RF MOSFET Power Devices

Application Note

Cost-Effective Low-Power Gain Matching of RF MOSFET Power Devices

Power Matters.™

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Revision History

The revision history describes the changes that were implemented in the document. The changes are listed by revision, starting with the most current publication.

1.1 Revision 1.0

Revision 1.0 was the first publication of this document.

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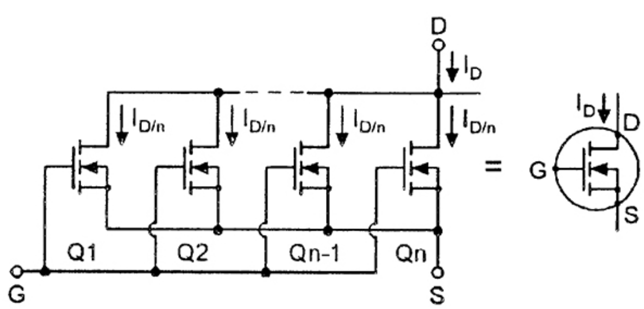
This application note will discuss the purpose and traditional techniques of using RF power to combine power semiconductors in RF power amplifiers. For efficient power combining, device parameters—such as gain, phase, gate threshold V_{th}, transconductance (gFS), and time delay—have all been used to select matched devices. This note will focus on V_{th} and low- and high-power gain measurement as methods for matching power devices. A novel low-power RF gain measurement technique, which closely approximates high-power measurements, will be described, and the empirical results will be presented. This technique will provide excellent gain-matching results for reliable and efficient high-power parallel amplifier circuits. The specific device presented is the Microsemi ARF466A/B, which is a TO247 package, VDMOSFET operating at 300 W in the 27 MHz industrial, scientific, and medical (ISM) band.

2.1 The Need for RF Power Combining

In the design of high-power RF amplifiers, many times a single power device is insufficient to achieve the desired RF output power target for the system. Typical single devices available for ISM applications are in the 1 kW range. "Paralleling," or RF power combining, must be utilized to achieve the high RF power levels required by ISM band systems with output power requirements of nearly 50 kW. Another purpose for power combining is to use smaller, less expensive power devices to achieve the power of a single, costlier power device. Many times this is possible if the cost of the splitter/combiner circuits is kept low and there is sufficient space on the PCB for multiple devices.

Power splitting and combining can be as simple as two or more devices operating in phase and parallel, as shown in the following illustration. "Hard Parallel" circuits can and usually do exhibit stability problems (oscillations). This is due to the lack of electrical isolation between the individual devices and the resultant positive feedback. Hard parallel circuits can be stabilized with gate resistance for isolation, at the cost of significant reduction in high-frequency response. This occurs because the gate resistor combined with the device gate capacitance form an RC low-pass filter. This configuration is similar to those found within large power devices, which have many parallel cells on the same silicon chip. For more information, see Microsemi Discrete Product Group Application Note 1814, *Paralleling MOSFETs in RF Amplifiers*, October 2010.

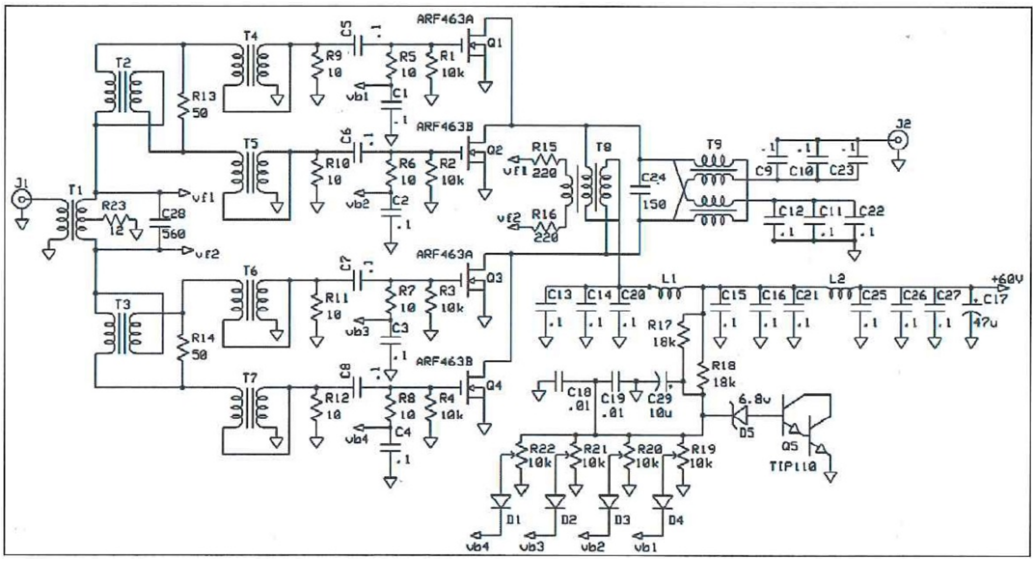
Figure 1 "Hard Parallel," In-Phase RF Power-Splitting/Combining Circuit



A more complex, but also more practical, four-way circuit is shown in the following illustration. The circuit provides device-to-device isolation for stability. In this circuit, Q1/Q2 and Q3/Q4 each form a pair of devices, driven in phase (a push-pull device in a single package could replace two discrete transistors). Isolation between the paired devices is provided for the upper circuit by T2, T4, T5, and R13, and for the lower circuit by T3, T6, T7, and R14. These types of splitter circuits are sometimes referred to as Magic-T circuits. For more information about Magic-T circuits, see "Combiner and Splitters" on the W8JI website at http://www.w8ji.com/combiner_and_splitters.htm. An excellent technical resource for ferrite impedance transformers, including splitters and combiners, is *Transmission Line Transformers 5th Edition* by Jerry Sevic (2001).

