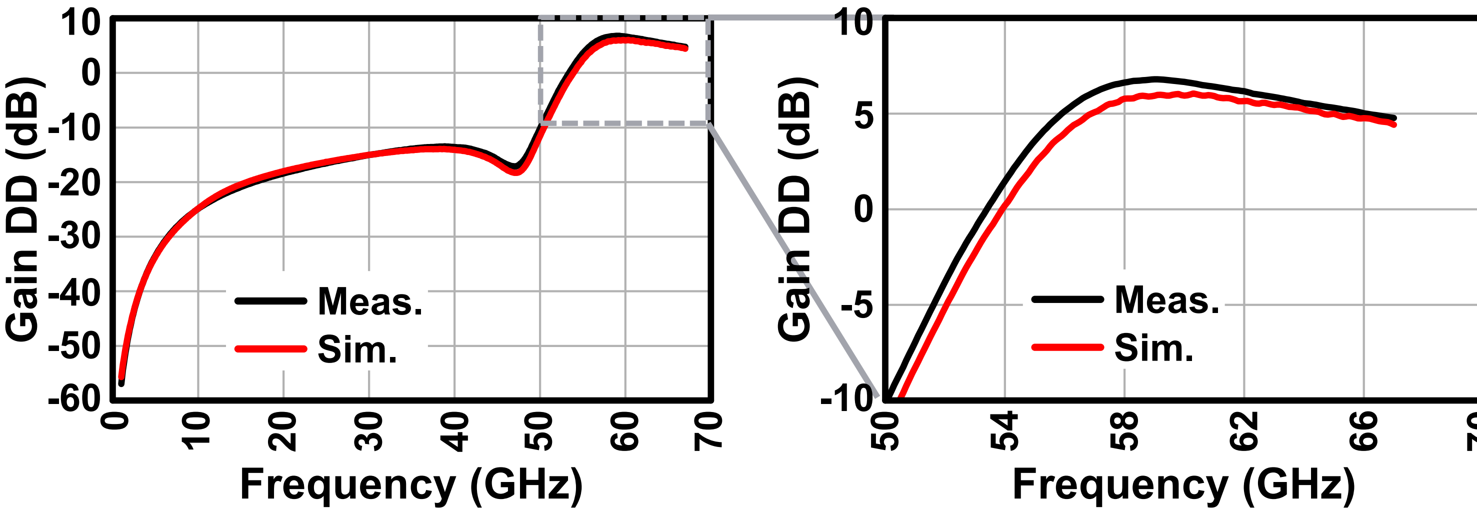


Application on Diff. Amp.









Conclusions

- An electrically symmetrical cross-line
  - Reduced amplitude and phase imbalance
- Characterization using two structures
- Mixed-mode S-parameters based calculations
  - Virtual-thru method for common and differential mode
- Model and measurement results for structure shows good agreement up to 67 GHz
- Amplifier model and measurements well-matched up to 67 GHz

Thank you very much for your attention!