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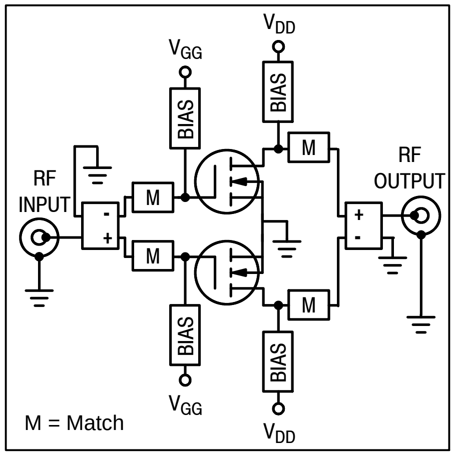
RF Power Reference Design Library

VHF Digital TV Broadcast Reference Design

High Ruggedness N-Channel Enhancement-Mode Lateral MOSFETs

MRFE6VP61K25H
MRFE6VP61K25HS
VHF Broadcast

170-230 MHz, 225 W AVG., 50 V
VHF DIGITAL TV BROADCAST
REFERENCE DESIGN



Reference Design Characteristics

Solid-state broadcast transmitters require transistors that are broadband, highly efficient and very rugged. There is also demand for transistors with higher power capability to minimize device count and combining losses. This document describes the design and performance of a VHF DVB-T power amplifier using the MRFE6VP61K25H LDMOS transistor.

- Frequency Band: 170-230 MHz
- Output Power: 225 Watts Avg. DVB-T
- Supply Voltage: 50 Vdc
- Power Gain (Typ): 25 dB
- Drain Efficiency (Typ): 30%

The MRFE6VP61K25H device is capable of 1250 watts CW operation and suitable for high power applications between 1.8 and 600 MHz. The LDMOS technology used is designed to operate at 50 volts, thereby increasing the power capability per device and reducing the number of devices needed per system. A temperature compensation circuit has been included in the amplifier design to keep the quiescent current stable over temperature.

VHF DIGITAL TV BROADCAST REFERENCE DESIGN

This reference design is designed to demonstrate the RF performance characteristics of the MRFE6VP61K25H/HS devices when applied to the 170-230 MHz VHF broadcast frequency band. The reference design is tuned for performance at 225 watts avg. output power, V_{DD} = 50 volts and I_{DQ} = 2.0 A.

REFERENCE DESIGN LIBRARY TERMS AND CONDITIONS

Freescale is pleased to make this reference design available for your use in development and testing of your own product or products. The reference design contains an easy-to-copy, fully functional amplifier design. It consists of "no tune" distributed element matching circuits designed to be as small as possible, and is designed to be used as a "building block" by our customers.

HEATSINKING

When operating this fixture it is critical that adequate heat-sinking is provided for the device. Excessive heating of the device may prevent duplication of the included measurements and/or destruction of the device.

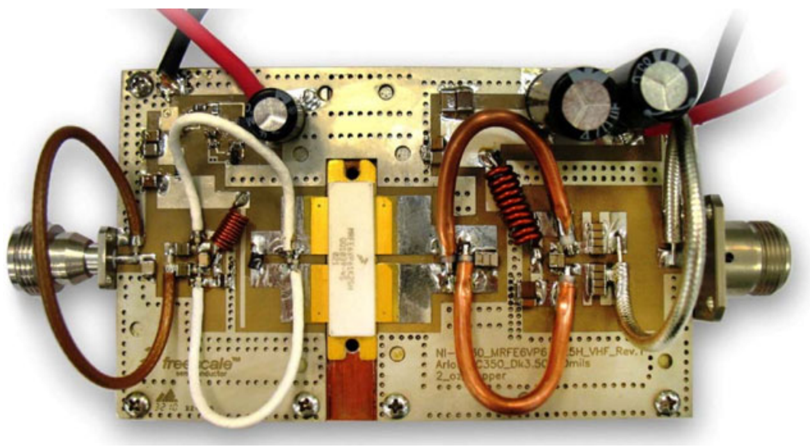


Figure 1. VHF Broadcast Reference Design Fixture

MEASUREMENTS

SMALL SIGNAL

The amplifier is first measured with a small signal over a large frequency range to verify that there are no resonances or gain peaks due to the transistor matching or decoupling network. The small signal measurement can be seen in Figure 2.

PULSED

Although the MRFE6VP61K25H device is capable of 1250 watts CW operation, some of the matching components, e.g. capacitors used in this DVB–T amplifier, could be close to or over their rated temperature at such high power. Therefore a pulsed signal is used to measure power, gain and efficiency of the amplifier.

As shown in Figure 3, the P1dB is more than 1250 watts with an I_{DQ} of 150 mA. The results with I_{DQ} = 2.0 A is shown in Figure 4.

The power capability and P1dB with a pulsed signal gives an indication of the average DVB–T power that the amplifier is capable of with a PAR above 8 dB (0.01% probability, CCDF) and a (non–corrected) shoulder distance below –30 dBc. A rough estimation is that the available DVB–T average power is about 7 dB below the pulsed P1dB power.

