From mm-Wave Measurement to Design: Measurement, De-embedding and Design

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Outline

- Purpose
- Transmission Media
- S-parameters
- Power
- Noise Figure
- De-embedding
- Design

Purpose

- Describe and Understand the Key Aspects of work at mmW frequencies

- mmW frequencies:
  - Working definitions tend to be ‘soft’
  - 1mm to 7.5mm(10mm)
    - (30) 40 GHz - 300 GHz

Outline

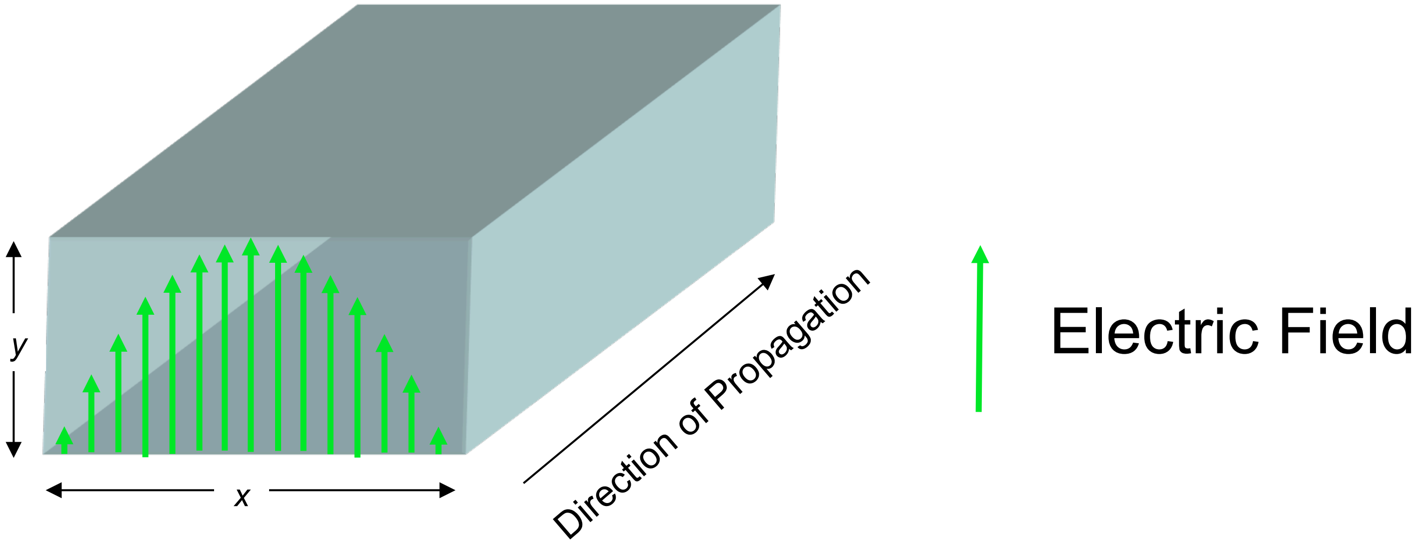
- **Transmission Media**
- Power
- Noise Figure
- S-parameters
- De-embedding
- Design

Transmission Media

- 3 types of signal transmission media are used in mmW applications.
  - Rectangular waveguide
  - Coaxial transmission-line
  - ‘Planar’ waveguide

Waveguide

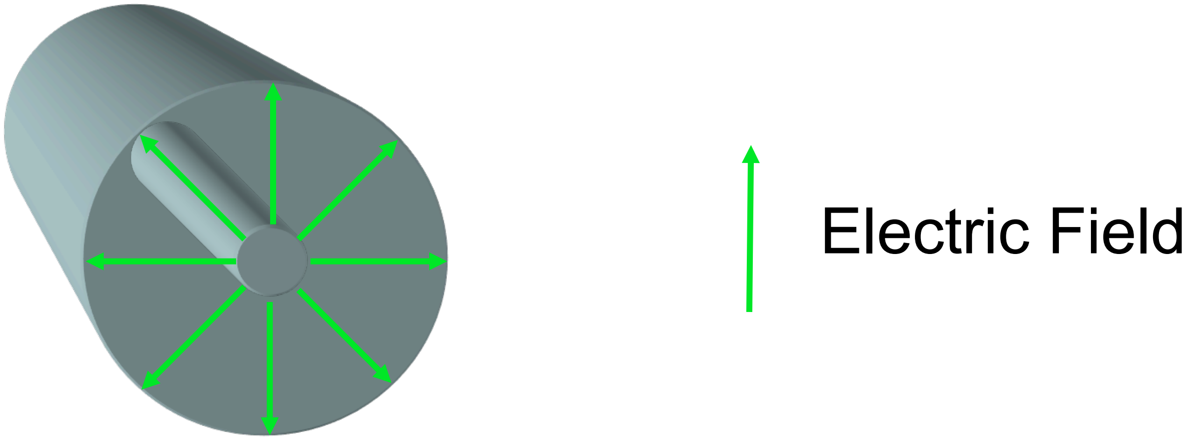
- Examples of Rectangular Waveguides and their cut-off frequencies
- Won't support DC, just TE- and TM-modes
- Dominant mode: TE_{01}



$$f_c = \frac{c}{2\pi}\sqrt{\left(\frac{n\pi}{x}\right)^2 + \left(\frac{m\pi}{y}\right)^2}$$

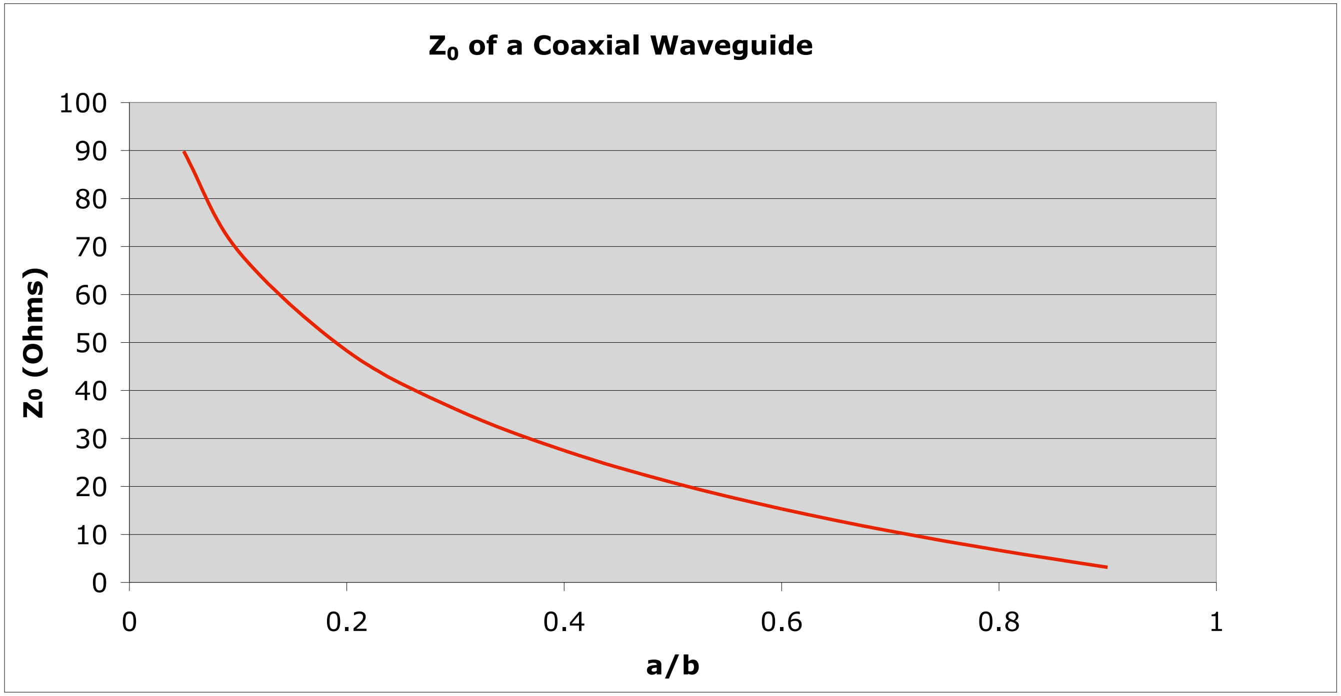
n, m are integers
c is velocity of propagation in free space

Coaxial Transmission-line



$$Z_0 = \frac{\ln\left(\frac{b}{a}\right)}{2\pi}\sqrt{\frac{\mu_r\mu_0}{\varepsilon_r\varepsilon_0}}$$

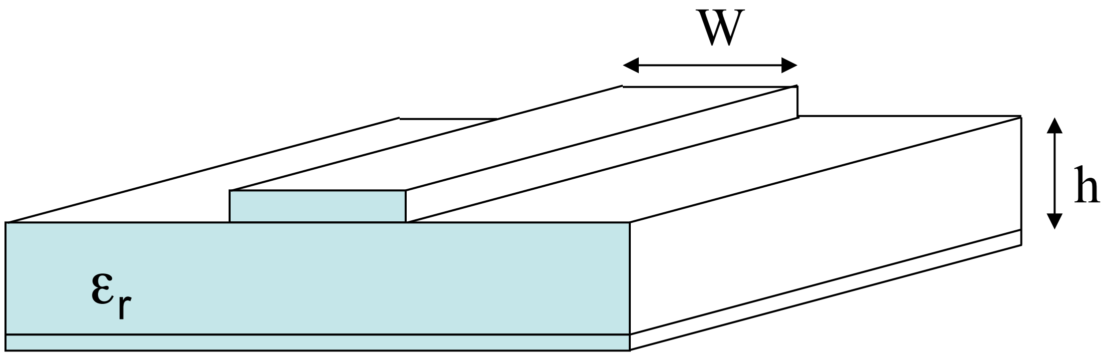
a=Inner radius
b=Outer radius



Planar Waveguide

- Consists of at least two conductors
- Three popular types:
  - Microstripline
  - Stripline
  - Coplanar Waveguide (C.P. Wen)

Microstripline



- Quasi-TEM (mixed dielectric)
- 2nd lowest loss
- Single ground plane
- Dispersive ($Z_0(f)$, $v_p(f)$)

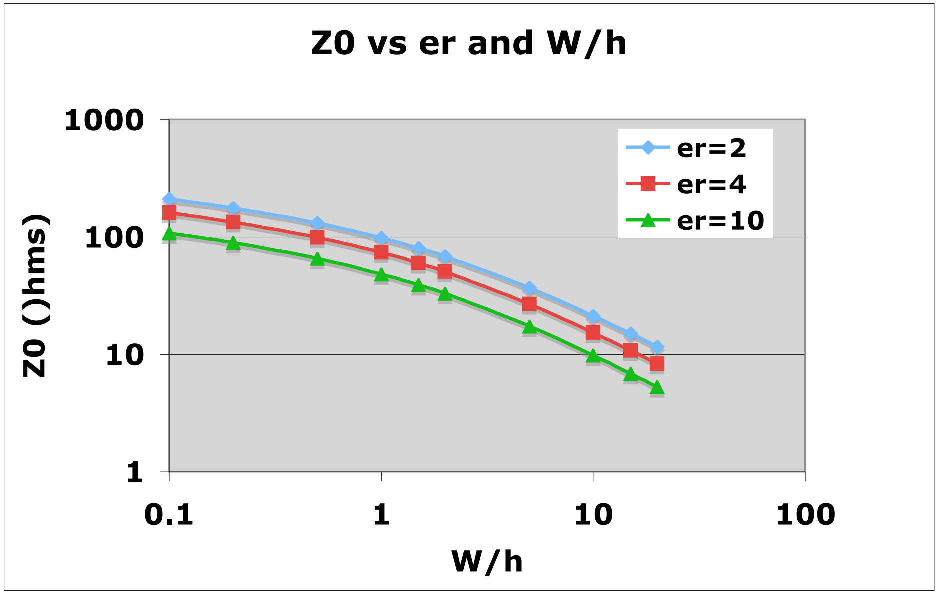
$$\frac{W}{h} \le 1$$

$$Z_0 = \frac{\eta}{2\pi\sqrt{\varepsilon_{re}}} \ln\left(\frac{8h}{W} + 0.25\frac{W}{h}\right)$$

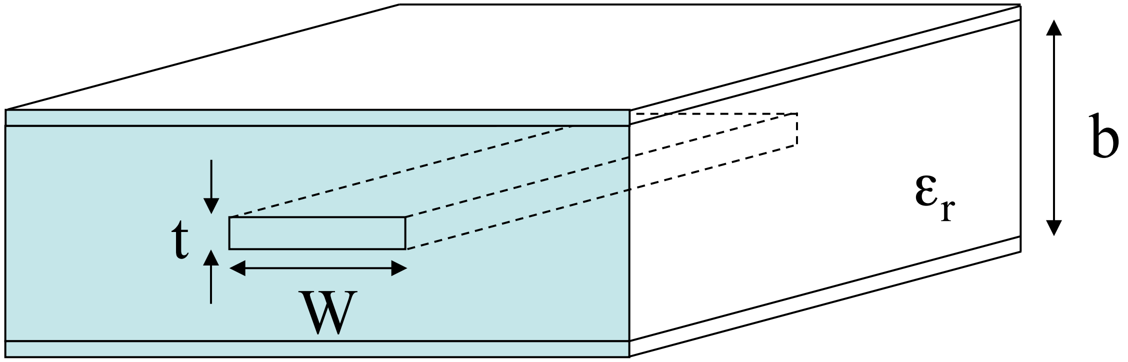
$$\frac{W}{h} \ge 1$$

$$Z_0 = \frac{\eta}{\sqrt{\varepsilon_{re}}}\left[\frac{W}{h} + 1.393 + 0.667\ln\left(\frac{W}{h} + 1.444\right)\right]^{-1}$$

$$\varepsilon_{re} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left(1 + 10\frac{h}{W}\right)^{-1/2}$$



