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The Design and Test of a 600-Watt RF Laser Driver Using LDMOS Transistors

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This article decribes the major differences in the behavior of RF MOSFETs and LDMOS devices in RF power amplifiers used for laser driver applications, which have varying VSWR during striking and operation

The use of LDMOS transistors in RF laser drivers presents major potential improvements over MOSFETS like the MRF151 and BLF177 that have been used successfully for many years. This article describes a two-transistor push-pull design at the commonly used frequency of 40.68 MHz, comparing its performance with a design using push-pull MOSFETS using the MRF151 or BLF177.

The design of a reliable laser driver involves ensuring that the RF power amplifier (RFPA) is stable and protected from mismatches that can vary from a voltage standing ratio (VSWR) of 1:1 to as high as 20:1 at any phase angle of the reflection coefficient. The RFPA must be able to strike the laser when its VSWR is highest. Normally, the RFPA cable length between the RFPA and laser is selected for the best striking voltage across the laser resonant circuit. This also results in the maximum power dissipation in the transistors should the laser fail to strike, requiring suitable protection. The average power dissipation of the transistors must not be exceeded, the RFPA must be free from any unstable operation that may cause it to be uncontrollable by protection methods, and drain voltage excursions must be limited so that drain voltage breakdown is avoided.

	Push-Pull MRF151s	Push-Pull MRF6V2300NBR1s2
Data Sheet Specifications		
1. V_{dss}:	125 V	V_{dss}: –0.5, +110 V
2. V_{gs}:	±40 V	V_{gs}: –0.5, +10 V
3. I_d:	16 A	Not Given
4. P_d:	300W at T_c = 25 deg. C	729W at T_c = 25 deg. C
5. T_j:	200 deg. C	T_j: 200 deg. C
6. R_{jc}:	0.6 deg. C per watt	R_{jc}: 0.24 deg. C per watt
RFPA Performance		
1. B+:	48 V	48 V
2. Power output:	600 W pk, 300 W average	600 W pk, 600 W average
2. *Striking power:	800 W pk	600 W pk
3. Gain:	15 dB	25 dB
4. Efficiency:	75%	80%
5. Operating VSWR:	2:1	14:1
6. Harmonics:	>30 dBc	>30 dBc
7. Spurious:	>50 dBc	>50 dBc

**Striking power is the maximum forward power developed into a 10:1 VSWR and represents the RFPA's ability to strike the laser before lasing, after which the input is matched.*

Table 1 · Basic push-pull RFPA comparison.

Basic Push-Pull Circuit

The basic circuit for both RFPAs is the well-known push-pull input and output design using ferrite loaded 4:1 and 1:4 tube type transformers. The cores in the output transformer are enclosed in a heat-sink to provide cooling. Additional low pass filtering in the output circuit reduces the harmonics. The output transformer for the MRF6V2300-NBR1 uses larger cores because of the 600 W average power. Care must be exercised to prevent the cores from overheating or saturating due to the RF power, which can cause core losses to increase permanently. An alternate output circuit is used for the MRF6V2300NBR1 that uses a balun transformer in order to reduce the possibility of saturation of the cores and the resulting increase in losses. However, the balun transformer requires DC blocking and LC matching circuit components. Little power is dissipated in the balun transformer cores from out-of-phase currents and heat-sinking of the cores may not be required as long as the core temperature remains below about 80 degrees C.

Drain Voltage Problems

High efficiency RF amplifiers have an ongoing problem with regard to drain voltage excursions that exceed the manufacturer's DC breakdown ratings. At a B+ voltage of 50 V, drain voltage peaks can approach four times the B+ or close to 200 V [1]. The oscilloscope waveform of Figure 1 was taken under the following test conditions:

· B+: 40 V
· Frequency: 40.68 MHz
· Power output: 544 W
· Efficiency: 85%
· V_d: 150 V pk
· Gain: 24 dB

These excursions are on the order of only 2 nsec long during the time they exceed the DC breakdown rating, and it is generally concluded that the RF breakdown is higher than the DC value specified by the manufacturer. In recognizing this problem, Microsemi has introduced versions of their VRF151 with an increased breakdown voltage from 130 V to 180 V, which should result in more rugged transistors when operated in one of the high efficiency modes—Classes D, E, Mixed Mode, etc. Some failures experienced with the MRF6V2300NBR1 appear to be caused by this failure mode.