In addition to in-phase combining, the need for matched devices also applies to quadrature (90-degree) and push-pull (180-degree) circuits, as well. Push-pull circuits should be considered in applications where linearity is a priority, as even-order harmonic cancellation is inherent in 180-degree splitter/combiner circuits.

Figure 2 Four-Way ISM Band Amplifier with Isolation and Impedance Matching Transformers

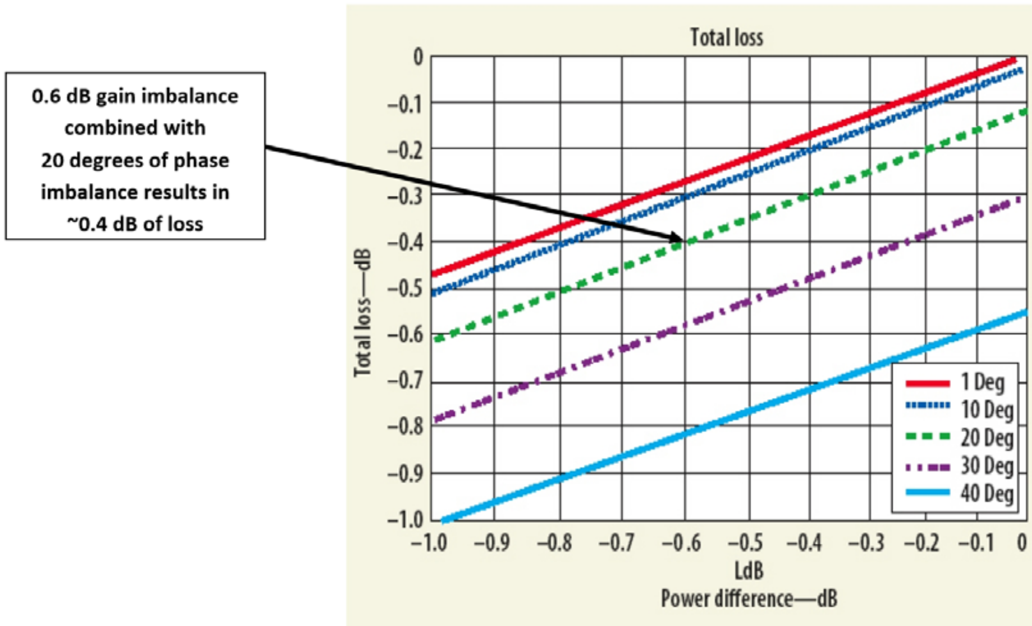


2.2 Matching Parameters for RF Power Combining at ISM Frequencies

There are two primary types of power splitting and combining circuits at ISM frequencies: in-phase and push-pull. In-phase, or hard parallel, indicates that two (or more) devices are driven with signals that are 0 degrees in phase difference or phase coherent. The second type of combiner, push-pull, gets its name due to the signals being 180 degrees out of phase. Each of these types of combining techniques have advantages and disadvantages; but for the most efficient operation of either type, only the phase is mentioned in the name. What about amplitude?

Both amplitude and phase must be considered for proper RF power combining. This total system includes the power-combined RF devices and both the input splitter and output combiner circuits. If the input splitter and output combiner have significant amplitude or phase mismatch, the result might actually help a pair of mismatched devices. However, it usually degrades the performance, so the designer should carefully consider the input and output circuits, as well as the amplitude and phase of the RF devices themselves. Matched or matched pair devices are devices that have had a specific parameter or number of parameters matched closely in value, which will result in best efficiency in a power combiner application. An excellent reference demonstrating the need for matched RF devices can be found in Howard Hausman's *Understanding Mismatch Effects in Power Combining Circuits*, found in the 2006 issue of *Microwaves & RF*. The following graph demonstrates the finite and significant loss that results in both gain and phase mismatch between devices operating in a parallel configuration.

Figure 3 Total Loss (dB) for 0 dB–1 dB Gain/Power Imbalance and 1°–40° of Phase Imbalance



For example, a split and combined system with a pair of RF devices having a gain imbalance of 0.6 dB, and a phase imbalance of 20 degrees results in a total power loss of approximately 0.4 dB. When discussing ISM or relatively low frequencies (<175 MHz), amplitude differences are the predominant source of combining losses—due to the long wavelengths involved, the phase differences between devices are negligible. Because gain imbalance is the major factor for efficient operation of power-combined ISM band systems, gain matching of the power devices is the practical and necessary consideration for the power-combined RF circuit designer.

2.3 Gate Threshold (V_{th}) and RF Gain Matching

V_{th} matching, in place of RF gain matching, has been utilized under the assumption that it is equivalent or similar to less costly implementation of RF gain matching. It is a simple test where the drain is tied to the gate and an arbitrary voltage is applied such that a specific drain current is measured, typically between 250 µA and 10 mA depending on the application. Lower drain currents are typically used for on-die or wafer measurements, whereas higher current measurements are performed at the packaged device level. Several studies within Microsemi, including the results shown in this document, have demonstrated that this test is not a sufficient measurement for efficient RF device gain matching; in fact, there is little correlation between V_{th} and RF gain. However, V_{th} matching is useful in simple circuits where gate voltage and the resultant drain current are not adjustable (a fixed bias circuit), and switch mode circuits, where switching power supply and RF bridge circuits need to turn on precisely to avoid shoot-through damage. Similarly, gFS, or transconductance, has been used as a substitute for gain matching with equally poor correlation to gain, but will not be discussed in this application note.