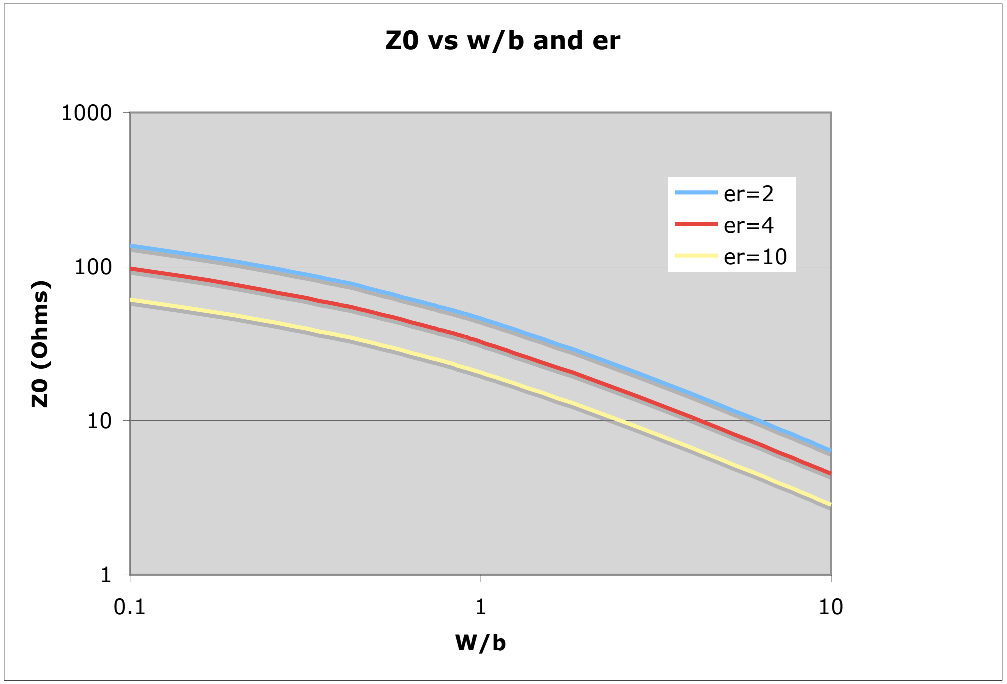
Stripline



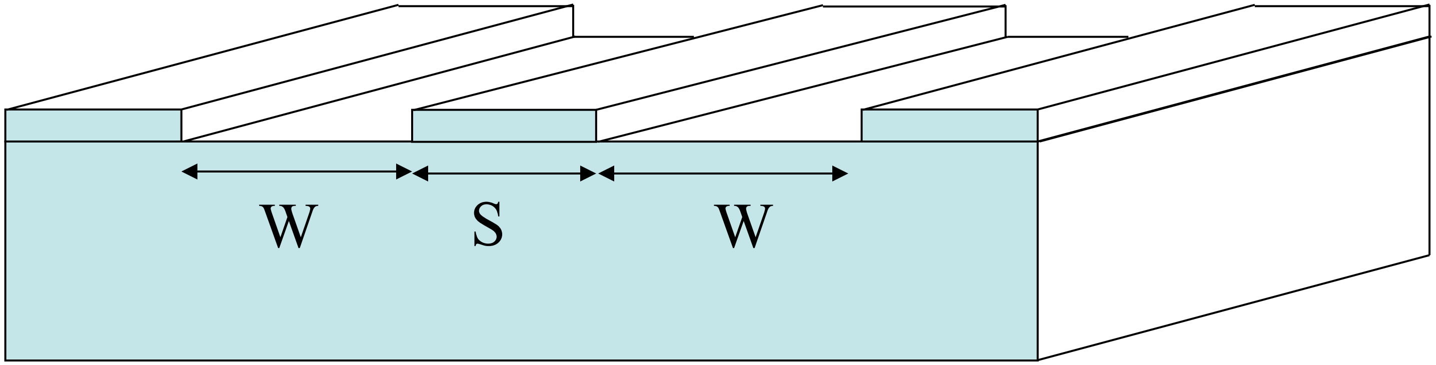
- TEM (uniform dielectric)
- Lowest loss
- Two ground planes
- ‘Non-dispersive’

$$Z_0 = \frac{30}{\sqrt{\varepsilon_r}} \ln\left[1 + \frac{4b}{\pi W}\left(\frac{8b}{\pi W} + \sqrt{\left(\frac{8b}{\pi W}\right)^2 + 6.27}\right)\right]$$

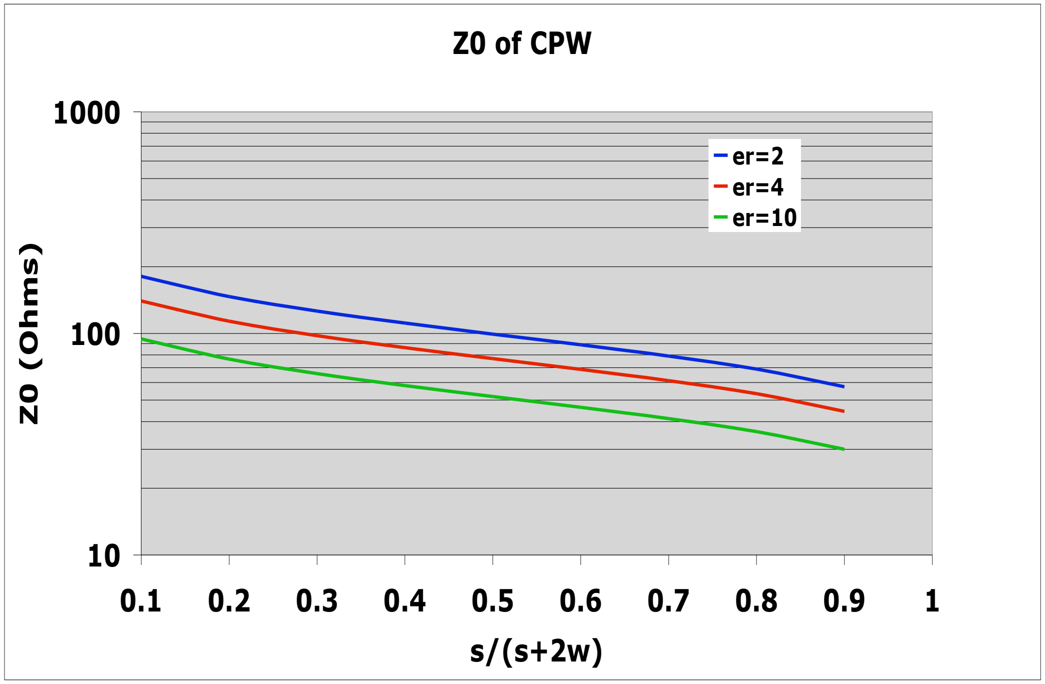
‘Thin’ strip approximation



Coplanar Waveguide



- Quasi-TEM (mixed dielectric)
- Highest loss
- Single split ground plane
- Dispersive ($Z_0(f)$, $v_p(f)$)



$$Z_0 = \frac{30\pi}{\sqrt{\varepsilon_{re}}}\left[\frac{1}{\pi}\ln\left(2\frac{1+\sqrt{k^{\prime}}}{1-\sqrt{k^{\prime}}}\right)\right]^{-1} \quad 0 \le k \le 0.7$$

$$Z_0 = \frac{30\pi}{\sqrt{\varepsilon_{re}}}\left[\frac{1}{\pi}\ln\left(2\frac{1+\sqrt{k}}{1-\sqrt{k}}\right)\right] \quad 0.7 \le k \le 1$$

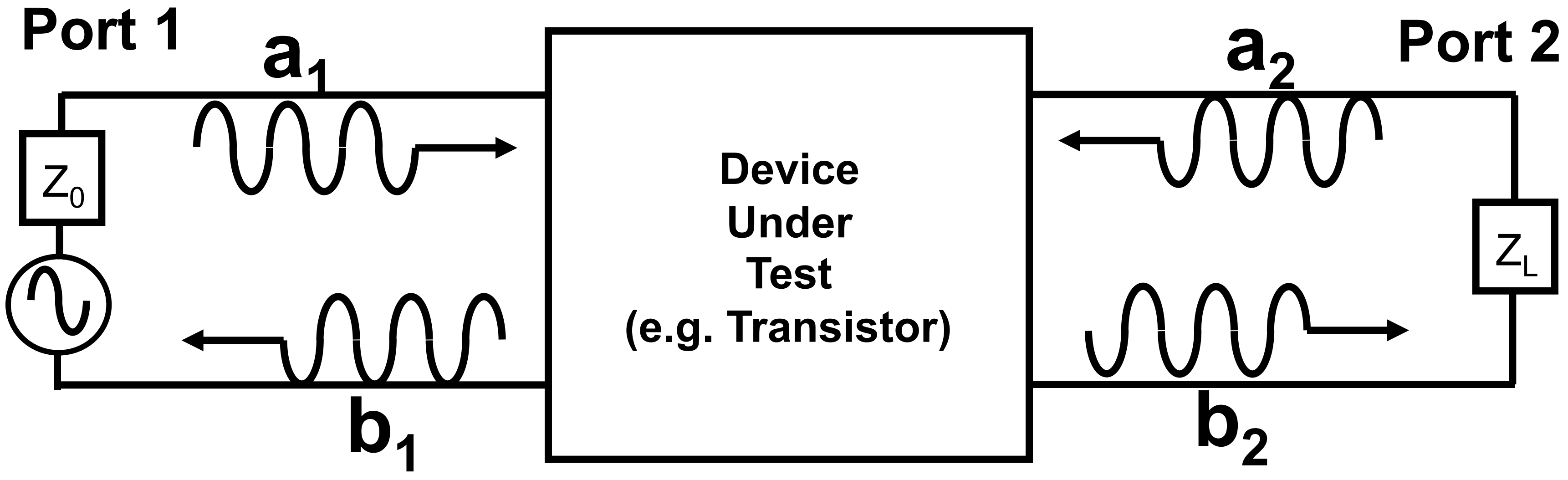
$$k^{\prime} = \sqrt{1-k^2} \qquad k = \frac{S}{S+2W}$$

$$\varepsilon_{re} = \frac{\varepsilon_r + 1}{2}\left[\tanh\left(1.785\log\left(\frac{h}{W}\right)+1.75\right) + \frac{kW}{h}\left(0.04 - 0.7k + 0.01(1-0.1\varepsilon_r)(0.25+k)\right)\right]$$

S-Parameters

- Technical name: Scattering Parameters
  - 2 port network description
    - Can be applied to n-ports
  - Other network parameters not suitable for microwave frequencies
    - Can’t build high quality short circuits and open circuits
- Workhorse of the mmW industry
- Used for:
  - Design
  - Modeling
  - Assess performance through Figures of Merit

S-Parameters: A Little Bit of Theory



- **a_1 and a_2 are the waves into Ports 1 and 2**
- **b_1 and b_2 are the waves out of Ports 1 and 2**
- **b_1 is due to transmission of a_2 and the reflection of a_1**
- **b_2 is due to transmission of a_1 and the reflection of a_2**

S-Parameters: Interpretation of a_1, a_2, b_1 and b_2

- Power Definitions:

$$P_{in,Port1} = \tfrac{1}{2}\left|a_1\right|^2$$

$$P_{in,Port2} = \tfrac{1}{2}\left|a_2\right|^2$$

$$P_{out,Port1} = \tfrac{1}{2}\left|b_1\right|^2$$

$$P_{out,Port2} = \tfrac{1}{2}\left|b_2\right|^2$$

- Formal Definition:

$$S_{11} = \frac{b_1}{a_1}\bigg|_{a_2 \equiv 0} \qquad S_{12} = \frac{b_1}{a_2}\bigg|_{a_1 \equiv 0}$$

$$S_{21} = \frac{b_2}{a_1}\bigg|_{a_2 \equiv 0} \qquad S_{22} = \frac{b_2}{a_2}\bigg|_{a_1 \equiv 0}$$

S_{11} - Input reflection coefficient
S_{22} - Output reflection coefficient
S_{12} – Reverse Isolation / Gain
S_{21} – Forward Gain / Isolation

Smith Chart Properties

- A Smith Chart is a convenient way to simultaneously display:
  - Reflection coefficients: S_{11} and S_{22}
  - Impedances
  - Admittances
- ‘Inside’ Smith Chart

