A 700W Broadband Amplifier Using VRF2944

Introduction

This article describes a robust 700W 1.5-52 MHz broadband linear amplifier using the new Microsemi VRF2944 power MOSFETs. The VRF2944 represents the latest in high power VDMOSFET devices. With a minimum BVD_{SS} of 170V, it will operate from a 65V supply allowing the devices' optimum output power to be obtained with a simple 4:1 broadband transformer. In this circuit configuration, the VRF2944s are capable of providing 700W of continuous output power with enough design headroom to survive the momentary impedance transients that occur in typical operation. Features and requirements for all of the major components of the design are identified, with sourcing information. A printed circuit board layout is provided.

Topology

The basic broadband transformer-coupled push-pull circuit topology has remained unchanged for almost 70 years. The only changes over that time being the transformer construction, their ratios, and supply voltage, as determined by the ever-increasing capabilities of active devices. Push-pull operation offers several advantages over any single-ended design. First and foremost, it provides twice the output, without using a separate combiner. Its inherent circuit balance suppresses the even harmonics which then reduces the complexity of output lowpass filters needed for regulatory compliance. A single-ended broadband circuit requires a very strong supply bypass capacitor at the cold end of the output transformer, but in the push-pull circuit the supply voltage is applied at an RF-neutral point. This greatly simplifies the design and lowers the stress on the bypass capacitors.

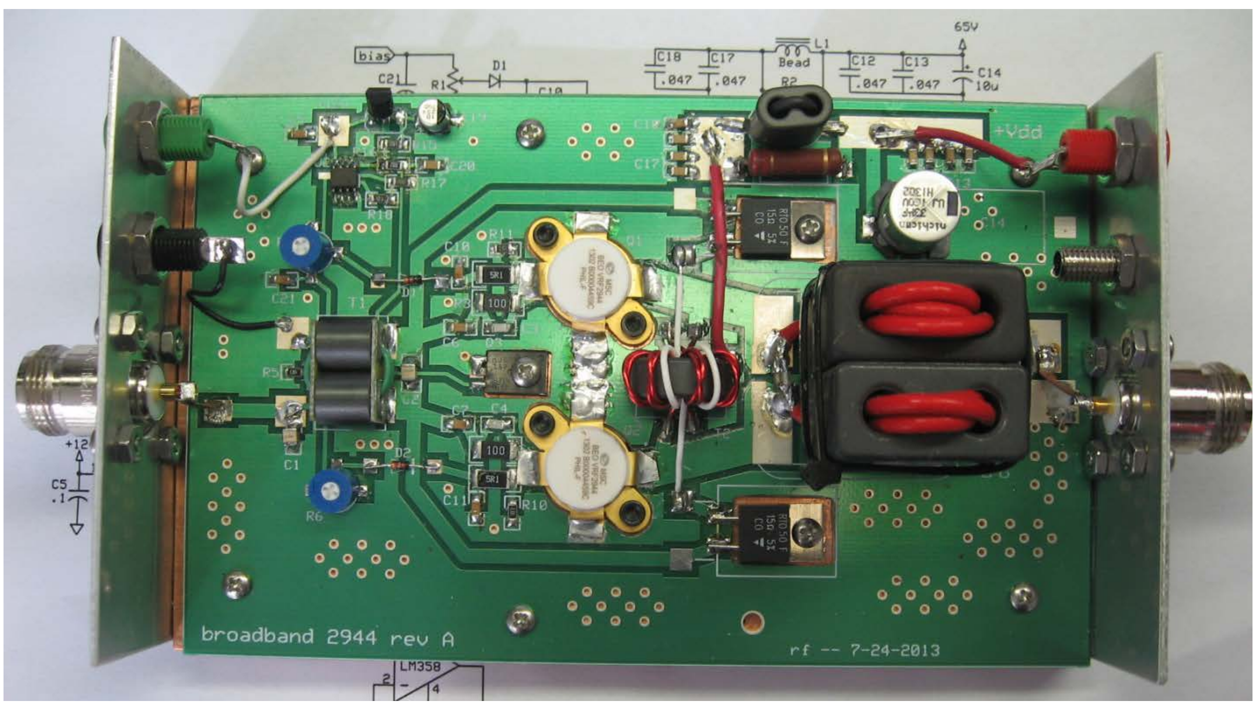


Figure 1 · Amplifier Top View

© 2013 Microsemi Corporation

Optimization

The relationship between the power supply voltage, drain-to-drain load impedance and output power is expressed as