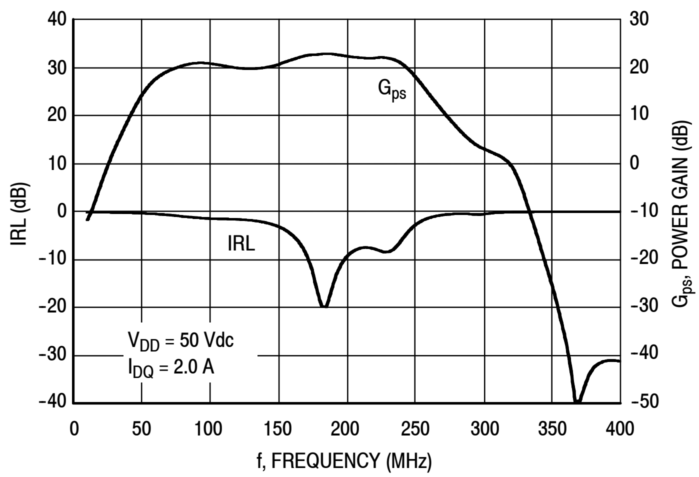


Figure 2. Small Signal Characteristics

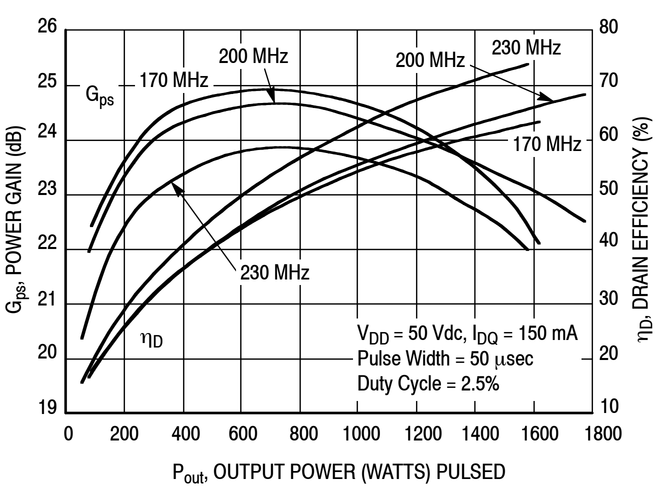


Figure 3. Pulsed Power Gain and Drain Efficiency versus Output Power

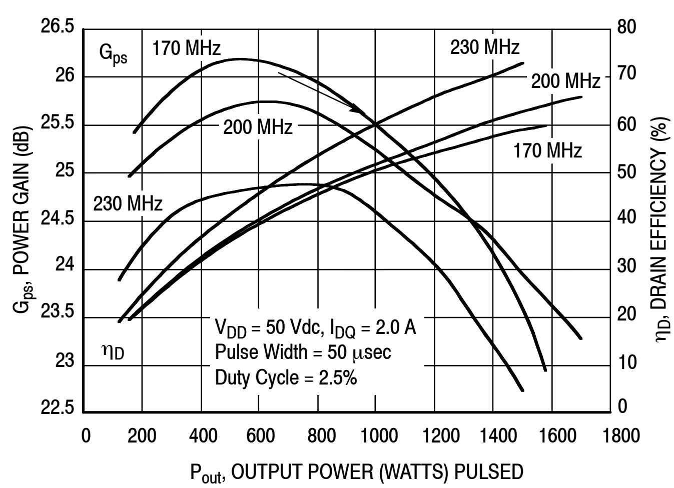


Figure 4. Pulsed Power Gain and Drain Efficiency versus Output Power

DVB-T

A DVB-T signal with a 9.6 dB peak-to-average (PAR) ratio at 0.01% probability on CCDF was used to quantify the broadband performance of the MRFE6VP61K25H device under a digital modulation scheme. The circuit is air-cooled and the device bolted down to the heatsink with thermal grease (Figure 1).

Figure 5 illustrates typical broadband performance at 225 watts avg. DVB-T power. The PAR is above 8 dB across the VHF band of 170-230 MHz with a 30% efficiency and gain of 25 dB.

The drive up data in Figures 6 and 7 shows that it is reasonable to use the device up to 250 watts avg. DVB-T power and still have a PAR above 8 and shoulder distance below -30 dBc. This is in line with the rough estimation that the average DVB-T power is about 7 dB below the pulsed P1dB. The shoulder distance is measured using delta marker at ±4.2 MHz offset.

The device can be used at lower supply voltage for lower output power or to optimize the tradeoff between linearity and efficiency. Decreasing the supply voltage will improve efficiency and decrease the linearity.

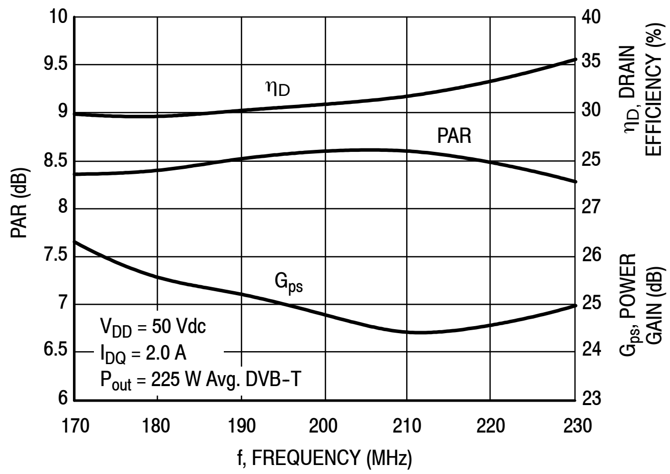


Figure 5. DVB-T Peak-to-Average Ratio, Power Gain and Drain Efficiency versus Frequency

