Field Effect Transistor - FET

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Field Effect Transistor - FET

Three Chapters

- **Chapter 1 - FET Evolution – 5 minutes**
- **Chapter 2 – Modern RF FET Fraternity – 10 minutes**
- **Chapter 3 - Example RF FET Circuits – 45 minutes**

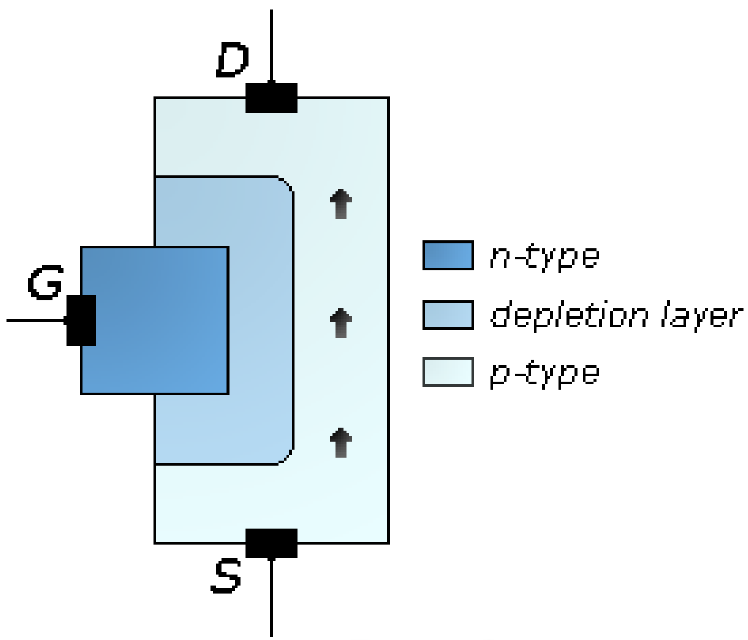
  Chapter 3a – Small Signal Low Noise Amplifiers (LNA)

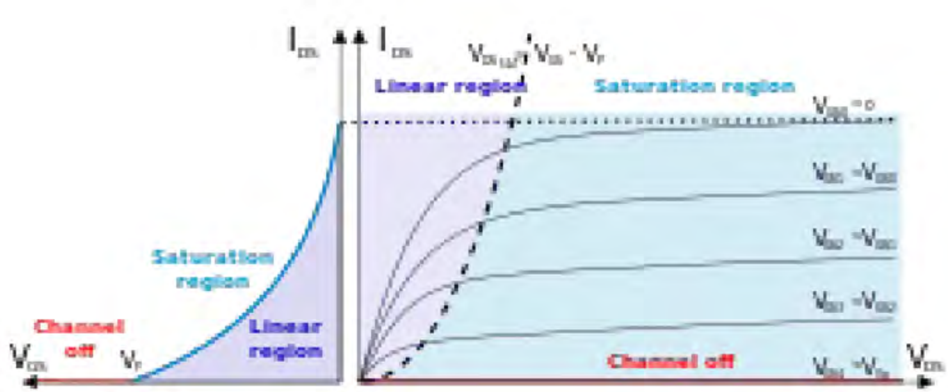
  Chapter 3b – Large Signal High Power Amplifiers (RFPA)

  Chapter 3c – 23 cm 15 Watt LDMOS RFPA Design Journey

Field Effect Transistor – FET

Chapter 1 - FET Evolution





- JFET Theory Patented by Julius Lilienfeld during 1920~1930
- However, JFET fabrication was Impossible until adequately pure silicon became available circa 1955, following silicon BJT
- Depletion Mode, Normally On

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Chapter 1 - FET Evolution

- First Junction Field Effect Transistors (JFET) Resembled Earliest Junction Bipolar Transistors (BJT) Physical Construction

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Chapter 1 - FET Evolution

- **At this time, the JFET was considered to be the first "solid state valve"**
- ***Although not strictly accurate, the JFET was coined to be "voltage operated" - a close cousin to the familiar vacuum tubes of the time***
- **In comparison the BJT was equally coined to be "current operated"**
- **Early BJT had low H_{FE} and therefore low input impedance, so this distinction made some sense. Early $H_{FE} < 50$, modern $H_{FE} > 500$**
- **However early JFET had low gain, low power, limited high frequency**

Modern BJT AC analysis models use "transconductance" $g_m \equiv \partial I_c / \partial V_{be}$

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Chapter 1 - FET Evolution

- **Early JFET struggled to achieve g_m ~ 2 $^{mA}/_{Volt}$**
- **Some contemporary vacuum tubes could achieve g_m > 20 $^{mA}/_{Volt}$**
- **Early JFET were limited to audio frequencies**
- **In contrast, vacuum tubes where processing *f* > 500 MHz!**
- **As with early junction BJT, the limitation was in its construction**
- **The solution – *adopt the BJT planar fabrication process***

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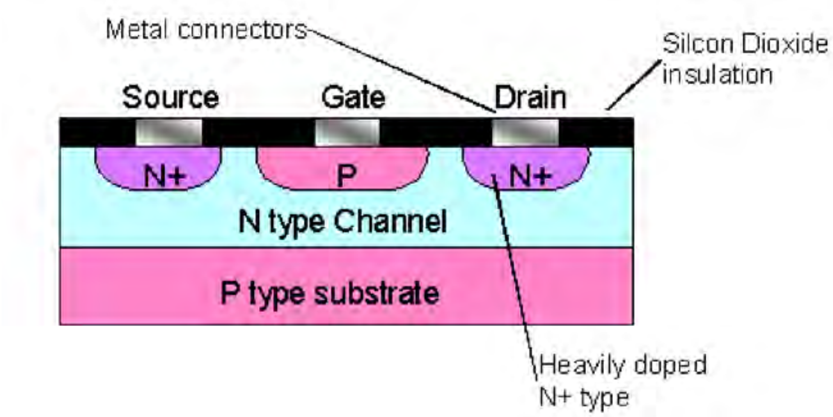
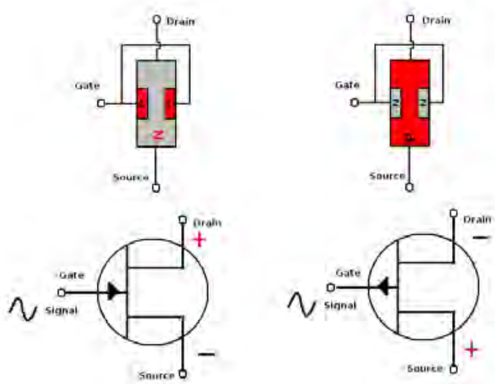
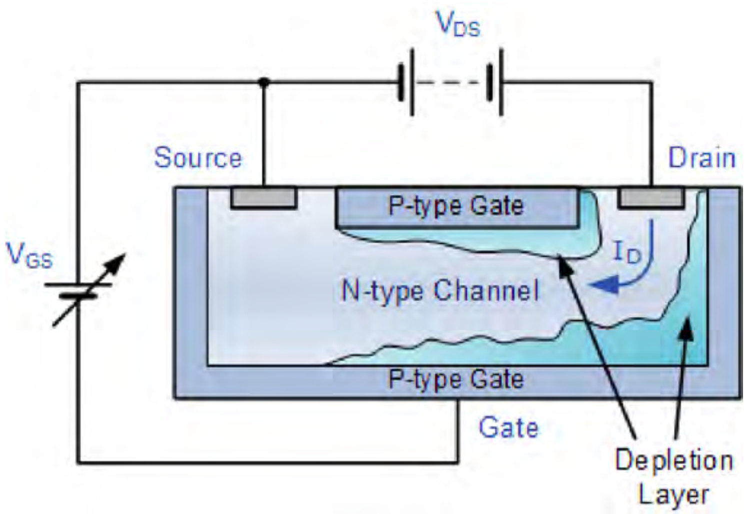
Chapter 1 - FET Evolution

Note - modern planar construction

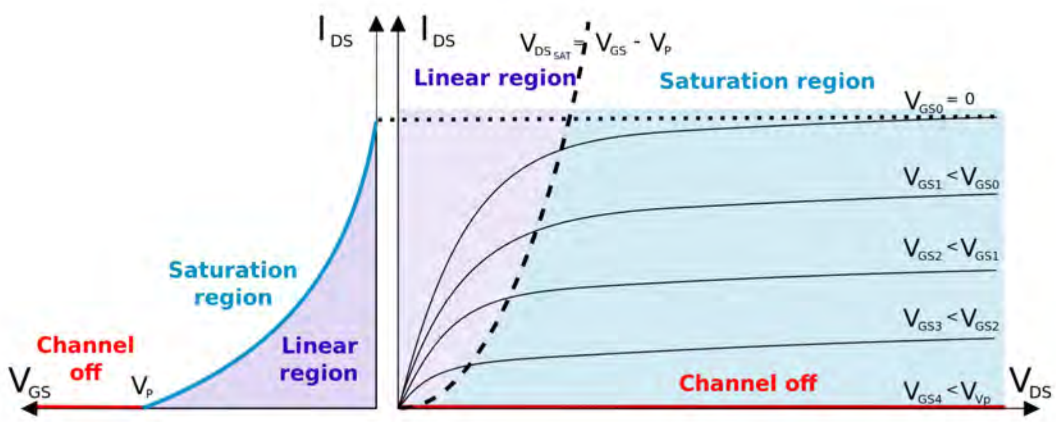


Note - same conceptual design!





Note – identical electrical characteristic



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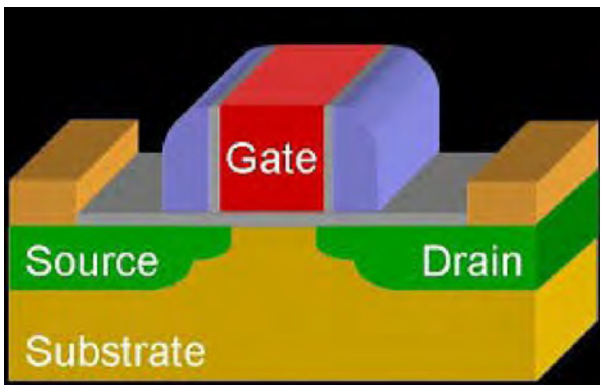
Chapter 1 - FET Evolution

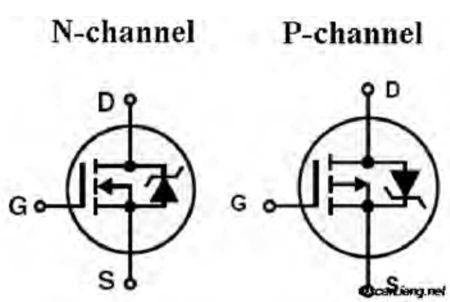
- JFET R&D investment downturn circa 1980
- However many popular JFET remain
- MPF102, 2N3819, 2N3823, 2N5459, J310, BF256
- Of these, the J310 die (originally U310 from Siliconix), was the pinaccle of high frequency JFET performance, g_m ~ 20 to 40 $^{mA}/_{Volt}$, f ~ 500 MHz
- R&D funding targets MOSFET, IGBT, LDMOS, HEMT

