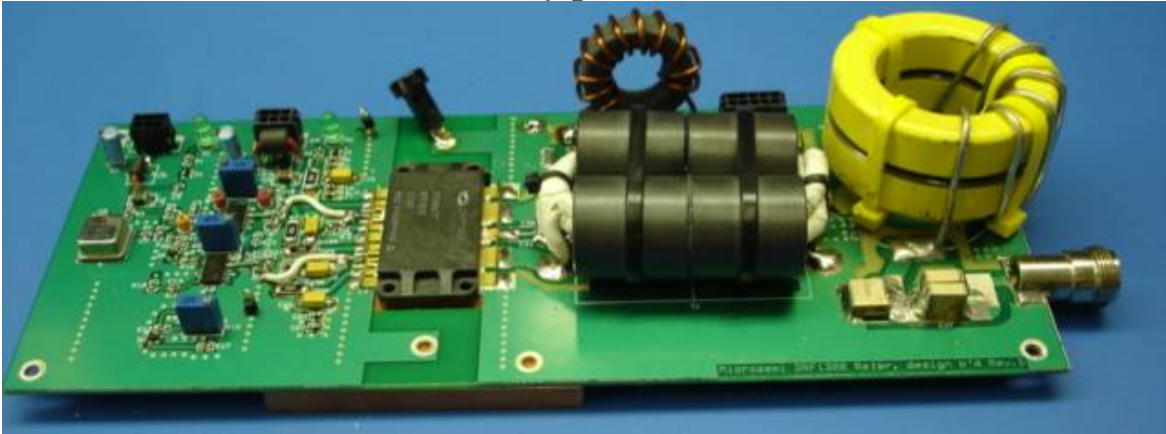


13.56 MHz, Class D Push-Pull, 2KW RF Generator with Microsemi DRF1300 Power MOSFET Hybrid

Gui Choi
Sr. Application Engineer
Phone: 541-382-8028, ext. 1205
gchoi@microsemi.com

The DRF1300/CLASS-D Reference design is available to expedite the evaluation of the DRF1300 push-pull MOSFET hybrid. This application note or the reference design does not represent a finished commercial-ready design. It is only an engineering tool to demonstrate the capability of the DRF1300 under 50 Ohm, flat line conditions. Each reference design has been verified to perform to the specifications of the application note. The application note contains a parts list, board layout and schematic that enables the user to facilitate any repairs resulting beyond its intended use. By purchasing this reference design the user takes full responsibility for repair and any modifications. No warranties, repairs or returns will be accepted.

**The reference design kit contains lethal voltages and high power RF.
Use safety precautions.**



Contents

- INTRODUCTION
- DESIGN CONSIDERATIONS
- THEORY OF OPERATION
- CIRCUIT DESCRIPTION
 - a. PULSE GENERATION
 - b. RF OUTPUT MATCHING
 - c. DC SUPPLY
- TEST REQUIREMENTS
 - a. TEST SET UP DIAGRAM
 - b. TEST REQUIREMENTS
- PERFORMANCE (DATA SUMMARY)
 - a. POWER AND VOLTAGE GRAPHS
 - b. VDS WAVEFORMS FOR VARIOUS HV PS
- CONCLUSION
- REFERENCES
- APPENDIX I (SCHEMATIC)
- APPENDIX II (PCB LAYOUT)
- APPENDIX III (PARTS LIST)
- APPENDIX IV (TRANSFORMER CONSTRUCTION)

INTRODUCTION

This application note contains the design procedures and measurement results for a 2KW 13.56MHz RF generator using a CLASS D Push-Pull amplifier. To optimize efficiency and minimize cost, the design uses a DRF1300 Power MOSFET Hybrid from Microsemi. The DRF1300 consists of two high power gate drivers, two 500V 30A MOSFETs, and several internal bypass capacitors. The internal layout of the T4 hybrid package has been optimized to minimize stray inductances allowing the DRF1300 to operate at frequencies of over 30MHz.

To support this application note the DRF1300/CLASS-D reference design is available from Microsemi. It allows designers to readily verify the principals of this application note and save weeks or even months of design work. It illustrates the high efficiency operation and critical PCB signal-ground layout required to minimize output/input noise interference.

DESIGN CONSIDERATIONS

To design the high-efficiency high-power RF generator the following issues were addressed.

- Choice of design complexity and efficiency trade offs.
- Selection of an adequate output matching circuit using a matching tool, to achieve the wanted power, drain waveform and efficiency.
- Selecting parts capable of handling RF output of 2KW including by-pass capacitors in the DC circuit, design and construction of a wide-bandwidth, high-current toroidal inductor and transformer, and sufficient capacitors for output matching circuit.
- The design of a cooling system for the amount of power dissipated.
- The design of the printed wiring board for a good ground, especially for the output matching circuit.
- Isolation techniques between power output and signal generation circuit

The table below is for the major specification of this RF Power Generator.

Freq	Output Power	Voltage	Current	Efficiency
13.56Mhz	2KW	250V	9.2A	85%

Table 1. Key Specification

THEORY OF OPERATION

A Class D push-pull amp requires control circuitry, a pair of MOSFET switches, a transformer for combining two outputs that are 180° out of phase, and an output matching network for tuning/creating a sinusoidal output signal. Class D operation theoretically can provide 100% efficiency, but because of the MOSFET on resistance, switching cross over transients, and magnetic losses, applications of approximately 85% efficiency are more achievable.

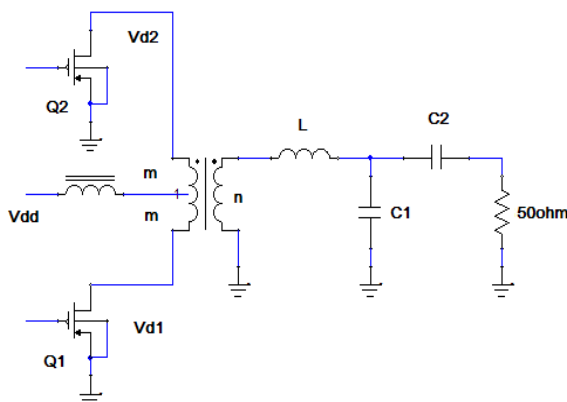


Figure 1. Simplified Push-Pull Circuit

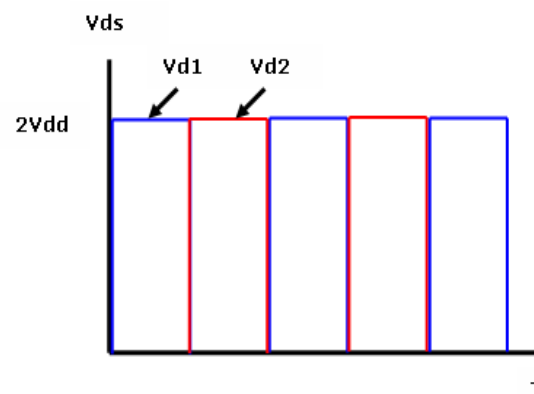


Figure 2. Waveforms at drains

Figure 1 shows a simplified CLASS D push-pull circuit. The two input signals are 180° out of phase causing Q1 and Q2 to switch ON and OFF alternately. The turn ratio of Transformer (n/m) is 2/1 for this application. For an ideal switch, when Q1 is ON, its drain voltage V_{d1} is zero and the V_{dd} on the center tap of the primary of transformer, is transformed to $(2/1) V_{dd}$ on the secondary. Alternately, when Q2 is ON, the reverse polarity of $(2/1) V_{dd}$ appears on the secondary. The ideal waveforms are shown in Figure 2.

A key technical difficulty for this push pull RF application is the transformer. The high current, high frequency and high voltage require careful design considerations. The inductor (L) and capacitors (C1 and C2) form a tank circuit to form a sinusoidal RF signal into the 50 Ohm load.

CIRCUIT DESCRIPTION

a. Pulse Generation

The pulse generation circuit operates from a 3.0VDC~5.5VDC supply. The 27.12MHz TCXO is divided down to 13.56MHz and split into two 180 out of phase signals by U2B. U2A and U3A allow pulse width adjustment of the two signal inputs to the DRF1300. The pulse width of each signal can be adjusted from 15ns to 35ns using Potentiometer R9 and R16 respectively. To minimize a conductive EMI, it is crucial to observe proper circuit layout with good ground conditions along signal lines, taking care to isolate them from the output switching noise. Figure 4 shows waveforms of outputs of pulse generation circuit at pin 4 and pin 10 of U1.