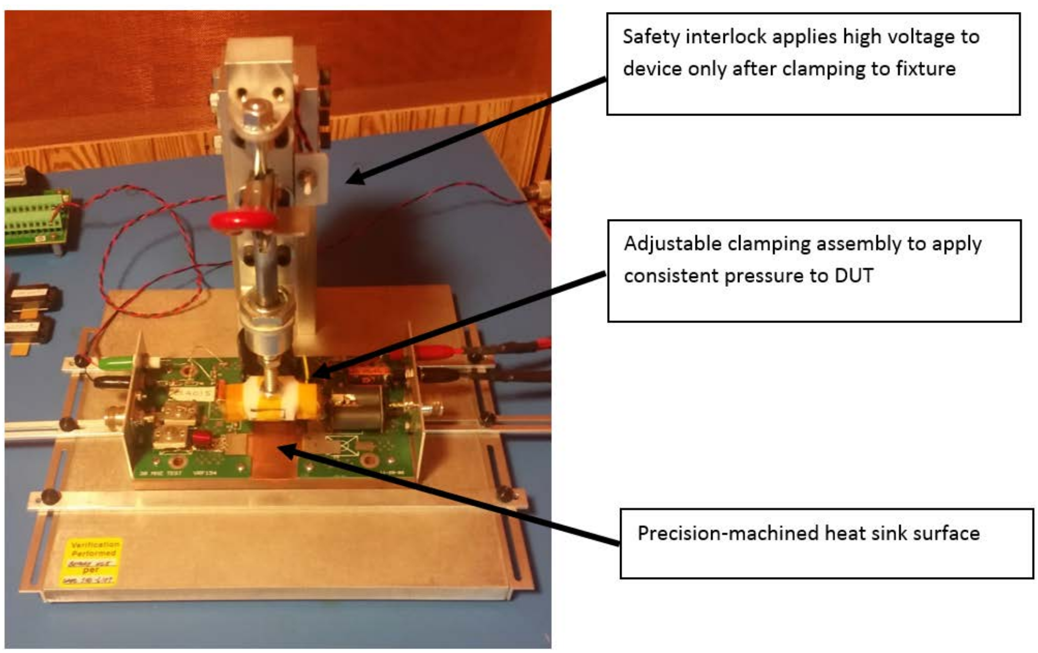
2.4 Large-Signal (High-Power) RF Power Device Gain Matching

Large-signal or high-power measurement of device gain has been performed for decades to ensure devices properly power combine in parallel systems. The devices are measured and labeled with gain in various “BINs,” which can vary from tenths of decibels to several decibels, depending on the system requirements. Ideally, the large-signal method is performed at exactly the same frequency, power level, and in the actual application circuit (including high-power, conjugate matching circuits), which appears to be the best solution. This ideal case, however, can be compromised such that it is not the ideal solution it might initially appear to be. Often, the use of the exact application circuit cannot be realized due to customer intellectual property (IP) issues, which require a similar, but not exact, copy of the end-use circuit.

2.5 High-Power RF Gain Matching and Limitations

Assuming the exact application circuit is made available, there are other factors that limit the ability of high-power RF testing to provide good, consistent, high-volume RF gain-matching results. The following photo is representative of a typical high-power RF test fixture. This fixture is used to test a linear 800 W CW device at 13 MHz. For an RF power amplifier designer, the circuit may look similar to what might be implemented in a high-power RF amplifier system, but there are differences.

Figure 4 Typical High-Power RF Test Fixture



The following changes have been made to the application circuit to support high production volume RF gain testing:

- A clamping assembly to hold the devices down to the circuit pads
- A safety interlock to keep high voltage off the fixture, unless the device is securely clamped
- A precision-machined heat sink surface without thermal interface material
- PCB cut-outs for easy device insertion and removal

- A set of correlation power devices that have been tested and qualified with aging limits to ensure the test system is calibrated at the beginning of each test session

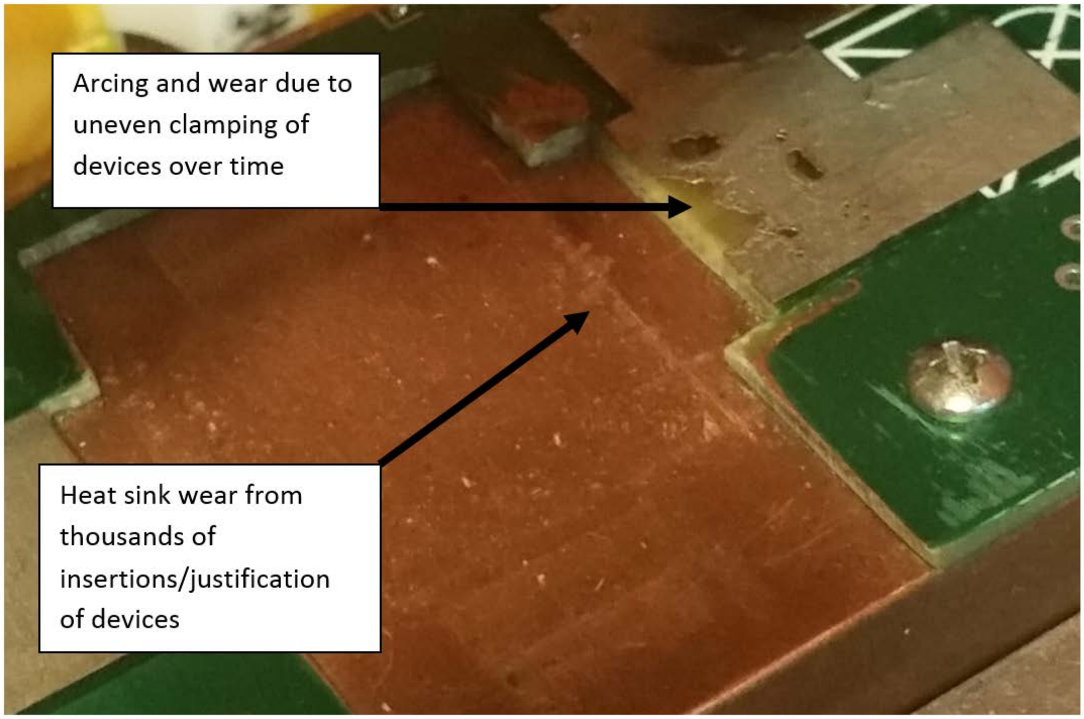
The following design and maintenance considerations result from limitations cause by circuit differences between the text fixture and the actual application:

- The clamp must be designed to place a consistent pressure on the device without damage, considering variation in device dimensions
- The clamp must be adjustable to accommodate wear/replacement
- The clamp must be inspected and repaired/replaced at a fixed maintenance interval
- Device RF contact pads must be inspected for wear and debris and repaired/replaced at a fixed maintenance interval
- Heat sink contact area must be inspected for wear and debris and repaired/replaced at a fixed maintenance interval
- Correlation devices used to ensure test system calibration may wear/degrade (primarily from the large number of physical insertions) and provide a false “fixture uncalibrated” condition at the start of a test session

Considerable maintenance involved in production volume use of a high-power RF gain test fixture adds up to significant cost, primarily in down time for repair and troubleshooting by test engineers.

The following examples highlight fixtures with significant wear and tear in order to highlight potential problem areas that occur within high-power RF gain test fixtures. The following image is a close up photo of the device socket area and drain output PCB trace. Note the wear and arcing damage from uneven placement of the device onto the pad. In this case, the problem is usually a slightly bent lead that does not make solid contact to the PCB pad. The added copper losses from the missing trace material and slight impedance mismatch will affect the measured RF gain, resulting in error. The slot for the device must be slightly larger than the worst-case device dimension to allow for easy insertion and removal. Because of this slight gap around the device, justification (back-and-forth and side-to-side) in each direction will produce a measureable difference in gain as well. Although cleaned, even the hard heat sink surface shows signs of wear, which must be compensated for by the clamp adjustment and may cause degraded DUT cooling (gain is significantly affected by die temperature).

Figure 5 Close-Up of Device Socket Area and Drain Output PCB Trace

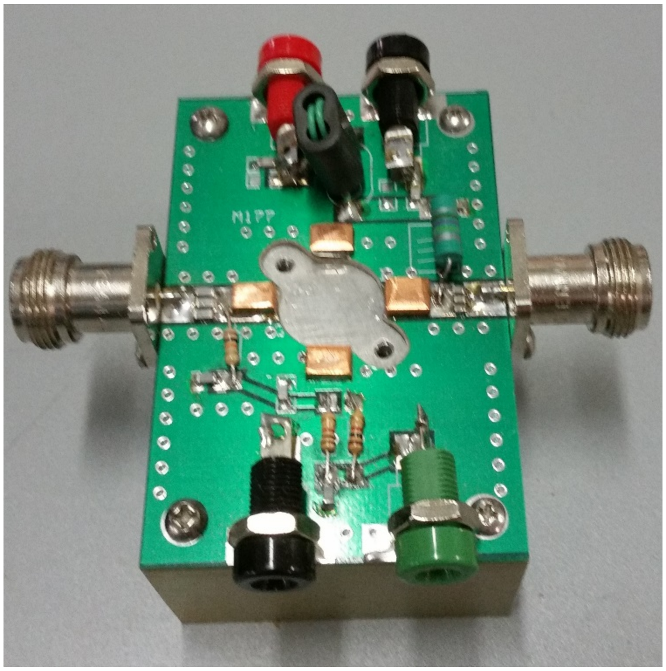


Because of the natural degradation of high-power test fixtures, correlation devices must be used before each test lot to ensure the measured gain is within specifications; but due to repeatability concerns, the acceptable gain window may be as high as 0.5 dB, depending on the application. This correlation window adds to the total error of gain-matched parts. In addition, correlation devices themselves degrade due to wear and tear. In actual use, RF devices are designed to be properly bolted with appropriate torque into a circuit with a solid thermal interface, with soldered leads, and in a stable physical environment for the life of the circuit (assuming only an occasional repair/replacement). Even when attempting to ideally recreate the application circuit and test the devices at the exact operating conditions, high-power RF gain testing is not perfect due to fixture limitations.

2.6 Low-Power RF Gain Testing and Small-Signal S Parameter Measurement

The concept of low-power RF gain measurement is very similar to taking an S21 S parameter measurement. The difference is that S parameter measurements are vector (gain and phase) and typically wideband. S parameter test circuits use resistive DC feeds to isolate the power supplies from the gain and phase measurements, as shown in the following image. DC bias levels are typically class A, but approximately 0 dBm of RF drive generates a few mA of drain current.

Figure 6 Typical S Parameter Test Fixture for M177 Device



Note the resistive gate and drain feeds (typically about >10x the Z_{IN} and Z_{OUT} of the DUT) that isolate the small amount of bypassing necessary for stability. In this specific fixture, the PCB lengths from the device leads to the connectors can easily be de-embedded from measured impedances due to the low frequencies (ISM) where the measurements are taken.

2.7 Low-Power RF Gain Measurement Technique

Unlike S parameter measurements, which are vector measurements requiring both gain and phase information, low-power RF gain measurement is a scalar measurement of gain only (phase at ISM frequencies can be neglected). For optimum power combining, the primary concern is between two or more matched devices' gain measurement, not absolute gain value. Absolute gain, which is measured in high-power testing and used in system design, is guaranteed by the device design and outlined in the datasheet.