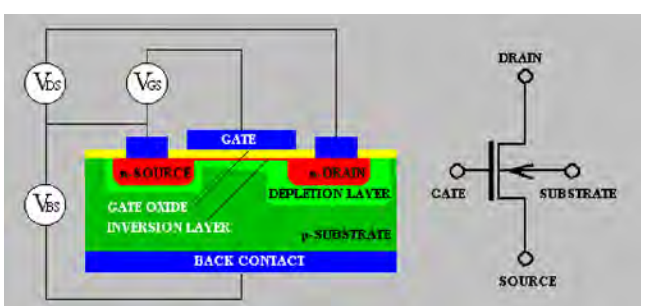
Field Effect Transistor – FET

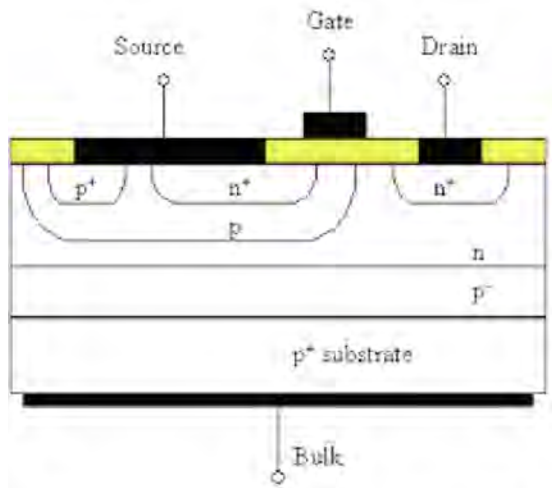
Chapter 1 - FET Evolution

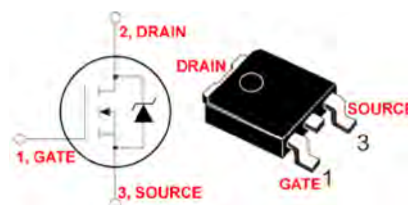
Generic MOSFET construction

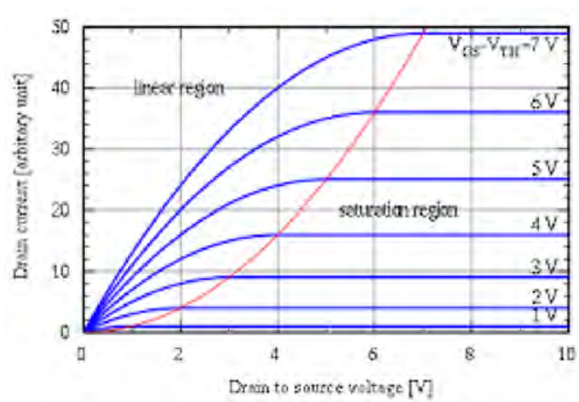












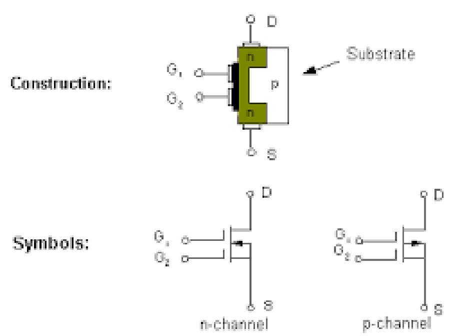
Modern FET Types

- MOSFET
- IGBT
- LDMOS
- MESFET
- GaAsFET
- HEMT
- pHEMT

Field Effect Transistor – FET

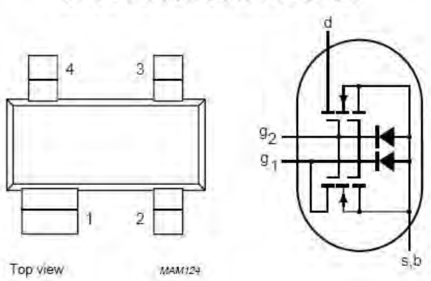
Chapter 1 - FET Evolution

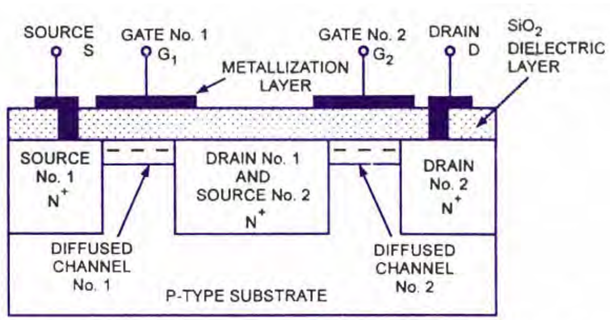
Dual Gate MOSFET



- Depletion and Enhancement modes available
- Very common in analog TV tuners as RF amplifiers
- Also well suited as mixers – BF1105 at 1296 MHz OK
- Typically cost less than $NZ 1:00 (Digikey NZ)

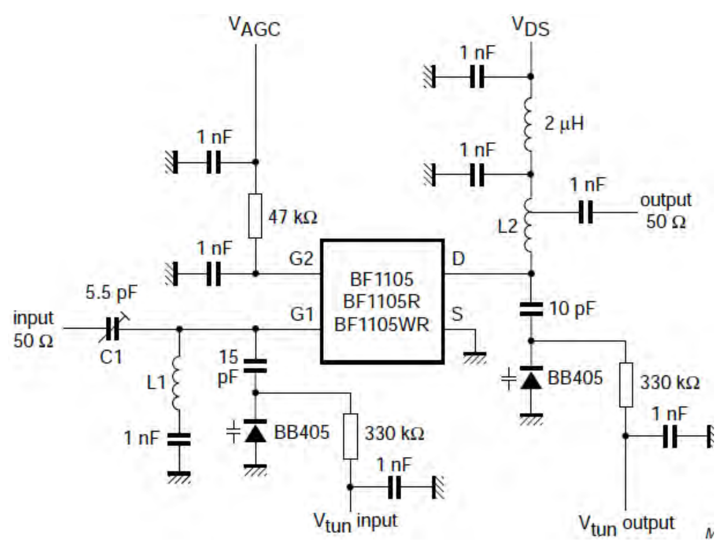
BF904 Dual-Gate MOSFET



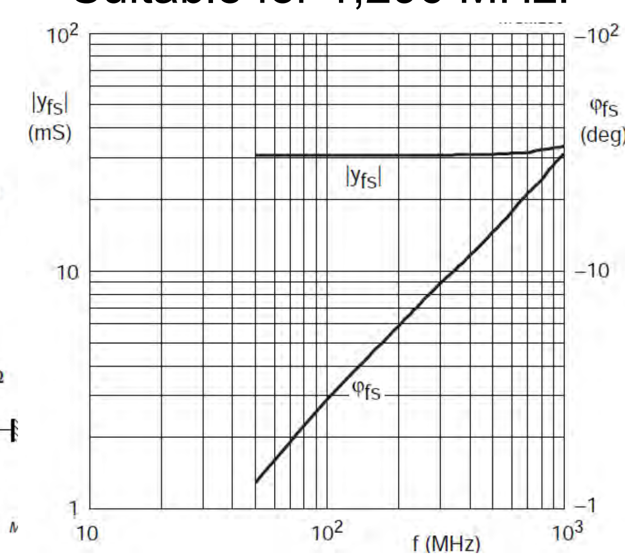


Dual-Gate N-Channel Depletion Type MOSFET

Infineon test circuit at 200 MHz



Suitable for 1,296 MHz!



From small signal LNA and mixers to high power...

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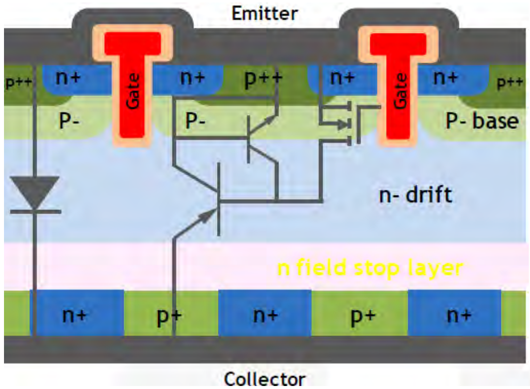
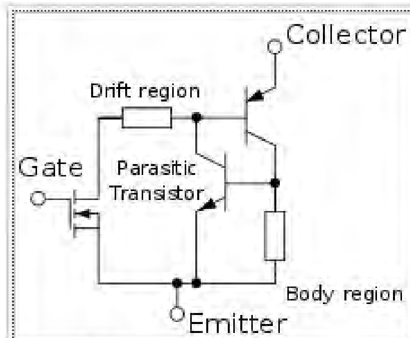
Chapter 1 - FET Evolution





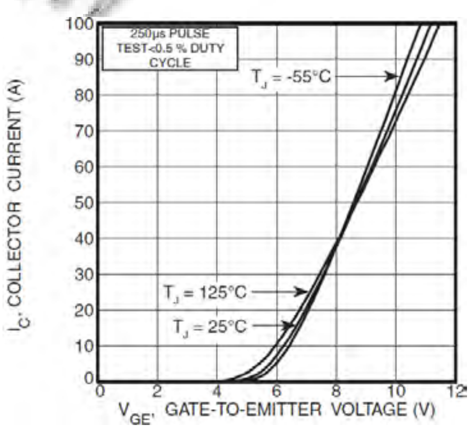
Equivalent circuit for IGBTs

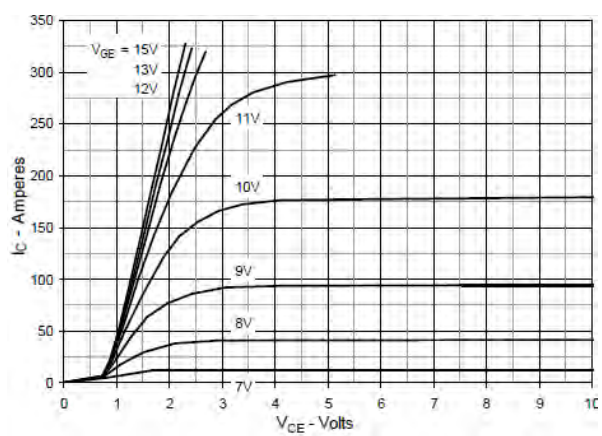
Insulated Gate Bipolar Transistor

IGBT

MOSFET input, common collector PNP BJT Output

IXXK300N60B3





- Ex. 600 V 300 Amp
- Switch to 100 kHz
- Speeds approach fast MOSFET
- Perhaps 80m RFPA

How about integrating 2 MOSFET in series?

Field Effect Transistor – FET

Chapter 1 - FET Evolution - Summary

- Early Junction Field Effect Transistor (JFET)
- Depletion Mode, Low Gain, Logic Unfriendly
- Some improvement with Planar Process
- Superseded by Logic Friendly Enhancement MOSFET
- Subsequent IGBT, LDMOS, GaAsFET, GaN HEMT

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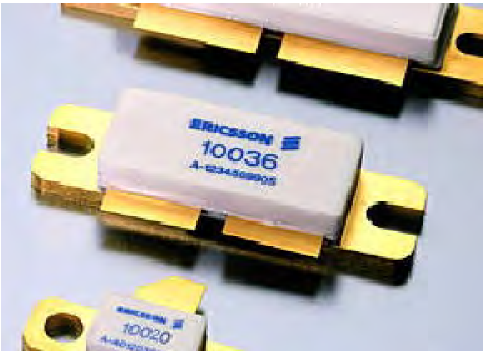
Chapter 2 – The RF FET Fraternity

Lateral Diffused MOS (LDMOS) – demonstrated 1969!



- Commercialized by Motorola – e.g. MRF181 1993
- Mature, > 10 years, Silicon, about $NZ 1~2 per Watt
- High Power Transmitters, 1.5 kW VHF, 1 kW to 1 GHz
- High power amplification, Typical G_p ~ 17 dB (50 x)

Gallium Arsenide FET (GaAsFET)