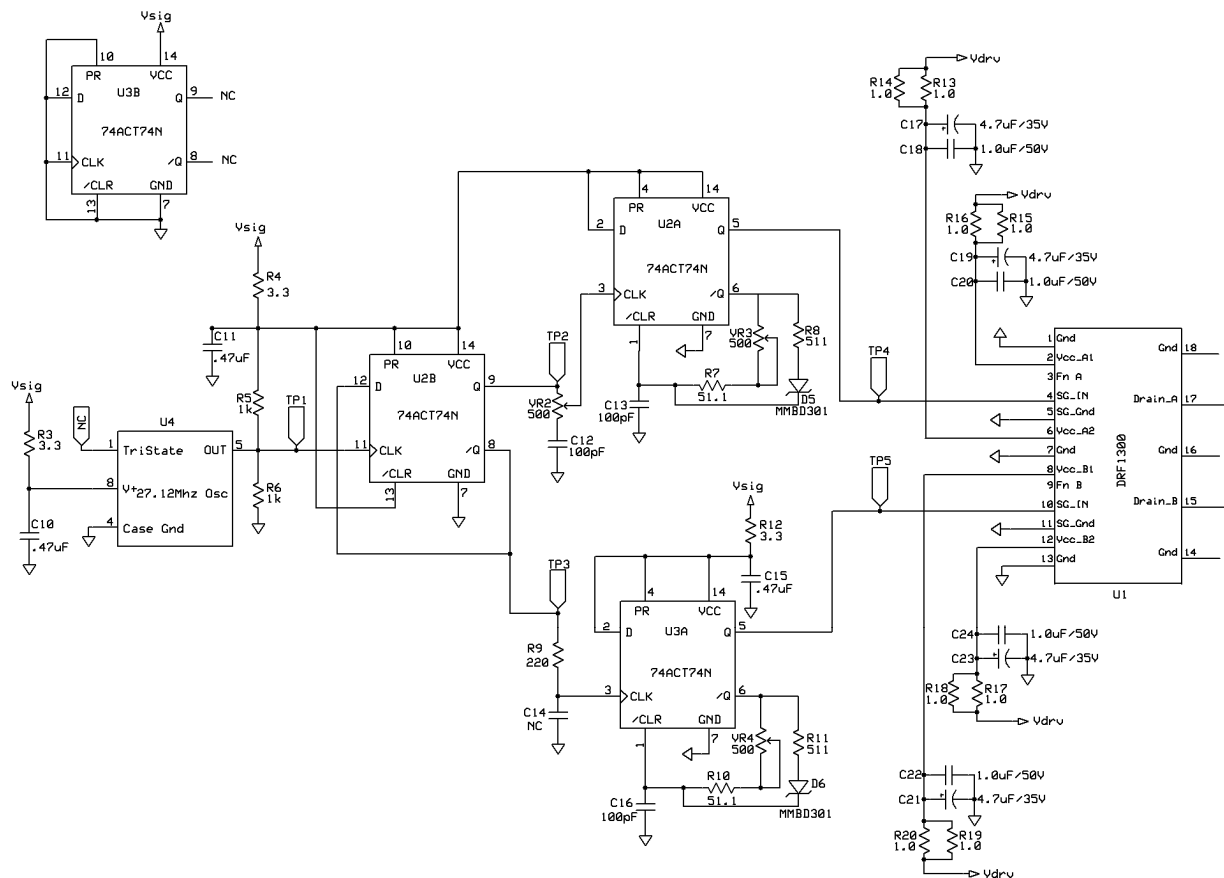


Figure 3. Pulse Generation Circuit

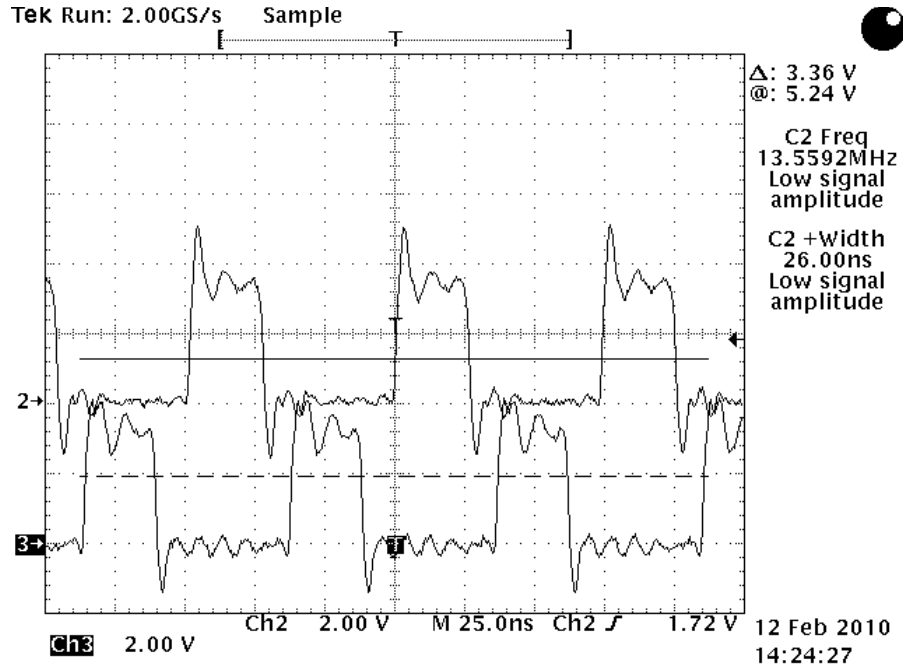


Figure 4. Waveforms into DRF1300

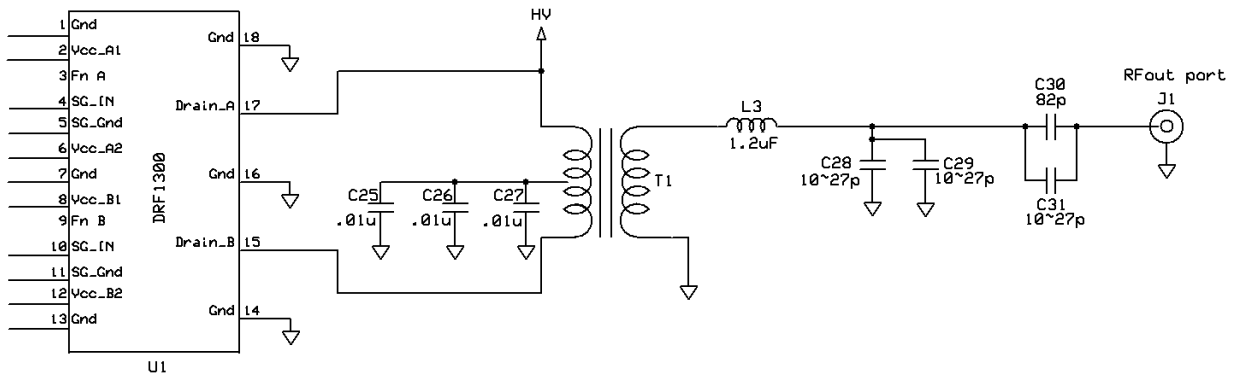


Figure 5. RF Output Matching and DC Supply Circuit

b. RF Output Matching

The output matching circuit was calculated by means of RF matching software tool (Smith Chart) to maximize power transfer to a 50 Ohm load at J1. The matching circuit consists of a custom built transformer (T1), shunt/series capacitors (C28 through C31) and a custom built series inductor (L3). The capacitors and inductor form a tank circuit that is used for matching and tuning. It is critical that the output stage consists of inductors, capacitors, wires, toroids and ferrite cores that can handle the high currents and voltages associated with a 2KW RF Generator. Refer to the recommended parts list for the DRF1300/CLASS-D provided in the appendix.

Transformers T1 for this type of application are not commercially available. The design of the transformer used in the DRF1300/CLASS-D took several iterations to overcome bandwidth and power issues. The low cutoff frequency was overcome by selection of a specialized core. Minimizing the transformer turn ratio to 1:2 or 1:3 was required to avoid power loss. Refer to the following equations.

$$P_o = (8/\Gamma^2) * (V_{eff}^2 / 2R) \text{ for Class D Push-Pull}$$

$$\text{For the Drain load line, } R = \left(\frac{m}{n}\right)^2 * R_o$$

m = number of primary turns and n = number of secondary turns

R_o = Output load

In this app note, R_o = 50Ω, m=1, n=2 therefore R=12.5Ω

The transformer design is comprised of ten (material 67) ferrite cores and was wound with insulated wire. It is highly recommended to use AWG14 wire for both the primary and secondary winding of the transformer. The detailed instruction of making the transformer is presented in Appendix V.