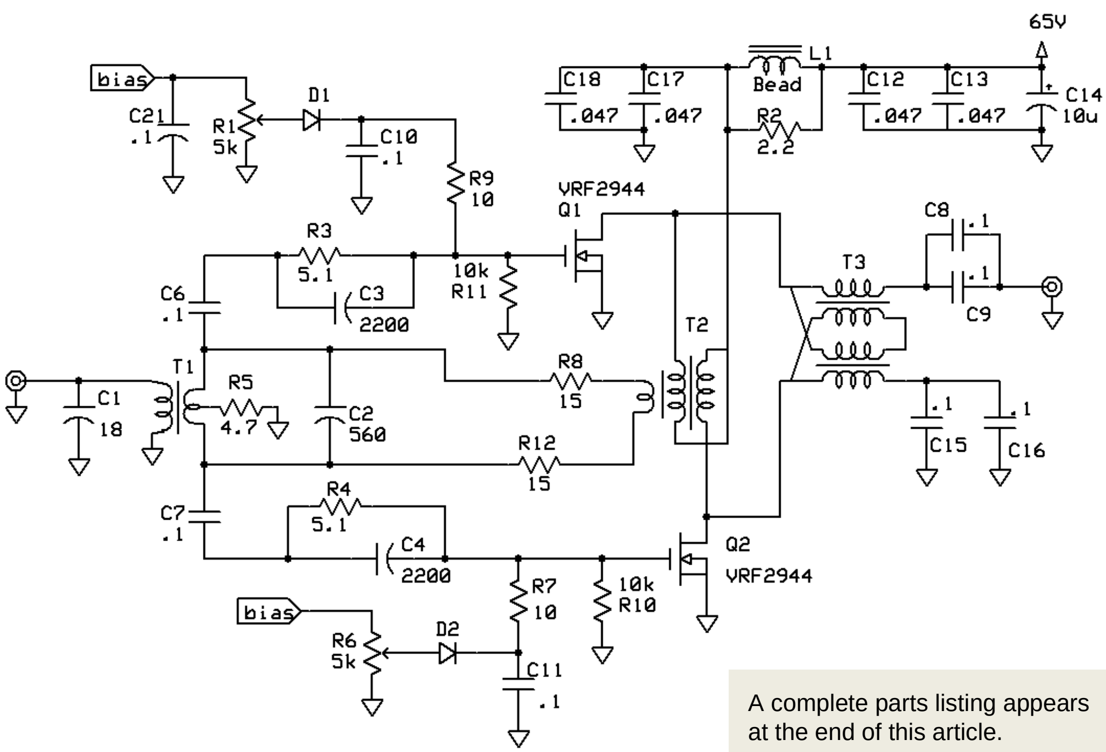
$$P_o = \frac{2V_{dd}^2}{R_L}$$

The rated output power of the VRF2944 is 400W. To add a little design headroom, especially for when air-cooling is used, this will be reduced to 350W or 700W for the pair. The simplest and most efficient broadband output transformers have an impedance ratio of 4:1. With a 50 Ω load, the drain-to-drain load as seen through the transformer is 12.5 Ω. Rearranging the formula and solving for Vdd gives 66V for this case.

$$V_{dd} = \sqrt{\frac{P_o R_L}{2}}$$

The breakdown voltage of the VRF2944 is 170V minimum at DC. At RF, the actual breakdown voltage is typically 25 to 30% higher than its DC value.[1] The peak drain voltage under normal class AB operation is typically two times the DC supply.[2] So even operating the VRF2944 at 70V does not violate the manufacturer's specifications, and there is plenty of BV headroom left to cover any transient or load mismatch events.

What we have established above is the notion of adjusting the supply voltage to make optimum use of the device capability while using an easily-realized load impedance. This is the key to high power broadband operation. For optimized operation at a single frequency, the designer is free to use tuned matching networks. This is especially useful in the case of pulsed operation where the device may be used for ten or even twenty times its nominal CW power but at a reduced duty cycle. The maximum pulsed operation for MOSFETs is determined by either the pulsed drain current limit of 4x IDmax or the value of RDS(on).



A complete parts listing appears at the end of this article.

Figure 2 · VRF2944 Broadband Amplifier

Transformers

The input transformer T1 is a "bead and tube" type with 3:1 turns ratio. The secondary is brass tubing fitted inside the two ferrite beads. The tubes are held in place by 32 mil circuit board end caps that also serve to terminate and secure the transformer to the main circuit board. The three turn primary is wound inside the tubing which reduces leakage flux and improves coupling, both add to the bandwidth of the transformer. The center tap of the secondary is not grounded directly which allows any difference current to be dissipated in R5. This usually improves balance as observed by even harmonic suppression. The transformer is available premade.[3] The leakage inductance compensation is by accomplished by C2. It is optimized at 30 MHz for best input match.