Since the existence of these drain voltage peaks is commonplace with high efficiency amplifiers, the choice is to either use a lower B+ voltage where the peaks don't exceed the manufacturer's DC breakdown rating, or risk possible failures at a higher voltage and increased power. To reduce the B+ to a safe level, can result in a substantial reduction in available output power, thereby requiring additional transistors at an increase in cost and complexity. To provide a way to ensure that the transistors are sufficiently rugged at a B+ voltage that results in

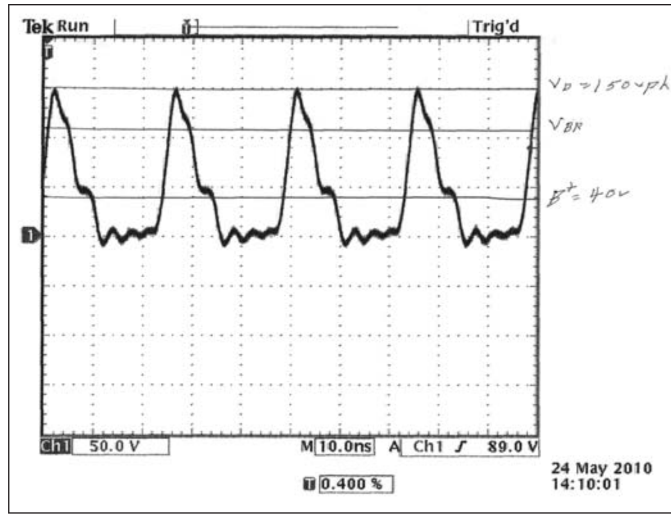
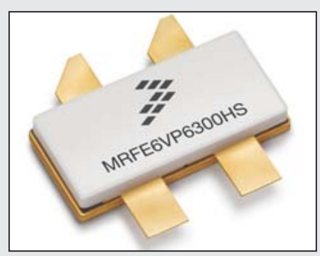


Figure 1 · Dain voltage waveform: P_V = 544 W; Eff. = 85%; 40.68 MHz.

New High Voltage LDMOS Devices

Freescale has added a line of transistors that have addressed the failure problems encountered with the MRF6V2300NBRE, particularly under high VSWR conditions. Since this article was written, the MRFE6VP6300H [2] has been tested and compared with the MRF6V2300NBR1 at 100 MHz. No failures have been encountered into an open circuit at all phase angles. The resulting performance of a single transistor in an LC input and output matching circuit under CW operation is shown below.



· B+: 48 V
· Power output: 350 W
· Efficiency: 73%
· Gain: 23 dB
· VSWR: 14:1 all phases CW
· Harmonics: >30 dBc

Six transistors were tested. Future testing will be at done at lower frequencies, like 40.68 MHz and 13.56 MHz, to ensure that the transistors are free from failure where the drain voltage waveform is more stressful because of its true switching characteristic and harmonic content.

maximum power from the transistor, but has drain voltages that exceed the manufacturer's breakdown specification, a test has been developed called a "Transient VSWR" test. In this test, the transistor is operated in the pulsed mode at a low duty cycle and short pulse length so that excessive dissipation will not be a factor. A VSWR of 14:1 is used and the reflection coefficient phase is rotated around the Smith chart to ensure that breakdown doesn't occur during mismatched loads where the drain voltage can increase over the matched condition. Since the average power dissipation is low, a jig can be used so that the transistor doesn't have to be soldered in the circuit. This test ensures that the transistor is rugged enough to be used in the circuit before it is actually installed for operation.

Even though this test has proven successful in making sure that transistors used in high efficiency RFPAs are free from this kind of breakdown before being used, it would be helpful if power device manufactures would provide sufficient RF breakdown ratings so this test would not be necessary.