Figure 6 shows plots for output matching which consists of transformer and “L” match of Toroidal Inductor and Capacitors in series and Capacitors in shunt to ground.

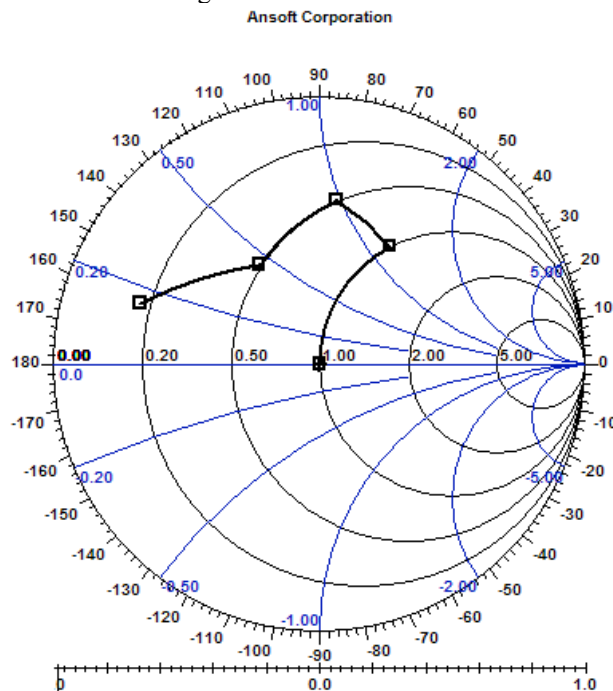


Figure 6. Plots for Output Matching

c. **DC Supply**

The high voltage DC supply (PS HV) circuit employs a RF choke coil (L1, L2) and bypass capacitors (C4-9) to minimize an interference with AC signal. The RFC of this coil L1 and L2 were designed for approximately 1K ohm at 13.56MHz with 11 turns AWG 14 enameled wire. The by-pass capacitors should be selected for a 2KV voltage rating. Refer to the parts list in the appendix for recommended parts. It is very crucial that the capacitors (C25 through C27) be located as close as possible to the center tap of the primary winding of power transformer T1 have a good RF ground. Figure 7 illustrates the capacitor location to T1 and the red circle indicates ground connections through a via to the bottom ground plane.

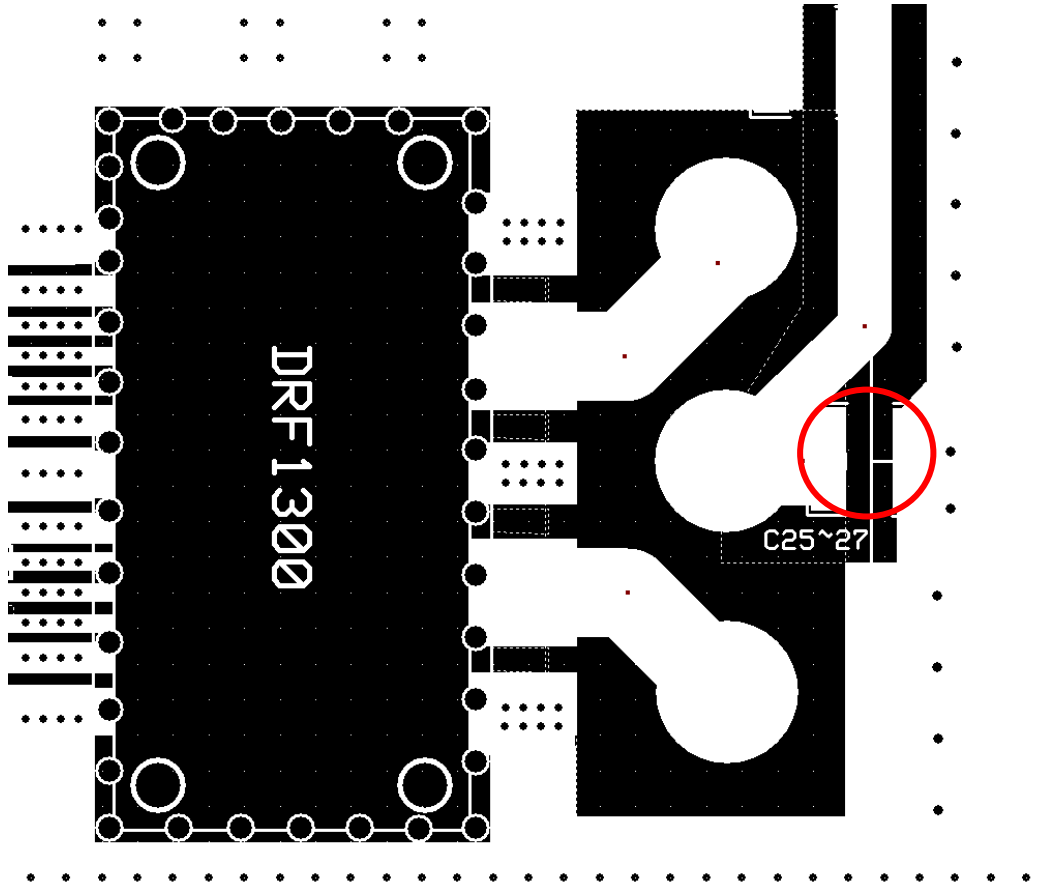
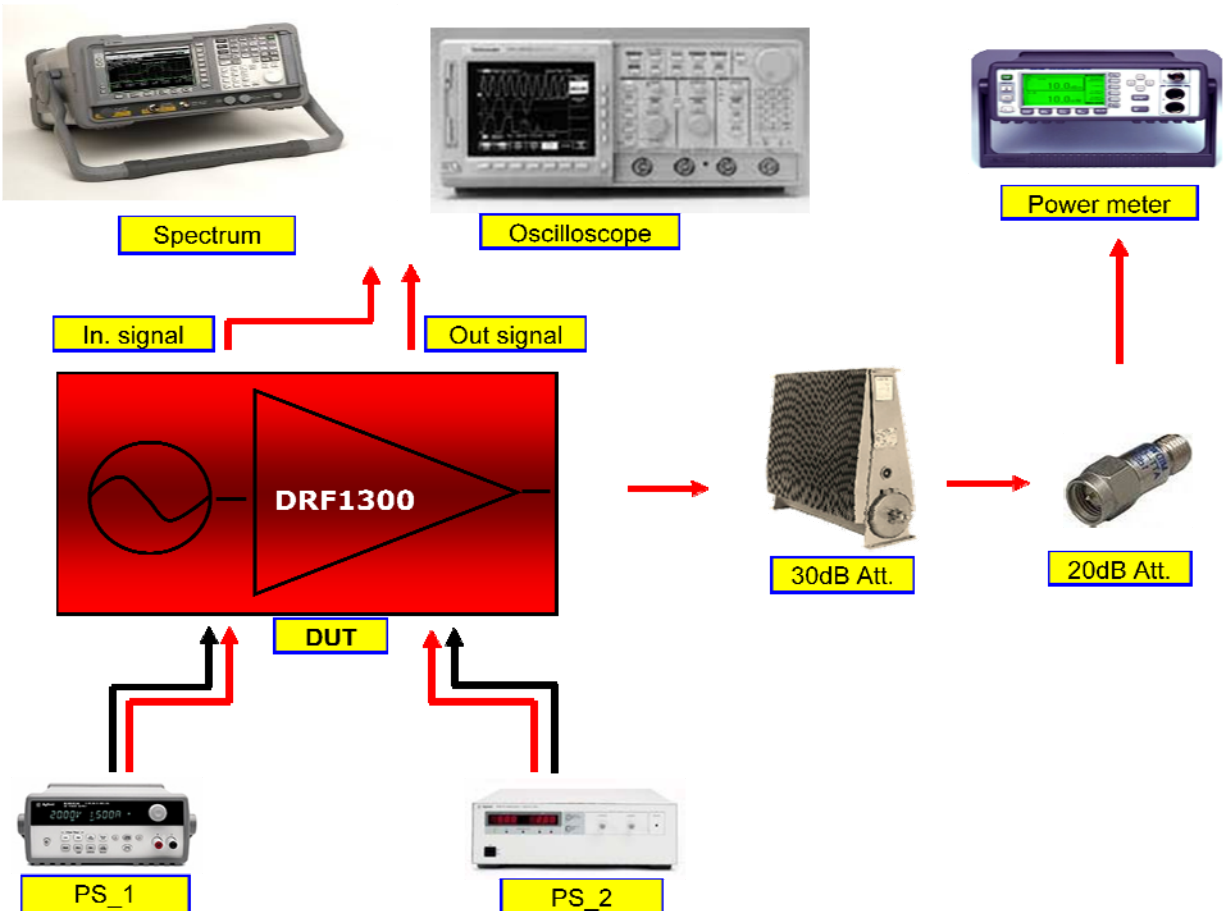