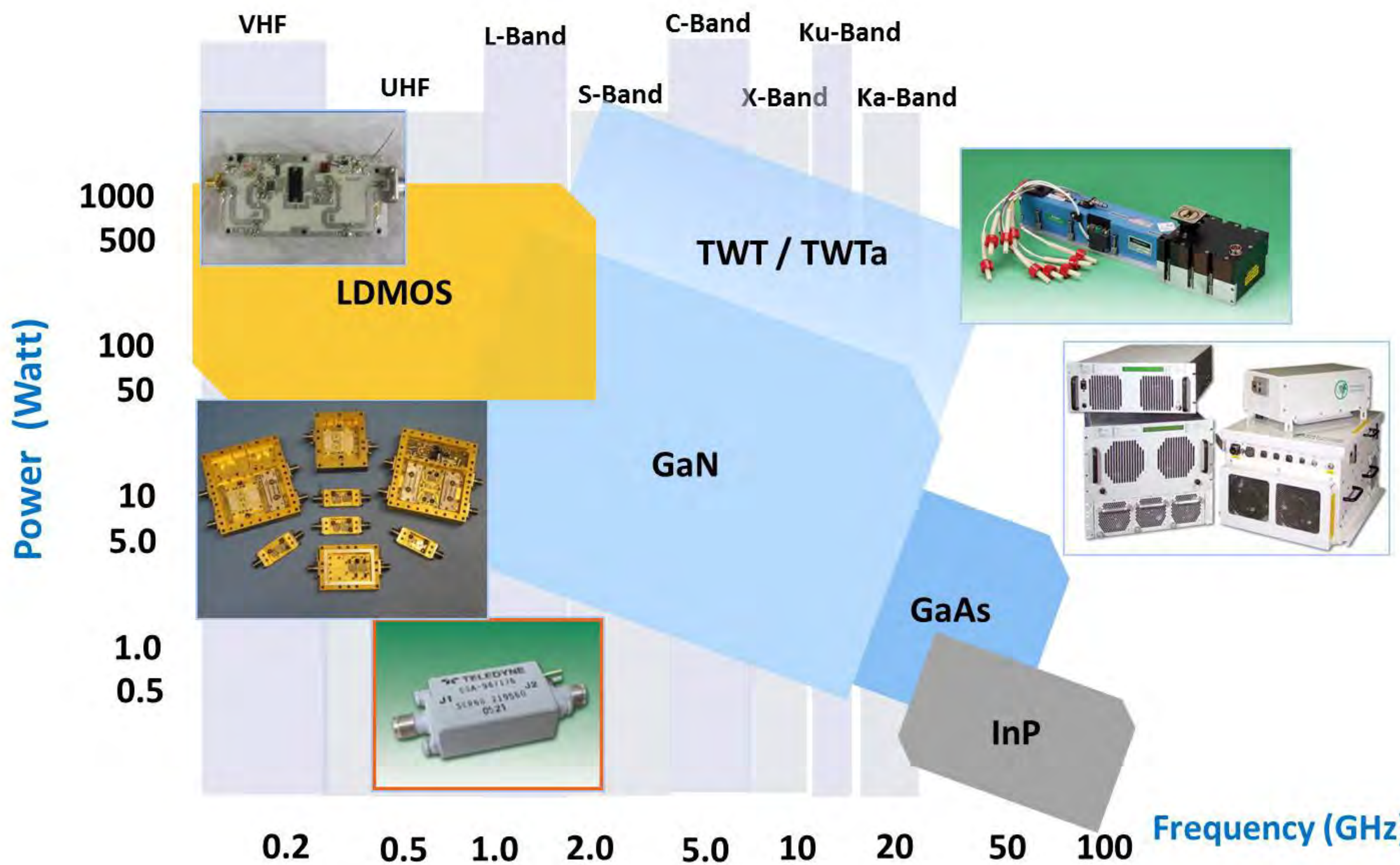
- Schottky Gate (same as MESFET, 1996) – Depletion Mode
- Low to Medium Power Linear Class A Microwave, $V_s \leq 10$ V
- Current R&D Investment Not Visible – Legacy Technology

High Electron Mobility Transistor (HEMT)

- Current R&D Investment **Extremely Active**
- Medium to High Power (300W), ~ $NZ 5 to 10 per Watt
- High Electron Mobility, ~ 5 x Silicon, Target DC To 6 GHz
- Small Signal LNA to 20 GHz, ~ $NZ 2
- Very Recent – Faster Switch-mode Alternative to MOSFET

Field Effect Transistor – FET

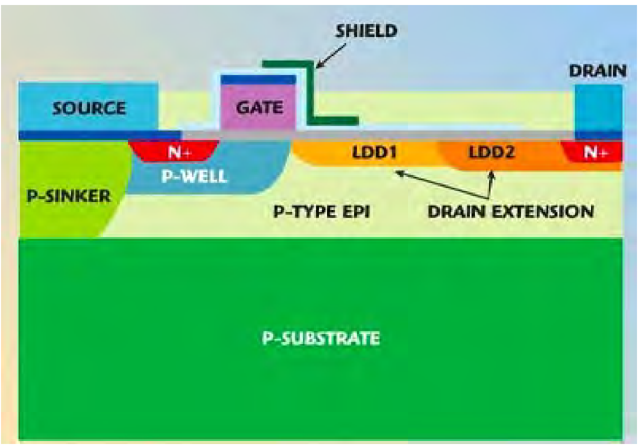
Chapter 2 – The RF FET Fraternity

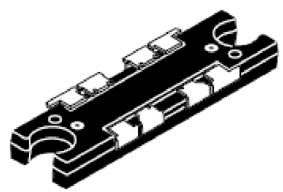


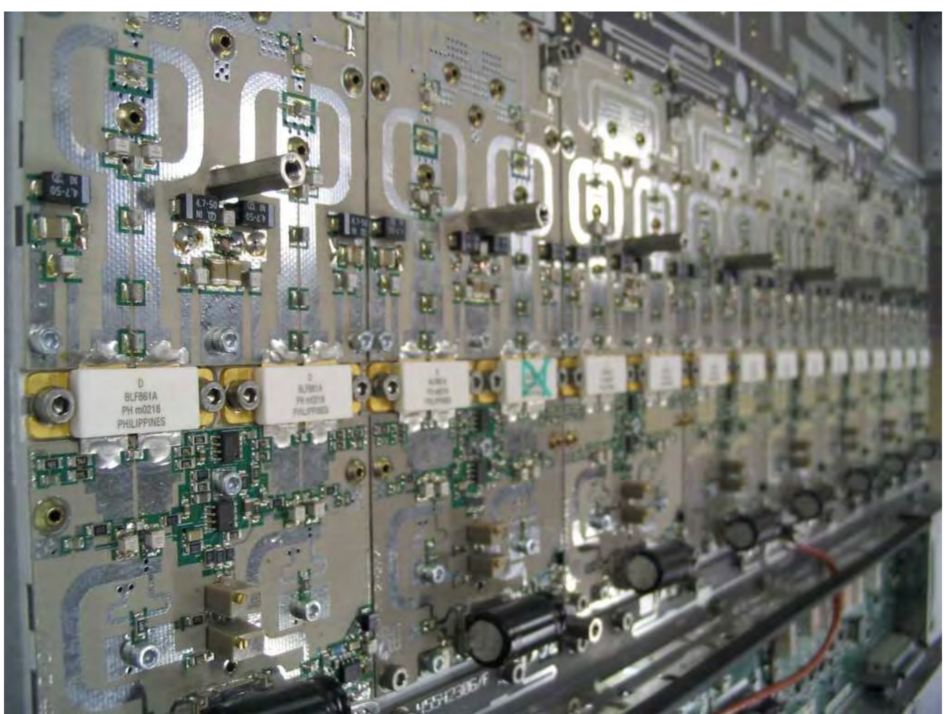
Field Effect Transistor – FET

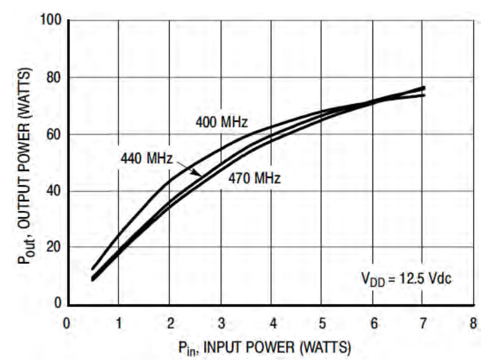
Chapter 2 – The RF FET Fraternity

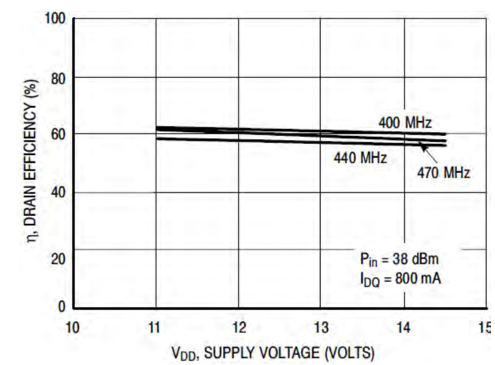
- Motorola Introduced **LDMOS**
- Immediately obsoleted BJT
- Upside down, heat from source
- MRF1570 70Watt $NZ 70.41

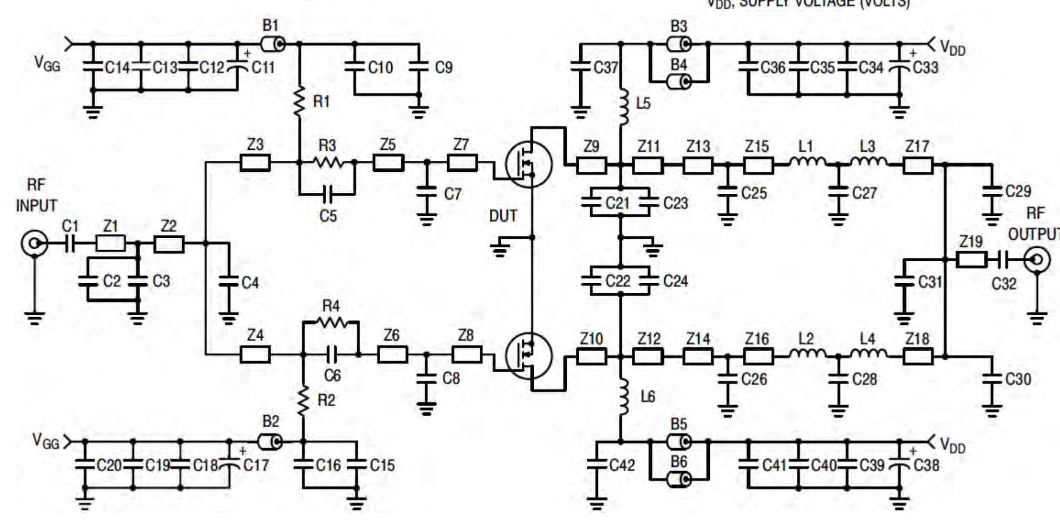






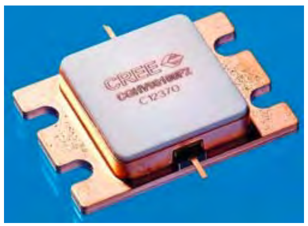


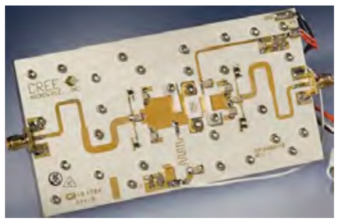




Field Effect Transistor – FET

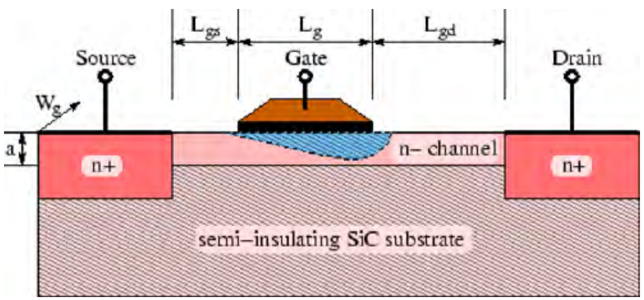
Chapter 2 – The RF FET Fraternity



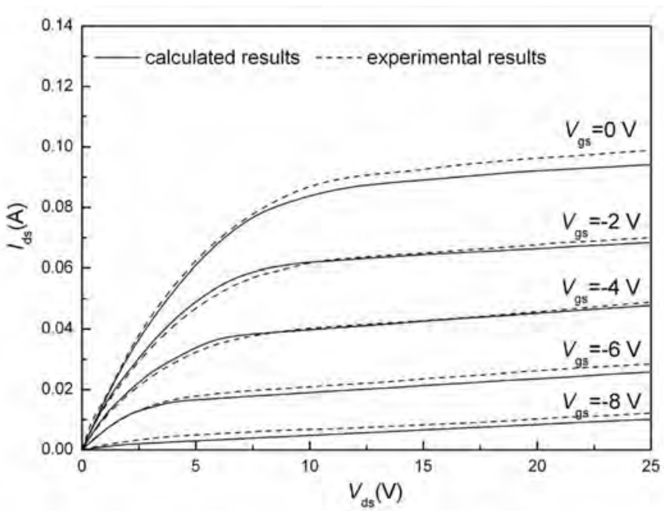


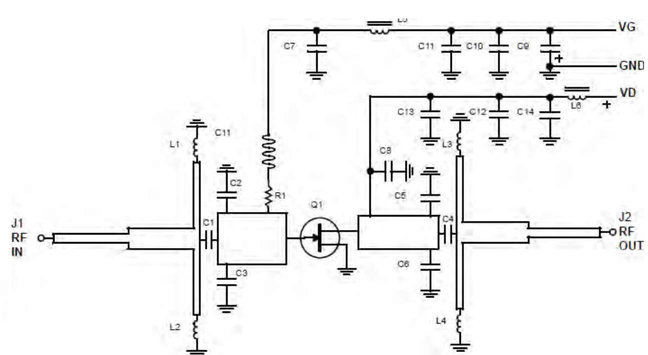
MESFET

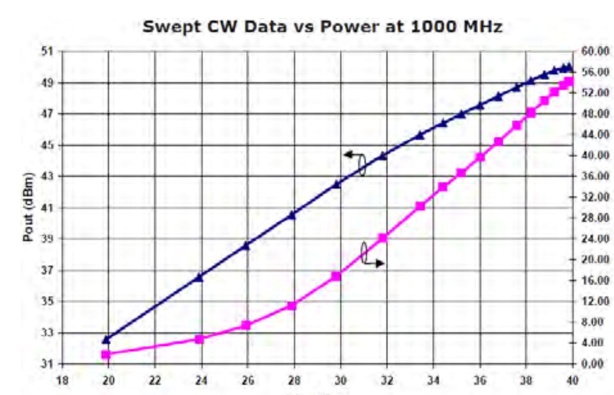
Metal Silicon Field Effect Transistor



- CREE CRF24060 60 Watt 48V
- Depletion mode, -V_{gate} bias
- Small signal types also, 2-gate
- Popularity appears on decline