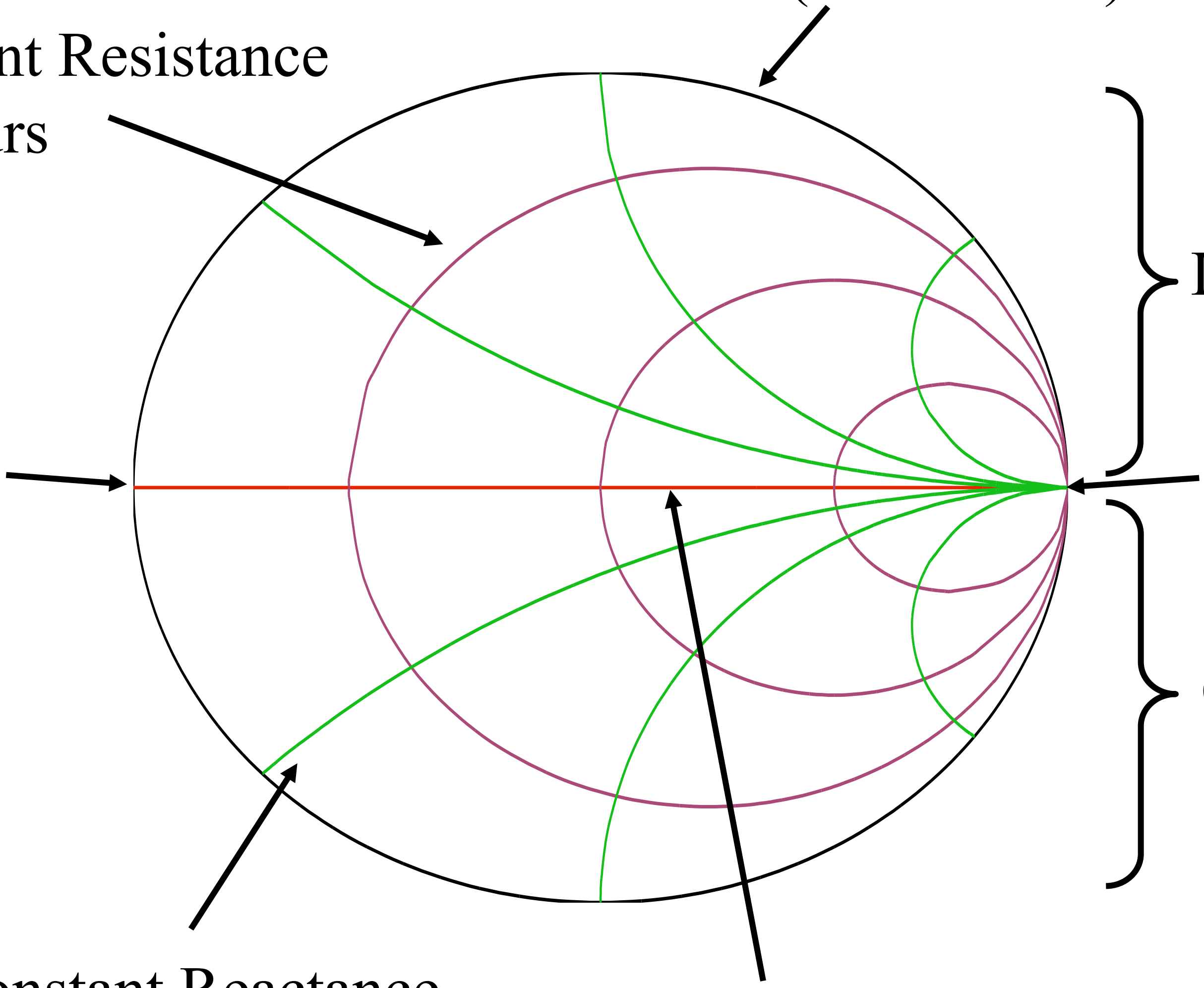
  ⇒ Positive Resistance Region

  ⇒ Contains all passive impedances
- ‘Outside’ Smith Chart

  ⇒ Negative Resistance Region

  ⇒ Unstable active devices

Displaying and Interpreting S_{11} and S_{22}



R=0 (Z≡Reactive)

Constant Resistance
Contours

Inductive

Short

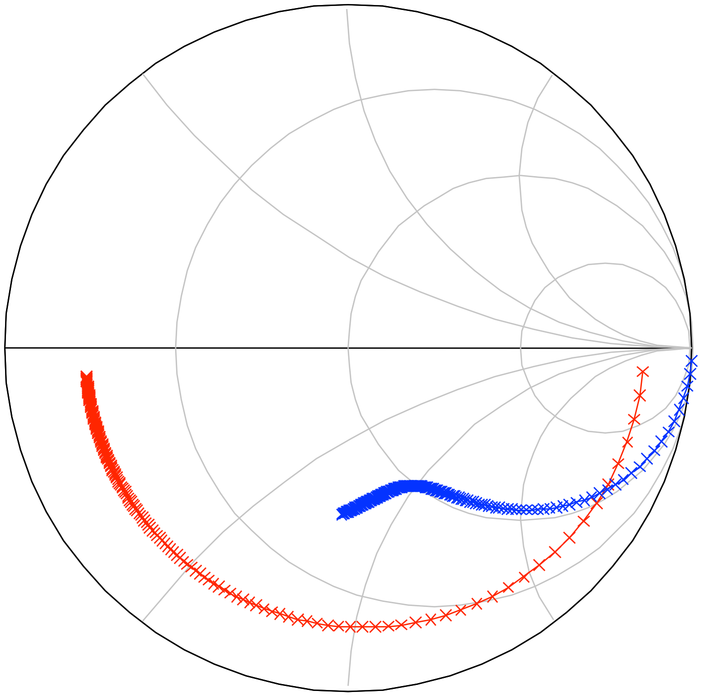
Open

Capacitive

Constant Reactance
Contours

X=0 (Z≡Resistive)

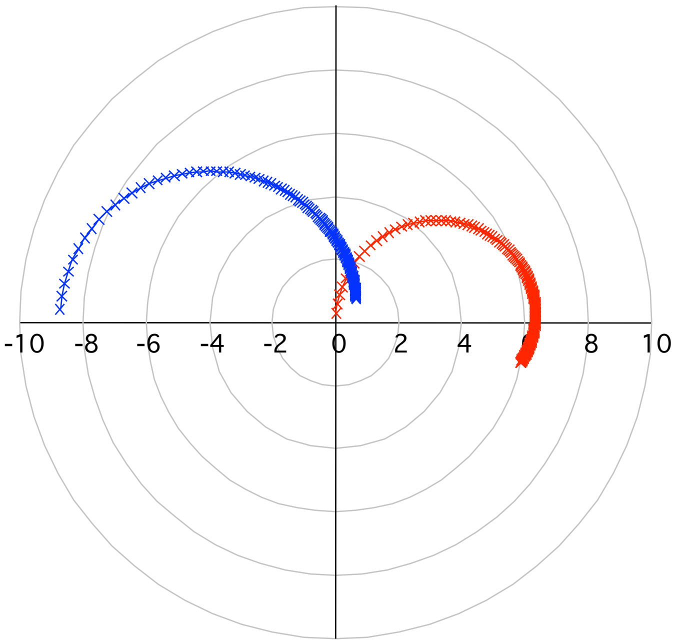
Sample S_{11} and S_{22} Results of an HBT



S_{11}
S_{22}

- $|S_{11}|$ and $|S_{22}| \leq 1$
- S_{11} and S_{22} indicate RC impedances.
- S_{22} demonstrates series RC behavior at low frequencies.
- Impedance levels range from nearly open to ‘low’ as frequency varies from low to high.
- S_{11} and S_{22} are smooth and continuous.

Sample S_{12} and S_{21} Results of an HBT



50*S_{12}

S_{21}

- S_{12} and S_{21} are presented on a polar plot
- $S_{21} > S_{12}$
- Phase shift in S_{21} can be quite large
- S_{12} can be difficult to measure due to its magnitude
  - Demands careful calibration

S-Parameters: Gain

- Numerous Gain definitions exist
- Each definition has specific applications

Transducer Gain (G_T)- Most General

Unilateral Gain (G_U) - Device

Power Gain (G_P) - Power Amp Design

Max. Stable Gain (G_{MS}) - Device

Available Gain (G_{AV})- Device, LNA

Power

- Definition
- Fundamental Issues with absolute measurements
- Classic Figures of Merit Related to Power
- Loadpull

Power: Basics

- Power = Rate of Doing Work = Joules*Sec^{-1}
- Units of Power= Watts (W)

$$P(W) = \frac{1}{T}\int_0^T e(t)i(t)dt$$

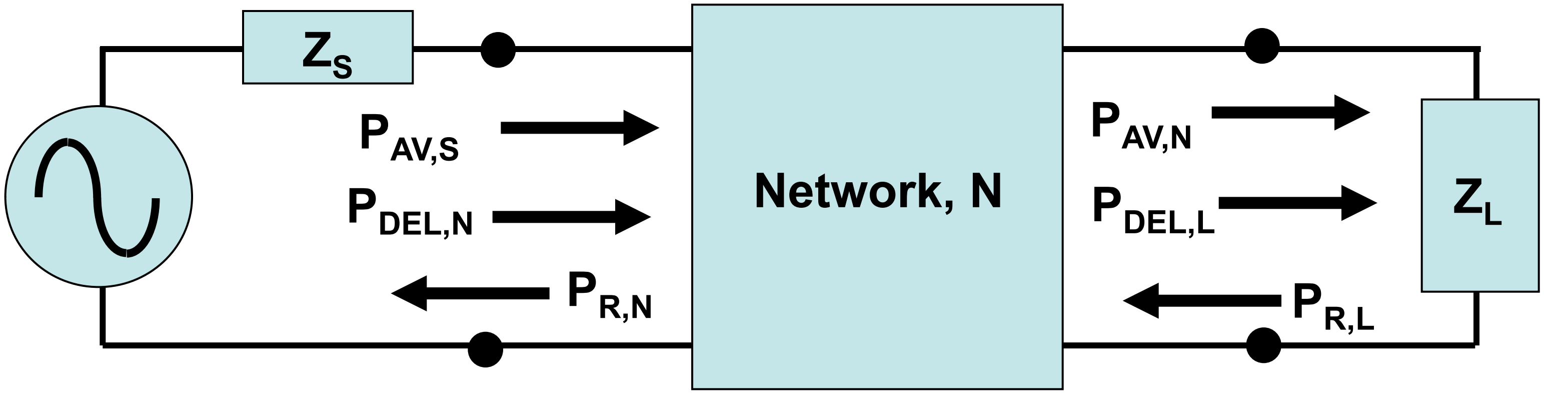
- Scalar quantity
- Range of power spans many orders of magintude
  - Define a new unit
- Typically report power in units of dBm:

$$P(dBm) = 10 * \log\left(\frac{P(W)}{0.001}\right)$$

Power Measurement at mmW Frequencies

- Can’t measure current and voltage at mmW frequencies
- Must measure power directly
- Two approaches:
  - Diode detector
    - Rectify the input signal and measure the resulting DC
  - Thermocouple
    - Absorbs the incident power
- Both types need to be carefully calibrated over frequency and power.
- Calibration needs to be done with reference standards that can be traced back to a precisely characterized reference
  - E.g. in the U.S.A., NIST provides reference standards
- National labs will carry out round-robin comparison tests.

Classical Figures of Merit: Power



- $P_{AV,S(N)}$: **Power available from the source (network)**
- $P_{DEL,N(L)}$: **Power delivered to the network (load)**
- $P_{R,N(L)}$: **Power reflected from the network (load)**
- $P_{DEL,N(L)} = P_{AV,S(N)} - P_{R,N(L)}$

Classical Figures of Merit: Gain

- **Numerous gain definitions exist**
- **Two gain definitions are relevant to large signal RF applications**
- **Transducer Gain, G_T:**

$$G_T = \frac{P_{DEL,L}}{P_{AV,S}}$$

- **Power Gain, G_P:**

$$G_P = \frac{P_{DEL,L}}{P_{DEL,N}}$$

- **$G_P \geq G_T$**

Classical Figures of Merit: Efficiency

- **Two common efficiency definitions exist**

- **Collector Efficiency, η_C:**

$$\eta_C = \frac{P_{DEL,L}}{I_C * V_C} \times 100$$

- **Power Added Efficiency, PAE:**

$$PAE(\%) = \frac{P_{DEL,L} - P_{DEL,N}}{V_C * I_C + V_B * I_B} \times 100$$

LoadPull

- The methodology for systematically determining the performance of a transistor under large signal operation.

- This methodology systematically varies the source and load terminations and records the response to various levels and types of excitation.