Figure 7. Location of Capacitors for DC circuit

TEST REQUIREMENT.

 a. **Test Set-Up Diagram.**

Figure 8. Test Set-Up diagram

 b. **Test Requirement**

- Cooling requirement: Testing is recommended to be performed using a water cooling system. If not available, use enough heat sink to maintain performance with sufficient fan capacity. It is recommended that an additional fan be directed onto the transformer to provide cooling for the magnetics that will extend allowable test time.
- Process for Turn-On/Off Power Supplies
 - i. Turn on Driver power supply PS_1 (10V~12V per circuit requirement)
 - ii. Then, turn on MOSFET PS_2 and slowly increase to 40V.
 - iii. While monitoring the RF power and waveform from Drain, ramp up PS_2 in steps, verifying the outputs are stable before proceeding to the next step.
 - iv. To turn off, reverse the turn on procedure.

If the RF output waveform (Vds) and/or RF power level fluctuates, immediate shut down of MOSFET PS and determine fault before resuming test.

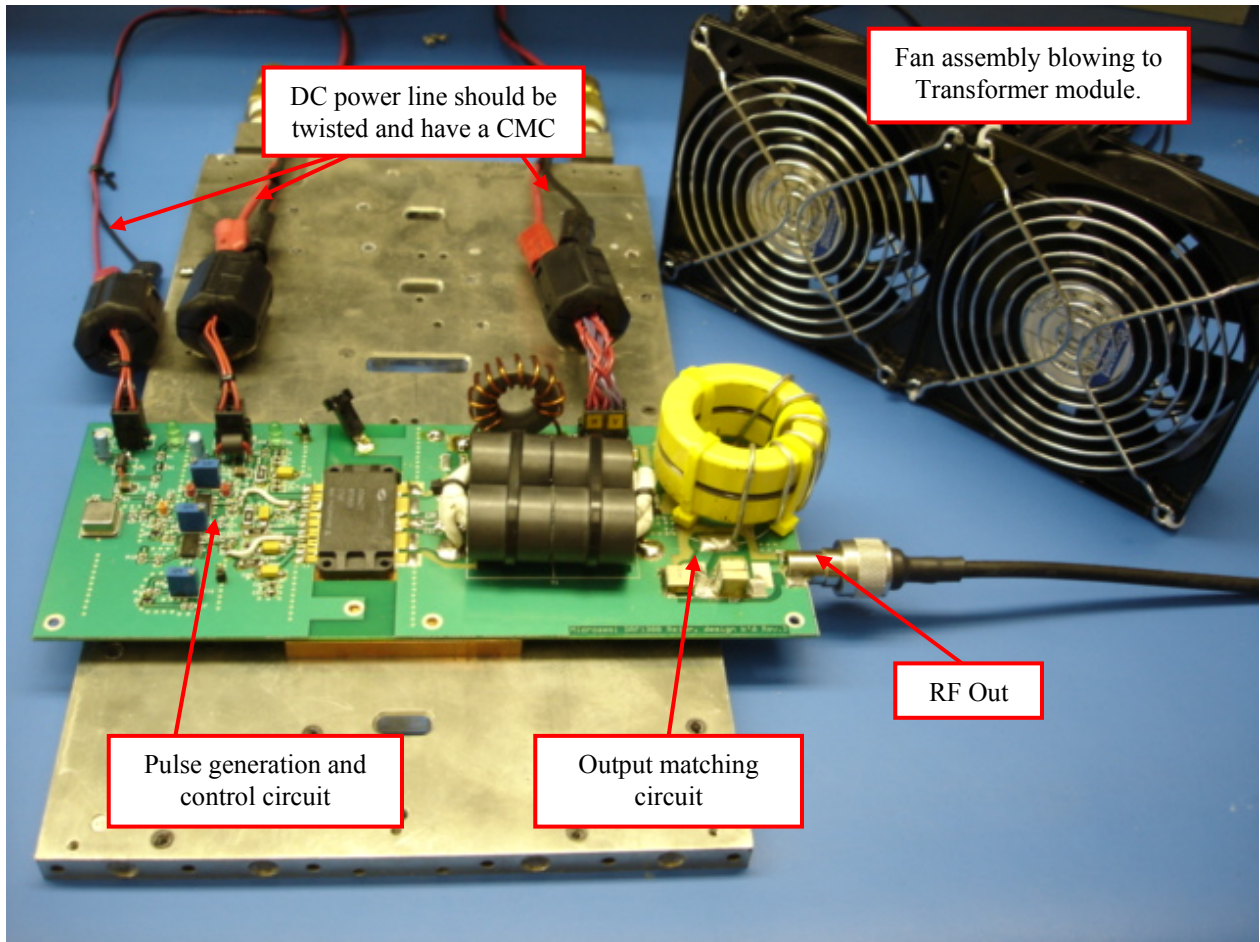


Figure 9. Bench Test Set-up for DRF1300

PERFORMANCE

Step	PS 2, V	Id, A	Pin, W	RF out, W	η , %	Vds, V
1	100	4.31	431	344	79.8	200
2	120	4.91	589	486	82.5	232
3	140	5.54	776	653	84.2	270
4	160	6.18	989	842	85.2	310
5	170	6.48	1,102	939	85.2	340
6	180	6.79	1,222	1044	85.4	360
7	190	7.11	1,351	1152	85.3	370
8	200	7.43	1,486	1270	85.5	390
9	210	7.75	1,628	1400	86.0	420
10	220	8.00	1,760	1500	85.2	430
11	230	8.36	1,923	1630	84.8	480
12	240	8.67	2,081	1770	85.1	506
13	250	9.18	2,295	1950	85.0	535

Table 2. Typical Performance Data

Table 2 shows the typical performance and the several steps that should be observed before proceeding to the next step and ultimately to 2KW. The table lists the input high voltage supply (PS_2), MOSFET drain current (Id), power in and power out with efficiency, and the voltage observed at MOSFET drain (Vds). Variation of efficiency vs. Pout is shown in Figure 10 and PS_2 vs. Vds is shown in Figure 11. Efficiency is calculated using RF power output and DC input power of the power MOSFET. The efficiency in the table is at 13.56Mhz.

It should be noted that Vds exceeded the maximum BVdss (500V) of the MOSFETs in steps 12 and 13. The excess voltage to achieve 2KW output power resulted from transformer leakage inductance and lack of the broadband transfer characteristics of the wire-coupled transformer. A 2KW power output can be achieved with a Vds less than 500V by further tuning and optimization of the transformer.