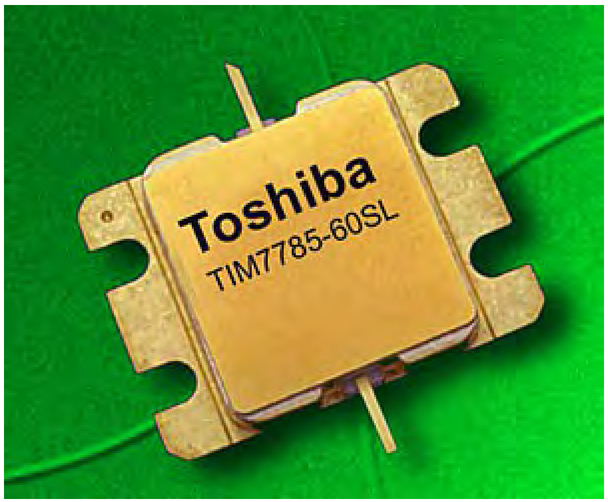






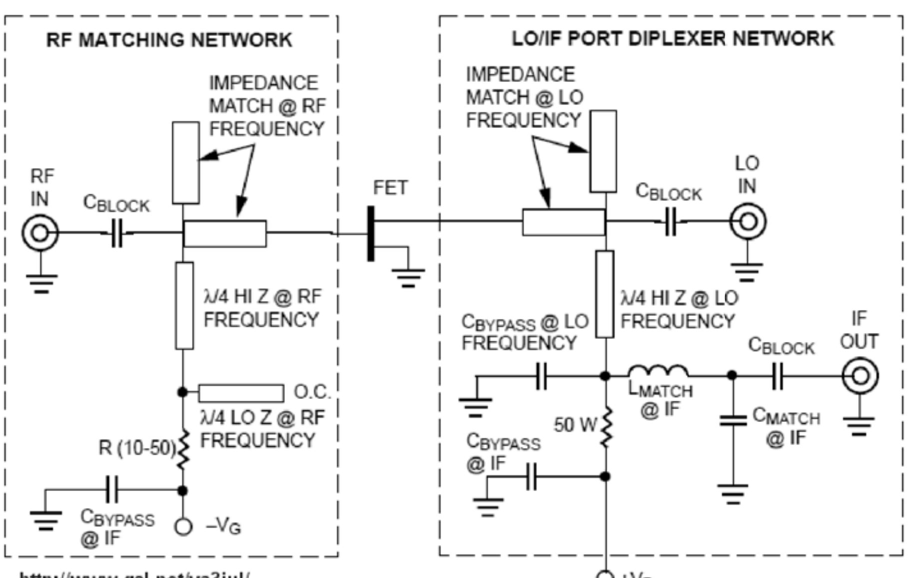
Field Effect Transistor – FET

Chapter 2 – The RF FET Fraternity



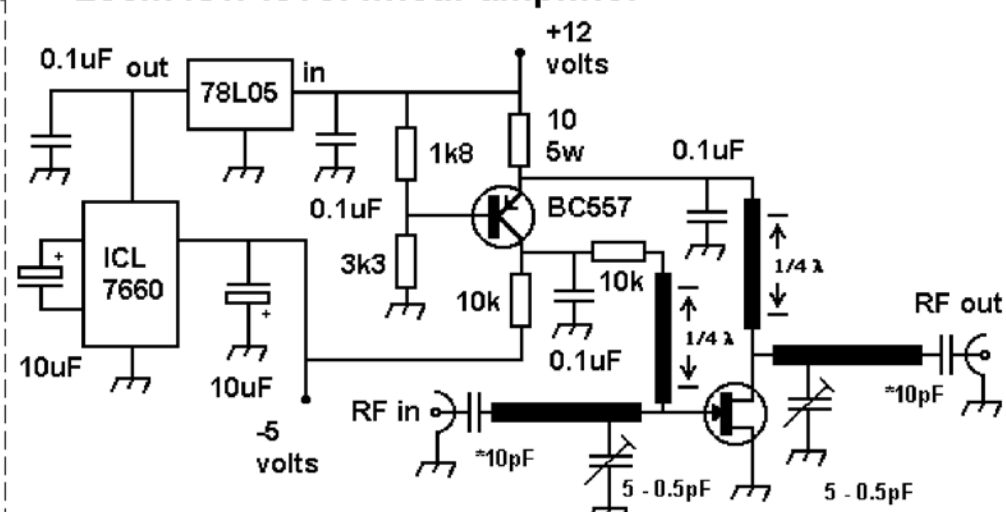
GAsFET

- Depletion mode, always class A
- Medium power and small LNA
- Appears to receive little R&D



http://www.qsl.net/va3iul/

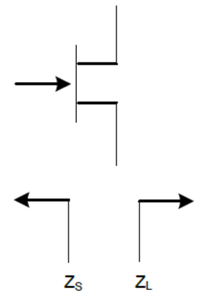
23cm low level linear amplifier

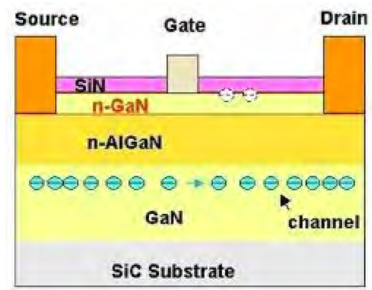


Field Effect Transistor – FET

Chapter 2 – The RF FET Fraternity

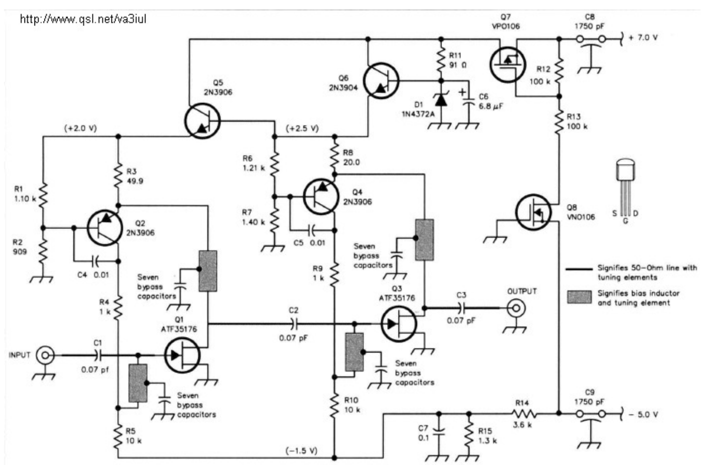
NPT2020 45 W 48 V
DC–2.5 GHz HEMT
$151.29 Digikey NZ





High Electron Mobility Transistor - HEMT

- Depletion mode FET
- Must sequence bias
- Gallium Nitride GaN
- Available, f > 6 GHz
- Power up to 350 W
- Benign impedance
- Currently 2~3 $/Watt



Bias Sequencing

Turning the device ON

1. Set V_{GS} to the pinch-off (V_P), typically -5 V.
2. Turn on V_{DS} to nominal voltage (48 V).
3. Increase V_{GS} until the I_{DS} current is reached.
4. Apply RF power to desired level.

Turning the device OFF

1. Turn the RF power off.
2. Decrease V_{GS} down to V_P.
3. Decrease V_{DS} down to 0 V.
4. Turn off V_{GS}.

Load-Pull Performance: V_{DS} = 48 V, I_{DQ} = 350 mA, T_C = 25°C

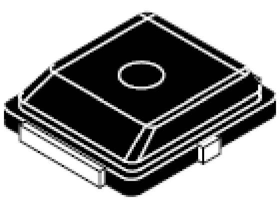
Reference Plane at Device Leads, CW Drain Efficiency and Output Power Tradeoff Impedance

Frequency (MHz)	Z_S (Ω)	Z_L (Ω)	P_{SAT} (W)	G_{SS} (dB)	Drain Efficiency @ P_{SAT} (%)
900	1.1 + j0.7	7.3 + j5.5	74	24	68
2000	1.4 - j6.1	2.9 + j2.4	65	17	68
2500	1.5 - j7.6	2.3 + j0.6	64	14	65

Field Effect Transistor – FET

Chapter 2 – The RF FET Fraternity

MRFG35010ANT1CT-ND pHEMT 3.55 GHz
9 Watt 10 dB 12 V PLD-1.5 $62.49, GaAs HEMT

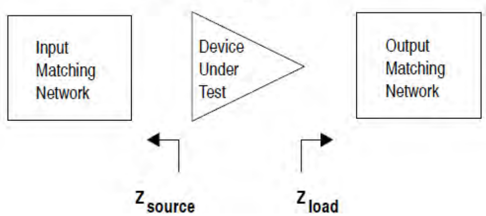


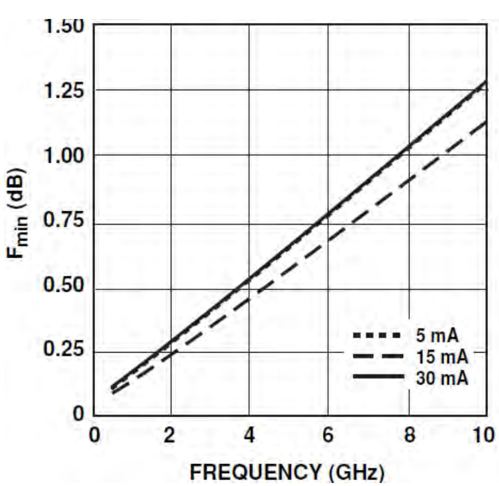
V_{DD} = 12 Vdc, I_{DQ} = 130 mA, P_{out} = 1 W Avg.

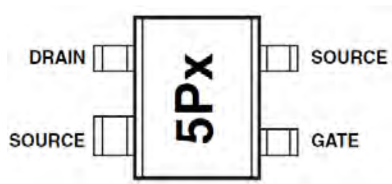
f MHz	Z_{source} Ω	Z_{load} Ω
3550	4.0 – j22.6	4.5 – j15.3

Z_{source} = Test circuit impedance as measured from gate to ground.

Z_{load} = Test circuit impedance as measured from drain to ground.



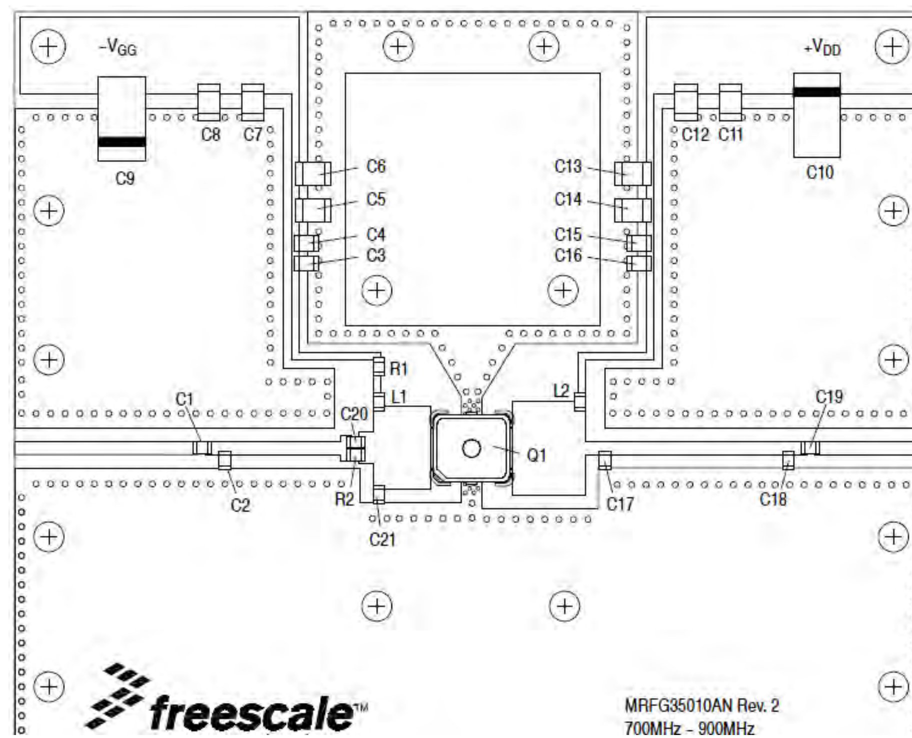




ATF-35143
$2.61 Digikey
Excellent
PDF data

Psuedomorphic HEMT - pHEMT

- LNA and Medium Power RFPA
- MRFG35010 z-Data is minimal
- ATF-35143 Avago z–Data is excellent
- Note – NF is ***inferred*** from PCB loss!