Relative gain sorting, or binning, ensures that all of the devices in a certain gain BIN will power-combine efficiently at both low and high power. V_{th}, Low-Power, and High-Power Results shows that low- and high-power gain binning strongly correlate. For this application, the gain BINs are in increments of 1 dB, as listed in the following table. The relative gain values of 36–45 are actually negative values due to the insertion loss of the test circuit. As relative gain values can be arbitrary, in this application note they have been converted to positive values to simplify the calibration process in production and avoid confusion for operators. As long as devices are installed in the parallel amplifier from the same BIN, power combining will be optimized without measuring absolute gain.

Table 1 Low-Power Relative RF Gain BINs

BIN	GRL	GRH
A	36	37
B	37	38

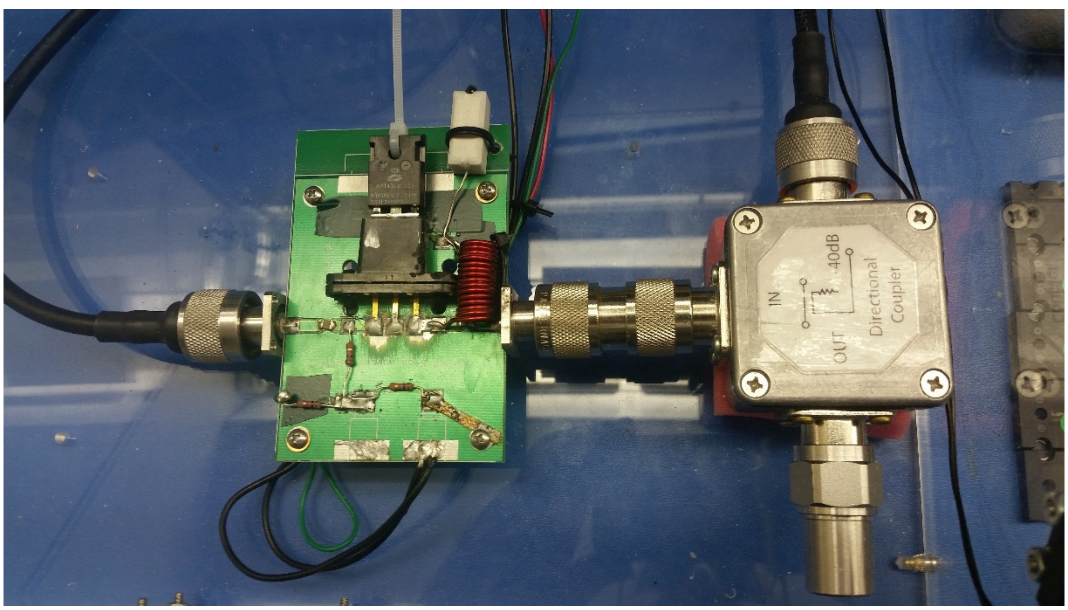
BIN	GRL	GRH
C	38	39
D	39	40
E	40	41
F	41	42
G	42	43
H	43	44
I	44	45

Test Condition: 27 MHz, 150 VDC, Idq (drain quiescent current) = 85 mA, Pin = 0 dBm.

2.8 Low-Power RF Gain Fixture

The low-power gain fixture circuit used in this application note differs somewhat from a typical S parameter fixture. The low-power gain fixture circuit has a high-impedance gate feed, similar to an S parameter fixture, but the drain feed has a series resonant choke feeding the drain that blocks the 27 MHz test signal from the power supply. Addition of the drain inductor ensures stable operation at the measurement frequency of interest. A power resistor is in series with the DC blocking choke to minimize in-rush current when inserting a new device while also aiding in stability. The socket shown is for a TO247 package device that will be discussed in this paper. The device installed in the photo is a test device that is shorted to ensure the test fixture is within acceptable loss limits during calibration.

Figure 7 Low-Power RF Gain Test Fixture



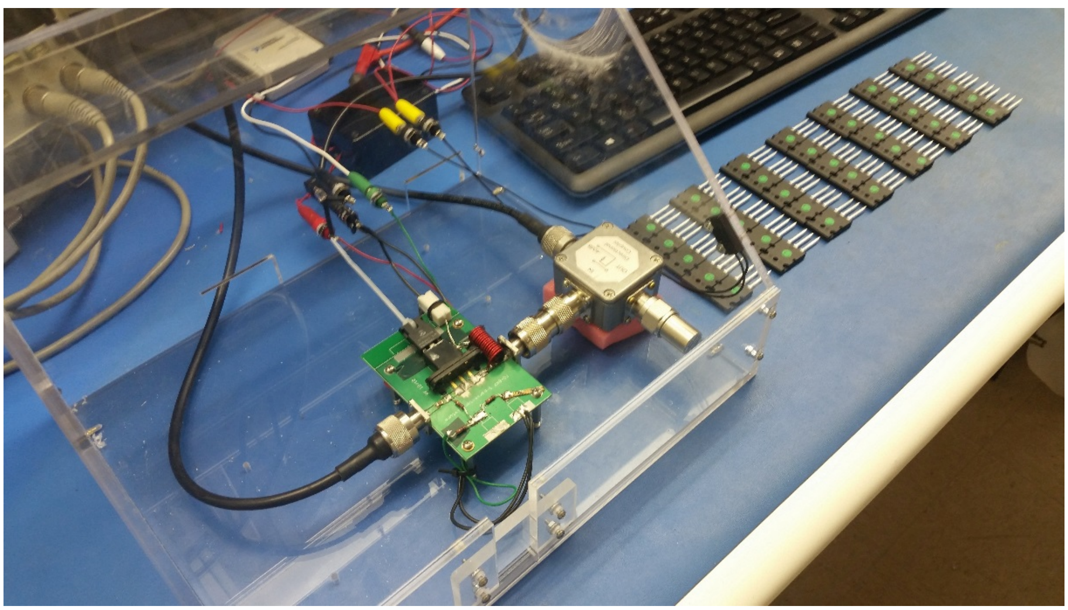
Comparing the low-power fixture to the high-power test fixture in Figure 4, there is no clamp or heat sink to wear or need adjustment. The TO247 socket is rated for thousands of insertions and is easily replaced after a long service life. The lower RF power and DC currents also add to the long life and repeatability of this type of test fixture.