c. **Power and voltage graphs**

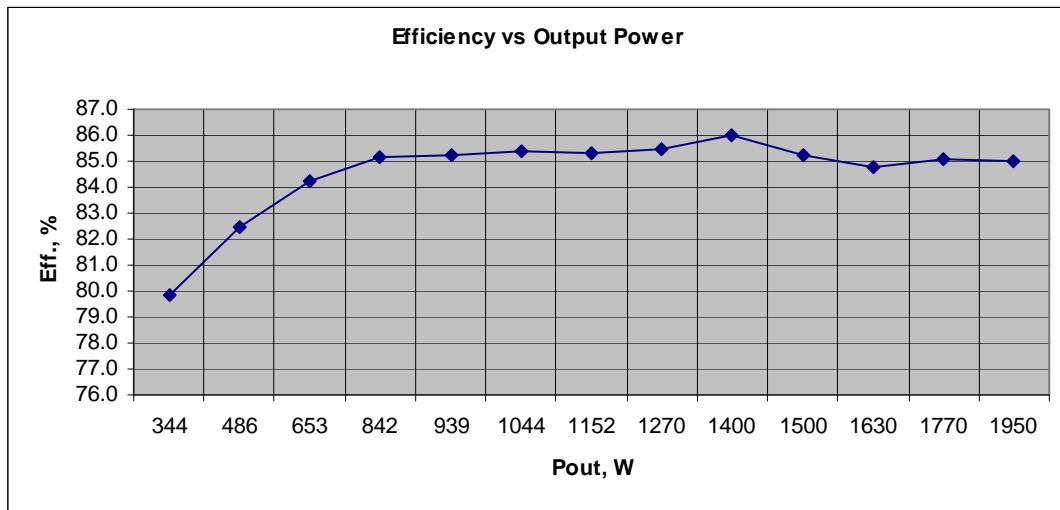


Figure 10. Efficiency vs. Power

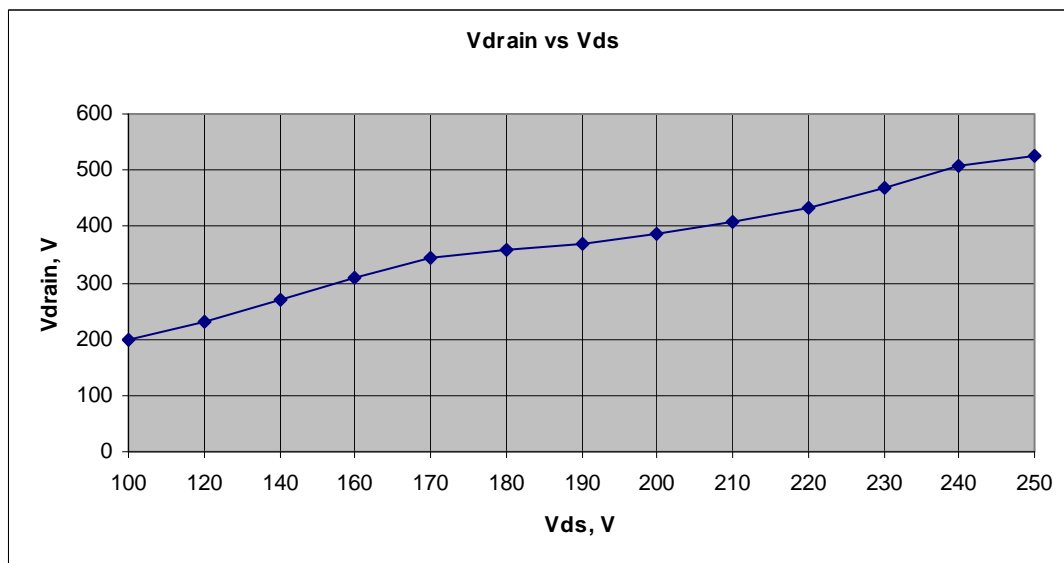


Figure 11. HV PS vs. Vds

d. Vds waveforms for various HV PS voltages

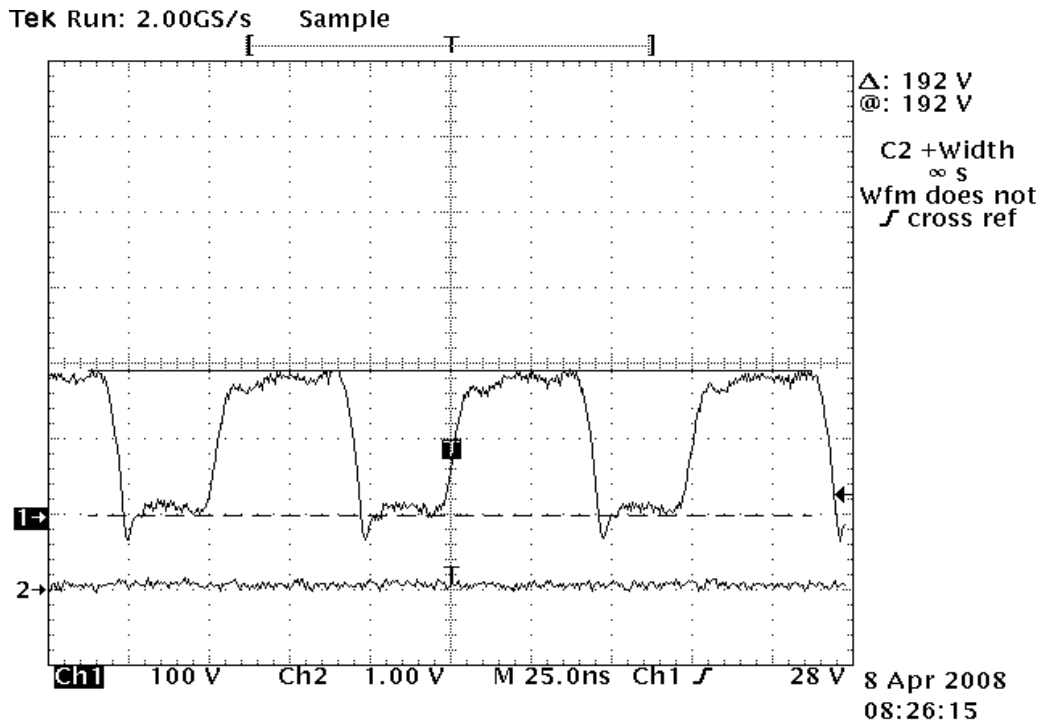


Figure 12. Waveform when HV PS =100V

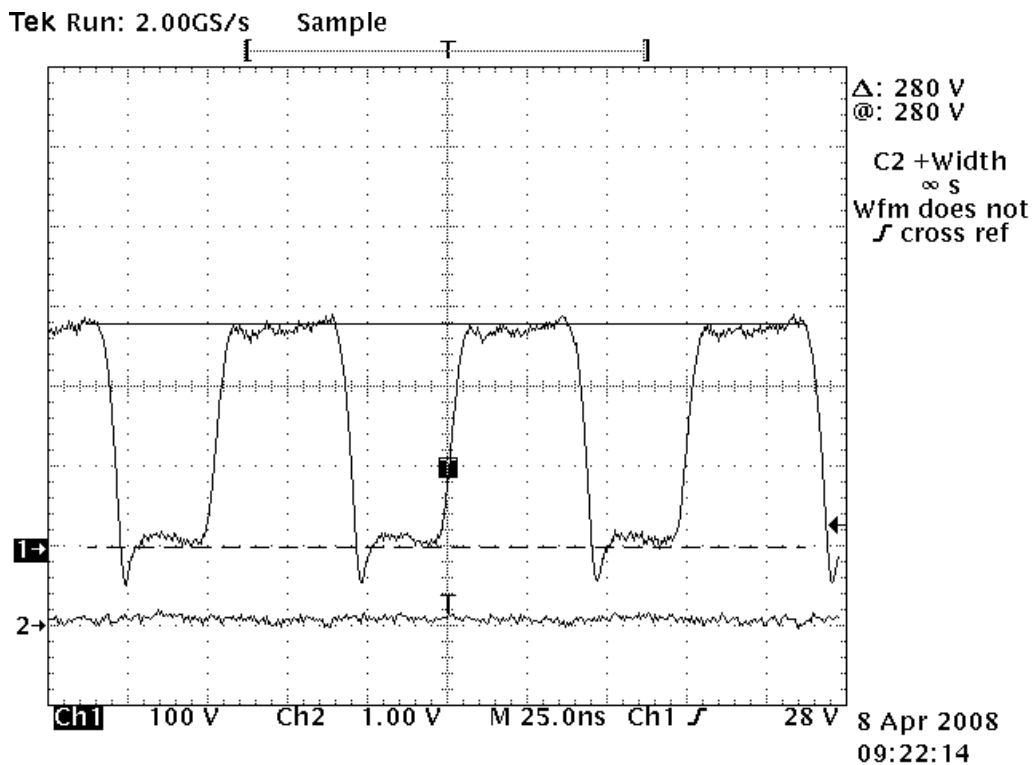


Figure 13. Waveform when HV PS = 150V

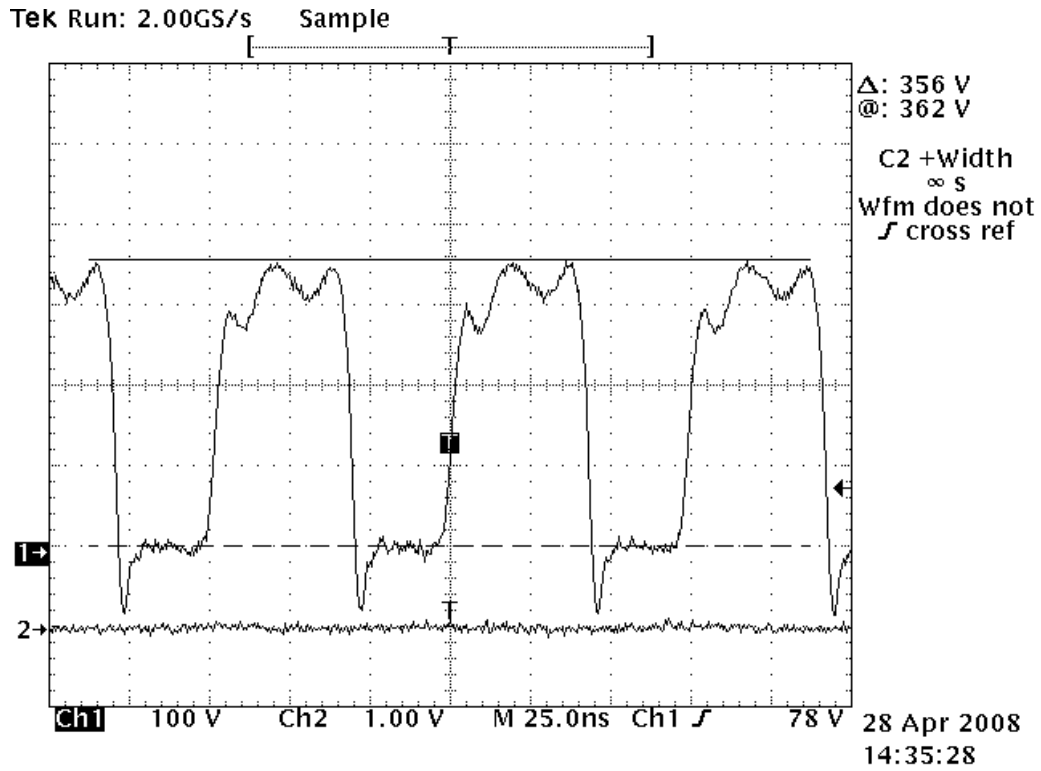


Figure 14. Waveform when HV PS = 180V

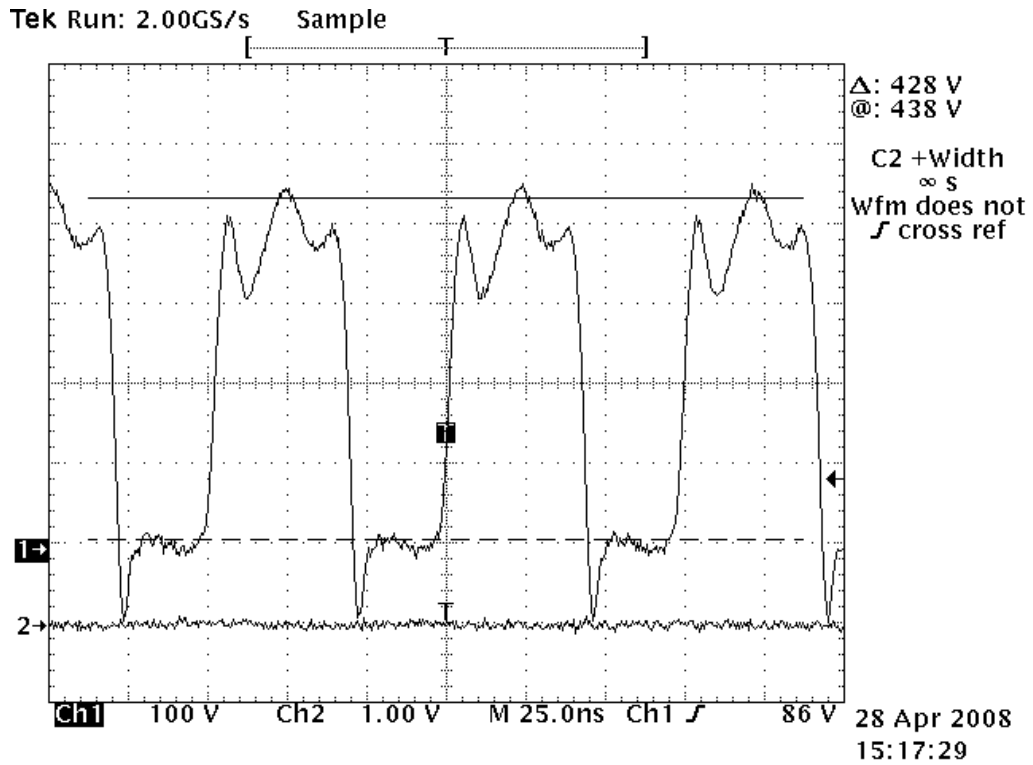


Figure 15. Waveform when HV PS = 220V

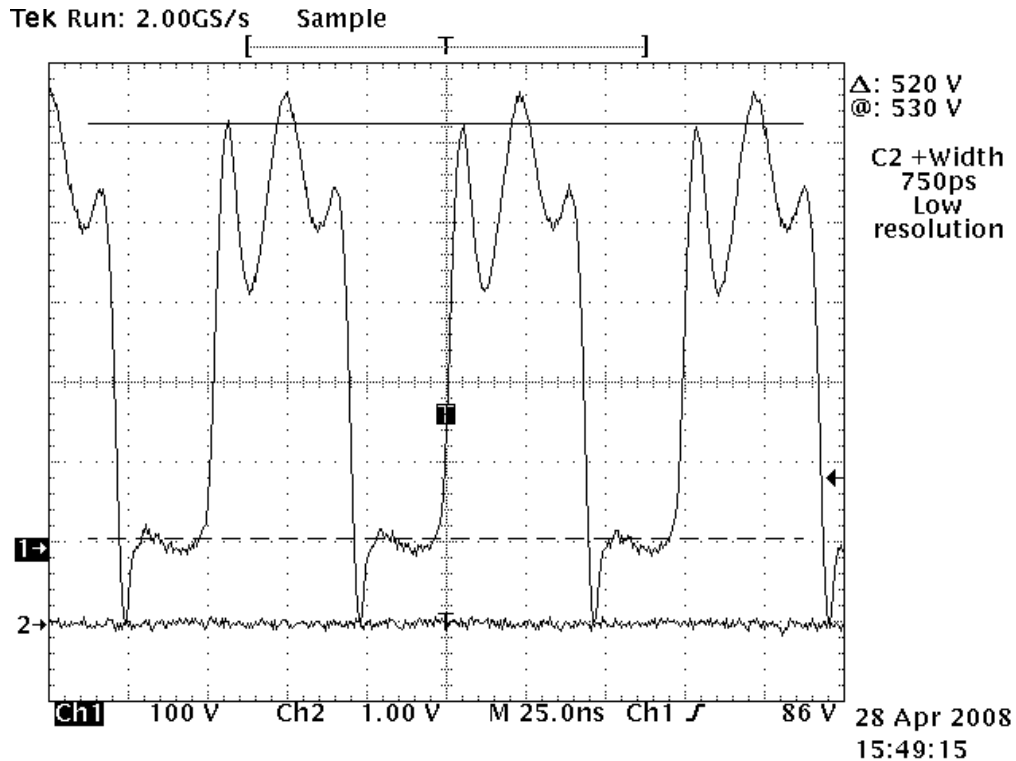