Field Effect Transistor – FET

Chapter 2 – The RF FET Fraternity - Summary

- LDMOS from Motorola, 1 kW to 1 GHz, Mature
- Higher Frequency Motivation – Early MESFET
- Close Cousin – GaAsFET – Medium Power - Class A
- High Electron Mobility Transistor (HEMT) – GaN
- HEMT - Massive Current R&D Investment – 6 GHz +

Field Effect Transistor – FET

Chapter 3 – Example RF FET Circuits

Chapter 3a – Small Signal Low Noise Amplifiers (LNA)

Chapter 3b – Large Signal High Power Amplifiers (RFPA)

Chapter 3c – 23 cm 15 Watt LDMOS RFPA Design Journey

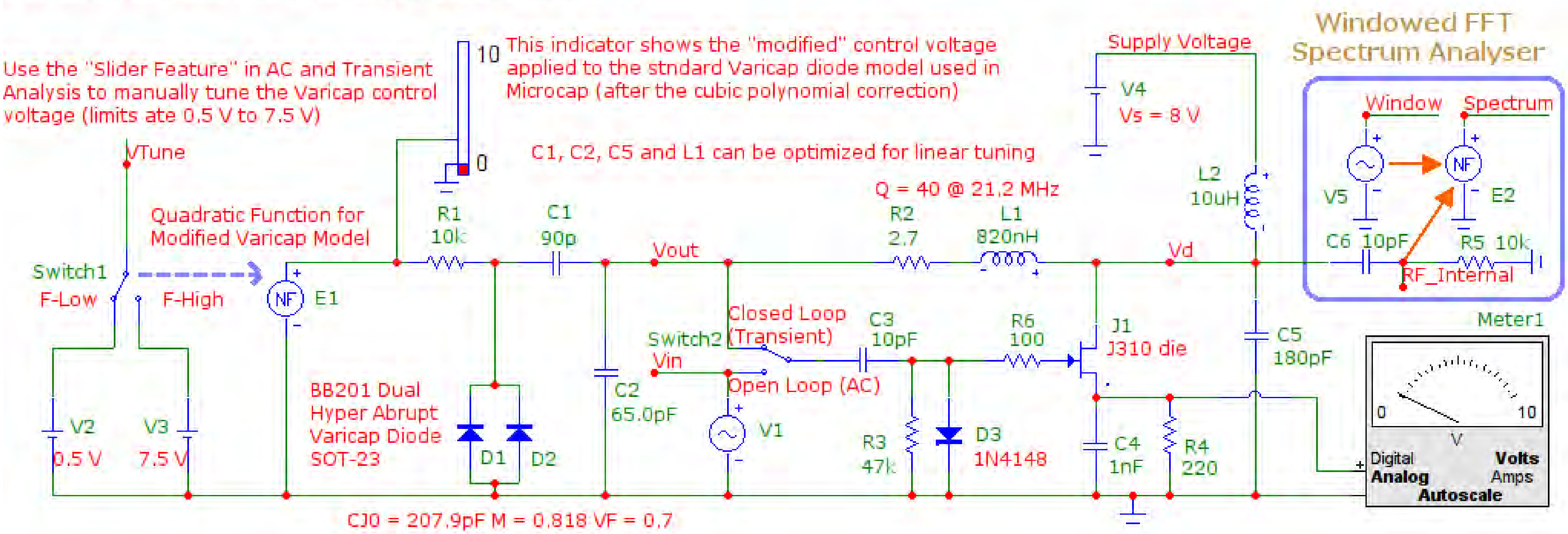
Field Effect Transistor – FET

Chapter 3 - Example RF FET Circuits

3a - Small Signal Low Noise Amplifiers (LNA)

Demonstration RF Voltage Controlled Oscillator (VCO) Simulation File by Ian Scott, 17 August 2013

Open loop (AC) and closed loop (Transient) analysis options are available (Switch2). Enhanced FFT Spectral analysis is provided by using a "Window Function" on the time domain data (V4, NF / E2). Two windows are used, data in the first window is ignored as this corresponds to start up oscillations. The second window processes signals once stable, steady state operation is achieved.



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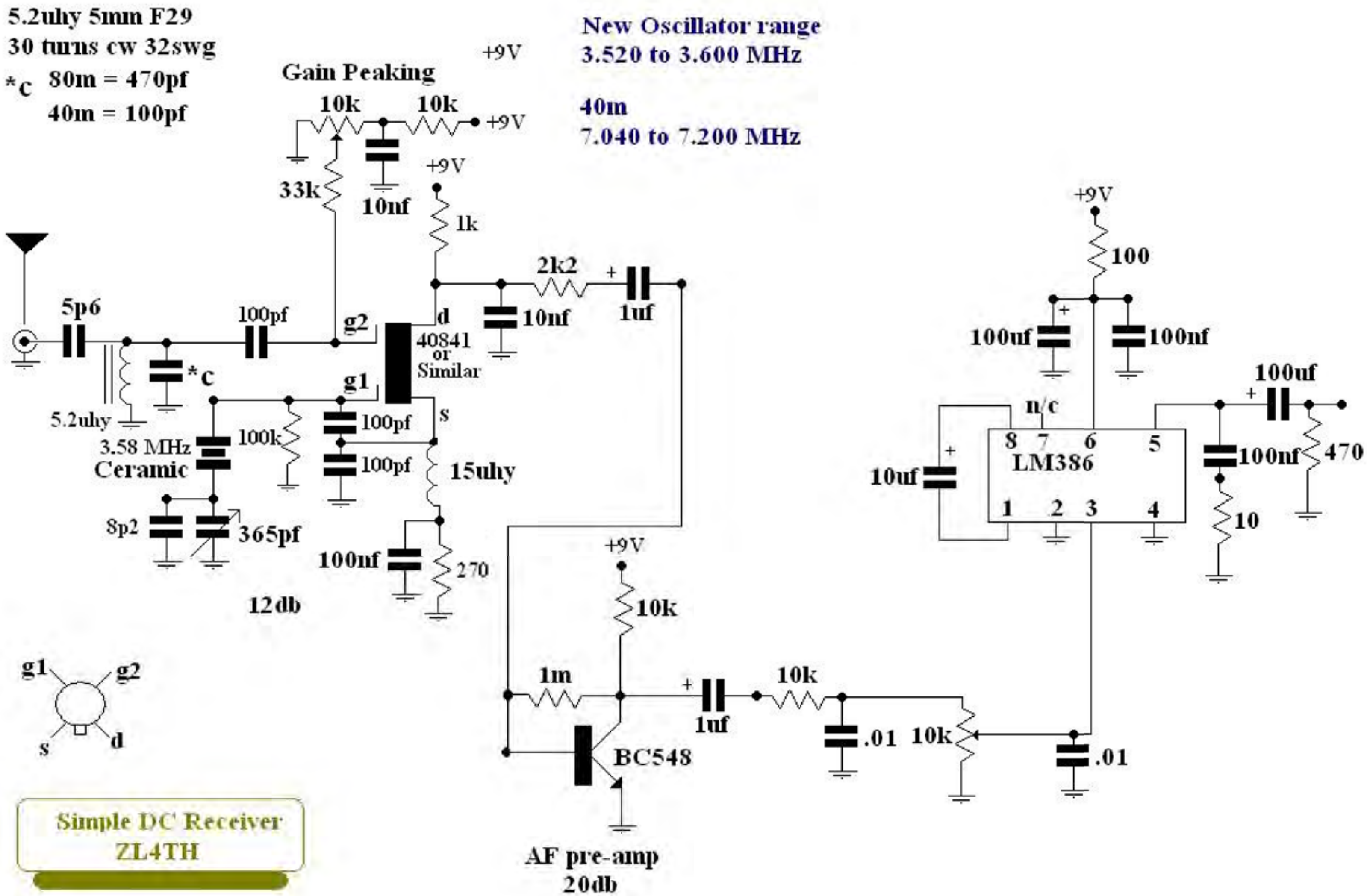
Chapter 3 - Example RF FET Circuits

3a - Small Signal Low Noise Amplifiers (LNA)



Field Effect Transistor – FET

Chapter 3 - Example RF FET Circuits

3a - Small Signal Low Noise Amplifiers (LNA)

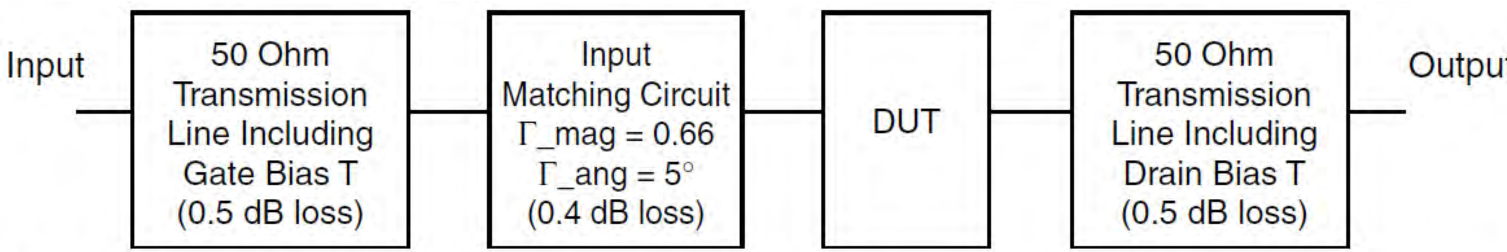
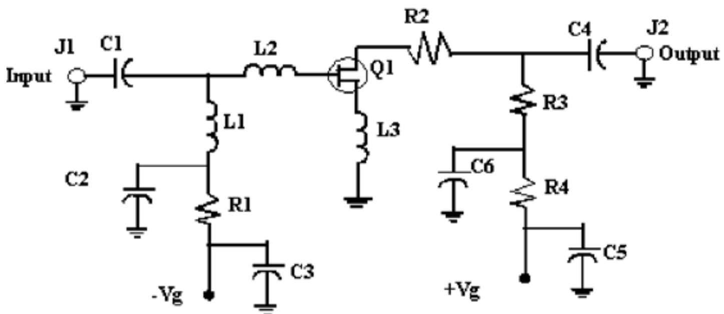
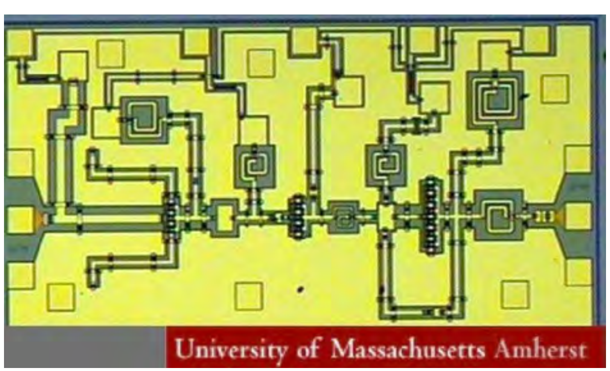


Figure 5. Block diagram of 2 GHz production test board used for Noise Figure, Associated Gain, P_{1dB}, and OIP3 measurements. This circuit represents a trade-off between an optimal noise match and a realizable match based on production test requirements. Circuit losses have been de-embedded from actual measurements.



- **<u>Note</u>** – Quoted NF is *Inferred* - Caveat Emptor!
- Typical pHEMT LNA – Needs Negative Gate Bias
- Best Input Noise Matching Only Uses Series L_2



- Unencapsulated pHEMT Devices – Three Cascaded
- Spiral PCB Drain and Gate Bias Inductors
- Large Output Die – Low Power RFPA?