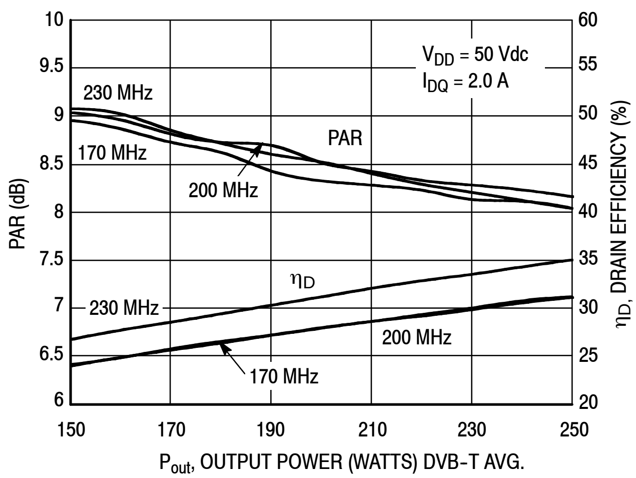


Figure 6. DVB-T Peak-to-Average Ratio and Drain Efficiency versus Output Power

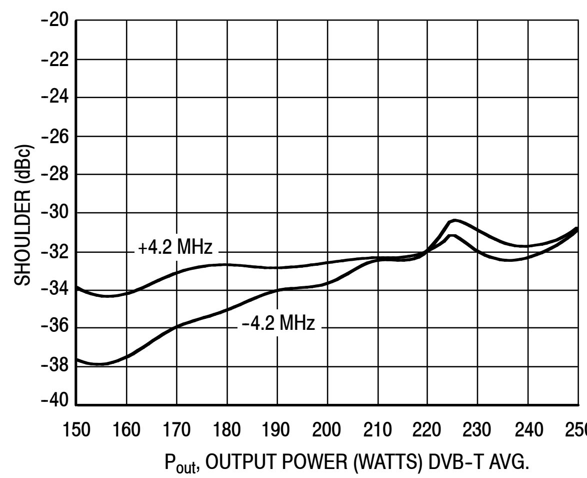


Figure 7. Power Sweep DVB-T Signal Frequency @ 200 MHz

AMPLIFIER DESIGN

MATCHING NETWORK

The first element in the output matching is a LC network made of microstrip lines and capacitors. The LC section is followed by a 4:1 coaxial transformer. The impedance of the coaxial cable is 25 Ω, which is the optimum impedance for a transformation from 12.5 to 50 Ω, following the equation $Z = \sqrt{Z_{in} \times Z_{out}}$.

A 1:1 balun made of a 50 Ω coaxial cable together with capacitors are finalizing the matching network to 50 Ω at the output of the demo board.

Due to the relatively high power of the amplifier, several capacitors were used in parallel instead of using only one. By using multiple capacitors, the total ESR (Equivalent Series Resistance) will be lower which improves the current handling capability.

A printed circuit board (PCB) with high thermal conductivity was also selected to improve the thermal capability of the amplifier and reduce the temperature of the components used in the matching network.

The input matching network is made in a similar way. Simulation software was used to get a first approach of the values needed and to understand the impact of each matching element.

In addition to the matching network, the decoupling circuits for gate and drain bias supply needs to be carefully designed. Small signal measurement and a low frequency probe was used to verify that the decoupling was adequate and without resonances.

A nonlinear electro–thermal transistor model for the MRFE6VP61K25H transistor is available for customers to optimize their design. The model is available online from Freescale's RF High Power Model Library at http://freescale.com/rf/models. Supported CAD tools include Agilent EEsof's ADS and Microwave Office® from AWR Corporation.

TEMPERATURE COMPENSATED BIAS CIRCUIT

Temperature Coefficient of the Transistor

The RF performance of a power amplifier depends on the quiescent current, I_{DQ}. For a fixed gate bias voltage, V_{GS}, the I_{DQ} increases with temperature. A thermal tracking circuit is introduced to compensate for the quiescent current variation versus temperature. Figure 13 shows the PCB layout with components for the amplifier including the thermal tracking circuit.

The tracking circuit is using a voltage regulator (U1) to provide a stable +5 volts.(1) A resistor network including a potentiometer (R7) sets V_{GS} to the desired I_{DQ}. The resistor values are selected to have a tuning range for the V_{GS} to be between 1.1 and 3.2 volts, hence covering both Class AB and Class C operation.

The bipolar NPN transistor (Q1) is used as a thermal tracking device. If the current through the transistor Q1 is kept constant, the base–emitter voltage decreases with increasing temperature. The temperature coefficient of the transistor (Q1) depends on the collector current, I_C, and can be found in the data sheet for Q1. For I_C = 4 mA, the temperature coefficient is around –2.1 mV/°C. This reduction in voltage is used to compensate for the increase in I_{DQ} of the LDMOS device due to temperature.

The temperature coefficient for the MRFE6VP61K25H was measured using a heat and cooling plate. The VHF amplifier with its copper heatsink was placed on the plate and the temperature varied between 0°C and 100°C. The temperature was measured close to the transistor. The gate voltage was adjusted to keep the quiescent current constant over temperature. The measurement was done for quiescent currents of 150 mA, 1.0 A and 2.0 A. The results are plotted in Figure 9. To keep the I_{DQ} constant at 2.0 A, the gate voltage needs to be reduced with 2.1 mV/°C.

The temperature coefficient of the device is depending on the bias point, which explains the difference in thermal coefficient for I_{DQ} = 150 mA (–2.4 mV/°C), I_{DQ} = 1.0 A (–2.3 mV/°C) and I_{DQ} = 2.0 A (–2.1 mV/°C).(2)

The next step is to measure the thermal compensation circuit when the temperature is varied between 0°C and 100°C. The temperature coefficient for the compensation circuit is –2.1 mV/°C. As can be seen in Figure 10, the circuit compensates well the thermal coefficient of the LDMOS device.

Figure 11 shows the behavior for the amplifier with the temperature compensation circuit. The temperature variation is less than 5% between 25°C and 115°C.