Other Comparisons Between LDMOS and MOSFET Transistors

1. The high gain of the MRF6V2300NBR1 and the low gate voltage break-down rating of +10, –0.5 V, can result in failure if the gate is over-driven. Therefore, it is important to use a driver transistor whose power rating is limited to about 1.0-1.5 W per device driven. For example, the MRF134 is rated at about 5 W and can drive four of the MRF6V2300NBR1s. Also, the MRF6V4300NBR1 has a gate voltage rating of +10, –6 V, and it may be better to use it under conditions where higher drive power is possible. Otherwise, no difference has been found between the two LDMOS transistors. MOSFETs like the MRF151 or BLF177 have a ±40 V gate breakdown rating and have no overdrive problems.

2. MOSFETS, like the MRF151, have significant changes to the input impedance as the drive level is varied. This makes cascading transistors difficult and subject to spurious responses. The LDMOS transistors are very linear with drive power and the input impedance changes very little. Because of the high gain and low feedback, there is very little exchange of power from the output to the input.

3. MOSFETS have a droop in power as the junction temperature increases from the power dissipated. Normal droop is from 0.5 to 1.0 dB. More than that is considered excessive. The MRF6V2300NBR1 shows very little change verses the junction power dissipation. This is due to its higher power rating, but the specifications also show a major improvement in temperature stability. This is important in applications where the average power varies over a wide range as is the case for lasers. It also allows operation into higher VSWR loads without failure.

4. The case for the MRF6V2300-NBR1 is much different from the MRF151. Its source is both the RF and thermal ground. Care must be taken to mount the transistor according to the Freescale application notes. AN3263 describes the method of mounting, including the preferred thermal pad. The TGON-805 was used in the testing of this RFPA. It appears from the application note, that measuring the temperature of the plastic top is very close to measuring the junction temperature and is useful in evaluating it under power. In the push-pull pair used, it appeared to be worthwhile to use a copper bar across the two transistors rather than to use only screws in the mounting holes. This method appeared to make better thermal contact across the length of the transistor. AN1965 is also informative in explaining how the measurement of the 0.24 degrees C per watt thermal resistance was made.

Conclusions and Recommendations

The superiority of the LDMOS transistors in power dissipation, gain, and linearity, compared to MOSFETs like the MRF151 and BLF177, make them an attractive choice for use in applications like laser drivers and plasma generators. However, to date there have been failures attributed to drain voltages that exceed the DC breakdown rating [2]. Also, they are not capable of providing as much peak current into mismatched loads, resulting in reduced striking power. However, there are other methods to enhance the striking power for laser applications. It is appreciated that the LDMOS transistors are capable of much higher frequency operation than the MRF151 or BLF177 and are superior as linear amplifiers. The choice of whether or not to use them in place of the MOSFETS is a matter of choosing the best transistor for the application.

References

1 Krauss, Bostian, and Raab, *Solid State Radio Engineering*, John Wiley & Sons, 1980, pp. 405, 408, 472.

2. Freescale Semiconductor, "RF Power Field Effect Transistors," data sheet.

Author Information

Richard Brounley is the founder of Brounley Engineering, and for more than 40 years has been developing high power RF equipment for communications, military, medical, industrial and scientific applications at frequencies from 2 to 1000 MHz.

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An Appendix describing VSWR testing for laser driver applications begins on the following page.

Appendix: VSWR Testing of RF Power Amplifiers to be Used in Driving Lasers

In order to ensure that a RF power amplifier can safely withstand operation into mismatched loads, a test procedure has been developed whereby a safe rating can be established as part of the RFPA's specification. It also gives useful information how to select the interconnecting 50 ohm cable length between the RFPA and laser to enhance the striking of the laser.