Field Effect Transistor – FET

Chapter 3 - Example RF FET Circuits

3b - Large Signal High Power Amplifiers (RFPA)

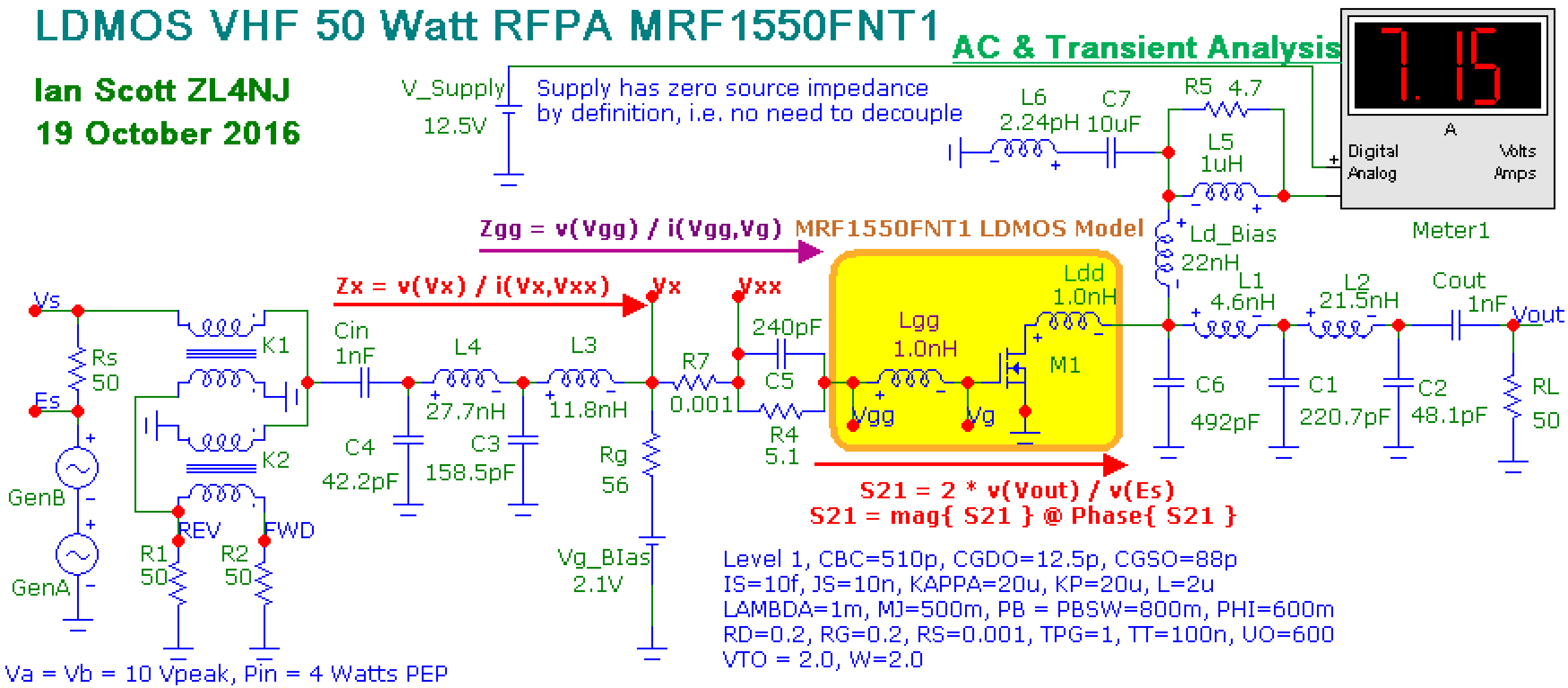
Radio Frequency Power Amplifiers

(RFPA)

Field Effect Transistor – FET

Chapter 3 - Example RF FET Circuits

3b - Large Signal High Power Amplifiers (RFPA)



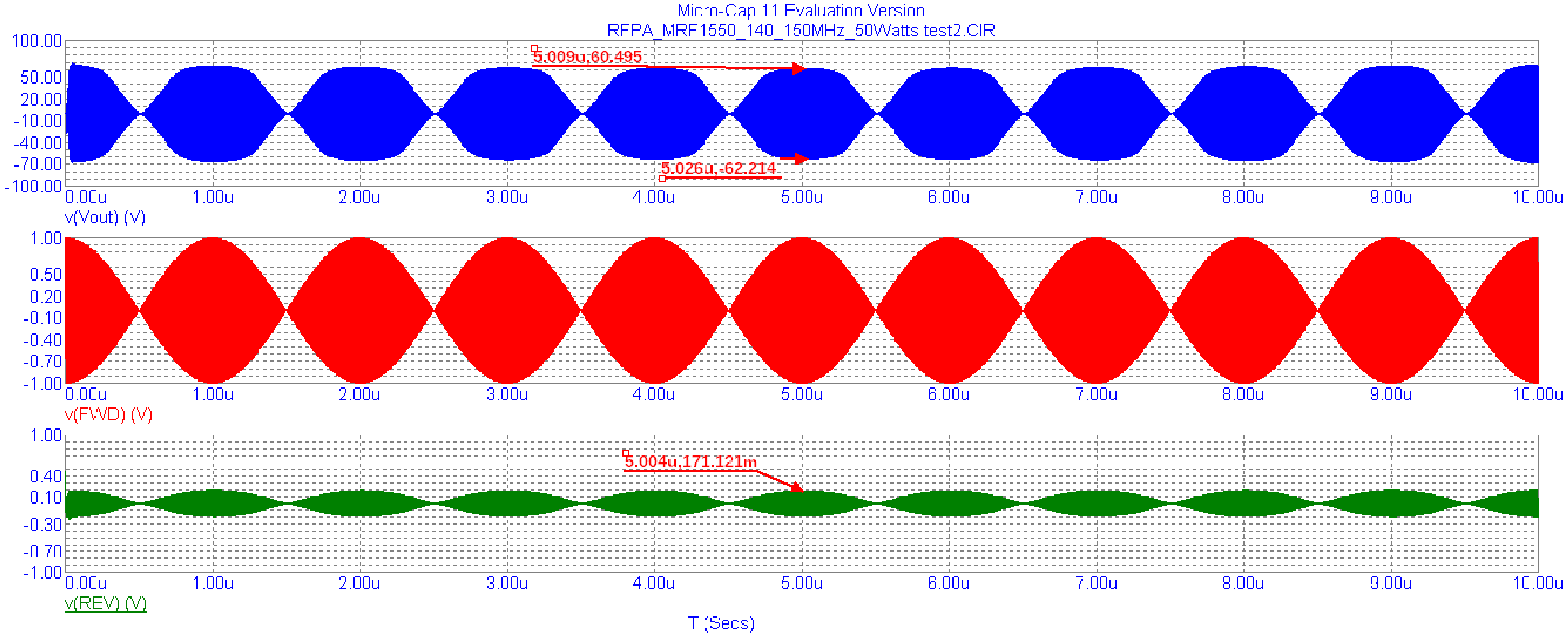
50 Watt VHF RF Power Amplifier using MRF1550 LDMOS Device

This topology is typical for all single ended LDMOS RFPA – lumped elements components are replaced with PCB micro-stripline at higher frequency and RF power

Field Effect Transistor – FET

Chapter 3 - Example RF FET Circuits

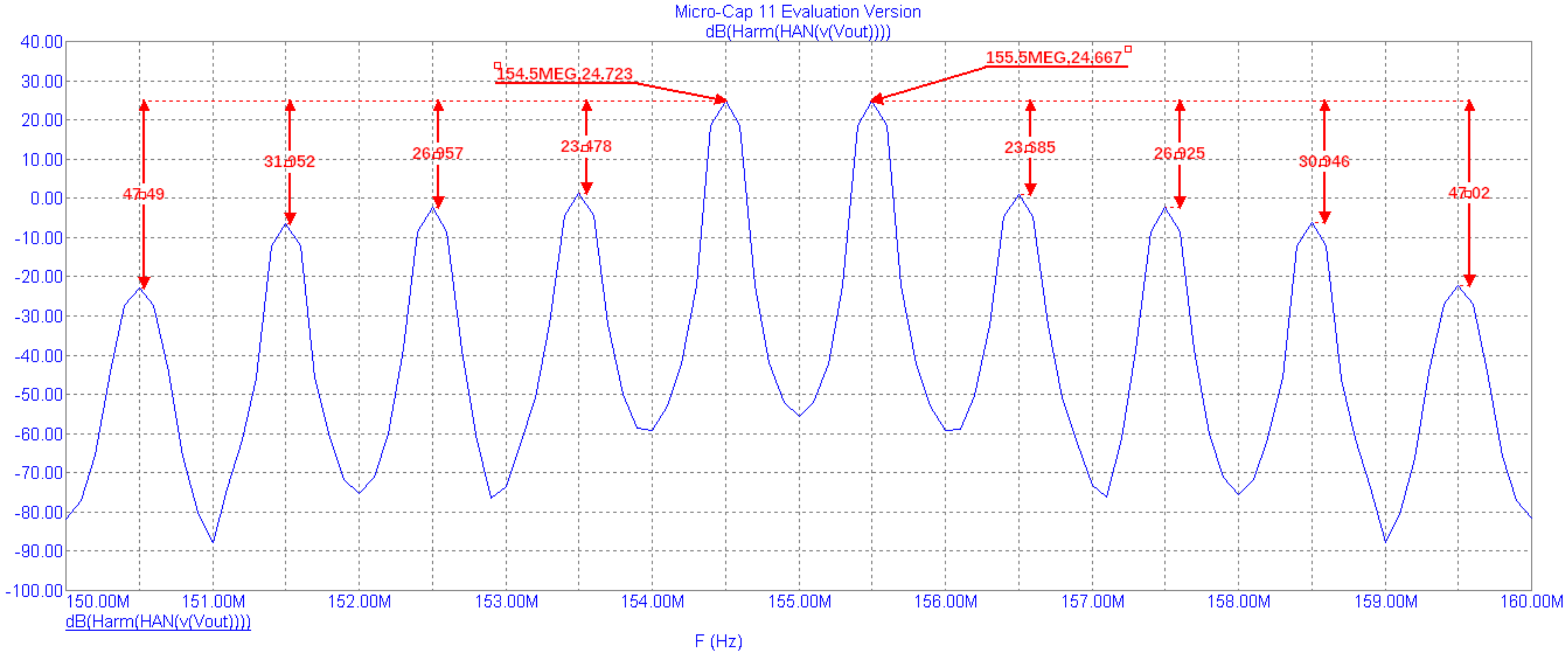
3b - Large Signal High Power Amplifiers (RFPA)



Field Effect Transistor – FET

Chapter 3 - Example RF FET Circuits

3b - Large Signal High Power Amplifiers (RFPA)



Field Effect Transistor – FET

Chapter 3 - Example RF FET Circuits

3c - 23 cm 15 Watt LDMOS RFPA Design Journey

1,250 – 1300 MHz 15 Watt LDMOS RFPA Design Journey

- **Applied RFPA Design Methodology**
- **Hypothetical 15 Watt 23 cm LDMOS RFPA**
- **Will use typical 870 MHz 15 Watt part**
- **Large Signal Impedance Data Extension from 500 – 1,000 MHz to 1,250 – 1,300 MHz**

Field Effect Transistor – FET

Chapter 3 - Example RF FET Circuits

3c - 23 cm 15 Watt LDMOS RFPA Design Journey

PD85015S-E 497-8296-5-ND 870MHz 15Watt 16dB 13.6V PowerSO-10RF $30.66

Symbol	Test conditions	Min	Typ	Max	Unit
P3dB	V_{DD} = 13.6 V, I_{DQ} = 150 mA f = 870 MHz	15	20	-	W
G_P	V_{DD} = 13.6 V, I_{DQ} = 150 mA, P_{OUT} = 15 W, f = 870 MHz	16			dB
h_D	V_{DD} = 13.6 V, I_{DQ} = 150 mA, P_{OUT} = P3dB, f = 870 MHz	60	70		%
Load mismatch	V_{DD} = 1 7 V, I_{DQ} = 300 mA, P_{OUT} = 25 W, f = 870 MHz All phase angles	20:1			VSWR