FIXTURE IMPEDANCE

V_{DD} = 50 Vdc, I_{DQ} = 2.0 A, P_{out} = 225 W Avg. DVB–T

f MHz	Z_{source} Ω	Z_{load} Ω
170	1.1 + j4.5	2.7 – j0.2
200	2.1 + j5.1	2.2 + j1.1
230	1.6 + j4.1	2.1 + j2.1

Z_{source} = Test circuit impedance as measured from gate to gate, balanced configuration.

Z_{load} = Test circuit impedance as measured from drain to drain, balanced configuration.

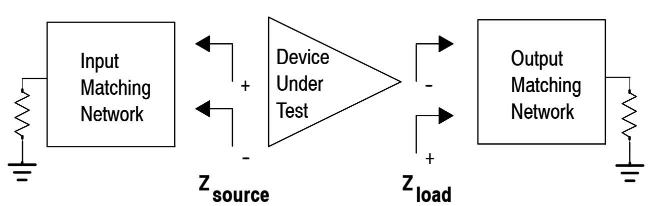


Figure 8. Series Equivalent Source and Load Impedance

TEMPERATURE COMPENSATED BIAS CIRCUIT

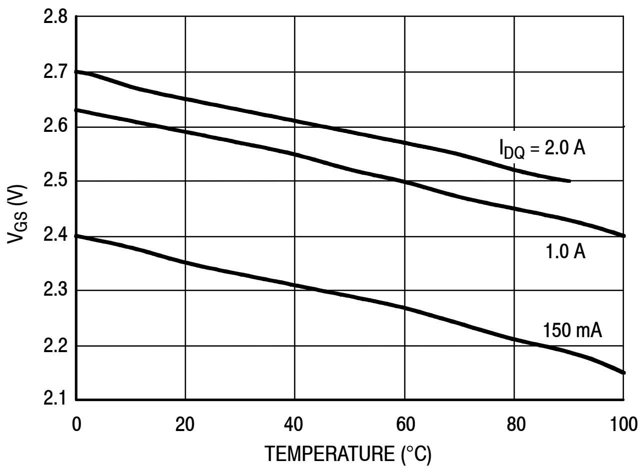