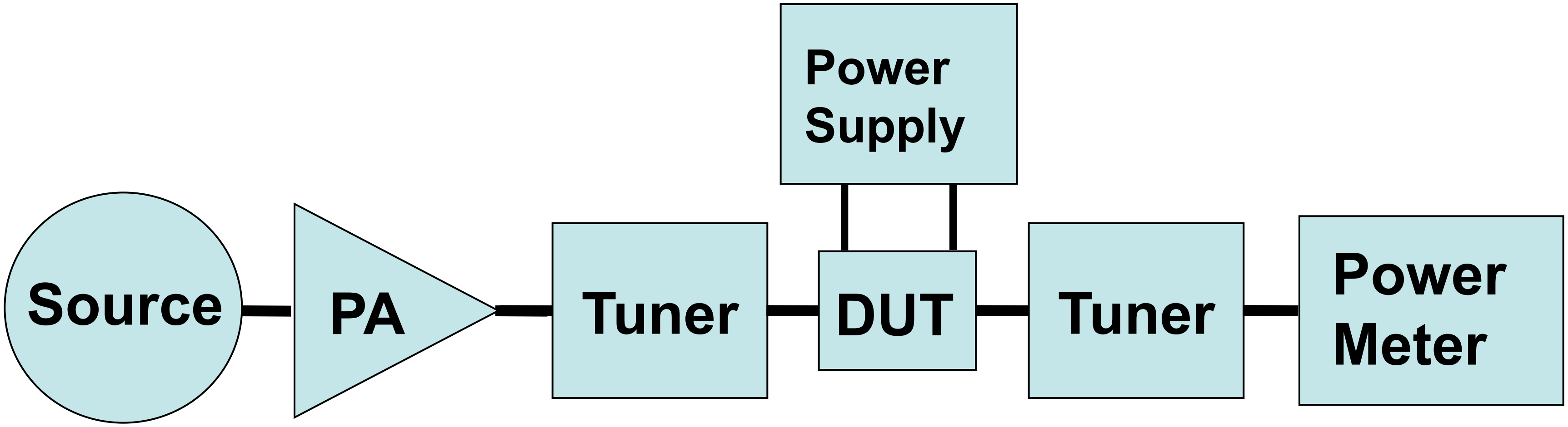
LoadPull

- There are 2 categories of loadpull:
  - Passive loadpull
  - Active loadpull

- Passive Loadpull synthesizes impedances using transmission lines with controlled discontinuities

- Active Loadpull synthesizes impedances by electronically generating ‘Reflected Waves’ which are injected into the signal path

Basic Load Pull System



- Basic system measures power, gain and collector efficiency of ‘small’ devices
- Tuner varies the impedance seen at the terminal of the DUT

mmW Application of Loadpull

- Silicon transistors have found their way into W-band circuit applications.

- Applications include power amplifiers.

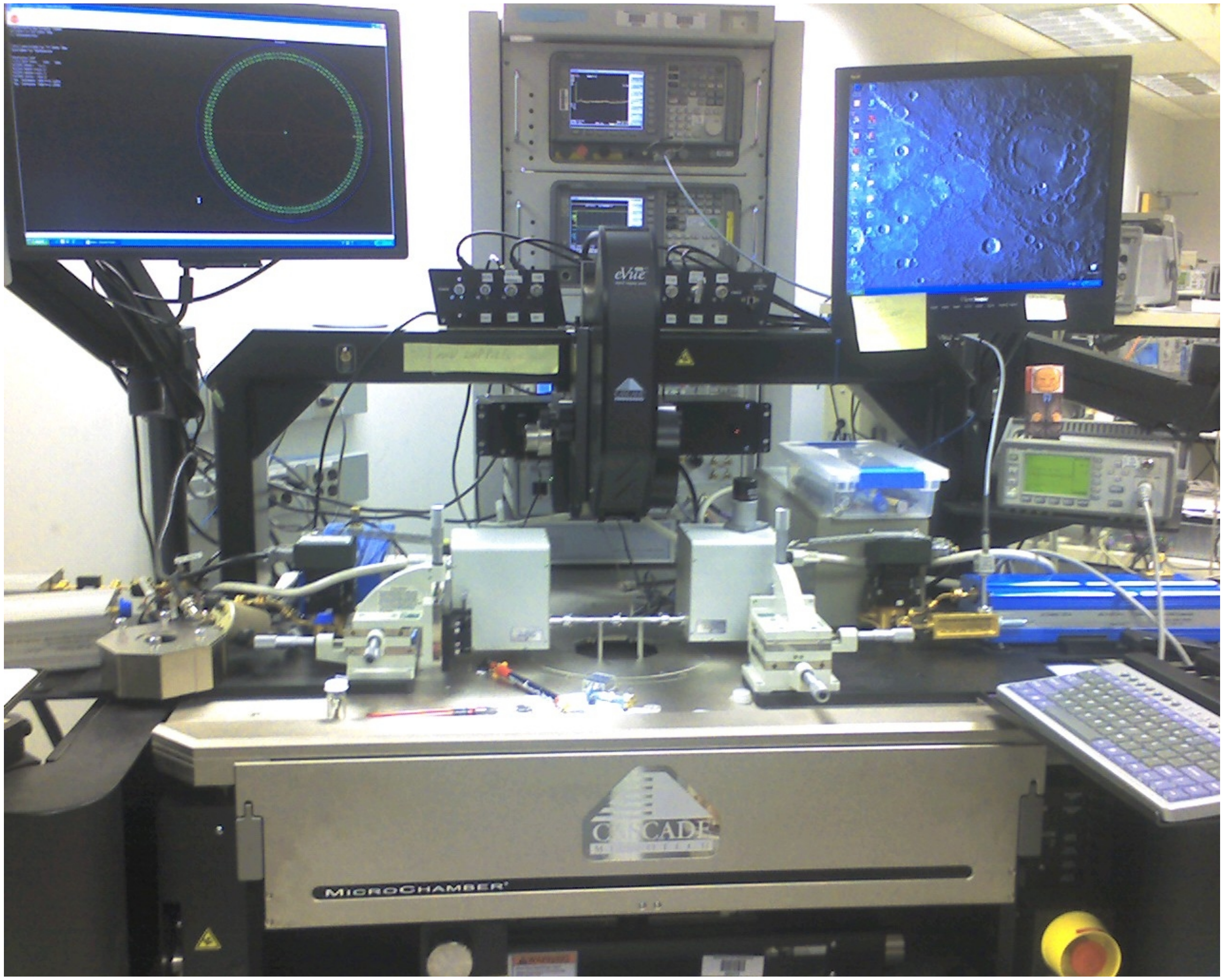
- Validation to DC and S-parameter data is not sufficient.

- Need to verify with large signal data.

SiGe HBT Technology

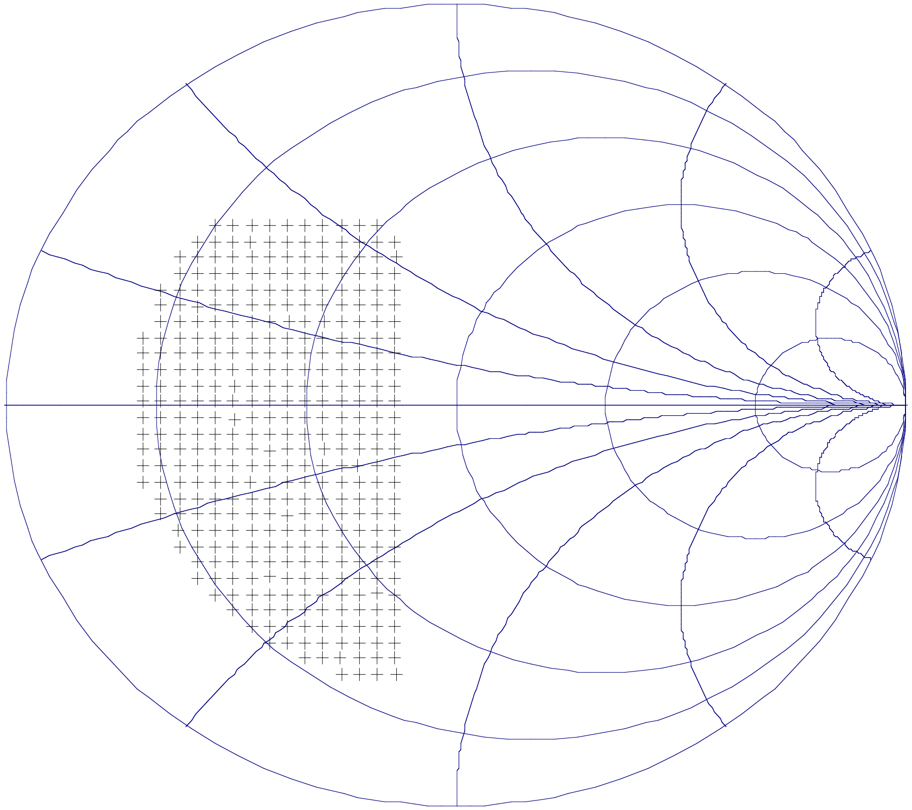
- Freescale 0.18μm SiGe:C BiCMOS process
- f_T = 200 GHz
- F_{max} = 300 GHz
- HBT module developed for 77 GHz applications
- Numerous mmW circuits have been realized using this technology.

mmW On-Wafer Load Pull System



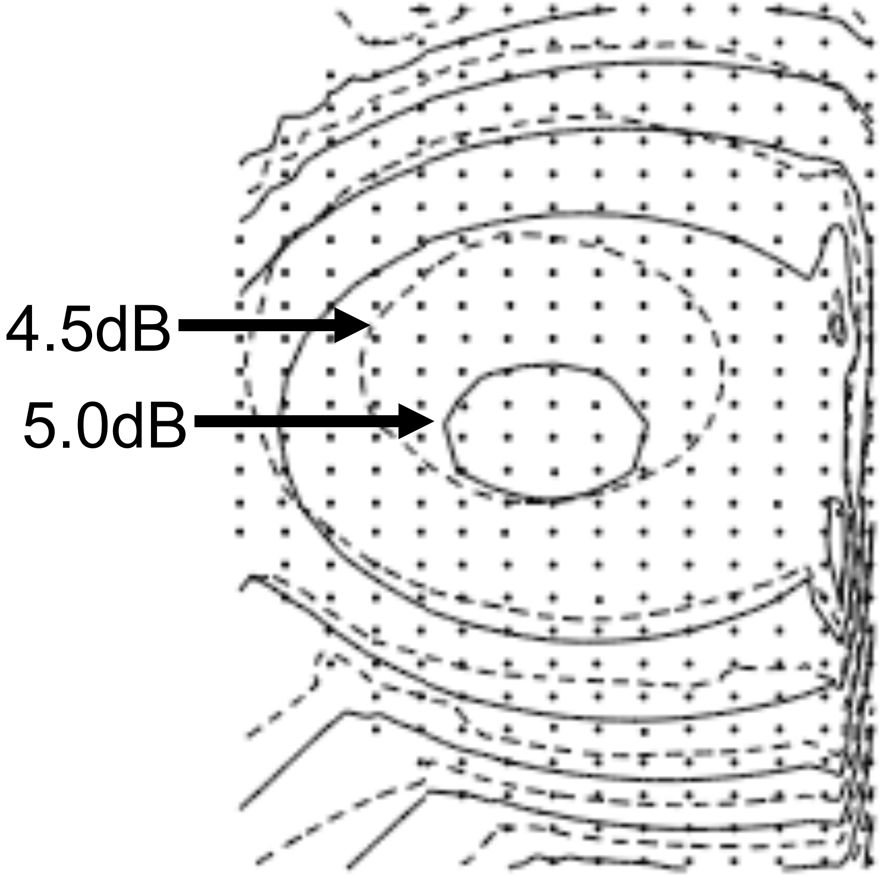
- Electromechanical tuner based load pull system

Comparison of Measured and Modeled Data



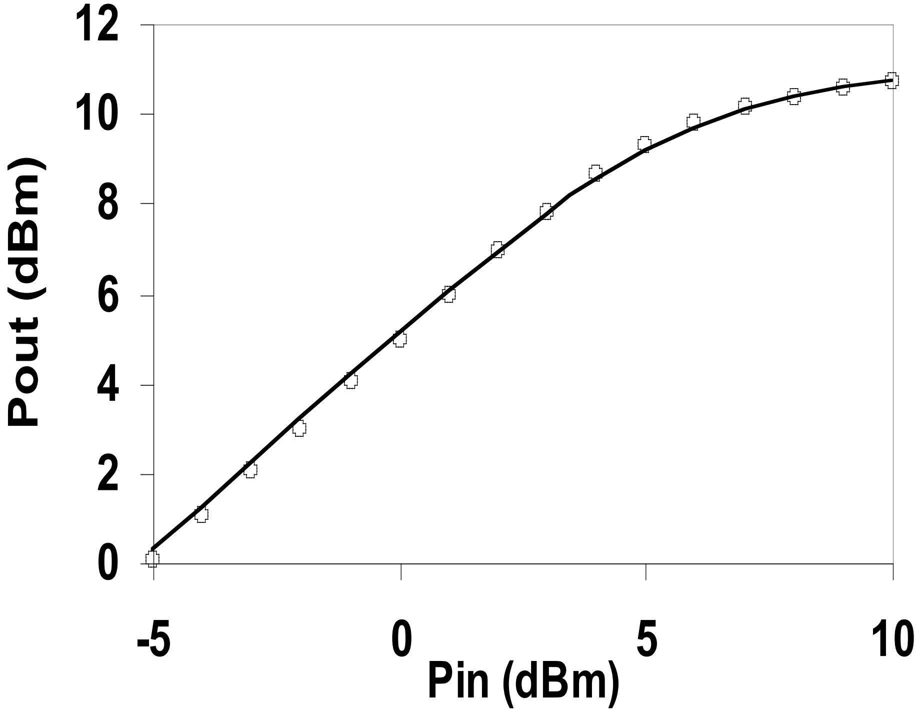
- 2 and 3 emitter HBT’s were load pulled at 367 different load states
- Pin=+7dBm
- Gain contours were generated