- Best Close Candidate – 23 cm amateur band has no commercial support
- PD85015S-E LDMOS Intended for f = 870 MHz operation, just below 23 cm band
- Excellent initial power gain Gp = 16 dB, fall -6 dB / octave, Gp ~ 16 – 3.5 = 12.5 dB
- Note its extreme ruggedness – VSWR = 20:1 all phase angles, massive overdrive
- All LDMOS devices are equally suited for linear SSB as well CW FM

Field Effect Transistor – FET

Chapter 3 - Example RF FET Circuits

3c - 23 cm 15 Watt LDMOS RFPA Design Journey

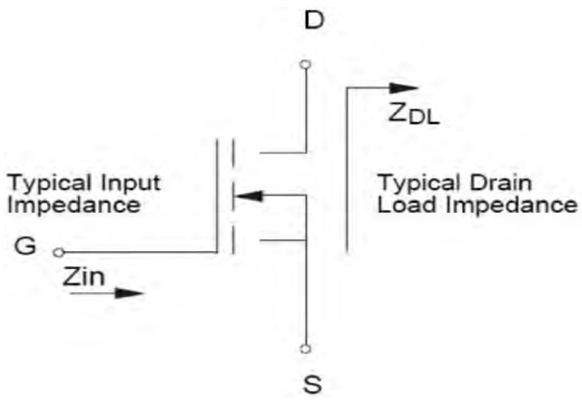


Table 7. Impedance data

Frequency	Z_{IN} (Ω)	Z_{DL}(Ω)
500 MHz	0.536 - j 2.968	4.930 + j 1.083
600 MHz	0.557 - j 1.224	4.329 + j 0.811
700 MHz	0.595 + j 0.236	3.784 + j 0.429
800 MHz	0.651 + j 1.512	3.305 - j 0.031
900 MHz	0.708 + j 2.671	2.889 - j 0.542
1000 MHz	0.761 + j 3.759	2.534 - j 1.085

Note - impedance conventions can be defined at each terminal or by test fixture

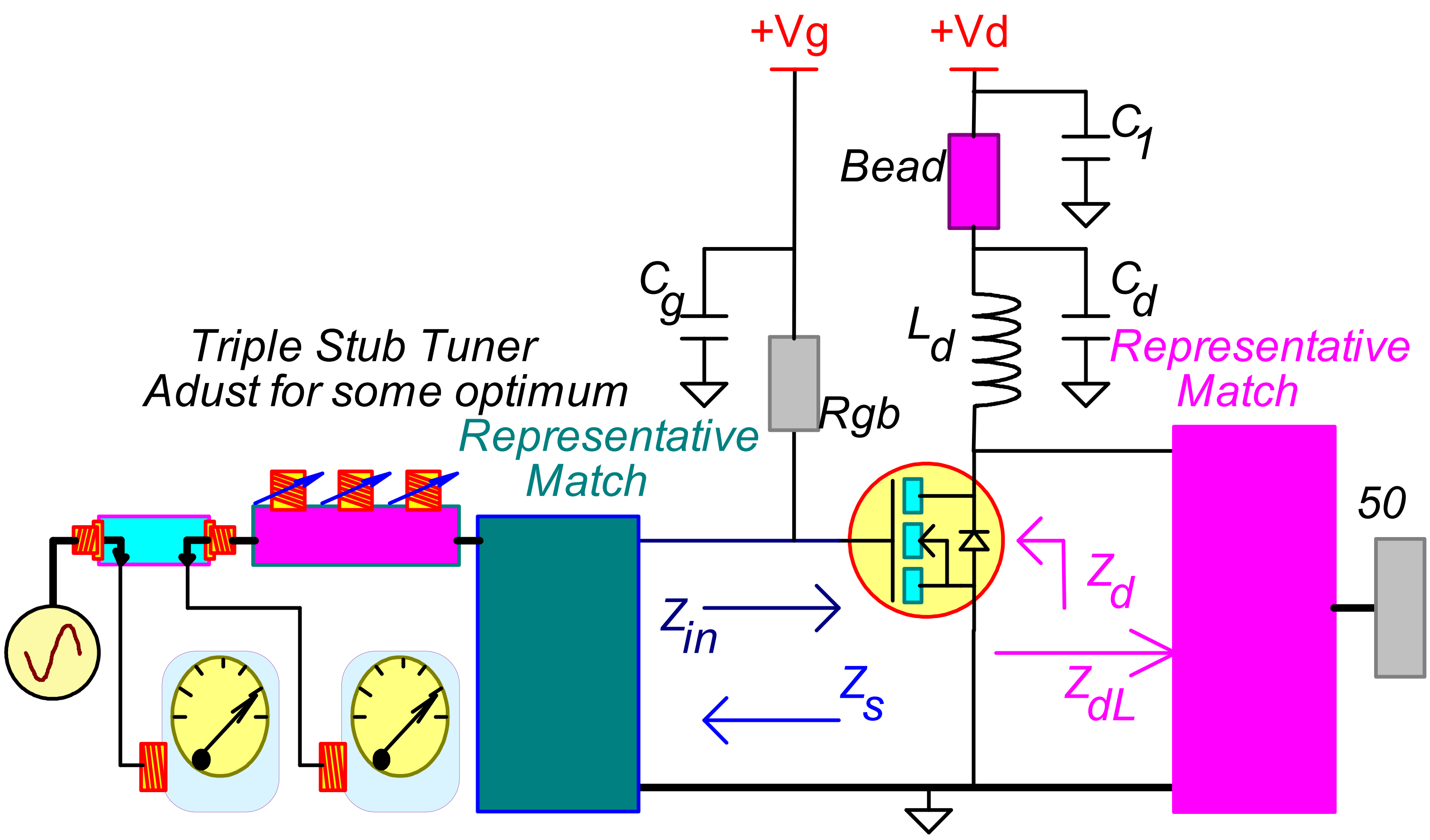
- Large signal impedance data limited to 500 – 1,000 MHz
- However the general trend is smooth and gradual with *f*
- The reactive component can be explained by lead inductance
- Can expect the input impedance Z_{in} to be high Q at 23 cm!

Field Effect Transistor – FET

Chapter 3 - Example RF FET Circuits

3c - 23 cm 15 Watt LDMOS RFPA Design Journey

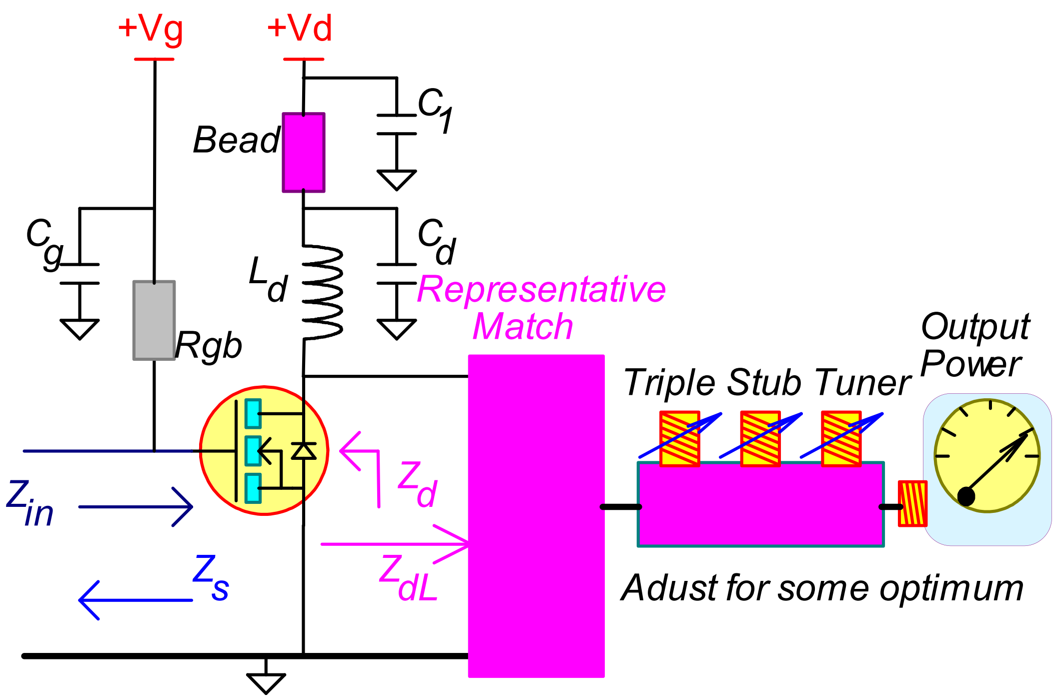
- Large signal device impedance use "load pull" measurement methodology
- Protects s-parameter measurement equipment from high RF Power levels
- Largely overcomes "harmonic interactions" - using representative matching networks



Field Effect Transistor – FET

Chapter 3 - Example RF FET Circuits

3c - 23 cm 15 Watt LDMOS RFPA Design Journey



- Output load pull characterization
- Drain load Z_{dL} defines output power, not device Z_d (meaningless)
- However "fictitious" conjugate impedances are used for designing suitable matching networks
- Only for **lossless networks** $Z_{in} = Z_s^*$ and $Z_d = Z_{dL}^*$

Field Effect Transistor – FET

Chapter 3 - Example RF FET Circuits

3c - 23 cm 15 Watt LDMOS RFPA Design Journey

$\alpha := \text{Find\_}\alpha(\text{Coefficients}, \Omega, \text{Zin})$ $\quad\quad$ $\beta := \text{Find\_}\alpha(\text{Coefficients}, \Omega, \text{ZL})$

$$\text{NewZin} := \text{Poly}(\alpha, \Omega) \quad \text{NewZin} = \begin{bmatrix} 0.536 - 2.968i \\ 0.557 - 1.224i \\ 0.596 + 0.236i \\ 0.651 + 1.512i \\ 0.708 + 2.671i \\ 0.761 + 3.759i \end{bmatrix} \quad \text{Zin} = \begin{bmatrix} 0.536 - 2.968i \\ 0.557 - 1.224i \\ 0.596 + 0.236i \\ 0.651 + 1.512i \\ 0.708 + 2.671i \\ 0.761 + 3.759i \end{bmatrix}$$

$$\text{NewZL} := \text{Poly}(\beta, \Omega) \quad \text{NewZL} = \begin{bmatrix} 4.93 + 1.083i \\ 4.329 + 0.811i \\ 3.784 + 0.429i \\ 3.305 - 0.031i \\ 2.889 - 0.542i \\ 2.534 - 1.085i \end{bmatrix} \quad \text{ZL} = \begin{bmatrix} 4.93 + 1.083i \\ 4.329 + 0.811i \\ 3.784 + 0.429i \\ 3.305 - 0.031i \\ 2.889 - 0.542i \\ 2.534 - 1.085i \end{bmatrix}$$

- Some Mathematics...
- Complex Polynomial z-Fit - Extrapolation
- Moore - Penrose Pseudo-matrix Inversion
- Singular Value Decomposition – SVD
- Excellent Test Cases

Field Effect Transistor – FET

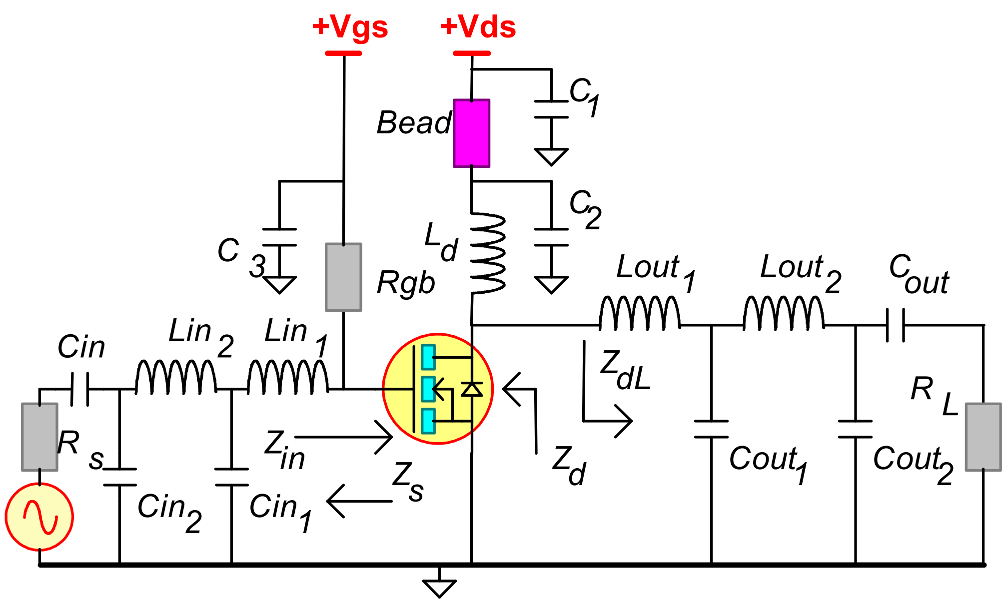
Chapter 3 - Example RF FET Circuits

3c - 23 cm 15 Watt LDMOS RFPA Design Journey

Frequency in GHz **Gate Impedance, Ω** **Load Impedance, Ω**

$$\frac{F}{1000} = \begin{bmatrix} 1.25 \\ 1.26 \\ 1.27 \\ 1.28 \\ 1.29 \\ 1.3 \end{bmatrix} \quad \text{NewZin} = \begin{bmatrix} 1.143 + 6.422i \\ 1.183 + 6.534i \\ 1.225 + 6.647i \\ 1.272 + 6.761i \\ 1.322 + 6.877i \\ 1.376 + 6.994i \end{bmatrix} \quad \text{NewZL} = \begin{bmatrix} 2.074 - 2.565i \\ 2.078 - 2.63i \\ 2.085 - 2.696i \\ 2.095 - 2.763i \\ 2.108 - 2.831i \\ 2.124 - 2.899i \end{bmatrix}$$