Figure 9. V_{GS} versus Temperature to keep I_{DQ} Constant

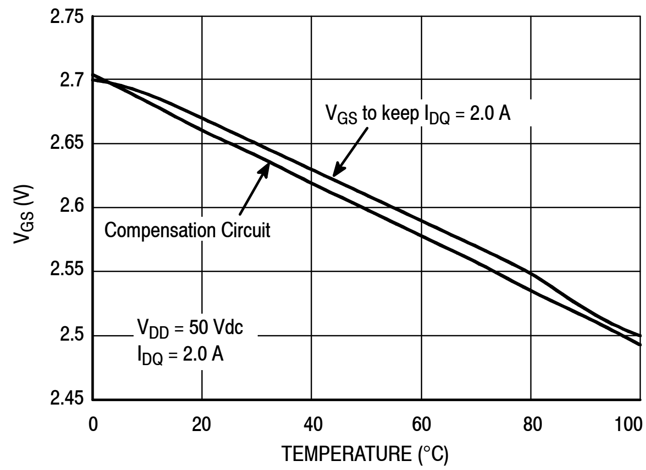


Figure 10. Temperature Compensation Circuit versus V_{GS} to keep I_{DQ} = 2.0 A

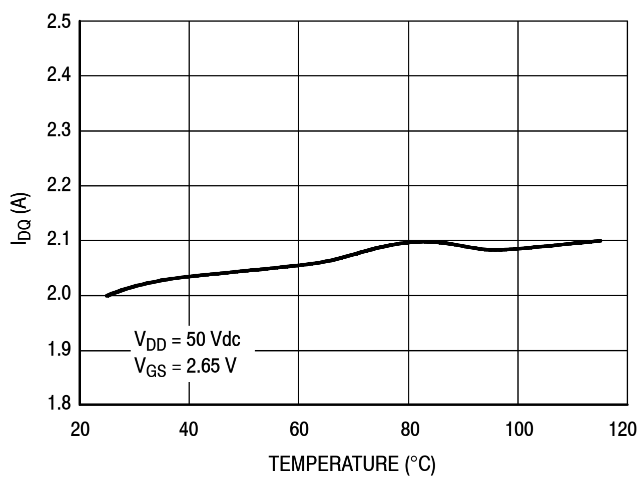


Figure 11. I_{DQ} Drift with Temperature Compensation Circuit

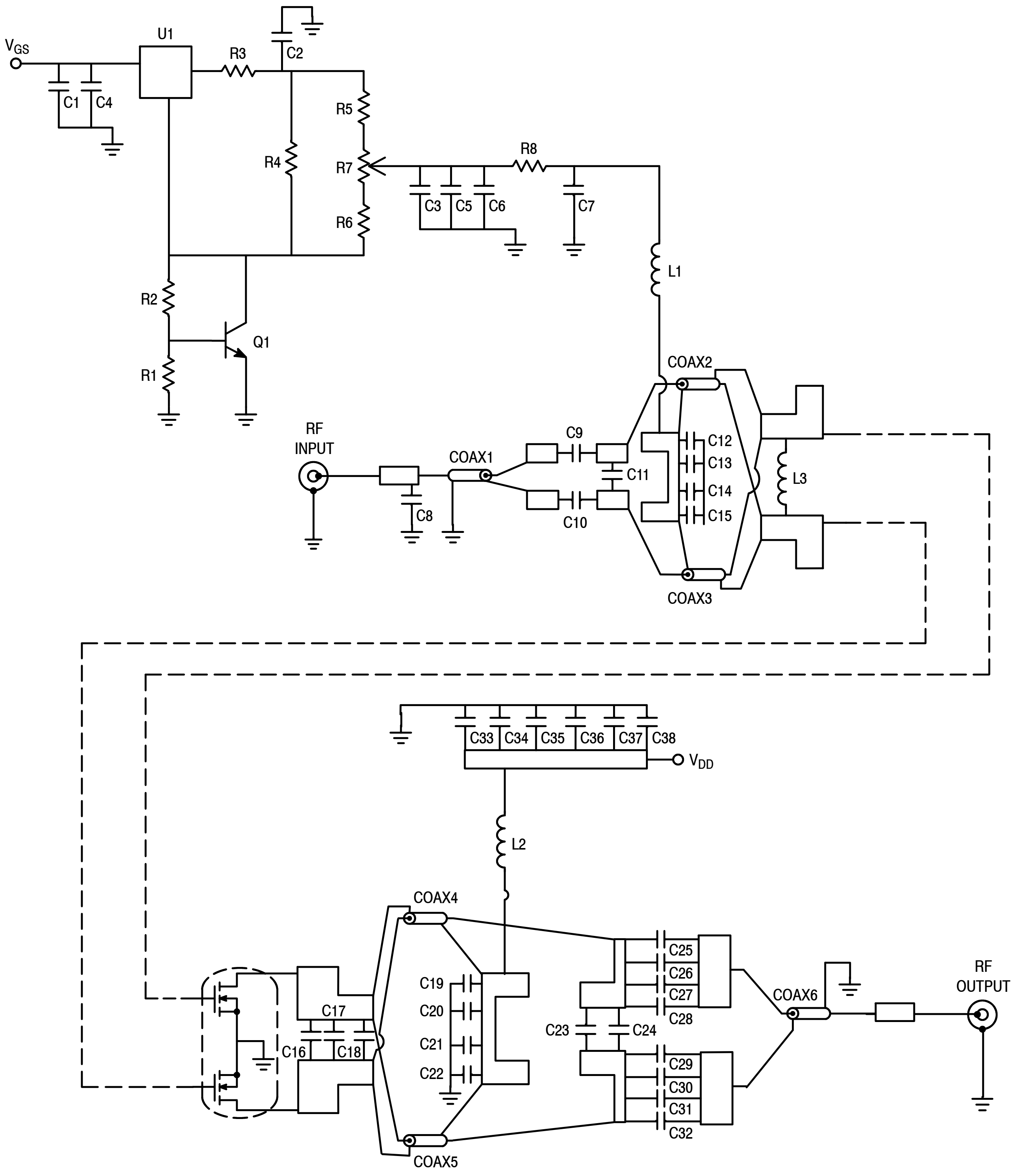
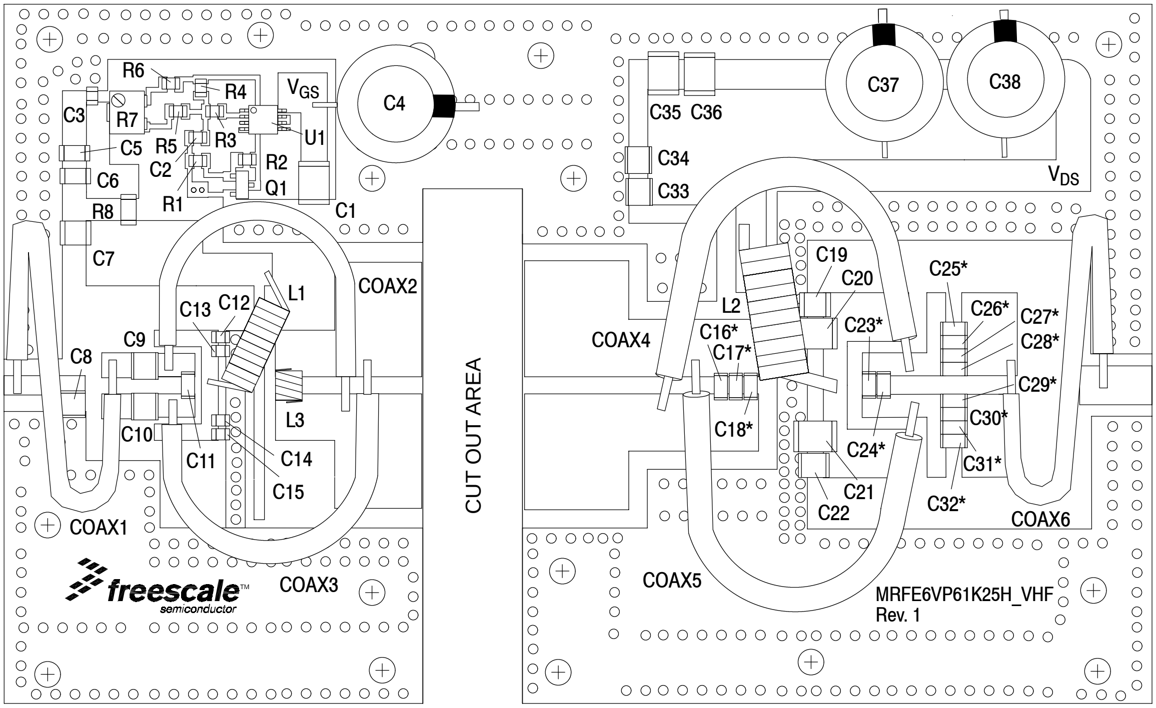


Figure 12. VHF Broadcast Reference Design Schematic Diagram



*C16, C17, C18, C23, C24, C25, C26, C27, C28, C29, C30, C31, C32 are mounted vertically.