Figure 16. Waveform when HV PS =250V

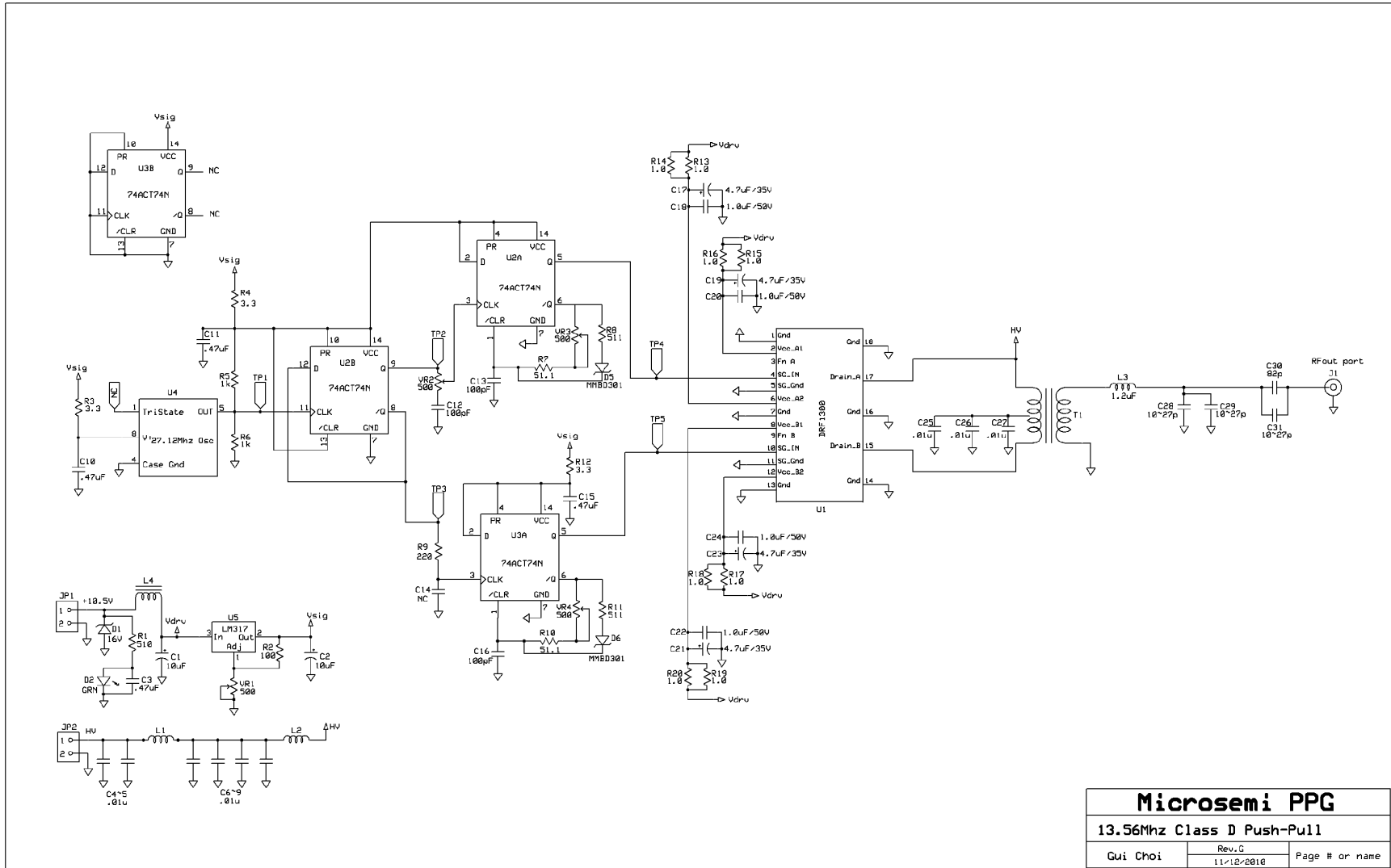
CONCLUSION

This Application Note describes design of a 2KW, 13.56MHz, Class D Push-Pull, RF generator. A Microsemi DRF1300 Hybrid was used to overcome layout parasitics that simplified the design and providing a single low cost, high efficiency RF generator. Limitations in transformer bandwidth caused this application to exceed the 500V breakdown voltage of the MOSFETs while achieving 2KW. Transformer design can be further optimized to eliminate the peaking as shown in the Vds waveforms. The principles of this application note can be verified