Comparison of Measured and Modeled Data



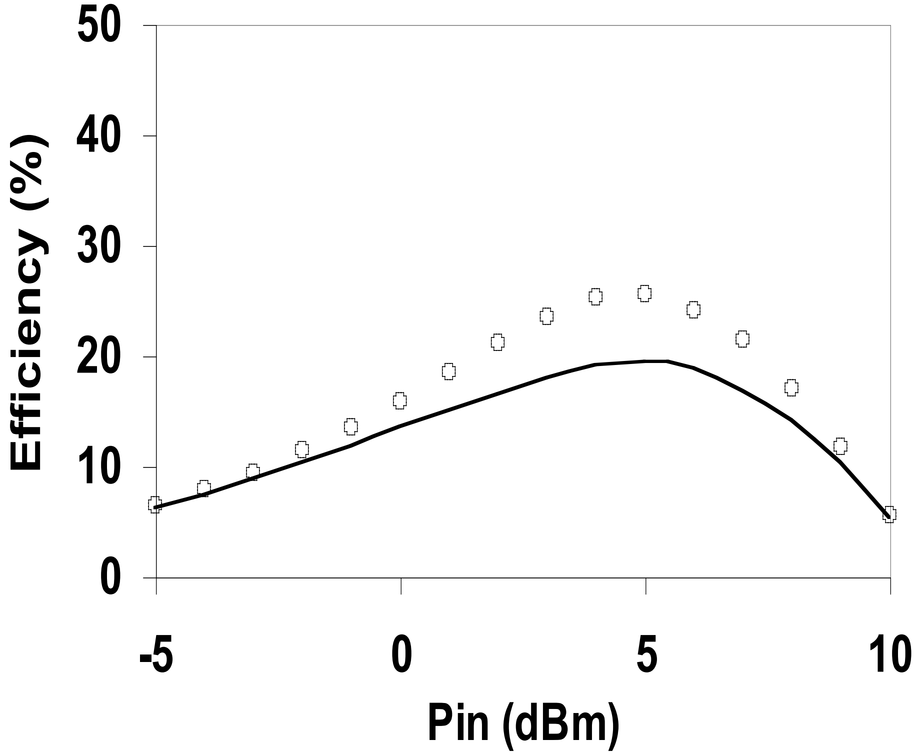
- Modeled Contours – Solid
- Measured Contours - Dash
- Measured $\Gamma_{L,OPT}=0.42\angle 179^\circ$
- Modeled $\Gamma_{L,OPT}=0.42\angle 170^\circ$
- Slight phase difference

Comparison of Measured and Modeled Data



- V_{CE}=1.5V and VBE=0.84V.
- 1 emitter, 0.6um x20.4um
- Common-emitter configuration
- Maximum P_{out} tuning.
- P_{out} results are within 0.3 dB
- Increasing VBE from 0.84V to 0.88V, the gain difference increased to 0.5dB.
- Maximum power difference is less than 0.5dB.

Comparison of Measured and Modeled Data



- V_{CE}=1.5V and VBE=0.84V.
- 1 emitter, 0.6um x20.4um
- Common-emitter configuration
- Maximum P_{out} tuning.
- Measured and modeled results are within 7 percentage points
- Results demonstrate the peak efficiency occurs at the same input power level, 5dBm.

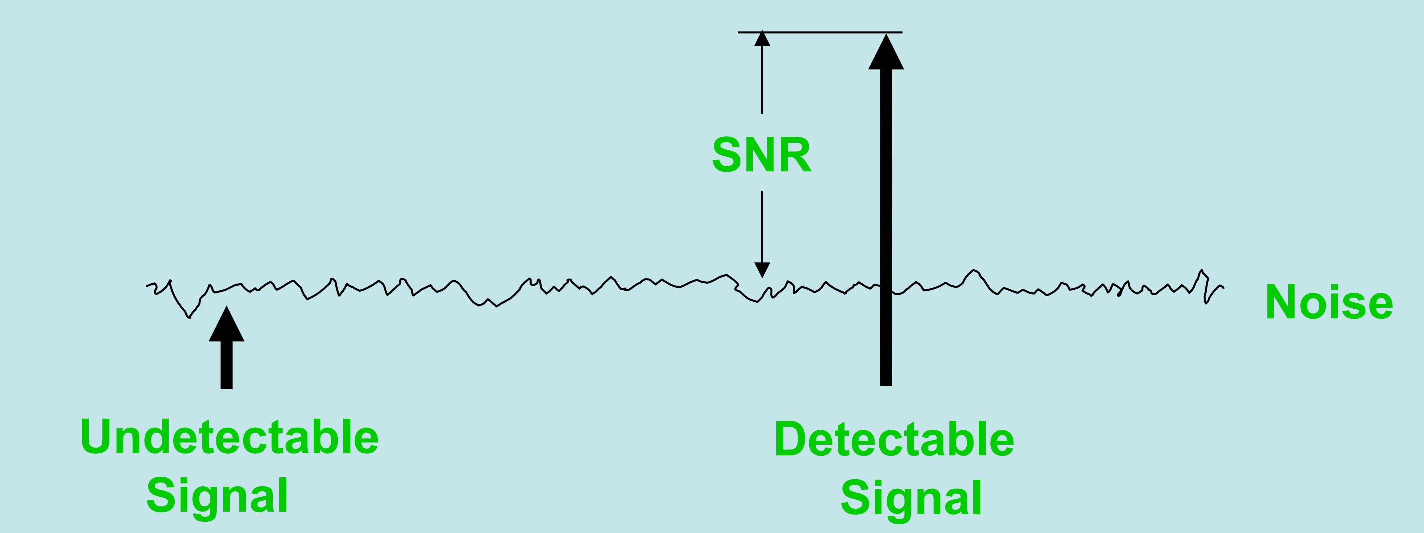
Noise

- Why worry about noise?
- What are noise parameters?
- Why are they used?
- How are they measured?

Why Worry About Noise?

- Noise sets the limit to the smallest signal that can be resolved by a receiver

  ⇒ Need to maximize S/N



- Need to be able to predict noise contribution of circuit components
- How do we predict noise contribution of devices?

  ⇒ Noise Parameters

Noise Factor, F and Noise Figure, NF

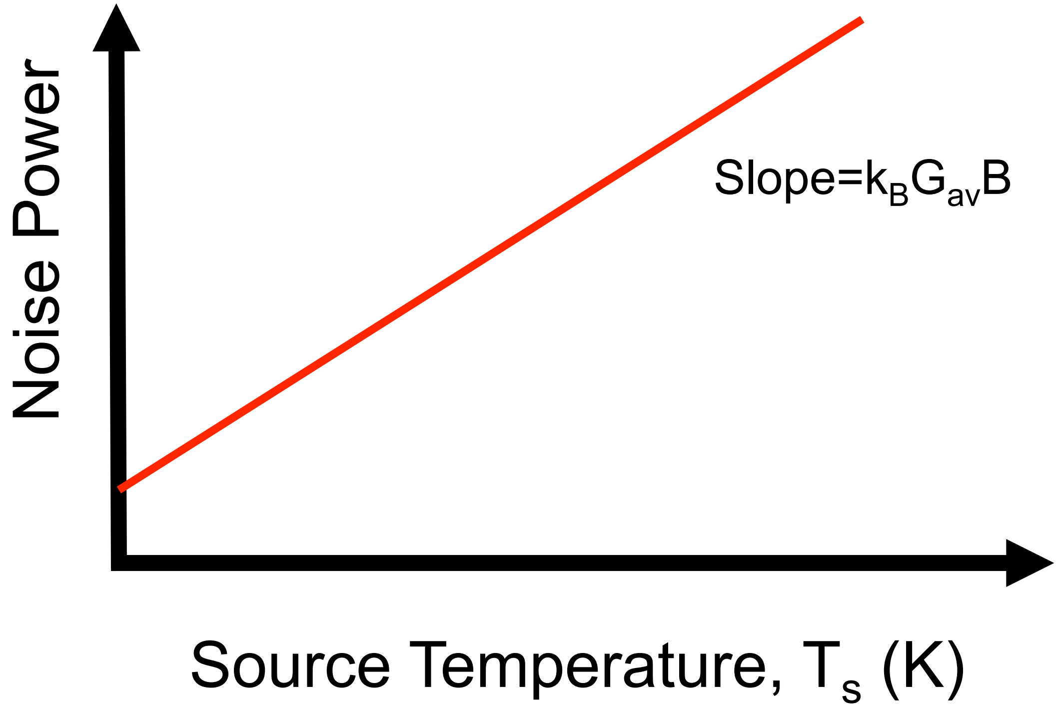
- In microwave applications, noise performance is described by the noise factor, F

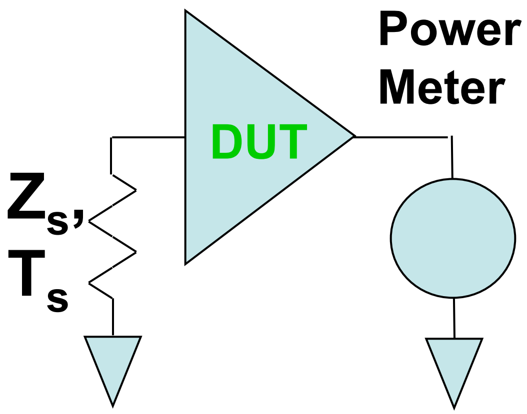
$$F = \frac{InputSNR}{OutputSNR} = \frac{\dfrac{S_i}{N_i}}{\dfrac{S_O}{N_O}} = \frac{\mathrm{S_i}\left(G_a N_i + G_a N_e\right)}{G_a S_i N_i} = 1 + \frac{N_E}{N_i} \geq 1$$

G_a: Available Gain;
N_i: Noise Power at the Input;
N_E: Noise contributed by DUT

- Noise Figure is the more common measure:
  - Noise Figure = $10\log_{10}(F)$

Basic Measurement of F



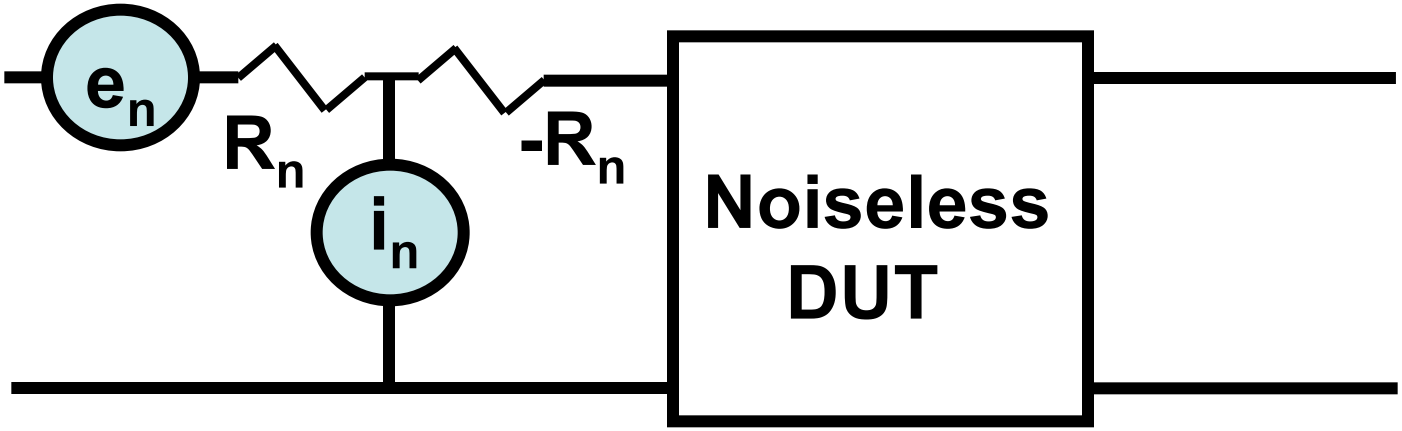


- Vary T_s
- Plot the measured noise power, N_1
- Determine the y-intercept, N_a

$$N_a = \frac{N_1}{k_B G_a B T_1} \qquad F = 1 + \frac{N_a}{N_i}$$

Noise Equivalent Circuit

- Numerous noise equivalent circuits exist.
- For our case:



- All noise related elements are ‘located’ at the input of the DUT
  - e_n: Equivalent Input Noise Voltage ($V/Hz^{0.5}$)
  - i_n: Equivalent Input Noise Current ($A/Hz^{0.5}$)
  - R_n: Correlation Resistance (Ohms)

Noise Factor, F

- Using the definition for F and the noise equivalent circuit we get the well known expression for the noise factor:

$$F = F_{\min} + \frac{4R_n}{Z_0}\left(\frac{\left|\Gamma_{opt} - \Gamma_s\right|}{\left|1 + \Gamma_{opt}\right|\left(1 - \left|\Gamma_s\right|\right)}\right)$$