Figure 13. VHF Broadcast Reference Design Component Layout

Table 1. VHF Broadcast Reference Design Component Designations and Values

Part	Description	Part Number	Manufacturer
C1	2.2 μF, 100 V Chip Capacitor	HMK432B7225KM−T	Taiyo Yuden
C2, C12, C13, C14, C15	1 μF Chip Capacitors	GRM21BR71H105KA12L	Murata
C3	10 nF Chip Capacitor	C0805C103J5RAC−TU	Kemet
C4	220 μF, 63 V Electrolytic Capacitor	227CKS050M	Illinois Capacitor
C5	100 nF Chip Capacitor	CDR33BX104AKWS	Kemet
C6, C25, C26, C27, C28, C29, C30, C31, C32, C33	1000 pF Chip Capacitors	ATC800B102JT50XT	ATC
C7	2.2 μF, 50 V Chip Capacitor	C3225X7R1H225KT	TDK
C8	22 pF Chip Capacitor	ATC800B220JT500XT	ATC
C9, C10	5.1 nF Chip Capacitors	ATC700B512JT50XT	ATC
C11	36 pF Chip Capacitor	ATC100B360JT500XT	ATC
C16, C17	39 pF Chip Capacitors	ATC800B390JT500XT	ATC
C18	47 pF Chip Capacitor	ATC800B470JT500XT	ATC
C19, C22	1 μF Chip Capacitors	GRM32CR72A105KA35L	Murata
C20, C21, C36	2.2 μF Chip Capacitors	HMK432B7225KM−T	Taiyo Yuden
C23, C24	8.2 pF Chip Capacitors	ATC800B8R2CT500XT	ATC
C34	10 nF Chip Capacitor	ATC200B103MT50XT	ATC
C35	100 nF Chip Capacitor	C1812F104K1RAC	Kemet
C37, C38	470 μF, 63 V Electrolytic Capacitors	MCGPR63V477M13X26−RH	Multicomp
L1	10 Turns, #22 AWG Magnetic Wire	8077	Belden
L2	10 Turns, #16 AWG Magnetic Wire	8074	Belden
L3	2.5 nH Inductor	A01TKL	Coilcraft

(continued)

Table 1. VHF Broadcast Reference Design Component Designations and Values (continued)

Part	Description	Part Number	Manufacturer
R1	2.2 kΩ, 1/8 W Chip Resistor	CRCW08052K20FKEA	Vishay
R2	1.2 kΩ, 1/8 W Chip Resistor	CRCW08051K20FKEA	Vishay
R3	10 Ω, 1/8 W Chip Resistor	CRCW080510R0FKEA	Vishay
R4	1 kΩ, 1/8 W Chip Resistor	CRCW08051K00FKEA	Vishay
R5	3.9 kΩ, 1/8 W Chip Resistor	CRCW08053R90FKEA	Vishay
R6	200 Ω, 1/8 W Chip Resistor	CRCW0805200RFKEA	Vishay
R7	5 kΩ Potentiometer CMS Cermet Multi-turn	3224W-1-502E	Bourns
R8	10 Ω, 1/4 W Chip Resistor	CRCW120610R0FKEA	Vishay
Q1	Bipolar NPN Transistor	BC847ALT1G	On-Semiconductor
U1	Voltage Regulator	LP2951ACDMR2G	On-Semiconductor
Coax1	50 Ω, 5.11″	RG-316	Micro-Coax
Coax2, Coax3	24 Ω, 2.75″	TC-24	RF Power Systems
Coax4, Coax5	25 Ω, Semi Rigid RF Cable, .118″ Line, 2.56″ length.	UT141-25	Micro-Coax
Coax6	50 Ω, 4.72″	EC141-50 Quickform/Hand Formable	NEXANS
PCB*	0.030″, ε_r = 3.5	TC350	Arlon
Heatsink	NI-1230 Copper Heatsink	C193X280T970	Machine Shop

*PCB artwork for this reference design is available at http://freescale.com/RFbroadcast > Design Support > Reference Designs.

FREESCALE RF POWER 50 V TECHNICAL ADVANTAGES

ENHANCED VHV6

The MRFE6VP61K25H is fabricated using Freescale's sixth-generation, very high voltage 50 V LDMOS process technology with enhanced ruggedness (VHV6E). The VHV6 technology was introduced by Freescale several years ago and was a breakthrough for high power devices used for broadcast and other applications like industrial, scientific and medical (ISM) and commercial aerospace, where high power density is required. The high power capability per device allows the MRFE6VP61K25H to reach more than 1.25 kW peak power over the entire VHF band. The VHV6E technology is a further development of the VHV6 technology with improved ruggedness.

RUGGEDNESS

Ruggedness, the ability of the transistor to withstand severe load mismatch conditions under high output power without device failure or degradation in device performance, is a very important parameter when designing a broadcast amplifier. Although the matching circuit plays a role in determining the ruggedness of the amplifier, the intrinsic LDMOS ruggedness of the device is the foundation for the overall amplifier ruggedness.

The ruggedness failure of the MOSFET is the result of a drain breakdown (impact ionization) event. As described in Freescale's *50 V RF LDMOS White Paper*, there are three ruggedness failure mechanisms that can occur as a result of a drain impact ionization event.(3) The first two mechanisms involve the basic breakdown of the MOSFET drain junction, either laterally across the channel or vertically across the drain to source junction isolation. The third mechanism is triggered by an impact ionization event and is the self biasing "snapback" of the parasitic bipolar device.

The MRFE6VP61K25H device has been designed to address the three failure mechanisms resulting in extremely rugged devices. The MRFE6VP61K25H is capable of handling a load mismatch of 65:1 VSWR @ 50 Vdc.