T2 is a multi-function device. The seven turn bifilar #18 windings are the DC feed choke. The total series impedance must be at least 100 Ω at the lowest frequency of operation. Because the DC current flows in opposite directions in each wire, the net current is zero so the core does not saturate. The third winding, 3t of #24 PTFE, is used to apply negative feedback to the gates. This is a simple and reliable feedback method which also eliminates the need for a blocking capacitor.

The output transformer, T3, is both a 4:1 coaxial transformer and balun.[4,5] It has two independent coax lines that are loaded by ferrite cores. The ferrite loading on them makes their end-to-end or common-mode impedance greater than 200 Ω at the lowest frequency of operation while keeping the total coax length less than an eighth wave at the highest operating frequency. On the low impedance input side at the drains, the two coaxes are connected in parallel. They are connected in series on the output end which doubles the voltage and increases the impedance by a factor of four. The coax Zo impedance required to do this is 25 Ω, the geometric mean between the input and output impedances. The dissipation at 700W in most small coax, even PTFE types, becomes an issue. 2.75mm diameter cable is best for high duty cycle applications. Small quantities can be obtained readily.[6] For a one-time build, paralleled pairs of RG-188 can be used. For commercial applications, 2.75mm 25 Ω PTFE coax is readily available.[7,8]

Any broadband amplifier has variations in gain, efficiency, saturated output power, and input VSWR over its frequency range. The devices have an inherent gain slope. This is compensated by resistive swamping the input circuit to provide a more constant input impedance. R3, 4, 7 and 9 plus C3 and 4 provide T1 with a reasonable load while increasing the drive towards the high frequency end. Negative feedback, provided via R8 and R12 from the link on T2, works to suppress the gain at the lower frequency end and further stabilizes the input impedance. The circuit layout of the feedback link, rather long and circuitous, introduces inductance in the path which reduces the amount of negative feedback towards the top end of the frequency range.

The output power and efficiency are determined by the effective load, 12.5 Ω in our case. However, the devices' output capacitance, C_{OSS}, introduces a parasitic shunt element across the drains. This has the effect of reducing the effective source impedance with increasing frequency. It degrades both the gain and efficiency. For single frequency operation, its effects can be removed by resonating the C_{OSS} with a shunt inductor, sometimes incorporated into T2. A compensating capacitor across the T3 input to can be used to provide a better single frequency match at the top end. It must be a low loss type because of the very high RF currents involved. It is not used in this amplifier.

As the bandwidth increases, transformer design becomes a most critical factor. Selection of the ferrite and compensating for transformer leakage reactance are important. The ferrite must exhibit low loss at the high end yet have enough permeability, μi, to provide the minimum necessary impedance at the low frequency end. The losses are not insignificant and the output transformer will run hot. The ferrite must have a Curie temperature > 200°C. Since T3 is both a transformer and a balun, it must provide sufficient common mode impedance to isolate the grounded output terminal from the drains. If not, the even harmonic suppression will suffer, hence the 200 Ω minimum Z at the low frequency end.

Thermals

No amplifier system is complete without its cooling system. If we assume that the devices will operate at 50% efficiency, the RF output power will equal the DC power dissipated in the heatsink. At peak power this amplifier will dissipate at least 750W, under severe load mismatch conditions the dissipation can be two or three times that. The heatsink must have sufficient thermal mass to absorb the transient heat load until other circuit protections can react. It should have a combination of a copper heat spreading plate that is then attached to a high-density finned aluminum heat dissipater or water-cooled cold plate. For air cooling, a forced air volume of at least 100CFM must be available under conditions of high dissipation. To minimize noise, the fan can be speed-controlled based on the heat sink temperature.

The MOSFET die temperature is limited to 200°C maximum. The device junctions have a very small thermal mass so the die temperature can rise very quickly – far faster than a sink-mounted thermal sensor can react. These devices have a thermal time constant of less than one second while the heat sink's time constant is measured in minutes. The copper mass and area integrates the thermal load and moderates temperature excursions of the sink. Proper mounting of the devices is essential for reliable operation. Thermal grease must be used sparingly. Grease is not a good thermal conductor, but it is much better than air.