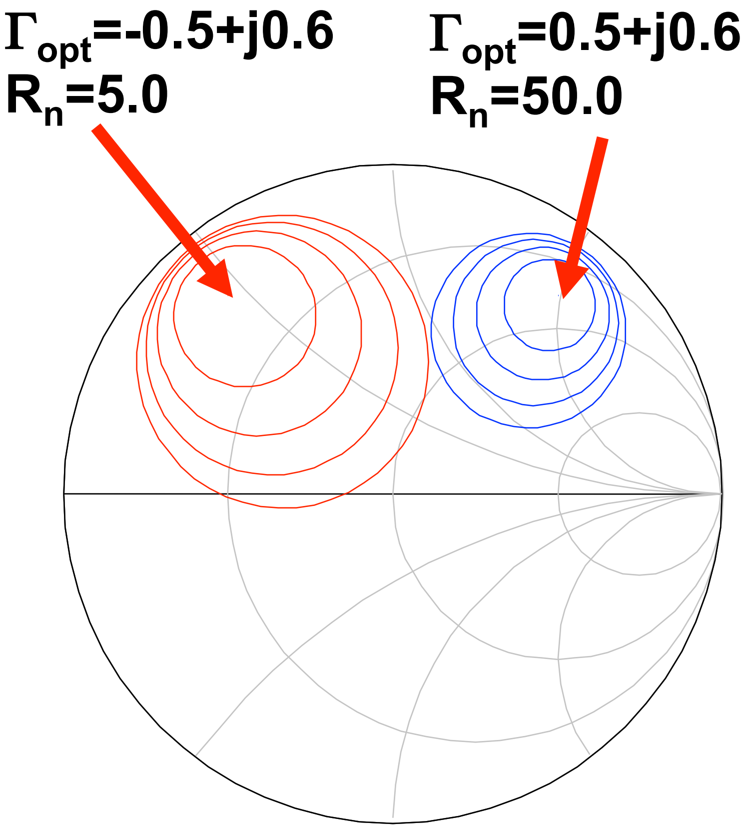
  - F_{min}: minimum noise factor
  - R_n: Noise resistance
  - Γ_{opt}: Optimum source reflection coefficient
  - Γ_s: Source reflection coefficient
  - Z_0: Reference impedance (usually, 50Ω)

Interpretation of Noise Parameters

- F_{min}: minimum noise factor
  - Minimum achievable noise factor for the device of interest
  - $F_{min} > 1$
- R_n: Noise resistance
  - Correlation resistance from the noise equivalent circuit
  - Sensitivity to the source mismatch
  - $R_n > 0$
- Γ_{opt}: Optimum source reflection coefficient
  - Optimum source admittance required to achieve the minimum noise factor, F_{min}
  - $|\Gamma_{opt}| < 1$

$$F = F_{\min} + \frac{4R_n}{Z_0}\left(\frac{\left|\Gamma_{opt} - \Gamma_s\right|}{\left|1+\Gamma_{opt}\right|\left(1-\left|\Gamma_s\right|\right)}\right)$$

Noise Contours



- Noise contours show which Γ_s provide a prescribed noise figure.
- Shows how Γ_s impacts device noise
- Noise contours show the noise parameters impact noise performance

Experimental Determination of Noise Parameters

- F is dependent on Γ_s

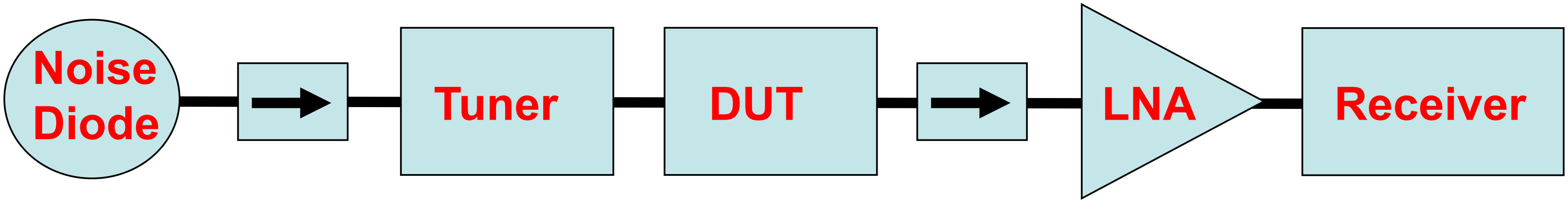
⇒ Measure F for a series of different Γ_s

⇒ Determine F_{min}, R_n and Y_{OPT} using least squares fitting

$$F = F_{\min} + \frac{4R_n}{Z_0}\left(\frac{\left|\Gamma_{opt} - \Gamma_s\right|}{\left|1+\Gamma_{opt}\right|\left(1-\left|\Gamma_s\right|\right)}\right)$$

Direct Noise Power Measurement

- Originally proposed by Adamian & Uhlir
- Uses diode noise source for calibration only
- F determined from noise power measurements with the noise diode turned off



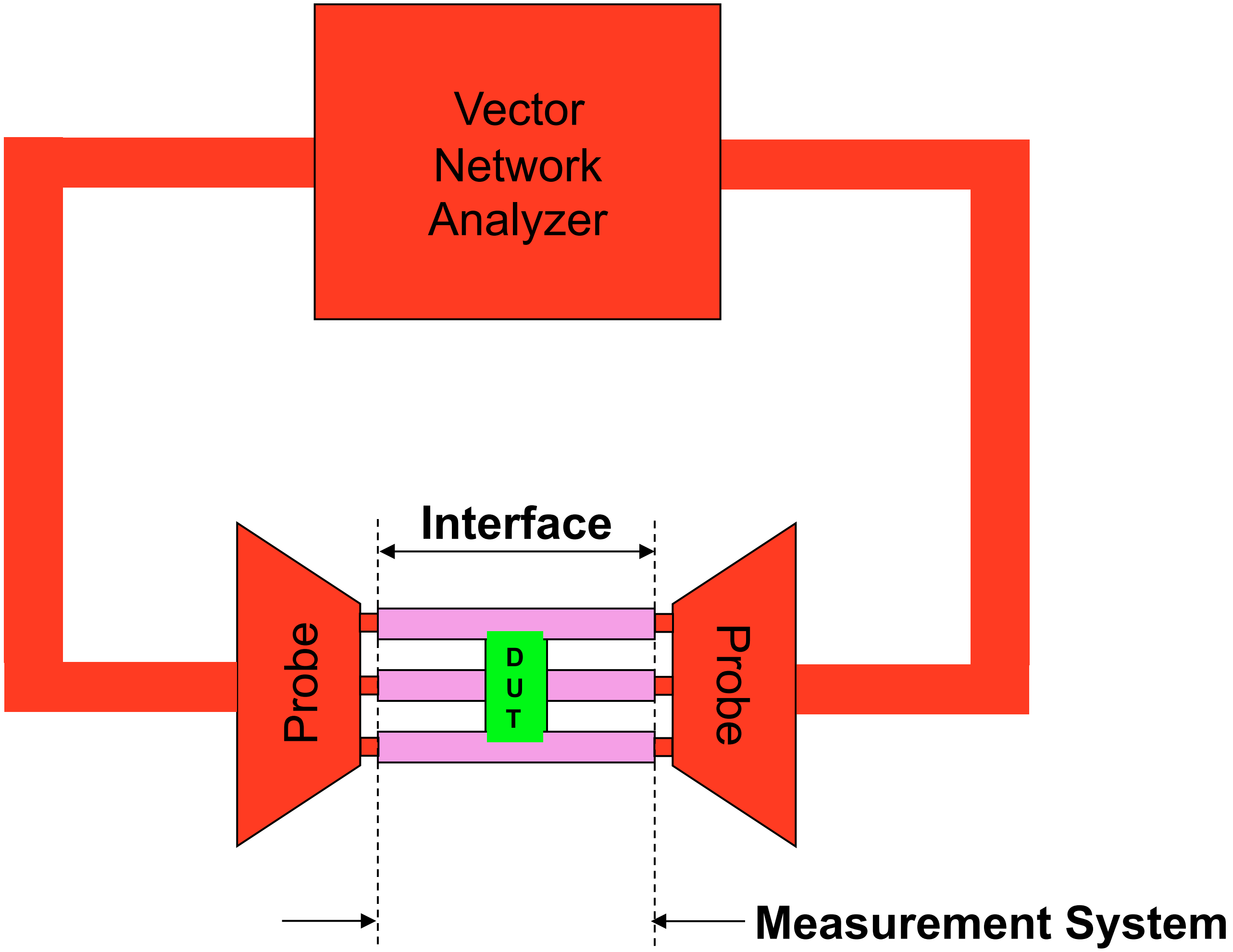
De-Embedding

- Real measurement systems are not ideal

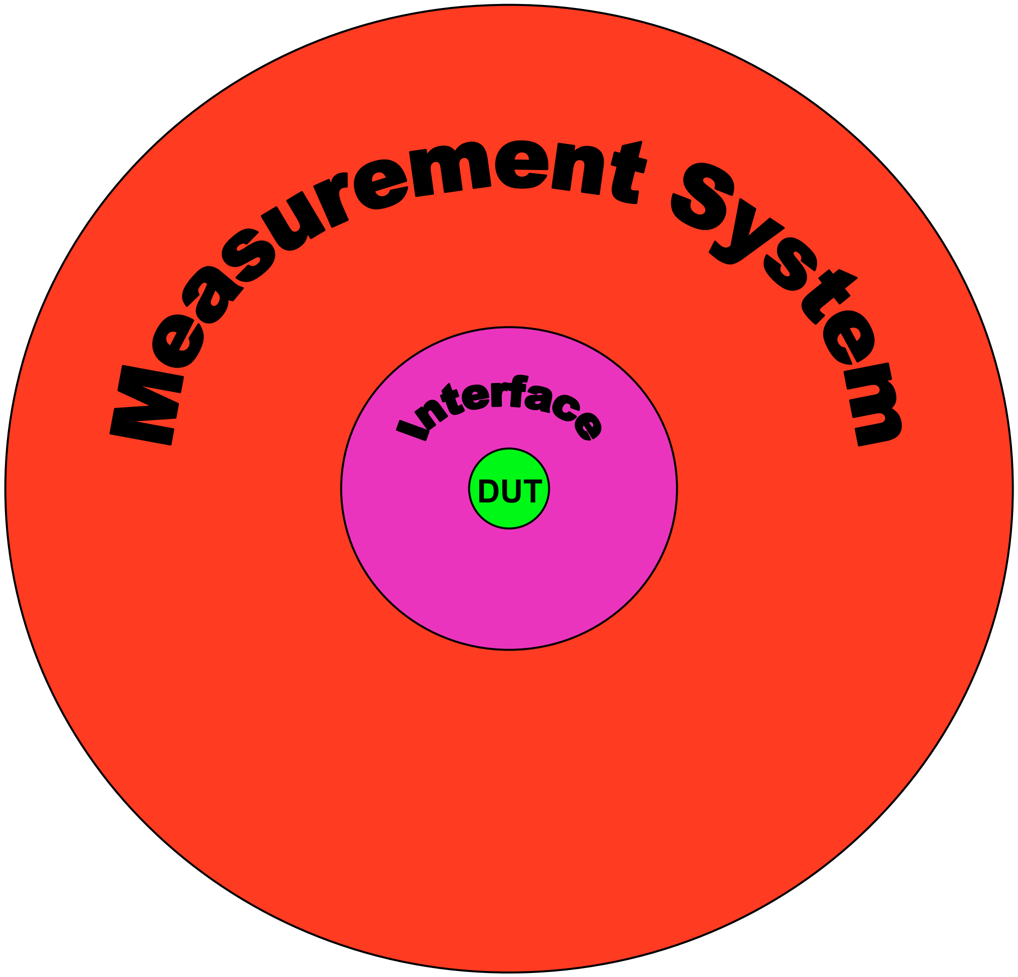
  ⇒ Measurement systems ‘distort’ the data
- We need to ‘strip-off’ the contribution of the measurement system
- This process is called:

  ERROR CORRECTION
- This is a major topic in the field of microwave measurements

S-Parameter Measurement: What Do We Measure?

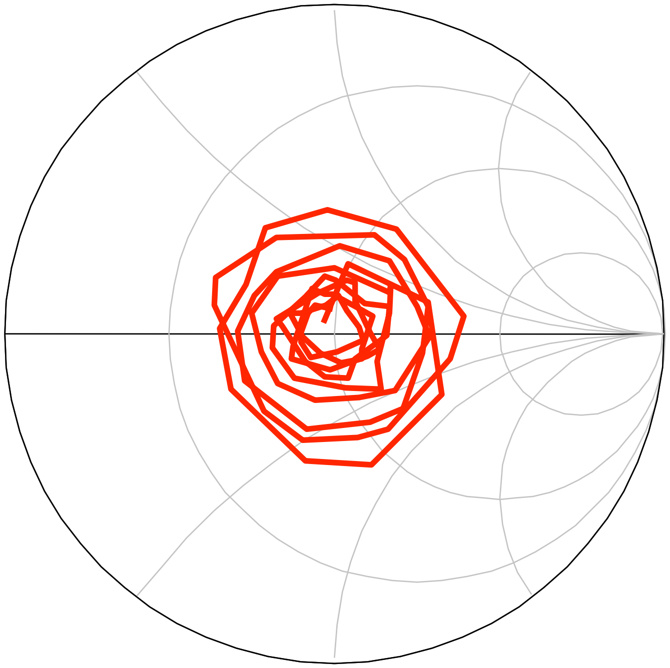


S-Parameter Measurement:
What Do We Measure?