RELIABILITY

In addition to ruggedness, the MRFE6VP61K25H transistor has been developed to meet quality and reliability standards demanded by transmitter manufacturers and operators. There is an MTTF (Median-Time-To-Failure) calculator(4) available to assist the customers in estimating the MRFE6VP61K25H device reliability in terms of electromigration wear-out mechanism. The MTTF is more than 1000 years when operated at V_{DS} = 50 V, P_{out} = 1250 W CW, efficiency = 75%, T_{case} = 63°C and T_J = 128°C.

The device is qualified for a maximum operating junction temperature, T_J, of 225°C.

Operational reliability is also an important aspect of design as reflected in stability of the device performance over its lifetime. All MOSFETs suffer from degradation due to hot carrier injection (HCI). In the case of NMOS FETs, high energy electrons are generated due to high electric fields near the drain corner of the gate. These "hot" carriers can be injected and trapped in the nearby oxide layers over time and impact device performance such as threshold voltage. A shift in threshold voltage will decrease the quiescent current (I_{DQ}) and alter the RF performance. Several device design innovations have been incorporated into the 50 volt VHV6 platform to result in I_{DQ} drift for the MRFE6VP61K25H of less than 5% over 20 years.

ESD PROTECTION

The MRFE6VP61K25H device incorporates enhanced protection against electrostatic discharge (ESD), which makes it less susceptible to damage during handling and manufacturing. As shown in Figure 14, the enhanced ESD protection also increases the maximum rating for the Gate–Source Voltage to –6.0 to +10 Vdc, which in turn allows a greater negative voltage swing without turning on the ESD structure. One example where this feature is very beneficial is Class C operation at high input RF power levels.

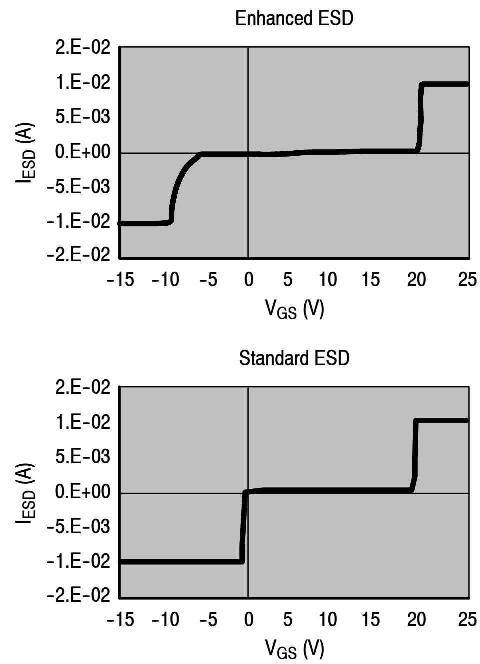


Figure 14. Gate Voltage Breakdown with ESD

THERMAL BEHAVIOR

THERMAL RESISTANCE

Accurate thermal characterization of the RF power transistor as well as the circuit components is necessary to analyze the reliability of the system in which the device is used. To calculate the junction–to–case thermal resistance ($R_{\theta JC}$), the maximum die surface temperature (T_J) during amplifier operation, the case temperature (T_C) and the dissipated power (P_{diss}) must be known.

Total dissipated power is calculated as:

$$P_{diss} = [\text{RF input power} + \text{DC power } (I_D{*}V_D)] - (\text{RF output power} + \text{RF reflected power})$$

Junction–to–case thermal resistance is calculated as:

$$R_{\theta JC} = (T_J - T_C)/P_{diss}$$

The maximum die surface temperature, T_J, of the device is measured with infrared (IR) microscopy, and a thermocouple element is used to measure the case temperature, T_C.

The thermal resistance of the MRFE6VP61K25H measured under CW signal:

$$T_{case} = 63°C,\ P_{out} = 1250\text{ W CW},\ R_{\theta JC} = 0.15°C/W$$

The thermal resistance, $R_{\theta JC}$, depends on both test condition and method. The thermal measurement methodology used by Freescale is described in Freescale Application Note AN1955, *Thermal Measurement Methodology of RF Power Amplifiers*.(5)

REFLOW MOUNTING

All RF performance data in this reference design document is taken with an air cooled copper heatsink and the device bolted down using a clamp and thermal grease as interface material. Reflow mounting, i.e. the device soldered to the heatsink, can be used to lower the overall thermal resistance which reduces the junction temperature and improves RF performance and reliability. For Si–based devices, each 15°C to 20°C reduction in junction temperature typically results in a doubling of the MTTF. Reflow mounting also improves the electrical contact. Proper grounding makes the power amplifier less susceptible to oscillation type damage.

The MRFE6VP61K25HS is a version of the transistor with an earless package for optimal reflow mounting.

More information can be found in Freescale Application Note AN1908, *Solder Reflow Attach Method for High Power RF Devices in Air Cavity Packages*.(6)

CONCLUSION

The design and performance of a VHF DVB–T power amplifier using the MRFE6VP61K25H has been presented. The MRFE6VP61K25H is a 1250 watt device fabricated using Freescale's sixth–generation VHV6E 50 V LDMOS process technology. Under a DVB–T signal using OFDM modulation, the MRFE6VP61K25H achieves 225 watts avg. power at –30 dBc shoulder performance (±4.2 MHz offset) with 30% efficiency and 25 dB gain across the VHF band of 170 to 230 MHz. In addition to very good RF performance, the transistor is also designed for excellent ruggedness and reliability. A thermal compensation circuit is included in the amplifier design to keep the quiescent current constant over temperature.