While the currents involved are much lower than high-power testing (which minimizes fixture wear) they are important. In this specific case and in other device testing, the best correlation between low-power and high-power RF gain testing is obtained by operating the low-power test as close to the actual application circuit Idq (drain quiescent current) as possible. Operating at somewhat high currents (unlike low-current S parameter measurements) puts the device into the thermal runaway region (especially with no heat sink), so a unique software algorithm pulses the gate voltage until the desired Idq is reached.

2.9 Low-Power RF Gain Measurement Production Test

The ARF466A/B is a mirror-image pair of devices, so each device must be placed into the fixture with the gate facing to the left side noted by a silver triangle. Should a device be inserted improperly, the software will detect the fault; however, the device will be damaged due to the drain voltage being placed on the gate lead, and the software will signal the operator the part is now damaged. While this fixture is much simpler than the high-power system in Figure 4, it does need a protective case due to the high drain voltage. Testing at lower voltages (approximately 50 VDC) shows similar results and will be the subject of an update to this application note in the future. The following image shows the production test fixture that features both a software and mechanical safety interlock for operator safety (drain voltage is 150 VDC).

Figure 8 TO247 Low-Power RF Gain Measurement Production Test Fixture

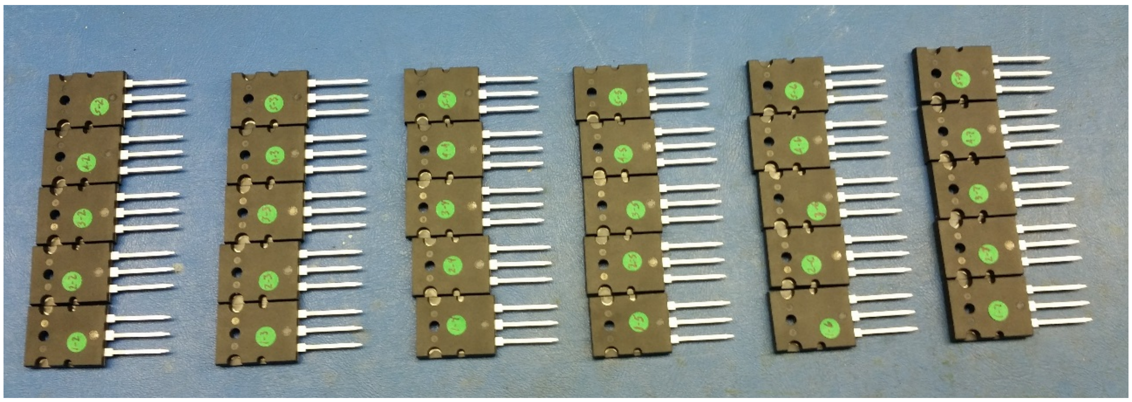


A total of 30 sample devices (shown in Figure 9) were taken randomly from a production lot of several thousand pieces. Using V_{th} (gate threshold) as a potential indicator of RF gain, a total of six consecutive V_{th} BINs were selected—five devices from each. These devices were then tested at both low-power and high-power RF gain and statistically compared to the V_{th} data. The V_{th} BINs, which are 0.25 V wide, are listed in the following table. V_{th} was measured in the TO247 package at a drain current of 1 mA. The BINs start at BIN2 and end at BIN7, as this particular application needed a lower and upper limit.

Table 2 V_{th} Gate Threshold BNS and Histogram Color Code

BIN	Vth_L (Low Gate Threshold)	Vth_H (High Gate Threshold)
BIN2	2.45	2.7
BIN3	2.7	2.95
BIN4	2.95	3.2
BIN5	3.2	3.45
BIN6	3.45	3.7
BIN7	3.7	3.95

Figure 9 Randomly Selected Devices, Five Each from Six V_{th} Gain BINs



2.10 Low-Power RF Gain Test Conditions

As the Microsemi ARF466 is a high-voltage VDMOSFET rated at 500 V drain breakdown, the device will be operating at the typical class-AB drain voltage of 150 V. Empirical testing at Microsemi has shown that low-power gain measurements correlate much better to large-signal measurements vs. V_{th} as the temperature of the die is increased. In production, there is a practical limit to the amount of heating that can be applied without heat sinking. Heat sinking, like high-power testing, could be applied, but the purpose of the low-power test is to be a simple, repeatable, cost-effective process. The maximum temperature achievable, without heat sinking, is at the point of thermal runaway. Thermal runaway in a VDMOSFET occurs when the die temperature is sufficiently high that V_{th} starts to decrease and a resultant exponential increase in drain current occurs. The test system applies the 150 VDC drain voltage and then pulses the gate voltage up in steps, until the drain current starts to rapidly increase or runaway. A unique software algorithm is used to increment and switch off the gate voltage until the desired drain current is achieved. For this device, with no heat sinking, the target drain current was 85 mA. The purpose of the low-power gain measurement is not to duplicate large-signal measurements, but to correlate sufficiently that the devices are effectively gain matched under high-power operation, which will be shown in the following sections.

