Microwave Technology
(COMM 903)

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Course Contents

- **Active Microwave & RF Circuits Analysis & Design**
  - Noise, Microwave Sources, Amplifiers, Mixers & Oscillators.

- **Metamaterials and Transmission Lines**
  - Basic properties, Transmission Line Implementations and Applications.

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References

→ Lecture Notes
Assessment

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Microwave Sources

- **Solid State Sources**
  - Low Power & Low Frequencies Sources
- **Microwave Tubes**
  - High Power &/or high frequencies Sources

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**Microwave Tubes**

**Types of Microwave Tubes:**
- Klystron
- TWT (Traveling Wave Tubes)
  - Helix TWT.
  - Coupled cavity TWT.
- Magnetron.
- Gyroton.
- Gridded Tube.
- CFA (crossed field amplifiers)

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**Solid State Sources**

- **Advantages:**
  - Small Size.
  - Low Cost.
  - Compatibility with microwave integrated circuits.

- **Disadvantages:**
  - Low power.
  - Low frequencies.
Solid State Sources

- Can be categorized as:
  - Two terminal devices
    - Ex.: Diodes.
  - Three terminal devices
    - Ex.: Transistor oscillators.

Diode Sources

- Most common diode sources:
  - Gunn diode.
  - IMPATT diode.

- Directly convert DC bias to RF power in the frequency range of 2 to 100 GHz.
**Gunn Diode**

- Even though everyone uses this term! It’s more accurate name is a “Transferred Electron Device” (TED). Why isn’t it a "real" diode? Because it only uses N-type semiconductor.
- Gunn diodes have been around since John Gunn discovered that bulk N-type GaAs can be made to have a negative resistance effect.
- **Three regions exist:** two of them are heavily N-doped on each terminal, with a thin layer of lightly doped material in between.

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**Gunn Diode**

Two Gunn diode sources. The unit on the left is a mechanically tunable E-band source, while the unit on the right is a varactor-tuned V-band source.
FET

Fixed Biasing Circuit For JFET

Small Signal Models

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The GaAs MESFET Structure

Cross sectional view of the GaAs MESFET structure shows the depletion region below the gate

The contact of the gate is made of metal-semiconductor Schottky Contact rather than a metal-oxide-semiconductor (MOS) structure, which is used in the MOSFET device. This approach minimizes the device’s gate to source capacitance, which otherwise would degrade the high-frequency gain performance.

The GaAs MESFET

\[ g_m = \frac{w \varepsilon_s v_{sat}}{h_d} \]

\[ f_T = \frac{g_m}{2\pi C_{gs}} \]

\[ C_{gs} = \frac{w \varepsilon_s l_g}{h_d} \]

At frequencies above \( f_T \) the current passing through the \( C_{gs} \) is greater than that produced by the transconductance, therefore, \( f_T \) represents a fundamental high-frequency limit.

For optimum high-frequency performance, the device designer must either increase the saturated carrier velocity or decrease the gate length.
Device Characterization and Modeling

- **Small signal model** Intrinsic & Extrinsic elements is determined using the hot and cold deembedded S-parameters measurements.

- **Large Signal model** is determined by using the semi-empirical method, and it uses the measured pulsed dc I-V data of the device and no assumptions are made relating to the physical operation of the device itself.

- One key issue in **S-parameters measurements** is the accurate calibration of the network analyzer. The calibration of the instrument should remove unwanted and repeatable information, such as the effects of non-ideal transmission lines, connectors, and circuit parasitic.

Small-signal device modeling procedure

1. Measure cold S parameters
2. Measure hot S parameters
3. Deembed cold S parameters
4. Deembed hot S parameters
5. Model and optimize deembedded cold S parameters
6. Model and optimize deembedded hot S parameters
7. Final small-signal equivalent circuit model

Cold
- $V_{ds} = 0$ V
- $V_{gs} = -3$ V (pinch off)
**Hot S-parameters Extraction**

![Diagram of Hot S-parameters](image)

\[ C_{dc} = \text{diode layer capacitance} \]

\[ R_g \text{ and } R_d \text{ represent the device's gate and drain resistance.} \]

\[ R_s \text{ and } L_s \text{ are the source resistance and inductance.} \]

The extrinsic parameters \( C_{gp}, C_{dp}, L_g, L_d, R_s, R_g \) and \( R_d \).

The gate and drain bond-pad capacitance \( (C_{pg} \text{ and } C_{pd}) \) in the modeling process.

**Cold S-parameters Extraction**

![Diagram of Cold S-parameters](image)
**Cold S-parameters Extraction**

\[
\begin{align*}
Z_{c11} &= R_s + R_x + j[\omega(L_x + L_s) + 1/\omega C_{ab}] \\
Z_{c12} &= Z_{c21} = R_x + j[\omega L_x - 1/\omega C_s] \\
Z_{c22} &= R_x + R_s + j[\omega(L_d + L_s) - 1/\omega C_{bc}] \\
C_{ab} &= C_a^{-1} + C_b^{-1} \quad C_{bc} = C_b^{-1} + C_c
\end{align*}
\]

\[
R_g = \text{Re}(Z_{c11} - Z_{c12})
\]

\[
R_s = \text{Re}(Z_{c12})
\]

\[
R_d = \text{Re}(Z_{c22} - Z_{c12})
\]

\[
\omega \text{Im}(Z_{c11}) = \omega^2(L_x + L_s) - 1/\omega C_{ab}
\]

\[
\omega \text{Im}(Z_{c12}) = \omega^2 L_x - 1/\omega C_s
\]

\[
\omega \text{Im}(Z_{c22}) = \omega^2(L_d + L_s) - 1/\omega C_{bc}
\]