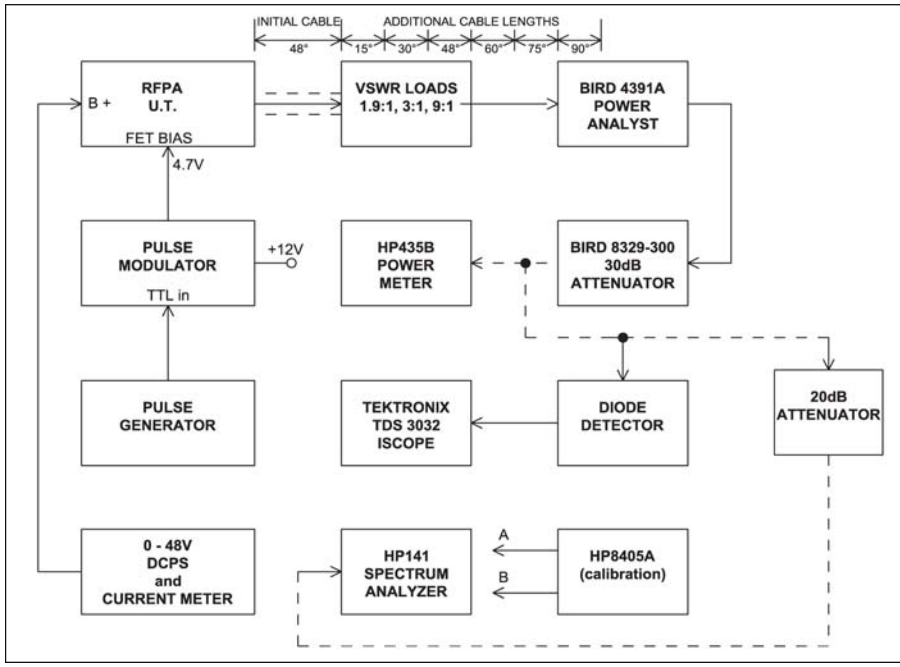

Figure A1 · RFPA VSWR testing block diagram.

Test Procedure

This is a description of the test for an 81.36 MHz RFPA capable of 600 W of average power and over 1250 W of peak power in the super-pulse mode of operation. Please refer to the block diagram in Figure A1. The block diagram consists of the components listed below.

1. The RFPA under test.
2. An initial length of coaxial cable is used to measure the power into the 50 ohm measuring system. A phase length of 48 degrees is used here.
3. VSWR loads for 1.9:1, 3:1, and 9:1 are alternately connected between the RFPA output and the 50 ohm measuring system. The loads are comprised of an inductor in series with the 50 ohm measuring system, which consists of the Bird 4391a Power Analyst, 30 dB attenuator and any interconnecting cable. The complex series impedance represents the desired VSWR indicated by the reflection coefficient magnitude and phase angle. The reflection coefficient is the vector sum of the forward and reflected voltages on the transmission line. At a phase angle of zero degrees, the forward and reflected voltages add in phase. At 180 degrees they subtract out of phase. In between they are complex impedances both inductive and capacitive. For the 1.9:1 VSWR, the reflection coefficient is 0.31 at an angle of +68º; for the 3:1 VSWR, the reflection coefficient is 0.5 at an angle of +54º and for the 9:1 VSWR, the reflection coefficient is 0.80 at an angle of +30º.
3. Cables are added to the initial cable in 15 degree increments up to 90 degrees. The cables have opposite gender connectors on the ends so they can be connected together to change the phase of the VSWR to cover the full Smith chart range. Six cables are used: 15, 30, 45, 60, 75, and 90 degrees. These cover the first 90 degrees. The second 90 degrees is covered by adding the 15, 30, 45, 60 and 75 to the first 90 degree cable. When preparing the cables, they can be measured using the HP84054A Vector Voltmeter.
4. A Bird 4391A Power Analyst is used to measure the peak power into the 50 ohm measuring system. This is used in conjunction with a HP435B, or equivalent power meter, to give an accurate measure of the power. The HP435B also has a 20 dB attenuator—the 8482H—in series with it. The peak reading HP4391 is more subject to error due to harmonics and transient spikes than the HP435A average reading power meter. The peak power of the HP435A is the average times the duty cycle of the modulator. The Bird 4391A is optional and the HP435B can be used alone.
5. A Bird 8329-300 30 dB attenuator, or suitable equivalent, reduces the power so it falls within the range of the HP435B power meter as well as the diode detector.
6. The detected peak power is displayed on the oscilloscope so that an accurate reading of the duty cycle can be seen and the pulsed detected waveform examined for any sign of instability, particularly with respect to any tendency for free running oscillations which can impair the protection circuit's effectiveness.
7. The HP8405A is useful as an RF voltmeter with 3% accuracy and can be used to measure the total loss