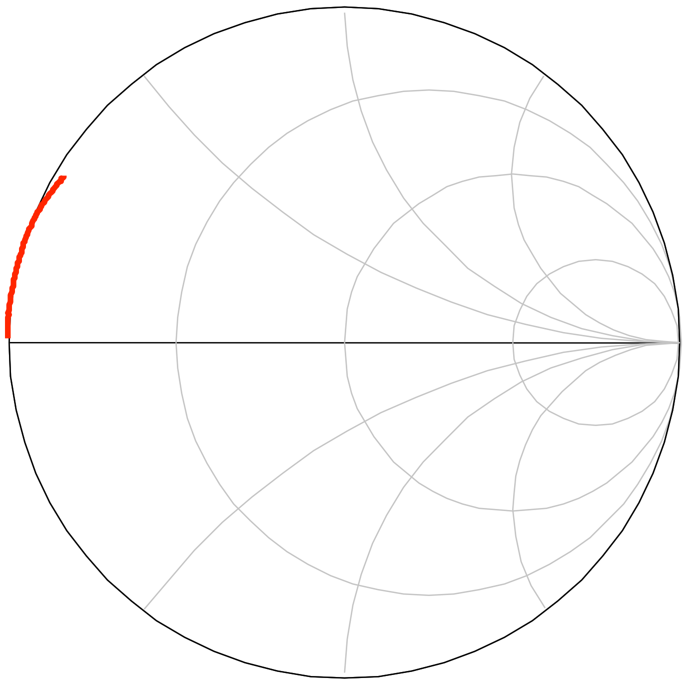
Measurement System Interface DUT

S-Parameters: Error Correction



- Uncorrected S_{11} measurements
- Test system obscures the results
- Need to remove the effect of the test system

S-Parameters: Error Correction



- Corrected S_{11} measurements
- Device behaves like a 1-port inductor

Calibration and De-Embedding

- Calibration
  - The Process of quantifying the measurement system behavior so that its effects can be mathematically removed from the measurements.
- De-Embedding
  - The process of quantifying the interface behavior so that its effects can be removed.
- In some cases, Calibration and De-Embedding can be combined into one step.
- Applicable to linear operation only

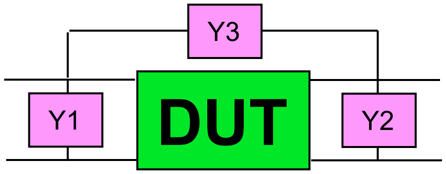
Calibration Methods for On-Wafer Measurements

- On-wafer calibration methodologies reasonably mature
- SOLT: Short, Open, Load, Through
- TRL: Through, Reflect, Line
- LRM: Line, Reflect, Match
- LRRM: Line, Reflect, Reflect, Match
- LRM+: Line, Reflect, Match extended

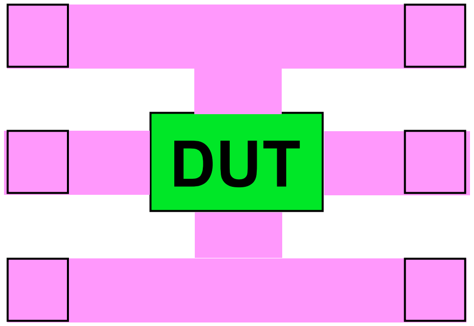
De-Embedding

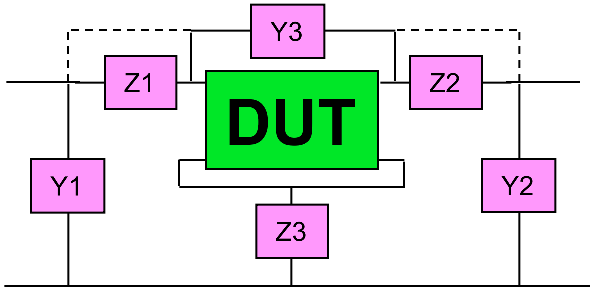
- De-Embedding Process:
  - Hypothesize embedding parasitics
  - Develop a strategy for quantifying the embedding parasitics
  - Verify the methodology using physical considerations

1, 2 and 3 Step De-Embedding

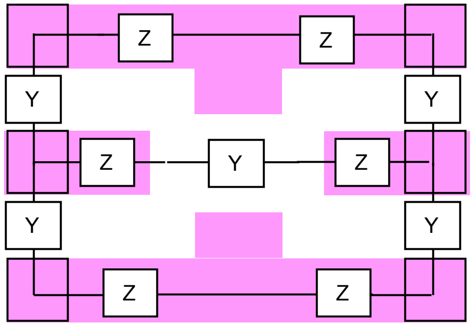


1-Step/Open De-embedding

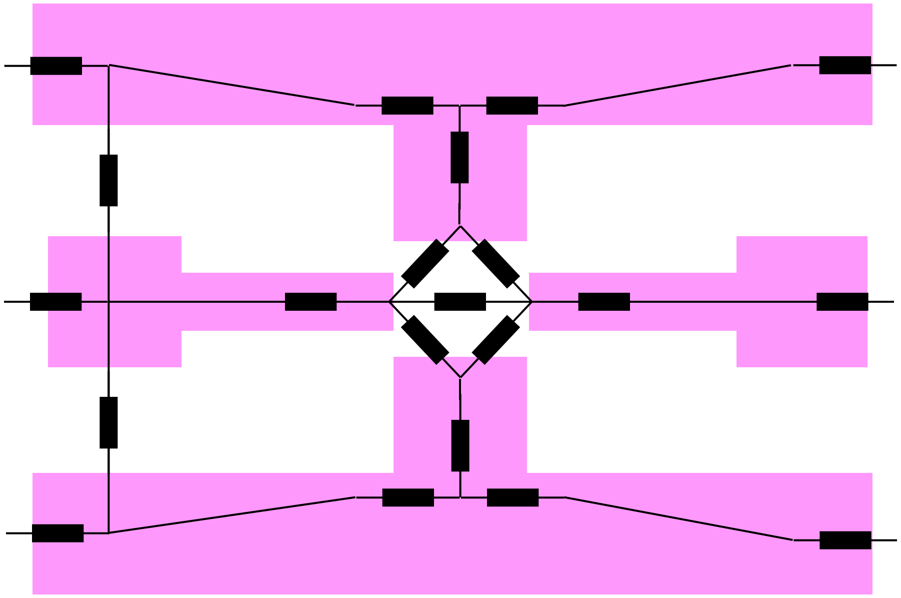


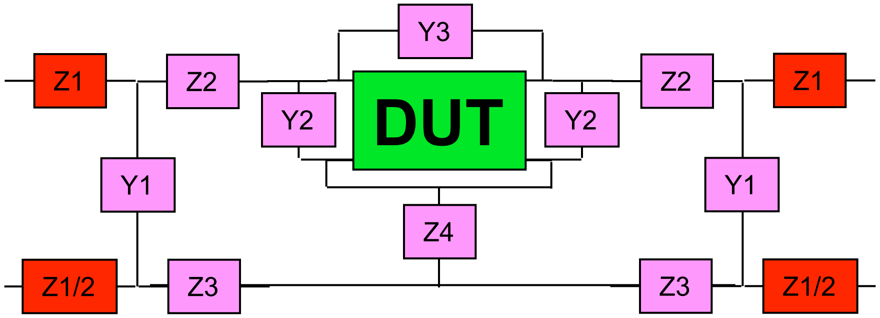


2-Step, 3-Step De-embedding
Open-Short
Open-Short-Thru



4-Step De-Embedding





In addition to accounting for the interface parasitics, it accounts for changes in probe contact after initial calibration

5-Step De-Embedding

In addition to accounting for the interface parasitics, it accounts for:

(i) Changes in probe contact after initial calibration
(ii) DC resistance to compensate for biasing
(iii) Contact to base and collector via additional parasitic

Proposed Methodology:

(i) Minimize pad size
(ii) Minimize interconnect size
(iii) Use a connection configuration that can be applied to all DUT's
(iv) Keep probe tip separation constant
(v) Use automated probing
(vi) Use a ground shield
(vii) Ground path to ground pads should use complete metal stack
(viii)Each parasitic element should have a specific methodology
(ix) Validate results using physical considerations

mmW Design Methodologies

- Design methodologies are difficult to describe in a short period of time
- Focus will be on challenges and unique aspects of mmW design
  - Use of the Cascode topology to boost gain
  - Distributed Matching
  - The Role of EM simulations

mmW Design Methodologies

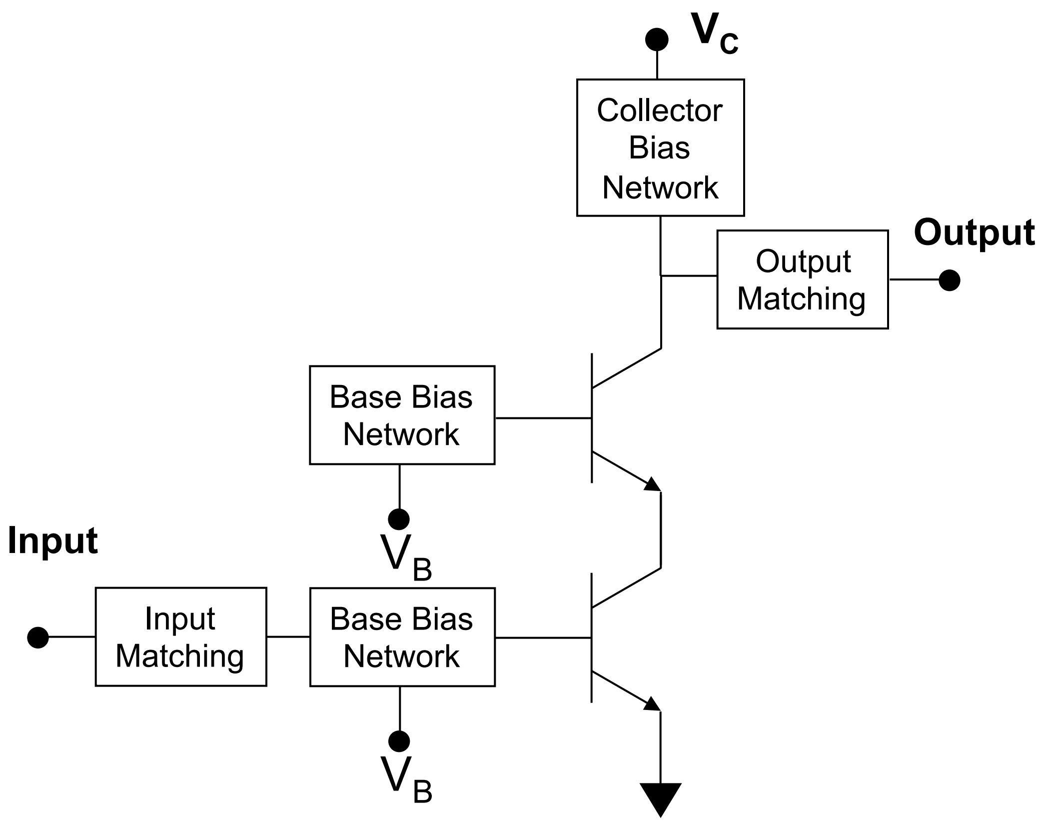
Circuit	Design Domain
Low Noise Amplifier	Frequency
Oscillators	Frequency
Power Amplifier	Frequency
Mixer	Frequency
Transient, switching	Time

mmW Circuit Topologies

- Circuit topologies developed at lower frequencies are adapted to mmW frequencies
- Problem:
  - Device gain ⇓ as frequency ⇑
    - 3dB/octave (k<1, MSG region), 6dB/octave (k>1, MAG region)
    - A device with F_{max}=200GHz has 8.5dB of gain at 75GHz