with the DRF1300/CLASS-D reference design from Microsemi. The reference design minimizes design time by allowing an engineer to evaluate the performance into a 50 Ohm load and provides a platform for more complex load matching.

REFERENCES

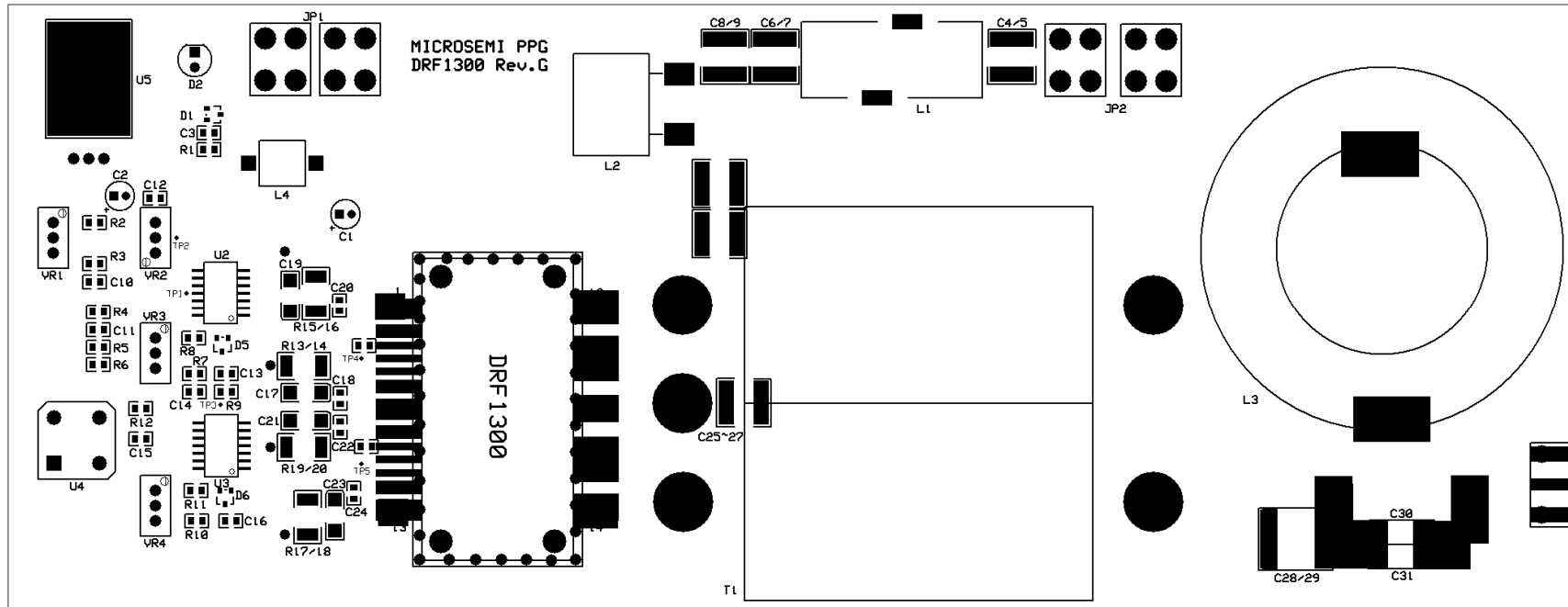
- Solid State Radio Engineering – Herbert L. Krauss and Charles W. Bostian
- Application Note: Simple and Inexpensive High Efficiency Power Amp using New APT MOSFET – Kenneth Dierberger 1994
- Application Note: 3KW and 5KW Half-Bridge Class-D RF Generator at 13.56Mhz with 89% Efficiency and Limited frequency Agility – DEI, Inc