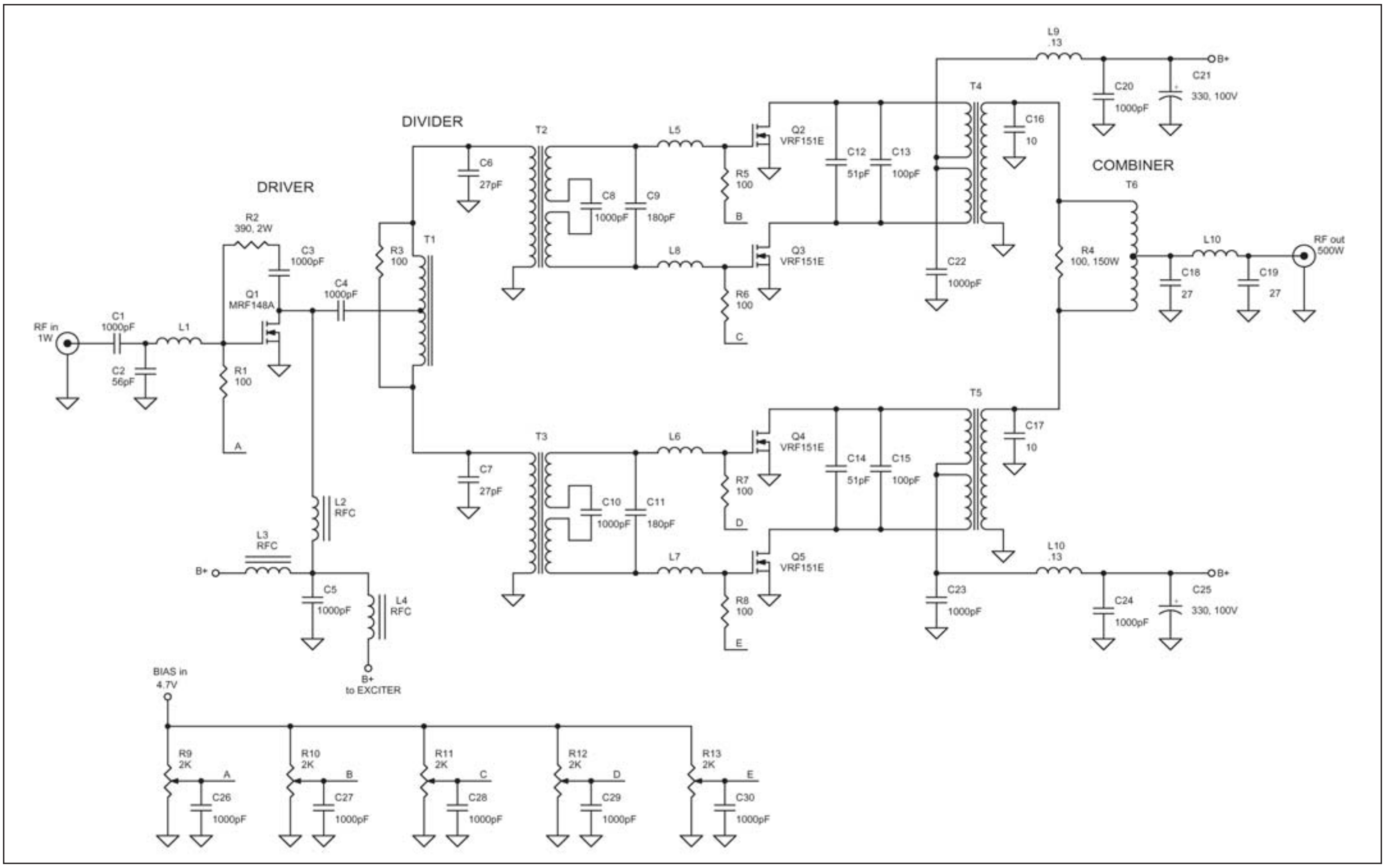

Figure A2 · RF power amp—81.36 MHz.