All MOSFETs have a negative gate threshold temperature coefficient at normal values of quiescent bias. The gate bias source must therefore be compensated to keep the quiescent drain current constant with increasing sink temperature. As shown in Figure 2, a NPN bipolar transistor is mounted directly to the heatsink close to the active devices. Its forward drop, VBE, has a negative thermal coefficient. U2 multiplies the VBE drop by five, and it supplies a temperature-compensated voltage to the two bias adjustment potentiometers through isolation diodes, D1 and D2. MOSFETS usually fail with a short between the gate and drain. The diodes prevent destruction of the bias supply and the other device should one fail. Far more elaborate biasing schemes can be designed to compensate for the thermal characteristics of MOSFETs. Some may incorporate some form of shutdown mechanism when a thermal limit is reached: standby switching, and/or thermally activated fan speed control.

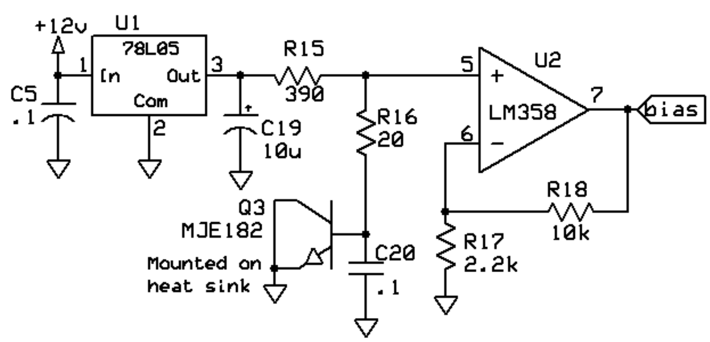


Figure 3 · Temperature-compensated Bias Supply

The Rest of the System

The amplifier described in this article is not complete. It is only one part of a system, like the car engine without the rest of the car. A power supply, output filter, and control and protection circuits are the other parts needed to make it complete. The power supply is rather obvious and if the other parts of the system are in place, needs no further description. The lowpass filter and/or output tuning network is needed for practical and regulatory reasons.

The amplifier needs three kinds of protection:

Thermal overload, usually some form of thermostat mounted on the heatsink to protect the devices from long-term overload or cooling failure.

Over-current: This places a limit on the peak and average power that can be drawn from the power supply. This prevents current excursions which could cause the junction temperatures to rise far higher and faster than any thermal protection method can react to.

Mismatch: This is needed for high load VSWR conditions that can result from mistakes like failing to connect a coax and other changes in load. A VSWR detection circuit on the output side of the amplifier can be used to disable the bias or attenuate the drive signal until the problem can be corrected.[9]

Each of these protections can easily be incorporated within the control and metering circuits because sink temperature, drain current and output power are usually measured anyway. All of them can be tailored for the intend end use of the power amplifier.[10]

Layout

The peak currents in this amplifier can easily exceed 25A. The PC board uses "1 ounce" copper and the high current traces are kept wide and short. All of the parts are mounted on or connected to the top side of the board which is mounted directly on the heat sink. Most small parts are surface mount types. The MOSFETs and the feedback resistors are mounted directly to the heat sink through windows cut in the PC board. The MOSFET leads are 100 mils higher than the PC board surface. The board could be mounted on 100 mil standoffs or 100 mil deep pockets could be milled in the heat sink so the leads would be level with the top of the board. But milling is expensive and fraught with its own set of problems regarding surface flatness and finish.