2.11 Low-Power RF Gain Results versus V_{th}

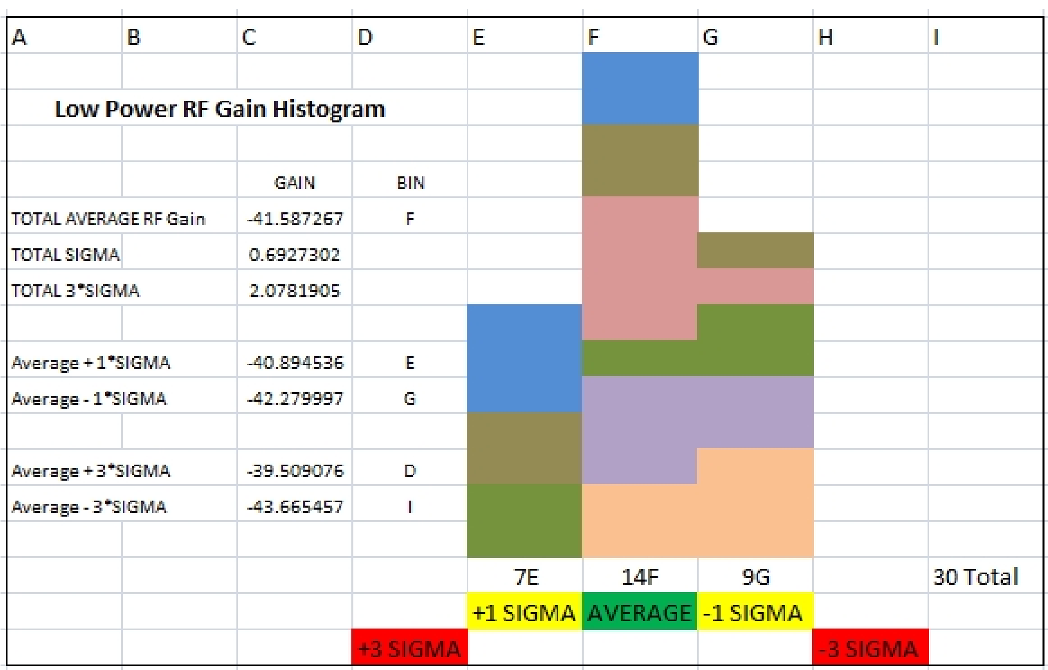
For this application, the low-power RF gain results are placed into BINs of 1 dB, as shown in the following table. The BIN width in dB can be adjusted to meet customer requests, but typically ranges from 0.25 dB–1.5 dB. Although the absolute gain is measured and recorded, the devices are labeled only to 1 dB relative BINs, which is sufficient for efficient gain matching. In this test system, the actual measured gain is a negative value due to test system losses and the numbers are changed to positive values to simplify the gain BIN table definition. If a gain value falls on an even number, the BIN is rounded up. For example, a measurement of 37.00 dB would be recorded as a BIN “B.”

Table 3   Low-Power RF Gain BINs

BIN	GRL	GRH
A	36	37
B	37	38
C	38	39
D	39	40
E	40	41
F	41	42
G	42	43
H	43	44
I	44	45

Test Condition: 27 MHz, 150 VDC, Idq = 85 mA, Pin = 0 dBm.

Figure 10   Low-Power RF Gain Histogram by V_{th}



The histogram in the previous image shows the measured low power gain BINs, and each cell color is the V_{th} for that specific device as shown in Table 2. Seven devices fell into BIN E, fourteen into BIN F, and nine into BIN G. The 30 devices, distributed across six V_{th} BINs, fell into three low-power RF gain BINs, which is a three-dB-total distribution. The significance of this histogram is that six V_{th} BINs resulted in only three low-power RF gain BINs. If V_{th} were a true indication of low-power RF gain, one would assume there to be more RF gain BINs. One can see by the V_{th} BIN colors that the devices cover a three-dB low-power gain window. Indeed, all of the V_{th} BINs result in a minimum of a two-dB-gain window, and two V_{th} BINs (BIN3 and BIN5) devices spread across a three-dB-gain window. Based on this graphical image, one can easily see that using V_{th} as an indicator of low-power RF gain will result in significant power-combining losses due to the wide window of measured gain for single V_{th} BINs. As the histogram is sufficiently Gaussian, the one and three sigma values are also shown, which suggests using V_{th} for gain matching could result in a much as a 5 dB gain spread at the three sigma limits.

2.12 High-Power RF Gain Results versus V_{th}

To make the high-power measurements, the low-power fixture was connected to input and output variable tuners to provide a conjugate output match to 50 Ω input and output. As each individual device could be slightly optimized in this method, one device was taken from each V_{th} BIN and the tuners were adjusted such that each device was close to its maximum achievable gain. The high-power test conditions were similar to the ARF466 datasheet, with 300 W of output power, 380 µS pulse width, and 2% duty factor. The only change versus the datasheet was for 27 MHz, which is what the test fixture decoupling is tuned for, and Idq of 85 mA. For the high-power test, the device was connected to a water-cooled heat sink to ensure consistent results and eliminate the thermal runaway condition.

The high-power RF gain results were placed into BINs of 1 dB, as shown in the following table. The BIN width in dB can be adjusted to meet customer requests, but typically ranges from 0.25 dB to 1.5 dB. Although the absolute gain is measured and recorded, the devices are labeled only to 1 dB relative BINs, which is sufficient for efficient gain matching. In this test system, the actual measured gain is a negative value due to test system losses, and the numbers are changed to positive values to simplify the gain BIN table definition. If a gain value falls on an even number, the BIN is rounded up. For example, a measurement of 37.00 dB would be recorded as a BIN “B.”