of the 50 ohm measuring system from the 4391A input to the output of the 8329-300 attenuator plus any interconnecting cables. This factor is used to correct the power reading. A detailed procedure for accurately calibrating the power measuring system is included in a later section,

8. A pulse modulator converts the pulse from the pulse generator to that required by the bias voltage for the FET transistors which is 4.7 V. Pulsing the gates of the FETS reduces the gain between pulses and increases the stability of the RFPA, particularly into high VSWR loads.

9. The spectrum analyzer can be used to see if any spurious frequencies occur during the VSWR test, particularly at high VSWRs. Such spurious may not be at the operating frequency of the laser and can result in ineffective operation with the laser.

10. A data sheet is used to record the peak power and peak current, versus the magnitude and phase of the reflection coefficient. Figure A2 is a schematic diagram of the amplifier. Table A1 is a sample data sheet shown for the 81.36 MHz, 600 W RFPA.

Calculation of Maximum Operating VSWR

Using the peak power recorded, the peak current and the B+ voltage selected for the test, the peak power dissipation in each output transistor is calculated according to the follow-

CW Power Output vs B+ Voltage

B+ (V)	CW Power (W)	DC Current (A)	Efficiency (%)
35	621	24	74
32	529	22	75
28	391	19	73
25*	299	16	73

**Minimum voltage for proper Exciter operation*

1. Frequency: 81.36 MHz ±.115% (crystal controlled)
2. Operating VSWR: 2:1 (external protection from excessive dissipation above 2:1 required)
3. Harmonics: 2nd = 20 dBc; 3rd and above >36 dBc
4. Maximum heat-sink temperature: 50ºC
5. Stability: Unconditionally stable into any VSWR and phase angle.
6. Modulation input: TTL

Table A1 · Final RFPA test results.

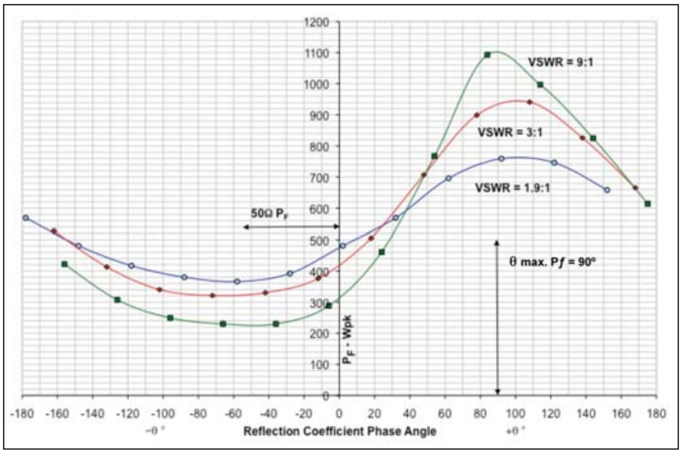

Figure A3 · Forward Power vs. θ for VSWRs of 1.9:1, 3:1, 9:1.

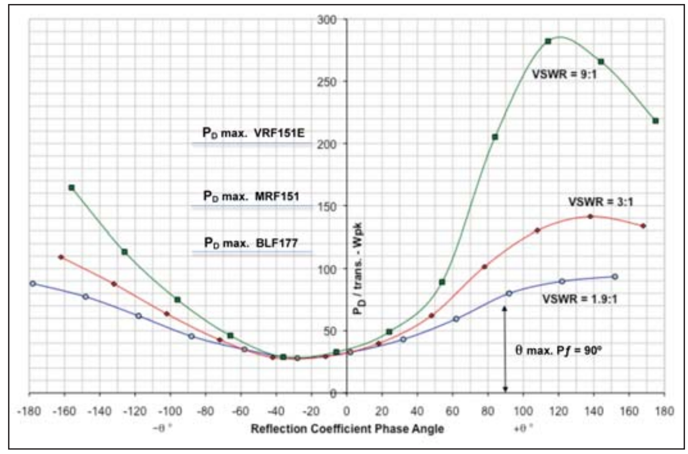

Figure A4 · Power dissipated per transistor vs. θ for VSWRs of 1.9:1, 3:1, 9:1.