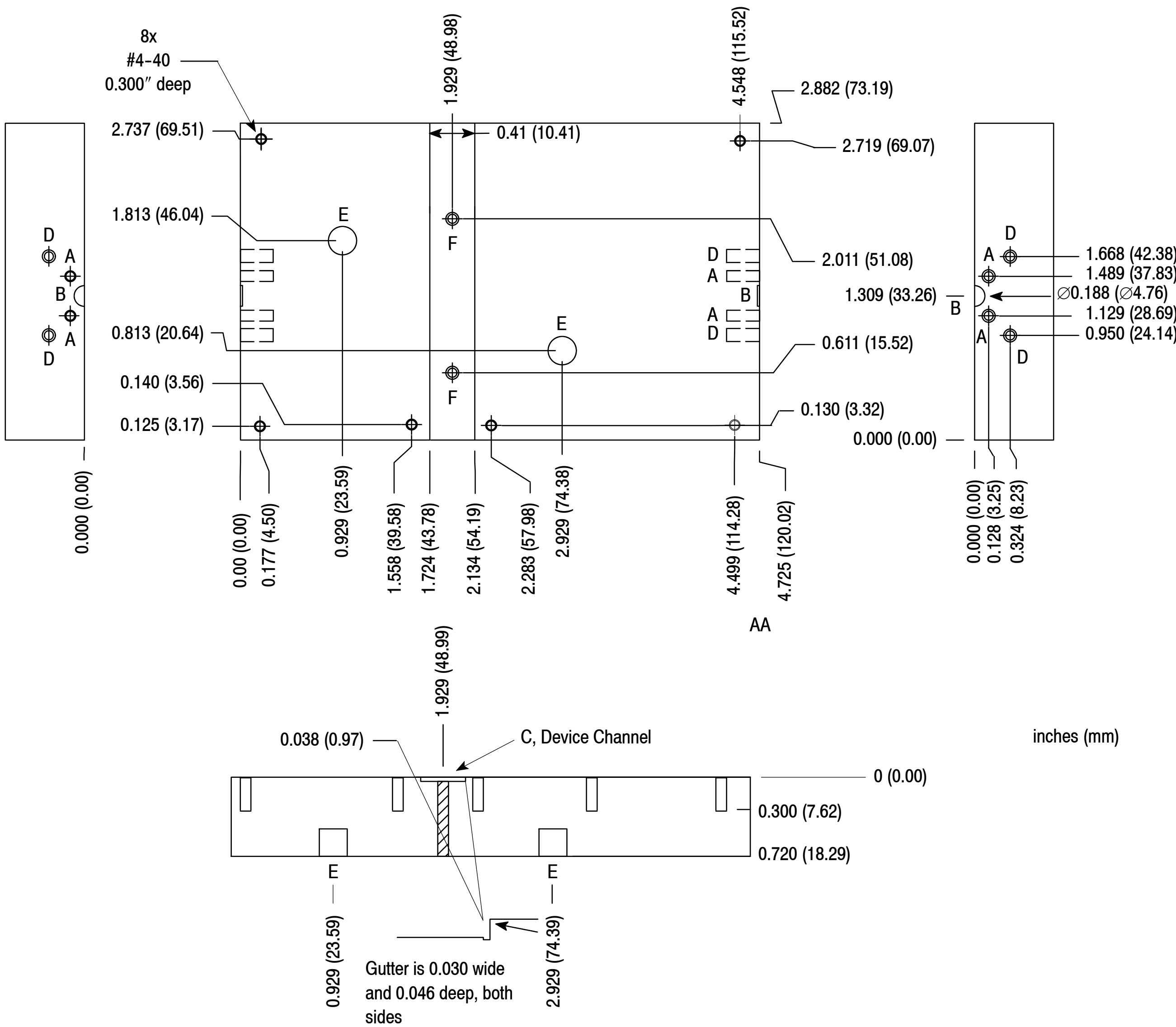
REFERENCES

1. "RF LDMOS Power Modules for GSM Base Station Application: Optimum Biasing Circuit." (Document Number: AN1643) Application Note, 1998.
2. O. Lembeye and J. C. Nanan, "Effect of Temperature on High Power RF LDMOS Transistors," *Applied Microwave & Wireless* (2002).
3. 50 V RF LDMOS White Paper: "An Ideal RF Power Technology for ISM, Broadcast and Radar Applications". Ref. 50VRFLDMOSWP. Available at http://freescale.com/RFpower.
4. MRFE6VP61K25H MTTF calculator available at http://freescale.com/RFpower > Software & Tools > Development Tools > Simulations and Models > Calculators. Enter the "part number" into the Search field for quickest results.
5. "Thermal Measurement Methodology of RF Power Amplifiers." (Document Number: AN1955) Application Note, 2004.
6. "Solder Reflow Attach Method for High Power RF Devices in Air Cavity Packages." (Document Number: AN1908) Application Note, 2011.

Technical documentation, including data sheets and application notes, for Freescale RF Power product can be found at: http://freescale.com/RFpower. Enter the applicable Document Number into "Keyword" search for quickest results.

APPENDIX A

Copper Heatsink for VHF Broadcast Fixture



0.720″ Copper Heatsink Hole Details

Designators	Details
A	2 places, both sides, drill and tap, #2-56 screw depth 0.300″
B	2 places, both sides, 0.1875″ diameter notch 0.020″ deep
C	NI-1230 channel 0.410″ wide by 0.0380″ deep
D	2 places, both sides, drill depth 0.250″ and tap for #4-40 screw
E	Locator holes from bottom diameter = 0.257″, depth = 0.400″
F	2 places, drill through and tap for #4-40 screw

Figure 15. NI-1230 Heatsink

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