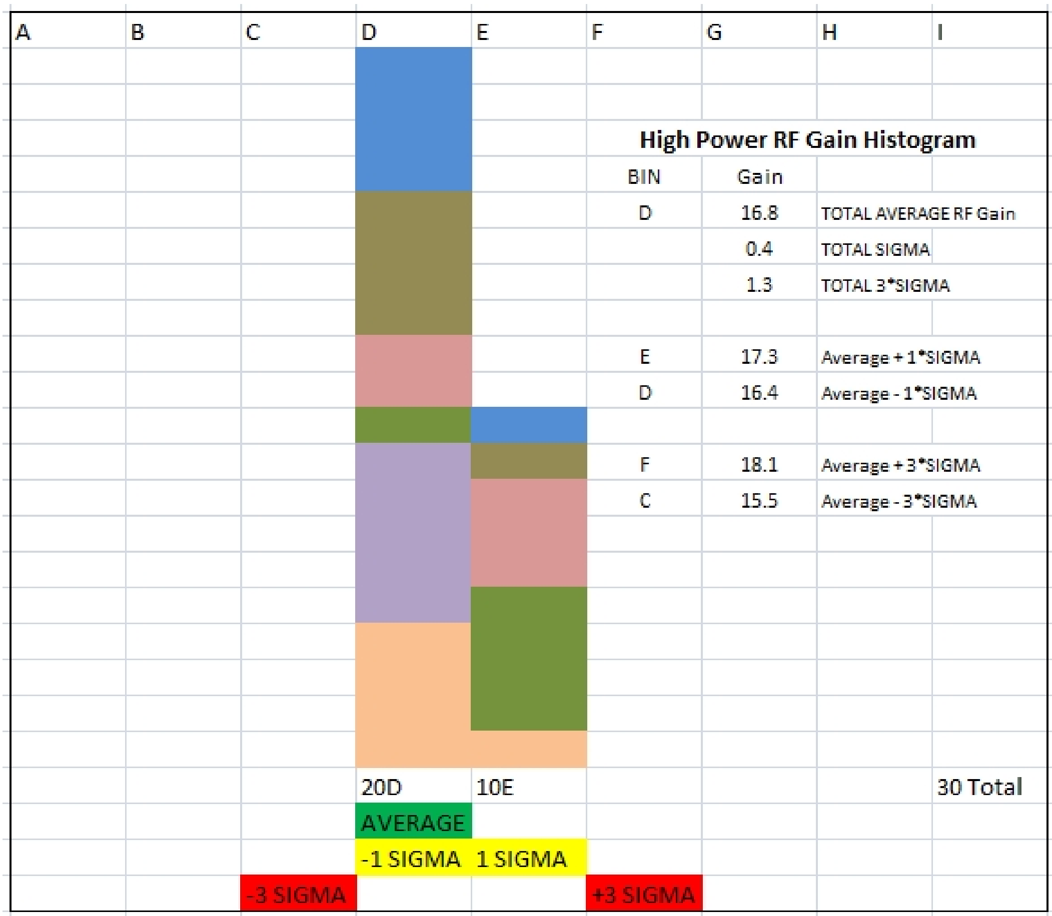
Table 4 High-Power RF Gain BINs

BIN	GL[1]	GH[2]
A	13	14
B	14	15
C	15	16
D	16	17
E	17	18
F	18	19

1. GL: gain absolute low.
2. GH: gain absolute high.
3. 250 µS pulse, 2% duty, 300 W PEP.

The following histogram shows the measured high-power gain BINs, also showing devices, by cell, by V_{th} color. Twenty devices from all six V_{th} BINs fell into RF high-power gain BIN D, and ten devices from five V_{th} BINs fell into high-power RF gain BIN E. The thirty devices, distributed across six V_{th} BINs, fell into only two high-power RF gain BINs, which is a 2 dB total distribution. Similar to the low-power results, a larger number of high-power gain BINs presumably would result from six V_{th} BINs. The V_{th} BIN colors (previously defined in Table 2) show that the devices cover a 2 dB high-power gain window. All of the V_{th} BINs result in a 2 dB gain window. This graph shows that using V_{th} as an indicator of high-power RF gain will result in significant power-combining losses due to the wide window of measured gain for single V_{th} BINs. As the histogram is sufficiently Gaussian, the one and three sigma values are shown, which suggests using V_{th} for gain matching could result in a much as a 4 dB gain spread at the three sigma limits.

Figure 11 High-Power RF Gain Histogram by V_{th}



2.13 V_{th}, Low-Power, and High-Power Results

It has been shown that V_{th} does not correlate strongly with either low- or high-power RF gain, despite this technique having been used extensively in the past. Indeed, sorting of V_{th} into the 0.25 V BINs seems to be excessive, as the six V_{th} BINs result in only three low-power gain BINs and two high-power BINs. While it appears that V_{th} BIN sorting is not sufficient for gain matching, low-power gain sorting correlates strongly with the high-power application. In addition to good correlation, low-power testing is simpler, more repeatable, and less costly to implement. The following table shows that in all cases, the statistical variation actually improves slightly at high power versus low power, resulting in less gain mismatch. This tightening of the gain statistic demonstrates that low-power RF gain testing is a viable alternative to high-power methods and is more repeatable, easier to implement, and less costly. This unique method of gain sorting should be considered in all RF power-combining applications for improved reliability and performance.

Table 5 Statistical View of Low-Power versus High-Power Gain BINs

Category	Low Power		High Power	
	RF Gain All V_{th} BINs	BIN	RF Gain All V_{th} BINs	BIN
Total average RF gain (dB)	–41.59	F	16.82	D
Total SIGMA	0.69		0.43	

Category	Low Power		High Power	
	RF Gain All V_{th} BINs	BIN	RF Gain All V_{th} BINs	BIN
Total 3*SIGMA	2.08		1.29	
Average + 1*SIGMA	–40.89	E	17.25	E
Average – 1*SIGMA	–42.28	G	16.39	D
1*SIGMA gain spread		3 dB		2 dB
Average + 3*SIGMA	–39.51	D	18.11	F
Average – 3*SIGMA	–43.67	H	15.53	C
3*SIGMA gain spread		5 dB		4 dB