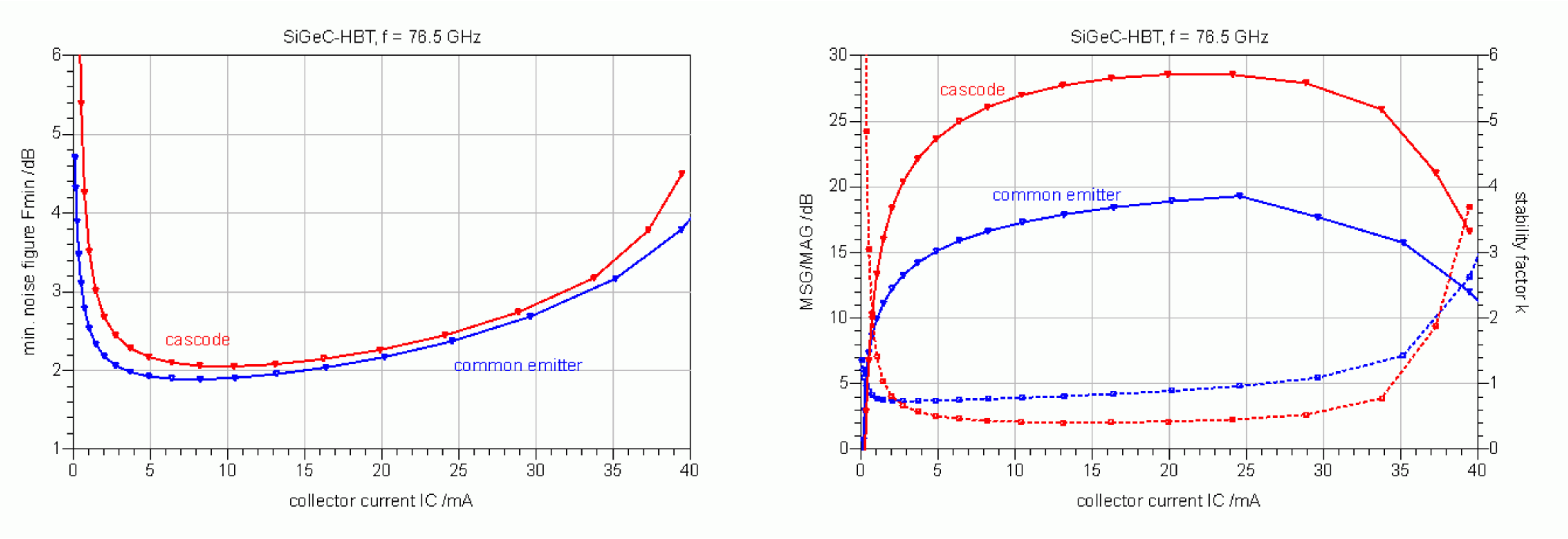
- Use of circuit techniques such as Cascode transistor configuration can be used to boost gain

Cascode Circuit Topology



- When device gain is adequate common source/ emitter configurations are used.
- When the device gain is low, addition of a common base/ gate network will boost gain.
- Gain boost comes from the reduced feedback capacitance of the common base
- Cascode complicates the circuit design
- Requires sufficient supply voltage
- Takes additional die area

Cascode Circuit Gain Properties



- Cascode slightly degrades noise performance
- Cascode shows higher gain MSG/MAG compared to common emitter
- Data from R. Reuter, Freescale Semiconductor

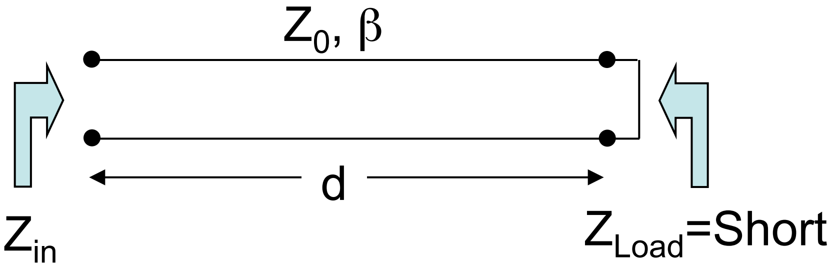
Models for mmW Design Methodologies

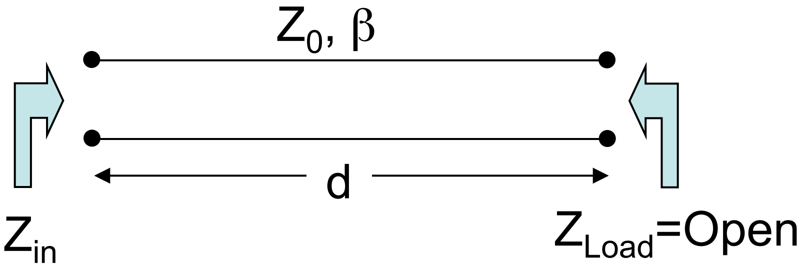
- As Frequency ⇑ Model Uncertainty ⇑
- Substrate effects are more significant but modeling is limited.
  - Considerable time and effort is required for proper calibration for simulators
- Model parameter extraction is more challenging.
- Beyond approximately 60 GHz, distributed matching methodologies are required.
  - Reactances are realized using transmission lines, not discrete capacitors and inductors.

Distributed Matching for mmW Design

- Circuit design involves transferring power from one network to another network
  - Power from a VCO core to a buffer amplifier
  - Power transfer between stages in a Power Amplifier
- At ‘low’ frequencies this is accomplished through the use of lumped element matching networks using L’s and C’s.
- At ‘high’ frequencies the L’s and C’s are replaced by transmission lines.

L’s and C’s from Transmission Lines





$$Z_{in} = jZ_0 \tan(\beta d)$$

$$Z_{in} = -jZ_0 \cot(\beta d)$$

A short circuited transmission line behaves like an inductor.

L is proportional to βd and Z_0

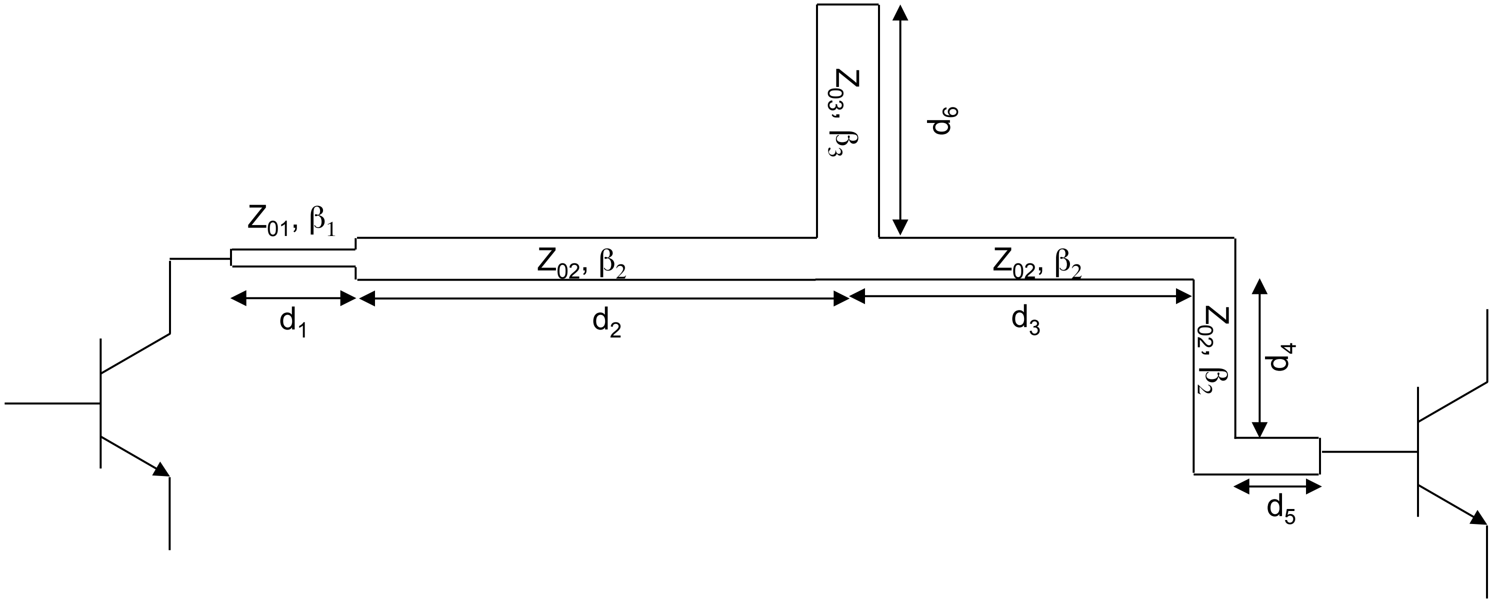
When the transmission line is λ/4,
$Z_{in} = 1/Z_{Load}$

An open circuited transmission line behaves like a capacitor.

C is proportional to βd and Z_0

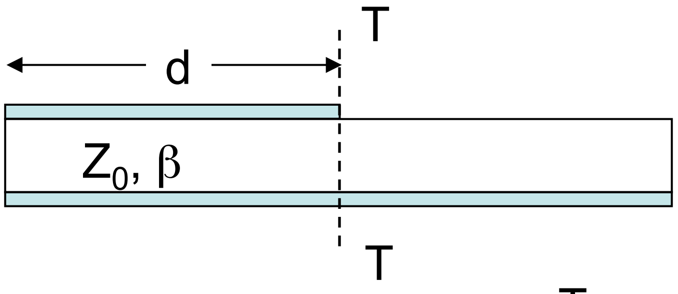
When the transmission line is λ/4,
$Z_{in} = 1/Z_{Load}$

Microstrip Discontinuities

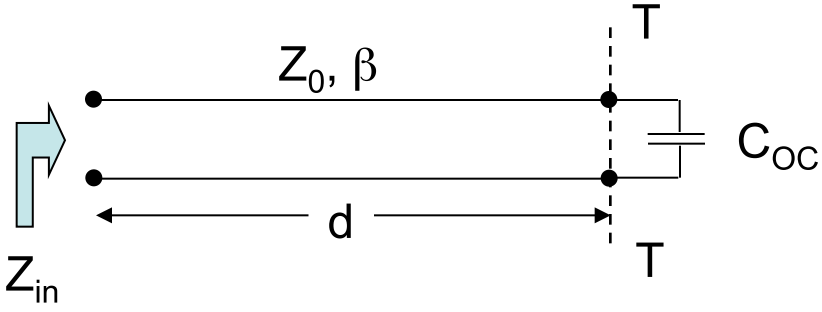


- This microstrip network cannot be accurately simulated using just uniform microstrip models.
- The discontinuities result in disturbances to uniform current and charge distributions.
- This results in parasitic inductive and capacitive components

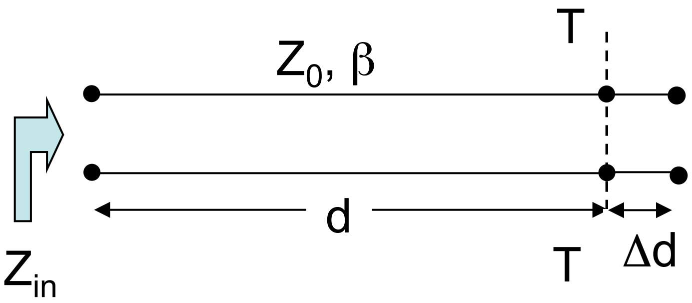
Equivalent Circuits of Some Microstrip Discontinuities



Side View of Open Circuit Micrstripline.

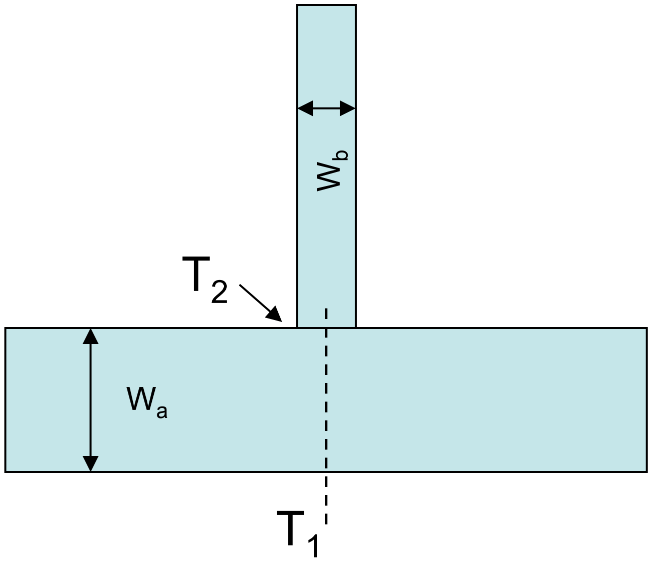


The open circuit microstripline has an excess charge resulting in an effective capacitance terminating the line.

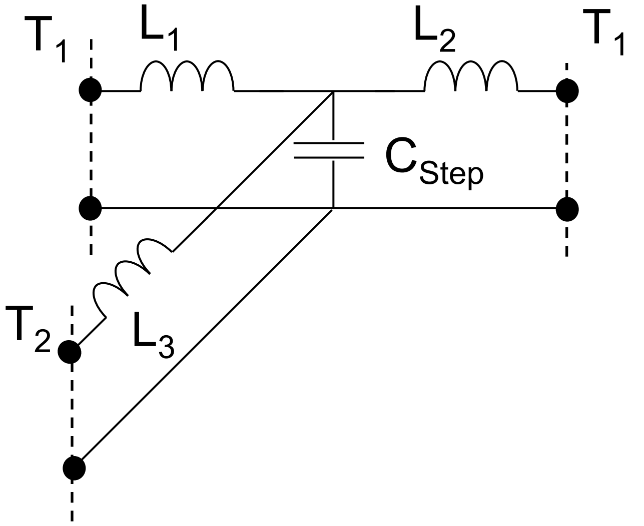


The C_{OC} is equivalent to effectively lengthening the line by Δd.

Equivalent Circuits of Some Microstrip Discontinuities



Top View of T-Junction.



The equivalent circuit of the T-junction. The inductance arises from magnetic energy and the capacitance comes from additional charge at the junction.

The Use of EM Simulators

- Large networks are not easily simulated.
  - Synthesis is extremely difficult
- Identify key elements that may not be accurately described by closed form analytical models
  - Simulate these elements
  - Fix the geometry
  - Use standard synthesis techniques to complete the network
- Always allow for tuning

Acknowledgements

- Thanks to Ralf Reuter, Freescale Semiconductor, for discussions on mmW design issues and challenges.