ing formula: Peak power dissipation per transistor, $P_d = [(P_{in} - P_o)(0.9)]/N$ where N equals the number of output transistors. The 0.9 factor subtracts power in the driver transistor from being included in the output transistors. P_{in} is the B+ voltage times the peak input current, I_p. This peak power dissipation is then plotted versus the reflection coefficient phase angles as shown in the graph of Figure A3.

The maximum operating average VSWR is determined by the maximum allowable junction temperature, T_j, of the output transistors. A conservative number for T_j maximum is 140 degrees C. The formula for calculating the junction temperature is: $T_j = T_c + P_d(R_o)$ where T_c is the expected transistor case temperature. R_o is the thermal resistance of the transistor and is specified by the transistor's manufacturer. R_o for the BLF177 is 0.8 degrees C per watt; for the MRF151 it is 0.6 degrees C per watt; and for the new VRF151E it is 0.45 degrees C per watt. This equates to a 25 degree C power dissipation rating of 218 W for the BLF177; 291 W for the MRF151 and 389 W for the VRF151E. The test is conducted by pulsing the FETs gates at a reduced duty cycle in order to prevent excessive dissipation in the transistors from causing a failure. A 50% duty cycle is used for the 1.9:1 VSWR. For the 3:1 VSWR, the duty cycle is reduced to 33.33%. For the 9:1 VSWR, the duty cycle is reduced to 16.7%. A 200 µs pulse width is used in all testing to prevent the junctions from overheating during the length of the pulse. The purpose of the test is to choose the reflection coefficient's phase angle where the maximum dissipation occurs and to give an estimate of the dissipation. The maximum dissipation occurs at a phase angle of +90 degrees for all three VSWRs. Notice how the three VSWR curves line up at approximately the same phase angle. This means, not only does the best initial striking occur here, but that during the laser striking transition time of about 10 µsec, maximum power is delivered until a good match is achieved.

While it is difficult to actually measure the junction temperature when determining the maximum operating VSWR, experience has shown that when the low duty cycle peak power decreases by about 25%, due to the junction temperature increasing as the duty cycle is increased, this appears to be the point of maximum allowable dissipation. Therefore, the test consists of first operating at a duty cycle of 10% and then gradually increasing the duty cycle while observing the drop in peak power. When the peak power decreases by about 25%, this is the point of maximum allowable junction temperature. If this occurs for the 1.9:1 VSWR for CW, then this is the correct rating. If it occurs for a duty cycle less than CW, then this indicates that the 1.9:1 VSWR rating is too high and the unit should be rated for a lower operating VSWR.

Because this test is run at the very worst phase angle and the 140 degrees C junction temperature maximum is conservative, judgment is necessary to actually determine an effective and practical VSWR activation set-point. If it is set too low, like at 1.2:1, the system may be too critical and unnecessary activation of the protection may occur. Therefore the set-point activation may have to be increased for practical operation. This is particularly true for burn-in stations where the VSWR tends to vary significantly and burn-in cycles may be interrupted unnecessarily. However, the test does give information useful in determining the operating VSWR of the RFPA.

The curve of Power Dissipation versus Phase Angle (Figure A4) shows the maximum peak power dissipation for the three transistors. This can be calculated by setting the maximum junction temperature to

140 degrees C and the expected maximum case temperature to 50 degrees C. The maximum dissipation is then P_d max = $[140 - 50]/R_o$ and equals 200 watts for the VRE151E, 150 watts for the MRF151 and 112.5 watts for the BLF177. These are the low duty cycle peak dissipation readings. The maximum CW dissipation needs to be determined using the method discussed above.