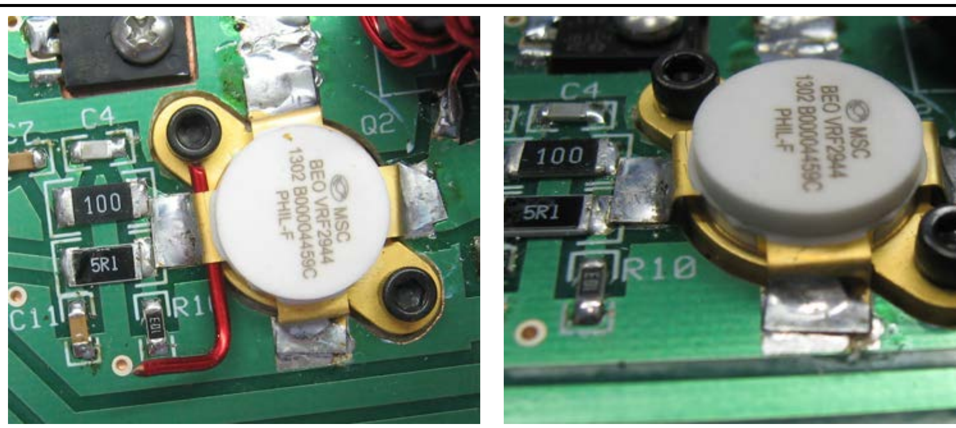


Figure 4 · Detail of lead bending to provide proper clearance

In this amplifier the MOSFET leads are preformed with an s-bend by forming them over a piece of #16 wire as shown in Figure 4. This insures that there is adequate clearance for the gate and drain leads around the mounting flange and prevents any stress concentration on the leads or solder joints during thermal cycling. Any increased source lead length as a result of the bends is not an issue since the device flanges are already internally bonded to the source.

T2 and T3 are both mounted by their leads. The T3 cores could easily be separated and mounted flat on the board to make them immune to vibration, at the expense of increased board area. The #18 wire used for T2 easily supports it and a drop of silicone sealant will keep it from vibrating in severe environments.

The printed circuit board sits directly on a copper heat spreader. It has a bare ground plane on the back side. The heat spreader is a piece of 4" wide copper buss bar .375" thick and 6" long. The surface finish of the bar has imperfections that can easily be dressed with a flat file or milled. It is critical that the surface where the devices are mounted is both flat and smooth. The heat spreader can be cooled by air or water, depending on the builder's requirements.

Performance

The design goal was 700W across the 1.8 to 30 MHz HF band. There was a stretch goal of 52 MHz, at somewhat reduced performance, to include 6m operation. The amplifier performance is shown below. Both gain and VSWR degrade above 30 MHz. In a practical amplifier this can be addressed with a switched matching network on the input and by changing the output lowpass filter to provide a slightly lower impedance load, Z_L = 26 -j22Ω in this case. With this load both the 52 MHz gain and efficiency improved to mid-band levels. The amplifier performance shown in Figures 5 and 6 can be affected by circuit parameters such as type of components, their values and their exact locations.

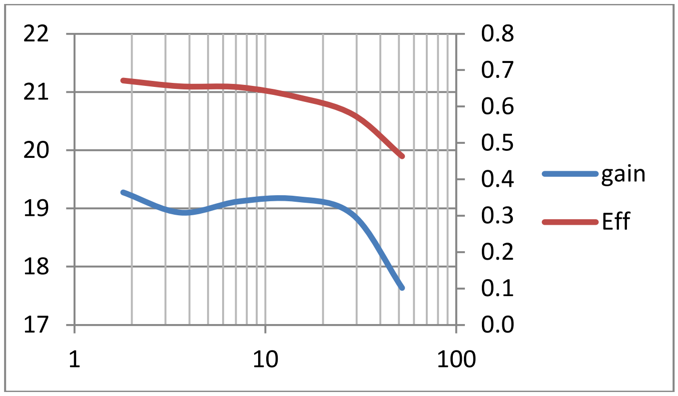


Figure 5 · Gain and Efficiency vs Frequency

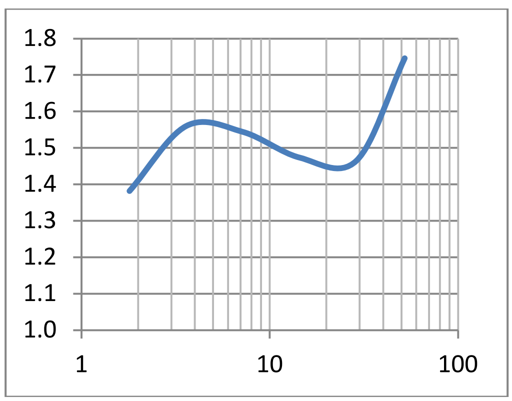


Figure 6 · VSWR vs Frequency

Summary

This article has demonstrated a 700W broadband amplifier using the Microsemi VRF2944. It provides a starting point for use in many applications, both fixed and broadband, over the 1 to 100MHz range of the VRF2944. A complete parts listing and circuit board layout is provided to simplify duplication. Finally, it must be pointed out that the component values given and/or the mechanical design may not be exactly optimum for the specific design goals stated. The intent was to make the circuit board layout as universal as possible to allow its use in designs for other applications and frequency ranges.