- Polynomial Prediction for 23 cm
- High Zin reactance - "Q" (bad)
- Very Benign Load Z_{dL}
- Use Conjugate $Z_d \equiv Z_{dL}^*$ for Output Network Synthesis



- Prototype Test Circuit
- Will Use Lumped Element N = 4 Matching Networks
- Convert to PCB Microstripline Later

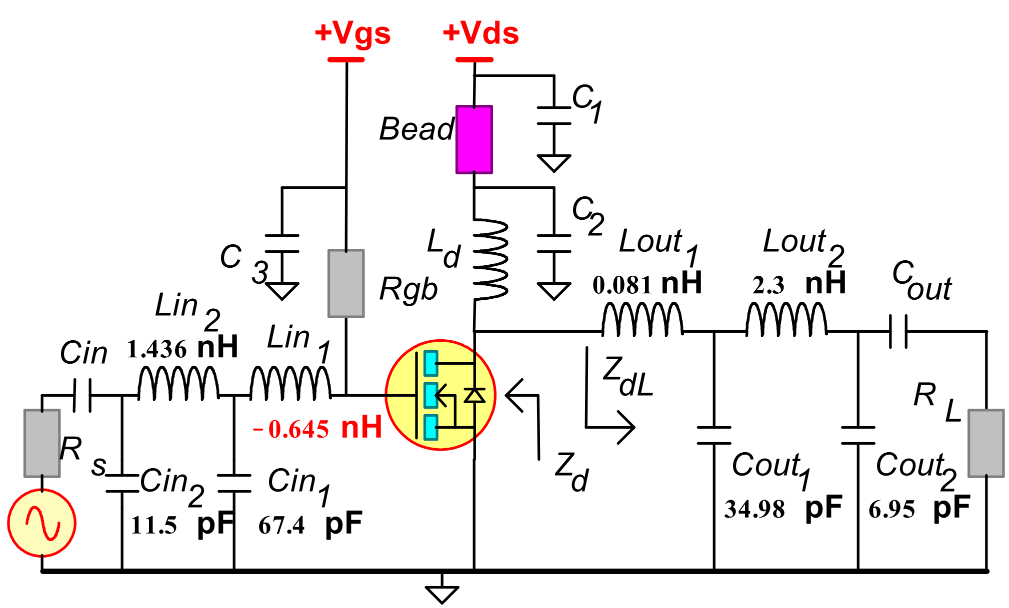
Field Effect Transistor – FET

Chapter 3 - Example RF FET Circuits

3c - 23 cm 15 Watt LDMOS RFPA Design Journey

Lin1	$= -0.645$	nH	Lout1	$= 0.081$	nH
Cin1	$= 67.352$	pF	Cout1	$= 34.981$	pF
Lin2	$= 1.436$	nH	Lout2	$= 2.358$	nH
Cin2	$= 11.502$	pF	Cout2	$= 6.95$	pF

- Network Synthesis using Numerical (iterative) Methods
- Note Lin1 is negative! - Suggests Excessive Package Gate Lead Inductance – Small Lin1, Probably Ignore

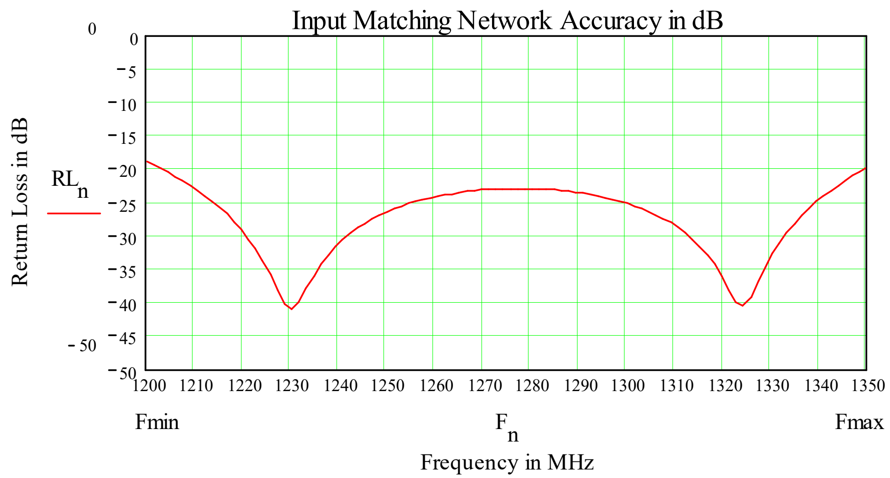


- Prototype LDMOS RFPA with Lumped Element Component Values
- Adequate to Proceed to PCB Microstripline Implementation
- Will Assume Inexpensive FR4

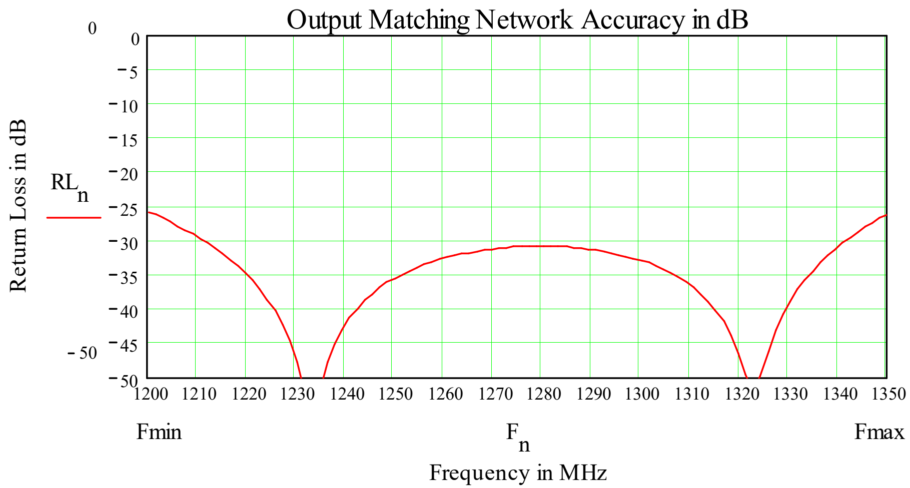
Field Effect Transistor – FET

Chapter 3 - Example RF FET Circuits

3c - 23 cm 15 Watt LDMOS RFPA Design Journey



- Note Dual Resonances – Expected for N=4
- Predicted Input Match Better Than -20 dB
- Design Bandwidth Window Should Exceed Required Target (1,200 ~ 1,350 MHz @ -20dB, >> 23 cm band, 1,240 ~1,300 MHz)



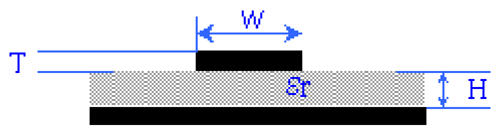
- Predicted Output Match Better Than -25 dB
- Design Bandwidth Window Should Exceed Required Target (1,200 ~ 1,350 MHz @ -20dB, >> 23 cm band, 1,240 ~1,300 MHz)

Field Effect Transistor – FET

Chapter 3 - Example RF FET Circuits

3c - 23 cm 15 Watt LDMOS RFPA Design Journey

$$Z0pcb(\varepsilon r, H, T, W) := \frac{87}{\sqrt{\varepsilon r + 1.41}} \cdot \ln\left(\frac{5.98 \cdot H}{0.8 \cdot W + T}\right)$$



This equation assumes that $0.1 < {}^{W}/_{H} < 3.0$ and $1 < \varepsilon r < 15$. The corresponding velocity factor VF is approximately equal to VF ~ $\varepsilon r^{-0.5}$.

$$w_{\text{eff}} = w + t\frac{1 + \frac{1}{\varepsilon_r}}{2\pi}\ln\left(\frac{4e}{\sqrt{\left(\frac{t}{h}\right)^2 + \left(\frac{1}{\pi}\frac{1}{\frac{w}{t} + \frac{11}{10}}\right)^2}}\right)$$

$$Z0pcb2(\varepsilon r, H, T, W) := \left| \begin{array}{l} Weff \leftarrow W + T \cdot \dfrac{1 + \dfrac{1}{\varepsilon r}}{2 \cdot \pi} \cdot \ln\left[\dfrac{4 \cdot e}{\sqrt{\left(\dfrac{T}{H}\right)^2 + \left(\dfrac{1}{\pi} \cdot \dfrac{1}{\dfrac{W}{T}} + \dfrac{11}{10}\right)^2}}\right] \\ k \leftarrow 1 + \dfrac{4 \cdot H}{Weff} \cdot \left[\dfrac{14 + \dfrac{8}{\varepsilon r}}{11} \cdot \dfrac{4 \cdot H}{Weff} + \sqrt{\left(\dfrac{14 + \dfrac{8}{\varepsilon r}}{11} \cdot \dfrac{4 \cdot H}{Weff}\right)^2 + \pi^2 \cdot \dfrac{1 + \dfrac{1}{\varepsilon r}}{2}}\right] \\ \dfrac{377}{2 \cdot \pi \cdot \sqrt{2 \cdot (1 + \varepsilon r)}} \cdot \ln(k) \end{array} \right.$$

- Convert Inductors to PCB Microstripline, relative permittivity ε_r ~ 4.8, standard FR4 substrate
- Use substrate height H=0.6mm
- Track Width W~0.8mm, Z_0=50Ω
- Simple formula for Z_0 applies
- More Complex “Wheeler’s” Formula for Very Wide Tracks

Field Effect Transistor – FET

Chapter 3 - Example RF FET Circuits

3c - 23 cm 15 Watt LDMOS RFPA Design Journey

- **Applied RFPA Design Methodology**
- **Hypothetical 15 Watt 23 cm LDMOS RFPA**
- **Used PD85015 15 Watt 870 MHz LDMOS Part**
- **Needed To Extrapolate z-Data to 23 cm**
- **Prototype Lumped Element Design**
- **Inductor Conversion to PCB Microstripline**

Field Effect Transistor – FET

- **FET Presentation in Three Chapters**
- **FET History, FET Types, FET Circuits**
- **Hypothetical 15 Watt LDMOS RFPA Design for 23 cm, PD85015 870 MHz**
- **Questions & Comments**

Field Effect Transistor – FET

Inexpensive components, overnight courier – postage waived for orders > $NZ 125

http://www.digikey.co.nz/

Interesting site detailing transistor history – primarily BJT

http://semiconductormuseum.com/Museum_Index.htm

Wikipedia on MOSFET devices – plenty of theory here!

https://en.wikipedia.org/wiki/MOSFET

White paper on LDMOS from NXP (ex Philips)

https://www.nxp.com/files/rf_if/doc/white_paper/50VRFLDMOSWP.pdf

Internet portal for RF products developed by MACOM

https://www.macom.com/products/rf-power-products/

Internet site for Spectrum – free download for Microcap 11 (non commercial use)

http://www.spectrum-soft.com/index.shtm

Internet site for "Quite Universal Circuit Simulator" QUCS – free, excellent RF tool

http://qucs.sourceforge.net/download.html