---

**Hot S-parameters Extraction**

\[
Y_{11} = j\omega C_{gd} + \frac{1}{R_i + j\omega C_{gs}}
\]

\[
Y_{12} = -j\omega C_{gd}
\]

\[
Y_{21} = g_m e^{-j\omega \tau} \left[ 1 + j\omega R_s C_{gs} \right] - j\omega C_{gd}
\]

\[
Y_{22} = \frac{1}{R_d} + j\omega (C_{ds} + C_{gd})
\]

\[\text{Broadband Microwave Amplifiers}\]

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Broadband Microwave Amplifiers by Bal S. Virdee, Avtar S. Virdee, & Ben Y. Banyamin

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Model Extraction

\[
C_{gd} = -\text{Im}(Y_{11})/\omega
\]

\[
C_{gs} = \frac{\text{Im}(Y_{11}) - \omega C_{gd}}{\omega} \left( 1 + \frac{[\text{Re}(Y_{11})]}{[\text{Im}(Y_{11}) - \omega C_{gd}]} \right)
\]

\[
R_e = \left[ \text{Re}(Y_{11}) / \text{Im}(Y_{11}) - \omega C_{gd} \right] + \text{Re}(Y_{11})
\]

\[
g_{mo} = \sqrt{[\text{Re}(Y_{21})]^2 + [\text{Im}(Y_{11}) - \omega C_{gd}]} \left[ 1 + \omega^2 C_{gs} R_s \right] \left( g_{mo} \right)
\]

\[
\tau = (1/\omega) \sin^{-1} \left[ \frac{-\omega C_{gd} - \text{Im}(Y_{21}) - \text{Re}(Y_{21}) \omega C_{gs} R_s}{g_{mo}} \right]
\]

\[
C_{ds} = \frac{\text{Im}(Y_{22})}{\omega} - \omega C_{gd}
\]

\[
R_{ds} = \frac{1}{\text{Re}(Y_{22})}
\]

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S-parameters files

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**Extraction Steps**

- Measure the S-parameters and save as .s2p file.
- Load file into Matlab (load file name.s2p)
- Convert the s2p to y-parameters using the equations (or using s2y command in matlab).

**MESFET Model Extraction Project**

\[
I_1 = Y_{11}V_1 + Y_{12}V_2 \\
I_2 = Y_{21}V_1 + Y_{22}V_2
\]
Finding $Y_{11}$ & $Y_{21}$

In case of $V_2 = 0$

\[ I_2 = -V_1(j\omega C_{gd}) + g_m v_{gs} \]

\[ v_{gs} = \frac{V_1(j\omega C_{gd})}{R_i + j\omega C_{gs}R_i} = \frac{V_1}{1 + j\omega C_{gs}R_i} \]

\[ I_2 = -V_1(j\omega C_{gd}) + \frac{g_m V_1}{1 + j\omega C_{gs}R_i} \]

\[ Y_{21} = \left. \frac{I_2}{V_1 \v_{V_2=0}} \right| = \frac{g_m}{1 + j\omega C_{gs}R_i} - j\omega C_{gd} \]

\[ Y_{11} = \left. \frac{I_1}{V_1 \v_{V_2=0}} \right| = j\omega C_{gd} + \left( \frac{1}{R_i + j\omega C_{gs}} \right) \]
Finding $Y_{11}$ & $Y_{21}$

\[ Y_{11} = j\omega C_{gd} + \left( \frac{j\omega C_{gs}}{1 + j\omega C_{gs}R_i} \right) \]
\[ Y_{11} = j\omega C_{gd} + \frac{j\omega C_{gs} + \omega^2 C_{gs}^2 R_i}{1 + \omega^2 C_{gs}^2 R_i^2} \]

\[ Y_{11} = \frac{\omega^2 C_{gs}^2 R_i}{D} + j\omega \left( \frac{C_{gs}}{D} + C_{gd} \right) \quad D = 1 + \omega^2 C_{gs}^2 R_i^2 \]
Extracted Model Parameters

NE321000  \( V_{ds} = 2 \) V  \( I_d = 10 \) mA

\[ C_{gd} = 2.2548 \times 10^{-14} F = 0.02548 \text{pF} \]
\[ C_{gs} = 1.1782 \times 10^{-13} F = 0.11782 \text{pF} \]
\[ R_i = 7.3838 \Omega \]
\[ g_m = 0.0664 S \]
\[ \tau = 3.5229 \times 10^{-13} \text{sec} = 0.35229 \text{psec} \]
\[ C_{ds} = 4.7753 \times 10^{-14} F = 0.47753 \text{pF} \]
\[ R_{ds} = 198.924 \Omega \]

Results \( Y_{11} \) (Measured Vs Calculated from extracted Model)
Results $Y_{12}$ (Measured Vs Calculated from extracted Model)

Results $Y_{21}$ (Measured Vs Calculated from extracted Model)
Results $Y_{22}$ (Measured Vs Calculated from extracted Model)