Appendix I – Parts List

Parts List

Reference designator	Value	Size	MFR	Part number
C1	18	1206 SMT	Kemet	C1206C180J5GACTU
C2	560	1210 SMT	AVX	SQCBEM561KAJME
C3	2200	1206 SMT	Kemet	C1206C222J5GACTU
C4	2200	1111 SMT	Kemet	C1206C222J5GACTU
C5-C11, C15, 16, 20, 21	0.1	1206 SMT	Kemet	C1206C104M1RACTU
C12	0.047	1206 SMT	Vishay	VJ1206Y473KBBAT4X
C13	0.047	1206 SMT	Vishay	VJ1206Y473KBBAT4X
C14	10u	axial 150V	CDE	WBR20-150A
C17	0.047	1206 SMT	Vishay	VJ1206Y473KBBAT4X
C18	0.047	1206 SMT	Vishay	VJ1206Y473KBBAT4X
C19	10u	SMT 25V	CDE	AFK106M16B12T-F
D1 D2	1N4148	DO35	Fairchild	1N4148TR
L1	Bead	1t #16	FairRite	284300202
Q1 Q2	VRF2944	M177	Microsemi	VRF2944
Q3	MJE182	TO-126	ON Semi	MJE182G
R1, R6	5k	3339H pot	Bourns	3339H-1-502LF
R2	2.2	3W axial	Yaego	PNP300JR-73-2R2
R3, R4	5.1	2512 SMT	Bourns	CRM2512-JW-5R1ELF
R5	4.7	1206 SMT	Yaego	RC1206JR-074R7L
R7, R9	10	2512 SMT	Bourns	CRM2512-JW-10R0ELF
R8, R12	15	50W TO-220	Bourns	PWR220-2FD15R0F
R10, R11	10k	1206 SMT	Yaego	RC1206JR-0710KL
R15	390	1206 SMT	Yaego	RC1206JR-07390RL
R16	20	1206 SMT	Yaego	RC1206JR-0720RL
R17	2.2k	1206 SMT	Yaego	RC1206JR-072k2RL
R18	1k	1206 SMT	Yaego	RC1206JR-071KL
T1	See text		FairRite	2661375102
T2	See text		FairRite	5961004901
T3	See text		FairRite	5961001801
U1	78L05	TO-92	ON Semi	MC78L05ACPG
U2	LM358	8p SOIC	ON Semi	LM358DR2G

The printed circuit board layout in ExpressPCB[11] format, can be obtained here.

[1] Norm Dye and Helge Granberg, *Radio Frequency Transistors Principles and Practical Applications*, Butterworth-Heinemann, Newton, MA, 1993.

[2] H. Krauss, C. Bostian, F. Raab, *Solid State Radio Engineering*, John Wiley, New York, 1980.

[3] Communications Concepts, Inc., 508 Millstone Drive, Beavercreek, OH 45434. Part # RF400 type43

[4] C.L.Ruthroff, "Some Broad-Band Transformers," *Proceedings of the IRE,* Vol. 47, August 1959, pp. 1337-1242.

[5] O. Pitzalis, T. Couse, "Broadband Transformer Design for RF Transistor Power Amplifiers," *1968 Electronics Components Conference,* pp. 207-216.

[6] Communications Concepts, Inc., part number DA25090.

[7] http://www.junkosha.co.jp/english/catalogue/densen/pdf/densen.pdf part # DFS014 or DFS017.

[8] http://www.pcs-electronics.com/semirigid-25ohm-other-special-coaxial-cable-p-1275.html

[9] H.O.Granberg, "VSWR Protection of Solid State RF Power Amplifiers," *RF Design*, February, 1991.

[10] The ARRL Handbook for Radio Communications, 2010 edition, Chapter 17, pp 17.32-17.44.

[11] ExpressPCB.com. Download the free software to view it. Gerber files are available at extra cost.

Microsemi Corporate Headquarters
One Enterprise, Aliso Viejo CA 92656 USA
Within the USA: +1(949) 380-6100
Sales: +1 (949) 380-6136
Fax: +1 (949) 215-4996

Microsemi Corporation (NASDAQ: MSCC) offers a comprehensive portfolio of semiconductor solutions for: aerospace, defense and security; enterprise and communications; and industrial and alternative energy markets. Products include high-performance, high-reliability analog and RF devices, mixed signal and RF integrated circuits, customizable SoCs, FPGAs, and complete subsystems. Microsemi is headquartered in Aliso Viejo, Calif. Learn more at **www.microsemi.com**.

© 2013 Microsemi Corporation. All rights reserved. Microsemi and the Microsemi logo are trademarks of Microsemi Corporation. All other trademarks and service marks are the property of their respective owners.

1819-B/09.13