Other Reasons for the VSWR Test

1. The drain voltage excursions in a high-efficiency amplifier can increase substantially when operated into a high VSWR. Passing the VSWR test insures that this won't occur and cause breakdown of the drains for conditions typical of striking the laser. Typically a 50% increase in peak drain voltage, over the value into a matched 50 ohm load, occurs during the VSWR 9:1 test. At a B+ voltage of 32 V, the 81.36 RFPA shown had a peak drain voltage of 80 V_{pk} into 50 ohms. Into the 9:1 VSWR it increased to 120 V_{pk} for the worst case phase angle.

2. As stated previously, it is important that the RFPA is free from any unstable operation during the VSWR test. Observing the detected voltage on the oscilloscope and spectrum analyzer can be useful to insure this.

3. The plot of forward power versus the reflection coefficient phase angle shows the phase angle of maximum forward power. This can be used to match the laser's unlit reflection phase angle back to the RFPA by using a 50 ohms cable of the correct phase length. The phase angle for maximum striking power for the example shown is +90 degrees. If the unlit phase angle for a correctly matched and operating laser is 0 degrees, then a cable length of 135 degrees is required. Remember that Smith chart degrees are twice the actual cable length degrees.

4. It needs to be recognized that phasing the RFPA and laser for maximum striking power, also results in maximum dissipation should the laser fail to strike. It is best to always strike the laser in the pulsed mode where the dissipation is low until striking is assured. Trying to strike a laser in the CW mode can lead to failures and suitable protection should be used when the set-point is exceeded. Brounley Engineering recommends a protection scheme that, once the VSWR set point is exceeded, the unit is put into an automatic pulsed mode whereby the pulse width and duty cycle are limited to 200 µs and 10% respectively, resulting in a safe operating condition. Normal operation is returned once the VSWR drops below the set-point.

50 Ohm System Calibration Using the Vector Voltmeter

The HP8405A Vector Voltmeter is capable of being used as a wide-range RF voltmeter with an accuracy of 3% of full scale (FS). For calibration, follow these steps:

1. Connect the A and B probes to a BNC 3-way T adapter including the HP8640B signal generator set to 0.77 V output. Record any difference between A and B as an error to be corrected later. Correction will be B/A if A is larger and A/B if B is larger.

2. Using a BNC 3-way T adapter, connect probe A to one port of the connector, the HP8640B Signal Generator to another and the input to the Bird 4391 to the third. Set the HP8640B to 0.7 V on the HP8405A 1000 mV scale.

3. At the 50 ohm measuring system output where the power is to be measured by the HP435B—8482H attenuator combination, connect a 50 ohm termination connected to probe B of the HP8405A. Reduce the attenuator of the HP8405A to the 30 mV scale. This is 30 dB below the 1000 mv scale. Read the voltage on the B probe. The attenuation is then: [Bv/0.7]·C where C is the correction factor in 1. Example: for B/A = 0.73/0.7 = 1.04; C = 0.96 since B is larger than A. If Bv = 22 mV, then the attenuation = [22/700]0.96 = .0316 = 30 dB. The HP435A—8482H combination power reading is to be multiplied by 1000.

50 Ohm Measuring System Calibration Using the Power Meter and Attenuator Combination

The HP435B Power Meter and 8482H 20 dB attenuator combination are connected to the output of the Bird 8329-300 30 dB attenuator including any connecting cable. In order to accurately use the dynamic range of the HP435B, a one-watt stable source is necessary. This consists of the HP8640B Signal Generator driving a calibration amplifier. The output of the amplifier is set to one watt at the operating frequency into the 8482H—HP435B combination. The 1 watt output is then connected to the input of the Bird 4391A Power Analyst. The 8482H—HP435B combination is then connected to the 50 ohm measuring system and the range of the HP435B reduced to read the output power. The attenuation is then the output power divided by the input power. For example, with the 1 W input, the output of the 50 ohm measuring system at Brounley Engineering is 30.6 dB below the 1 W input. Therefore, the power reading on the HP435B during the test should be multiplied by 1,148. The calibration using the HP435B and the HP8405B should agree within 0.5 dB or less.