Appendix I. Overall Schematic



Appendix II. PCB Lay-out

PCB size: 4.0W * 10.04L in inch
PCB: FR-4, 65mil T



Appendix III. Parts List

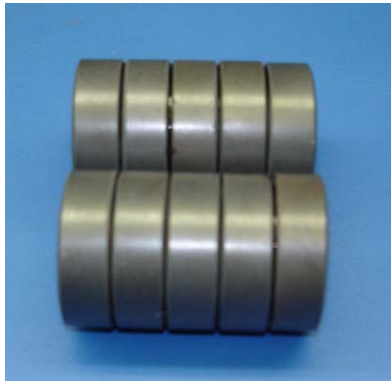
Part ID	Description	Size	Supplier	Supplier PN	Manufacturer	Manuf. PN
U1	DRF1300	T4B	Microsemi	DRF1300	Microsemi	DRF1300
C1	10uF/35V(Cer. cap)	1812	Digi-key	pcc2183ct-nd		
C2	10uF/16V(Elec cap)	5*11	Mouser	140-XRL16V10-RC	Xicon	140-XRL16V10-RC
C3	.47uF/50V(Cer. Cap)	805	Digi-key	490-3328-1-ND		GRM21BR71H474KA88L
C4	0.01uF/2KV	2225	Digi-key	478-3024-1-ND	AVX	2225GC103KAT1A
C5	0.01uF/2KV	2225	Digi-key	478-3024-1-ND	AVX	2225GC103KAT1A
C6	0.01uF/2KV	2225	Digi-key	478-3024-1-ND	AVX	2225GC103KAT1A
C7	0.01uF/2KV	2225	Digi-key	478-3024-1-ND	AVX	2225GC103KAT1A
C8	0.01uF/2KV	2225	Digi-key	478-3024-1-ND	AVX	2225GC103KAT1A
C9	0.01uF/2KV	2225	Digi-key	478-3024-1-ND	AVX	2225GC103KAT1A
C10	.47uF/50V(Cer. Cap)	805	Digi-key	490-3328-1-ND		GRM21BR71H474KA88L
C11	.47uF/50V(Cer. Cap)	805	Digi-key	490-3328-1-ND		GRM21BR71H474KA88L
C12	100pF/50V(Cer. Cap)	805	Digi-key	PCC101CGCT-ND		
C13	100pF/50V(Cer. Cap)	805	Digi-key	PCC101CGCT-ND		
C14	NC					
C15	.47uF/50V(Cer. Cap)	805	Digi-key	490-3328-1-ND		GRM21BR71H474KA88L
C16	100pF/50V(Cer. Cap)	805	Digi-key	PCC101CGCT-ND		
C17	4.7uF/35V(Tant cap)	6032-28	Digi-key	478-1717-1-ND	AvX	TAJ475K035R
C18	1.0uF/50V(Cer. Cap)	805	Digi-key	587-1438-1-ND	Taiyo Yuden	GMK212BJ105KG-T
C19	4.7uF/35V(Tant cap)	6032-28	Digi-key	478-1717-1-ND	AvX	TAJ475K035R
C20	1.0uF/50V(Cer. Cap)	805	Digi-key	587-1438-1-ND	Taiyo Yuden	GMK212BJ105KG-T
C21	4.7uF/35V(Tant cap)	6032-28	Digi-key	478-1717-1-ND	AvX	TAJ475K035R
C22	1.0uF/50V(Cer. Cap)	805	Digi-key	587-1438-1-ND	Taiyo Yuden	GMK212BJ105KG-T
C23	4.7uF/35V(Tant cap)	6032-28	Digi-key	478-1717-1-ND	AvX	TAJ475K035R
C24	1.0uF/50V(Cer. Cap)	805	Digi-key	587-1438-1-ND	Taiyo Yuden	GMK212BJ105KG-T
C25	0.01uF/2KV	2225	Digi-key	478-3024-1-ND	AVX	2225GC103KAT1A
C26	0.01uF/2KV	2225	Digi-key	478-3024-1-ND	AVX	2225GC103KAT1A
C27	0.01uF/2KV	2225	Digi-key	478-3024-1-ND	AVX	2225GC103KAT1A
C28	10P ~ 27PF/3600V	3838	ATC	100E100 ~ 270KW3600X		For tuning
C29	10P ~ 27PF/3600V	3838	ATC	100E100 ~ 270KW3600X		For tuning
C30	82PF/3600V	3838	ATC	100E820KW3600X	ATC	100E820KW3600X
C31	10P ~ 27PF/3600V	3838	ATC	100E100 ~ 270KW3600X		For tuning
R1	510ohm 1/8W	805	Digi-key	P510ATR-ND	Panasonic	ERJ-6GEYJ511V
R2	100ohm 1/8W	805				
R3	3.3ohm 1/8W 5%	805	Digi-key	P3.3ACT-ND	Panasonic	ERJ-6GEYJ3R3V
R4	3.3ohm 1/8W 5%	805	Digi-key	P3.3ACT-ND	Panasonic	ERJ-6GEYJ3R3V
R5	1.0K ohm 1/8W 1%	805	Digi-key	P1.00KCCT-ND	Panasonic	ERJ-ENF1001V
R6	1.0K ohm 1/8W 1%	805	Digi-key	P1.00KCCT-ND	Panasonic	ERJ-ENF1001V
R7	51.1ohm 1/8W 1%	805	Digi-key	P51.1CCT-ND	Panasonic	ERJ-6ENF51R1V
R8	511ohm 1/8W 1%	805	Digi-key	P511CCT-ND	Panasonic	ERJ-6ENF5110V
R9	220ohm 1/10W .5%	805	Digi-key	P220ACT-ND	Panasonic	ERJ-6GEYJ221V
R10	51.1ohm 1/8W 1%	805	Digi-key	P51.1CCT-ND	Panasonic	ERJ-6ENF51R1V
R11	511ohm 1/8W 1%	805	Digi-key	P511CCT-ND	Panasonic	ERJ-6ENF5110V
R12	3.3ohm 1/8W 5%	805	Digi-key	P3.3ACT-ND	Panasonic	ERJ-6GEYJ3R3V
R13	1ohm 1W 5%	2512	Digi-key	PT1.0XCT-ND	Panasonic	ERJ-1TYJ1R0U
R14	1ohm 1W 5%	2512	Digi-key	PT1.0XCT-ND	Panasonic	ERJ-1TYJ1R0U
R15	1ohm 1W 5%	2512	Digi-key	PT1.0XCT-ND	Panasonic	ERJ-1TYJ1R0U
R16	1ohm 1W 5%	2512	Digi-key	PT1.0XCT-ND	Panasonic	ERJ-1TYJ1R0U
R17	1ohm 1W 5%	2512	Digi-key	PT1.0XCT-ND	Panasonic	ERJ-1TYJ1R0U
R18	1ohm 1W 5%	2512	Digi-key	PT1.0XCT-ND	Panasonic	ERJ-1TYJ1R0U
R19	1ohm 1W 5%	2512	Digi-key	PT1.0XCT-ND	Panasonic	ERJ-1TYJ1R0U
R20	1ohm 1W 5%	2512	Digi-key	PT1.0XCT-ND	Panasonic	ERJ-1TYJ1R0U
VR1	POT 500ohm 1W	3/8" sq	Digi-key	3292W-501-ND	Bourns	SM:3269W-1 501
VR2	POT 500ohm 1W	3/8" sq	Digi-key	3292W-501-ND	Bourns	SM:3269W-1 501
VR3	POT 500ohm 1W	3/8" sq	Digi-key	3292W-501-ND	Bourns	SM:3269W-1 501
VR4	POT 500ohm 1W	3/8" sq	Digi-key	3292W-501-ND	Bourns	SM:3269W-1 501
D1	16V (Diode Zener)	SOT23	Digi-key	BZX84C16-FDICT-ND	Diodes	BZX84C16-7-F
D2	LED, green	5mm	Digi-key	P375-ND	Panasonic	LN31GPH
D3	NC					
D4	NC					
D5	30V/200mW(Diode Schot)	SOT23	Digi-key	MMBD301LT1GOSCT-ND	On Semi.	MMBD301LT1G
D6	30V/200mW(Diode Schot)	SOT23	Digi-key	MMBD301LT1GOSCT-ND	On Semi.	MMBD301LT1G
L1	RFChoke with 11T AWG14		Fair Rite Mouser	5961001701 566-8073	Belden	8073
L2	Toroidal RFC with 1T AWG22		Fair-Rite Digikey	2661000301 A2016R-100-ND		
L3	Toroidal Inductor with 6T 12AWG		Micrometals Mouser	T225-6 5.5T ---- 2ea 602-289-100	Micrometals Alpha	T225-6 5.5T 289
L4	Toroid RFC 2T AWG20		Fair-Rite Digikey	2643375102 A2040R-100-ND	Alpha	5856 AWG20 Red
T1	Transformer with 2:1 TR				Fair-Rite	5967001701 ---- 10ea 14 AWG
U2	Dual Flip-Flop	14SOP	Digi-key	296-13131-1-ND	TI	SN74ACT74NSR
U3	Dual Flip-Flop	14SOP	Digi-key	296-13131-1-ND	TI	SN74ACT74NSR
U4	27.12 MHz Osc		Allied	EP1100HSTSC-27.120M	Ecliptek Co.	EP1100HSTSC-27.120M
U5	Adj. Regulator			LM317		
J1	RFout port	Edge	Newark	12M4398	Bomar	161V504E
JP1	DC Terminal		Allied	839-0309	Keystone	8191
JP2	DC Terminal		Allied	839-0309	Keystone	8191

Appendix IV. Process of building the high-power high bandwidth transformer T1

Step 1.
Cement five ferrite cores together using epoxy glue.



Step 2.
Combine two ferrite cores assembly.



Step 3
Cut 5 12-inch lengths for each section (white and yellow) for the primary and 5 22-inch lengths for the secondary (black). These wires are insulated 18 AWG (Alpha 5877) for primary and 16AWG for secondary (Alpha 5858). Twist the two primary wires and the two secondary wires together.



Step 4
Pull the wire bundle through the ferrite cores.



Step 5
Pull the free ends of the wire bundle back through the ferrite cores.



Step 6
Pull the free ends of the wire bundle once more back through the ferrite cores.



Step 7
Finished transformer showing twisted wires through ferrite cores assembly with wire ends bent down to mount to printed wiring board. There is a 1:2 Turn Ratio, which means 1:4 Impedance ratio of the transformer.

